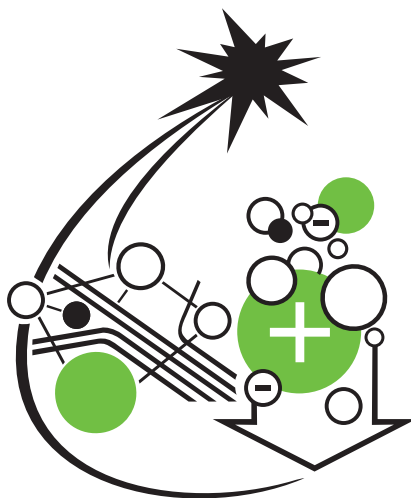


National Research Tomsk Polytechnic University  
Institute of High Current Electronics SB RAS  
Tomsk Scientific Center SB RAS



# EFRE

**INTERNATIONAL CONGRESS ON  
ENERGY FLUXES  
AND RADIATION EFFECTS**

# ABSTRACTS

**October 2-7, 2016**

Tomsk, Russia



Tomsk

Tomsk Polytechnic University Publishing House

2016

National Research Tomsk Polytechnic University  
Institute of High Current Electronics SB RAS  
Tomsk Scientific Center SB RAS

# **International Congress on Energy Fluxes and Radiation Effects**

Abstracts

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2016

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The proceedings includes the abstracts of reports presented at the V<sup>th</sup> International Congress on Energy Fluxes and Radiation Effects (EFRE-2016). The Congress combines three International Conferences held in Tomsk: Symposium on High Current Electronics (SHCE), Conference on Modification of Materials with Particle Beams and Plasma Flows (CMM) and Conference on Radiation Physics and Chemistry of Condensed Matter (RPC).

The Congress is a large-scale scientific event and a communication platform for discussing the most urgent and relevant achievements in such fields as pulsed power technology, ion and electron beams, high-power microwaves, sources of plasma and particle beams, modification of material properties, pulsed power applications in chemistry, biology and medicine, physical and chemical non-linear processes in inorganic dielectrics under the action of particle and photon beams, and physical principles of radiation-related technologies.

Full materials of the Congress will be published in the following journals: Journal of Physics: Conference Series, Izvestiya vuzov. Fizika, Russian Physics Journal and Vacuum.

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To participants of the V International Congress  
on Energy Fluxes and Radiation Effects (EFRE 2016),  
Tomsk, October 2–7, 2016

Highly esteemed colleagues and guests of the Congress!

Welcome to the V International Congress on Energy Fluxes and Radiation Effects!

In 2000 a joint decision of the heads of Tomsk Polytechnic University and the Institute of High-current Electronics of SB RAS gave birth to the periodical international forums uniting the International Symposium on High-Current Electronics (SHCE), International Conference on Modification of Materials with Particle Beams and Plasma Flows (CMM) and International Conference on Radiation Physics and Chemistry of Condensed Matter (RPC). Remarkably, at that time each of those already had a prominent background of its own. So, the united event was doomed to succeed. Subsequent Congresses took place in 2006, 2012 and 2014, and each time they attracted a great number of scientists and developers from many countries around the globe. Today's forum is the 5th event.

Congress delivers the most value through stimulating connections between three vast fields of physics and technology that play an increasingly important role in the technological development of the society. Pulsed power energy and high-current electronics provide an engineering base for electric discharge, plasma beam and radiation technologies. Those effectively fill and augment technological niches in most diverse industrial branches: military defense, chemistry, biology and medicine. The participants of the Congress are presented a wide landscape of fundamental and applied problems, as well as possibilities to investigate them from the perspective of a theorist, experimentalist or engineer.

It is no coincidence that the Congress was originated and is regularly held in Tomsk. It is home to a tremendous research and education network and to outstanding physical and technological schools. It is Tomsk where many scientific research trends – outlined in the Congress's sections – have germinated and have been fostered. Forum activities involve representatives of Tomsk student communities whose members are ready to implement scientific achievements and try themselves as researchers and developers.

The participation of world's leading scientists makes the Congress an important platform for global scientific communication and for networking collaborations. Those ensure more efficient fundamental research and implementation of knowledge-intensive technologies.

I wish to Congress organizers a successful execution of the event, and to all its participants, a fruitful working experience, engaging communication and many advances in research and development!

Congress Chair  
Academician Gennady Mesyats



26.9.2016



# **19<sup>th</sup> International Symposium on High Current Electronics**



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**Sessions:**

Intense electron and ion beams  
 Pinches, plasma focus and capillary discharge  
 High power microwaves  
 Pulsed power technology  
 Discharges with runaway electrons  
 Pulsed power applications

**THE INFLUENCE OF SPACE CHARGE AND ANGULAR DIVERGENCE  
OF THE ELECTRON BEAM TO REFLECTION ELECTRONS FROM MAGNETIC  
MIRROR DURING TRANSPORTATION**

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In the Institute of Nuclear Physics SB RAS on the open magnetic trap GOL-3 an experiments were carried out on an electron beam generation (up to 100 keV, 100 A, diameter up to 5 cm) in the multiaperture diode with plasma emitter. The beam was formed in moderate magnetic field (5–20 mT), transported along magnetic field increasing up to 1 T and injected into the trap. Beam duration (0.1–0.5 ms) was limited due to electrical breakdown of diode which was observed in the experiment. One of possible causes of this limitation may be electrons reflected by increasing magnetic field. The present paper considers reflection of electrons analytically and numerically, taking into account angular velocity divergence, self-azimuthal magnetic field of the beam and its volume charge of different degree of neutralization that to compare it with experiment.

Firstly, an analytical estimate of the vacuum beam current limit, taking into account the initial pitch angles of electrons and beam compression in magnetic field was made. A numerical code POISSON-2 was used to calculate velocity divergence of electron beam generated in the diode. It was used then together with experimental one for simulation by the codes ERA and POISSON-2 of transporting the beam through the channel in conditions corresponding to real experiments. As a result, maximal beam currents without reflection of electrons were found and compared with corresponding experimental values. They were found to be in a good agreement.

**Keywords:** *vacuum limit current, electron beam transportation, magnetic mirror, pitch angle.*

## ON THE STABILITY OF OPERATION OF AN EXPLOSIVE-EMISSION CATHODE IN A PLASMA-FILLED DIODE

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To provide stable operation of high-current electron guns is an actual and, at the same time, a complicated task. The complexity of this task is caused by explosive emission of the cathode which represents especially non-stationary and non-equilibrium phenomena.

Resistive decoupling is well-known method stabilizing an operation of explosive-emission cathodes. It allows one to suppress the emission centers-leaders, consistently appearing while operation of wide-area explosive-emission cathodes. Availability of centers-leaders reduces a number of concurrent emission centers and therefore degrades the homogeneity and stability of cathode operation. To suppress centers-leaders it is needed to limit the current through each of them. Current of each center may be limited by space charge of electron flux emitted by respective center, or by connecting resistors in series to each emitter. In the case of vacuum diode, the resistive decoupling can be easy realized. But in the case of plasma-filled diode, it requires careful isolation of the cathode substrate because an unacceptable emission can be initiated on a flat surface touched by the anode plasma.

We have developed and studied two cathodes with metal (not carbon) emitters. The first cathode was made from resistors of type TBO-1 (156 pcs), wire leads of which served as emitters. Emitters of the second cathode were made of Ni-Cr wires of 100  $\mu\text{m}$  in diameter (297 pcs) inserted into ceramic tubes. It was found that the first cathode reveals more stable operation in comparison with the second one and in comparison with traditional copper-braid, multi-wire cathode.

**Keywords:** *plasma-filled diode, explosive-emission cathodes, resistive decoupling, high-current electron gun.*

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## THE INFLUENCE OF RESONANCE EFFECTS ON THE RADIATIVE CHARACTERISTICS OF HELIUM PLASMA

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In the present work, the influence of an alternating circularly polarized electric field on the energy spectrum of the He atom is studied. The calculations are performed by the method of the energy matrix diagonalization of an atom in the electric field. This method has allowed us to study the behaviour of the helium energy spectrum from the same numerical procedure under resonant and non-resonant excitations by the electric field. Based on the calculation results, we have found that the resonance effects take place not only in the vicinity of resonance, but they influence on the shift directions of the Stark states even under non-resonant excitation. Additionally, we have established that the helium energy spectrum behaves consistently in the electric field. The results obtained have allowed us to clarify mechanisms of the influence of the resonance effects on the radiative characteristics of helium plasma.

**Keywords:** *radiative characteristics of helium plasma.*



## LOW-IMPEDANCE ROD-PINCH DIODE EXPERIMENT ON THE MIG GENERATOR

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Low-impedance rod-pinch diode, described in this paper, is preliminarily shorted with a radial wire array. In the initial stage of the generator current pulse energy accumulates in the inductive load. The J B force accelerates the wire plasma to the anode rod tip. A vacuum gap (electron diode) forms when plasma of the wire material is detached from the anode rod. In the subsequent time, the size of the gap and diode impedance is determined by the movement of wire and rod plasmas. The experiments were performed on the MIG pulsed power generator (1 MV, 1.5 MA, 80 ns) at Institute of High Current Electronics SB RAS. It is shown that the transition from axisymmetric configuration with injected plasma or radial foil to not significantly axisymmetric configuration with multiple wire arrays does not modify any substantial result in part of the electron beam focusing on the rod tip.

**Keywords:** *rod-pinch diode, wire array, focused electron beam, hard x-ray.*

## DISTRIBUTION OF THE ENERGY DENSITY OF A PULSED ION BEAM

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The paper investigates distribution of the energy density over the cross section of a pulsed ion beam formed by a diode with passive anode in magnetically insulation mode.

Studies of three types of diodes, in a mode of external magnetic insulation (BIPPAB-450 accelerator, 400 kV, 80 ns) and self-insulation (TEMP-4M accelerator, 250 kV, 120 ns) have been performed. Studied diodes utilize different methods for anode plasma formation: dielectric surface breakdown followed by ionization by accelerated electrons (BIPPAB-450 accelerator, a barrel diode), and explosive electron emission (strip planar and spiral diodes in TEMP-4M accelerator). To analyze the energy density of the ion beam we used infrared imaging diagnostics with a spatial resolution of 1–2 mm.

The calculation of the energy density using the 1-D Child-Langmuir equation was performed. We observed effective formation of plasma layer on the working surface of the anode for all investigated diodes. It was found that the magnetic induction in the A-C gap of the barrel diode is much higher than the critical value and the experimental values of energy density coincide with the calculation for carbon ions and the energy density distribution is uniform over the cross section. By reducing the magnetic induction in the A-C gap to a value close to the critical, the ion beam energy density is 3–6 times higher than the calculated by 1-D Child-Langmuir limit and the energy density of the ion beam is non-uniform.

This research was supported by the «Science» project № 2159.

**Keywords:** *pulsed ion beam, energy density, surface modification.*

## ION BEAM DEFLECTION IN FOCUSING MAGNETICALLY INSULATED ION DIODES WITH PASSIVE ANODE

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High-intensity pulsed ion beam deflection are investigated and compared in two types of focusing magnetically insulated ion diodes (MID) of the passive anode, i.e. with external magnetic insulation and self-insulation of electrons. The anode plasma formation processes are also varied for the external- and the self-magnetic field MID, either based on surface breakdown of dielectric covering on the anode (an one-pulse mode) or explosive electron emission (a two-pulse mode). Typical energy density per pulse is in the range of 3–6 J/cm<sup>2</sup>, at an accelerating voltage of 200–300 kV with a pulse duration of 120–150 ns. IR-diagnostics with the spatial resolution 1 mm is employed for analysis of the ion beam. The ion beam deviation is about ±1.5 mm for external-magnetic field MID and ±2.5 mm for the self-magnetic field MID, leading to a fluctuation in the energy density of 10–12 % and 10–27 % within 10 mm range at the focal point, respectively. It is shown that displacement of different parts of a beam cross-section is nonsynchronous, revealing that ion beam deflection is mainly caused by processes in anode-cathode gap other than in the transportation region.

This research was supported by the by National Science Foundation of China under Grants Nos. 51371043 and 51321004, and grant RFBR No. 16-48-700012.

**Keywords:** ion beam deflection, IR-diagnostics, fluctuation in the energy density.

**CATHODES FOR NANOSECOND ELECTRON ACCELERATORS TYPE URT*****SERGEY SOKOVNIN AND MICHAEL BALEZIN****Institute of Electrophysics of the Ural Branch of the Russian Academy of Sciences, Russia  
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In many technological applications the electron beams of big size on one of coordinates are required. The cold cathode used for these purposes has to possess high stability of characteristics, durability and to generate a uniform distribution of the electron beam current density. Complex research of properties of metal dielectric (MD) cathode on the URT-1M accelerator was executed. Influence of quantity and a relative positioning of the emission elements (plates) on a beam parameters and distribution of the electron beam current density was established. Also influence of a form of the cathode case, on stability of work on high repetition rate (more than 50pps) was investigated. The measurement technique using pulsed cathode luminescence (PCL) of phosphor to estimate distribution of the electron beam current density was developed. This PCL-technique was tested by dosimetry technique using SO PD(F)R-5/50 detectors, qualitative compliance of the both techniques results was established. By selecting the number and arrangement of MC plates, it is possible to obtain a rather uniform (15 %) electron beam current density distribution on the output foil. For generating an electron beam up to 420 mm widewith a non-uniform distribution of the electron beam current density on the output foil ~ 15 % the MD cold cathode was created. It was used with the repetition rate up to 300pps in electron accelerators type URT-1 and URT-0,2 for food irradiation (milk and eggs) in flow.

***Keywords:*** *cold cathode, electron beam, accelerator.*

**PLASMA-ANODE ELECTRON BEAM SOURCE SUPPLIED BY  
MARX GENERATOR WITH RECTANGULAR VOLTAGE PULSE**

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Experimental results on electron beam generation in the electron source with the explosive emission cathode and plasma anode supplied by Marx generator with rectangular waveform of the output voltage are presented. Presence of three phases in the process of the electron beam conductivity rise was registered: the phase of the initial rise of conductivity, the quasi-stationary phase and the phase of the iterated rise of conductivity. Possibility to obtain electron beams with quasi-constant values of the beam current and voltage at the interelectrode gap in the quasi-stationary phase was demonstrated. At the interelectrode gap voltage of 100-120 kV, electron beams with currents up to 4 kA and length up to 10  $\mu\text{s}$  as well as currents of up to 5-6 kA and length up to 5  $\mu\text{s}$  with the cross-section of 50  $\text{cm}^2$  and energy density of 25-30  $\text{J}/\text{cm}^2$  were obtained.

***Keywords:*** *explosive emission cathode, plasma anode, Marx generator with rectangular pulse.*

## OPTICAL AND THERMAL CHARACTERISTICS OF DBD-DRIVEN ATMOSPHERIC PRESSURE PLASMA JET SOURCES

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It is shown that for the minimal gas flow rate ( $\sim 0.5$  L/min) in conditions of the barrier discharge with excitation pulse parameters  $\tau = 1\text{--}1.5$   $\mu\text{s}$ ,  $f = 65\text{--}85$  kHz, and voltage amplitude up to 13 kV, plasma jets of length  $l$  up to 4 and 3 cm are formed in air and nitrogen, respectively, with typical diameters not exceeding 0.5–1.0 mm. Study of optical and thermal parameters of the atmospheric pressure plasma jet sources is performed. The obtained data allow us to choose applications for these devices.

The work is performed in the framework of the Russian Science Foundation (the project #14-29-00052).

**Keywords:** *plasma jet, atmospheric pressure, nitrogen, air.*

## TEMPORAL AND SPATIAL PROFILES OF IONIZATION WAVES OF APOKAMP

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Atmospheric pressure plasma jets represent the process of ionization waves propagation. It is observed visually as a set of so-called «plasma bullets». In current work the spatial-temporal structure of ionization waves in apokamp is obtained. Apokamp is a new kind of plasma jet which has been discovered in 2016. Images with a temporal resolution in the range from several ns to several tens of ns indicates that apokamp realized in air is a set of plasma bullets with velocity value of from 100 to 220 km/h.

**Keywords:** *apokamp, atmospheric pressure, ionization waves, plasma bullets.*

**ENERGY DISTRIBUTION OF METALLIC IONS IN A PULSED IMPLANTER***OLGA SHIPILOVA, ALEXEY CHERNICH AND VICTOR PAPERNY**Irkutsk State University, Russia  
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Energy distribution of ion beam (IED) originated from a pulsed ion implanter MEVVA.RU (pulse duration of 200 microsecond, ion current peak up to 1 A) was studied by means of electrostatic energy analyzer in a range of energies up to 15 keV. It was found that the characteristics of the IED depended on an applied accelerating voltage. Namely, the most probable energy per a charge unit was less than accelerating voltage, and ratio of difference between these values to energy decreases from 0.25 at accelerating voltage of 2 kV down to 0.14 at voltage of 10 kV. Moreover, ratio of width of the IED to accelerating voltage decreased from 0.75 to 0.28 when the voltage varied within the same range. It was found as well that the IED contained an appreciable amounts of ions with energies significantly exceeding values of probable energy per a charge unit. A possible mechanism for this effect is considered.

**Keywords:** *energy distribution, ion beam, electrostatic energy analyzer, accelerating voltage.*



**PLASMA OPTICAL SYSTEMS  
FOR THE INTENSE-ELECTRON-BEAM TRANSPORT**

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The paper presents the recent researches of plasma-optical systems and some results in intense-electron-beam forming and transport through ones. The plasma-optical system on one side is formed by the grid-bounded plasma emission surface in vacuum arc electron source, and on the other hand the open (gridless and electrodeless) plasma boundary. The plasma is created by the axis-symmetric cylindrical electrostatic plasma lens configuration similar an anode layer thruster with closed drift electron. Studies were carried out several geometries plasma lens. The plasma properties as well as the plasma-optical properties of an electromagnetic system of the lens for the electron beam transport were studied in detail. The experiments show that with the plasma-optical system of the studied geometries it is possible to form and transport an intense electron beam (up to 80 A) with high stability and pulse shape reproducibility of the beam current in a wide beam energy range close to 40 kV. This mode of transportation features a high electric strength of the plasma acceleration gap, namely almost entire absence of the high-voltage breakdowns.

The work supported by RFBR (Russia) under the grant № 16-08-00370 and SFBR (Ukraine) under the grant № F53.2/013.

**Keywords:** *Plasma-optical system, plasma electron source, anode layer thruster vacuum arc.*

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**SOURCE OF ELECTRONS BASED ON LITHIUM NIOBATE  
CRYSTAL DOPED BY IRON**

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Investigate the emission of electrons in the process of heating or cooling a crystal of lithium niobate doped by iron. For researching was used crystals of various sizes with Z orientation of the polarization plane. Investigation of electron emission was carried out in the pressure range of 1–10 Pa. Current pulses manifested heating at temperatures 17, 38, 56, 94, 98, 100, 105, 106, 107°C. The current value increases with the size of the sample. Maximum current reached 3 mA on the sample  $14,5 \times 10,5 \times 10 \text{ mm}^3$  when heated at  $20 \text{ }^\circ\text{C}/\text{min}$  from  $-10$  to  $107 \text{ }^\circ\text{C}$ .

***Keywords:*** *discharge, electron source, plasma flow, lithium niobate crystal*

**ELECTRON BEAM FORMATION IN A GRID PLASMA CATHODE ELECTRON  
SOURCE BASED ON A LOW-PRESSURE CONSTRICTED ARC  
IN AN INHOMOGENEOUS MAGNETIC FIELD**

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The paper presents plasma cathode discharge systems with a grid-stabilized plasma emission boundary and current amplitude of up to 300 A based on a low-pressure constricted pulsed (200 us) arc and considers the generation of emission plasma and electron beams in the systems penetrated by an inhomogeneous longitudinal magnetic field of up to 0.035 T. Research results are reported to clarify the effect of the discharge system configuration on the beam profile at a collector for an accelerating voltage of 10 kV and longitudinal magnetic field of up to 0.1 T.

**Keywords:** *electron source, plasma cathode, arc discharge, magnet field.*

## NUMERICAL SIMULATION OF PLASMA EXPANSION IN SPARK STAGE OF A VACUUM ARC

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This article is devoted to the kinetic numerical simulation of an expanding current-carrying plasma plume, which arises from an explosive-emission center in the vacuum breakdown. The model developed to simulate the expanding plasma plume is a model of 1D3V particle-in-cell and direct simulation Monte Carlo type. The model takes into account the main types of elastic and inelastic collisions of particles in the plasma as well as evaporation and thermofield electron emission from the cathode. A series of calculations of the plasma plume expansion at different rates of increase of current was carried out within the model. The growth rate of the current was regulated by the voltage across the vacuum gap and limiting resistance.

It was found that at the current density rise less than about of  $10^9$  A/cm<sup>2</sup>/s the expansion of the plasma generally has a self-similar character. At the higher current density growth rate the plasma expansion has an essentially non-stationary character. The high density current leads first to the development of ion-acoustic instability and then to the development of Buneman instability. The strong current instability leads to the rupture of the plasma and the creation of conditions for the collective (anomalous) acceleration of ions to the cathode and the anode. Anomalous accelerated ions with energies up to 80 keV create an additional powerful heat flux to the cathode, which should facilitate the reproduction of the cathode spots in the spark stage of vacuum breakdown.

**Keywords:** *vacuum breakdown, vacuum arc, plasma plume, numerical simulation.*

## MODEL OF THE FORMATION OF LIQUID METAL JETS AND DROPS IN A VACUUM ARC CATHODE SPOT

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Microjets formation is studied during the extrusion of a melted metal by the plasma pressure from craters formed on a cathode in a burning vacuum arc. An analytic model of liquid-metal splashing that includes two stages is proposed (see also Ref. [Gashkov M.A., Zubarev N.M., Zubareva O.V., Mesyats G.A., Uimanov I.V., *JETP* 122, 776 (2016).]). At the first stage, the liquid motion has the axial symmetry and a liquid-metal wall surrounding the crater is formed. At the second stage, the axial symmetry is broken due to the development of the Plateau-Rayleigh instability of the toroidal edge of the wall [Mesyats G.A., Zubarev N.M., *J.Appl.Phys.* 117, 043302 (2015).]. The wall breakup process is shown to have a threshold (depending on the cathode plasma pressure, two main regimes of liquid motion can be realized: liquid spreading and splashing). We have found the minimal plasma pressure and the minimal electric current flowing through the crater required for obtaining the liquid-metal splashing regime. The basic spatial and temporal characteristics of the jet formation process are found using the analytic model. Our estimates of the number of jets, their velocity, and time of formation are in good agreement with the available experimental data [Mesyats G.A., *Ectons in a Vacuum Discharge: Breakdown, the Spark, and the Arc* (Nauka, Moscow, 2000).].

The work was performed according to the State program 0389-2014-0006/5 and supported by the RFBR (projects 14-08-00235, 14-02-00575, 16-08-00228) and by the Presidium of the RAS (program no. 9).

**Keywords:** *vacuum arc, liquid metal, jets, threshold current, cathode spot.*

## DEVELOPMENT OF AZIMUTHAL INSTABILITIES OF THE LIQUID METAL FREE SURFACE DURING THE FORMATION OF CRATERS IN A VACUUM ARC CATHODE SPOT

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Using a combination of numerical and analytical approaches, the dynamics of melted metal during the crater formation in the cathode spots of a vacuum arc discharge is investigated theoretically. In the initial stages, a liquid-metal wall, surrounding the crater, is formed. This process is simulated numerically in the framework of 2D axisymmetric model of heat and mass transfer for a viscous incompressible liquid with the free surface (see also [Mesyats G.A., Uimanov I.V., *IEEE Trans. Plasma Sci.* 43, 2241 (2015).]). In the developed stages, the motion of the molten metal loses its axial symmetry which corresponds to the tendency of forming the jets. The development of the 3D azimuthal instabilities of the wall is analyzed using the dispersion relations for linear surface waves. It is shown that the maximal increments correspond to the Plateau-Rayleigh instability (they essentially exceed the increments of the Rayleigh-Taylor instability). The most-probable number of liquid-metal jets and the time of their formation are calculated [Mesyats G.A., Zubarev N.M., *J. Appl. Phys.* 117, 043302 (2015).]. Basing on the idea that the electric explosion of jets plays a key role in self-sustaining of arc discharge [Mesyats G.A., *IEEE Trans. Plasma Sci.* 41, 676 (2013).], estimations for the threshold current and the arc cycle time are made.

The work was performed according to the State program 0389-2014-0006/5 and supported by the RFBR (project nos. 14-08-00235, 14-02-00575, 16-08-00228) and by the Presidium of the RAS (program no. 9).

**Keywords:** *vacuum arc, liquid metal, jets, threshold current, cathode spot.*

## ACTIVATION OF THE EXPLOSIVE-EMISSION-CATHODE IN CONDITIONS OF ARTIFICIAL INITIATION OF FIELD EMISSION

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Activation dynamics of explosion-emission cathode for subnanosecond scale interval is of interest in the aspect of relativistic microwave generators phase fixation relative to the current front of electron beam and, respectively, to the accelerating voltage front applied to the cathode.

The report presents the data about the cathode activation in terms of field emission initiating by leading pulse (prepulse) generated in three modes. In the first case, the nanosecond prepulse of the order of tens of kilovolts is due to the peaking spark gap capacitance of the high-voltage generator. The second mode is implemented in the presence of reflections in the path between the generator and unmatched diode. In this case the leading of the initiating pulse reaches ten nanoseconds. In the third variant, the leading voltage pulse with variable duration and amplitude is supplied with adjustable delay from the special high voltage generator. Of particular interest is the mode of cathode initiation with doublets of subnanosecond pulses with amplitude of about  $-150$  kV, with a delay of less than a nanosecond. Measurements of electron beam current and the impedance of magnetically isolated diode in the above-described modes are presented taking into account the influence of the shielding effect of explosion-emission centers at different external magnetic fields. The general conclusion of the experiments consists in the pronounced influence of the advancing initiation of field emission at the cathode on the dynamics of explosion-emission processes.

The work was supported by the RFBR, grant # 14-08-00111.

**Keywords:** *explosion-emission cathode, electron beam, high voltage generator.*

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**INFLUENCE OF ION FLOW FROM THE ANODE PLASMA BOUNDARY  
OF ACCELERATING GAP TO DISCHARGE VOLTAGE IN THE PLASMA  
ELECTRON EMITTER**

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Current-voltage characteristics of low ( $\sim 10^{-2}$  Pa) pressure pulse arc discharge in axial magnetic field were studied. It used for cathode plasma generation in intense low-energy (30 keV) electron beam sources. The work has been carried out at beam current up to 500 A, pulse duration up to 200  $\mu$ s and axial magnetic field 50 mT. It was shown that an ion current into discharge cell from electron source anode plasma plays the most important role in decreasing of anode-cathode voltage of the discharge cell.

**Keywords:** *plasma cathode, electron source, arc discharge, current-voltage characteristics.*



## STUDY OF PLASMA DYNAMICS DURING INTERACTION OF ELECTRON BEAM WITH POLYMERIC MATERIALS

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In studying an interaction of the relativistic high current electron beam (REB) with solid target it is very important to know dynamics of diode plasma generated during pulse energy release in target surface layers. The plasma expansion rate determines the parameters of shock wave in the target and the recoil impulse. We present the results of plasma dynamics study obtained in Kalmar diode (NRC KI) upon interaction of the pulse electron beam (its duration is  $\sim 100$  ns) with polymeric targets. The maximum of electron energy in the pulse was about 350 keV, electron current was 25 kA and the surface density of the energy release was varied in the range of 200–800 J/cm<sup>2</sup>. The main experimental results on the plasma dynamics in the diode were obtained using optical streak camera with a slit placed parallel to the beam axis. The energy release into the target was calculated according to the current and voltage profiles; the interaction region of the electron beam with anode was determined on the pin-hole X-ray image.

3D modeling of the REB interaction with polymeric targets was carried out in the one temperature hydrodynamic approximation using MARPLE3D code (KIAM RAS). The semiempirical equation of state QEOS (TERMOS, KIAM RAS) was used for determination of matter properties. It takes into account the equilibrium liquid-vapor two phase state. The numerical chronograms of plasma radiation are in a good agreement with the experimental data.

This work was partially supported by the projects of RFBR 14-01-00678a and 15-02-03544a.

**Keywords:** *relativistic high current electron beam, plasma dynamics in the diode, polymeric target, 3D modeling.*

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**INITIATION OF HYDROCARBONS OXIDATION BY AN ELECTRON BEAM*****YURY SAVINYKH<sup>1</sup> AND VIKTOR ORLOVSKI<sup>2</sup>****<sup>1</sup>Institute Petroleum Chemistry SB RAS**<sup>2</sup>High Current Electronics Institute SB RAS, Russia  
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An investigation of the effect of high-current electron beam with an energy of 140 keV to initiate chemical reactions of liquid hydrocarbon oxidation by atmospheric oxygen was carried out. The results show that the oxidation of n-alkanes proceeds with high selectivity and leads mainly to the formation of alcohols and carbonyl compounds – aldehydes and ketones. Resinous substances, acids and hydroperoxide usually formed during autoxidation are missed.

**Keywords:** *e-beam, alkane, oxidation.*

**BREAKDOWN IN THE ACCELERATING GAP OF ELECTRON SOURCES BASED  
ON AN ARC DISCHARGE AND A GRID STABILIZATION  
OF THE PLASMA EMISSION BOUNDARY**

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This work leads a theoretical research on the grid electrode potential with regard to the discharge plasma for its generation in the electron source with an arc discharge in the low-pressured gas. We investigated the influence of the positive feedback and breakdown mechanism in the mode of emission current enhancement. It has been shown that the main mechanism of breakdown in the accelerating gap of the given source is the interelectrode breakdown limiting beam threshold energy in a pressure range of 0.1–0.02 Pa. The defining factor of the interelectrode breakdown is the exceeding of plasma potential higher the critical value  $\varphi_{cr}$  of discharge ignition that depends on electron beam power density and gas kind.

**Keywords:** *electron source, accelerating gap breakdown, plasma grid stabilization, plasma potential.*

## ANGULAR DISTRIBUTION OF BEAM ELECTRONS IN A SOURCE WITH ARC PLASMA EMITTER

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Information about beam angular distribution is valuable for a numerous electron beam applications. In this paper the diagnostic technique is described and the results of experiments on electron beam angular distribution measurement are presented.

The beam was generated in a source with an arc plasma emitter and multiaperture electron optical system. Main beam parameters were as follows: energy of electrons up to 100 keV, beam current up to 120 A, pulse duration of 0.1– 0.3 ms. The beam was formed and transported in an axial magnetic field onto the perforated stainless steel mask placed at 0.8 m from the source. As a result, a number of beamlets were cut out from the initial beam. These beamlets were absorbed in a thin (1 mm) stainless steel plate (x-ray converter), placed at 20 mm behind the mask. X-ray image of the beamlet imprints was visualized on the phosphor screen located directly behind converter. The screen glow was imaged with 45-degrees mirror and fast CCD-camera, and the angular spread of the electrons is determined from the analysis of the distribution of the brightness over the imprint. The spatial resolution was evaluated in special tests and was found no worse than one pair of lines per 4 mm for 10 % contrast level. An algorithm of the brightness data processing is also described. The results on angular distribution are in good agreement with those obtained in experiments on the beam passage through the magnetic mirror.

**Keywords:** *electron beam, plasma emitter, pepper-pot method, electron angular distribution.*

## STUDY OF ELECTRON BEAM UNIFORMITY IN WIDE-AREA MULTI-APERTURE DIODE WITH ARC PLASMA CATHODE

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We report on an experimental investigation of the current density distribution over cross-section of the electron beam produced by a multi-aperture source with arc plasma cathode. The source has a diode-type electron optical system (EOS) with cathode and anode electrodes in the form of a flat «grid» with a large number of round openings aligned coaxially. Two variants of EOS were employed: the first with 241 apertures packed in hexagonal grid inside of circle with diameter of 82 mm and the other with 499 apertures in a circle with diameter of 118 mm. The beam source was immersed in a guiding external magnetic field, which is used to transport and to focus the electron beam, producing desired current densities on the target. Typical energy of the beam electrons was about 100 keV and the pulse duration was 0.1–0.5 ms. An X-ray diagnostic technique was developed that allows to obtain 2D-image of the beam current density distribution over the flat metal collector in a single shot. With this technique it was shown that the current density distribution is homogeneous and has an almost flat profile, especially in a case of 241 aperture EOS. In operation modes with selected values of the guiding magnetic field and the accelerating voltage it was possible to evaluate the current density in every individual aperture.

**Keywords:** *electron beam, plasma cathode, multi-apertured diode, beam cross-sectional uniformity.*

**STUDY OF THE CHARGE-STATE COMPOSITION OF THE IONS  
IN THE 2 - 160 A VACUUM ARC PLASMA VIA  
THE THOMSON SPECTROMETER**

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Charge-state composition of cathode material ions in the vacuum arc plasma was investigated via the Thomson spectrometer. The aim of this study was the investigation of the charge-state composition of copper ions at the discharge current value near the minimum spot current for copper cathode. The cathode was a copper disk with 8 mm diameter. The anode was hollow with a thick copper ring entrance. The gap between the cathode and the ring was about 0.8 mm. The voltage source was a capacitor bank with 4–6 kV charge voltage. Current pulse amplitude was determined by the limiting resistance. The resistance and capacitance were varied simultaneously to keep pulse duration value about 8  $\mu$ s. Ion beam was formed at the gap between the hollow anode exit grid and extracting grid. The voltage in the gap was about 1–2 kV. Parameters of the accelerated beam were analyzed via the Thomson spectrometer with automated recording and processing of spectrograms. Quantitative characteristics of the mass-charge composition of the ions were obtained by means of integration of signal intensity of the ion components on the detector screen. The measurement results show that the average charge number for copper ions decreased with arc current decreasing from 1.98 at the 100–160 A value of current amplitude to 1.55 at the 1.7 A value. Generally, average charge number was affected by increasing of the Cu<sup>+</sup> fraction and decreasing of higher charged fractions with decreasing of the current pulse amplitude.

**Keywords:** *vacuum arc, low current, ions, charge-state composition, average charge number, copper.*

## SEMIEMPIRICAL MODEL OF THE MICROCRATER FORMATION ON THE CATHODE OF A VACUUM ARC

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In the context of a 2D axisymmetric statement of the problem of electric heat and mass transport in a cathode, a semiempirical hydrodynamic model has been developed to describe the formation of a microcrater and the initial stage of the formation of liquid-metal jets in the cathode spot of a vacuum arc. The crater formation has been simulated for a copper cathode at a constant cathode spot cell current mode. It has been shown that for the cell current ranging between 1.6 and 7 A and the time of current flow through the cell ranging between 15 and 60 ns, the diameter of the formed crater is 3–7  $\mu\text{m}$ . These results are in agreement with experimental data on the crater size on copper and on cathode spot lifetime (the time of current flow through a cell) at near-threshold arc currents. The simulation predicted the maximum current density in a cell equal to  $(1-3) \times 10^8 \text{ A/cm}^2$  for all calculation variants where the formation of a micrometer-size crater took several tens of nanoseconds. We note that convective heat transport plays an important part in the heat balance of a cathode during the formation of a crater. The extrusion of the heated liquid metal from the crater accompanied by the formation of jets promotes stabilization of the temperature of the crater bottom surface; otherwise the heat fluxes of density  $(1-3) \times 10^{12} \text{ W/m}^2$  entering the cathode from the plasma would heat the cathode to a temperature above the critical point.

**Keywords:** *Vacuum Arc, cathode spot, explosive electron emission, crater.*

## CONVECTIVE MODEL OF THE DEUTERIUM DESORPTION IN THE CATHODE SPOT OF A VACUUM ARC WITH A ZRDX CATHODE

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Although the development and use of neutron tubes with arc source of deuterium ions has been developed for nearly half a century, the mechanism of desorption of hydrogen isotopes from deuterated cathode in arc discharge is not studied yet. In this work model of convective diffusion of hydrogen isotopes and their desorption into plasma of vacuum arc has been developed upon functioning of cathode sport cells on ZrDx cathode. It was shown that limiting factor, which mainly determines deuterium desorption in hydrodynamic stage of functioning of CS cell, is its transfer in the cathode from the volume to the surface. In this case deuterium, regardless significant temperature gradients in cathode, thermal transfer of hydrogen isotopes is insignificant in comparison with its diffusion and convection together with molten mass. High gradient of hydrogen isotope concentration near the surface is maintained by pressing of almost desorbed surface layers of molten metal to crater peripheral area. Basing on simulation results it was proved that most part of deuterium desorbs in active phase of cathode spot cell functioning (in discharge current flow phase). Cathode volume, from which the gas is completely desorbed, is approximately equal to the volume of molten metal, pressed out upon formation of crater, Convective nature of deuterium desorption upon formation of microcrater results in the fact that the number of deuterium ions is by 4–6 times larger than the quantity of zirconium ions in CS plasma of vacuum arc with ZrD0.67 cathode.

**Keywords:** *Vacuum Arc, cathode spot, crater.*



## ACCELERATION OF METALLIC IONS BY A PICOSECOND CONFINED ELECTRON BEAM

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Characteristics of particle beam originated from a small-size electron accelerator with 280 keV voltage, 5 kA current and 500 ps pulse duration (i.e. about of  $2 \times 10^{13}$  A/s<sup>-1</sup> current rise rate) were studied. It was found that the electron beam originated from a needle-like tungsten cathode and passing through Ti anode foil at a distance of 5 mm from the cathode expanding into a vacuum gap as a filament of diameter less than 20 micrometer. This implies that the current density in the electron beam exceeds of  $2 \times 10^9$  A/cm<sup>-2</sup>. This effect, obviously, is due to pinching of the plasma jet when flowing through the interelectrode gap. An intensive beam of the cathode ions was recorded as well with a circular cross-section about of 2 mm diameter at a distance of 2.5 cm from the anode foil and this value hold at a distance of 4 cm from the foil, where the electron beam already was not recorded. It was supposed that this result is due to ions carrying away by the self-consistent electric field of the space charge produced within the electron beam. Energy of the ion beam was evaluated being about of 10 MeV.

**Keywords:** *particle beam, electron accelerator, self-consistent electric field.*

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**THE EXPERIMENTAL INVESTIGATION OF AN ION FLOW  
IN A VACUUM ARC AT A THRESHOLD CURRENT*****ILYA MUZYUKIN****IEP RAS, Russia  
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A time dependence of ion generation during a lifetime of a single cathode spot is of a great importance. To obtain such dependence it is necessary to investigate vacuum discharge at a threshold current with small size electrode setup. Vacuum arc was fed by capacitor with restrictive resistor. After arc ignition the arc current decreases in time of 300–500 ns up to threshold current. When threshold current was achieved there was only single cathode spot operating in a vacuum arc. A small discharge setup was used to obtain nanosecond time resolution on the ion flow measurement. Cathode–anode gap and anode–collector gap was established as 0.1 mm. The average time of fly of ions from cathode spot to the collector can be estimated as 10 ns. The estimated lifetime of cathode spot on a molybdenum cathode is 20–50 ns. Thus the electrode setup built at the present experiments can be used to obtain ion generation dependence during a single cathode spot lifetime. The electron flow time dependence was obtained too. The results obtained make it possible to connect charged particle flow fluctuations with cathode spot life cycle.

**Keywords:** *vacuum arc, ectons, particle flows, cathode spot.*

## THE HIGH-POWER PULSED BEAMS SOURCE WITH TUNABLE OPERATION MODE

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The electron and ion pulsed accelerator design is discussed in this report. The powerful high-voltage pulse generator of accelerator and the vacuum bushing insulator allow changing the polarity of output voltage. The low inductance matching transformer provides an increase of 4 times of the DFL output impedance. The generator based on a high voltage pulse transformer and pseudospark switch is applied to DFL charging.

The high impedance magnetically insulated focusing diode with Br magnetic field and the «passive» anode was used to realization of the ion beam generation mode.

The plasma formed on the surface of anode caused by electrical breakdown on the voltage edge pulse as a result the carbon ion and proton beam is generated. This beam has the following parameters: current density is about  $400 \text{ A/cm}^2$  (in focus): applied voltage is up to 450 kV.

The accelerator is designed to research on the interaction of charged particles pulsed beams with the materials and for development of the technological processes of material modification.

**Keywords:** *High-voltage pulsed generator, Pulsed accelerator, Electron and ion beam.*

## SIMULATION OF AN ELEMENTARY CRATER FORMATION ON THE CuCr CATHODE OF A VACUUM INTERRUPTERS

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Currently CuCr composite granular alloys are the predominant contact materials for medium-voltage, high-current vacuum interrupters. Their properties depend on the composition and microstructure of the Cr phase. It has been shown, that during the operation of the arc on the CuCr composite granular cathodes there is an essential change of the morphology of the Cr phase. The grains size is reduced at least 100 times, and their distribution in the Cu matrix to become more uniform. To investigate these processes, the nonstationary hydrodynamic model based on the cellular structure of the cathode spot of a vacuum arc has been developed that describes the formation of an elementary crater and the initial stage of the formation of liquid metal jets. In model are considered cathode spots attached to Cr grains in the Cu matrix in a wide range of values of the ratio of the grain radius to the radius of the crater. It has been shown that at a spot current 1.5–7 A per elementary cell, the crater diameter on the uniform Cr cathode is 3–7 mm. In a case if the Cr grains size is more than diameter of a melt zone even on half-micron, characteristics of the crater formation process are identical to a case of the pure Cr cathode. If the initial Cr grain size is smaller than the diameter of the crater formed, the heat balance in the cathode is significantly affected by the melting and extrusion of Cr from the crater.

**Keywords:** *Vacuum Arc, Vacuum Interrupter, cathode spot, crater.*

## PIN-DIODE DIAGNOSTICS OF PULSED ELECTRON BEAM FOR HIGH REPETITION RATE MODE

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This work describes the operating principle and test results of diagnostics for measuring pulsed electron beam parameters under repetitive operation mode. The diagnostics is based on a PIN-diode, which is used as a bremsstrahlung detector. The signal from a PIN-diode was converted to a pseudo constant voltage signal which can be measured by a conventional voltmeter. Then the signal acquired by the voltmeter was compared with a reference signal indicating the normal operating regime of the accelerator, thus information about the shot-to-shot reproducibility of the electron beam parameters was given. The system was developed and tested for the ASTRA-M accelerator with the following operating parameters: 470 kV accelerating voltage, 120 ns beam duration and up to 50 pulses per second repetition rate.

This work was partially supported by RFBR grant No16-32-0028МОЛ\_a.

**Keywords:** *pulsed electron accelerator, electron beam diagnostics, PIN-diode bremsstrahlung detector.*

## HIGH-CURRENT PULSED INDUCTION PLASMA SOURCE FOR GENERATION OF HIGH INTENSITY ION BEAMS OF DIFFERENT GASES

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The paper describes a plane induction plasma source with a pulsed gas puffing to the discharge area. The use of a cone-shaped multi-start two-turn shock coil (inductor) with a bipolar power supply enabled to significantly increase a transformed current into inductive-coupled plasma under high values (about 350 V/cm) of a vortex electrical field. The set of the defined conditions stabilized the beginning of initiation and evolution of a discharge, as well as ensured the required level of the ion-emission capability of the source for generation of high intensity ion beams. Within a range of a gas pressure 1–10 Pa, the source demonstrated rather high efficiency of energy input into plasma (about 70–80 %). The electrophysical characteristics of an induction source, the parameters of a gas flow in the discharge area and plasma at the output in the plane of emission are described.

The work is supported by the Russian Science Foundation, Grant No.14-19-00439

**Keywords:** *plasma source, intense ion beams, inductive discharge.*

## CONVERSION AND TRANSPORTATION OF THE INTENSE ION BEAMS IN SCATTERING MAGNETIC LENSES

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The paper describes the problem of the conversion of the intense ion beams convergent on the axis to the quasi-cylindrical beams or to the long-focus beams by the scattering magnetic lenses with the topology of the magnetic field  $B = f(1/r)$  и  $B = f(r)$ . The first ion-optical system is a toroidal lens with an axial current filled with plasma from an additional source to neutralize the space charge of the beam. The second system is a cylindrical plasma channel with a longitudinal current. The trajectories of the motion of the ions in the single-particle approximation were calculated. The properties of the scattering magnetic lenses were considered on the example of the conversion of ion beams with a spherical and a tapered focusing. An important feature of the ion movement is the realization of the asymptotic approaching of the ions to the axis of the plasma scattering channel at a certain critical value of the current in the channel. The dependence of critical current in the channel on the input parameters of ions is presented in the work.

**Keywords:** *intense ion beams, plasma lenses, ion beam transportation.*

## PLASMA FORMING BY SPREADING OF PULSED ELECTRON BEAM IN HIGH PRESSURE GASES

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Presently, the forming of chemical active plasma under the action of pulsed high current electron beam attracts attention of many experimental and theoretical groups. Interest of the studies is possibility to employ of results for synthesis of nanoparticles. One of the possible ways of a nonequilibrium plasma formation is the action of pulsed electron beam with the power flow of  $10^6$ – $10^9$  W/cm<sup>2</sup> on a high pressure gas medium. In this case the chemically active plasma is formed which allows to synthesize the nanoparticles and nanooxides.

Our theoretical investigation is devoted to analyze of the spreading of the pulsed electron beam with the power flow of 10–10 000 MW/cm<sup>2</sup> in the oxygen-hydrogen gas mixture. The time evolution of the electron distribution function is described within the framework of Boltzmann equation. The plasma conditions for the synthesis of the nanoparticles and nanooxides are discussed.

**Keywords:** *electron beam, plasma, modeling, nanooxides, Boltzmann equation.*



## CURRENT DENSITY DISTRIBUTION OF THE RIBBON ELECTRON BEAM DURING ITS PROPAGATION AT FOREVACUUM PRESSURE RANGE

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We present research results of processes affecting the uniformity of the ribbon electron beam current density during its propagation at the forevacuum pressure range. It has been shown that increasing the accelerating voltage increases the non-uniformity of the beam near the extractor. Further scattering by gas molecules, the electron beam leads to an improvement of the homogeneity. Thus electron beam treatment zone with most uniform current density distancing from the extractor of electron source.

**Keywords:** *forevacuum pressure range, plasma electron source, beam plasma, ribbon electron beam.*

## EXPERIMENTS ON ALUMINUM FOIL LINER IMPLOSIONS ON THE HIGH-CURRENT MIG GENERATOR

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Results of experiments on aluminum foil liner implosions on the high-current MIG generator at Institute of High Current Electronics with current rise time about 80 ns are presented.

Plasma with density about  $10^{17} \text{ cm}^{-3}$  is preliminarily injected in the area of the liner using a set of radial plasma guns. The J B force accelerates the injected plasma in the axial direction. Since the magnetic field pressure is inversely proportional to the radius squared, the maximum displacement of plasma occurs near the surface of the liner, the plasma movement becomes two-dimensional, a gap forms between the plasma and the liner and the generator current switches to the liner. The plasma motion velocity at the liner surface is close to the Alfvén velocity and the time of current switching to the liner can be estimated as the liner length divided by the Alfvén velocity. The considered scheme enables to significantly reduce the current rise time through the liner and, as a result, reduce the initial radius of the liner and increase the stability of liner implosion.

**Keywords:** *high-current generator, foil liner, stability of liner implosion, soft x-ray.*

## INFLUENCE OF EXTERNAL AXIAL MAGNETIC FIELD ON THE BISMUTH LINER IMPLOSION DYNAMICS

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The influence of the external axial magnetic field on the dynamics of the liner implosion was investigated. The liner was a plasma jet, which was injected into the generator IMRI-5 interelectrode gap through the collimator with diameter of 5 mm. A plasma gun with bismuth electrodes was used as the plasma source. The arc current was  $92 \pm 2$  kA. The current arc discharge is periodic with a period of a quarter of  $6.67 \mu\text{s}$ . An external magnetic field created by the two coils located directly behind the return current posts of the IMRI-5 load. The external magnetic field is varied in the range of 0.15–0.6 T. This work aims to study the reliability of determining the Z-pinch implosion dynamics using electrical measurements. In the experiments along with the traditional measurements of current flowing through the liner, its derivative and voltage drop we recorded 4 frame liner image in the optical range, as well as signals from inductive loops disposed at different distances from the axis of the liner. Comparing the liner diameter, obtained by three different methods, it was concluded about the reliability of these techniques.

This work was supported by Russian Science Foundation, grant No. 16-19-10142.

**Keywords:** *vacuum arc discharge, Z-pinch, the magnetic field.*

## DETERMINATION OF CONDUCTANCE AND TEMPERATURE OF BISMUTH JET PLASMA

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An experimental study of the influence of the arc current value on the conductivity and temperature of the Bi jet plasma were carried out. The plasma gun with arc current of 10 to 50 kA was used as a plasma source. Arc current was regulated by the capacitor bank voltage in range of 5 to 20 kV. The arc discharge current is periodic with a period of about 15  $\mu$ s. Maximum plasma Bi concentration in the field of measurement of the magnetic loop was approximately  $5 \times 10^{17} \text{ cm}^{-3}$  at the ionization close to 1.2. The test signal oscillations had a half-period of about 120 ns. This time scale of the test signal has been chosen because of the characteristic times of Z-pinch implosion. Experiments have shown that the conductivity and temperature of the bismuth jet plasma are proportional to the arc current.

**Keywords:** *Arc discharge, B-dot, Magnetic field diffusion.*

**MODELING OF A NONLINEAR MAGNETIC FIELD DIFFUSION WAVE****VLADIMIR ORESHKIN<sup>1</sup>, STANISLAV CHAYKOVSKY<sup>1</sup> AND EVGENY ORESHKIN<sup>2</sup>**<sup>1</sup>*HCEI SB RAS*<sup>2</sup>*P.N. Lebedev Physical Institute RAS, Russia**oreshkin@ovpe.hcei.tsc.ru*

This paper analyzes the results of experiments on the explosion of copper conductors carried out on the MIG generator at the level of the current through the conductor 2 MA and the front rise of the current pulse is 100 ns. It is shown that the growth of instabilities developing at the late stage of the explosion, the predefined development in close proximity to the surface of the conductor thermal instabilities that occurs after the front of nonlinear magnetic field diffusion wave . The wave front of the nonlinear diffusion is stable against thermal instabilities.

**Keywords:** *MHD-simulation, Diffusion magnetic field, Electrical explosion.*

**THE INITIAL STAGE OF NECK FORMATION IN AN X-PINCH**

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A model is proposed to describe the initial stage of neck formation in an X-pinch that proceeds in three stages: the electrical explosion of metal wires that generates the X-pinch; the expansion of the wire material that occurs due to an excess of the gas-kinetic pressure over the pressure of the magnetic field. The model allows one to predict the minimum rate of current rise at which the formation of a «hot spot» in an X-pinch is possible. The minimum current rise rate is determined by the thermodynamic parameters of the wires at a critical point; it is of the order of 1 kA/ns.

**Keywords:** *X-pinch, Electrical explosion, Hot spot.*

## STUDY OF QUASI-SPHERICAL LINERS BASED ON MULTICHANNEL VACUUM ARC DISCHARGE SYSTEM

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The results of experiments on the study of metal-puff quasi-spherical compression are presented. A liner shell was created by a multichannel vacuum arc system. The studies were carried out on a high-current generator IMRI-5 (the rise time  $\approx 500$  ns, the current amplitude  $\approx 500$  kA). The plasma guns with the overall arc current a)  $\approx 90$  kA (the current rise time  $\approx 7$   $\mu$ s) and b)  $\approx 120$  kA (the current rise time  $\approx 1.4$   $\mu$ s) were used as an Al plasma source. A plasma injection was made as from the IMRI-5 grounded electrode, and with two opposite sides. Cone geometry of electrodes was used in the experiments. To register the image of compressing liner (in the visible range of light) the 4-frame HSFC-Pro camera was used. Experiments have shown that when it was used the cone – flat mesh electrode geometry, there is not only radial but also axial implosion of the liner. When it was used the cone – cone electrode geometry, the liner implosion occurs mainly in a radial direction, wherein the stored energy was lost on the cone electrodes.

Work was supported by the Russian Foundation for Basic Research (grant No.14-02-00382-a and No.15-08-03845-a)

**Keywords:** *Vacuum arc discharge, Z-pinch, Dense high-temperature plasma.*

## INVESTIGATION OF THE PREBREAKDOWN CURRENTS IN A SEALED-OFF COLD-CATHODE THYRATRON

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Currently, the low-pressure high-current switching devices with the hollow cathode, often named the pseudospark switches, are widely used. The principle of the switch operation resembles that of a classical thyatron with a grounded grid. However, in these types of switches a hot cathode is absent.

A range of operating pressures of the switch corresponds to the conditions of the left branch of the Paschen's curve when the electron free path for ionization is much in excess of the electrode separation. Under such conditions, as a distinct from the high-pressure discharges, the mechanism of the switch breakdown is not related to the development of classical electron avalanches that are initiated by single electrons. For both self-breakdown and external discharge triggering a considerable prebreakdown electron current is required to ignite a high current discharge in the main gap.

On the other hand, the presence of a prebreakdown current leads to a decrease of a static breakdown voltage. To solve this problem the so-called blocking electrodes are used. Another approach deals with the use of multi-gap design of the main gap. In this case the gradient electrodes are inserted in the main gap, dividing it on the several sections.

In this paper the results of the investigations of prebreakdown currents in a sealed-off two-section thyatron with the cold cathode TPI1-10k/50 are presented. It is demonstrated that the prebreakdown current in the lower section of the thyatron gap appears at a lower voltages as compared to the upper section.

**Keywords:** *cold cathode thyatron, prebreakdown current, pseudospark switch.*



**EXPERIMENTAL RESEARCH OF NEUTRON YIELD AND SPECTRUM FROM  
DEUTERIUM GAS-PUFF Z-PINCH ON THE GIT-12 GENERATOR  
AT CURRENT ABOVE 2 MA**

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The Z-pinch experiments with deuterium gas-puff surrounded by an outer plasma shell at currents of 2 MA were carried on the GIT-12 generator (Tomsk, Russia). The plasma shell consisting of hydrogen and carbon ions was formed by 48 plasma guns. The deuterium gas-puff was created by a fast electromagnetic valve. This configuration provides an efficient mode of the neutron production in DD reaction, and the neutron yield reaches a value above  $1e12$  neutrons per shot. Neutron diagnostics included scintillation TOF detectors for determination of the neutron energy spectrum, bubble detectors BD-PND and BDS-1000, a silver activation detector, a Sodium Iodide (NaI) detector, a high-purity Germanium (HPGe) detector and several activation samples for determination of the neutron yield. Using this neutron diagnostic complex, we measured the total neutron yield, the anisotropy of neutron fluence, amount of high-energy neutrons and neutron energy spectrum.

***Keywords:*** *z-pinch, gas-puff, neutron diagnostics, neutron activation.*

**HYBRID MHD/PIC SIMULATION OF A DEUTERIUM GAS PUFF Z PINCH*****DMITRY SHMELEV<sup>1</sup>, VLADIMIR ORESHKIN<sup>2</sup> AND STANISLAV CHAIKOVSKY<sup>1</sup>****<sup>1</sup>Institute of Electrophysics, RAS**<sup>2</sup>Institute of High Current Electronics, SB, RAS, Russia**dlshmelev@yandex.ru*

We present the hybrid MHD/PIC simulations of the time evolution of a deuterium gas puff z-pinch. Recent experiments with 3-MA current pinches [1] made in a novel configuration have shown that the neutron yields can reach  $3.6 \times 10^{12}$ . There was shown that the observed neutron spectra could be explained by a suprathermal distribution of deuterons with a power law fall off in the ion energy distribution function at large energy. In order to perform the numerical simulation of gas puff z-pinch a new hybrid model was developed. The described hybrid model treats the electrons as a massless fluid and ions as macroparticles. The macroparticle dynamic is calculated with the use of PIC method. Ion-ion Coulomb collision is considered with the use of MC method. In the model simulation, in the configuration close to described in [1], it was obtained the neutron yields up to  $1.2 \times 10^{12}$ . Most neutrons are not thermonuclear. This level of the neutron yield is reached only when a strongly nonuniform neck-like constriction of z-pinch plasma occurs. In this case, the obtained deuteron spectra (with energy up to several tens MeV) have suprathermal high energy tail. These simulations demonstrate the utility of the developed hybrid model for the z-pinch simulation.

**Keywords:** *z-pinch, numerical simulation, hybrid methods, particle-in-cell methods, Monte Carlo methods, plasma.*

## MEGAAMPERE Z-PINCH IN THE SCHEME OF MICROSECOND CURRENT GENERATOR GIT-12 WITH A LOAD CURRENT DOUBLER AND PLASMA SWITCH

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A scheme of the formation of terawatt current pulses in a Z-pinch load was tested. The microsecond current generator GIT-12, the megaampere load current doubler with ferromagnetic core (LCD/FC) and the plasma switch (MPOS) were the elements of this scheme, which is investigated in two variants of the MPOS and LCD/FC concatenation. In the first operating mode (MPOS+LCD/FC), the current in a Z-pinch load was up to 4 MA and the current rise time was about 250 ns. In the second mode (LCD/FC+MPOS), when the plasma shell is attached behind LCD/FC, the current at the load input reached the value of 5 MA and the current rise time was  $\sim 1 \mu\text{s}$ . In the latter case, the energy input into the dynamic load demonstrates the 1.5-fold enhancement in comparison with the GIT-12 operated without LCD/FC. Analysis of the experiments with the double-shell Ne gas puffs showed that for achieving of high levels of K-shell radiation yield an optimization of gas puff implosion parameters and an improvement of the design of 'LCD/FC – load' region for elimination of current losses in this region are required.

**Keywords:** *Marx generator, load current doubler, gas puff.*

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**OPTIMIZATION OF PARAMETERS OF NEON GAS PUFF WITH OUTER PLASMA SHELL IN THE EXPERIMENTS ON THE GIT-12 GENERATOR**

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An investigation of the microsecond implosion of double-shell neon gas puffs with outer plasma shell was performed and the results are given. For the peak currents up to 4 MA and the implosion times up to 1.3  $\mu\text{s}$  the definitive influence of the outer plasma shell on the neon K-shell radiation yield was demonstrated. An optimization of gas puff parameters was fulfilled. The gas shell masses and the injection times, at which an optimal gas distribution is realized in the inter-electrode gap, were determined. For these conditions the corresponded K-shell radiation yield was about 15–17 kJ/cm.

***Keywords:*** *Z-pinsh, microsecond implosion, gas puff.*

**DEPENDENCE OF PLASMA FORMATION AT SKIN EXPLOSION OF CONDUCTORS  
ON THE FINISH QUALITY OF CONDUCTORS SURFACE**

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The paper reports on experiments to investigate how the quality of surface finish, i.e., surface roughness, influences the plasma formation in a skin explosion of conductors. The experiments were performed on a MIG terawatt generator with current amplitude of up to 2.5 MA and current rise time of 100 ns. The plasma formation at the conductor surface and the evolution of the plasma boundary was recorded using a four-frame optical camera with an exposure time of 3 ns per frame. It is shown that the quality of surface finish little affects the onset of plasma formation in a skin explosion of stainless steel and steel St.3 conductors at a magnetic field of up to 400 T.

The work was supported by the Russian Foundation for Basic Research (grant No. 14-08 00524 and 16-08-00658).

***Keywords:*** *electrical explosion of conductors, high-temperature dense plasma, strong magnetic field, high-current pulse generator.*

## MEASUREMENT OF NANOSECOND MEGAAMPERE PULSES OF CURRENT BY THE MAGNETIC PROBES

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The paper presents data on the method of measuring the «MIG» pulse generator current (the current amplitude of up to 2.5 MA, pulse rise time of ~100 ns) in the load node of self-magnetically insulated transmission line based on the measurement of the voltage across the groove in the measuring flange. The design of maintenance-free magnetic probes, ensuring their long-term operation is presented. It is shown that the skin effect influences the reading of magnetic probes. Using the described geometry the increase of the effective area leads to an overestimation of the calculated current pulse amplitude of ~25 % in nanosecond time range. Accounting for changes of the effective area in time make it possible to reduce the error in determining the amplitude and waveform of the current pulse to about 3 %.

The work was supported by the Russian Foundation for Basic Research (grant No. 14-08 00524 and 16-08-00658).

**Keywords:** *high-current nanosecond pulse generator, current of megaampere level, electrical explosion of conductors, strong magnetic field.*

## OPTICAL DETECTION OF SKIN-ELECTRICAL EXPLOSION PROFILED CYLINDRICAL CONDUCTORS

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The paper presents the results of the experiments that were carried out on the pulsed power generator MIG (the current amplitude up to 2.5 MA, the current rise time of 100 ns) in magnetic fields with the induction of 2–8 MG. The appearance of the self-emission of conductor surface in the visible range of the spectrum was observed at field induction of 3–4 MG. The plasma jet formation was registered in experiments with illumination of conductor by external source of radiation. Jets flowed from the edges of steps in the radial direction at a speed up to  $2.7 \times 10^6$  cm/s, which exceeded 5–6 times the speed of surface plasma expansion of steps.

The work was supported by the Russian Foundation for Basic Research (grant No. 14-08 00524 and 16-32-00631).

**Keywords:** *high-current pulse generator, electric explosion of conductors, strong magnetic field.*

## RECOVERY OF THE ELECTRIC STRENGTH IN A SEALED-OFF COLD CATHODE THYRATRON

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The cold cathode thyatron (or the pseudospark switch) is considered as an advanced alternative to ignitrons, vacuum switches and classical thyratrons in the facilities that require an extremely high current. On the one hand, a usage of the cold cathode is quite definite advantage from the viewpoint of increasing the switching current. On the other hand, the problem of increasing the pulse repetition rate in the pseudospark switch is more severe than that in the thyatron with hot cathode.

The upper level of the pulse repetition rate in the switch is determined by the conditions when a characteristic recombination time for plasma in the gap becomes comparable with the time interval between the pulses. In these conditions, a residual plasma from a preceding discharge remains in the gap to the instant when a successive pulse arrives to the electrodes thereby the pulsed breakdown voltage for the switch decreases.

One of the methods to enhance a limited value of the pulse repetition rate is based on the idea to extract the products of the breakdown from the cathode cavity. For this purpose the blocking electrodes can be applicable. These electrodes can be inserted in a main cathode cavity. But for the case of sealed-off design the blocking electrode should be one of the electrodes of the thyatron.

In this paper we investigate the method which allows extracting the plasma of the discharge from the cathode cavity and from the main gap of the sealed-off thyatron with the cold cathode TPI1-10k/50.

**Keywords:** *cold cathode thyatron, electric strength, non-self-sustained discharge.*



**EXPERIMENTAL INVESTIGATION OF PZ-PINCH IMPLOSION DYNAMICS**

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The paper presents results of experimental investigation of plasma radiation source with small spatial dimensions for radiography. Experiments have been carried out on a compact 250 kA, 180 ns XPG-2 pulsed power generator with the Mo and Mg plasma jets. The radiating hot plasma was produced on compression of small size plasma jet conducting a XPG-2 current pulse. The height of the XPG-2 high-current generator gap, in which was formed PZ-pinch, was 1.4 mm. The PZ-pinch implosion dynamics was recorded with the HSFC Pro four-frame camera (3 ns exposure time). It has been found that the hot point size of the molybdenum PZ-pinch radiating in the energy range  $> 3$  keV was 6.5  $\mu\text{m}$  in diameter and 13  $\mu\text{m}$  in height. PZ-pinch x-ray pulse width at half-maximum was 2–3 ns.

This work was supported by Russian Science Foundation, grant No. 16-19-10142.

**Keywords:** *Current generator, Arc discharge, PZ-pinch.*

## SKIN ELECTRICAL EXPLOSION OF DOUBLE-LAYER CONDUCTOR WITH A LOW CONDUCTIVITY OUTER LAYER

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The plasma formation occurs on the electrodes surface in strong magnetic fields. That results in overlap of the vacuum gap by expanding plasma and deterioration of the transport efficiency of the energy to the generator load.

In this paper the skin explosion of thick homogeneous and double-layer cylindrical conductors were studied at the threshold values of the magnetic field 200–400 T. Double-layer conductors were prepared by following technique. Titanium outer layer with low conductivity and thickness of 20–80  $\mu\text{m}$  was deposited on the copper or duralumin conductor by vacuum arc method on ion-plasma setup QUINTA. The experiments were carried out on the MIG high-current generator at a current level of up to 2.5 MA with a current rise time of 100 ns.

It is shown that delay process of plasma formation higher 200 ns takes place at the use of double-layer structure conductor with a low conductivity outer layer compared with the homogeneous copper or duralumin conductor. Calculations have shown that a delay of plasma formation can occur due to redistribution of the current density over the cross-section and reduce of the Joule heat on the surface of the double-layer conductor.

The work was supported by the Russian Foundation for Basic Research (grant No. 14-08 00524 and 16-08-00658).

**Keywords:** *electrical explosion of conductors, double-layer conductor, strong magnetic field, high-current pulse generator.*

## STUDY OF RADIATIVE PROPERTIES OF DOUBLE SHELL GAS PUFFS WITH AN OUTER PLASMA SHELL

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A novel Z-pinch configuration, a gas puff with an outer plasma shell, has been tested as a K-shell plasma radiation source. The experiments were carried out on the GIT-12 generator (4.7 MA, 1.7  $\mu$ s) in the microsecond implosion regime. The Z-pinch load consisted of a Ne double shell gas puff surrounded by an outer plasma shell. Most of the experimental data were obtained for the gas puffs with an 80-mm-diameter outer shell and a 20-mm-diameter inner jet. The plasma shell was created by 48 plasma guns located at a diameter of 350 mm. In the experiments, the Z-pinch initial parameters were varied to achieve maximum Ne K-shell radiation yield and power. At optimized load parameters for the 80/20-mm-diameter gas puffs, the Ne K-shell yield exceeded 13 kJ/cm, and the K-shell radiation power was close to 1 TW/cm at the peak implosion current of 3.8 MA. Efficiency of the microsecond plasma radiation source based on a double shell gas puff with an outer plasma shell is discussed. Obtained experimental data are compared with the results of our previous experiments with Ne triple shell gas puffs and theoretical estimations of the expected K-shell yield.

**Keywords:** *Z-pinch, plasma radiation source, K-shell radiation.*

## KR LASER-ELECTRIC COMBINED BREAKDOWN AND DISCHARGE PLASMA DYNAMICS

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Pulsed gas discharge ignition has been investigated extensively. Energy efficiency issues of discharge ignition and sustenance are of great practical interest. Combining different electric field parameters (AC, RF, microwave) and configurations (orthogonal and collinear) is one of problem solution ways.

Experimental investigation of combined laser-electric (213, 266, 355, 532, 1064 nm; 0.5 ~ 18 ns;  $I_0 \sim 10^9\text{--}10^{11}$  W/cm<sup>2</sup>;  $E \sim 0\text{--}13.2$  kV/cm) breakdown in krypton at sub-atmospheric pressures ( $p \sim 10^1\text{--}10^5$  Pa) has been performed. It has been discovered that such a combined breakdown could take place at laser and electric components values significantly less than those for 'pure' optical or electric impact. Laser beam was orthogonal to electric field.

Discharge in Kr is less investigated than in other noble gases, despite it has good perspectives as an alternative to Xe in light sources. We defined thresholds of laser  $I_{\text{opt}}$  and electric  $E_{\text{el}}$  breakdown first and then used them as a reference for combined breakdown components dimensionless analysis ( $i = I / I_{\text{opt}}$ ,  $u = E / E_{\text{el}}$ ). The effect of gas pressure and radiation wavelength on combined breakdown threshold components was inversely proportional due to recombination probability decrease, multi-photon probability and electron acceleration rate increase as  $p$  and wavelength were reduced. In addition to often used electric, laser, laser-assisted electric and electric-assisted laser breakdown regimes we discovered a new synergistic combined one and evaluated its borders.

To find out nature of this combined regime, we also investigated discharge dynamics focusing on photoelectron and thermionic emission, multi-photon ionization and electron tunneling effects, laser and arc induced shock waves at different impact conditions.

**Keywords:** *laser spark, combined breakdown, gas discharge.*

## NUMERICAL MODELING OF ELECTRICAL EXPLOSION IN MEGAGAUSS MAGNETIC FIELDS

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MHD calculations of the electrical explosion of conductors in megagauss magnetic fields has been performed. The explosion time was associated with the plasma formation on the surface of the conductor. It is shown that in the planar case the plasma formation time does not depend on the rise rate of the magnetic field. In this case the explosion time is determined by the metal properties. In contrast, the plasma formation time depends on the rise rate of the magnetic field in case of the cylindrical conductors. In the planar case the absolute values of the magnetic field induction at which the plasma formation occurs, are simulated to be equal to: 5 MGs for copper; 4.25 MGs for tungsten;  $3.85 \pm$  MGs for aluminum; 3.6 MGs for titanium.

This work was supported by RFBR grants No. 14-08-00524 and 16-08-00969.

**Keywords:** *magnetohydrodynamics, electric explosion of conductors, megagauss magnetic field.*

## INVESTIGATION OF THE INITIAL STAGES OF PULSED DISCHARGE IN SALINE SOLUTION

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Currently, high-current pulsed discharges in saline solutions found wide application in biology, hydro-acoustics, and for the destruction of various rocks. As distinct to distilled water, the discharges in the saline solutions appear at a rather low voltage. In an initial stage, the microbubbles are formed near an active electrode. When the voltage reaches a threshold value, the discharge plasma is generated in the bubbles. The present report concentrates on studying the impact of these processes on the character and the magnitude of discharge current under conditions when the value of  $V_0$  is substantially less than the breakdown voltage.

The discharge in electrode a point-plane system placed in a water-salt solution is investigated (density of NaCl = 3 %). The pulse voltage  $V_0 \leq 1.5$  kV is applied to the gap. Maximum discharge current is about 300 A. Current and voltage waveformson the discharge gap are recorded using the oscilloscope «Tektronix TDS 3034». For the investigation of dynamics of the discharge development the CCD camera is used. The behavior of emission from discharge gap with spatial-time resolution is observed.

**Keywords:** *gas cavities, breakdown, non-steady processes.*

**STUDY OF THIN METALLIC FILM EXPLOSION IN VACUUM**

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An experiment with Al, Cu and Ni exploding foils was carried out at a current density of  $(0.5-1) \times 10^8$  A/cm<sup>2</sup> through the 6- $\mu$ m foil with a current density rate of about  $(0.5-1) \times 10^8$  A/s cm<sup>2</sup>. To record the metal foil effervescence during the foil explosions, a two-frame radiographic system was used. It was shown that the duration of the explosion resistive phase is considerably less than the metal boiling time. The foil energy deposition is equal to 30–70 % of the sublimation energy.

This work was supported by RFBR, grant No. 15-08-03845-a.

**Keywords:** *foil explosion, X-pinch, X-ray radiography.*

## ELECTRON AND PHONON SPECTRA DYNAMICS AND FEATURES OF PHASE TRANSITIONS IN SODIUM AT PRESSURES 0-100 GPa

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In our opinion, the features of a melting curve of sodium are specified by the dynamics of electronic and phonon spectra, and by anharmonicity of the least. Let's also notice that, the behavior of the melting temperature of sodium under pressure near the maximum of the melting curve and structural transition bcc  $\rightarrow$  fcc are similar to behavior of a substance under the second-order phase transition.

We use a first – principles calculations for both electronic and phonon spectra, and for total interaction energy of electrons with cores by means of Savrasov's software package LmtART-7. Variation search procedure to both thermodynamic stable structure of an anharmonic crystal lattice and parameters of interaction potentials of lattice neighbouring atoms at the given pressure and temperatures was used; the procedure was carried out by means of the MathLab package. For construction of the melting curve we used both the Lindeman criterion, and an approach introduced earlier in our paper, according to which liquid metal is a mix of clusters with vapor. Comparison of our results with experiments and theoretical work is carried out. It is shown that metal really displaced the critical behavior both in region of the maximum melting temperature under pressure and in the region of structural transition bcc  $\rightarrow$  fcc.

This work carried out within the state order No.0389-2014-0006 and under the partial financial support of the RFBR (project No.16-08-00466) and the Ural Branch of RAS within the UB RAS fundamental research program «Matter at high energy densities» (project No.15-1-2-8).

**Keywords:** *electronic and phonon spectra, structural transitions, high pressures.*



## RADIOGRAPHIC RESEARCH OF THE BI PLASMA JET FORMED BY THE VACUUM ARC DISCHARGE

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The results of experiments on soft x-ray radiography ( $\approx 1\text{--}2$  keV) of bismuth plasma formed by the high-current vacuum arc discharge are represented. The plasma gun with the arc current  $\approx 60$  kA and the current rise time  $\approx 7$   $\mu\text{s}$  was used to produce a Bi plasma jet. The compact pulsed radiograph XPG-1 (250 kA, 220 ns) with X-pinch load consisting of four Mo wires with diameter 25  $\mu\text{m}$  was used as a source of the soft X-ray radiation. X-ray backlighting images of the researched plasma jet and the Bi step-wedge with a step thickness of  $\approx 100$  nm were recorded simultaneously at the experiment. The comparison of the plasma jet x-ray image with the current trace has made possible to estimate dependencies of the plasma density and the linear mass from the arc current. Experiments have shown that when the arc current density reaches  $\approx 3 \times 10^5$  A/cm<sup>2</sup> the sharp increase evaporation rate of electrodes substance was occurred. This indicates that after the arc current density exceeds the some threshold value the evaporation process begins to acquire explosive character. The plasma density increases on the order and reaches  $\approx 1 \times 10^{19}$  cm<sup>-3</sup> during 1 s after the arc current maximum, and the linear mass of plasma jet reaches  $\approx 535$   $\mu\text{g}/\text{cm}$ .

Work was supported by the Russian Foundation for Basic Research (grant No.15-08-03845-a and No. 14-02-00382-a).

**Keywords:** *Vacuum arc discharge, X-ray radiography, X-pinch.*

## ABOUT EFFICIENCY OF ENERGY INPUT OF A HIGH-VOLTAGE ELECTROMAGNETIC PULSE WITH PICOSECOND FRONT INTO THE DISCHARGE CHAMBER

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Progress in the powerful electronics allows to investigate the fast processes in substance at influence of high-voltage electromagnetic pulses (EMP) with picosecond front duration on metals. It is known the intensity of radial electric field on micro-conductor surfaces can reach values up to tens MV/cm. This essentially impairs the efficiency of the EMP input into the discharge chamber, and also transformation of the EMP energy to radiation. The purpose of the presented work is the experimental research aimed at the efficiency enhancement.

The EMP generator used is RADAN-220. The discharge chamber is a non-uniform coaxial line containing a 5–15 mm long gap being either open-ended or short-circuited with micro-conductors. Measurements of voltage and electric current waveforms were carried out by the capacitive divider and shunt correspondingly and registered via the Tektronix oscilloscopes; and the beam current in cross direction to the chamber axis was measured using the Faraday cup. Photographing of the discharge radiation in the central area of the chamber and at the electrodes ends was also performed. It is shown, that use of dielectric materials for electron deceleration allows to increase efficiency of the EMP energy transformation into electromagnetic radiation one.

This work is carried out within the state order No. 0389-2014-0006 and under the partial financial support of the RFBR (project No. 16-08-00466) and the Ural Branch of RAS within the UB RAS fundamental research program «Matter at high energy densities» (project No. 15-1-2-8).

**Keywords:** *electromagnetic pulse, picosecond front, energy transformation.*

## DEVELOPMENT OF LARGE-SCALE INSTABILITIES AT STRONG MAGNETIC FIELDS

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This paper presents experimental results on electrical explosion of copper cylindrical conductors with a diameter of 2 mm at the magnetic field up to 400 T. The experiments were carried out on the MIG high-current generator at a current level up to 2.5 MA with a current rise time of 100 ns. Plasma jets expanded in radial direction with a velocity of  $7 \times 10^6$  cm/s have been recorded on the surface of the conductor. A possible cause of formation of such plasma structure is a growth of flut-like instabilities.

The work was supported by the Russian Foundation for Basic Research (grant No. 16-32-00631).

**Keywords:** *strong magnetic field, lager-scale plasma instabilities, high-current pulse generator.*

## ELECTRIC PROBE MEASUREMENTS IN HIGH-CURRENT CHANNEL AT HIGH PRESSURE HYDROGEN

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The diagnostics of a high-current discharge in a high pressure gas is a very difficult task. The basic difficulties of the diagnostics are connected to the high density of plasma. Recently, it was developed the magnetic probe diagnostics for the high-current high-pressure discharge [Pinchuk M.E., Budin A.V., Leontev V.V., Leks A.G., Bogomaz A.A., Rutberg Ph.G., Pozubenkov A.A. // *IzvestiaVuzov, Physica*, 2014, vol. 57, n12/2, pp. 240–244, (in Russian), Pinchuk M.E., Bogomaz A.A., Budin A.V., Leontev V.V., Leks A.G., Pozubenkov A.A., Rutberg Ph.G. // *Journal of Physics: Conference Series*, 2015, vol.653, n1, pp. 012149].

In the report preliminary results for the original differential electric probes, working in the condition of the high-current high pressure discharge, are presented.

The discharge initiated by copper wire explosion in hydrogen with the initial pressure of 1 MPa was investigated. A discharge chamber had an axisymmetric geometry. The capacity of the energy storage was 40mF. Charging voltage was varied from 1 to 5 kV. The stored energy was up to 500 kJ. The current amplitude was up to 150 kA with half-period duration about 2 ms.

It is shown that main voltage drop falls near the electrodes and the total nearelectrode voltage drop was  $\sim 1$  kV, whereas the mean electric field strength was about 50 V/cm.

This work was partially supported by Russian Foundation for Basic Research (grant 15-08-04219-a, 16-08-00767-a).

**Keywords:** *high-current discharge, high-pressure discharge, differential electric probe, high-pressure hydrogen.*

## ABSORPTION LASER SHADOW IMAGING OF THE INITIATION OF VACUUM ARC CATHODE SPOT

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In our work the cathode processes at the cathode spot of vacuum arc of the current 5 A are investigated by the pulsed laser shadowgraphy technique. The aim of this investigation is to obtain data on the size and lifetime of the dense plasma of the ecton process within cathode spot of vacuum discharge.

The tunable solid state laser pumped by second harmonic of pulsed Nd:YAG laser (532 nm) with pulse length 20 ns was used to obtain shadow images of discharge gap. QM100 long distance microscope (reflector) was used to obtain magnified image of electrodes at the entrance of CORDIN 173 streak camera. Time resolution was up to 0.2 ns and spatial resolution up to 2.9 mm.

Discharge was initiated at the cathode by 25 kV rectangular voltage pulse 350 ns of duration applied to the anode pin. Due to the low-inductance resistor 5 kOhm in anode circuit the discharge current was 5 A. Cathode was the titanium wire with 30 microns tip and the wire tungsten anode was about 20 microns in diameter at the tip of anode pin. Interelectrode gap was about 20 microns.

It was found that for wavelength 364.3 nm at initial stage of the discharge (first 50 ns) the absorption image could be observed. The size of dense plasma object is 20–30 microns. At another wavelength investigated: 363.5 nm (ground state), 365.3 nm, 394.8 nm (ground state), 398.1 nm, 399.8 nm no absorption was found.

**Keywords:** *vacuum discharge, laser shadowgraphy, streak camera, ecton.*

## STUDY OF MHD INSTABILITIES DURING Z-PINCH IMPLOSION

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We present a series of 3D simulations of multiwire arrays implosion carried out by means of RMHD code MARPLE-3D (Keldysh Institute of Applied Mathematics) with the aim to explore plasma instabilities arising at the end of plasma ablation and developing up to the final stage of the wire array implosion. Different configurations of wire arrays were investigated. Cylindrical and quasispherical wire arrays were studied, as well as single and nested array designs were considered.

Plasma emission was reproduced via prolonged plasma ablation model including spatial nonuniformity of plasma production rate consistent with experimental X-ray images of lower plasma emission areas. The distinctions of wires evaporation in nested arrays were implemented.

It was demonstrated that dedicated design of the electrodes, the wire array, and mass distribution along the wires results in very compact spherical bright radiation source in the centre of the array. The formation of magnetic flux breakthroughs during wire array implosion was reproduced.

The numerical results were compared with the experimental data obtained at Angara-5-1 facility (TRINITI, Troitsk).

Computations were carried out using supercomputers K-100 (KIAM RAS), MVS-100K/ MVS-10P (JSCC RAS) and «LOMONOSOV» (MSU).

This work was supported by the RFBR grant 5-01-06195 a.

**Keywords:** *z-pinch, quasispherical wire-array liners, MHD simulation.*

**RESEARCH IN DYNAMIC BEHAVIOR OF MATERIALS USING GNUV-P FACILITY*****EVGENIY KARNAUKHOV***

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The paper presents results of research activities aimed to further apply methods of strong magnetic field loading. These studies used GNUV-P facility with the accumulated energy up to 250 kJ. High-strain-rate deformation of  $\text{Æ}30\text{mm}$  cylindrical liners was observed within deformation rates  $10^4$  through  $10^6 \text{ s}^{-1}$ : the total deformation was  $\sim 100\%$  and the liner compression rate was  $\sim 0.8 \text{ km/s}$ . Acceleration of aluminum current-carrying plates and strikers made of various materials was attained in the speed range from 0.5 to  $\sim 3 \text{ km/s}$ . Velocity profiles for flat plates and cylindrical liners, as well as free-surface velocity profiles for the samples under consideration were registered with PDV-, or VISAR-interferometer. It is shown that GNUV-P facility allows loading pulses sufficient to conduct research into the dynamic properties of materials at the strain rate from  $10^4$  to  $10^6 \text{ s}^{-1}$ .

**Keywords:** *magnetic pulse acceleration of plates, magnetic pulse compression of liners, profile of plates (liners) motion velocity, profile of free surface velocity, strain rate, shock wave.*

## INFLUENCE OF FOIL THICKNESS ON HOMOGENEITY OF ITS ELECTRIC EXPLOSION

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The paper presents experimental results that demonstrate how thickness of the flat electrically-exploding foil contributes to inhomogeneity and time delay of its explosion. In the experiments, quartz sensors measured the «amplitude-time» pressure profiles in the central and side (explosion moves from edges to the center) regions of the flat foil. Thick foils (14–100  $\mu\text{m}$ ) made of aluminum, copper, titanium, and nickel alloy 80 NHS were used for experimentation. The collected data show that inhomogeneity and time delay of the foil explosion increase with the foil thickness.

**Keywords:** *electrical foil explosion, foil thickness, homogeneity, quartz sensor of pressure.*



## THE METHOD OF INITIATION OF CHEMICAL REACTIONS BY USING ELECTRON BEAM PLASMA AND ITS APPLICATIONS

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A new method of initiation of chemical reactions in a gas phase CVR (Chemical Volume Reactions) and on a surface CVD (Chemical Vapour Deposition) using an electron beam plasma created in a supersonic flow is presented. The method is based on the activation of initial gas molecules by electron beam and fast convective transfer of the radicals to a substrate or zone of reactions by means of a supersonic jet. In the report the description of the method and its basic technological elements (electron gun, nozzle block and additional tools) are given. The method is universal and allows implementation in a wide range of technologies, from vacuum to obtain layers and films on the surface to atmosphere to produce various chemical products. Advantages of method are described in various fields of application. The directions of the conducted developments and achievements are presented.

**Keywords:** *Cold nonequilibrium plasma*

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**PROPERTIES OF CAPILLARY DISCHARGE BY INTERACTION WITH METALS*****DMITRI LEONIDOVICH KIRKO AND IGOR DMITRIEVICH EGOROV****National Research Nuclear University MEPhI, Russia  
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Influence of capillary discharge plasma at thin metal foils is considered. Plasma parameters in an interaction region and properties of plasma regions, separating from the discharge range are researched. Spectrum of electromagnetic radiation was obtained and plasma temperature was determined. The research of properties of plasma regions due to magnetic field was realized. A possible model of an origin of plasma regions is discussed.

***Keywords:*** *Torch of capillary discharge, plasma region.*

**CHARACTERISTICS OF ELECTRICAL DISCHARGE IN ELECTROLYTE*****D.L. KIRKO, A.S. SAVJOLOV****National Research Nuclear University MEPhI, Russia,  
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A discharge origin in an electrolyte medium is made with a thermal heating and a luminous region appearance near one electrode. Electrolyte discharges are used at a working and modification of metal surfaces, for a coating made, and at plasma chemical processes [*Gaisin A.I.F., Nasinullin R.T. // Plasma Physics Reports. – 2011. – Vol. 37. -№10. pp. 896-903; Kanarev F.M. // Low temperature electrolysis of water. - Krasnodarsk. Univ., Krasnodar, 2010*].

In these experiments discharges were researched by electrolytes containing sodium carbonate, sodium hydro carbonate, potassium hydroxide and distilled water. A power source contained two half period rectifier with voltage 0–250 V and frequency 100 Hz. A bar cathode (material: tungsten, titan) and a plate anode (material: stainless steel, molybdenum) are electrodes of the devise. After a breakdown intensive radiation forms around the cathode. Current voltage characteristics (CVC) were researched at different concentrations of the electrolyte matter. In the working region of the discharge burning current was in the range 0.5–1.5 A. A comparable analysis of measured dependences and an influence of working matter concentration at CVC form were realized.

Due to the hydrogen lines plasma temperature near the cathode was defined, it placed in the region  $T = 2200\text{--}2700$  K. Electrical oscillations of the discharge in the range 10 kHz–80 MHz were researched. The most intensive frequencies of electrical oscillations were determined and spectrum of these oscillations was measured.

**Keywords:** *electrolyte discharge.*

## DIFFRACTION OF NANOSECOND ELECTROMAGNETIC PULSES AT DISK-SHAPED WIDE-APERTURE DUMMY LOADS OF LIQUID MICROWAVE CALORIMETERS

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Results are presented of S-band numerical simulation with the PiC code KARAT [Tarakanov V.P. *User's Manual for Code Karat*. – Berkley: Springfield, 1992.] of nanosecond high power microwave pulses [Benford J., Swegle J.A., Shamiloglu E. *High Power Microwaves*. – New York–London: Taylor & Francis, 2007.] diffraction by disk-shaped wide-aperture dummy loads of liquid calorimeters [Vykhodtsev P.V., Elchaninov A.A., Klimov A.I. et al. // *Instrum. Exp. Tech.* – 2015. – V. 58. – No 4. – P. 510.] as applied to typical experimental conditions like [Kitsanov S.A., Korovin S.D., Klimov A.I. et al. // *Tech. Phys. Lett.* – 2004. – V. 30. – No 8. – P. 619.]. The simulation results show that the microwave pulse envelope behind the load is formed due to microwave diffraction by the load rather than to microwave flow directly through the load layers.

It is also demonstrated that under typical experimental conditions, the microwave energy can be underestimated by 10–20 % when measured by the calorimeter with its disk-shaped load immediately ahead of the aperture of the transmitting conical horn antenna [Kitsanov S.A., Korovin S.D., Klimov A.I. et al. // *Tech. Phys. Lett.* – 2004. – V. 30. – No 8. – P. 619.]. Measuring circuits are proposed to reduce the underestimate of microwave energy and to provide more accurate measurements of the pulse envelope.

This work was supported by Russian Foundation for Basic Research under Project No 14-08-00243-a.

**Keywords:** *high power microwave pulses, diffraction, disk-shaped wide-aperture dummy load, liquid calorimeter.*

## 2.4 GHZ RELATIVISTIC TRAVELING WAVE OSCILLATOR WITH SHORT TRANSIENT TIME BASED ON A CIRCULAR CORRUGATED WAVEGUIDE

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VLADIMIR TARAKANOV<sup>3</sup> AND VLADIMIR KONEV<sup>1</sup>**

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Reducing the transient time (TT) of high power microwave oscillators based on relativistic electron beams (REBs) widens the microwave pulse [Totmeniniov E.M., Klimov A.I., Konev V.Yu., et al.//*Tech. Phys. Lett.* – 2014.–Vol. 40. –No 2. – P. 152., Totmeniniov E.M., Klimov A.I. // *Tech. Phys.* – 2016. – Vol. 61. – No 6. – P. 950.]. This can be done by increasing the coupling impedance (CI) between the operating wave and REB. In a low-frequency (1 GHz) RBWO [Totmeniniov E.M., Klimov A.I., Konev V.Yu., et al.//*Tech. Phys. Lett.* – 2014.–Vol. 40. –No 2. – P. 152.], coaxial design of the slow wave structure (SWS) and interaction of REB with (–1) harmonics of TEM wave enable significant reduction of TT.

At higher frequencies, in an oscillator using no external magnetic field, based on conventional hollow SWS and interaction with (0) harmonics of TM<sub>01</sub> wave, CI as high as 10 Ohm is achievable [Totmeniniov E.M., Klimov A.I. // *Tech. Phys.* – 2016. – Vol. 61. – No 6. – P. 950.].

We present PiC modeling (using 2.5D and 3D versions of KARAT code [Tarakanov V.P. *User's Manual for Code Karat.* – Berkley: Springfield, 1992.] and a simple 1D model) of 2.4 GHz traveling wave oscillator in which the key role plays the Cherenkov interaction of 420 keV, 3 kA REB guided by magnetic field with (0) harmonic of TM<sub>01</sub> wave slowed down to speed of light. The CI is 9 Ohm. The simulated TT is as short as 15 ns and the microwave power is 320 MW (25 % efficiency) in both strong (0.6 T) and weak (0.2 T) magnetic fields.

This work was supported by RFBR, Project 16-08-00004-a.

**Keywords:** *traveling wave oscillator, transient time, coupling impedance.*

## LABORATORY MICE ARE STRESSED AFTER EXPOSURE TO NANOSECOND REPETITIVE PULSED MICROWAVES

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It is known [Davidov B.I. et. al. // *Biological effects, regulation and protection from electromagnetic radiation.* – M.: Energoatomisdat, 1984.] microwave exposure with a high power density causes stress. Our experiments were conducted to evaluate the possibility of stress after exposure to nanosecond repetitive pulsed microwaves (RPM) on laboratory mice.

The study was conducted according to the ethical standards for laboratory animals on 40 white outbred male mice weighing 25–30 g. Laboratory generators based on the MI-505 magnetron served as RPM sources. The head and epididymal adipose tissue area of the animal was subjected to daily (within 10 days) 4000 nanosecond pulses RPM (100 ns pulse duration) with a pulse repetition frequency 6–22 Hz, peak power density 1500 W/cm<sup>2</sup>. The mouse body were covered with radio absorbing materials for local irradiation of brain and adipose tissue. The animals were divided into sham-irradiated and an irradiated group. The effect was assessed by hormone corticosterone content in blood serum.

Experiments have shown the influence of nanosecond repetitive pulsed microwaves may have a significant effect on some of the physiological responses of irradiated mice. After 10 days of irradiation hormone corticosterone content in blood serum were increased. The most significant changes were observed after exposure to the frequency 6, 13 and 22 Hz. Changes in corticosterone levels indicates stress development and depends on the pulse repetition frequency. Those data will be useful in the development of safe levels nanosecond RPM in hygienic and ecological norms.

**Keywords:** *nanosecond repetitive pulsed microwaves, laboratory mice, corticosterone.*

## VISUALIZATION OF THE ELECTRIC FIELD OF THE MICROWAVE IN THE MEGAWATT LEVEL SOURCES

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A method for visualizing the electric field strength of a powerful microwave radiation, based on the photographing luminous screen containing metal filings, is proposed. Glow in the optical range is called the air breakdown between the sharp metal microparticles under the influence of incident electromagnetic microwave pulses produced in vacuum and plasma relativistic oscillators and amplifiers. The data allow us to judge not only the magnitude but also the direction of the field lines. These results are compared to numerical modeling of power distribution lines to the corresponding geometry of the waveguide and horn in CARAT code.

**Keywords:** *relativistic microwave electronics, diagnosis of high-power microwave radiation, the output of the microwave structure of the horn.*

## MITOCHONDRIAL RESPIRATION INHIBITION AFTER EXPOSURE TO UWB PULSES AS A POSSIBLE MECHANISM OF ANTITUMOR ACTION

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It is known that the UWB radiation has an antitumor activity. The intracellular ATP level decreased in the irradiated tumor cells after UWB exposure [Frandsen S.K., et al. *Calcium electroporation: evidence for differential effects in normal and malignant cell lines, evaluated in a 3D spheroid model // Plos ONE, 2015, 10(12): e0144028*]. The amount of ATP in the cells depends on the mitochondrial respiration efficiency and integrity of inner membrane. The respiration of isolated liver mitochondria after exposure to nanosecond UWB pulses (0.15–36 kV/cm, 0.6–1.0 GHz center frequency, 3–20 ns pulse duration) was investigated.

Mitochondria respiration was measured by an oxygen meter AKPM-02 (Russia). Respiratory control (RC) (the ratio of oxygen consumption) was estimated. The possibility of mitochondrial membrane electroporation was detected as the decrease in the electrical resistance according to the  $\beta$ -dispersion of the electric current (measurements by LCR meter, Belarus).

After 1000 UWB pulses from 0.15 kV/cm the monotonous decrease of RC was observed. That indicates the deterioration of mitochondrial respiration and the inhibitory effect of UWB radiation. The ohmic resistance of mitochondria suspension was reduced by 23 % after the same UWB irradiation. That can be explained by the non-specific pores in the inner membrane induced by UWB (electropores, MPTP-structures).

**Keywords:** *mitochondria, nanosecond, UWB.*



## ULTRAWIDEBAND PULSE RADIATION BY LINEAR ARRAYS OF CYLINDRICAL HELICAL ANTENNAS

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In the frequency and time domains characteristics of linear arrays ( $4 \times 1$ ) of cylindrical helical antennas with different distances between elements were investigated. Array elements were excited by bipolar pulses of the length 1 ns. The investigations were carried out in the synchronous excitation mode of elements by pulses and in the presence of time delays. A single array element with the number of coils  $N=4,5$  was studied in detail by means of numerical simulation and experiment. For the numerical simulation of ultrawideband radiators the program based on the finite-difference time-domain method was developed, allowing to simulate infinite linear arrays.

**Keywords:** *ultrawideband pulse, finite-difference time-domain method, arrays, elliptical polarization, helical antenna.*

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**MODES OF CYLINDRICAL WAVEGUIDE WITH LONGITUDINAL GROOVES***M.P. DEICHULY, V.I. KOSHELEV**Institute of High Current Electronics SB RAS, Russia  
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Using the stitching of partial regions, the equation for the modes of a circular waveguide with longitudinal grooves has been obtained and solved numerically. The number of azimuth-located grooves with identical geometry is infinite. By the example of a two-groove waveguide, the analysis of their influence on the dispersion characteristic of modes and their space structure was made. The solution of the problem is related to the application of the waveguide sections in the azimuthally nonuniform multiwave Cherenkov generator to control the mode content of the field and to suppress the side lobes of the linearly polarized radiation pattern.

**Keywords:** *dispersion characteristicse, azimuthally nonuniform waveguide, multiwave Cherenkov generator.*

**RESEARCH AND DEVELOPMENT OF THE REFLECTING ANTENNA  
FOR HIGH-POWER SOURCE OF ULTRAWIDEBAND RADIATION  
WITH LINEAR POLARIZATION**

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The results of the simulation of the reflecting antenna system for a high-power source of ultrawideband radiation with linear polarization are presented. Antenna system is intended for radiation of maximum pulsed electric field at a distance of 5 m from the antenna. The antenna system consists of a parabolic offset feed reflector and the compact ultrawideband combined antenna that is set near the focus of the reflector. The results of the calculation of the distribution of the electric field strength in the aperture of the reflector antenna, as well as the results of the optimization of the reflector geometry and location of the feed antenna are presented.

**Keywords:** *ultrawideband radiation, parabolic antenna, short-pulse radiation*

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**ABOUT THE SELECTION OF TRANSVERSE MODES IN THE X-BAND OVERSIZED OSCILLATOR WITH OUTPUT POWER 2.5 GW**

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The article describes the concept of the microwave O-type oscillator based on oversized slow wave structure (SWS). The feedback is applied to the design scheme, which provides intense modulation of the electron beam in the cathode-anode region and two special cavities before SWS. Selectivity TM02 operating mode occurs due to increased diffraction loss of parasitic modes in the cathode part. Slow wave system consists of two identical sections with the phase-shifting region. The use of this configuration, the SWS leads to the formation of a locked TM01 surface wave, having a good radiation conditions into the working mode TM02. In the experiments, a stable generation regime with pure TM02 mode at a frequency of 10 GHz with an efficiency of about 30 % and output power of 2.5 GW in the magnetic field below the cyclotron resonance was obtained.

***Keywords:*** HPM, electron beam, BWO, modes competition, modes selectivity.

## SYNTHESIS OF ULTRAWIDEBAND RADIATION OF COMBINED ANTENNA ARRAYS EXCITED BY NANOSECOND BIPOLAR VOLTAGE PULSES

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To broaden the spectrum of high-power ultrawideband radiation, it is suggested to synthesize an electromagnetic pulse integrating pulses of different length in free space. On the example of model pulses corresponding to radiation of combined antennas excited by bipolar voltage pulses of the length of 2 and 3 ns, possibility of twofold broadening of radiation spectrum was demonstrated. Radiation pulses with the spectrum width exceeding three octaves were obtained. Pattern formation by the arrays of different geometry excited by the pulses having different phase shifts was considered. Optimum array structure with the pattern maximum in the main direction was demonstrated on the example of a  $2 \times 2$  array.

The work was supported by the Russian Science Foundation, Project # 16-19-100081.

**Keywords:** *ultrawideband pulses, radiation synthesis, combined antenna, antenna array.*

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**ULTRAWIDEBAND RADIATION CHARACTERISTICS OF FOUR-ELEMENT ( $2 \times 2$ ) ARRAYS OF CYLINDRICAL HELICAL ANTENNAS**

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Investigations of ultrawidband radiation of four-element ( $2 \times 2$ ) arrays of cylindrical helical antennas with fixed distance between elements has been done both in time and frequency domain. Array elements were excited by bipolar voltage pulse with 1 ns duration. Array elements were excited simultaneously. Helixes with number of turns  $N=2, 4, 5$  and 6 were chosen as array elements. Comparative research of single helix antennas with the same number of turns were also performed.

**Keywords:** *helical antennas, antenna arrays, ultrawideband radiation, elliptical polarization.*

**COMB STRUCTURE AS A SWITCH OF RESONANT MICROWAVE COMPRESSOR***SERGEY ARTEMENKO, STANISLAV GOREV, SERGEY NOVIKOV AND YURY YUSHKOV**Tomsk Polytechnic University, Russia  
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Microwave resonant compressors maintaining fast energy extraction include switches of waveguide T-junction type when the cavity – load transmission factor is designed to be close to unity. A large size of the T-junction switch and a relatively long time of switching plasma formation are disadvantages. The report proposes the switch installed into a regular waveguide. The switch is made as a two-row comb structure filter and some its rods have capacity parts. The filter is rejection one at the resonant frequency during excitation of a cavity. Once the capacity parts are broken down the filter turns into the bandpass one with the transitive attenuation in the range 0 – (–1) dB. The switch can operate at the spontaneous breakdown mode or with controlling external triggering. Frequency – transition attenuation characteristics are presented for storage and extraction modes. Comb structure dimensions variation allows matching the rejection frequency and, after switching, bandpass frequency. Operation of the X- band compressor with the cavity made of the oversized rectangular waveguide was simulated. The estimated power gain was 18 db at the output pulse width of about several nanoseconds.

**Keywords:** *microwave compressor, switch, waveguide, power gain.*

## COHERENT MICROWAVE POWERS SUMMATION OF NANOSECOND GUNN OSCILLATORS WITH INITIAL PHASES FIXED BY THE LEADING EDGES OF ELECTRICAL PULSES OF SYNCHRONIZED MODULATORS

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The results are presented of a four-channel system development based on X-band nanosecond Gunn oscillators like [Gubanov V.P., Klimov A.I., Kova'lchyk O.B., et al. // *Instrum. Exp. Tech.*–2010.–Vol. 53. –No5.–P. 710.]. The system is intended for coherent summation of the oscillators microwave powers. The scheme of the system includes a modulator based on partial discharge of a capacitor, a triggering circuit, and two IXYS IXDN630YI chips that control two DE275X2-501N16A tandem transistors connected to the oscillators. Thus, all the oscillators are excited independently in the channels.

The standard deviations of the phase differences for different pairs of the oscillators are in the range of 16.6–24.0° that are higher than in the case of concurrent excitation the pair of the oscillators by a common modulator [Konev V.Yu., Klimov A.I., Koval'chuk O.B., et al. // *Tech. Phys. Lett.*–2013.–Vol. 39. – No.11.–P. 957.]. This can be explained by relative instability of the modulating pulses produced in different channels and by some instability of the oscillators carrier frequencies near 10 GHz.

Using a special waveguide circuit, the microwave powers of the oscillators were summarized. The maximum and average amplitudes of the total power were respectively 98 % and 95 % of the quadruple microwave power amplitude of a single oscillator.

This work was fulfilled according to the topic II.13.1.2 in the frame of priority areas II.13 of basic researches of Siberian Branch of Russian Academy of Sciences.

**Keywords:** *four-channel system, Gunn oscillator, coherent summation of microwave powers.*



## NUMERICAL OPTIMIZATION OF DUMMY LOADS FOR HIGH POWER MICROWAVE CALORIMETERS

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Numerical optimization is performed applied to 1–11 GHz operating band of wide-aperture absorbing loads for calorimeters [Vykhodtsev P.V., Elchaninov A.A., Klimov A.I. et al. // *Instrum. Exp. Tech.* – 2015. – V. 58. – No 4. – P. 510.] intended for high power microwave [Benford J., Swegle J.A., Shamiloglu E. *High Power Microwaves.* – New York-London: Taylor & Francis, 2007.] energy measurements. Calculations are conducted by using gradient-less Nelder-Mead optimization routine w.r.t. two-dimensional axisymmetric load models. We took the reflection coefficient of TM<sub>01</sub>-mode wave from the input window as an objective function for desired frequency range. Input window relief parameters and the depth of the working fluid are independent parameters of the optimization procedure. Optimization includes the solution of the direct electromagnetic scattering problem. The method is based on finite element method (FEM) for Maxwell's equations in frequency domain in two-axisymmetric coordinate system [Kozhevnikov V.Yu., Klimov A.I. // *13th Intern. Workshop FEM-2016. Florence, Italy, 2016.* – P. 170.]. It allows use of mesh repeating relief of any geometric non-uniformity without significantly increasing of elements density. Frequency dependencies of materials parameters for each material of dummy load (polyamide, polycarbonate, etc.) have been measured experimentally. Metal parts are simulated as perfect electric conductors. For optimized absorbing load the electromagnetic energy losses in the input window were estimated.

This work was supported by Russian Foundation for Basic Research under Project No 14-08-00243-a.

**Keywords:** *high power microwave, energy measurements, calorimeter.*

## APERTURE CALORIMETER WITH OPTICAL SENSOR FOR MEASUREMENT THE HIGH POWER MICROWAVE PULSE ENERGY

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The calorimeters like [Vykhodtsev P.V., Elchaninov A.A., Klimov A.I. et al. // *Instrum. Exp. Tech.* – 2015. – V. 58. –No4. – P. 510.] with a disk-shaped three-layer wide-aperture dummy loads filled with alcohol-based working liquid are used for measurement high power microwave pulses energy [Benford J., Swegle J.A., Shamilogl E. *High Power Microwaves.* – New York–London: Taylor& Francis, 2007.].

In the present work a calorimeter had been developed and investigated analogous to [Vykhodtsev P.V., Elchaninov A.A., Klimov A.I. et al. // *Instrum. Exp. Tech.* – 2015. – V. 58. –No4. – P. 510.] in which an optical sensor with transparent capillary tube is used for the measurement the liquid volume increase due to microwave energy absorption. A linear LED packages aligned along the tube produce light flux of red color across the capillary. A TLS1412S charge-coupled line imaging device 98 mm long with 400 dpi resolution was used as a sensor of the light flux passed through the tube. Read off the signal from the device, the data processing and controlling the liquid-air interface is effectuated by a controlling system and especially developed software. The system controls the liquid meniscus position in the capillary tube by means of automatically regulation the liquid heater power supply.

The calorimeter is calibrated like in [Vykhodtsev P.V., Elchaninov A.A., Klimov A.I. et al. // *Instrum. Exp. Tech.* – 2015. – V. 58. –No4. – P. 510.]. Accomplish this, the microprocessor generates controlling signal of variable length to control the power supply of the calibrator.

This work was supported by Russian Foundation for Basic Research under Project No 14-08-00243-a.

**Keywords:** *aperture calorimeter, optical sensor, high power microwave pulse.*

**ESTIMATION OF EFFICIENCY OF ENERGY CONVERSION  
IN UWB RADIATOR: FROM ELECTRIC ENERGY TO ENERGY  
OF DIRECTED RADIATION**

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The computer simulation of aperture antenna radiation is carried out. Antenna surface is modeled by Huygen elements, which are exciting non-uniform and non-synchronous over the surface by electric pulses. It is computed amplitude and temporary parameters of the radiation in far-field zone, energy spectrum of radiation, parameters of radiation divergence, amplification and energy efficiency of main petal of the directivity diagram of antenna. The source of UWB radiation with pulse duration of 100 ps is developed. The parameters of semiconductor excitation pulser are 40 kV, 100 ps rise-time, 1000 pps repetition rate. Conversion efficiency of DC energy/pulser is 30 %. The specific power of the pulser with its power supply constitutes 150 kg/kW. The effective radiation power of the source is 0.3 GW and 40 W average power for 1000 pps repetition rate pulses. Electrodynamics' efficiency of horn antenna-feeder is 0.8, antenna gain factor is 5. The effective width of frequency spectrum of radiation pulse is 4 GHz. The results of experiments and computer simulation of radiation for azimuth angles 0...40 degrees are carried out. The satisfactory conforming between the measured and simulation data allows to do reconstruct all parameters of radiation by computer simulation. The attitude of radiation energy and the pulse energy of antenna excitation is estimated by the value of 75 %. The part of radiation energy within the angular of divergence is equal to 20 % for the given excitation pulse. Efficiency of the energy conversion from the power supply of the pulser to the energy of directed UWB radiation for the given UWB radiator reaches 4–5 %.

**Keywords:** *UWB Pulsed Antennas, Pulsed Power Radiators, 'Energy Efficiency of Pulsed Radiator.*

## HIGH POWER RADIATORS OF ULTRA-SHORT ELECTROMAGNETIC QUASI-UNIPOLAR PULSES

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Paper presents results of creation, operation and diagnostics of the high power radiators of ultra-short length electromagnetic pulses (EMP) with quasi-unipolar profile, which have been developed in our laboratory. The radiating module contains: the ultra-wideband (UWB) antenna arrays with jointed four TEM-horns, the exciting semiconductor high voltage pulse generator (GpV), primary energy source and control unit. It is known, basic TEM-horns with square cross-section are UWB antennas with middle efficiency of  $A_{eff}/A_a=0.6$  ( $A_{eff}$  -effective aperture for receiver-mode,  $A_a$ -physical aperture area). Increase of antenna efficiency up to 0.9 we obtained by using the antenna array from four TEM-horns and with shielded electrodes in each TEM-horn. Sizes of the antenna apertures were (16–50) cm. Used GpV generators were produced by «FID Technology» company with parameters: 50 Ohm connector impedance, unipolar pulses (10–100) kV, rise-time (0.04–0.15) ns and half-width (0.2–1) ns. The modules radiate the EMP waves with (1–100) kHz repetition rate, with UWB spectrum 0.1 GHz–10 GHz, and with the effective potential of  $E_p(R) \times R = (20–400)$  kV-(product of peak E-field in far-zone by the R-distance). The GpV can be used in multi-module radiator with sync control with 30 ps deviation. It has allowed to made radiators with the effective potential of multi-megavolt level. Parameters of EMP waves were measured by calibrated sensor with characteristics: sensitivity 0.32 V/(kV/m), rise-time 0.03 ns, duration up to 7 ns. The measurements were in good accordance with simulation results by the 3-D code «KARAT». The EMP waves with the (1–10) kV/m amplitudes and (0.5–100) kHz- pulse repetition rate were successfully used to examine various electronic devices on electromagnetic immunity.

**Keywords:** *Pulsed High Power Radiators, UWB Pulsed Antennas, Measurements of EMP Radiation.*

## ADVANCED LAYOUT OF RELATIVISTIC BACKWARD WAVE OSCILLATOR WITH EXPANDED REGION OF E-BEAM PREMODULATION

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The new scheme of X-band relativistic backward wave oscillator (RBWO) with enhanced e-beam premodulation at the input of slow wave structure (SWS) has been suggested and simulated by particle-in-cell method. As opposed to RBWO with one resonant reflector [Kurkan I.K., Rostov V.V., Totmeninov E.M. *Tech. Phys. Lett.*, **24**(5), 388, (1998)., Korovin S.D., Kurkan I.K., Rostov V.V., Totmeninov E.M. *Radiophys. Quant. Electron.*, **42**(12), 1047 (1999).], two discrete cavities for intense e-beam modulation are used. One of them reflects most part of power, but another one improves the quality of compact bunches formation. Most attention was focused on interested for the practice conditions of low magnetic field with induction of 7.5 kG at the cathode and decreased in the SWS. Due to the increased values of optimal phase velocity of minus first spatial harmonic, the coupling of e-beam with synchronous wave grows that is a main reason of enhanced efficiency up to 35–37 %. Simulations were carried out for accelerating voltage 450 kV and beam current 4.5 kA.

**Keywords:** *backward wave oscillator, synchronous harmonic, coupling coefficient.*

## VIRCATOR BASED ON PLASMA-FILLED DIODE WITH 10KA/CM<sup>2</sup> ELECTRON BEAM DENSITY

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The vircator prototype based on the single section plasma-filled diode with injection current of 10 kA/cm<sup>2</sup> was de-signed and tested. The spectrum of output radiation was spread, covering S, C and X-bands. Numerical simulations of the vircator were performed in 2.5D code KARAT, using PiC model for plasma. The simulation results demonstrated the formation of few virtual cathodes, the substantial ion acceleration in the electric fields of virtual cathodes, the rapid filling of the electrodynamic system by injected plasma ions with the formation of virtual anodes. Complicated dynamics of uncompensated space charges of electrons and ions in the oversized cavity resulted in the spread spectrum of output EM oscillations. Numerical simulation results are in good agreement with the experiment.

**Keywords:** *plasma-filled diode, vircator, virtual cathode, electron beam.*

**RADIATION CHARACTERISTICS VARIATIONS OF RELATIVISTIC KA-BAND  
BACKWARD WAVE OSCILLATORS IN TIME AND FREQUENCY DOMAINS**

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MARAT R. ULMASKULOV, VALERII G. SHPAK, SERGEY A. SHUNAILOV  
AND MICHAEL I. YALANDIN**

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Electronic tuning of oscillation frequency for quasi-stationary 8-mm nanosecond relativistic BWO with a power more than 100 MW was investigated. The task is actual for the summation of several wave beams from phase-stable BWOs with shifted frequencies. In this mode the time and space radiation beats with a variation of power fluency from zero to square value during each pulse are realized. Oscillation frequency shift is carried out with the change of electron beam energy in several ways. First, the accelerating voltage at the cathode of the coaxial magnetically isolated diode (CMID) is varied. Second, the energy and frequency tuning is carried out by the change of the CMID gap. The third method is related to a change of a tubular beam potential at a variation of its distance from the slow-wave system wall. The radiation frequency change, essential variation of oscillation power and transient period was observed here.

The electron accelerator RADAN-303 was used in experiments. The formed accelerating pulse was sharpened in non-linear transmitting line. Tuning of the voltage at the cathode and beam current were determined by dynamic reflectometry method. The central frequency and radiation spectrum were registered by the record of a radio pulse with real time oscilloscope. The data about the varied oscillation frequencies, microwave pulses spectrums and their time characteristics are cited. Comparison of the obtained data with numerical calculations was carried out for some cases.

This work was supported by research program of IEP UB RAS 0389-2014-0005 and grant of RFBR №15-08-02066.

**Keywords:** *electron beam, backward wave oscillator, frequency tuning.*

## OVERSIZED INTERFERENCE MICROWAVE SWITCHES WITH DISTRIBUTED POWER OF A SWITCHING WAVE

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These are the results of the research of the oversized(multimode) interference microwave switch at operating mode TE<sub>01</sub>. The switch was made of few H-plane T-junctions being connected to each other through either straight arms (series connection) or side arms (parallel connection). Two types of T-junctions were used. One was based on the oversized waveguide with  $25 \times 58 \text{ mm}^2$  in cross section and another has straight arms with the same total cross section that was consisting of a package of regular waveguides at TE<sub>10</sub> operation mode. The operating frequency was 9.1 GHz. The conducted simulation showed the conditions of the «proper» TE<sub>01</sub> mode at «open» and «close» states of the switch. Moreover, the relations between the arm' lengths and field intensity distribution were compared with the similar relations of the regular cascade microwave plasma switch. In additional, experiments were carried out at low and high power level.

This research was performed with partial financial support from the National Research Tomsk Polytechnic University Competitiveness Programme and with support of the Russian Foundation for Basic Research (Grant No.15-08-01853a).

**Keywords:** *microwave compressor, switch, waveguide, power gain.*



## MITOCHONDRIAL RESPIRATION AFTER EXPOSURE TO NANOSECOND MICROWAVE PULSES: DEPENDENCE ON THE NUMBER OF PULSES

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AND VLADISLAV ROSTOV<sup>1</sup>**

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The effect of microwave nanosecond pulses on mitochondrial respiration was investigated (the number of pulses 1–1000 for the session, pulse repetition frequency 8 and 22 pulses per second (pps)). The source was a laboratory generator based on a MI-505 magnetron, Russia (frequency 10 GHz, pulse duration 100 ns, output peak power of 180 kW, electric field strength  $1.5 \times 10^3$  V/cm, peak power density  $1500$  W/cm<sup>2</sup>). The nonlinear dependence of the rate of oxygen consumption and the degree of coupling of oxidation and phosphorylation on the number of pulses was revealed. After exposure to 10 and 50 pulses at the frequency of 13 pps the effect reached 30–40 % compared to falsely irradiated samples. The possible explanations of the changes in breathing of mitochondria are considered and compared with the reactions of electrical systems to microwave exposure.

**Keywords:** *microwave radiation, nanosecond pulses, mitochondrial respiration.*

## FORMING OF LONG NANOSECOND PULSES WITH A RECTANGULAR ENVELOPE IN A COMPACT ACTIVE MICROWAVE PULSE COMPRESSOR

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This work presents the results of the study of an active microwave pulse compression system capable of forming rectangular pulses with duration  $\sim 10\text{--}100$  ns and having dimensions many-fold smaller than the emitted wave train. Such compression system is based on the compact planar-voluminal resonant cavity made in the shape of a meander from waveguide sections and H-plane tees. The sections of the resonant cavity are parallel and are located in the same plane with tees. The energy input element is located in the input end of the first section. The output device designed as the H-tee interference switch is connected to the output end of the last section. Each end of remaining sections is connected through a straight arm to a H-tee with a short-circuited quarter-wave second straight arm.

Experiments demonstrated that under certain conditions such compressors with compact storage cavity can generate nearly rectangular pulses with duration equal to the time of wave double traveling along the resonant cavity, and with power compatible with the power of the wave in the resonant cavity and the length of radiated wave train several-fold exceeding the size of compressor. At pulse duration equal to 25 ns, gain coefficient was 13 dB and pulse power was 40 MW. The work demonstrates the possibility to change the geometry of resonant cavity by rearrangement of its components without changing the output pulse parameters, and the possibility to make microwave compressing system with a compact voluminal resonant cavity made of moderately multimode waveguide with TE<sub>01</sub> working mode.

**Keywords:** *microwave compressor, microwave compression system, high-power, plasma switch, waveguide, cavity.*

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**RF PULSE FORMATION DYNAMICS IN GYROMAGNETIC  
NONLINEAR TRANSMISSION LINES***ILYA ROMANCHENKO, PAVEL PRIPUTNEV AND VLADISLAV ROSTOV**Institute of High Current Electronics SB RAS, Russia  
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We present the results of RF oscillations growth dynamics as the high voltage pulse propagates through the gyromagnetic nonlinear transmission line (NLTL). Several equidistant electrical and magnetic probes were placed inside the NLTL in order to examine the oscillatory wave formation and the role of higher order modes in this process. The corresponding equation system is discussed. RF pulses are generated at 2 GHz frequency with nonaveraged peak power of 100 MW.

**Keywords:** *gyromagnetic nonlinear transmission lines, high power microwaves, higher order modes.*

## WIDEBAND TEM-TE11 MODE CONVERTOR FOR HPM APPLICATIONS

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Mode convertor design of the fundamental coaxial TEM to the lowest asymmetric TE11-mode of a circular waveguide was proposed and optimized with ANSYS HFSS software. It includes the input coaxial line with the high voltage insulator, conical coaxial matching line and wave-coax transition section. The most losses in this type of convertor caused by the wave of coaxial TE11-mode running back to the microwave source. To minimize these losses there is the matching conical coaxial line with the cut-off insertion for coaxial TE11-mode. Characteristics of the convertor are as follows: central frequency – 1.14 GHz, maximum input peak power – 3 GW, operating frequency band –20 % with the efficiency of 90 % at least.

**Keywords:** *mode convertor, high power microwave, coaxial line, circular waveguide.*

**EXPERIMENTAL STUDY OF AN AXIAL VIRCATOR WITH RESONANT CAVITY**

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Microwave devices with a virtual cathode attract many researches by the ability to provide high output power and tunability of operation frequency. The obvious disadvantage of the vircator is a low efficiency. The studies of axial vircators with multicavity resonators prove the possibility of the resonant increase of efficiency. Various aspects of the system behavior were analyzed numerically using XOOPIC and two self-developed PIC codes [Gurnevich E., Molchanov P. // *IEEE Transactions on Plasma Science*. –2015. – V. 43. – №. 4. – pp 1014–1017.].

On the basis of this analysis we developed and experimentally investigated several designs of a multicavity resonator for an axial vircator with 300–400 keV electron beam [Gurnevich E., Molchanov P. // *IEEE Transactions on Plasma Science*. –2015. – V. 43. – №. 4. – pp 1014–1017.]. The developed axial vircator was driven by a pulsed power supply using a 30 kJ/100 kV capacitor bank and an exploding wire array (EWA), capable of generating a 600 kV voltage pulse. The EWA is designed to be filled with gas at pressures up to 5 guage atmospheres; the length, the diameter, and the number of wires can vary. A pressured SF6 spark gap sharpens the high-voltage output that provides an applied diode voltage of about 400 kV. The frequency and radiation power were analyzed for different cathodes and anode meshes and varied cathode-anode gaps.

**Keywords:** *virtual cathode oscillator, electron beam, high power microwave generation.*

**PROLONGATION OF GUIDED DISCHARGE 10-100 CM  
INITIATED BY FEMTOSECOND LASER FILAMENTATION IN AIR FROM 1-MKS  
SCALE UP TO 1-MS**

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Generally, the duration of a guided discharge stimulated by femtosecond laser filamentation is defined by the high voltage source. In our guided discharge experiments a Marx generator was used for creation up to 180-kV pulse and a Tesla Coil for up to 360-kV pulse. More exactly, the discharge duration is defined by the product of the Marx «stack» capacitance or the Tesla geometrical output one and there load resistance. Both a circuit resistance and any discharge resistance present the load charge. In both cases the discharge duration was inside 1  $\mu$ s.

For different applications a guided discharge of much longer duration is required.

We present here experiments carried out with the discharge length from 8.5 cm (Marx generator) up to 100 cm length by using the Tesla coil HV source. To increase the duration of the discharge we employed a second circuit which injects an additional current pulse under much smaller voltage. Our first experiments were done with prolongation of 85-mm discharge up to 130  $\mu$ s. With help of high speed imagery we showed that 10–100-cm discharge guidance has been achieved successfully during more than 1 ms.

**Keywords:** *guided discharge, Marx generator, Tesla Coil.*

## NOVEL CONTROL SYSTEM OF THE HIGH-VOLTAGE IGBT-SWITCH

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HV solid-state switch control circuit was developed and tested. The switch is made with series connected IGBT transistors. The distinctive quality of the circuit is the ability to fine-tune the switching time of each transistor. Simultaneous switching provides dynamic voltage balancing on all switch elements. Switching on and off of each transistor is provided by a separate control board. On and off signals are sent to the board from the main conductor with current pulses of different polarity. Positive pulse provides the transistors switch on, while negative pulse provides their switch off. The time interval between pulses sets the time when the switch is turned on. The minimum time when the switch is turned on equals to few microseconds, while the maximum time is not limited.

This paper shows the test results of using the 4 kW switch prototype. The switch was used to produce rectangular pulses of microsecond range on resistive load. The possibility of generating damped harmonic oscillations was also tested. Positive test results open up the possibility of creating switches on the operating voltage of tens of kilovolts on the basis of this approach.

**Keywords:** *solid-state switch, IGBT based switch, control system.*

## MASON'S EQUATION APPLICATION FOR PREDICTION OF VOLTAGE OF OIL SHALE TREEING BREAKDOWN

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Electrical treeing is observed in the low conductive materials. Partial discharges and treeing can occur in carbonaceous rocks, such as oil shale. They lead there to the breakdown of large inter-electrode distances at a relatively low voltage. This effect can be used for breakdown and underground heating of solid fuels formation in technologies of in situ processing. However, this need to know the voltage required for the breakdown of a given inter-electrode distance. The Mason's formula describes the field at the tip of the electrode in the tip-plane electrode system. Use of this equation can help to determine the field on the tips of the dendrites. According to this formula the field on the tip is dependent on the radius of tip, inter-electrode distance and the voltage on the electrodes. If the tip field has critical value, which is correspond to the partial discharge activity, then this equation can express treeing breakdown voltage as a function of distance between electrodes. The tip radius is the radius of dendrite head. It was defined due to microscopy. We experimentally obtained the dependence of treeing breakdown voltage for oil shale on inter-electrode distance in the range 0.03–0.5 m. This dependence was approximated by Mason's equation and the critical field was defined due to approximation. The average error of approximation relative to the experimental data is less than 1 %. The compliance of the model on a large inter-electrode distances should be checked in the field conditions.

**Keywords:** *Mason's equation, treeing breakdown, oil shale.*



## CONCERNING CURRENT TRANSITION THROUGH ZERO IN SUBNANOSECOND HIGH-PRESSURE GAS-DISCHARGE SWITCHES

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Pieces of short lines and pressurized spark gaps are used to form nanosecond-length bipolar pulses of the amplitude above 100 kV. In the circuits of bipolar pulse formers with one or two spark gaps where the switch current changes its direction, one fails to obtain bipolar pulses of the duration less than 3 nanoseconds. Probably, when changing the current polarity, the cathode layer has not enough time to be formed for transmitting high discharge current at the low voltage drop across the layer. The paper presents the results of research of a subnanosecond high-pressure gas-discharge switch in the conditions of current polarity change for two types of electrodes: point – point and point – plane. Both cases revealed no violations of current monotonicity at the transition through zero after propagation of a pulse less than 1 ns.

**Keywords:** *bipolar pulses of voltage, pressurized spark gaps, current transition trough zero.*

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**AUTOMATION OF WIDE-APERTURE ELECTRON ACCELERATOR WITH PLASMA CATHODE AND BEAM OUTPUTTING IN THE ATMOSPHERE**

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The paper presents work results on basic characteristics study of an electron accelerator with plasma cathode and grid stabilization of emission plasma boundary and effective output of large cross-section beam ( $750 \times 150 \text{ mm}^2$ ) in the atmosphere. It has been shown that the weak interdependence of beam parameters facilitates control of such electron accelerator, and, respectively, its automation. Remote control of beam parameters such as energy and beam current amplitude, its duration and the pulse repetition frequency opens up new possibilities for the electron accelerator application for both scientific and for new technological purposes, and high energy efficiency allows the use of such electron accelerator in close to the industrial scale.

**Keywords:** *plasma emitter, grid stabilization, electron accelerator, electron beam output foil window, beam losses.*

**SOLID-STATE REPETITIVE PULSED POWER AT ELECTROPHYSICS INSTITUTE*****SERGEI RUKIN****Institute of Electrophysics, Russia  
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The presentation reviews recent results of studies on solid-state repetitive pulsed power generators developed by Electrophysics Institute. The generators are based on the approach in which Semiconductor Opening Switch (SOS) is used for powerful nanosecond pulse generation. The base physical processes that determine the mechanism of operation of opening switches, which are based on the SOS effect, are considered. The main characteristics of the semiconductor opening switch including ultimate cutoff current density, operating voltage, and pulse repetition frequency are discussed. Typical electric circuit diagrams of the SOS generators and their operating principle are given. The presentation reviews design and specifications of compact desk-top generators, which are capable to operate at output voltage of 50 to 200 kV, peak power of several hundreds of MW, and pulse repetition frequency of 1 to 20 kHz. SOS generators providing a peak power of GW-range are described also. At pulse repetition frequency up to 1 kHz and pulse duration of several nanoseconds the generators are capable to operate at up to 1 MV output voltage and over 10 GW peak power. Finally, applications of the SOS generators in various fields of pulsed power electronics will be given. They are applied mostly for generating nanosecond electron beams and X-ray pulses, supplying high-power microwave generators and gas lasers, and electric discharge ignition in gases.

**Keywords:** *repetitive pulsed power, semiconductor opening switch, SOS-based generators.*

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**ESTIMATION OF ENERGY LOSS IN VACUUM TRANSMISSION LINES  
BY TAKEN RELATIVISTIC ELECTRONS INTO ACCOUNT**

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In multi-MA generators, the voltage across the transmission lines could be as high as dozen megavolts. If these lines are vacuum insulated, such high voltage will result in current loss in the gap between the line electrodes and formation of the magnetically insulated space-charge flows. The kinetic energy of the electrons in these flows will exceed sufficiently their rest-mass energy. In the report we suggest how the energy loss across the magnetically insulated transmission line should be estimated by taken such electrons into account.

**Keywords:** *high-current generator, transmission lines, magnetic insulation.*

## FEATURES OF A COLD-CATHODE THYRATRON OPERATION IN THE CONDITIONS OF OSCILLATORY SWITCHING CURRENT

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The paper deals with the investigations of the so-called pseudospark switches. These switches are considered as an advanced alternative to ignitrons and vacuum switches in facilities that require an extremely high current. The principle of the switch operation resembles that of a classical thyatron with a grounded grid. However, in these types of switches a hot cathode is absent. Then the term «grounded-grid thyatron» or the «cold cathode thyatron» is also used in the current literature.

One of the advantages of the cold cathode thyatron seems to be a possibility to operate with an oscillatory current. However the switch is able to pass the current in direct and in reverse direction if only the design is based on a hollow anode. If the anode of the device has a flat design, then a phenomenon of current interruption in the second half-period manifests itself. On the other hand, for some application the current interruption is important prerequisite for correct operation of electric circuit. In this paper the features of thyatron operation in the conditions when a voltage of negative polarity is applied to the anode are investigated. The experiments are carried out with the sealed-off switch TPI1-10k/50. It is demonstrated that depending on the external conditions a partial and or complete interruption in current are possible. The physical reasons for interruption are discussed.

**Keywords:** *cold cathode thyatrons, pulsed glow discharge, current interruption.*

## INVESTIGATION OF THYRISTOR-BASED SWITCHES TRIGGERED IN IMPACT-IONIZATION WAVE MODE

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Commercial thyristors of tablet design with diameters of silicon wafers of 32 to 56 mm and an operating voltage of 2 to 2.4 kV DC were triggered by an external overvoltage pulse applied across the thyristor main electrodes. In experiments a voltage rise rate across the thyristor was changed from 0.5 to 6 kV/ns. Under such conditions the thyristor closing process occurred due to initiation and propagation of a fast ionization front across the semiconductor structure. The time of switching the thyristor from the blocking state to the conducting state was within 200 to 400 ps. The thyristor based switches contained 2 to 9 series connected thyristors and operated in this triggering mode in different discharge circuits. Operating voltage was 5 to 20 kV, capacitance of discharge capacitors was 2  $\mu$ F to 1.2 mF, and stored energy was 0.4 to 15 kJ. The experimental results obtained covered the following range of discharge parameters: discharge current amplitude of 10 to 200 kA, current-rise rate of 15 to 130 kA/ $\mu$ s, current rise time (0.1–0.9 level) of 0.4 to 5  $\mu$ s, pulse duration (FWHM) of 1 to 20  $\mu$ s, and switching efficiency of 0.85 to 0.97. Effect of the voltage rise rate at the triggering stage as well as temperature of the silicon wafer on the thyristors main switching characteristics will be shown. The paper will discuss the experimental circuitry, tested switches design, and results obtained. The results of numerical simulations of the thyristor switching process will also be given.

**Keywords:** *commercial tablet thyristors, fast ionization front, high current-rise rate, subnanosecond switching process.*

## RAIL-TYPE GAS SWITCH WITH PREIONIZATION BY AN ADDITIONAL CORONA DISCHARGE

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Characteristics of high-current rail-type gas switch with preionization of the gas (air) in the spark gap by an additional corona discharge are presented. The experiments were performed in a voltage range from 10 to 60 kV using a two-electrode switch consisting of two cylindrical electrodes with a diameter of 22 mm and a length of 100 mm, arranged parallel with a gap varying from 6 to 15 mm and a set of sideways located corona discharge needles. The number of the needles and inter-needle step corresponds to effective use of the entire length of the rail electrodes. Requirements were defined for the position and size of needles, ensuring ignition of the corona discharge before the breakdown of the main gap and excluding transition of the corona discharge in the spark form. The implementation of these requirements ensures a stable operation of a switch with a small variation of the pulse breakdown voltage, which is not more than 1 % for a fixed voltage rise time in the range from 40 ns to 4.5  $\mu$ s. A small time delay and high stability of pulsed breakdown voltage make it possible to ignite the two-electrode switch by an over-voltage of nanosecond duration. This ignition method eliminates the need of the third thin trigger electrode and significantly increases the lifetime without degradation of dynamic characteristics of the switch.

**Keywords:** *Spark gas switch, rail-type switch, corona discharge, preionization.*

## LINEAR TRANSFORMER AND PRIMARY LOW-INDUCTANCE SWITCH AND CAPACITOR MODULES FOR FAST CHARGING OF PFL

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A pulsed power source with voltage amplitude of 800 kV for fast (300 ns) charging of a pulse forming line (PFL) is developed. The source includes primary capacitive energy storage and a step-up linear pulse transformer. The linear transformer consists of set of 20 inductors with circular ferromagnetic cores and primary windings located inside of common tube of 260 mm inner diameter and about 1.5 m long. The secondary winding is formed by tube walls and a voltage adder – central stock with film-glycerol insulation installed inside of the primary windings of the inductors. The primary energy storage consists of 10 modules, each of them is a low-inductance assembly of two capacitors with a capacity of 0.35  $\mu\text{F}$  and one gas switch mounted at the same enclosure. The total stored energy is 5.5 kJ at charging voltage of 40 kV. According to test results the parameters of the equivalent circuit of the source are the next: capacity is 17.5 nF, inductance – 2  $\mu\text{H}$ , resistance – 3.2 Ohms.

The study was supported by the Russian Science Foundation (project 16-15-10355).

**Keywords:** *capacitive energy storage, linear pulse transformer, gas spark switch, film-glycerol insulation.*



## **CORONA PRE-IONIZED GAS SWITCHES WITH AN INCREASED LIFETIME FOR MARX GENERATOR OF THE LIGHTNING TEST COMPLEX**

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A new design of triggered spark gas switches with an increased operation life and stable dynamic performances for 2.4 MV, 4 MJ Marx generator of the lightning tests complex is developed. Mode of operation of switches in the test complex is the next: the total voltage – up to 80 kV, the discharge current – up to 50 kA, the charge flowing – up to 3.5 C/pulse, the working gas – dry air at atmosphere pressure. An increased operating life is achieved by using torus-shaped electrodes with an increased working area and by the application of a thick disk with a hole as a trigger electrode installed between the two torus-shaped electrodes. Low breakdown time delay and high stability of the breakdown voltage under dynamic conditions are provided by gas pre-ionization in the spark gap by UV-radiation of an additional corona discharge in the axial region of the switch. The design as well as the performance of the switch will be presented and discussed.

**Keywords:** *Marx generator, gas spark switch, corona discharge.*

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**SANDIA-HIGH CURRENT ELECTRONIC INSTITUTE (HCEI)  
COLLABORATION IN FAST LTD DEVELOPMENT**

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Following the impressive operational success of the first slow (~1 microsecond) LTD in Gramat, France, that was invented, designed and built by the team at HCEI headed by Boris Kovalchuk, Dillon McDaniel of Sandia asked the inventors if they could apply this technology for the production of fast ~100 ns pulses. The inventors accepted the challenge, and a number of communications were exchanged between Sandia and HCEI on how the fast LTDs could be used for this research. The first published theoretical analytical study of such fast LTDs was presented in the 1999 Pulsed Power Conference in Monterey, California by M.G. Mazarakis et al. This paper attracted a lot of interest in the pulsed power community, resulting in a large number of requests for copies. Following that, a strong collaboration started between Sandia and HCEI that culminated in the production of 10 of the largest to-date 1 MA, 1 GW fast LTD cavities which compose now the MYKONOS voltage adders at Sandia. The different stages of the fast LTD development through the years and the up-to-date accomplishments will be presented. Although this technology has mushroomed around the globe, this paper will concentrate solely in the Sandia-HCEI collaboration.

***Keywords:*** *Linear transformer drivers, Pinches, Accelerators.*

**PSEUDOSPARK SWITCHES COMMUTATION DEPENDING  
ON TRIGGER CHARACTERISTICS**

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Commutation characteristics of TPI-type pseudospark switches depending on parameters of trigger circuits are studied. An influence of trigger pulse rise time on pseudosparks time jitter is explored. It has been shown that pseudospark switches can be triggered on a pre-ionization electrode with cathode and grid simultaneously grounded. Double and triple gap deuterium and hydrogen switches were explored. Time jitter values of 1–2 ns on deuterium switches triggered on pre-ionization electrode have been achieved.

**Keywords:** *Pseudospark switch, commutation, time jitter.*

## SHOCK-EXCITED, FERRITE-LINE HIGH VOLTAGE GENERATOR OPERATING AT 4 GHz AND REPETITION RATE OF 1000 HZ

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The results of testing of four-channel system of coaxial gyromagnetic non-linear lines (NLTL) rf-generators with external biasing and frequency of rf-modulation of high-voltage pulse envelope  $\sim 4$  GHz are presented. The Generator operates at repetitive rate up to 1 kHz and burst time of 1 second. The solid-state modulator S-5 was used as a driving generator [1], forming high-voltage unidirectional pulse with duration  $\sim 5$  ns (FWHM) and amplitude  $\sim 500$  kV across a load 50 Ohm. The pulse was splitted in 4 channels with individual NLTL. The transformer oil under pressure up to 10 atm. was used. Voltage at each single channel was  $\sim (-165)$  kV (at 500 Ohm).

The pulses with fast damped rf-modulation were formed at the NLTL output. Peak amplitude value of a modulated pulse reached  $\sim 230$  kV, while maximum depth of modulation was to 50 %. The maximum of the frequency spectrum was at 4 GHz. When total spread in amplitude of the initial pulse was 10 %, the maximum time domain instability was estimated at 30 ps when peak value amplitude was  $\sim 165$  kV. The generator can form the radiofrequency wave by high voltage low-cut filters to supply the antenna array with controlling directional diagram.

This work was supported by research program of IEP UD RAS 0389-2014-0005 and grant of RFBR №16-08-00058.

**Keywords:** *multi-channel generator, nonlinear transmission lines, ferrite line.*

## PECULIARITIES OF USING THE INDUCTANCE IN THE TRIGGERING CIRCUIT OF THE LTD SWITCH

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Fast LTD stages with oil insulation contain a number of parallel bricks, each brick including two storage capacitors, that are charged to peak voltage of  $\pm 100$  kV, and the bipolar spark gap LTD switch. To protect the trigger cable of this switch, it contacts the switch trigger electrode via a series trigger resistor. The tests of such single brick with a liquid trigger resistor have shown [Kim A.A., Mazarakis M. G., Sinebryukhov V.A., et al. *Lifetime of the HCEI spark gap switch for linear transformer drivers // IEEE International Pulsed Power Conference 2015, Austin, 31 May-4 June 2015.*, Kim A.A., Sinebryukhov V.A., Alexeenko V.M., et al. *Jitter of the LTD spark gap switches // Russian Physics Journal. – 2015. – V. 58. – №. 9/2. – pp. 156–160.*], that the lifetime of the brick is determined by the lifetime of the trigger resistor because of gas bubbles that appear in such resistor after  $\sim 8 \times 10^3$  shots, and increase the resistance of the resistor and the time delay between the trigger pulse and the load voltage. In this paper, we describe the tests of the LTD brick including instead of the trigger resistor the trigger inductance which is designed as an elastic spiral produced of stainless steel wire.

This work was supported in part by Russian Foundation for Basic Research (project #15-08-01324).

**Keywords:** LTD stage, gas switch, trigger resistor, trigger inductance.

**COMPUTER SIMULATION RESEARCH OF ENERGY RELEASE MODES  
IN A DISCHARGE CHANNEL AND ITS INFLUENCE ON THE  
STRESS-STRAINED STATE FORMATION IN A SOLID MATERIAL  
AT ELECTRO-BLASTING TECHNOLOGY**

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In electro-blasting technology for solid destruction the pulse power generators with different types of switches could be used. One of them is the vacuum switch, that easy to operate, has good lifetime of  $10^4$ – $10^5$  commutations in average, could pass of about 100 coulombs of charge, but in most cases could pass only the half-cycle of current in the ringing mode operation. In this paper the influence of the ringing current pulse duration on the stress-strained state formation is investigated. The simulation results of energy release modes in a discharge channel are given. The difference of energy input and the discharge channel pressure amplitude in dependence on the current half-cycles quantity are presented. The crowbar mode of operation is also investigated and comparison with the ringing mode are presented.

**Keywords:** *electro-blasting, pulse power, stress-strained state, discharge channel.*

## LOW-INDUCTANCE SWITCH AND CAPACITOR ENERGY STORAGE MODULES MADE OF PACKAGES OF INDUSTRIAL CONDENSERS IK50-3

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Low-inductance modules of capacitive energy storage with an operating voltage of 40 kV for pulsed power system of a high-current electron accelerator on the basis of a linear transformer are developed. The module includes two capacitors of 0.35  $\mu\text{F}$  each, one triggered gas switch, and 2 groups of 4 output cables from each of the capacitors mounted in a common housing with dimensions  $314 \times 314 \times 160 \text{ mm}^3$ . The design feature of the module is the application of one section of the industrial condenser IK50-3. The section consists of a set of bandages tighten flat-shaped packages of two series-connected capacitors for voltage of 50 kV each. Located in the middle of the section the common point of the two capacitors is connected to the charging cable and to the high voltage electrode of the gas switch installed in front of it on the cover of the module housing. Central wires of the output cables are connected to the outer packages of each of two capacitors. A topology of bus bars developed for the switch and capacitor module provides a small total inductance of the discharge circuit, for output cables KVIM of 0.5 m long it is less than 40 nH. The application of the capacitor packages of industrial condensers reduces the cost and simplifiers of the modules production. Design of the module and the results of tests of single module and the set of 10 modules will be presented.

The study was supported by the Russian Science Foundation (project 16-15-10355).

**Keywords:** *low-inductance modules of capacitive energy storage, triggered gas switch, linear transformer.*

## TWO-PHASE GENERATOR FOR ELECTROHYDRODYNAMIC FLOWS ACCELERATION IN VOLUME

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Two-phase generator of rectangular pulses to accelerate the ion cloud in the air at atmospheric pressure was developed and investigated. The generator consists of 4 high-voltage (HV) switches combined in two half-bridge circuits and operates at frequencies of 100 Hz to 60 kHz and voltages up to 9.6 kV, HV DC power source. It controlled by two low voltage two-channels synchronized generators and allowed to change the width of HV rectangular pulse from 100 ns to tens of millisecond and phase shift time from 25 ns (jitter time) to the end of the period or using the manual triggering mode. Due to the controlled closure of the switches the minimum time of HV pulse was less than 100 ns, and the problem of fast rise time of drain-source voltage ( $dV/dt$  capability) was solved. The generator was loaded on capacitive load of multistage two-phase system for weakly ionized medium acceleration.

**Keywords:** *High voltage solid-state switches, Rectangular pulses, Ion cloud acceleration.*



## DESIGN AND TESTING OF FLUID RESISTOR FOR REPETITIVE HIGH-VOLTAGE PULSE GENERATOR

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Paper presents design and results of testing of the liquid resistive load for a repetitive high-voltage generator (200 kV, 0.5 ms). The load uses a sealed dielectric case, which must be placed into a vacuum volume ( $5 \times 10^{-4}$  Torr) for electrical strength ensuring. Repetitive testing of the generator with the load (10 pps) caused electrolyte heating, load resistance decreasing and changing of the generator mode. Expansion tank is used to compensate thermal expansion of the electrolyte, which make it possible to absorb up to 1 MJ of energy in the load without breaking of seals. Generator load curve can be obtained for one experiment with a help of the fluid load without any additional depressurization of the vacuum volume.

This work was partially supported by RFBR grant No16-32-0028мол\_a.

**Keywords:** *liquid resistive load, high voltage pulse generator, generator load curve.*

**CALCULATION OF THE CURRENT FLOWING THROUGH  
THE THICK-WALLED TUBE USING THE ELECTRIC FIELD INTENSITY  
MEASURED ON THE INNER SURFACE OF THE TUBE**

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Using the time dependence of the electric field intensity measured on the inner surface of the tube the current flowing through is restored. Thus, using the data on the full current flowing through the electrode gap, can be individually determined the fraction of the current flowing through the plasma formed on the outer surface of the tube and flowing through the tube itself, being in condensed state.

The proposed method can be also used in the case of a thick-walled tube (the thickness of the skin layer  $\delta$ , determined at the room temperature, significantly less than the wall thickness of the tube  $h$ ). While restoring of the current the inverse problem is solved, the incorrect decision of which is connected with the rapid attenuation of higher harmonics with electromagnetic field diffusion through the electrode material. The incorrectness of the problem was solved in the following way: for the restoration of the current profile the smoothed experimental voltage profile was used, and the number of terms in the expansion for calculation of the numerical solutions was limited; so, only the smooth components were taken into account.

Applying the offered method, the current profile was restored for the experimental data obtained in the Angara-5-1. The evolution of the current density and temperature distributions over thickness of the tube were also obtained. Numerical results for the electric field in the inner surface of the tube are in a good agreement with experimental data.

**Keywords:** *restoring of the current, electromagnetic field diffusion, Angara.*

## COMMUTATION OF A CAPACITIVE ENERGY BANK BY PSEUDOSPARK SWITCHER IN SELF-BREAKDOWN MODE

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Dependence curves of self-breakdown voltage from heat power of the hydrogen generators were obtained for capacitive power bank (45 nF, 40 kV, charge time 12  $\mu$ s) commutated by pseudospark switch TPI1-10K/50. Special settings for the hydrogen generators have been found when the pulse-to-pulse fluctuations of the breakdown voltage less than 1 %. The value of the voltage fluctuations stayed the same after 0.1 million of 10 pps shoots.

This work was partially supported by RFBR grant No16-32-0028мол\_a.

**Keywords:** *pulse power generator, pseudospark switch, self-breakdown voltage fluctuations.*

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## NEW VACUUM TECHNOLOGIES

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MILLAB company is the official distributor of European manufacturers of vacuum equipment such as Agilent Technologies, Vacuubrand and EVAC. More than ten years MILLAB works with clients that used vacuum equipment and knows about the problems and needs of vacuum solutions for laboratories and enterprises. Thanks to our European partners and the experience gained, MILLAB offers optimum solutions for tasks of varying complexity.

Agilent Technologies Incompany (formerly Varian Inc) is a world leader in the production of vacuum equipment. The nomenclature includes equipment for creating vacuum in all ranges: from low to ultra-high, measuring and monitoring instruments to control the vacuum created.

For creating ultra-high vacuum Agilent Technologies presents the new ion pump VIP-200 with performance of 200 l/s. Because of optimized distribution of magnetic field and an all-new design, VIP-200 is the most compact pump in that class.

VIP 200 reaches a peak performance in the pressure range of  $10^{-8}$  mbar, while conventional ion pumps are at their peak at higher pressure ( $10^{-6}$  mbar). Among the analogues of the pump VIP 200 has better pumping speed for nitrogen and argon.

The latest development at the field of Agilent Technologies turbo-molecular pumps is a new line of TwisTorr pumps FS technology – the unique characteristics which meet the most stringent technical and performance requirements.

TwisTorr FS is a turbo-molecular pump with patented Molecular stage helical shape that provides unprecedented compression of lung gas and the ability to work at high foreline pressure. Also, the technology used in the pump floating suspension FS. The rotor and stator are connected not through the bearings directly, but through the polymer damping insert that can compensate for both axial and transverse vibrations of a rotating rotor at the start, breaks of the atmosphere.

Agilent Technologies specializes also on the helium leak detectors VS MD15 +, VS BD15 +, VS MD30 + and VS BD30 +. Now all oil-free leak detectors are equipped with a combined pump system, which consists of a spiral and diaphragm pumps. This combination allows to create a higher level of gas compression. Using the system of pumps significantly reduced helium flow with a reverse exhaust pumping system, thereby reducing the background to a minimum.

As a Summary: MILLAB company is an integrator and supplier of European vacuum components and vacuum solutions for both scientific applications and for industry.

## RUN-AWAY ELECTRON PREIONIZED DIFFUSE DISCHARGE AS A SOURCE OF EFFICIENT LASER EMISSION IN THE IR, UV, VUV

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In present report, REP DD was suggested as an excitation source of different gas lasers. Efficient lasing in the IR, UV, and VUV spectral ranges was obtained.

Ultimate intrinsic efficiency of non-chain chemical lasers on HF(DF) molecules was achieved. The HF laser output was as high as 100 mJ with emission power over 1 MW. Spectral parameters of non-chain lasing in H<sub>2</sub>(D<sub>2</sub>)–SF<sub>6</sub> mixtures are studied, as well.

N<sub>2</sub> laser with the limiting theoretical efficiency and maximal efficiencies obtained experimentally was developed on the base of REP DD. Maximal energy of the UV radiation at 337 nm was 4.1 mJ with peak power over 1 MW at the electrical efficiency over 0.2 %. New operation modes of nitrogen laser with 2 or 3 laser peaks in oscillating REP DD was also demonstrated.

Laser action on F<sub>2</sub>\* in the VUV at 157 nm and rare gas fluorides (ArF\*, 193 nm, KrF\*, 248 nm, XeF\*, 351–353 nm) was obtained in REP DD for the first time. It was shown that volume stage of REP DD in mixtures with fluorine can lasts over 50 ns during several current half-cycles. Therewith the efficiency and pulse duration of lasers on rare gas fluorides and VUV F<sub>2</sub>\* laser parameters under REP DD excitation are comparable with those obtained in convenient transverse volume discharges with preionization.

The results allow the conclusion that the homogeneity of a REP DD in mixtures with F<sub>2</sub> and SF<sub>6</sub> is high enough for attaining high laser efficiency.

**Keywords:** *run, away, electron, preionized, diffuse, discharge, efficient, lasing.*

## CURRENT AND SPECTRA OF RUNAWAY ELECTRON BEAMS IN SF<sub>6</sub>, NITROGEN AND AIR

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The generation of a supershort avalanche electron beam (SAEB) in SF<sub>6</sub> in an inhomogeneous electric field was studied on three generators with pulse rise times of 0.3, 0.5 and 2 ns. The SAEB parameters in SF<sub>6</sub> are compared with those obtained in other gases. It is shown that the SAEB amplitude in SF<sub>6</sub> at pressures range from 0.05 to 0.2 MPa is commensurable with that in krypton and is much lower than that in air and nitrogen. It was confirmed that quantity of RAE generated at the breakdown of SF<sub>6</sub> more than on the order of magnitude less than at the breakdown of air. Results showed that the energy of SAEB in air was not smaller than that in SF<sub>6</sub> in nanosecond-pulse discharges under otherwise equal conditions. Moreover, the difference between the maximum energy of the electron distributions in air and SF<sub>6</sub> increased when the rise time of the voltage pulse decreased. As part of hybrid mathematical model of gas-filled high-voltage breakdown diode fast electron spectra calculations have been carried out. In this study, we calculated the spectra of fast electrons appearing in the breakdown of two different gases in atmospheric pressure, such as nitrogen and sulfur hexafluoride. Naturally, the number of fast electrons in nitrogen was several orders of magnitude higher than that of sulfur hexafluoride, if all other parameters are the same. It was confirmed that the average energy of fast electrons in SF<sub>6</sub> is lower than in nitrogen for close levels of fast electrons current.

**Keywords:** *hexafluoride, nitrogen, air, supershort avalanche electron beam.*

## RUNAWAY ELECTRONS AND X-RAYS DURING BREAKDOWN OF HIGH PRESSURE GASES

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The properties of a supershort avalanche electron beam (SAEB) and X-rays produced at gas pressures ranging from 1 Torr to 15 atm was investigated. In the studies reported the number of electrons detected in atmospheric pressure air downstream of a thick Al foil is up to 60 000 000 000. It corresponds to a SAEB amplitude of 100 A at a FWHM of the current pulse of 100 ps. Collector measurements reveal an electron beam downstream of the foil in sulfur hexafluoride and xenon at a pressure of up to 2 atm, in air at a pressure of up to 3 atm, in nitrogen at a pressure of up to 5 atm, and in helium at a pressure of up to 15 atm. In a nanosecond discharge in atmospheric pressure air, the SAEB current pulse downstream of the foil is no longer than 25 ps, when measured from a small foil area, and is 100 ps, when measured from the entire gas diode foil. The highest SAEB amplitudes with a pulse width of 100 ps are attained in helium, hydrogen, and nitrogen at a pressure of 60, 30, and 10 Torr, respectively. Decreasing the pressure below the above values changes the beam generation mode, thus making it possible to gradually control the FWHM of the beam current pulse in the range from 100 to 500 ps in all gases studied.

This work was supported by the Russian Science Foundation (project No. 14-29-00052).

**Keywords:** *runaway electrons, supershort avalanche electron beam, X-rays, high pressures.*

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**OPTICAL CHARACTERISTICS IN THE VUV SPECTRAL RANGE OF PLASMA  
FORMED DURING THE HIGH-PRESSURE REP DD IN MIXTURES  
OF RARE GASES**

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Nonequilibrium low-temperature dense plasma was obtained at the runaway electron preionized diffuse discharge (REP DD) in mixtures of He, Ne, Ar, Kr with small (0.001–10 %) admixture of Xe under total pressures up to atmospheric. Narrowband ( $\leq 2$  nm at the basis) radiation in the VUV spectral region near wavelength of 147 nm was observed from plasma of the REP DD in mixtures He-Xe and Ar-Xe. Spectral energy distribution of this radiation consists of at least two components and is formed, obviously, due to spectral transitions in heteronuclear dimers HeXe\* and ArXe\*. Amplification of this radiation in the REP DD's plasma in mixture Ar-Xe at total pressure of 0.5 atm and xenon's concentration of 0.1 % was found.

**Keywords:** *runway electrons, diffuse discharge, heteronuclear dimer, nonequilibrium plasma, VUV.*



## VOLTAGE PULSE RISE TIME EFFECT ON ENERGY SPECTRUM OF RUNAWAY ELECTRON BEAMS IN SF<sub>6</sub> AND AIR

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The parameters of a supershort avalanche electron beam (SAEB) in SF<sub>6</sub> and air in an inhomogeneous electric field was studied. Three generators with pulse rise times of 0.3, 0.5 and 2 ns were used. Results showed that the difference between the maximum energy of the electron distributions in air and SF<sub>6</sub> decreased when the rise time of the voltage pulse increased. The amplitude of SAEB for generator with pulse rise time 2 ns was measured using diamond detector. The amplitude of SAEB after anode decrease almost linearly with increased the thickness of Al foils on the anode.

The work on the experimental setup #1 and #2 was supported by grants RFBR #15-58-53031\_ГФЕН\_a. The work on the experimental setup #3 was supported by the National Natural Science Foundation of China under Contracts #51222701, #51207154, and #51511130040.

**Keywords:** *runaway electrons, diffuse discharge, sulfur hexafluoride.*

**SPECTRAL AND AMPLITUDE-TIME CHARACTERISTICS OF LUMINESCENCE  
OF POLYMETHYL METHACRYLATE EXCITED BY RUNAWAY ELECTRON BEAM  
AND BY KRCL EXCILAMP**

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The results of experimental investigations of luminescence excited in polymethyl methacrylate (PMMA) by a runaway electron beam and by a KrCl excilamp with a wavelength of 222 nm are presented in this paper. It is shown that the major contributor to the luminescence of PMMA in both cases is a luminescence band with a maximum intensity at ~490 nm. Based on experiments with the excilamp, it is supposed that Cherenkov radiation with a wavelength shorter than 300 nm is bound to increase the intensity of this band. The intensity Cherenkov radiation against the background of luminescence is low and in this experiments was not registered.

The work was performed in the framework of the Russian Science Foundation under grant No. 14-29-00052.

**Keywords:** *polymethyl methacrylate (PMMA), runaway electron beam, luminescence, spectra, Cherenkov radiation.*

## MC MODEL OF FORMATION OF THE RUN AWAY ELECTRONS IN GLOW DISCHARGE

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The actuality of investigation of a spatial distribution of the main plasma parameters in glow discharges is governed by the wide application of glow discharges for plasma-chemical processes. The existence of a strong electric field in the cathode fall region leads to the creation of the electrons with the high energy up to the potential drop of the cathode fall. These electrons provide non-local ionization and excitation in the nearest discharge regions and that is why they should be taken into account for the correct modeling of the cathode region of the glow discharge. The paper presents MC model of the formation and energy relaxation of the run-away electrons in the negative glow region of abnormal glow discharge in helium at low pressures ( $<1$  Torr). The angular scattering at the elastic and inelastic collisions was taken into account at the evaluation of the electron trajectories of the movement. The measured distribution of emission into 361.4, 396.5 and 501.6 nm He spectral lines along the discharge axis is in a good agreement with the calculated one. The wall recombination losses due to ambipolar diffusion evaluated from the probe measurements also are in good agreement with the ionization rate calculated for the negative glow region. The obtained results can be used for the construction of the self-consistent hybrid model of the cathode region of the glow discharge.

**Keywords:** *glow discharge, Monte-Carlo simulation, non-local process.*

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**STABILITY OF THE RUNAWAY ELECTRON BEAM CURRENT  
IN A GAS DIODE AT LOW PRESSURE**

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The paper studies the current of a runaway electron beam current in a subnanosecond high-voltage breakdown of nitrogen at a pressure of 30 Torr. As the interelectrode gap is increased from 4 to 12 mm, the spread of beam currents decreases greatly such that their distribution at 12 mm is close to Gaussian. The observed behavior of the runaway electron beam current is explained by variations in the cathode emission surface from pulse to pulse and its stabilization with increasing the gap width.

The work was supported by RFBR grants No. 14-02-00136 and No. 15-08-03983.

**Keywords:** *nanosecond high-voltage discharge, stability of the runaway electron beam current, sharply-nonuniform electric field, numerical simulation.*

## EFFECT OF EMISSION ON SUBNANOSECOND BREAKDOWN IN A GAS DIODE AT LOW PRESSURE

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The paper presents experimental and numerical research results on the operation of a gas diode at low pressure. A large spread in runaway electron beam current (from 20 to 100 A) with respect to the average ( $\sim 50$  A) is observed for a tubular cathode with a working edge radius of 30 mm, nitrogen pressure of 30 Torr, and interelectrode gap of 6 mm.

Numerical simulation data show that the low beam current ( $\sim 20$  A) is due to early electron emission from the cathode (at the stage of low-voltage voltage prepulse) in which the runaway electron beam is formed from the boundary of a plasma layer developed early in the breakdown. The high beam current ( $\sim 100$  A) is due to delayed electron emission from the cathode, which increases the diode voltage and the runaway electron beam current. In the latter case, the runaway electron beam is formed directly at the cathode.

The work was supported by RFBR grants No. 14-02-00136 and No. 15-08-03983.

**Keywords:** *nanosecond high-voltage discharge, sharply-nonuniform electric field, runaway electrons, numerical simulation*

## FORMATION OF 25 KEV ELECTRON BEAM WITH TRIPLY ELECTRODE SYSTEM OF THE OBSTRUCTED GLOW DISCHARGE IN H<sub>2</sub> AND D<sub>2</sub>

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The report presents the results of experimental studies on generation of electron beams with energies up to 25 keV using obstructed low-pressure discharge ( $P = 0.5\text{--}2$  Torr) in hydrogen and deuterium. The original design of electrode system consisting of solid metal cathode and two mesh anodes was proposed. High-current obstructed glow discharge with current amplitude up to 20 A (current density about  $5\text{ A/cm}^2$ ) and voltage drop up to 25 kV was generated using this electrode system. The duration of high-voltage discharge stage, in which the effective (95 %) generation of an electron beam is occurred, is limited by development of spark. The electron beam pulse duration is equal to 100–500 ns in range of experimental parameters. It is shown that the electron beam generation occurs in both single mode and a mode of repeating high-voltage pulses with repetition rate of 1 kHz. The intensive processes of ionization and excitation of atoms and molecules of surrounding gas occurs during the propagation of the beam, leading to formation of plasma and plasma – beam discharge. It was found that the characteristic time of the discharge development along the axis of electron beam propagation is equal to tens of nanoseconds. A partial contraction of plasma – beam discharge has been found with increasing pressure of the working gas. The results obtained indicate that contraction occurs in the region most distant from the exit of beam out of the discharge.

This work was supported by RSF (grant № 16-12-10458).

**Keywords:** *obstructed glow discharge, electron beam, hydrogen, deuterium, plasma.*

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**CALCULATION OF PARAMETERS OF AVALANCHE  
OF RUNAWAY ELECTRONS*****EVGENY ORESHKIN****P.N. Lebedev Physical Institute of the Russian Academy of Sciences, Russia  
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With the help of the numerical model are investigated regularities avalanche of runaway electrons in air at atmospheric pressure. The results of numerical calculations show that in addition to characteristic time and length by an exponential increase of the avalanche of runaway electrons can be characterized by other parameters such as the velocity of propagation of avalanches and the average kinetic energy of runaway electrons.

***Keywords:*** *Runaway electron avalanche, gas discharge, numerical modeling.*

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## NUMERICAL STUDY OF GENERATION OF RUNAWAY ELECTRONS ON STAGE OF CATHODE LAYER FORMATION

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The paper reports about results of numerical modeling of formation of the subnanosecond gas discharge and generation of runaway electrons in forming cathode layer.

The calculations were carried out with a help of the one-dimension numerical model consisting of the system of balance equations for slow and fast electrons, ions, and Poisson equation. The kinetic coefficients as function of electric field, including the probability of transition of electrons into escape (or runaway) mode, were received as a result of modeling of electron motion by Monte-Carlo method.

The calculated kinetic constants, electron energy distribution functions probabilities of transition into runaway mode are presented in the paper.

The results of calculations show that runaway electrons are generated in forming cathode layer where the values of  $E/N$  ( $E$ -electric field strength,  $N$ - density of neutral molecules) and potential are sufficiently high.

The work was supported by RFBR Project N 16-08-00894.

**Keywords:** *Cathode layer, runaway electrons, numerical study.*



**THE DEPENDENCE OF THE FACTOR OF THE DISCHARGE  
GAP OVERVOLTAGE FROM PRESSURE AT SUBNANOSECOND  
DISCHARGE IN NITROGEN**

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In this paper the data on the factor of the discharge gap overvoltage ( $K$ ) of nitrogen diodes depending on the gas pressure ( $p$ ) and the length ( $d$ ) of the discharge gap were obtained in subnanosecond range. The experiments were carried out in a uniform electric field. The radius of stainless steel cathode and anode was one sm. Nitrogen now is the mostly used gas in the high-pressure gas dischargers. The pressure of nitrogen was changed within from atmospheric to 40 atm. The voltage pulse with the amplitude of  $102 \pm 2$  kV, full width at half maximum of about 380–400 ps, and the front of about 250 ps at the level of 0.1–0.9 from amplitude, full duration of the front of about 500 ps, was applied to the studied gas gap. In this case the voltage rise rate at the gap at the prebreakdown stage was up to  $7 \times 10^{14}$  V/s. The dependences of  $K$  for different pressures of nitrogen and the length of the discharge gap  $d$  were obtained. The maximum overvoltage  $K=30$  was obtained. It was shown that when the pressure is raised from 1 atm to 40 atm the overvoltage factor  $K$  of the discharge gap decrease approximately in 15–18 times.

**Keywords:** *factor of the discharge gap overvoltage, pulse breakdown voltage, static breakdown voltage, breakdown formation time, runaway electrons, subnanosecond gas discharge.*

**DYNAMICS OF NANOSECOND DISCHARGES SPATIAL STRUCTURE FORMATION  
IN DENSE GASES IN GAPS POINT (CATHODE)-PLANE  
OF MILLIMETERS LENGTH AT TRANSITION FROM DIFFUSIVE  
PHASE TO SPARK**

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This paper presents a physical model of kern formation dynamics: thin and bright channel on the background of a discharge diffusive luminescence. The kern provides transition from the diffusive phase to a spark in nanosecond discharges in dense gases in the gaps point (cathode)-plane of millimeter length. The model is based on experimental data and uses the discharge microstructure, when the current channel represents itself a bunch of many microchannels. In this case, gas in the microchannels heats up to the temperature of associative ionization beginning at a time of 10 ns, and causes increase of the conductivity and discharge current. This provides formation and movement of the kern from the cathode to anode. At the same time, the current is localized (contraction) to the kern area at the expense of ionization-overheated (thermal) instability, which provides the kern diameter of 0.1–0.4 mm. One should note similarity of the considered processes with the processes revealing in other gas-discharge phenomena. These are: sudden acceleration of the gas discharge channel heads in the bridging phase of the discharge gaps, generation of high-energy electrons and bremsstrahlung at multi-channel diffusive discharge.

**Keywords:** *nanosecond gas discharge, spatial structure, ionization front, ionization instability, microstructure, associative ionization, ionization-overheated (thermal) instability*

## GENERATION OF ACCELERATED ELECTRONS IN NANOSECOND ELECTRICAL DISCHARGES USING EXTENSIVE SLOT CATHODES LIMITED BY DIELECTRIC WALLS

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The spatio-temporal formation dynamics and basic electrical and optical characteristics of nanosecond discharges with an extended slot cathode in helium are investigated. It is established that electrons ribbon beams are formed in such discharges with energy of several hundred eV. It is demonstrated that the restriction of the discharge gap in dielectric walls leads to the trapping of electrons in the gap and an increase in effectiveness of excitation and ionization of atoms of beam electrons, which leads to a substantial increase in current density and intensity of optical radiation of the limited discharge. Experimental data obtained on the relaxation of charge density on the deposited surface of the charge limiter and the value estimates of the electric potential of the dielectric surfaces, were analyzed. It is demonstrated that the variation in the discharge structure restricted by the dielectric walls corresponds with the variation in the distribution of the electric field in the gap, as well as under the influence of the surface potential.

**Keywords:** *nanosecond discharges, runaway electrons, slot cathode.*

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**THE ROLE OF HIGH-ENERGY ELECTRONS IN THE FORMATION  
OF THE TRANSVERSE PROFILE OF HIGH-SPEED IONIZATION  
WAVE FRONTS IN GASES**

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A comprehensive experimental study of the spatio-temporal structure of the fronts of discrete, high-speed ionization waves (HSIW) in shielded discharge tubes filled with inert gases is carried out. It is shown that the ionization wave front at low gas pressures (below 1 Torr) has a volumetric structure, but at gas pressures above 10 Torr assumes a cylindrical form, compressed into the dielectric boundary of the discharge tube. The high-energy electrons generated at the ionization wave front have a significant impact on its structure and their energy relaxation modes. Evaluations of the energies of electrons accelerated at the HSIW front are provided along with an analysis of the influence of the energy relaxation regimes of the high-energy electrons on the structure and dynamics of the development of the ionization wave front in the shielded dielectric discharge tubes.

**Keywords:** *high-speed ionization waves, runaway electrons, nanosecond discharge, ICCD camera*

## THE SUBNANOSECOND BREAKDOWN STAGE IN THE SWITCH BASED ON THE “OPEN” DISCHARGE WITH COUNTER-PROPAGATING ELECTRON BEAMS

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The subnanosecond breakdown stage in the kivotron, a switching device with counter-propagating electron beams based on the open discharge in helium, was experimentally studied. The influence of gas pressure and working voltage on development of breakdown was investigated. It was shown that the fast discharge stage arises when the discharge self-sustaining regime is ensured by the photoelectron emission from the cathodes due to resonant radiation emitted by fast helium atoms that have large Doppler shifts with respect to the line center; as a result, the emitted radiation reaches the cathodes without re-absorption by the helium gas. Since the excitation cross-section of a helium atom by another fast helium atom increases rapidly with the energy of the fast atom, the duration of the breakdown stage strongly depends on the working voltage. The transient characteristic is modulated by microwave oscillations of frequency  $f \sim 4\text{--}8$  GHz frequency generated during the discharge of kivotron self-capacitance through its self-induction which depends on kivotron dimensions. An increase in working pressure leads to suppression of oscillations. The switching time less than 80 ps was achieved when discharge circuit loaded to a resistance  $R_L \geq 50 \Omega$ . Decrease of  $R_L$  down to  $10 \Omega$  increases the switching time to about 100 ps at 1.5 kA current with current density  $120 \text{ A/cm}^2$ . A minimum switching time that can be achieved via kivotron design optimization is estimated to be about 35 ps.

This work was supported by RSF project №14-19-00339.

**Keywords:** *photoelectron «open» discharge, ounter-propagating electron, subnanosecond switch.*

## THE MECHANISM OF THE CURRENT DEVELOPMENT IN THE «OPEN» DISCHARGE WITH COUNTER-PROPAGATING ELECTRON BEAMS

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To interpret the mechanisms of the current development, EB and fast heavy particles generation, and switching processes the experimental studies of the electric field and the emission lines shape evolution in the «open» discharge with the generation of counter-propagating electron beams were carried out.

The experiments were performed in planar rectangular cells with two grids and two cathodes with an interelectrode distance of 3 mm, and the distance between the grids of 6 mm. It was shown that even at low current densities ( $j \approx 100 \text{ mA / cm}^2$ ) the electric field is completely concentrated near the cathode, and voltage or helium pressure increases lead to potential «collapse» acceleration. When  $j_{\text{max}} = (100\text{--}200) \text{ A / cm}^2$  field is concentrated in a narrow region near the cathode, where the super-strong electric fields (up to 100 MV/m) are realized. From the spectral measurements in the wings of the helium line at the transition with  $\lambda = 501.6 \text{ nm}$  the maximum energy of heavy particles was estimated. In the case of strong fields ( $E / N \approx 10^{-13} \text{ Vcm}^2$ ) asymmetry of the lines and radiation in the far wings was observed. The maximum shift value exceeded  $6.5 \text{ \AA}$  or  $2.36 \times 10^{11} \text{ Hz}$  in the shortwave region, which corresponds to the atom speed  $\sim 3.82 \times 10^5 \text{ m/s}$  and its energy  $\sim 3 \text{ keV}$ , which is close to the applied voltage amplitude equal to 4.2 kV.

This work was supported by RSF project №14-19-00339.

**Keywords:** *photoelectron «open» discharge, Doppler shifted atomic radiation, electric field «collapse».*

## A STUDY OF THE «OPEN» DISCHARGE WITH COUNTER-PROPAGATING ELECTRON BEAMS AT HIGH VOLTAGE

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Experimental and theoretical studies of the ignition and combustion of the gas discharge at high and ultra-high electric field strength of the «open» discharge with counter-propagating electron beams in a planar geometry with a voltage up to 120 kV and gas pressure up to 1 atm are presented.

The homogeneous discharge at 24 kV was obtained with atmospheric pressure of helium and at 120 kV with helium pressure 2–8 torr. A discharge modeling for different gas pressures and voltages up to 100 kV was carried out. It is shown that development of the electron avalanche occurs in less than 2 ns at 5.4 Torr of helium pressure, and therefore when charging time of the working capacity is too long the breakdown begins before the maximum voltage value is achieved. It is shown that discharge current oscillations are main factor limiting the discharge time, which supports previously obtained experimental results. By increasing the gas pressure (at  $p > 15$  Torr) oscillations almost disappear, and the breakdown time becomes  $\tau_s \approx 250$  ps. The calculations of the electron emission under the influence of ions, fast atoms, electrons and Doppler shifted photons for the helium pressure of 5.4 Torr at the voltage  $U = 25$  and 120 kV were carried out. It is shown that at  $U = 100$  kV processes dynamics is determined by photoemission with Doppler shifted photons followed by the dominant role of the secondary electron emission when the voltage drops in the discharge gap in the breakdown period.

This work was supported by RSF project №14-19-00339.

**Keywords:** counter-propagating electron beams, high voltage «open» discharge, numerical modeling.

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**FEATURES OF FORMATION AND DEVELOPMENT  
OF IONIZATION FRONTS IN THE PRE-IONIZED GAS ENVIRONMENT**

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Here we present the results of experimental studies of space-time dynamics of the formation of a volume discharge in atmospheric pressure helium in the centimeter gap obtained with the application of streak-camera diagnostics. The studies of space-time evolution of a volume discharge formation, including local inhomogeneities on the cathode, are made on the basis of two-dimensional diffusion-drift model. The results of numerical calculations are in a satisfactory agreement with experimental data.

***Keywords:*** *plasma, volume discharge, two-dimensional diffusion-drift model.*



**4-KW MULTI-PHASE BATTERY POWERED POWER SUPPLY**

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A method was developed for building powerful battery power supplies. Based on the method a battery power supply with a 4 kW max power and up to 93% efficiency was developed to supply «Yasen» X-ray apparatus. Two 60 A × h series-connected starter lead-acid batteries were used as a primary power supply. DC output voltage of the source is stable on all the power range and equals to 310 V. The power supply is based on a 5-phase HF-inverter. There is no difficulty in developing such power supplies with different power outputs. It can be done by increasing or decreasing the number of phases (of inverter channels). This approach is not limited with number increase of inverter channels. The maximum output power will be determined by the battery characteristics only.

The power supply is mounted on a mobile trolley to increase the mobility of the entire set of equipment. The unit dimensions are 410 × 320 × 440, the weight is about 40 kg. The unit is forced air-cooled. Power operating mode is short and periodic.

**Keywords:** *battery powered power supply, multi-phase power supply, HF-inverter.*

## COMPOSITION OF PYROLYSIS GAS FROM OIL SHALE AT VARIOUS STAGES OF HEATING

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Underground pyrolytic conversion of oil shale may become an alternative source of fuel gas and synthetic oil. The main scientific problem in designing of this technology is to provide a methodology for determination of the optimal mode of heating a subterranean formation. Such a methodology must allow predicting the composition of the pyrolysis products and energy consumption at a given heating rate. The experimental study of heating of oil shale sample was carried out. The goal was to define the dynamic of sample heating and pyrolysis products composition. Sample of the rock was heated in conditions similar to the underground during 19 hours. The electrodes were made from graphite and spaced in 250 mm. The temperature was measured in 4 points. The first point was located in the center between electrodes. The second, third and fourth points was removed from the axis between the electrodes at 30 mm, 60 mm and 90 mm, respectively. The chamber with the sample was evacuated and then filled with nitrogen to a pressure of 5 kgf/cm<sup>2</sup>. In the experiment, the temperature in the center of the heated zone reached more than 900 °C at the time when the temperature in fourth point was less than 100 °C. That is the evidence of low thermal conductivity of oil shale. During the heating the content of the hydrogen and carbon oxides in the pyrolysis gas is increased, and the content of methane and other hydrocarbons is reduced. The combustion heat of gas is reduced.

**Keywords:** *pyrolysis gas, oil shale, heating.*

## MEASUREMENT OF CHARGE OF ION COMPONENT OF PLASMA GENERATED BY NANOSECOND SURFACE FLASHOVER IN VACUUM

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Faraday cups are widely used to measure parameters of ion and electron beams. In these cases, measurement errors are caused mainly by SEE from collector, backscattering, penetration of electron flow, etc. In this work, Faraday cup was used for study of quasi-neutral plasma flows. This task implies separation of oppositely charged particles in incident bunch, which is yet another cause of errors.

Plasma flows were generated by high-voltage discharge over a surface of PTFE. Parameters of pulse are as follows: voltage amplitude is 120 kV; pulse duration at half maximum under the load-matched conditions is 20 ns. Stored energy of the generator is 0.2 J. Linear and coaxial electrode geometries were tested. Interelectrode distance was 10 mm in both cases. 120-mm Faraday cup was located 6 mm far from the discharge. Transverse magnetic field used to suppress the SEE from collector and to separate plasma electrons. The result show, that full charge of ion component of plasma is equal 1.2  $\mu\text{C}$  for coaxial and 0.6  $\mu\text{C}$  for linear geometry.

**Keywords:** *plasma bunch, surface flashover, high-voltage discharge.*

## USING NANOSECOND ELECTRON BEAM FOR SILVER NANOPOWDER PRODUCING

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Synthesis of weakly agglomerated silver nanopowders is important for making of nano materials used in microelectronics, electrochemistry and synthesis of optoelectronic sensors, pigments, etc.

Bactericidal properties of silver ions are of special importance since thanks to these properties silver nanopowders may serve as the basis for development of new classes of bactericidal preparations and various pharmaceutical substances in medicine and agriculture.

Experiments with the URT-0.5 accelerator (0.5 MeV, 50 ns, 1 kW) irradiation of silver nitrate in various liquid solutions to product a silver nanopowder were done. Was found that a radiochemical reaction allows making weakly agglomerated pure Ag powders with particles 3–5 nm and 20–50 nm size by irradiation in toluene and water respectively. The optimal input of the electron beam energy to the solution and a considerable increase in the absorbed dose do not lead to the increase in the reaction yield, but cause a larger agglomeration of the synthesized powders. Was developed the technology of producing a silver nanopowders in isopropyl alcohol solutions with a specific surface 0.8–2.6 m<sup>2</sup>/g.

The last experiments have shown a possibility to produce significantly smaller powders of silver (7–39.1 m<sup>2</sup>/g) if to carry out the irradiation in polyatomic alcohol (xylitol) solution. Is experimentally established the essential influence of number of hydroxyl groups in the alcohols used for solution preparation, on a specific surface of the produced powders.

**Keywords:** *silver nanopowder, radiochemical reaction, radiation technology.*

## REPETITIVE NANOSECOND ELECTRON ACCELERATORS TYPE URT-1 FOR RADIATION TECHNOLOGY

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The electron accelerators used in radiation technologies have to meet to a number of requirements, in particular such as profitability, stability of parameters and reliability, simplicity in service and repair. Considerably the repetition nanosecond electron accelerators of the URT series created according to the circuit thyatron – the pulse transformer – the semiconductor opening switch. Accelerators of the URT series are successfully used for industrial modification of film polymers, radiation sterilization, producing nanopowders, development of new sorbents and dosimeters, i.e. in radiation technologies on the surface, in gases and layers of liquid, loose or solid materials with layer thickness up to  $0.3 \text{ g/cm}^2$ .

For application in the mobile installation, the weight and the geometrical sizes has essential value, and also accelerator transportation possibility with working capacity preservation. The specified problems were solved at creation of the URT-1M-300 accelerator.

For generating an electron beam up to 400 mm wide are used metal- ceramic and metal-dielectric cold cathodes from several emission elements with nonuniformity of electron beam current density distribution on output foil  $\sim 10 \%$ .

Accelerator tests results showed that productivity of vacuum system was insufficient for long operation of accelerators at high repetition rates (more 50 pps). It leads to critical increasing pressure at which there is a breakdown in gas vapors and it is impossible to generate an electron beam.

**Keywords:** *electron accelerator, radiation technologies, semiconductor opening switch.*

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**ELECTRON BEAM ACCELERATOR BASED ON A DIODE  
WITH ELECTRO-EXPLOSIVE CATHODE FOR TREATMENT OF METAL PARTS**

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Electron beam accelerator has been developed for investigations of possible use of pulsed electron beam in sub-microsecond range for treatment of the metal parts surfaces. It was shown that energy density can be varied in range 0.5–20 J/cm<sup>2</sup> (at pulse length ~0.5 μs) by change of the cathode length and diode voltage. Possibility of treatment was demonstrated for metal parts with different shapes, thus proving opportunities for future development of this technology.

**Keywords:** *electron beam, accelerators, electro-explosive cathode.*

**NON CATALYTIC METHANE FORMATION FROM SYNGAS  
IN THE DIELECTRIC BARRIER DISCHARGE PLASMA, INITIATED  
BY MICROSECUND PULSES**

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From year to year the depletion of energy sources is becoming serious issue. Great attention is paid to the replacement of non-renewable energy resources. One of the examples of producing synthetic hydrocarbons is the Fischer –Tropsch process. However, Fisher-Tropsh process has some disadvantages: using of catalysts, high temperatures and pressure means use of expensive constructional materials. An alternative of the thermo-catalytic Fischer-Tropsch synthesis is a plasma-chemical synthesis of hydrocarbons. In this study, the principal possibility of methane formation from syngas (the mixture of hydrogen and carbon monoxide) in the dielectric barrier discharge plasma, initiated by microsecond pulses, was shown. Paper presents results of syngas treatment in the five-tube reactor under the influence of pulses with voltage amplitude of 12 kV and pulse repetition rate of 1000 1/s. It was found that reducing the volume flow rate of syngas increases the energy contribution, which positively influences the methane formation. Paper shows that the dependence of the volume fraction of the methane on the flow rate of initial gas mixture correlates with dependence of the energy contribution. Addition of nitrogen to the initial mixture in order to increase the concentration of reactive species in fact has a negative effect on the methane formation. Authors associated it with that the excited nitrogen reacts with carbon monoxide. This is a competitive process to the methane formation.

**Keywords:** *syngas, methane, dielectric barrier discharge, plasma.*

## PULSED GENERATORS FOR A LIGHTNING SIMULATION

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Compact transportable generators are required for simulating a lightning current pulse for electrical apparatus testing. A bi-exponential current pulse has to be formed by such a generator. Several approaches can be pointed out in the design of lightning simulators. One type was developed in the Russian Federal Nuclear Center – VNIIEF. Those simulators are based on a cascade of magnetic cumulative generators. Obvious disadvantages of such an approach are the very complex installation, low efficiency and too long a rise time of the current. A second approach is MV-scale Marx generator systems. Inductive energy storage, in combination with an opening switch, offers several attractive features for pulsed power applications when compared to the aforementioned Marx technology. The objective of this study was to develop and investigate both Marx and intermediate inductive storage approaches. Marx generator based systems (10 kA and 50 kA current amplitude) have been designed and numerically simulated. Compact pulse generator with intermediate inductive storage and a fuse opening switch has been designed, numerically simulated and tested. The generator operates without SF<sub>6</sub> and without oil in atmospheric air. The current rise time is lower than 1200 ns, and the damping time from can be varied from 35–125 μs. Moreover, 1D MHD calculations of the fuse explosion were carried out self-consistently with the electric circuit equations, On the basis of the obtained results, the design of a transportable generator was developed for a lightning simulator with current of 50 kA and a pulse shape corresponding to the IEEE standard.

**Keywords:** *Lightning, inductive storage, Marx generator.*



## REPETITIVE PULSED X-RAY SOURCE BASED ON CYLINDRICAL PLASMA FILLED DIODE

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Pulsed X-ray source with a pulse repetition frequency of  $\sim 1$  Hz has been developed. The source based on a cylindrical plasma filled diode with a rod anode of diameter 1 cm. The massive anode resolves the problem of the energy converter lifetime. The plasma source based on cathode flare produced in a vacuum discharge allowed us to realize electron beam pinching at a voltage of less than 200 kV. In the mode of pinching, the diode is an efficient source of high-power X-rays. With a pulse repetition frequency of 1 Hz, the electron beam peak power in the source is 1.5 GW at an accelerating voltage of 180 kV. At a distance of 20 cm from the diode, the radiation peak power is  $\sim 10^6$  R/s and the radiation dose per pulse is  $\sim 0.1$  R. The FWHM of the radiation pulse is 40 ns. The standard deviation of the radiation power and dose per pulse is 25 % of the average.

**Keywords:** *pulsed X-ray source, plasma filled diode, electron beam.*

## CYLINDRICAL ELECTRON DIODE FOR LONG METAL PARTS TREATMENT

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The electron diode with radial converging beam has been investigated for long cylindrical metal parts treatment with a diameter of 1–10 mm. The electro-explosive cathode is a thin metal disk with a hole of diameter 30 mm at its center. The workpiece passes through the center of the cathode hole and serves as the anode in the electron diode. The information about beam length on the anode and a beam energy distribution along the anode is obtained by means of anode X-ray image. The beam length on the anode is about 30 mm, energy density varies in range 3–100 J/cm<sup>2</sup> depending on the diode voltage and anode diameter. The power density on the anode is 6–100 MW/cm<sup>2</sup> at pulse length of 0.5–1 μs.

**Keywords:** *electron diode, beams, accelerator.*

**NUMERICAL SIMULATION OF LASER RADIATION FORMATION  
IN A NONUNIFORM DISCHARGE OF KrF-LASER WITH A PULSE  
DURATION OF 30 NS**

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For the study of the influence of the shape of electrodes on the discharge width and the laser generation, the 2D simulation of the operation of aKrF laser with a pulse width of 30 ns was carried out for different radii of electrodes. Electrodes for which the electric field strength in the center of the discharge remained the same, but width of its profile was different were used. As a result, basic causes of changing the discharge width and of reduce the maximum current density with the increasing electrode radius were revealed. Furthermore, it was shown that there is the maximum for depending the radiation energy from the radius electrodes.

**Keywords:** *2D simulation, non-uniform discharge, KrF laser.*

## GALVANIZED STEEL PIPE JOINING FEATURES UNDER MAGNETIC PULSE WELDING

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Conventional and widely used liquid phase welding remains limited in some applications due to the high temperature heating. For instance, a weld seam produced by this kind of welding is known to be the weakest link in terms of corrosion in galvanized steel pipelines due to the expansive zinc oxidation during the welding. Therefore, the problem of producing an economical corrosion-resistant galvanized steel tubular joint is of interest. A solid-state bonding without a significant heating can be obtained by magnetic pulse welding. It is an impact welding process which uses intensive magnetic pressure to drive one part against another thus combining them into one. The work studies weld seam production in pairs of galvanized steel tubes. Since contact front moving is essential to obtain an impact joining, two part configurations were applied to realize the moving different ways: a pair of cylindrical tubes placed in non-uniform magnetic field and a pair of cylindrical outer tube with a conical inner tube placed in uniform magnetic field. A steel single turn coil was energized by pulsed current to generate the magnetic field. The sufficient peak magnetic induction to make a stable joining was found to be at 40 T. Steel-to-steel joints with zinc edges fully covering the steel were obtained. The weld area length and microstructure were investigated by metallographic examination of polished and etched longitudinal specimen sections.

The study was performed within the state assignment No.0389-2014-0002, partially financed by RFBR (No. 16-08-00919-a) and UB RAS Fundamental research program (No. 15-17-2-27).

**Keywords:** *magnetic pulse welding, solid state bonding, galvanized steel.*

## PULSED PLASMA CHEMICAL SYNTHESIS OF SIXCYOZ NANOSIZED COMPOSITE POWDER

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The  $\text{Si}_x\text{C}_y\text{O}_z$  nanosized composite powder with a number-average particle size of 10–50 nm was produced using a pulsed plasma chemical method. The experiments on the synthesis of the nanosized composite were carried out using a TEA-500 pulsed electron accelerator. To obtain the composite,  $\text{SiCl}_4$ ,  $\text{O}_2$ , and  $\text{CH}_4$  were used. Most experiments were done using the plasma chemical reactor (quartz, 140 mm in diameter, 6 liters volume). The reactor was equipped with a manometer, vacuum meter, pressure sensor, shut-off and control valve of initial reactant mixture inlet and pumping out the gas. The initial reactants were injected into the plasma chemical reactor, i.e. the pulsed electron beam which initiated the chemical reactions whose product was the  $\text{Si}_x\text{C}_y\text{O}_z$  nanosized composite powder.

To define the particle morphology, the JEOL-II-100 transmission electron microscope with an accelerating voltage of 100 kV was used. The substances included into the composite nanosized powder were identified using the optical absorption spectrum in the infrared region. To carry out this analysis, the Nicolet 5700 FT-IR Spectrometer was used. The EDX analysis was conducted. Fluorine was distributed uniformly in the powder.

**Keywords:** *nanosized composite powder, pulsed plasma chemical method, pulsed electron accelerator.*

## ULTRASMALL NANOPARTICLES SYNTHESIS IN THE MULTIGAP PULSE SPARK DISCHARGE GENERATOR

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The need for nanoparticle synthesis in various fields of science and technology has been growing significantly over the past decades. The spark discharge is the most effective way to produce small particles among other methods such as electric explosion of wires, plasma synthesis, laser evaporation of samples. The spark discharge allows producing particles down to 2 nm and even atomic clusters. Production of small nanoparticles with high electrical efficiency and high output rate is of great interest as it can be applied to a lot of applications including printed electronics.

In this study we investigate electrical processes in the spark discharge at different voltages, interelectrode distances and using different electrode materials. We measure electrical current in an electrode gap with custom-made Rogovskii coil and voltage with voltage divider. Then we calculate the energy delivered into electrode gap and show that there is optimal discharge voltage that minimizes the specific energy consumption of nanoparticles synthesis. Our method also allows to calculate plasma resistance in the gap and electrode voltage drop. We tested electrodes made of different metals and semiconductors and in particular obtained TiO<sub>2</sub>, Si and SiO<sub>2</sub> particles with sizes of 10–20 nm.

This work was supported by the Russian Science Foundation (project № 15-19-00190).

**Keywords:** *spark discharge, nanoparticle synthesis, specific energy consumption, plasma resistance, Rogovskii coil.*

## MACROPHAGE AND TUMOR CELL RESPONSES TO REPETITIVELY PULSED X-RAY RADIATION

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**Aim.** To study response of tumor cells and macrophages to repetitively pulsed low-dose X-ray radiation. **Methods.** Tumor growth and lung metastasis were analyzed using C57Bl6 mice injected with Lewis lung carcinoma. Monocytes were isolated from human blood using CD14+ magnetic beads. IL-1 $\beta$  was determined by ELISA. For macrophage phenotyping confocal microscopy was applied. «Sinus-150» was used for generation of pulsed X-ray radiation (absorbed dose below 0.1 Gy, pulse repetition frequency 10 pulse/sec). **Results.** Irradiation of mice with 0.1 Gy of pulsed X-rays significantly inhibited growth of primary tumor and reduced the number of metastatic colonies in the lung. Furthermore, changes in macrophage phenotype and IL-16 secretion were observed after repetitively pulsed X-ray radiation. **Conclusion.** Macrophages and tumor cells differentially respond to low-dose pulsed X-ray radiation. Activation of immune system through changes of macrophage phenotype can result in significant antitumor effect of low-dose repetitively pulsed X-ray radiation. **Funding.**

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The study was performed on equipment of Tomsk regional common use center, with the support of the Russian Ministry of the Agreement No.14.594.21.0001 (RFMEFI59414X0001).

**Keywords:** *pulsed X-ray, monocytes, tumor cells.*

## **SIMULATION OF PRE-BREAKDOWN PHASE OF ELECTRICAL DISCHARGE IN REINFORCED CONCRETE**

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The possibilities of electrical discharge technology implementation for reinforced concrete destruction for its recycling is considered. Advantages in comparison with the mechanical methods is that the electrical discharge channel acting as rock-breaking tool has an unlimited service life, and the lifetime of electrode systems is much higher. The physico-mathematical model of the discharge development is described. The simulation results of discharge channel propagation velocity and trajectory depending on reinforcement locality and voltage amplitude are presented. Increasing the voltage effects on average speed of the discharge structure development that reaches the speed of up to  $v = 5 \cdot 10^3$  m/s. It is also shown that the reinforcing elements located between electrodes attracts the discharge growing structure. The less the distance between the high voltage electrode vertical axis and the metal reinforcement position the more probability that discharge channel will orient towards this element.

**Keywords:** *breakdown, discharge channel, reinforced concrete destruction.*



## **ILU RADIO FREQUENCY PULSE ELECTRON ACCELERATORS FOR VARIOUS INDUSTRIES**

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The report describes industrial electron accelerators type ILU along with their main features and parameters. Applications of these accelerators in medicine and various industries are described. The new possibilities and applications of these machines in food industry are considered. A concise review of legal problems restricting electron beam and X-ray treatment for food products is also given.

**13<sup>th</sup> International Conference  
on Modification of Materials  
with Particle Beams and Plasma Flows**



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**Sessions:**

Beam and plasma sources  
 Fundamentals of modification processes  
 Modification of material properties  
 Coatings deposition  
 Nanoscience and nanotechnology

## COMPRESSION PLASMA FLOWS GENERATED BY QUASI-STATIONARY PLASMA ACCELERATORS AND THEIR CAPABILITIES FOR MATERIALS MODIFICATION

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Plenary lecture: Wide opportunities for materials surface modification are opened up by using compression plasma flows generated by quasi-stationary plasma accelerators of a new generation. Such accelerators operate in the ion-current transfer mode and provide the ion-drift acceleration of magnetized plasma. The physical bases of compression plasma formation in such systems are presented.

The interest to these systems is connected with their applications in plasma technology for enhancement of performance characteristics of various metals and alloys, semiconductor and others by means of substantial modifications to the surface microstructure and morphology, phase and structure transformations under the action of compression plasma flows, which is beyond capabilities of other techniques.

The capabilities of compression plasma flows as applied to embodiment of proposed principles of surface-plasma metallurgy are considered.

The main factors ensuring the implementation of surface-plasma metallurgy are:

- the rapid heating of the surface due to kinetic energy thermalization of compression plasma flow during its deceleration,
- melting of both doping elements and a substrate,
- liquid phase mixing under plasma flow pressure,
- keeping the temperature and pressure at necessary levels during long time until the completion of physicochemical transformations in the surface layer,
- the fast cooling and crystallization of the molten layer.

**Keywords:** *quasi-stationary plasma accelerator, compression plasma flow, materials surface modification, surface-plasma metallurgy.*

## CHARACTERISTICS OF COLD ATMOSPHERIC PLASMA SOURCE BASED ON LOW-CURRENT PULSED DISCHARGE WITH COAXIAL ELECTRODES

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This work investigates the characteristics of the gas discharge system used to create an atmospheric pressure plasma flow. The plasma jet design with a cylindrical graphite cathode and an anode rod located on the axis of the system allows to realize regularly reproducible spark breakdowns mode with a frequency  $\sim 5$  kHz and a duration  $\sim 40$   $\mu$ s. The device generates a cold atmospheric plasma flame with 1 cm in diameter in the flow of various plasma forming gases including nitrogen and air at about 100 mA average discharge current.

In the described construction the cathode spots of individual spark channels randomly move along the inner surface of the graphite electrode creating the secondary plasma stream time-average distributed throughout the whole exit aperture area after the decay of numerous filamentary discharge channels.

The results of the spectral diagnostics of plasma in the discharge gap and in the stream coming out of the source are presented. Despite the low temperature of atoms and molecules in plasma stream the cathode spots operation with temperature of  $\sim 4000$  °C at a graphite electrode inside a discharge system enables to saturate the plasma by CN-radicals and atomic carbon in the case of using nitrogen as the working gas.

**Keywords:** *Cold plasma jet, Atmospheric pressure plasma, Spark discharge.*

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## FEATURES OF PLASMA GENERATION BY ELECTRON-BEAM EVAPORATION OF METAL TARGET IN FORE-VACUUM PRESSURE RANGE

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We describe an experiment on generation of gas-metal plasma by electron beam evaporation of copper target in He with simultaneous ionization of evaporated material by e-beam in fore-vacuum pressure range (2–12 Pa). Parameters of gas-metal plasma were investigated using computerized single Langmuir probe. We found the increase in plasma density and electron temperature with intensive evaporation of the copper target.

**Keywords:** *Fore-vacuum pressure range, Plasma electron source, Beam plasma, Gas-metal plasma.*

## OPERATIONAL TESTING OF SELF-HEATED CATHODE MADE FROM COMPACTED TIN POWDER

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The results of tests of self-heated hollow cathode made by magnet-pulse pressing of the mixture of TiN (90 %) and Ti (10 %) powders with further high-temperature annealing and fusing during operation of the compact as a cathode in high-current (0–45 A) discharge are presented. It was found that the rate of the cathode mass loss during operation in Ar/N<sub>2</sub> mixture made  $2.3 \cdot 10^{-7}$  g/s. The possibility of the cathode use for oxygen-argon plasma generation at separated gas feeding (argon – through cathode cavity, and O<sub>2</sub> – to anode area of discharge) was shown. Testing of massive tubular cathodes with increased thickness of the wall (up to 2.5 mm) and large inner diameter (up to 12 mm) possessing enhanced resource (300–500 h) was carry out.

**Keywords:** *Self-heated hollow cathode, Titanium nitride, oxygen-argon plasma.*

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## FORMING OF ACCELERATED GAS CLUSTER ION BEAMS FOR SURFACE ULTRA-SMOOTHING

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In last decade it has been shown that the gas cluster ion beams can serve a unique tool for modern technological applications: polishing of the surface of various materials down to nanometer level, low-temperature formation of thin films, ultrashallow implantation etc. [1, 2]. For materials treatment the accelerated cluster ion beams with sizes from dozens up to thousands of particles (atom or molecule) per cluster and with energy of up to 30 keV are required. In this work the physical features of the formation of accelerated gas cluster ion beams are discussed. As a source of intense flux of neutral clusters, the supersonic gas jets after conical shaped nozzles are used. Capabilities for ultra-smooth surface materials are illustrated by the obtained experimental results.

**Keywords:** *Cluster ion beam, Gas cluster, Surface smoothing.*



## LOW-PRESSURE LOW-FREQUENCY INDUCTIVE DISCHARGE WITH FERRITE CORES FOR LARGE-SCALE PLASMA PROCESSING

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Inductively coupled plasma sources (ICP), being widely used in semiconductor industry, have a few disadvantages that significantly complicate a task of ICP scaling for the future 450 mm silicon wafers technology (low power factor of ICP coil, hence high coil current leading to significant increase in coil voltage affecting plasma and discharge chamber, with increasing of coil size). Using closed ferrite cores to improve magnetic coupling between coil and plasma (low-frequency ICP) allows overcoming the limitations of conventional radio-frequency ICP and gives new possibilities for large-scale plasma processing.

Electrophysical characteristics of a low-frequency (100 kHz) low-pressure (10–100 Pa) argon inductive discharge with ferrite cores have been investigated for discharge currents of 1–50 A, discharge chamber diameter of 230 mm. The dependencies of electric field strength on the argon pressure and discharge current were measured. Radial profiles of electron density and temperature were determined with double probes. Experimental results were compared with numerical results obtained by developed self-consistent radial model of the low-frequency ICP, based on the assumption of Maxwellian electron energy distribution function and simultaneous solution of balance equations for the electron and metastable atom densities, electron energy and gas temperature. It is shown that numerical results are in satisfactory agreement with the results of probe and electric field strength measurements.

**Keywords:** *ICP, Inductively coupled plasma, Transformer coupled plasma, Large-scale plasma processing.*

## EFFECT OF TEMPERATURE THE ELECTRON ON DISTRIBUTION OF PLASMA PARAMETERS ON THE PHASE PLANES FOR LOW-TEMPERATURE EMITTER OF THERMIONIC DIODE

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For some combination of parameters thermionic diode plasma processing characteristics probe gives two distributions of the electron temperature in the electrode gap: in the low (thermal) energy of electrons and in high-energy of electrons. The latter group is associated with the electrons, which have major influence on the processes of generation of excited atoms and ions. There is a mechanism that does not mix the two groups of electrons and maintains temperature difference for these groups in the field of low plasma densities. Spectroscopic measurements make it possible to obtain only one distribution of electron temperature in high-energy.

Using known expressions (formulas) can receive the distribution of the plasma parameters which are not measured in the experiment: the ion current density, electron energy stream density, function generating ions in the plasma volume, for spectroscopic measurements of the potential of the space occupied by the plasma. It is interesting to study the influence of two electron temperature distribution in the distribution of unmeasured plasma parameters, including the function generating ions in the electrode gap diode.

As a method of research used analysis experimental and unmeasured plasma of distributions parameters on the phase planes.

In this paper we investigate the electron distributions of two temperature influence the distribution of experimental and unmeasured (calculated) parameters cesium plasma for low-temperature thermionic emitter diode on the configuration planes and on the phase planes. On the experimental material verified the results of theoretical research in the phase plane, developed in previous works.

**Keywords:** *Plasma, diode, Modeling.*

## STAND FOR IRRADIATING REACTOR MATERIALS

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At linear accelerator with radio frequency quadrupole (RFQ) HIP-1 (heavy ion prototype) in Institute of Theoretical and Experimental Physics new nuclear materials are irradiated by heavy ion beams. New nuclear materials are irradiated by HIP-1. Radiation-induced changes are investigated by transmission microscopy [Robertson C., Panigrahi B.K., Balaji S., Kataria S., Serruys Y., Mathon M.H., Sundar C.S. *Journal of Nuclear Materials*, 2012. 426 pp.240-2469] and the atomic-probe tomography [S.V. Rogozhkin, A.A. Aleev, A.G. Zaluzhnyj, R.P. Kujbida, T.V. Kulevoy, A.A. Nikitin, N.N. Orlov, B.B. Chalyh, V.B. Shishmarev. *SCIENCE PHYSICS OF METALS AND METAL*, 2012, vol. 113, № 2, pp. 1–12].

Stand for Irradiation of Reactor MATerials (SIRMAT) was created in ITEP to enlarge the intensity of the experiments.

At SIRMAT samples are irradiated up to  $10^{16}\text{cm}^{-2}$  by metal ions generated by MEVVA ion source with energies up to  $100\text{ keV } z$ , where  $z$  – ion charge. The gas ion source is under preparation for installation at the SIRMAT.

**Keywords:** *Ions, beams, Modificaton of material, Plasma.*

## THE COMPLEX INVESTIGATION OF PULSE NEUTRON GENERATOR'S SPARK-ARC ION SOURCES

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The interest to the neutron technologies employing pulse neutron generators (PNG) significantly raised during last decades, their key issues (KI) became higher as a result of the thorough investigation of physical processes determining these issues. VNIIA is the main Russian NG, especially PNG, producer. The key PNG element – sealed neutron tube (SNT) – is a small size line accelerator of hydrogen isotopes ions bombarding the target. The spark-arc ion sources (SAIS) used in SNT. The exact determination of the beam profile and mass-charge composition as functions of the construction and electric scheme parameters is indispensable for the high efficiency pulse NG production especially from the point of view of KI rising. They are the internal electric durability, the tritium target time of life, the neutron yield etc.

The investigation of the PNG plasma generator has began in ITEP with the aim to rise its lifetime. The ion source based on PNG plasma generator has been designed for subsequent analysis of its mass-charge composition and its dependencies on the plasma generator working regimes. The results of such investigation made on the universal ITEP ion sources test bench (UTB) are presented below in comparison of the results obtained in VNIIA as well as other Russian scientific centers. The mass-charge beam spectra registered with time of flight (TOF) and magnetic (Dempster) methods are among the results. The ion beam parameters and its composition dependencies on the energy consumption are studied.

**Keywords:** *Pulse neutron generators, Plasma generator, Mass-charge beam spectra.*

## THE ONE-PARTICLE APPROXIMATION IN THE REFLECTING DISCHARGE SIMULATION

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The method of some reflecting discharge (Penning discharge) characteristics evaluation, based on the one-particle approximation is proposed. In fact it's similar to the approach used in the early times of first glow discharge investigations and crossed fields ion sources. This method may be applied for the early discharge stages (the Townsend regime) description. It is somehow simpler than the diffusion-drift approximation usually used for the stationary state description because plasma doesn't exist yet. That's why the initial fields distributions are not disturbed by the plasma and the charges motion trajectories may be calculated exactly even including charge-neutrals interactions, that is ionization, recombination etc.

On the other hand one doesn't need to use most of usual diffusion-drift simplifications e.g. 1 or 2D models, uniform magnetic field etc. So the process of discharge formation may be described exactly for different kinds of Penning cells geometries and fields configurations. The discharge ignition condition for the Penning cell, analogous to the Townsend law is evaluated. It permits one to appreciate the discharge formation time as a function of cell geometric parameters, fields configurations, anode voltage and Townsend's coefficients  $\alpha$  and  $\gamma$ . This time, or exactly the trajectory length during this time plays the role of the Townsend parameter  $d$  – the distance between electrodes. The calculated values of such times show good agreement with experimental data.

**Keywords:** *Reflecting discharge (Penning discharge), One-particle approximation, The Townsend regime, The Townsend discharge ignition condition, The discharge formation time.*

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## SPECIAL FEATURES OF PLASMA DENSITY PROFILE IN DIELECTRIC HOLLOW AT HEGHTENED ELECTRON BEAM ENERGIES

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We describe an experiment on generation of beam-produced plasma during injection of e-beam in dielectric cylindrical hollow. We found non-monotonic profile of plasma density inside the hollow. This profile could be explained by composition of two trends affecting on plasma density – longitudinal decrease due to e-beam scattering on gas molecules, and increase due to additional gas ionization by secondary electrons accelerated in near-bottom sheath.

**Keywords:** *Fore-vacuum pressure range, Plasma electron source, Beam plasma, Dielectric hollow.*

## HIGH INTENSITY PLASMA IMMERSION METAL ION BEAM SOURCE FOR SURFACE MODIFICATION OF MATERIALS

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The results of investigation on development of the vacuum arc discharge based high current low ion energy repetitively pulsed ion source for surface modification of materials are presented. DC vacuum arc was used to produce metal plasma flow. Plasma immersion approach was used for high frequency short pulse metal ion beams formation. A grid semispheres with a radii 7.5 and 10.5 cm, and a cell size  $1.8 \times 1.8 \text{ mm}^2$  with transparency 0.7 were immersed in titanium vacuum arc plasma.

High frequency short pulse negative bias amplitude in the range of 1–2.6 kV, pulse duration in the range of 2–8  $\mu\text{s}$ , pulse repetition rate 105 pulse per second were applied to the grid for ion beam extraction, formation and focusing. Repetitively pulsed mode of bias formation provided a possibility to increase the amplitude of bias potential up to several kilovolts and focusing ion beams space charge neutralization.

The influence of bias amplitude, pulse duration and titanium plasma density on parameters of formed ion beam were investigated. Titanium ion beams with a current density up to  $1 \text{ A/cm}^2$  and pulsed ion beam power density up to  $3 \cdot 10^8 \text{ Wt/cm}^2$  were obtained. It was shown that the focusing of ion beams allows multiple reduction of macroparticles and ion beam fluxes ratio. The possibility of macroparticle free high intensity ion beams formation for surface modification of materials are demonstrated. The use of metal ion source for high intensity ion implantation with enhancement of dopant penetration to the greater depth is discussed.

**Keywords:** *Vacuum arc, Plasma, Ion beams, Repetitively pulsed bias.*

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## GLOW DISCHARGE WITH THERMIONIC AND LARGE SIZE HOLLOW CATHODES FOR ARC DISCHARGE EVAPORATION PLASMA ASSISTING

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The gas plasma generating system with thermionic and large size hollow cathodes for arc discharge evaporation plasma assisting is considered. It is shown that such system provides generation of gas plasma at a pressure from 0.01 Pa, at the same time interference of gas and arc discharge parameters is not significant.

**Keywords:** *Plasma, glow discharge, Arc discharge, Hollow cathode, Thermionic cathode, PVD*



## ANALYSIS OF WORK AND INCREASING OF EFFICIENCY OF THE ILUR-03 INSTALLATION MAGNETRON SYSTEM FOR TUBULAR SPECIMENS OUTER SURFACE MODIFICATION

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The method of material near-surface layers doping by mixing of alloying elements films with ion beam widely used in science and technology. Three magnetrons with independent power systems, integrated in installation for ion-beam treatment of long-range products

ILUR-03, were used as deposition systems. Targets for magnetrons were in the form of disks 60 mm diameter and 5 mm thickness and consists of the following elements: Al, Fe, Mo, Zr, Cr of purity better than 99.99 at.%. Deposition was performed in argon atmosphere at 1–5 Pa pressure and room temperature in stable current mode at 30–100 mA. Analysis of the obtained films on the surface of cylindrical specimens from zirconium alloys outer diameter of 9.15 mm showed high uniformity of coating on length of 300 mm, good adhesion and absence of discontinuities in the films body.

**Keywords:** *Ion beam, Magnetron, Sputtering, Thin films, Modification.*

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## COMPOSITION OF GAS ATMOSPHERE DURING ELECTRON-BEAM PROCESSING QUARTZ GLASS IN THE FOREVACUUM PRESSURE RA

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The results of measuring the composition of the atmosphere gas during electron beam processing quartz glass at the forevacuum pressures ( $\sim 30$  Pa) are present. In these conditions, SiO molecules in the gas phase were detected. Both SiO molecules and SiO<sub>2</sub> molecules were found in the coating formed on a silicon substrate during processing. Silicon dioxide is probably formed due to oxidation of SiO on the substrate.

**Keywords:** *Plasma electron source, Forevacuum pressure range, Electron beam, Quartz glass, Melding, Evaporation.*

## MEASUREMENT OF THE RADIAL FIELD DISTRIBUTION IN A PENNING DISCHARGE BY ISOLATED PROBE

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The question about the formation of a defined spatial profile of the electric potential in the plasma is important in the plasma separation method of spent nuclear fuel [Smirnov V.P., Samokhin A.A., Vorona N.A. and Gavrikov A.V. Plasma Phys. Rep. 39, (2013)]. The combination of electric and magnetic fields leads to spatial separation of «light» ( $m < 160$  u) and «heavy» ( $M \sim 240$  u) component of spent fuel. At the ends of the cylindrical chamber are the electrodes. To these electrodes is applied a negative voltage. A grounded vacuum chamber in conjunction with these electrodes forms a reflex discharge. This discharge generates a radial profile of the electric plasma potential. The work is devoted to the study of this profile.

In the work reflex DC discharge in helium was explored. It was studied the effect of parameters such as magnetic field of 0.03 to 0.2 T, the pressure of 0.1–100 mTorr, discharge voltage of 0–1.2 kV, the distance cathode-cathode and cathode-anode on plasma column potential. It was shown that the dependence of the plasma column potential on pressure has two maxima. The position of the maxima was determined by the magnetic field. By isolated probe method was measured radial profile of the plasma potential. Using a double probe was measured concentration and the electron temperature. The range of the potential oscillations of the plasma column in different modes was defined.

The study was supported by a grant of the Russian Science Foundation (project No. 14-29-00231).

**Keywords:** *Plasma separation method, Penning discharge, Reflex discharge, Isolated probe.*

**PLASMA JET CHARACTERISTICS IN VACUUM ARC  
WITH DIFFUSED CATHODE SPOT**

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The present paper reviews the experimental results dedicated by the effect of the irradiation conditions by intense pulsed electron beams on crater creation taking place on the surface of VT6, DN8, VT9 refractory titanium alloy targets. The most probable mechanisms of crater creation are also analyzed.

***Keywords:*** *Crater, Creation, Surface, Titanium, Blade, Intense, Pulsed, Electron, Beams.*

**SPECTRAL MEASUREMENTS IN THE LOW-INDUCTANCE VACUUM DISCHARGE***VALERY CHIKOMASOV, SERGEY GORBUNOV AND VICTOR PAPERNY**Irkutsk State University  
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The results of spectral measurements of plasma emission in the low-inductance vacuum discharge with copper cathode in the range of 250 nm to 700 nm wavelength are presented. It was found that the vacuum discharge plasma irradiation spectra contain emission lines from atoms and ions both the cathode material and residual gases. Namely, the emission lines with wavelength of 465 nm, 514 nm, 393 nm and 375 nm corresponding to emission from ions  $N^+$ ,  $C^+$ ,  $Cu^+$ ,  $Cu^{++}$ , respectively, and emission from atoms H, O, Cu were recorded. The results obtained are as follows: (i) The lines corresponding to emission from atoms of the cathode material were sufficiently intense. This means a relatively high content of atoms of the cathode material in the plasma of vacuum spark, that is possibly, as a result of evaporation of microdroplets in the plasma flow. (ii) Plasma emission spectra were measured also after training of the vacuum chamber by plasma of a lot of shots. This measurements show a sufficient decrease in intensity of lines of the residual gases as result of desorption atoms of residual gases from material of vacuum chamber and the subsequent removing of these atoms. (iii) The intensity of all registered lines increased with rising discharge current, but rise rate of intensity of the line from  $Cu^+$  ions was more than that from the residual gases and this rise rate was similar to this of the ion current emitting from the discharge.

**Keywords:** *Vacuum discharge, Plasma emission spectra, Desorption atoms.*

## THERMAL STRESSES COMPUTATION UNDER HIGH-CURRENT PULSED RADIATION OF AISI M2 STEEL

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Surface modification of metallic materials and alloys with concentrated energy flows (powerful electron beams and ion plasma flow, laser beams) has been widely used at various manufacturing fields with the aim of the physical and mechanical properties improvement of the critical parts performance from modified materials.

Such energy impacts give rise to radiation, thermal and mechanical effects causing the change on the morphology, microstructure, elemental and phase composition of surface layers, which in turn may lead to increased hardness, wear, corrosion resistance and red hardness of modified materials.

However, as experimental investigations have shown, irradiation in some cases promotes the crystal defects occurrence and often non-uniform heating leads to the cracks formation at the surface layers.

Thus, the selection of incident electrons energy, its current density and pulse duration, taking into account of the thermal stress state is an actual problem of modern radiation technologies.

The result of temperature fields calculation provided here with longitudinal and transverse thermal stresses computation using multigrid technology for numerical solution of differential equations in partial derivatives also examined for R6M5 (AISI M2) high-speed steel with medium-energy (up to 400 keV) high-current (up to 1 kA/cm<sup>2</sup>) pulsed (up to 1 μs) electron beam radiation.

The obtained results can be useful at the optimal modes selection of tool steels and products processing by electron beam radiation and evaluation of its service life.

**Keywords:** *Radiation processing, Electron beam processing, Beam power, AISI M2 steel, Thermal stresses, Temperature fields.*

## FEATURES OF AN ATMOSPHERIC-PRESSURE PLASMA JETS FORMATION

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In our days, the atmospheric-pressure discharges in a gas flow attract considerable attention. The systems for obtaining these type of discharges usually consist of two specially configured electrodes allowing the gas flowing through the discharge gap area. The well-known example of such system is the so-called low current nonsteady-state plasmatron used in this work.

The paper describes the results of the investigation of the plasma jet formation at atmospheric pressure. Plasma jets were generated by the nonsteady-state low current plasmatron at average glow discharge currents up to 250 mA, and air flow rate up to 1 g/s.

It was demonstrated that the reduced electric field in the plasma jet has no to provide the plasma sustainment due to gas ionization. On the basis of experimental data, velocity of the gas, the plasma conductivity and the charged particles density in the plasma jet area were estimated.

**Keywords:** *Non-equilibrium plasma, Discharges in a gas flow, Plasma jet, Plasma torch, Plasmatron, Atmospheric-pressure plasma sources.*

## ICP SOURCE ANTENNA SYSTEM

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The ICP sources have become widely used in manufacturing technologies of micro- and nano-electronics products, and also optics and optical electronics. Due to the tendency of samples size enlargement and the necessity for the improved of the layers and structures characteristics being formed the requirements to plasma treatment uniformity increase. That's why the development of technological devices providing large-surface samples with less than +1 % nonuniformity processing are of interest. The main ICP source component, which influences on this technological parameter, is an antenna system, being considered in this article.

**Keywords:** *Helix antenna system, Inductively coupled plasma, ICP, PECVD, Planar ICP source.*



## NUMERICAL SIMULATION OF THE COAXIAL MAGNETO-PLASMA ACCELERATOR AND NON-AXISYMMETRIC RADIO FREQUENCY DISCHARGE

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The paper presents the results of mathematical modeling of physical processes in electronic devices such as helicon discharge and coaxial pulsed plasma thruster [Melazzi D, Cardinali A, Manente M and Pavarin D 2012 *J. Phys.: Conf. Ser.* 401 012015, Chen F F 2015 *Helicon discharges and sources: a review, Plasma Sources Science and Technology* 24 014001, Chen F F 2015 *Helicon discharges and sources: a review, Plasma Sources Science and Technology* 24 014001, Vavilin K V, Kralkina E A, Nekludova P A, Petrov A K, Nikonov A M, Pavlov V B, Airapetov A A, Odinokov V V, Pavlov G Ya and Sologub V A 2016 *J. Phys.: Conf. Ser.* 669 012033, Fredriksen Å, Mishra L N, Gulbrandsen N and Miloch W J 2010 *J. Phys.: Conf. Ser.* 257, 012019]. An approximate mathematical model of coaxial magneto-plasma accelerator (with a preionization helicon discharge), which allows you to estimate the transformation of one form of energy to another, as well as to evaluate the level of the contribution of different types of energy, the increase in mass of the accelerated plasmoid in the process of changing the speed.

A simplified kinetic scheme used to calculate the component composition of molecular hydrogen plasma in the chamber helicon discharge. The kinetic scheme includes the processes of ionization of molecules and hydrogen atoms by electron impact recombination processes, various mechanisms dissociation of hydrogen molecules by electron impact. The results of numerical modeling of the kinetics of ionization and dissociation of molecular hydrogen in a partially ionized plasma, helicon discharge.

A system based on a coaxial magneto-plasma accelerator (CMPA) is discussed. Numerical simulation of the CMPA and non-axisymmetric radio frequency discharge is done. The calculations revealed that the most significant factor (along with the formation of a shock wave), limiting the amount of plasmoid velocity in the channel of coaxial magneto-plasma accelerator is attached mass, increasing over time.

**Keywords:** *Coaxial magneto-plasma accelerator, Helicon pre-ionization source, Pulsed plasma thruster, Radio frequency discharge.*

## MODERNIZATION OF HIGH-POWER (5 KW) BROAD ION BEAM SOURCE

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In the course of long-term performance (during 5 years) of high-power source of gas ions (25 keV, 0.2 A, 600 cm<sup>2</sup>) with plasma emitter based on cold cathode discharge the character and rate of key constructive elements faults were determined, which allowed to calculate the inter-repair time, complexity and cost of repair. The peculiarities of gas-discharge system and ion beam forming system limiting the effectiveness of ion beam treatment were revealed as well. Conditions favored decreasing of discharge voltage on 50–200 V and igniting voltage up to 1.5–2 times are determined. The possibilities of lowering of the minimal flow of working gas are ascertained. The design of discharge system with reduced sputtering rate of local areas of the hollow cathode is offered. The changes added to ion source design, aimed to enhance the lifetime of plasma chamber that is exposed to cyclic heating by back electron beam leading to through cracks development, and to enlarge the rupture life of glow discharge hollow cathode by optimizing its configuration and the conditions of discharge ignition and burning are described. The upgraded design of multislit ion-optical system with enhanced performance ensures uniform surface distribution of ion fluence.

The work was supported in terms of the item of State task № 0389-2014-0006 and partially supported by the Program of fundamental research of Ural Branch of RAS (Project №15-17-2-28)

**Keywords:** *Glow discharge, Plasma, Broad gaseous ion beam source, Ion beam, Modification of materials surface.*

## GENERATION OF BORON PLASMA BY SHORT-PULSE VACUUM ARC WITH LANTHANUM HEXABORIDE CATHODE

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Plasma containing boron ions is used in a different ion beam and plasma technologies. In addition to the traditional use of boron plasma for ion doping of semiconductors, it is also can be used for surface modification of materials to improve these parameters and increase life-time of machine parts or tools. In this work, the plasma of boron ions were generated using short-pulse high-current vacuum arc discharge with a cathode made from lanthanum hexaboride. The plasma composition was investigated by time-of-flight technique with different arc currents and pulse durations. It has been shown that the vacuum arc discharge with a cathode of lanthanum hexaboride provides efficient plasma generation with a high content of boron ions. Also it has been shown that for all the investigated parameters of the arc discharge the ratio of ions of boron and lanthanum in the plasma satisfactorily corresponds to the stoichiometric composition these elements in used arc cathode.

This work was supported by Russian Scientific Foundation under grant # 16-19-10034.

**Keywords:** *Vacuum arc discharge, Plasma, Lanthanum hexaboride, Boron ions.*

## GENERATION OF PLASMA FLOWS BY ARC PLASMATRONS

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Plasma technologies of material modifying and deposition of coatings with different functional properties can be implemented, if the efficient sources of plasma flows are available. These sources are the electric-arc generators of thermal plasma (plasmatrons). The effect of different plasmatron schemes on distribution of temperature and velocity of the plasma flows is considered in the current study. For example, it is shown that a partitioned interelectrode insert and gas injection between the sections ensure a plateau in temperature distribution  $T(r)$ . A similar result was obtained for the plasma flow at the exit of the plasmatron with a stepped output electrode.

**Keywords:** *Arc discharge, Plasmatron, plasm jet, Temperature distribution, Interelectrode insert, Electrode of stepped geometry.*

## THE EFFICIENCY OF ION GENERATION IN DISCHARGE WITH SELF-HEATING HOLLOW CATHODE

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The results of research of the characteristics of plasma generated in a large volume ( $0.4 \text{ m}^3$ ) chamber by DC-discharge (50 A) with self-heated hollow cathode are presented. The influence of applying of axially-symmetric magnetic field and constricting of discharge with aperture, of the form and sizes of anode on discharge voltage, degree of spatial inhomogeneity of plasma, ion current density and efficiency of ion generation were studied. Distribution of density of ion current from plasma inside the chamber volume was measured. Erosion rate of massive cathode made of titanium nitride by magnetic pulse pressing of TiN powder was estimated, and the conditions of steady discharge with active zone located on the edge of hollow cathode were determined. The cathode was tested in the regime of oxygen-containing plasma generation.

**Keywords:** *Self-heating hollow cathode, Titanium nitride, High-current discharge, Gas discharge plasma generator, Ion current density.*

**DETERMINATION OF MAGNETRON PLASMA PARAMETERS  
BY OPTICAL EMISSION SPECTROSCOPY AND ARGON  
COLLISIONAL-RADIATIVE MODEL**

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Optical emission spectroscopy (OES) is widely used for plasma diagnostics. Combined with some of plasma light emission models it becomes non-intrusive and versatile method of plasma parameters determination. In this work we determined electron density and its temperature in magnetron plasma by OES method based on a fitting of emission line intensities calculated from collisional-radiative model to experimental ones. The model describes kinetics of first 40 excited states of neutral argon Ar. The following processes are taken into account: electron impact excitation/deexcitation, spontaneous light emission, radiation trapping, electron impact ionization, and metastable quenching due to diffusion to walls. The population of various excited levels for argon plasma of midrange magnetron have been calculated and compared with OES measurements. Experimental spectra were registered by Avaspec 3648 spectrophotometer. The optical system has been calibrated with a tungsten-ribbon lamp. Determined electron density and temperature for magnetron plasma in different operating modes were tested and validated from its comparison with Langmuir probe measurements. The agreement between data of both techniques is satisfactory.

**Keywords:** *Optical emission spectroscopy, Collisional-radiative model, Magnetron plasma.*

## HIGH-SENSITIVITY PLASMA ION COMPOSITION TIME-OF-FLIGHT ANALYZER WITH WIDE RANGES OF ION MASS AND PARTICLE FRACTION

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An ion composition is one of the most important factors in processes of modification of materials with ion beams and plasma flows which determines the desired properties of the treated object. To measure it, a time of-flight spectrometer with radial focusing of analyzed ions and high sensitivity detector is designed. The spectrometer provides a mass resolution of 1 Da starting from hydrogen ions, and a measurement of particle fractions down to  $10^{-3}$ . The features of the spectrometer operation are discussed. The results of measurements of hydrogen plasma ion composition are presented.

**Keywords:** *Plasma ion composition, Time-of-flight spectrometer, Hydrogen ions  $H_3^+$ .*

## ATMOSPHERIC PLASMA GENERATOR BASED ON THE DISCHARGE IN ARGON FLOW

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The results of studies device generating the plasma flow and the hot gas by passing the gas stream through the discharge channel are presented. Plasma generator represented double electrode system, consisting of a central electrode in the form of a pointed rod and a spherical electrode located coaxially with a central hole. In the absence of the flow of gas discharge operated in the discharge system at atmospheric pressure, and had a kind of superposition of multiple channels, localized near the tip of the central electrode. In the presence of the gas stream at a rate of 5 to 20 l/min were observed the following phenomenon: the removal of the conductive channel through the central aperture in a spherical electrode, the division into separate channels of different lengths, the ends of which are closed on one side on the tip of the center electrode, on the other hand – on the sharp edge of the hole. Also present diffuse glow that spreads to a distance of 8 mm from the outer surface of the spherical electrode.

**Keywords:** *Atmospheric pressure discharge, Plasma flow, Corona discharge, Gliding arc.*



## BORON IONS BEAM GENERATION IN THE VACUUM ARC SOURCE WITH LANTHANUM HEXABORIDE CATHODE

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The results of research of elemental charge composition of the plasma vacuum arc with lanthanum hexaboride cathode. An analysis of the elemental composition of ion beams was carried out with the magnetic separator. Vacuum arc operated in a frequency pulsed with current 140 A, a duration of about 350 microseconds at a pulse base, and 2 Hz of pulse repetition rate. Extracts the ions of constant voltage, was 20 kV. The dependence of boron and lanthanum fractions in plasma vs time during vacuum arc pulse were investigated. It was shown that the content of  $B_2^+$  ions in the beam at 75 microseconds since the initiation of the arc was 45 %, and reduced, for the duration of the discharge pulse to 30 %. The fraction of singly charged boron ions during the arc pulse increased from 18 to 30 %. The absolute values of the ion currents of boron ions  $B^+$ ,  $B_2^+$  and  $B_3^+$  was a few hundred microamperes. It is shown that the ratio of fractions of ionized boron and lanthanum atoms in the extracted ion beam in agree to the stoichiometric composition of the material of the vacuum arc cathode. The extraction of mono-element B ion beams with a low energy spread from the plasma of a vacuum arc is attractive for use in ion beam boriding technologies.

**Keywords:** *Vacuum arc discharge, Bending magnet, Multiply charged boron ions.*

## NEW BEAM LINE FOR HEAVY ION RFQ

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The study of stopping power for heavy ions in the gas-discharge plasma target are resumed at the 27 MHz RFQ HIP-1 (Heavy Ion Prototype) in the Institute for Theoretical and Experimental Physics (ITEP). There is an electrical discharge in gas with special configuration of electrodes with opposite direction of current used for reducing the ion beam focusing effect in the target. The new transport line at the output of HIPr-RFQ is under development to enable the experimental work with plasma target. From other hand, the beam line has to keep up ongoing experiments with the RFQ beam to the study of irradiation resistance of reactor structural materials. To obtain required beam parameters for both experiments, the beam dynamic simulation was carried out. The results of simulation are presented and discussed.

**Keywords:** *Beam line, Plasma target, Reactor structural materials, Beam dynamic*

**RESEARCH OF ELECTRIC STRENGTH OF ACCELERATING GAP  
OF THE LARGE-AREA PULSED PLASMA ELECTRON SOURCE  
IN THE FORE-VACUUM PRESSURE RANGE**

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The research of electric (breakdown) strength of the accelerating gap of a plasma electron source based on the arc discharge, generating a pulsed large-radius low-energy electron beam in the fore-vacuum pressure range is presented. Maximal electron beam current at constant energy of 10 keV is chosen as a parameter to measure the electric strength of the accelerating gap. An increase of the working gas pressure (3–30 Pa) and an increase of current pulse duration (67–300 ms) lead to a decrease in breakdown strength of the accelerating gap. A type of working gas also affects the electric strength. The influence of working gas pressure and its type is caused by ionization processes in the acceleration and electron beam transport regions. This ionization processes occur much more intense in the fore-vacuum pressure range than in the usual for the electron sources pressure range (<0.1 Pa). Influence of current pulse duration is caused by ionization process, and, probably, by the thermal processes occurring in the accelerating gap.

**Keywords:** *Plasma electron source, Electric strength of accelerating gap, Pulsed electron beam, Fore-vacuum pressure range.*

## GENERATION OF GAS DISCHARGE PLASMA BASED ON UNBALANCED MAGNETRON-SPUTTERING SYSTEM

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The paper presents the results of a study of unbalanced magnetron sputtering system with geometric imbalance coefficient  $KG = 0.3$  for the generation of its gas-discharge plasma of the working gas (argon) away from its target. It has been found that the created and investigated magnetron-sputtering system with a silicon (Si) targets generating a argon plasma with ion current density of it  $\approx 0.2 \text{ mA/cm}^2$  in the placement of workpieces at a distance of 440 mm from the target. Power limit parameters of the magnetron-sputtering system to melt silicon target to generate a high density of gas discharge plasma were investigated.

**Keywords:** *Plasma, Gas-discharge, Magnetron-sputtering, Unbalanced magnetron-system.*

## EMISSION SPECTRA OF THE TORCH IN LOW-CURRENT NON-STEADY PLASMATRON

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Low-current non-steady plasmatron is one of alternative devices to create a non-equilibrium atmospheric pressure plasma. Currently plasma has found wide use in the systems support combustion and conversion of hydrocarbons, or surface modification, disinfection and wound healing, as well as selective effects on cells. Traditionally, one of the areas of research this plasma is associated with the recording and study of emission spectra.

In this work, the emission spectra of the plasma torch in non-steady plasmatron are investigated with spatial resolution. The experimental setup is shown. Studies are carried out for different designs of the plasmatron in a stream of air atmospheric pressure. The flow rate is  $G = 0.2\text{--}1$  gram per second at average discharge power up to 200 Watt. Features of the spectra are described. Reactions occurring in the plasma are analyzed. Questions related to the degree of nonequilibrium of the plasma torch are discussed.

**Keywords:** *Non-steady low-current plasmatron, Emission spectra, Plasma torch.*

## OPERATING MODES OF PLANAR MAGNETRON WITH THE ELECTRONS INJECTION

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The two-stage discharge systems with central and peripheral injection of electrons and their subsequent acceleration in the cathode layer of magnetron discharge with a planar metal target are developed and investigated. Plasma glow discharge with a hollow cathode was used as the an electron emitter. The minimum operating pressure of non-selfsustained form magnetron discharge was  $3 \cdot 10^{-4}$  Torr at the discharge current equal 400 mA. For two types of discharge system a few stable operating modes were observed. This modes are different from each other by the discharge voltage and the parameters of the generated plasma. For these operating modes the spatial density distribution of the ion flux was measured.

**Keywords:** *Magnetron discharge, Target, Hollow cathode, Electron injection, Ion current.*

## ELECTROPHYSICAL PARAMETERS OF THE DIELECTRIC-BARRIER DISCHARGE TO OBTAIN THE ATMOSPHERIC PRESSURE COLD PLASMA JET IN A LAMINAR FLOW OF HELIUM

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The formation of an atmospheric pressure plasma jet (APPJ) in a gas flow passing through the discharge gap depends on both gas-dynamic properties and electrophysical parameters of the plasma jet generator. The paper presents the results of experimental and numerical study of the propagation of the APPJ in a laminar flow of helium. A dielectric-barrier discharge (DBD) generated inside a quartz tube equipped with a coaxial electrode system, which provided gas passing through it, was served as a plasma source. For the laminar regime of the gas flow, the discharge currents and voltages were measured. They are of tens of mA and units of kV, correspondingly. The discharge power and specific energy were calculated from the volt-coulomb characteristics. They are of 1–5 W and tenths of mJ/cm<sup>3</sup>, correspondingly. The transition of the laminar regime of gas flow into turbulent one was controlled by the photography of a formed plasma jet. The corresponding gas outlet velocity and Reynolds numbers were revealed experimentally and were used to simulate a gas dynamics with OpenFOAM software. The data of the numerical simulation suggest that the length of plasma jet at the unvarying electrophysical parameters of DBD strongly depends on the mole fraction of ambient air in a helium flow, which is established along the direction of gas flow.

**Keywords:** *Atmospheric pressure plasma jet, Dielectric-barrier discharge, Laminar regime, Helium plasma jet.*

## COMBINED IMPACT FEATURES FOR LASER PLASMA GENERATION

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Laser-induced plasma has been considered for multiple applications by the moment, and its characteristics strongly depend on laser radiation parameters. Reaching of demanded values for the latter might be rather costly, but, in certain cases, similar or even better could be reached in case of additional impact (optical, electric, magnetic, corpuscular, mechanical etc.). Combined impact effects are mainly based on target properties or interaction mechanism change, and found to decrease plasma generation thresholds by orders of magnitude, improve energy efficiency by several orders, and also broaden the range of plasma parameters control. Application area, efficiency and optimal regimes for laser plasma generation at such combined impact have been considered. Analysis based on published data and own experiments was performed for both target material and induced plasma flows. Criterial parameters have been suggested to characterize both combined impact and response to it.

Experimental results for several examples of combined impact effects are presented: target UV photopolymerization leading to solidification and optical properties change; ferrofluid's viscosity increase and droplets retrieval in a magnetic field; shock-compressed laser-electric discharge; deposition of seed electrons into dielectric targets.

**Keywords:** *Laser ablation, optical breakdown, combined impact, plasma flows.*



## VACUUM ARC WITH HOT ANODE AS A SOURCE OF METALLIC PLASMA FOR MASS-SEPARATION PROJECT

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Results on experimental studies of characteristics a nonself-sustained arc discharge with current about of 3 A and voltage in the range of 50–200 V are presented. The ion energy distributions of produced plasma flow are measured by a retard field analyzer. It is shown that both the directed ion energy and energy dispersion vary in wide ranges by change a bias of ionization electrode and the anode voltage, respectively. Namely, the directed energy increases from 50 eV to 100 eV with the electrode bias increasing from 60 to 110 V and energy dispersion increases from 20 eV up to 80 eV with the anode voltage increasing from 60 to 110 V. It is shown as well that the ionization degree attains of 20 % and plasma density is about of  $10^{12} \text{ cm}^{-3}$ . These results show that the sources is a promising one for application in technology of plasma mass separation .

**Keywords:** *plasma mass separation, nonself-sustained arc discharge, ion energy distributions.*

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**RESEARCH OF SPATIAL DISTRIBUTION OF DENSITY OF THE GAS-METAL PLASMA GENERATED BY COAXIAL AND EXTENDED PLASMA GENERATORS**

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In this work the spatial distribution of density of gas-metal plasma, which created by the coaxial generator of metal plasma and the extended generator of gas plasma, by means of measurement of density of an ionic saturation current from gas-metal plasma is investigated. Distribution shows that density of plasma is strongly uneven near an arc evaporator, but is considerably leveled already in the middle of a vacuum chamber. The obtained data allows deposition of the uniform coverings on the squares much exceeding the sizes of the cathode of an arc evaporator by installation of details in the corresponding zones of a vacuum chamber.

**Keywords:** *low-temperature plasma, gas discharge, vacuum arc, vacuum arc deposition, plasmagenerators, plasma parameters*

## EXPERIMENTAL RESEARCH OF DYNAMICS AND MACROSTRUCTURE OF LIGHT EROSION RADIATIVE PLASMODYNAMIC DISCHARGES

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High current light erosion optic-plasmadynamic discharges (OPDD) are discharges with plasma generation due to light erosion mechanism (generation, heating and acceleration of irradiating plasma jets) in which electromagnetic energy is converted in to kinetic energy of quasi stationary irradiating gas-plasma flow. Studies of OPDD are stimulated by the prospects of their use as a high power and manufacturable sources of UV and VUV spectra for lithographic processes as well as a shock waves (SW) and radiating plasma flows generators which can be used for modeling of thermophysics and optic-plasma dynamics processes in high density radiation plasma flows – matter interactions or, for example, for plasma chemistry applications such as implementation of special conditions for photochemical reactions.

The dynamics and investigations of optic-plasma gas dynamic discharge microstructure (spatial and temporal distributions of charged particles) are briefly presented. The plasma are heated as a result of the thermolization due to shock interaction of high kinetic energy plasma flows with gas medium, which work as stopping barrier for these kind of discharges.

The holographic setup providing light field mode of Thepler's schlieren scheme and two-exposition holographic interferometry in combination with laser plasma diagnostics is used for visualization and measurements. It was shown that the deceleration of radially inhomogeneous flow at deformable gas barrier has an essentially two-dimensional nature: complex system of conical shock waves forms in hypersonic plasma flow.

This work was performed at the facility «Beam-M» supported by state task of the RF Ministry of Education and Science and by RFBR (14-08-01087)

**Keywords:** *Light erosion optic-plasmadynamic discharges, dynamics and macrostructure, shock waves.*

## STUDY OF MULTISTAGED CORONA DISCHARGED ASSISTED SYSTEM FOR ELECTROHYDRODYNAMIC FLOW GENERATION

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The research system of forming electrohydrodynamic (EHD) flows using corona discharge in air depending on the number of stages and type of scheme connections.

Two type of stages electrical connection were investigated: 1) in series, in which grid electrodes (ion collectors) attached to one pole of the power source and plasma emitters to another; 2) alternating polarity connection, in which the collector of previous single stage was connected to the emitter of the next one. The results of measurements with increasing number of stages from 2 to 14 showed an increase in the maximum speed from 3 to 3.5 m/s (in series) and from 4 to 5.5 m/s (alternating), with increasing volume flow of 4 to 7.3 l/s (in series) and of 4 to 9 l/s (alternating).

The shape of the velocity profile is very different. In a system with alternating stages a distinct, parallel to plasma emitter maximum was observed and with the growth of the number of stages up to 5 it was increased, but the velocity profile was slightly sprawled. The velocity profile for series connected stages was wider and had cross shape with maxima in the center of the emitter wire.

**Keywords:** *electrohydrodynamic flow, corona discharge, multistage system, in series and alternating cascade scheme.*

**THE INFLUENCE OF APPLIED VOLTAGE PERIOD DURATION ON THE LENGTH OF SINGLE MICRO-DISCHARGES AND THE AREA OF A DISCHARGE ZONE IN A SURFACE DIELECTRIC BARRIER DISCHARGE**

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The results of high-speed photography of the surface dielectric barrier discharge in an axially symmetric electrode system for an alumina ceramic plate of 1 mm thick as a barrier for an AC voltage with the period of 50 and 200 microseconds are presented. The photo exposing of the discharge zone was carried out separately for a positive and negative half-wave of the signal at the gradually increasing of the voltage from an ignition value up to 3.5 kV (RMS). The exposure duration was determined from the shape of a micro-discharge current signal. It is shown that for a shorter period the area of the discharge zone is expanding more rapidly than for a longer period. However, the length of single micro-discharges channels was higher for a longer period (by 10–30 %). It is likely that the emission area of the discharge zone is completely determined by the voltage rise rate (kV/μs), while the length of the single microdischarges is related to the recharging of the barrier due to the development of low-current avalanches.

This work was supported by Russian Foundation for Basic Research (grant no. 16-08-00870).

**Keywords:** *surface dielectric barrier discharge, plasma diagnostics, high-speed imaging.*

## ENERGY AND MASS-CHARGE DISTRIBUTION PECULIARITIES OF IONS EMITTED FROM PENNING SOURCE

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The optimization of hydrogen Penning sources used, in particular, in plasma chemical processing of materials and DLC deposition, is still very important. Investigations of mass-charge composition of ion beams emitted by these sources are relevant for miniature linear accelerators (neutron flux generators) nowadays.

In this paper, the energy and mass-charge distributions of the beams that are emitted from the penning source are presented. The correlation between the discharge current abrupt jumps with increasing plasma density in the discharge center and increasing potential drop (up to 50 % of the anode voltage) is shown. Also the energy spectra in the different modes of the discharge as a function of pressure and voltage on the anode are presented. These spectra show complicate energy structure for different discharge modes. The atomic hydrogen ions concentration was about 5–10 %. It is demonstrated that amount of atomic ions increases with the anode voltage (in the range between 1 and 3.5 kV). Whereas, the pressure and the discharge current (in the investigated range of 1 to 10 mTorr and 50 to 1000  $\mu$ A) weakly influence atomic/molecular ions ratio.

These studies were supported by RFFI grant №12-02-13510-ОФН\_M\_PA and was done in NRNU MEPhI in collaboration with All-Russia Research Institute of Automatics (VNIIA).

**Keywords:** *ENERGY DISTRIBUTION, MASS-CHARGE DISTRIBUTION, Penning Source, Penning discharge.*

## MASS SPECTROSCOPY OF THE ION FLUX PRODUCED DURING INDUCTIVELY COUPLED PLASMA NITRIDING PROCESS

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The effectivity of technological plasma processing devices strongly depends on the plasma parameters such as plasma density, electron temperature, plasma potential, and ion composition. The latter is of substantial importance since many of the surface modification processes in plasma require certain amounts of species bombarding the substrate. Particularly, the fluxes of atomic nitrogen are essential for the plasma nitriding of titanium, aluminum alloys and steels. Moreover, for the plasma ion immersion implantation (PIII) technique, where the ion energies reach 100 keV, the  $N^+ / N_2^+$  ratio affects the specific energy of incident ions and hence their penetration depth. It is therefore vital to study the behaviour of ion fractions incident at the substrates during the plasma processing.

We studied the ion fluxes on material surfaces in the experimental inductively coupled plasma (ICP) reactor under the typical conditions for titanium alloy nitriding: total pressure  $3.3^{-3}$  mbar ( $Ar/N_2 = 70\% / 30\%$ ) and rf power 1500 W. The gas composition was independently monitored by the quadrupole analyzer. The ion fluxes were sampled using a specially designed electrostatic extractor and then analyzed with a magnetic sector mass-separator. The extractor design allowed us to apply a bias voltage to the plasma facing electrode thus imitating the substrate during the plasma processing.

The ion fluxes of  $Ar^+$ ,  $N_2^+$ , and  $N^+$  were measured. The mass spectroscopy diagnostics unit is suitable for extensive ion content studies in the plasma technology facilities.

**Keywords:** *ICP discharge, plasma mass spectrometry, ion content, plasma nitriding, magnetic sector mass analyser.*

## STUDY OF PARAMETERS OF A FACILITY GENERATING COMPRESSIVE PLASMA FLOWS

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Recently much attention has been given to issues of plasma treatment of materials. As against laser technologies the plasma treatment has a number of unanswerable advantages. Firstly, the plasma treatment of structural materials is much cheaper than laser technologies and traditional chemical methods. Moreover, plasma facilities have high capacity, t.i., high rate of modification of a unit area of the material surface in a unit of time. If a fine powder is introduced in plasma, a range of possible coatings is enlarged if compared with evaporation of the material with other methods for further deposition.

Intensive study of the effect of compressive plasma flows on materials are under way at [Uglov V.V., Anishchik V.M., Astashinskiy V.V. // *ZhETF*. – 2001. – Vol. 74, no.4. – pp. 234–236]. The prosperity of plasma technologies stimulates making of a facility generating compressive plasma flows at the South Ural State University. The facility is a compact-geometry magnetoplasma compressor [Uglov V.V., Anishchik V.M., Astashinskiy V.V. // *ZhETF*. – 2001. – Vol. 74, no.4. – pp. 234–236] with the following parameters: stored energy up to 15 kJ, voltage of a bank from 3 to 5 kV, working gas – nitrogen, air.

The investigation of parameters of the facility showed the following parameters of compressive plasma flows: impulse duration – 100 mks, discharge current, speed of plasma flow – 20 km/s. The designed facility differs from the available ones in the possibility to control parameters of compressive plasma flows in a wide range. A vertically oriented compressive plasma flow allows drastically simplifying a mechanism of replacement of samples without loss of sealing of the chamber.

**Keywords:** *compressive plasma flows, impulse duration, discharge current, speed of plasma flow.*



**THE INFLUENCE OF PARAMETERS OF LOW-PRESSURE  
NON-SELF-SUSTAINED GLOW DISCHARGE WITH HOLLOW CATHODE  
ON THE COMPOSITION OF PLASMA**

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The influence of parameters such non-self glow discharge with the hollow cathode as a burning voltage, discharge current, pressure on the composition of the plasma generated. With the use of an optical spectrometer measures the relative change in the intensity of the emission spectra in a wide range of operating parameters of the discharge. A comparison of the changes depending on the atomic concentration of nitrogen in the plasma from the plasma parameters such as the electron temperature and concentration.

**Keywords:** *low-pressure non-self-sustained glow discharge, hollow cathode, atomic concentration of nitrogen.*

**THE LIMITATION OF MAXIMUM CURRENT VALUE OF LOW-PRESSURE  
NON-SELF-SUSTAINED GLOW DISCHARGE WITH LARGE  
AREA HOLLOW CATHODE**

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In the paper the phenomenon of current limiting of pulsed non-self-sustained glow discharge with the large area hollow cathode was studied, which is displayed in the uncontrolled growth of current at a certain amount of a discharge power which leads to the shutdown of the power source in the moment of achievement of discharge current limit. The data about the dependence of value of the maximum current of non-self-sustained glow discharge on the size of the grid cells of an anode auxiliary arc discharge were obtained. The extraction of the electrons to the main glow discharge from auxiliary arc discharge was implemented.

**Keywords:** *non-self-sustained glow discharge, hollow cathode, arc discharge.*

## VACUUM ARC ION SOURCE WITH BEAM MAGNETIC SEPARATOR FOR POLYMER SURFACE PROPERTY MODIFICATION

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The results of research of vacuum arc ion source, generating a mono-element ion beams solid conductive substances with respect to the implantation of these ions in the surface layers of organic polymers, are presented. Ion extraction with a predetermined mass-to-charge ratio  $M/Q$  was carried out by passing the beams through a permanent magnetic field of the separator. Vacuum arc was kept in a frequency pulsed current with an amplitude of 150 A, a duration of about 350  $\mu\text{s}$  at a pulse base, and a frequency of 5 Hz. Silver was used as a cathode material. Ion extracting DC voltage was 20 kV.  $\text{Ag}_2^+$  ion spatial characteristics after passing through the magnetic separator were observed. When ion source was used as an implanter, dose gathering rate was provided at level  $1 \cdot 10^{13}$  ion/cm<sup>2</sup> · s. Polylactide and polylactide/hydroxyapatite composite surface resistivity versus exposure dose of the implanted ions  $\text{Ag}_2^+$  was investigated. Surface resistivity of the composite material experimental samples is shown to be mainly determined by the concentration of polylactide as sensitive to ion radiation exposure material.

**Keywords:** *ion implantation, magnetic separation, polylactide, hydroxyapatite, surface resistivity.*

## ROLE OF CRYSTALLOGRAPHIC ANISOTROPY IN THE FORMATION OF SURFACE LAYERS OF SINGLE NITI CRYSTALS SUBJECTED TO ION IMPLANTATION

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NiTi shape memory alloys are known to enjoy medical applications, but a problem is the creation of protective layers, which improve performance characteristics and prevent the release of toxic Ni. The purpose of this work is to identify the role of the crystallographic orientation in formation of the structure of the ion-modified layers of the NiTi through experiments on single crystals. The structure of the surface and near-surface layers of NiTi single crystals having ‘soft’ [111]B2 and ‘rigid’ [001]B2 orientations relative to the direction of ion beam was investigated with the aid of TEM. The Si ion treatment was performed using an implanter ‘DIANA-3’ with pulsed ion beams to a fluency of  $D = 6 \times 10^{17} \text{ cm}^{-2}$  at an voltage of 60 kV and a pulse repetition frequency of 50 Hz. The structure of the oxides and ion-modified amorphous layers is found to depend on the ion implantation geometry. It was found that the orientation effects of selective sputtering and the channeling control the thickness of the oxide and amorphous layers, the depth of penetration of ions and impurities, the distribution of Ni with depth. Different scenarios of deformation microstructure evolution are observed in the near-surface layers of NiTi crystals having of ‘soft’ orientation and ‘rigid’ orientation.

**Keywords:** *NiTi, Single crystals, Crystallographic anisotropy, Ion implantation, Surface layers structure.*

## ION-BEAM FORMATION AND MODIFICATION OF SEMICONDUCTOR AND METALLIC NANOCCLUSERS IN SILICON AND SILICA

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Single-crystalline n-doped (100) Si wafers with a thin layer of SiO<sub>2</sub> (40 nm) or structures with thermally grown SiO<sub>2</sub> with a thickness of 0.6 μm on silicon were implanted subsequently with As (170 keV,  $3.2 \times 10^{16}$  cm<sup>-2</sup>) and In (250 keV,  $2.8 \times 10^{16}$  cm<sup>-2</sup>) ions or Zn (150 keV,  $5 \times 10^{16}$ ,  $1 \times 10^{17}$  cm<sup>-2</sup>) ions at 550 °C or at 20 °C. A part of the samples was annealed at 900 °C in argon atmosphere for the precipitation of InAs nanoclusters: 45 min for SiO<sub>2</sub>(40 nm)/Si and 30 min for SiO<sub>2</sub>(600 nm)/Si as well as for the precipitation of Zn nanoclusters at 700°C for 1h. Then, the annealed part and a part of annealed samples were irradiated by high-energy Xe<sup>+</sup> ions (167 MeV,  $3 \times 10^{14}$  cm<sup>-2</sup>) at room temperature. «Hot» implantation conditions lead to a broadening of the concentration profiles of implanted atoms in comparison with the calculated distributions. The effects of the target sputtering and non-equilibrium diffusion caused a significant redistribution of impurity atoms to the surface. Subsequent high-temperature annealing initiates a more significant redistribution of embedded impurities for both systems. The TEM-microimages showed that the subsequent heat treatment causes an increase in the average size of the both types of nanoclusters. The Xe ion irradiation stimulates further increase in the nanoclusters sizes. In the systems SiO<sub>2</sub>(600 nm)/Si after irradiation with Xe ions, it is detected the ordering of nanoclusters along the direction of incident ion beam and changing their shape from spherical to elliptical. Raman scattering and photoluminescence spectra are measured and discussed, also.

**Keywords:** *InAs and Zn nanoclusters, ion implantation, swift ion irradiation*

## FEATURES OF PLASTIC DEFORMATION NUCLEATION IN THE ELASTICALLY LOADED ALUMINIUM CRYSTALLITES DURING IRRADIATION

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A molecular dynamics study of the features of plastic deformation nucleation in fcc aluminium with different crystallographic orientations of the irradiated surface was carried out. Interatomic potential for aluminium was described in the framework of the embedded atom method. Crystallite sizes ranged from 75 000 to 1 000 000 atoms. Both unloaded samples and samples with preliminary elastic uniaxial deformation of 4 % were simulated. The crystallographic orientations of the irradiated free surfaces were (001), (011) and (111).

Molecular dynamics simulations had shown that the crystallographic orientation of the irradiated surface affects the features of plastic deformation nucleation. In the samples with the (001) irradiated surface the symmetry of local environment of individual atoms was changed. However, the formation of structural defects did not occur. Preliminary elastic deformation had no significant effect. In the case of unstrained crystallite with the (111) irradiated surface intrinsic and extrinsic stacking faults were formed in (111) planes in the surface region. Preliminary deformation caused defects to be formed in the adjacent planes. Under the irradiation of the (011) surface atoms with changed symmetry of local environment were formed, some of which restore the symmetry of their environment, and the others form a stacking faults. The size of the defects increased with increasing preliminary elastic deformation. Stacking faults were formed in the adjacent planes, interacted with each other forming a vacancy chains. This slowed down the accumulation of defects.

The work is supported by the Programme of Presidium of Russian academy of sciences № 13 «Thermophysics of high energy densities».

**Keywords:** *irradiation, plastic deformation, stacking faults, molecular dynamics.*

## OPTIMIZATION OF BEAM OUTPUT CHANNEL OF LINAC HIPR FOR IMITATION EXPERIMENT

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In Institute for Theoretical and Experimental Physics (ITEP) the research of the material radiation resistance by accelerated ion beams is under progress. The investigated samples are irradiated by accelerated ions of the same chemical element as the material of samples in RFQ linac Heavy Ion Prototype (HIPr). The paper describes the tuning of the beam output channel of the linac for the intensity irradiation increase. By simulating the parameters for quadrupole lenses in the output channel of the linac were obtained for providing irradiation a sample by  $\text{Fe}_2^+$  (5.6 MeV) and  $\text{Ti}_2^+$  (4.8 MeV) ion beams up to a dose of  $10^{16}$  ions/cm<sup>2</sup> per one work session. The paper presents the results of the simulation and its comparison with the experiment results.

**Keywords:** *imitation experiment, ion beam, profilometer, simulation of ion beam dynamic.*

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**CALCULATION OF IRRADIATION DOSE BY ION BEAM IN THE OUTPUT CANNEL  
OF LINAC HIPR FOR IMITATION EXPERIMENT**

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In Institute for Theoretical and Experimental Physics (ITEP) the research of the material radiation resistance by accelerated ion beams is under progress. The investigated samples are irradiated of the same chemical element as the material samples (Fe, V, Ti) by accelerated ion beams in RFQ linac Heavy Ion Prototype (HIPr). A system of beam profile measurements and a measurement data processing algorithm were developed for on-line control of the irradiation dose. The paper describes in detail the design of measurement system and experimental data processing algorithm

***Keywords:*** *imitation experiment, ion beam profile measurements, calculation of irradiation dose.*



## MULTISCALE MODELS OF METAL BEHAVIOR AND STRUCTURAL CHANGE UNDER THE ACTION OF HIGH-CURRENT ELECTRON IRRADIATION

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We present our models of tensile fracture of metals in solid and molten state, melting and plastic deformation of solid metals, as well as implementation of these models to describe the high current electron beam action on metals. The models are constructed by the following way: the atomistic simulations are used at the first stage for investigation of dynamics and kinetics of structural defects in material (voids, dislocations, melting sites); equations describing evolution of such defects are constructed, verified, and their parameters are identified by means of comparison with the atomistic simulation result; finally, the defects evolution equations are incorporated into the continuum model of the substance behavior on the macroscopic scale. The obtained continuum models with accounting of defects subsystems are tested by comparison with the experimental results known from literature. The proposed models not only allow to describe the metal behavior in the conditions of intensive electron irradiation, but they also allow to determine the structural changes in the irradiated material.

We discuss: (i) the model of tensile fracture of solid metals, (ii) the model of tensile fracture of metal melts (cavitation or nonequilibrium phase transition from liquid to vapor), (iii) the dislocation plasticity model, and (iv) the homogeneous melting model, including underlying atomistic simulation results, evolution equations for defects and verification by comparison with experimental data. Also we present results of application of these models for numerical investigation of the problem of substance dynamics under the action of the high-current electron beam.

**Keywords:** *Plasticity, Tensile fracture, Melting, Molecular dynamics, Continuum model, Metal, High-current electron irradiation.*

## DYNAMICS OF MOLTEN METAL IN THE ENERGY ADSORPTION AREA OF THE HIGH-CURRENT ELECTRON BEAM: MULTISCALE MODELING

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High-current electron irradiation leads to fast heating, melting and expansion of the metal inside the energy adsorption area. An initial expansion of the irradiated metal layer is due to the pressure gradients within this layer, while subsequent expansion is due to inertia that leads to a tensile state with negative value of pressure; this state is metastable. Decay of this metastable state is the tensile fracture of melt, which is realized by means of cavitation. A continuum model of the metal melt dynamics at tension is formulated on the basis of the continuum mechanics and theory of metastable liquid. The continuum model is verified, and parameters of the model are fitted with the use of the results of the molecular dynamics simulations for ultra-high strain rates ( $> 1/\text{ns}$ ). Dynamic tensile strength of initially uniform melts of several metals within a wide range of strain rates (from 1–10/ms to 100/ns) and temperatures (from melting temperature up to 70–80 % of critical temperature) is calculated. With the help of molecular dynamic simulation, we investigate late stages of aluminum melt tension up to the deformation degree of about 10 including a stage of bubble liquid, a foamed melt, and a fragmentation with formation of droplets. Description of these late stages was incorporated into the continuum model. The model is applied to numerical investigation of a problem of the high-current electron irradiation of metal targets.

**Keywords:** *Metal melt, Tensile fracture, Foamed metal, Continuum model, Molecular dynamics, High-current electron irradiation, Energy absorption area.*

**RADIATION, HEAT AND SHOCK-WAVE PROCESSES IN THE SYSTEM  
«HIGH POWER ON BEAM – METAL»**

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Active research in physics of shock waves resulted in the development of a wide range of ways of excitement and registration of shock load pulses in condensed media. High energy concentration, which is achieved by the corpuscular and laser beams exposure of sub-microsecond duration at the condensed beam stop, determines their increasingly wide use both for scientific investigations and when solving different practical tasks. Modern systems of pulse beam generation of charged particles allow receiving concentrated energy fluxes in a wide range of intensities  $W=10^5-10^{14}$  W/cm<sup>2</sup>, at pulse duration  $10^{-9}-10^{-5}$  sec. In the present range of parameters high power ion beams (HPIB) are a versatile tool for solution of a variety of technological and scientific problems, including the problems of radiation material and inertial thermonuclear process. In the power density range of  $10^7-10^{10}$  W/cm<sup>2</sup> interaction of HPIB with metals is accompanied by simultaneous thermal, mechanical and radiation effects. The generalized physics-mathematical model of the elastoplastic medium, describing the behavior of the metallic beam stop under the external high-power energy exposure, was formulated in the course of the research conducted.

The paper presents the results of the simulation of radiation, heat and shock-wave processes occurring in the system «HPIB-metal». The influence of each of them on the formation of modified layers in the irradiated volume of the metal target is investigated.

**Keywords:** *high power ion beam, impulse of mechanical load, shock-wave.*

## MODELING OF THE PORCESS OF LOCAL ION NITRIDING IN A GLOW DISCHARGE WITH HOLLOW CATHODE

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It is known that the usage of a discharge with hollow cathode is a promising approach for local hardening treatment.

Discharge with hollow cathode has a complicated dependence on various energy, technological and geometrical parameters, systemic experimental diagnosis is difficult. The computer simulation hence becomes an important method to reveal the physics of treatment process.

Nitriding process with application of discharge with hollow becomes more complicated. In case of local ion nitriding with hollow cathode the heating rate of the surface covered by technological mesh screen is greater than heating rate of entire surface of the part. Therefore, there is irregularly temperature distribution during the nitriding process.

It is known that the temperature is the critical factor affecting the nitrogen diffusion into steel and diffusion zone formation of the nitrided case. Nowadays, modeling heating and diffusion processes during nitriding is an important task. Investigating and understanding processes occurring in the near-surface material of the part would give the possibility of using optimal process parameters and increasing nitriding efficiency.

In that work we present our results of modelling of glow discharge plasma with hollow cathode and thermal and diffusion processes during ion nitriding with hollow cathode.

**Keywords:** *hollow cathode, glow discharge, local ion nitriding i.*

**INVESTIGATION OF INFLUENCE ULTRAFINE-GRAINED STRUCTURE  
OF MARTENSITIC STEELS ON DIFFUSION PROCESS  
AT LOW TEMPERATURE ION NITRIDING**

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The performance of structural steel surface can be improved by different surface modification techniques – coating and ion – vacuum treatment in a glow discharge.

During the ion nitriding steel forming the hardened layer is carried out by diffusion of nitrogen atoms in the bulk of the material. It is known that the diffusion mobility of the saturating element great stimulus have such structural defects as vacancies , dislocations and their clusters.

Ultrafine-grained (UFG) materials obtained by severe plastic deformation (SPD) have high hardness , and their structure is characterized by ultrafine grain size of 200–300 nm and the presence of non-equilibrium grain boundaries with high concentration of vacancy and dislocations. Thus, a combination of SPD and ion nitriding should give much better result compared to traditional methods of hardening the surface of structural materials.

The results on the influence of high pressure torsion (HPT) on the microhardness, microstructure and diffusion processes at low-temperature ion nitriding of martensitic steel 13H11N2V2MF was investigated.

**Keywords:** *low temperature ion nitriding, diffusion process, ultrafine-grained structure.*

## THE INFLUENCE OF PLASMA PARAMETERS ON THE ELECTRON TEMPERATURE AND DENSITY

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In this study it was investigated RF-magnetron plasma parameters such as the electron temperature and density at different RF – power and working pressure by using optical emission spectroscopy (OES) and double Langmuir probe. The hydroxyapatite was used as a target for sputtering in pure Ar atmosphere. The RF – power was varied from 100 to 400 W. The study was done at a pressure 0.1 Pa and 0.4 Pa. With the increase of RF – power of the discharge the electron temperature was increased. The degree ionization and electron density were also increased. Moreover, some heterogeneities of the electron temperature and density in different parts of the target were observed.

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**Keywords:** *Plasma treatment, RF-magnetron plasma, optical emission spectroscopy.*

**SURFACE CRATERING IN TINI SHAPE MEMORY ALLOYS IRRADIATED WITH  
A LOW-ENERGY, HIGH-CURRENT ELECTRON BEAM  
PART 1 OF 2: EFFECT OF INCLUSIONS**

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This work is the first part of a two part paper aimed at studying the surface cratering under pulsed melting of TiNi shape memory alloys with microsecond low-energy (10–30 keV), high-current (10–25 kA) electron beam. Main types of inclusions in commercial (VIM) and precision TiNi alloys as potential centers of crater formation were identified by the TEM/SAED/EDS analysis. The topographical features of microcraters formed by a single-pulse irradiation of TiNi samples near the surface melting threshold of the B2 matrix phase were identified, and 3 types of microcraters were distinguished by optical microscopy, SEM and laser profilometry. It was found by SEM/EDS analysis, that microcraters are mainly nucleated on titanium oxycarbide TiC(O) (commercial alloy) and oxide Ti<sub>4</sub>Ni<sub>2</sub>O<sub>x</sub> (precision alloy) inclusions; in both cases, the central region of microcraters is enriched with oxygen. The physical processes induced by pulsed e-beam heating (melting) at the [TiC(O)]/matrix (TiNi) interface are discussed and mechanism of cratering is proposed in part 2 of this study.

**Keywords:** *shape memory alloys, electron beam, cratering.*

## INCREASING OF SURFACE FREE ENERGY OF COPPER BY RUNAWAY ELECTRON PREIONIZED DIFFUSE DISCHARGE PLASMA TREATMENT

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Experiments of a runaway electron preionized diffuse discharge plasma treatment in pulse periodic mode on the surface of the copper are presented in the work. According to Auger spectroscopy data, full clean-up of the surface from carbon contaminants take place after modification of the copper specimens by more than 400 000 pulses. Along with that, the surface free energy of the copper specimens was calculated by means Owens-Wendt method. Increasing of surface energy is arise both due to cleaning by diffuse discharge plasma and the forming of high polarity chemical groups as a result of plasma-chemical reactions. Surface free energy of copper specimens modified by diffuse discharge plasma increases in 2 and more times and decreases to the initial value of untreated specimen within 24 hours.

**Keywords:** *runaway electron preionized diffuse discharge, surface cleaning, surface free energy,*



## MODELING OF THE ELECTRON-BEAM BORIDING IN THE SYSTEM FE-B-C-O<sub>2</sub>

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This paper discusses the conditions of iron borides formation and modeling of layers formation process depending on the stoichiometry of the initial components. Also, temperature fields were researched depending on the pressure in the chamber and power of the electron beam in which are formed the different phases. Thermodynamic study of phase equilibriums in systems Fe-B-C-O was performed. It was done to optimize the conditions for the formation of functional layers on the surface of iron-carbon alloys as a result of electron-beam boriding in a vacuum. Strength characteristics of the layers of iron borides were determined. A comparative analysis of the layers obtained by different methods and using different starting components was performed.

Simulation of the thermal properties and the nature of dissociation of borides FeB and Fe<sub>2</sub>B depending on the total pressure in the system were performed. The influence of temperature and pressure on their behavior was defined. Thus, at a pressure of 10<sup>5</sup> Pa the interaction of Fe<sub>2</sub>O<sub>3</sub> with different boriding components starts at temperatures of 1300–1600 K and at a pressure of 10<sup>-2</sup>–10<sup>-3</sup> Pa the temperature is reduced to 850–900 K. It is found that in mixtures with B<sub>4</sub>C and B should originally occur the phase change in the condensed state to form a liquid phase B<sub>2</sub>O<sub>3</sub>. The layers have a clear boundary between the base and the layer. The thickness of the layers is 200–350 microns, and microhardness reaches 3500 MPa.

**Keywords:** *Modeling of the electron-beam boriding, Thermodynamic study, Strength characteristics, Conditions for the formation of functional layers.*

**SURFACE CRATERING IN TINI SHAPE MEMORY ALLOYS IRRADIATED WITH  
A LOW-ENERGY, HIGH-CURRENT ELECTRON BEAM  
PART 2 OF 2: MECHANISM OF CRATERING**

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This paper discusses the results of experimental study of the surface cratering in TiNi alloys, irradiated with microsecond low-energy, high-current electron beam, described in part 1 of this study. The processes initiated by a pulsed heating (melting) at the inclusion [TiC(O)]/matrix (TiNi) interface are considered on the basis of the Ti-Ni-C and Ti-Ni-O phase diagrams. The role of thermocapillary and chemicapillary forces in the radial melt mass transfer (Marangoni effect), which determine the formation of microcraters, was analyzed. It was shown, that dominant role in this process plays chemicapillary forces, induced by decreasing the surface tension of the melt enriched by oxygen.

**Keywords:** *TiNi SMAs, Nonmetallic inclusions, Pulsed electron beam, Surface cratering, Capillary forces.*

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**THE MATHEMATICAL MODEL OF THE INITIAL STAGE OF SURFACE  
TREATMENT WITH PARTICLE FLUX***ELENA PARFENOVA AND ANNA KNYAZEVA**National Research Tomsk Polytechnic University, Russia  
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The paper presents a mathematical model of the initial stage of ion implantation into the metal surface. The model takes into account the finiteness of relaxation times of heat and mass flows. It was established that the interrelation between mechanical and diffusion waves leads to the distortion of deformation (and stress) wave profile, and the concentration distribution does not correspond to pure diffusion process.

**Keywords:** *mathematical model, ion implantation, diffusion, mechanical stress.*

## ATOMISTIC SIMULATION OF STRUCTURAL DAMAGE DURING ION IRRADIATION OF IRON SINGLE CRYSTALS

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The evolution of atomic displacement cascades initiated near free surfaces with different crystallographic orientations in bcc iron specimens was studied on the base of molecular dynamics approach. In case of the (111) surface irradiation the craters surrounded by adatom mounds were formed. After the (110) surface irradiation the dislocation loops consisted of vacancies were generated. The dislocation Burgers vector was  $a/2 \langle 111 \rangle$  or  $a \langle 100 \rangle$ . It was shown that the type of structural damage is determined by the anisotropy of propagation of shock waves generated by atomic displacement cascades. For energies of the atomic displacement cascade lower than 20 keV the number of adatoms and survived point defects was higher for specimen with the (110) free surface due to different character of surface damage. Increasing of the cascade energy up to 20 keV results in formation of almost the equal number of survived point defects for the (110) and (111) free surfaces as displacement cascades were developed on larger distance from the surfaces.

The work was carried out at the support of the Programme of fundamental research of state academies of sciences for 2013-2020.

**Keywords:** *atomic displacement cascades, dislocation loops, free surface, molecular dynamics.*

## NUMERICAL STUDY OF THE PROCESS OF HEATING AND EVAPORATION OF QUARTZ PARTICLES IN THE INDUCTIVELY COUPLED RF PLASMATRON (ICP)

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Numerical simulation of heating and evaporation processes of quartz particles, which were supplied by the carrier gas to the ICP within a gas-cooled, was studied. The model of sparse heterogeneous medium was used. The fundamental equations included Maxwell's equations, plasma dynamics equations, as well as equations of heat and evaporation of particles. Numerical simulation with a two-dimensional approach was carried out using the application package ANSYS CFX. Calculations were performed for ICP torch with a current amplitude range in 25–170 A (frequency  $f = 3$  MHz) and various values of specific number of coils. Argon works as plasma gas. Diameter of quartz particles varied in range 50–200  $\mu\text{m}$ .

The parameters and structure of the plasma flow in ICP with axial gas flow were obtained. The distribution of velocity, namely, the toroidal vortex flow before high temperature area were showed. The conditions of formulating a vortex and its parameters in ICP were determined.

The effects of discharge current and carrier gas flow rate on the evaporation efficiency of quartz particles were studied. The influence of plasma flow state on evaporation dynamics of quartz particles was learned. The optimal values of discharge current amplitude and specific number of coils were found for the ICP with power of approximately 10 kW, in which quartz particles with sizes up to 150 microns can be fully evaporated. The results were considered as the basis for the choice of operating and design parameters of the ICP in the process of plasma processing quartz concentrate for the polycrystalline silicon.

**Keywords:** *ICP, vortex, efficiency of evaporation, carrier gas flow rate, discharge current, diameter of particles.*

## CHARACTERIZATION OF PULSE HEAT IMPACT ON TUNGSTEN TARGET BY SUB-MILLISECOND ELECTRON BEAM

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In recent years, tungsten is considered as the main candidate for the material of the divertor wall in the ITER project.

Plates of the divertor can be exposed to the burst of plasma with a typical duration of 0.1–1 ms and heat load from 1 to 10 MJ m<sup>-2</sup>. This shall lead to evaporation of tungsten, droplets formation and thus, contamination by the tungsten dust.

In this connection in Budker Institute of Nuclear Physics a facility for study of tungsten erosion over melting threshold was developed.

An electron beam with 100 keV energy is transported in a longitudinal magnetic field to the W target to produce heat flux over 1 MJ m<sup>-2</sup> with pulse duration of up to 300 ms and typical diameter of exposed target area up to 15 mm. Diagnostics of pulse heat impact on tungsten target are reviewed. First experimental results are discussed.

**Keywords:** *electron beam, heat impact, melting of tungsten, tungsten dust, ITER divertor*

## THE ENERGY FLUX ONTO SUBSTRATE DURING COATING DEPOSITION USING MAGNETRON WITH LIQUID METAL TARGET

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Experimental and theoretical studies showed that the use of liquid-phase targets in the magnetron sputtering systems (MSS) can significantly increase the rate of coating deposition. This effect is created due to evaporation on the very heated target surface in addition to sputtering. The hot target and vaporized particles in the deposited flow can significantly affect the structure and properties of produced coatings and heating of substrate.

To find out the features of heating the substrate and the amount of energy supplied to it depending on the parameters of the MSS with the liquid target the experiments were carried out. The growth rate of the copper coating and substrate temperature were measured. The heating rate reached almost 2 K/s, which is much higher than at conventional magnetron sputtering.

The mathematical model was developed to determine structure of the energy flux coming to the substrate and the dependence of its components on the MSS parameters. It describes erosion processes in the target, transfer of atoms from target to the substrate and substrate heating. Calculations and comparison with the experimental results show that for power density of the MSS with liquid target from 10 to 100 W/cm<sup>2</sup>, the energy flux is composed of the following components: heat radiation (from 70 to 98 %), energy released due to condensation and kinetic energy of deposited atoms (less 2 %). The dependence of energy coming to the substrate per a deposited particle on magnetron power very differs from the case of deposition with cold target.

**Keywords:** *magnetron sputtering, evaporation, energy flux onto substrate, liquid-phase target.*

## PLASMA IMMERSION ION PROCESSING OF PRODUCTS WITH DIFFICULT-BRANCHED SHAPE OF THE SURFACE

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One of the ways to increase the biocompatibility of medical implants is to modify their surfaces by plasma-immersion ion processing. However, a significant number of implants are difficult-branched shape of the surface, which can lead to inhomogeneous surface treatment. In particular intravascular stents, which are used for restoring blood vessel lumen when it the narrowing.

In connection with the above, the paper presents a theoretical analysis of the possibility plasma-immersion ion processing of the surface of the intravascular stent of nickel-titanium with achievement in all their surfaces of the same rate of the formation of doped layers. The analysis took into account the design of stents (geometric size and shape of the stents and their structural elements). The values of technological parameters of process of plasma-immersion ion treatment allowing the doping of the inner surface of the stent, have been defined.

Experimental verification of the results of the analysis were performed on the «SPRUT» device in Tomsk state University on the example of plasma-immersion processing by ions of silicon self-expanding nitinol stents to the peripheral blood vessels. The results of the study of the chemical composition of the surface layers of stents have confirmed the possibility of doping silicon of the inner surfaces of stents.

The work was supported by Federal Target Program under agreement No. 14.578.21.0118, a unique identifier of the project RFMEFI 57815X0118.

**Keywords:** *medical implants, plasma-immersion ion treatment, surface modification.*



## COMPUTER ANALYSIS OF THE FIELD ION MICROSCOPY IMAGES OF PLATINUM IRRADIATED WITH AR<sup>+</sup> IONS (E = 30 KEV)

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This paper presents the results of the application of a specially developed algorithm and a computer program for the analysis of ionic field microscopy images to study the effect of Ar<sup>+</sup> ions (E = 30 keV) on the structure of the surface atomic layers of pure platinum.

The coordinates of atoms, the brightness of their images, and their sizes were determined. The curves of the distribution of the brightness and atomic radii were built. It is shown that the width of the distributions significantly increases as the distance to the exposed surface decreases. The number of atoms in the field ion microscopy images increases with distance from the irradiated surface.

Field ion microscopy images with only those atoms whose brightness (or radius) is in certain range were taken. These atoms can be highlighted in the ionic field microscopy images. The zones where irradiation-induced changes in the field microscopy images are mostly pronounced were determined. They are zones of the passage of the dense cascades of atomic displacements. Damaged zones include images of atoms with both abnormally low and abnormally high radii.

The work presents the layer-by-layer images of the surface layers of the irradiated platinum (from 1st to 5<sup>th</sup> and more distant). The possibility of reconstruction of the 3D-picture of the irradiated metal at a temperature of liquid nitrogen (T ~ 77 K) is shown.

**Keywords:** *field ion microscopy, irradiation by argon ions, radiation defects, algorithm and a computer program.*

## EFFECTS OF LOW-ENERGY HEAVY ION IRRADIATION ON THE SURFACE SPATTERING AND STRUCTURE OF TiNbN COATINGS

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The main effects of irradiation with heavy ions of metallic materials are the degradation of physical and mechanical properties of the surface and competing process – the surface sputtering (for alloys – ion etching due to the difference in the sputtering yield of alloy components).

This paper presents the research results of the degradation of the physical and mechanical properties and the surface sputtering of the ternary coating TiNbN irradiated by heavy ions  $^{84}\text{Kr}_{14}^+$  и  $^{134}\text{Xe}_{18}^+$  to fluences in the range of  $10^{16}$ – $10^{17}$   $\text{cm}^{-2}$ .

Specimens for investigations were prepared by following manner: TiNbN compound were deposited on a steel substrate by magnetron sputtering from two magnetrons in nitrogen atmosphere. Thickness of TiNbN layers were from 600 nm (for measuring of sputtering yield) to 2000 nm.

Irradiation of specimens with TiNbN coatings were carried out on the low-energy channel of accelerator DC-60 by ions  $^{84}\text{Kr}_{14}^+$  and  $^{132}\text{Xe}_{18}^+$  with energy 20 keV/charge to fluences of  $10^{16}$ ,  $5 \cdot 10^{16}$  and  $10^{17}$   $\text{cm}^{-2}$ . Irradiation temperature was not exceed 150 °C.

Thickness of sputtered layers was determined by the RBS measurements of the thickness of TiNbN layers before and after ion irradiation. From measured thickness of TiNbN sputtered layers were done the estimations of Ks values and their dependence on the fluence.

Surface structure was studied by scanning electron microscopy, atomic force microscopy and nanohardness measurements.

**Keywords:** *ion irradiation, coating, sputtering yield.*

## NUMERICAL STUDY OF MASS TRANSFER OF A MATERIAL UNDER INTENSIVE FLOWS OF HIGH-SPEED ELECTRONS AND PLASMA

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Nowadays the treatment of materials with intensive energy flows used to modify properties of a material is one of the promising methods in modification of structural materials. The treatment can increase strength of a material, change the surface micro relief, advance adhesion of materials of a coating and a support and is used to alloy the surface.

By the moment a large body of empiric data has been accumulated [1]. Theoretical studies [2, 3] permitted explaining a number of facts observed in experiments. However, within the limits of current notions a noticeable difference between results of numerical computations and experimental data, such as an amount of mass ablated from a treated surface and a depth of melting, is observed.

The paper provides numerical and experimental studies on mass loss from the surface of a sample, when treated by Compressive Plasma Flow in the first case and High-Current Electron Beam in the second case. The mass ablated from the material surface was computed with the BETAIN [4] software. The effects of a shocked layer on mass transfer of the material and processes of formation of a depth of the molten pool and erosion of mass from the material surface were investigated.

**Keywords:** *mass transfer, modify properties of a material, Numerical study.*

## DAMAGE IN SODA-LIME GLASS INDUCED BY HIGH-POWER ION BEAM NANOSECOND DURATION

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It is known that the effect of high power ion beam (HPIB) on various materials can lead to the appearance of cracks. In this case the damage is caused by dynamic and quasistatic stresses generated in the near surface layer. The prospects of using HPIB for the modification and creation of new materials require detailed study of the damages, produced by the action of this beam. The experiments were performed on industrial soda-lime glass. Irradiation was performed on a Temp accelerator by a proton-carbon beam with the energy  $\sim 200$  keV, duration 60 ns, in the current density range 20–15 A/cm<sup>2</sup>. The estimated ion ranges for the applied beam in the studied glass are  $\sim 0.6$   $\mu\text{m}$  for carbon ions and  $\sim 3.5$   $\mu\text{m}$  for protons. It was established that, during HPIB action with the current density  $\sim 60$  A/cm<sup>2</sup>, surface damages in the form of cracks parallel to the sample surface are observed on glass. It was found that the cracks are formed at a distance of  $10^{-5}$  m a glass surface. Part of the surface fragments can be removed revealing a well developed fracture surface. The morphological features of these surfaces was examined using scanning electron microscopy. The effect of heating of samples on the fracture process has been investigated. A possible mechanism of the observed phenomenon is discussed.

**Keywords:** *ion, beam, glass, damage.*

## EFFECT OF BASE PRESSURE ON A PURITY OF MAGNETRON SPUTTERED METALLIC FILMS

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This presentation discusses a contamination of thin films sputtered from pure Ag target using RF magnetron by gas atoms contained in the residual gas atmosphere in the deposition chamber at different values of the basic pressure. As a working gas were used Ne and Ar. The silver Ag as a target of the magnetron was used as an example for our investigation. The amount of O atoms generated at different values of base pressure is compared with the amount of Ag atoms sputtered at different deposition rates  $aD$  of Ag film. This comparison reveals a great problem in the formation of pure metallic films at low deposition rates and high values of the base pressure  $p_0$ . It is shown that the Me films sputtered at low rates  $aD \leq 30$  nm/min in the deposition chamber evacuated to the base pressure  $p_0 \approx 3 \times 10^{-3}$  Pa are strongly contaminated by reactive gases from the residual gas atmosphere. No pure Ag films can be deposited at low deposition rates  $aD$  in deposition chambers evacuated with diffusion or root pumps to the base pressures lower than 1 mPa only.

**Keywords:** *magnetron sputtering, contamination of films, mass spectrometry.*

## REFRACTORY PHASES SYNTHESIS AT THE SURFACE ELECTRON-BEAM ALLOYING

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The experimental results indicate the possibility of obtaining layers, modified by alloying with the help of electron-beam technology, on the surface of a wide range of materials. Such layers were obtained, thanks to the initiation of exothermic chemical reactions between a base and a deposited thin film. Thus the formation of new phase components was detected in the reaction products.

This process based on the task of creating reliable integration of the synthesized compounds to the surface layer of a product by the excitation of a chemical reaction between the metals of IV–V group and nonmetals of the 2nd period on its surface. In this case, the product must contain such nonmetals in its structure or be able to saturate them with the formation of solid solution or of any volatile compounds. The metal is applied as a coating on the surface of the product, for example, using a magnetron sputtering. Then the SHS reaction is initiated in a mode of thermal explosion by pulsed heating surface of the processed object. In some cases it is possible interaction between the metals in the base and in the coating with the formation of intermetallic phases.

**Keywords:** *surface modifying, electron beam, SHS synthesis.*

## RECEIVING ASH MICROSPHERES BY USING LOW-TEMPERATURE PLASMA ENERGY

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These investigations allowed producing spherical particles having the size range of 65–110  $\mu\text{m}$  based on fly ash generated from the coals combustion collected at Seversk TTP, Tomsk region, Russia. The spherical particles were obtained as a result of fly ash treatment with low temperature plasma energy. The exterior surface of the obtained spherical particles is smooth and without defects. The test bench was designed to carry out the experiments on spheroidization of fly ash-based particles. Thus, the conditions favorable for the particle transition to a viscous flow state were achieved within the temperature range observed at 20 mm distance from the jet center. The fly ash particles underwent the XRP analysis both grinded (original state) and plasma-treated. Using the Rietveld method, it was determined that fly ash contains 56.23 wt.%  $\text{SiO}_2$ , 20.61 wt.%  $\text{Al}_2\text{O}_3$  and 17.55 wt.%  $\text{Fe}_2\text{O}_3$  phases that make the dominating contribution to the integral (experimental) intensity of the diffraction maximums. The LTP treatment resulted in a complex redistribution of the amorphous phase amount in the obtained spherical particles, i.e. the considerable decrease of  $\text{O}_2\text{Si}$  phase; increase of  $\text{O}_{22}\text{Al}_{20}$  and  $\text{Fe}_2\text{O}_3$  phases and change in Al, O density of  $\text{O}_{22}\text{Al}_{20}$  chemical unit cell.

**Keywords:** *Fly ash, cenosphere, agglomerate, spheroidization of silicate particles, low temperature plasma.*

## ION-PLASMA NITRIDING OF AUSTENITIC STEEL IN LOW-PRESSURE LOW-FREQUENCY INDUCTIVE DISCHARGE WITH FERRITE CORES

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New plasma nitriding technologies based on the «external» low-pressure, high-density plasma sources allow enhancing the speed of nitriding layer formation, increasing its thickness and give more flexibility to control over processing parameters. Inductively coupled plasma sources (ICP) having high lifetime and high ion density at low pressures seem to be a good choice for ion-plasma treatment but have a few disadvantages: high current frequency ( $\sim 1\text{--}10$  MHz), low power factor of ICP coil thus high power losses in it. Using closed ferrite cores to improve magnetic coupling between inductor and plasma fixes the disadvantages of ICP and gives new possibilities for plasma processing.

An experimental investigation of ion-plasma nitriding of austenitic stainless steel 12X18H10T (an analog of AISI 321) in the plasma of low-pressure (7 Pa) low-frequency (100 kHz) nitrogen inductive discharge has been performed for the nitrogen ion density of  $\sim 10^{11}$  cm<sup>-3</sup>, sample temperatures of 440–630 °C, the densities of current on the sample surface of 1.2–3.3 mA/cm<sup>2</sup>, sample biases of –500 and –750 V. The time of ion-plasma treatment was 20 and 60 min. The temperature dependence of nitrated layer thickness and microhardness was obtained. The microstructure analysis of nitride samples was carried out by X-ray diffraction. It is shown that even for the short (20 min.) ion-plasma treatment in the low-frequency inductive discharge, formation of nitrated layers with the thickness up to 40 micrometers and microhardness up to 9 GPa is observed, comparable with those for 1 hour nitriding in a hot-cathode gas arc.

**Keywords:** *ion nitriding, inductively coupled plasma, transformer coupled plasma, ICP, austenitic steel.*



## EFFECT OF STRUCTURAL STEEL ION PLASMA NITRIDING ON MATERIAL DURABILITY IN PULSED HIGH MAGNETIC FIELDS

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As is known, coil tools (inductors) for magnetic pulsed welding of metals have poor durability. Coil failure usually occurs at working surface where material is subjected to intense thermo-mechanical stresses due to current concentration. Thus, modifying the inductor current-carrying layer, changing its conductivity and strength, may be the useful way to improve the inductor performance. Nowadays structural steels are considered to be alternative inductor materials instead of high strength copper-based alloys (Cu-Be, Cu-Cr, Cu-Cr-Zr) due to their low cost, high strength, easy machining, and applicability to modification by, e.g., plasma nitriding.

The work was aimed to study the influence of plasma nitriding on electrical and mechanical properties of structural steels and their durability in pulsed high magnetic field.

The plates and cylindrical inserts (field shapers) were made of several steel grades, including 30XГСА, 50XГА, 40X, 38X2MIOA, heat-treated and subjected to the low-temperature (400–500 °C) plasma nitriding. Electrical and mechanical properties of materials, phase composition at steel layer surface, microstructure and microhardness profiles were investigated on flat samples before and after plasma treatment. Microstructure and microhardness profiles across a working surface of plasma treated and untreated cylindrical inserts being applied for high magnetic field generation were also studied. Magnetic field of 50 T under tens of microseconds in duration inside the inserts was generated by long-life outer coil.

The study was performed within the state assignment No. 0389-2014-0002, partially financed by RFBR (No. 16-08-00919-a) and Fundamental research program of UB of RAS (No. 15-17-2-27, No. 15-17-2-28).

**Keywords:** *plasma nitriding, plasma modification of steel, steel inductor, pulsed high magnetic field application.*

## METALLIZATION OF THE SURFACE OF B<sub>4</sub>C CERAMICS BY COMBINED ELECTRON-ION-PLASMA METHOD

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The «film (Ti) / (B<sub>4</sub>C ceramics) substrate» system and «film (Cu) / (B<sub>4</sub>C ceramics) substrate» was investigated after irradiation by an intense pulse electron beam.

On the polished surface of the samples a titanium or copper film with thickness of 0.5 μm was sputtered. Formation of the film was carried out on the modernized installation of ion-plasma sputtering «Quinta». The treatment of the film/substrate system by an electron beam was carried out with the «SOLO»: energy of the accelerated electrons was 16 keV, energy density of the electron beam made 17 J/cm<sup>2</sup>, time between pulses made 0.3 s<sup>-1</sup>, number of pulses was 3, pulse duration made 200 μs, residual atmosphere pressure (argon) in the working chamber ≈ 2 × 10<sup>-2</sup> Pa. Just before irradiation the film/substrate system was heated by the electron beam up to temperature of (800–850) °C.

It was found that the multiphase structure crystallized on the eutectic reaction was formed in the surface layer of the film/substrate system.

Spraying on the surface of titanium boron carbide ceramic layer (0.5 mm) and its subsequent irradiation of intense pulsed electron beam results in the formation of titanium diboride surface layer.

Irradiation intense pulsed electron beam System «film (Ti) / (B<sub>4</sub>C-ceramic) substrate» leads to the formation of a surface layer (5–7) microns multiphase eutectic structure consisting of crystallites of boron carbide, titanium diboride and titanium.

Formation of new phases in the «film (Cu) / (B<sub>4</sub>C ceramics) substrate» is not found.

**Keywords:** *ceramics, metallization, intense electron beam.*

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**THE IMPACT OF VOLUME DISCHARGE UNDER NORMAL PRESSURE  
OF NITROGEN ON THE SURFACE LAYERS OF TITANIUM AND NIOBIUM**

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The effect of the number of volume discharge pulses initiated by a beam of runaway electrons on the surface of the niobium and alloy VT-1(titanium) in a nitrogen atmosphere under normal pressure investigated. Dependences the number of carbon compounds and oxides on metal surfaces, depending on the exposure dose are shown.

***Keywords:*** *surface modification, titanium, niobium, oxidation, cleaning, volume discharge.*

## TECHNOLOGY OF PROCESSING OF BUILDING MATERIALS WITH THE PLASMA HEATER

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Resolved two inverse heat conduction problems – definition of power and the characteristic size of the heat source on measurements of temperature at different depths of the warmed-up material and surface temperature, and identification of characteristics of a source and temperature of a surface only on temperature measurements in technologically significant zone. The stationary problem about heating of a concrete plate by a mobile thermal source of Gaussian type is also solved. The analytical formulas allowing to estimate the useful power of plasma device and the maximum temperature with depths not less than 1 mm with sufficient accuracy for practical purposes are received. The values of the basic technological parameters for the treatment of concrete panels are recommended.

**Keywords:** *plasma device, electric arc treatment of materials, thermal conductivity, thermal characteristics of concrete.*

## LEGITIMACIES OF GROWTH OF THE OXIDE FILMS ON ION-MODIFIED SAMPLES FROM E110 ALLOY AT HIGH-TEMPERATURE OXIDATION

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The possibility of barrier layers production during surface ion-plasma modification to decrease oxidation and hydrogenation rate of fuel claddings from zirconium alloys at various operation conditions is studied in this paper.

Fuel claddings from E110 opt alloy outer surface ion polishing mode is defined based on calculations and experiments performed: average ion energy in beam 3–4 keV, ion current 0.4–0.7 mA/cm<sup>2</sup>, total irradiation dose  $5 \times 10^{18}$  ion/cm<sup>2</sup>.

Cleaning and polishing of the samples form E110 alloy outer surface is performed on installation ILUR-03 with radial wide energy spectrum ion beam source. Thin films (up to 100 nm) of alloying elements – Fe, Al, Mo, Y, Mg, Cr were deposited on polished surface by means of magnetron deposition and then implanted into near-surface layer under radial argon ion beam influence.

Cleaned and modified near-surface layers element composition studying was performed by X-ray microanalysis method.

Some samples were previously autoclaved (500 h,  $T = 350$  °C,  $P = 17$  MPa, distilled water) to produce protection layer from oxide film, enriched by implanted elements.

It is shown, that alloying elements dislocated mostly at oxide-metal boundary and in oxide.

**Keywords:** *ion beam, corrosion, E110, oxide, modification, high-temperature.*

**CREATION OF TEXTURE INTO SURFACE LAYERS OF TARGETS FROM Ti6Al4V  
TITANIUM ALLOY DURING THEIR IRRADIATION WITH INTENSE PULSED  
ELECTRON BEAMS**

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The present paper reviews the X-ray experimental results dedicated to the texture formation into surface layer of gas turbine engine blades from VT6 refractory  $\alpha+\beta$ -titanium alloy as a result of irradiation with intense pulsed electron beams.

**Keywords:** *blades, texture, VT6, intense, pulsed, electron, beams.*

**THE EFFECT OF IRRADIATING REGIMES WITH INTENSE PULSED ELECTRON  
BEAMS ON CRATER CREATION TAKING PLACE  
ON THE SURFACE OF TARGETS FROM TITANIUM ALLOYS**

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The present paper reviews the experimental results dedicated by the effect of the irradiation conditions by intense pulsed electron beams on crater creation taking place on the surface of VT6, DN8, VT9 refractory titanium alloy targets. The most probable mechanisms of crater creation are also analysed.

**Keywords:** *crater, creation, surface, titanium, blade, intense, pulsed, electron, beams.*

**ABOUT THE POSSIBILITY OF SELECTIVE ELECTRON-BEAM SINTERING  
OF CERAMIC POWDERS IN THE FOREVACUUM PRESSURE RANGE**

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The results of investigations about selective electron-beam sintering of non-pressed ceramic powders (zirconia and the system zirconia – alumina having a weight ratio of 6:1) in the forevacuum pressure range are presented.

**Keywords:** *ceramic powder, sintering, electron beam, forevacuum.*



## REGULARITIES OF FORMATION OF SUS321 STEEL SURFACE LAYER UNDER IRRADIATION BY INTENSE ELECTRON BEAM

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Creation of new volume-alloyed materials is currently problematic due to the scarcity and high cost of alloying elements. Economically and technically feasible to develop a new approach, in which the special properties of the article surface provided with a continuous or local formation of a relatively thin modified layer, the properties of which correspond to the operational requirements [*Laskovnev A.P., Ivanov Yu.F., Petrikova E.A., Koval N.N., et al. // A modification of structure and properties of the eutectic silumin by electron-ion-plasma treatment. – Belaruskaya Navuka Publ., Minsk, 2013. – 287 [in Russian]*].

Purpose of the work – identification and analyzing of regularities formation of nanostructured nanophase surface layers in austenitic steel subjected to surface alloying by methods of beam-plasma technologies. SUS321 steel was used as research material. The modification of the surface layer of steel was carried out by intense electron beam (18 keV, 50  $\mu\text{s}$ , 0.3  $\text{s}^{-1}$ , 3 pulses, (10–25) 25  $\text{J}/\text{cm}^2$ ) with submillisecond pulse duration. This allows to study the evolution of structure and properties of the steel surface layer, which is formed in a high-speed hardening of the solid- and liquid-phase state.

Electron-beam steel treatment accompanied by a decrease in 1.5–2 times of the average grain size; reduction of the carbide phase particles up to nanosized state; enrichment of solid solution based on iron by atoms of the alloying elements. Accordingly, with an increase in electron beam energy density it is observed a decrease in microhardness of modified layer on  $\approx 27\%$ , increase in corrosion resistance in  $\approx 1.44$  times and fatigue life in  $\approx 3.5$  times, increase in wear resistance in  $\approx 2.4$  times and a reduction of the coefficient of friction in  $\approx 5$  times.

**Keywords:** *austenitic steel, carbides, intense electron beam, structure, properties.*

## **SURFACE MICROSTRUCTURE AND WEAR RESISTANCE OF THE STAINLESS STEEL-COPPER SURFACE ALLOY FORMED WITH A LOW-ENERGY HIGH-CURRENT ELECTRON BEAM**

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The work is devoted to the enhancement of wear resistance of copper substrates by formation of surface alloy with stainless steel by a low-energy high-current electron beam (LEHCEB). In particular, the effect of parameters of LEHCEB such as electron energy on wear resistance of formed samples as well as microstructure of the near-surface layer and its chemical composition has been investigated.

Formation of the stainless steel-copper surface alloy was carried out with the electron-beam machine «RITM-SP». Formation of the surface alloy is the result of several iterations of the magnetron deposition of stainless steel films onto copper substrate and its subsequent mixing by a LEHCEB irradiation in single vacuum cycle. The thickness of film in each cycle of deposition was 100 nm. The electron energy of LEHCEB irradiation was ranging from 17 to 27 keV. Total thickness of deposited films was equal to 1  $\mu\text{m}$ .

It has been established that roughness and chemical composition of the samples with the formed surface alloy depend on the electron energy of LEHCEB. The smoother surface is formed at the lower electron energy of LEHCEB irradiation. The concentration of copper on the surface samples increases with an increase of electron energy of LEHCEB irradiation whereas the concentration of Fe, Cr and Ni is reducing. A wear resistance test showed that the wear resistance of the samples with surface alloy contentiously increases with an increase of electron energy of LEHCEB irradiation and at 27 keV it is 7 times more than that for initial copper.

**Keywords:** *surface alloy, wear resistance, low-energy high-current electron beam.*

## MODIFICATION OF TECHNICALLY PURE TITANIUM WITH NITROGEN IN A LOW PRESSURE ARC DISCHARGE PLASMA ASSISTED BY PLASMA GENERATOR «PINK»

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Titanium and its alloys are widely used in industry and medicine, owing to their properties as a low specific weight, high corrosion resistance and biological compatibility. However, their low hardness and thus low wear resistance are one of the causes that limit their broader application. A low pressure arc discharge plasma nitriding assisted by plasma generator «PINK» is a perspective method of improving the service characteristics of titanium.

The material of the study were samples of commercially pure titanium VT1-0. Saturation of the sample surface with nitrogen have been carried out on the modified technological setup, equipped with plasma generators «PINK» (the development of HCEI SB RAS). Three series of experiments with different nitriding temperature have been conducted : 600 °C, 650 °C and 700 °C.

It has been found that the microhardness of titanium nitriding at temperatures of 600–650 °C is 4.3 GPa, which in 1.3 times exceeds the microhardness of titanium in the initial state (3.3 GPa), wear resistance of these samples increased in 1, 1 times. The formation of a solid solution  $\alpha$ -Ti(N), and titanium nitride Ti<sub>2</sub>N can cause increasing microhardness and wear resistance.

Titanium nitriding at a temperature of 700 °C allows to enhance its microhardness up to 9.5 GPa, and the wear resistance in 1.7 times that due to both the increase in the volume content of these phases and the formation of a thin surface layer of a solid cubic nitride titanium TiN.

**Keywords:** *technically pure titanium, arc discharge plasma, plasma generator «PINK», nitriding, structure.*

## STRUCTURE AND MECHANICAL PROPERTIES OF TI-SI-ME (ME=ZR, NB) ALLOYS FORMED BY COMPRESSION PLASMA FLOWS IMPACT

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The metal and semiconductor systems based on silicon compounds like metal silicides or silicon nitride are promising materials for different technological applications. The latest research showed the enhanced oxidation resistance of the titanium-based or niobium-based silicides. Being nanostructured, such materials can show addition radiation resistance. Therefore in the present work the possibility of alloys based on titanium silicides formation with compression plasma flows is considered. The compression plasma flows (CPF) were generated by quasi-stationary plasma accelerators in the residual nitrogen atmosphere. The influence of the CPF was made on the multilayers systems like Nb/Si/Ti, Zr/Si/Ti and Nb/Ti/Si. Such combination of the substrates and coatings allowed us to change the elements concentrations in a wide range. It was found that CPF influence results in melting both coatings and substrate providing the alloys formation after the crystallization of the mixed layers. X-ray diffraction examination of the surface after the CPF treatment showed the growth of both titanium high-temperature based solid solution and silicides. The formed multiphase alloy possess enhanced thermal stability under the oxidation at elevated temperatures.

**Keywords:** *compression plasma flows, titanium, alloying, solid solutions, thermal stability.*

## CARBON SYNTHESIS BY ELECTRON BEAM IRRADIATION OF POLYVINYL HLORIDE

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The paper demonstrates the fundamental possibility of forming carbon structures in polyvinyl chloride (PVC) films without additives and in PVC films added with 5 wt% of ferrocene. Radiation-chemical transformations was realized in air on a repetitive pulsed plasma cathode electron accelerator at a maximum electron energy of no more than 160 keV, pulse duration of 40  $\mu$ s, and current density of 5 mA/cm<sup>2</sup>. Semi-quantitative X-ray microanalysis shows that the irradiated PVC film free of additives contains 92 wt% of carbon, 6 wt% of oxygen, and 2 wt% of chlorine, representing an amorphous carbon material. Possible mechanisms of the observed phenomenon are discussed.

**Keywords:** *plasma emitter, grid stabilization, electron accelerator, electron beam irradiation, carbon, PVC film.*

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**INVESTIGATION OF DIFFUSION INFLUENCE ON PLASMA CHANNEL FORMATION  
WHEN TRANSPORTING A LOW-ENERGY HIGH INTENSITY ELECTRON BEAM  
IN THE LOW PRESSURE GAZ**

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In this work we consider the beam current in the range of 100–400 A and the external magnetic field in the range of 100–300 G. It is shown that plasma channel expands under the influence of diffusion. The channel expansion is inversely proportional to external magnetic field magnitude. Dependences of virtual cathode formation from beam current, beam energy (10–30 keV) and gas pressure ( $\sim 0.0005$  Torr) are found.

**Keywords:** *electron beam, argon, virtual cathode.*

## CREATION OF THE NANOSTRUCTURED SUPERHARD AND HEAT RESISTING LAYERS ON DIE STEEL AT INFLUENCE OF INTENSIVE ELECTRON BEAMS IN VACUUM

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Modern mechanical engineering and tool industries show to a surface of products raised and often contradictory requirements which cannot be realized within use of one technology. For accomplishment of these requirements it is the most effective to use technologies which have functionally various effect on a surface.

Thermodynamic calculations have allowed to determine molar structures of phases, pressure of gaseous components, thermodynamic properties at each temperature. The analysis of dependence of  $H(T)$  in certain temperature intervals has given an opportunity to reveal sharp changes which could be referred to the phase or chemical equilibrium transformations connected with formation of new or intermediate connections. The change of a complete enthalpy of  $N$  at a transformation completion temperature referred to number of moths of the condensed substance at a temperature of the beginning of sharp increase in  $N$  is close to sizes of thermal effects  $H$  of equilibrium transformations.

For pulse melting of blankets the source the high-current of low-energy pulse electron beams who on set of parameters have no analogs is used. Pulse electron beams provide training from fusion of blankets with chilling speeds in the range from 106 to 109 Fps. These conditions of synthesis are created a possibility of forming of blankets with nano- and submicrocrystalline multiphase structure, possessing the increased physicomechanical and operational properties.

Researches have shown what after training the microhardness of a surface of steel AISI Type D2 has increased twice in comparison with a basis.

**Keywords:** *Electron beam, borides, alloys, microhardness, X-ray diffraction, structure, the self-propagating high-temperature synthesis (SHS).*

## STRUCTURAL CHANGES DURING MELTING OF QUARTZ-FELDSPAR RAW MATERIALS IN LOW-TEMPERATURE PLASMA

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A detailed x-ray analysis of a quartz-feldspar raw materials as in the initial state and after plasma exposure. An amorphous product of fusion, the resulting plasma exposure, consists mixture of amorphous phases: [O<sub>2</sub>Si], [O<sub>22</sub>Al<sub>20</sub>], [O<sub>192</sub>Si<sub>96</sub>], [O<sub>240</sub>Si<sub>120</sub>], a significant proportion of which are based on phase SiO<sub>2</sub>. It is established that the phase composition of the raw material consists of a mixture of ([O<sub>22</sub>Al<sub>20</sub>] and [O<sub>2</sub>Si]).

**Keywords:** quartz-feldspar raw materials, crystal structure, quantitative phase analysis.



## INFLUENCE OF ION IMPLANTATION ON MECHANICAL PROPERTIES OF U8A STEEL AND COBALT-TUNGSTEN CARBIDE PLATES

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In paper the influence of ion implantation on mechanical properties of materials using in metal treatment was carried out. Particular, it was shown that wear resistance of U8A steel after ion implantation by C, Si, Ti, Mo, Re increases linearly as function of the number of implanted atomic element.

As the initial blade tool of the hard-alloy R300-0828E-PM 1030 plates were used. Tests of hard-alloy plates for resistance were made at turning of HN77TYUR steel. The greatest resistance plates treated by Ar ion implantation ( $F = 1 \times 10^{18}$  ions / cm<sup>2</sup>) have shown. Plates treated by Ar ions have resistance 5 times higher and 3 times higher treated by Re compare plates without treatment.

**Keywords:** *ion implantation, resistance were, hard-alloy.*

## THERMAL STRESSES COMPUTATION UNDER HIGH-CURRENT PULSED RADIATION OF AISI M2 STEEL

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Surface modification of metallic materials and alloys with concentrated energy flows (powerful electron beams and ion plasma flow, laser beams) has been widely used at various manufacturing fields with the aim of the physical and mechanical properties improvement of the critical parts performance from modified materials.

Such energy impacts give rise to radiation, thermal and mechanical effects causing the change on the morphology, microstructure, elemental and phase composition of surface layers, which in turn may lead to increased hardness, wear, corrosion resistance and red hardness of modified materials.

However, as experimental investigations have shown, irradiation in some cases promotes the crystal defects occurrence and often non-uniform heating leads to the cracks formation at the surface layers.

Thus, the selection of incident electrons energy, its current density and pulse duration, taking into account of the thermal stress state is an actual problem of modern radiation technologies.

The result of temperature fields calculation provided here with longitudinal and transverse thermal stresses computation using multigrid technology for numerical solution of differential equations in partial derivatives also examined for R6M5 (AISI M2) high-speed steel with medium-energy (up to 400 keV) high-current (up to 1 kA/cm<sup>2</sup>) pulsed (up to 1 μs) electron beam radiation.

The obtained results can be useful at the optimal modes selection of tool steels and products processing by electron beam radiation and evaluation of its service life.

**Keywords:** *Radiation processing, electron beam processing, beam power, AISI M2 steel, thermal stresses, temperature fields.*

**HIGH TEM INVESTIGATION COATINGS BASED ON ZR-Y-O / SI-AL-N**

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The majority of ceramic materials are developed on the basis of zirconium dioxide that is partially stabilized in the tetragonal phase. The tetragonal phase is capable of a monoclinic martensitic phase transition.

The paper deals with investigation of change in grain structure, grain and interphase boundaries, structure and phase composition during heating mode «in-situ» in the microscope column and followed by thermoelastic phase transition in the multi-layer coating based on Si-Al-N / Zr-Y-O in ZrO<sub>2</sub> layer.

The structural-phase state of the surface layers of the copper substrate was investigated by transmission electron microscopy using the JEM-2100 microscope at temperature 9000 °C. Foils were prepared by the «cross-section» method using the ION SLISER-EM-09100IS installation (Jeol Ltd., Japan).

By TEM it has been established that coatings on the basis of Zr-Y-O produced by the magnetron sputtering methods have a nanograin column structure where the columns are spread through the entire coating thickness.

In the initial state layers on the basis of Zr-Y-O are two-phase and consist generally of the tetragonal phase ZrO<sub>2</sub> with a small amount of monoclinic one.

At heating layer in a column of TEM in the «in-situ» mode we can observe: 1) turns of grains of the main phase together with change in the angle of disorientation crystallographic planes, 2) martensitic transition of the tetragonal phase to the monoclinic 3) modification of grain boundaries– their total length increases, the form of grains changes, in initial column grains there are cross boundaries, i.e. there is a process of fragmentation of grains.

**Keywords:** *structure-phase state, magnetron coatings, phase transformation, TEM investigation, column grains.*

**FABRICATION, INVESTIGATIONS OF STRUCTURE AND IN VITRO STUDIES  
OF HYDROXYAPATITE-COATED ELECTRON BEAM MELTED TITANIUM  
SUBSTRATE**

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Coating based on biocompatible hydroxyapatite (HA) was deposited by radio-frequency (RF) magnetron sputtering. Electron beam melting (EBM) was proposed for fabrication of titanium alloy Ti-6Al-4V porous coin-like discs scaffolds. The scaffolds with HA coating were characterized by Scanning Electron microscopy, X-ray diffraction, wettability measurements. HA coating showed a nanocrystalline structure with the crystallites of an average size of  $32 \pm 9$  nm. In according to in vitro assessment, the thin HA coating stimulated the attachment and proliferation of cells. Human mesenchymal stem cells cultured on the HA-coated scaffold also formed mineralized nodules.

**Keywords:** *Hydroxyapatite, RF-magnetron sputtering, Electron beam melting, in vitro study.*

## TEST-BENCH FOR SIMULTANEOUS IRRADIATION OF CONSTRUCTION MATERIALS

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Now accelerated ion beams are widely used for material modification and investigation. A new facility for ion beam irradiation of materials is under development at the Institute for Theoretical and Experimental Physics. This facility will provide simultaneous irradiation of target by two ion beams. One is a heavy ion beam and another is proton or helium ion beam. It will enable to realize simulation experiments for evaluation of radiation resistance of advanced fusion and fission reactor materials. In this work we present and discuss the test-bench preliminary design.

**Keywords:** *ion beam, material modification, radiation resistance, simultaneous irradiation, simulation experiments.*

## MODIFICATION OF OPTICAL AND ELECTRICAL PROPERTIES $\text{SnO}_2$ UNDER THE INFLUENCE OF ARGON ION BEAM

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The transparent conductive oxide films are widely used in various industries. These optically transparent electrodes are for displays, solar panels, photoelectric devices, touch panels, etc. One of them is tin oxide, which has found wide practical application.

Thin films of tin oxide were deposited on the glass substrates at a room temperature using reactive magnetron sputtering. The ratio  $\text{O}_2/\text{Ar}$  and the discharge voltage was maintained in such a mode when the deposited films are dielectrics. After the deposition, the films were irradiated with an argon ions beam. The modification of the optical and electrical properties of the films depending on the irradiation time was studied. Optical properties of the films were analyzed in the range of 300–1100 nm using photometry and structural X-ray diffraction. The diffractometric research showed that the films, deposited on a substrate, had a crystal structure, and after argon ions irradiation they became quasi-crystalline (amorphous). The average value of the transmission of the films on the impact of the ion beam first dropped and then increased exceeding the initial value. It was determined that as a result of exposure the argon ions dielectric films  $\text{SnO}_2$  became electroconductive. The surface electric resistance of the films with the increase of the ions exposure time initially decreases but then begins to increase. Observed a good direct correlation between optical and electrical properties of the films

**Keywords:** *film of tin oxide, magnetron deposition, ion beam.*

## STUDY OF SORPTION PROPERTIES OF COAL CAKE TREATED BY PLASMA ARC FOR SEWAGE TREATMENT

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The article presents the results of studies on the structure and properties of the coal cake, the last arc-plasma treatment in order to obtain carbon sorbent, as well as considering the possibility of practical application of these sorbents for wastewater treatment engineering. The main limiting factor in the processing of coal cakes sorbents is their high water content, with most of the moisture introduced into the cake as a result of falls on hard-coal preparation and colloidal hydrated constituents. Using electric arc allows to intensify the processes of thermal activation of coal cakes associated with thermal shock, destruction and vapor-gas reactions occurring at the surfaces of the particles at a temperature exposure up to 3000 °C, thus increasing the yield of the desired product synthesis (sorbent) and thereby reduces manufacturing costs and improves environmental performance. Study of thermal activation zone is also carried out in the plasma reactor chamber by thermal imaging method, followed by mapping-and 3D-modeling of temperature fields. The technique of obtaining carbon sorbents from coal cakes with the study of the elemental composition of raw materials before and after thermal activation. Also studied the most important physical and chemical properties of the sorbent. The studies established the fundamental possibility thermally activated coal cake, changing its material composition, the appearance of porosity and associated sorption capacity applied for wastewater treatment. Thus, the coal cake, as the final stage of coal preparation going to waste, in principle suitable for the preparation of his carbon sorbent by thermal degradation in plasma reactor.

**Keywords:** *arc plasma, plasma reactor, the temperature field, the coal cake, material composition, porosity, spectroscopy, colorimetry, electrophoresis, wastewater, adsorption, thermal power plants.*

## THE CORROSION BEHAVIOR OF NI-BASED SUPERALLOY IRRADIATED BY INTENSE PULSED ION BEAM

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Intense pulsed ion beam (IPIB) has been extensively used in the surface strengthening of metal materials in the past decades. Quite a lot of these materials need to be operated in the corrosive environment. Therefore, it is of significance to research the corrosion behavior of metal materials after IPIB irradiation. In this work, the corrosion behavior of Ni-based superalloys irradiated by IPIB in NaCl solution was studied. Compared to the original samples, after IPIB irradiation the corrosion resistance of samples were improved, and craters were formed on the surface of Ni-based super alloys. It is found that micro-areas with craters would be eroded prior to other areas in caustic solutions. The analysis revealed that craters play an important role in the corrosion process of the metal after irradiation. This research would help understand the influence of craters induce by IPIB on the operational performance of metal materials.

**Keywords:** *Intense pulsed ion beam, Ni-based superalloy, crater, corrosion behavior.*



## ALLOYING OF INSTRUMENTAL STEEL SURFACE LAYER WITH SI AND ZR ATOMS BY COMPRESSION PLASMA FLOWS IMPACT

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Mixing of a «coating/substrate» system by ion, electron, plasma and laser beams allows alloying the substrate material with the coating elements. This process is of special interest in producing nonequilibrium, immiscible and metastable compounds. The use of such a technique for materials treatment leads to formation of surface layers with improved properties. Treatment by plasma flows generated by a gas discharge allows incorporating additional atoms of a plasma-forming gas, thus expanding the number of compounds to be synthesized in the surface layer. This approach was used for simultaneous alloying of instrumental steel (0.9 wt.% C) surface layer with silicon and zirconium atoms by means of compression plasma flows (CPF) treatment.

The zirconium coating (thickness of  $\sim 2.5 \mu\text{m}$ ) on steel was formed by cathodic arc vapour deposition while silicon coating (thickness of  $\sim 1 \mu\text{m}$ ) was formed by magnetron sputtering. CPF were obtained in nitrogen atmosphere using a gas-discharge magneto-plasma compressor of compact geometry. Structure, element and phase composition of the surface layer were characterized by the X-ray diffraction analysis, scanning electron microscopy and energy-dispersive X-ray microanalysis. Vickers microhardness and tribological tests were carried out.

The findings showed formation of the surface steel layer with the thickness of up to  $\sim 10 \mu\text{m}$  alloyed with zirconium and silicon atoms. Formation of  $\text{Zr}(\text{C}, \text{N})$  thin layer at the surface as well as  $\text{Fe}_2\text{Zr}$  in the bulk of the alloyed layer was found. The change of phase composition and quenching effects resulted in microhardness increase and friction coefficient decrease.

**Keywords:** *plasma treatment, steel, phase and element composition.*

## PHYSICOCHEMICAL PROCESSES OF STRUCTURE FORMATION IN GLASS-CERAMIC MATERIAL

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The paper presents physicochemical investigations of the structure formation in glass-ceramic material obtained by the innovative melting technique, namely the low-temperature plasma treatment. Physicochemical processes occurred at melt production and its crystallization are studied in this paper. The main conditions of crystal phase formation are shown herein.

**Keywords:** *plasma, silicate systems, glass ceramic material, Ash, plasma sources, Nanoscience and nanotechnology, Modification of material properties.*

## THE FORMATION OF BIOCOMPATIBLE SURFACE LAYERS IN Ti-6Al-4V ALLOY BY COMBINED ION-PLASMA TREATMENT

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Titanium alloys (in particularly Ti-6Al-4V) are widely used for implants manufacture. Alloy Ti-6Al-4V has good mechanical properties, relatively low weight, and excellent resistance to corrosion. However, the main alloying elements (Al, V) of the alloy can cause health problems. The concentration of these toxic elements can be eliminated or reduced in a thin surface layer in order to increase the biocompatibility. Surface alloying can be used to improve the titanium alloys surface properties and biocompatibility.

In this work surface layer alloying was carried out by compression plasma flows impact on titanium alloy preliminary coated by zirconium or titanium. The coating was deposited on the sample surfaces by means of cathodic vacuum-arc deposition technique. The thickness of the coating was about 2 micrometers. The treatment of the systems samples was carried out by three pulses of compression plasma flows in the nitrogen atmosphere (energy density absorbed by the surface was varied from 14 to 23 J/cm<sup>2</sup> per pulse). The phase and elemental composition, microhardness, friction coefficient and surface roughness of Ti-6Al-4V alloy samples after plasma treatment were investigated.

It has been established that the action of compression plasma flows on both systems leads to formation of TiN nitride. Treatment of Zr/Ti alloy system results in the formation of solid solution based on the high-temperature titanium phase  $\beta$ -Ti(Zr). The combined effect of ion-plasma flows results in aluminum and vanadium concentration decrease in the surface layer, leads to the growth of its microhardness and surface roughness, decrease of the friction coefficient.

**Keywords:** Titanium alloys, implants, biocompatibility compression plasma flows.

## THE EFFECT OF SOFT X-RAYS ON THE ELECTRICAL CHARACTERISTICS OF MIS STRUCTURES BASED ON MBE HgCdTe WITH NEAR-SURFACE GRADED-GAP LAYERS

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We used the X-ray radiation produced by the plasma generation of laser-induced vacuum spark. The radiation generated pulse YAG: Nd laser operating in Q-switched. The range of soft X-rays after the filter is concentrated in the range of 1.5–5 keV. To study its effect on the properties of the material well suited admittance investigation of MIS structures. The MIS structures were fabricated on the basis of p-HgCdTe grown by MBE on the Si (013) substrates. Graded-gap layers with high content of CdTe were grown on both sides of the working layer. Insulator (Al<sub>2</sub>O<sub>3</sub>) was deposited over the graded-gap layer.

It is shown that exposure soft X-rays appears to increase the density of fast surface states near the middle of the band gap by approximately an order, in increase of the density of slow surface states and in change of the differential resistance of the space charge region in the strong inversion. Thus, the effect of soft X-ray radiation causes a change in the properties of impurity-defect system of the insulator-semiconductor interface and near-surface layer of HgCdTe.

The study was performed at financial support by RFBR and the Administration of Tomsk region as part of a research project № 16-42-700759.

**Keywords:** MIS structure, HgCdTe, soft X-rays, molecular beam epitaxy, graded-gap layer, capacitance-voltage characteristic.

## SOME PROPERTIES OF NEAR-SURFACE LAYER OF GRADED-GAP MBE HgCdTe AFTER BORON ION IMPLANTATION

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The narrow-gap HgCdTe semiconductor is widely used to create highly-sensitive infrared detectors. Ion implantation method is often used when creating HgCdTe photodiodes. The admittance measurements for MIS structures allow to investigate the changes in the properties of near-surface of semiconductor layer after ion irradiation.

The structures based on n-Hg<sub>0.775</sub>Cd<sub>0.225</sub>Te were grown by MBE on the GaAs (013) substrates in Institute of Semiconductor Physics SB RAS. Graded-gap layers with high content of CdTe were grown on both sides of the working layer. The hole concentration at 78 K was  $8.6 \times 10^{15} \text{ cm}^{-3}$ . Hetero-epitaxial film was divided into three parts. The first part was used to make a control sample. The second part was subjected to ion milling during 5 minutes with ion energy of 0.5 keV at current density of  $0.1 \text{ mA/cm}^2$ . Implantation of boron was carried out in the third part with ion energy of 100 keV and dose of  $10^{15} \text{ cm}^{-3}$ . MIS structure based on all parts of the film were created by deposition of SiO<sub>2</sub>/Si<sub>3</sub>N<sub>4</sub> insulator and indium electrodes.

The conductivity type in the near-surface layer of HgCdTe changes after both radiation impacts. The electron concentration after implantation was much higher than after milling. The electron concentration determined from the CV characteristics were equal to  $5.88 \times 10^{16} \text{ cm}^{-3}$  and  $2.47 \times 10^{17} \text{ cm}^{-3}$  for the ion milling and ion implantation, respectively.

The study was performed at financial support by RFBR and the Administration of Tomsk region as part of a research project № 16-42-700759.

**Keywords:** *HgCdTe, Molecular beam epitaxy, Ion implantation, infrared detectors.*

## PLASMA GAS-CYCLIC NITRIDING OF STAINLESS STEEL

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The electron beam excited plasma gas-cyclic nitriding (GCN) of austenitic stainless steel (SS) is carried out at the conditions of periodic alternation of nitrogen saturation stage (nitriding) and isothermal annealing stage (denitriding). The nitriding is performed at Ar/N environment, but the denitriding is performed at Ar environment only. It is established that average surface roughness reaches 60 nm and doesn't depend on duration of the GCN. On the contrary, increase of duration of continuous nitriding from 1 to 16 hours leads to increase of surface roughness from 95 to 230 nm. This advantage of GCN is caused by decrease of nitrogen concentration in a modified surface layer at the denitriding and formation of the  $\alpha$ -Fe(N) phase. GCN of SS provides increase of hardness of surface layer by 5 (up to 11 GPa) which thickness reaches 70  $\mu\text{m}$  after 16 hours of processing time at 500 °C.

**Keywords:** *nitriding, plasma, electron beam, stainless steel, roughness, X-ray phase analysis.*

**THE INFLUENCE OF PULSED VOLUME NANOSECOND DISCHARGE IN AIR AT ATMOSPHERIC PRESSURE ON THE SURFACE POTENTIAL DISTRIBUTION OF MIS- STRUCTURES BASED ON P-CDHGTE IN THE V-DEFECT REGION**

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The effect of pulsed nanosecond volume discharge in air at atmospheric pressure on the surface potential distribution of MIS structures (In/Al<sub>2</sub>O<sub>3</sub>/CdHgTe) based on epifilms CdHgTe p-type conductivity was experimentally investigated. In our work we carried out the investigation of the surface potential distribution (the contact potential difference (CPD) between the cantilever needle-point and the surface) by means of the Kelvin force probe microscopy which is a type of atomic-force microscopy. The CPD are measured for V-defect and defect free regions. It is shown that the effect of the volume discharge leads to significant changes in the CPD distribution. The experimental data can be explained by the formation of a thin dielectric layer at the interface Al<sub>2</sub>O<sub>3</sub>/CdHgTe that contains an embedded uncompensated positive charge.

***Keywords:*** *Pulsed volume nanosecond discharge, MIS-structures, HgCdTe, kelvin force probe microscopy, surface potential.*

## INFLUENCE OF A HIGH-FREQUENCY PULSED NANOSECOND DIFFUSION DISCHARGE IN THE NITROGEN ATMOSPHERE ON THE ELECTRICAL CHARACTERISTICS OF A CDHGTE EPITAXIAL FILMS

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The effect of a high-frequency nanosecond volume discharge forming in an inhomogeneous electrical field at atmospheric pressure on the CdHgTe (MCT) epitaxial films is studied. The measurement of the electrophysical parameters of the MCT specimens upon irradiation shows that that the action of pulses of nanosecond volume discharge leads to changes in the electrophysical properties of MCT epitaxial films due to formation of a near-surface high-conductivity layer of the n-type conduction. The preliminary results show that it is possible to use such actions in the development of technologies for the controlled change of the properties of MCT narrow-band solid solutions and production of structures heterogeneous with respect to conduction.

**Keywords:** *high-frequency nanosecond volume discharge, CdHgTe, electrophysical parameters.*



## THE FEATURES OF A RADIATION DEFECT FORMATION AT BORON IMPLANTATION IN HgCdTe EPITAXIAL FILMS

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The aim of this paper is to investigate the specific properties of the formation and accumulation of the spatial distribution of electrically active radiation defects after B ion implantation in  $\text{Hg}_{1-x}\text{Cd}_x\text{Te}$  (MCT) epitaxial films of different material composition ( $x$ ) in the region of introduction of the implant. The MCT samples were irradiated by B ions at room temperature in the radiation dose range  $10^{12} - 6 \cdot 10^{15}$  ions/cm<sup>2</sup> and with ion energy 100 keV. Measurements of the electro-physical parameters of the samples before and after irradiation were made at the temperature of liquid nitrogen using the Hall Electromotive Force method in the Van-der-Pau configuration. The electron concentration distribution as a function of semiconductor depth was determined by the method of differential Hall measurements using an etching process. The experimental results are shown that the material composition ( $x$ ) of an epitaxial film significantly effect on boron implantation results and determine both the electrical parameters of the implanted layer, and the spatial distribution of the donor type radiation defects.

**Keywords:** *HgCdTe, ion implantation, electrically active radiation defects, electrophysical parameters.*

## COMPOSITION AND PROPERTIES OF THE CATALYTIC LAYERS PREPARED BY ION BEAM ASSISTED DEPOSITION OF PLATINUM AND CERIUM FROM A PULSED ARC-DISCHARGE PLASMA ONTO CARBON PAPER SUBSTRATES

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Binary catalyst system were prepared by ion beam assisted deposition (IBAD) of platinum and cerium onto carbon (AVCarb® Carbon Fiber Paper P50 and Toray Carbon Fiber Paper TGP-H-060 T) electrocatalysts supports. The deposition method is characterized by the use of deposited-metal ions as assisting ions. Metal deposition and mixing between the precipitable layer and surface of the substrate by accelerated ions of the same metal were carried out from a neutral vapor fraction and the vacuum-arc discharge plasma of a pulsed electric arc ion source, respectively. Ion accelerating voltage is 10 kV.

Investigation of the composition and morphology of obtained layers was carried out by XRF, RBS, SEM, and EPMA methods. It has been established that the layers contain atoms of the deposited metals, substrate material, and oxygen; their thickness reaches ~30–100 nm. Content of cerium and platinum atoms in the layers is  $\sim 2 \times 10^{16} \text{ cm}^{-2}$ . Concentration of deposited metals equals about a few atomic percent.

According to investigations with use of cyclic voltammetry the electrocatalysts with prepared layers exhibited activity in the reactions of oxidation of methanol and ethanol, which form the basis for the principle of operation of low temperature fuel cells (DMFC and DEFC).

In comparison with the traditional multistage chemical methods of preparation of the supported catalysts, the proposed IBAD method allows of the introduction of micro amounts of a doping impurity in the near-surface of a substrate under non equilibrium conditions and of the formation of cohesive catalytic layers at ultra-low platinum consumption.

**Keywords:** *ion beam assisted deposition, catalytic layers, composition, electrocatalytic properties.*

## ELECTRICAL CHARACTERISTICS OF EPITAXIAL CMT AFTER AS+ IMPLANTATION

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Molecular beam epitaxial (MBE) layers of mercury-cadmium-telluride (MCT) solid solutions is widely used to create infrared receivers. We studied the characteristics of MBE MCT films, after the introduction of different energies As<sup>+</sup> with different doses of irradiation. Some of the samples were subjected to post-implantation annealing.

Electrical characteristics of the samples were determined from Hall measurements. By means of secondary ion mass spectrometry were obtained distribution profiles of implanted impurity. Voltage-current characteristics of the structures were measured also.

Activation As up to 100 %, as well as modification of the characteristics of CMT outside the implanted layer after annealing has been detected. It can be explained by the formation of vacancy-type defects and annealing the initial donor defects. Also we found differences in the p-n junction depths and electrically active defects profiles.

**Keywords:** *Ion implantation, HgCdTe, Electrical characteristics.*

## JOINT INFLUENCE OF STEERED VACUUM ARC AND NEGATIVE REPETITIVELY PULSED BIAS ON TITANIUM MACROPARTICLES SUPPRESSION

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This paper presents the results of experimental study of titanium macroparticles accumulation on a negatively biased substrate immersed in DC vacuum arc plasma. Macroparticle and plasma emission properties of random and steered arc evaporators were investigated. It was shown that using of steered arc with a tangential magnetic field strength 200 Gs reduces the generation of macroparticles 4 fold compared to a random arc source. Application of repetitively pulsed negative bias significantly decreases macroparticle assembling on a substrate surface for both evaporator designs. After 20 minutes of ion-plasma treatment with negatively pulsed bias ( $-2$  kV,  $7$   $\mu$ s, 105 p.p.s.) and steered arc, the observed macroparticle surface density appears 2 orders of magnitude smaller than after vacuum arc plasma deposition at anode potential with random arc. Thus, the possibility of high-frequency short-pulse plasma immersion ion implantation by implementing DC vacuum arc plasma is discussed.

**Keywords:** *Vacuum steered arc, Plasma, Macroparticles, High frequency pulsed bias.*

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**APPLICATION OF A PULSED ELECTRON BEAM FOR SURFACE POLISHING  
OF METAL PRODUCTS OBTAINED BY LASER OR ELECTRON-BEAM  
POWDER SINTERING**

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The paper presents research results on pulsed electron beam surface finish of porous metal articles obtained by selective powder sintering. On the example of VT6 alloy, it is shown that surface finish with a pulsed electron beam in a vacuum of  $3.5 \cdot 10^{-2}$  Pa (Ar) at an electron energy of 15 keV, pulse duration of 200 microseconds, and pulse energy density of  $45 \text{ J/cm}^2$  provides a considerable decrease in surface roughness and porosity. The proposed method of surface finish is an alternative to conventional techniques of surface treatment of articles for use in mechanical engineering, implantology, industry, science, education, designing, and other fields.

**Keywords:** *additive technologies, electron beam, finishing treatment, structure, properties.*

**WATER IR SPECTRUM MODIFICATION BY NANOSECOND ELECTRON BEAM*****VIKTOR ORLOVSKII AND VIKTOR PANARIN****Institute of High Current Electronics SB RAS, Russia  
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Modification of IR absorption spectra of melt water and heavy water after multiple action of nanosecond electron beam is obtained and studied. Analysis of the Fourier absorption in the IR range revealed differences between irradiated and non-irradiated water. Changes in the absorption spectrum of melt water consisted in the fact that the band of stretching vibrations of OH groups expanded without express highs for the test liquid. Since heavy water is a wide range of concentrations is a mixture of H<sub>2</sub>O, HDO and D<sub>2</sub>O molecules, the IR spectrum is the sum of the molar absorption coefficients corresponding isotopic modifications. The changes were found for H<sub>2</sub>O and HDO molecules. Changes in absorption of heavy water after e – beam action were as follows: the band of stretching vibrations of OH groups of H<sub>2</sub>O and HDO molecules expanded, and the absorption band of OH bending vibration overtone HDO molecules become more intense, the band width being the same. Deformation vibrations of H<sub>2</sub>O molecules and HDO heavy water have a shift of the maximum in the direction of higher frequencies and the maximum bending vibration D<sub>2</sub>O molecule remains unchanged. Thus, irradiation of the e-water flow can be used to modify the water and aqueous solutions.

**Keywords:** *nanosecond electron beam, IR absorption spectrum, chemical reactor.*

## FIRST PRINCIPLES CALCULATIONS OF HYDROGEN DIFFUSION IN ZNO CRYSTALS

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Knowledge of the atomic and electronic structure of defective/doped ZnO is of great importance for improving performance of electrodes in optoelectronic devices based on transparent conducting oxides, e.g. LED displays etc. A particular interest is understanding of a role of hydrogen impurities penetrating into ZnO thin films from plasma during film preparation. It is known that hydrogen could be interstitial (Hi) and substitutional H (HO) in O lattice site [A. Usseinov et al, *Physica Scripta* 89, 045801 (2014)].

We report the results of the ab initio modeling of atomic hydrogen in both positions (Hi and HO) in ZnO based on hybrid DFT method as incorporated into the CRYSTAL-2009 computer code using the supercell model and linear combination of atomic orbitals (LCAO) basis set. This approach allows us to obtain very accurate calculations of the energy barriers of impurity migration along different paths. We compare properties of the hydrogen in the bulk with that on ZnO (10–10) surface. We calculated also the defect-induced electronic charge redistribution, lattice distortion, defect formation energy for the bulk and on the surface, as well as density of the electronic states (DOS). It is confirmed that Hi in the bulk is a shallow donor with a considerable contribution into the conduction band bottom. At the surfaces, hydrogen shows a strong binding to oxygen ions.

**Keywords:** *hydrogen, diffusion, ZnO.*

## PULSED BEAM MODIFICATION OF HIGHLY DOPED GE:SB LAYERS DEPOSITED ON THE DIFFERENT SUBSTRATES

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Germanium (Ge) is a promising material for micro- and optoelectronics to produce high performance field-effect transistors, photodetectors, light-emitting diodes and lasers. For such applications the formation of tensile-strained and/or highly doped by donor impurity Ge layers are needed. In this Letter the formation of such layers was carried out by ion-beam sputtering of composite Sb/Ge target, deposition of thin amorphous Ge:Sb films (200-nm thick) on the different substrates (c-Si, c-Al<sub>2</sub>O<sub>3</sub>,  $\alpha$ -SiO<sub>2</sub>) followed by pulsed annealing with nanosecond laser or ion beams for their crystallization. The obtained polycrystalline n-Ge:Sb layers (NSb ~ 1 at.%) are characterized by increased values of tensile strain (up to 1 %) and homogenous dopant distribution within layer thickness. The electrical measurements at 300 K revealed the low sheet resistance (up to 40 Ohm/ $\square$ ) and extremely high electron concentration (up to  $5.5 \times 10^{20} \text{ cm}^{-3}$ ) that indicated 100 % electrical activation of Sb dopant. The increased values of tensile strain and electrical conductivity for n-Ge:Sb films on  $\alpha$ -SiO<sub>2</sub> substrate are explained by low values of thermal conductivity and thermal expansion coefficients of quartz.

**Keywords:** *Germanium, thin films, vacuum deposition, pulsed annealing, melting crystallization, sheet resistance.*



**IRRADIATION OF  $\text{Fe}^{+8.25}$  AT % MN SUPERSATURATED SOLID SOLUTION WITH IONS OF VARIOUS ATOMIC MASSES ( $\text{Ar}^{+}$ ,  $\text{Kr}^{+}$ ,  $\text{Xe}^{+}$ ) AND ANALYSIS OF THE ROLE OF NANOSIZED DYNAMIC EFFECTS IN THE ACTIVATION PROCESSES OF LONG-RANGE TYPE**

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The atom redistribution and the characteristics of  $\alpha(\text{bcc}) \rightarrow \gamma(\text{fcc})$  structure phase transformation in the volume of the foils of  $\text{Fe}^{+8.25}$  at % Mn alloy (30  $\mu\text{m}$  thick) during  $\text{Ar}^{+}$  ion irradiation ( $E = 20$  keV,  $j = 50\text{--}100$   $\mu\text{A}/\text{cm}^2$ , a projected ion range of  $<0.003$   $\mu\text{m}$ ) were studied. The Cowley parameter of short-range atomic order, the number and composition of the  $\alpha$  and  $\gamma$  phases formed during  $\alpha \rightarrow \gamma$  transition were calculated. The parameters of the hyperfine electric and magnetic interaction of  $^{27}\text{Fe}$  nuclei, which illustrate the change in the electronic structure of iron atoms depending on the alloy state, were determined in the various nearest neighborhood of atoms.

The supersaturated  $\text{Fe}^{+8.25}$  at % Mn solid solution decomposition was found to become more intensive as the atomic weight of implanted ions increases. This is the case of both pre-precipitation stage with the formation of short-range atomic order and the stage of the structural  $\alpha \rightarrow \gamma$  phase transformation.

The comparison of the results obtained for the exposure to the beams of  $\text{Ar}^{+}$ ,  $\text{Kr}^{+}$  и  $\text{Xe}^{+}$  ions of different masses with previously studied data obtained in the case of light beam exposure of the hardened  $\text{Fe}^{+8.25}$  at % Mn alloy (under the same heat conditions) indicates the existence of a nonthermal component in the effect of accelerated ion beams, the role of which increases with the atomic ion mass. The latter is associated with greater energy release density for more massive ions.

**Keywords:** *ironmanganese alloy, powerful ion beams, Mössbauer spectroscopy, short-range ordering,  $\text{bcc} \rightarrow \text{fcc}$  phase transformation.*

## EFFECT OF TEMPERATURE AND PULSED ELECTRON BEAM IRRADIATION ON THE GRAIN BOUNDARY ENSEMBLE OF THE ULTRAFINE-GRAINED MOLYBDENUM

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Comparison studies of grain boundary ensemble evolution of the ultrafine-grained molybdenum were performed under free annealing and pulsed electron beam exposure.

Grain-subgrain ultrafine-grained structure with an average element size 0.4 micrometers and nonequilibrium grain boundaries was formed in molybdenum by the method of torsion under hydrostatic pressure (THP). Misorientation spectrum of grain boundaries at the grain boundary ensemble of the ultrafine-grained molybdenum after THP has a pronounced bimodal character. The first peak is in the misorientation range  $\theta < 4^\circ$ , the second one is blurred within the angles 30–60°. Total fraction of low angle boundaries at the molybdenum grain boundary ensemble amounts to 25 %.

Transition of grain boundaries of molybdenum ultrafine-grained structure to the equilibrium state is found to observe during annealing at temperatures of 773–1023 K for 30–60 min. Character of grain boundary ensemble remains unchanged. Pulsed electron beam irradiation for 30 min in the indicated temperature range leads to decrease in the fraction of the low angle boundaries with misorientations  $\theta < 4^\circ$  and increase in fraction of high angle boundaries with misorientations  $\theta = 60^\circ$  in the molybdenum grain boundary ensemble. Misorientation spectrum of grain boundaries at the grain boundary ensemble becomes unimodal.

**Keywords:** *molybdenum, ultrafine-grained structure, pulsed electron beam.*

## MODELLING OF THE DIFFUSION SATURATION OF METALS AND ALLOYS IN THE GLOW DISCHARGE PLASMA INSIDE A HOLLOW CATHODE

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The generation of low-temperature glow discharge plasma forms the basis of vacuum plasma technology that used for surface modification. In the hollow cathode with low-pressure nitrogen, the ion current density is required to keep of approximately  $1\text{mA}/\text{cm}^2$  on the treated target surface and the operating discharge voltage is prescribed of hundreds volt. The external injection of electrons provides a possible control of the discharge current and voltage whatever the used gas kind and its pressure. After 1–2 hours of nitriding in nitrogen inside the cathode, the microhardness on surface and by depth of steel increases more than 3 times.

The main parameters of plasma treatment include the gas composition or gas mixture ratio, temperature and time of the process, operating pressure, discharge parameters, the degree of the working gas dissociation and ionization, ion energy and ion current density on the treated target surface. It is important to control process of layer modification, reaching the specified behaviors of material.

This work models the processes of plasma generation in hollow cathode and metal diffusion saturation by nitrogen atoms in the plasma of a low-pressure non-self-sustained glow discharge. The model includes the mechanism of low-pressure glow discharge generation in the hollow cathode, the mechanism of mass transfer and the task corresponding information.

Mathematical model allows linking the technological parameters with the structure modified layer that is formed by the nitriding of metals and alloys.

Model results stay in an agreement with the experimental data and investigations of other researchers.

**Keywords:** *diffusion saturation of metal, glow discharge, hollow cathode, plasma, nitriding.*

## INVESTIGATION OF CERAMICS BASED ON CU-SN POWDER, OBTAINED BY PLASMA DYNAMIC METHOD

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Composites based on copper matrix are of a great interest in various applications. Copper-tin alloys are intensively investigated due to their thermal and chemical stability in combination with good mechanical properties. This work shows the possibility to obtain Cu-Sn ceramics by spark plasma sintering using nanoscale powders consisting of copper and tin, synthesized by plasma dynamic method. This method is implemented by using coaxial magnetoplasma accelerator with copper electrodes and adding the solid precursor (tin) in the accelerator before carrying out the synthesis process. The synthesized Cu-Sn powders were investigated by X-Ray diffractometry and transmission electron microscopy. It was determined that the final material consists of phase  $\text{Cu}_{41}\text{Sn}_{11}$ . Using this product, the bulk ceramics samples were obtained by spark plasma sintering at different temperatures (150 °C, 250 °C and 500 °C). The changes in microstructure of copper-tin ceramics in dependence on the sintering temperature were also studied. After analyzing all ceramics samples by X-Ray diffractometry and scanning electron microscopy methods, it was found that the optimal temperature for sintering Cu-Sn ceramics, which was made of the powder synthesized by plasma dynamic method, was equal to 250 °C at pressure 60 MPa. At these conditions, the ceramics sample had the lowest porosity with the smallest grain size.

**Keywords:** *coaxial magnetoplasma accelerator, copper-tin, high conductivity, ceramics.*

## PARTIAL OXIDATION OF NATURAL GAS TO SYNTHETIC GAS WITH AIR USING A LOW-CURRENT DISCHARGE IN GAS FLOW

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Partial oxidation to synthetic gas of natural gas composition in volume percent such as methane (C1) – 90.37, ethane (C2) – 3.23, propane (C3) – 1.133, butanes (C4) – 0.315, pentanes (C5) – 0.038, carbon dioxide – 0.424, nitrogen – 3.62, oxygen and argon – 0.87 was carried out using a low current glow discharge in a gas flow. The natural gas feeding varied in the range of 0.025–0.065 gram per second, and stoichiometric ratio was changed from 0.5 to 0.3. The ignition and maintenance of the discharge was carried out using a DC voltage source. The discharge power was changed in the range 100–400 watts.

The variation of the discharge power allows to reach the hydrogen concentration in the gas exiting the conversion of 15–16 and carbon dioxide of 10–11 volume percent (in terms of dry gas and STP). The use of the heating mode the gas and air entering plasmatron and placing after plasmatron output the stainless steel mesh allows to reach the hydrogen and carbon dioxide yield up to 20 and 12–14 consequently.

In some modes of operation in the reacting gases was observed unsaturated hydrocarbons (ethylene, acetylene, propylene, butylenes). Modes of reactions in which the content of acetylene in the reaction gases was about 1 with hydrogen concentrations of 17.7–19.6 and carbon dioxide of 13.0 was discovered. The conditions of the reaction where the hydrogen content in the reaction gases above 20, and there are no C<sub>2</sub><sup>+</sup> hydrocarbons were identified.

**Keywords:** *glow discharge, partial oxidation, catalyst, natural gas.*

## MODELLING OF THERMAL DIFFUSION PROCESSES IN ELECTRON-PLASMA TREATMENT

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In order to strengthen the material surface, the combined treatment method matching the electro-explosive alloying and the sequential irradiation of electron beam is applied in effect.

The electro-explosive alloying effects on material mechanical properties by modifying the structural phase state of the treated surface layer. The electron-beam posttreatment on the surface allows removing the dripping fraction of the powder material and controlling the concentration gradient of alloying element.

The surface electron-beam treatment comes with the diffusion of alloying element atoms into the material bulk. Energy characteristics (electron-beam power density and the number of action impulse) of the electron-beam treatment have a considerable influence on the material microhardness since its largest value owes to a specific range of alloying element concentration.

This work leads a mathematical modelling of electron beam treatment on metal surface layer after an electro-explosive alloying. Model includes the solving of the heat equation with a consideration of phase change and dependence of thermophysical coefficients on alloying element quantity and diffusion equation with coefficients depending on temperature.

This work also investigates the influences of electron-beam power density and number of action impulse on the gradient of copper concentration in steel exposed to electro-explosive alloying.

We obtained that at an electron-beam power density of  $15 \text{ J/cm}^2$  the copper concentration gradient formed after electro-explosive alloying does not change practically. At a power density of  $30 \text{ J/cm}^2$ , the copper concentration reaches 7–10 wt% with a layer width of  $14 \mu\text{m}$ . This range is optimal for microhardness of steel alloyed by copper based on experimental data.

**Keywords:** *thermal diffusion processes, electron-beam treatment, electro-explosive alloying, phase change.*

## EFFECT OF ION BEAM TREATMENT ( $\text{Ar}^+$ , $E=30$ KEV) ON THE MICROSTRUCTURE OF TITANIUM ALLOYS

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The effect of argon ions with an energy of 30 keV on the structure and properties of the samples (2.5–3 mm thick) of  $\text{Gr}_2$  and  $\text{Ti}_6\text{Al}_4\text{V}$  titanium alloys being in different initial states were studied in order to investigate the radiation-dynamic effects under ion irradiation and their possible use for the modification of the structure and properties of the titanium alloys.

The samples were irradiated with  $\text{Ar}^+$  ions in a continuous mode using an ILM-1 ion implanter, changing the exposure parameters: at ion energy  $E = 30$  keV, ion current density  $j = 200\text{--}500 \mu\text{A}/\text{cm}^2$ , and fluence of  $F = 10^{16}\text{--}2 \cdot 10^{18} \text{cm}^{-2}$ .

It was found that the initial microstructure retained after irradiation of the annealed alloys under selected conditions. In the case of the irradiation of  $\text{Ti}_6\text{Al}_4\text{V}$  alloy samples, the initial fine fiber structure was retained and the microhardness remained the same. Irradiation of the deformed  $\text{Gr}_2$  alloy samples with the initial fine fiber structure reduces its microhardness, which is associated with the recrystallization in the entire volume of samples, resulting in the formation of fine equiaxed grains of 5–10  $\mu\text{m}$  in size. Such radiation-induced annealing during ion bombardment occurs during heating of the samples to a temperature that is lower by 150–180  $^\circ\text{C}$  than the conventional annealing temperature of these alloys (680  $^\circ\text{C}$ ) and for a shorter time (10 min instead of 35 min). Thus, the possibility of rapid radiation annealing of the titanium  $\text{Gr}_2$  alloy with beams of accelerated ions of inert gas at low temperatures was shown.

**Keywords:** *ion irradiation, radiation-dynamic effects, titanium alloys, microstructure, microhardness.*

## PULSED ELECTRON BEAM HEATING OF TINI AND STAINLESS STEEL SPECIMENS CONTAINING SECONDARY PHASE INCLUSIONS

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In the present work, the simulations of temperature field during pulsed electron-beam irradiation of TiNi and 316L stainless steel specimens containing the  $Ti_2Ni$  and manganese sulphide MnS inclusions, correspondingly, has been carried out. Particularly emphasize of the modeling has been given to the simulation of temperature field in the places of location of the secondary phase inclusions. The calculations based on solution of two-dimensional nonlinear nonstationary heat conduction equation. It was shown, that the temperature field is nonuniform for the both types of specimens, and there is an overheating of material in the places of location of secondary phase inclusions but the degree of overheating is strongly depends on the interrelation between thermal properties of the inclusion and surrounding material. It was shown that the behavior of molten material strongly depends on interrelation of thermal properties of the inclusion and surrounding material also. The phase diagrams have been calculated for both type of specimens containing inclusions.

**Keywords:** *temperature field, electron beam, secondary phase inclusion.*



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**DYNAMICS OF TITANIUM SURFACE CHARACTERISTICS AFTER ITS TREATMENT  
BY RUNAWAY ELECTRON PREIONIZED DIFFUSE DISCHARGE**

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Data of dynamics of oxidized layer on titanium surface after its activation in diffuse discharge are presented. Calculation results of titanium surface free energy for different moments of time after plasma processing have been made. Possibilities of application of this type of discharge in some fields of science and technology have been shown.

**Keywords:** *titanium, surface free energy, oxidation, diffuse discharge.*

## STUDY OF TI-CU SURFACE ALLOYS FOR NEUTRON-GENERATING TARGETS OF GAS-FILLED NEUTRON TUBES

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Gas-filled neutron tubes produces fast neutrons in the  $T(D, n)4He$  or  $D(D, n)3He$  reactions. These tubes are a key part of neutron generators widely used for geophysics, security inspection systems, analytical and scientific applications. Neutrons born in collision of accelerated deuterium ions with deuterium or tritium atoms captured in the surface layer of neutron generating target. This target should operates in dynamic equilibrium mode, when ion implantation are balanced by deuterium desorption from the surface.

Micrometer-scale titanium layer on a copper substrate is commonly used as a neutron-generating target. Deuterium content in this layer should exceed  $nD/nTi = 1.5$  for achievement of nominal neutron yield of the tubes. Saturation of titanium layer by such ultimate content of hydrogen often caused flaking away the titanium layer.

A technology of multicomponent Ti-Cu surface alloys formation was applied for creation of flaking-resistant titanium film. Formation of surface alloys are performed using deposition of Ti films by means of magnetron sputtering followed by liquid-phase mixing with low-energy high-current electron beam (LEHCEB) of microsecond duration in a single vacuum cycle. The targets produced by discussed technology are studied by means of electron scanning microscopy and X ray diffraction analysis before and after irradiation by deuterium beam in the neutron tube. The targets demonstrated good resistance against flaking of titanium layer despite strong blistering and surface erosion. Formation of oriented crystal structure of copper substrate is discovered by X-ray diffraction analysis.

**Keywords:** *Neutron tubes, LEHCEB, titanium films.*

**MODELING OF PROCESS FORMATION OF THE NANOCOMPOSITE TiN-CU  
LAYERS RECEIVED BY VACUUM-ARC EVAPORATION  
OF Ti AND MAGNETRON SPUTTERING OF CU**

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The studies of new technologies for making composite layers with good plasticity and high hardness are of special interest. In connection with this, the approach of TiN-Cu composite coatings creating by pairing two discharge processes (vacuum arc evaporation of titanium in a nitrogen-containing plasma and ion-plasma sputtering of the copper target) is proposed. Features of the installation design that implements this approach, the variety forms of condensation surface, the heterogeneity of the streams density distribution and their characteristics in the working volume – all of this puts the geometric factors in a number of insufficiently studied parameters that significantly affect on the properties of the resulting coatings. In this work the modeling of the TiN-Cu layers deposition process on a substrate from fusing quartz under the set conditions is carried out. The calculations allow us to calculate the film thickness and uniformity of film on the substrate in the case where the substrate holder is positioned at an angle of 45 degrees to the normals of mutually perpendicular planes the evaporated titanium cathode and sputtering copper cathode of a magnetron. The thermodynamic modeling for identify mechanism and sequence of the phase transformations are considered. These transformations occur during the synthesis of TiN-Cu layers on fusing quartz at interaction of Ti, Cu and nitrogen with SiO<sub>2</sub> in the conditions of low pressure. The results of this work will be used to analyze the distribution speed of substance streams condensation and nature of the formed layers depending on geometry of the system cathode-substrate.

**Keywords:** *nanocomposite TiN-Cu, vacuum-arc evaporation, magnetron sputtering, phase composition, layers.*

## PLASMA MODIFICATION OF 3-D BIODEGRADABLE SCAFFOLDS TO IMPROVE SURFACE WETTABILITY

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3-D biodegradable polymer scaffolds are promising in repair of different defect parts of injured bone. The 3-D scaffolds prepared by a method of electrospinning have a wide range of physical properties and high porosity to promote successful penetration of osteoblasts into the scaffolds. However, synthetic biodegradable polymers as polycaprolactone (PCL) are hydrophobic in nature that leads to poor surface wettability of 3-D scaffolds and impedes the penetration of cell into the interior structure. Poor wettability and cell adhesion as a result of poor migration and proliferation of osteoblasts can impede bone regeneration process.

Plasma treatment is one of the most perspective methods to improve surface wettability and biocompatibility of polymers [1]. Investigation of 3-D scaffolds wettability using measurements of water contact angle showed significant changes of scaffolds wettability depending on reactive gas. Untreated scaffolds are hydrophobic with contact angle in range of 130–140°. The minor changes of wettability were revealed in the case of 3-D scaffolds treated in argon (~100°) or ammonia plasma (~120°). An improvement of 3-D scaffolds wettability took place after they were undergone to treatment in oxygen plasma due to grafting of hydrophilic functional groups on the surface. Water droplets penetrated into the porous 3-D scaffolds for less than 2 seconds.

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**Keywords:** *3-D scaffold, polycaprolactone, plasma modification, wettability.*

**THE NITRIDING OF VT1-0 TITANIUM ALLOY IN THE PLASMA  
OF NON-SELF-SUSTAINED GLOW DISCHARGE WITH  
THE LARGE AREA HOLLOW CATHODE**

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In the work a study of the results of nitriding of VT1-0 titanium alloy in the plasma of DC and pulsed non-self-sustained glow discharge at a separate potential bias of treated titanium samples from the hollow cathode was carried out. There were determined nitriding process speeds for different nitriding temperatures and different values of samples bias potential of VT1-0 titanium.

**Keywords:** *nitriding, VT1-0 titanium alloy, hollow cathode, non-self-sustained glow discharge.*

**PULSED ION BEAM INDUCED CHANGES IN A TOPOGRAPHY  
OF THE SURFACE LAYERS OF VT1-0 AND VT6 TITANIUM ALLOY**

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Samples were subjected to PIB impact on the TEMP. Irradiation was carried out by beam pulses containing 70 % of carbon ions and 30 % of hydrogen ions. The beam energy was 250 keV, the pulse duration was ~ 100 ns, and the current density in a pulse was 150–200 A/cm<sup>2</sup>. The energy density on the sample surface under the impact of a single pulse varied from 0.5 to 3.0 J/cm<sup>2</sup>.

The surface topography was checked by a Quanta 200 3D scanning electron microscope with thermal emission and a Quanta 600 FEG with field emission.

Traces of the ion beam impact in the form of a topographical feature, mainly concentric, were observed. Recesses of a crater form with more or less clear circular structure appear on the surface with the increase in the energy density to 1 and 3 J/cm<sup>2</sup>.

The average size of craters at the energy density of 1 and 3 J/cm<sup>2</sup> is  $\sim 20 \pm 2$  and  $25 \pm 2$   $\mu\text{m}$ , the density of craters (on irradiated surface) has made the order of  $5 \cdot 10^4 \text{ cm}^{-2}$ . Features of generated which structure (a drop phase, formation of crosspieces) are formed testify to course of processes of melting and fast crystallization. At an irradiation of VT6 by 1 pulse of beam (density of energy 1 J/cm<sup>2</sup>) on a surface of the sample forms microcraters with the average diameter about 2–3  $\mu\text{m}$  and depth 2–3  $\mu\text{m}$  too.

**Keywords:** *ion beam, surface topography, titanium alloy.*

## MODIFICATION OF SURFACE TI-FIBER BY AIR, NITROGEN AND ARGON PLASMA ON AIR

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Structural transformations on a surface Ti-fiber after its processing air, nitrogen and argon plasma on air are studied by means a Quanta 2002D scanning electron microscope with thermal emission. The surface structure of titanium before and after three types of plasma treatment have not changed, it consists of large crystals. The presence of porosity in the surface layer after treatment with plasma is not detected. After treatment of argon plasma on the surface of the titanium formed a single crater with a diameter of 2–3  $\mu\text{m}$  (2–3 crater 1 sq. mm surface).

After treatment with air plasma across the surface finish of titanium particles of flat shape with a size from 20–40 to 100–120 nm are formed.

Elemental composition has been determined in various areas of Ti-fiber surface before and after treatment with plasma.

**Keywords:** *plasma treatment, surface modification, titanium alloy,*

## MODIFICATION OF SURFACE PYROLYTIC GRAPHITE BY NITROGEN AND ARGON PLASMA ON AIR

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Structural transformations on a surface pyrolytic graphite after its processing nitrogen and argon plasma on air are studied by means a Quanta 2002D scanning electron microscope with thermal emission. On a surface pyrolytic graphite (after irradiation of nitrogen plasma) finds out craters circular forms in diameter from 1 up to 10  $\mu\text{m}$  in which particles from 10 up to 100 nanometers having the wrong form rare located. After irradiation of argon plasma on a surface pyrolytic graphite (on bottom of crater) are forming carbon ellipsoids.

**Keywords:** *plasma treatment, pyrolytic graphite, argon plasma.*



## NITRIDING OF TITANIUM ALLOY VT3-1 IN GLOW DISCHARGE WITH HOLLOW CATHODE

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Titanium alloys have various applications in modern industry due to great physical and technological properties such as low density, high strength, and great corrosion resistance. However, application of titanium alloys as design material is limited by low hardness and wear resistance. Ion nitriding is one of methods of titanium alloys surface hardening. Solid nitride film forms in titanium alloys surface due to nitriding negatively affects on diffusion rate of nitrogen into surface and leads to long process time. In this work we offer to use a glow discharge with hollow cathode for effectively ion nitriding of titanium alloys in high-density plasma. Effective ion bombardment of a surface allows to sputter a nitride film and to accelerate the diffusion process. Microhardness test of nitrided samples showed that surface microhardness increased up to 100–150 HV comparing to conventional nitriding. Microscopic examination of nitrided samples of VT-3-1 showed presence of nitride layer and diffusion zone. Process had leads to titanium nitrides of various stoichiometry (TiN, Ti<sub>2</sub>N) formation. From analysis of obtained data revealed the ion nitriding in glow discharge with hollow cathode leads to effective wear resistance and other mechanical properties improvement. Therefore, it is an effective way to better the operational properties of parts of VT-3-1 titanium alloy.

**Keywords:** *glow discharge, hollow cathode, ion nitriding, Titanium alloys, VT3-1.*

## HARDENING ROLL SURFACE BY PLASMA NITRIDING WITH SUBSEQUENT HARDFACING

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Studied and simulated wear of the surface layer of rolls after ion nitriding in glow discharge, followed by a coating of TiN – TiAlN plasma arc. Simulated stress-strain state of the material rolls under asymmetric rolling with ultra-high shear deformations. The effect of thermal fields, formed upon contact of the tool and a deformable sheet, the structure of aluminum alloys.

**Keywords:** *ion nitriding, glow discharge, coating of TiN – TiAlN, vacuum arc plasma.*

**INVESTIGATION OF SiC CERAMICS, MODIFIED BY INTENSE ELECTRON BEAM**

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SiC ceramics is widely used in a different branches of industry [*Gnesin G.G. Silicon carbide materials, Metallurgiya, Moscow, 1977, Luchinin V., Tairov Ju. // Nanoindustrija. – 2010. – Vyp. 1. – S. 36–39*]. SiC has the property to crystallize in different modifications (polytypes) [*Andrievskij R.A. // Uspehi himii. – 2009. – № 78 (9). – S. 889-900*].

The work purpose is studying of structural-phase transformations in the surface layer of SiC ceramics, subjected to intense electron beam with parameters: 15 keV, 10, 15, 20 J/cm<sup>2</sup>, 200 μs, 3 pulses; gas pressure (argon) in the chamber was 10<sup>-2</sup> Pa.

SiC powder (average particle size of 0.9 microns) with the addition of 1 wt.% of SiC nanopowder was used for producing ceramics.

Samples of ceramics consolidated by the SPS method at following modes: temperature 2100 °C, pre-pressing 70 MPa, duration 10 min. Microstructure and phase transformations, physical-mechanical properties versus conditions of electron beam irradiation were carried out at the TPU Nano-Centre.

The nanostructuring of the surface layer (crystallite sizes from 10 to 30 nm) was revealed after irradiation by the electron beam with the energy density 15 J/cm<sup>2</sup>. It was shown that irradiation of SiC ceramics is accompanied with appropriate changes of the surface layer polytype composition in comparison with the initial one. Decreasing of the β-SiC (6H) polytype content was about two times at beam energy density 10 J/cm<sup>2</sup>, but increasing of such content was about two times at the beam energy density 20 J/cm<sup>2</sup>. The reasons of such behavior are discussed.

Thus, irradiation of SiC ceramics by the intensive electron beam allows to vary the polytype composition of surface in wide range; it leads to change of mechanical properties.

**Keywords:** SiC, ceramic, electron, beam, SPS.

## DAMAGES ON PURE TUNGSTEN IRRADIATED BY ELMS-LIKE TRANSIENT HIGH HEAT FLUX FROM VARIOUS DEVICES

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Pure tungsten are candidates of plasma facing materials (PFMs) in the tokamak divertor. PFMs will be subjected to transient high heat load from edge localized modes (ELMs) that will reduce the working life of the material, and the ablation products can have harmful effects on core plasma. There are many experimental devices over the world to simulate the thermal effects of ELMs, including plasma beam(QSPA-T,QSPA Kh-50,CPFs), intense pulse electron beam(JUDITHI & JUDITHII, EMS-60), intense pulse ion beam(TIA-450, BIPPAB-450). Heat flux density, heat flux parameter, or bulk density of heat deposition are usually used as benchmarks to estimate the thermal damage effects of heat pulses from different devices. However, the parameters of thermal pulses may span several magnitudes, so that is not possible to have an universal description for their effects with one benchmark. So this paper compared damages on pure tungsten irradiated under different devices common parameters with heat flux parameter as a reference. The comparison was made based on aspects including temperature distribution, thermal stress distribution, crack, crack network and melting. According to the result of comparison, it is too rough to evaluate the overall thermal damage effect with single benchmark, and it is best to consider respectively individual thermal damage effect. So this paper discussed respectively equivalence of crack and melting from various devices.

**Keywords:** *pure tungsten, transient thermal load, heat flux parameter, temperature distribution, thermal stress distribution, crack, melting.*

**RESEARCHES OF INFLUENCE OF MOBILE CATHODIC STAINS  
OF THE VACUUM ARC FOR RECEPTION OF THE ADJUSTABLE ROUGHNESS  
OF METAL SURFACES**

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In the modern technics there is a requirement in micro- and macrorough surfaces of products for improvement of their operational characteristics (improvement of adhesive properties of various coverings, decrease in deterioration of rubbing details because of the best deduction of greasing, increase of the heat exchanging coefficient from a surface, stimulation of adhesive processes on sites of contact to a bone fabric of medical implants in stomatology and orthopedy etc.).

In the given work the modes of reception regulated micro- and macrorough surfaces on samples from a titanic alloy and stainless steel by electrothermal influence of moving cathodic stains in the vacuum arc discharge are investigated. Chaotically moving stains, possessing high specific power allocation ( $\sim 107 \text{ W/cm}^2$ ), «scan» the difficult design of a product, including «shadow» sites, doing rough its blanket. The sizes of roughnesses are regulated by a current and time of influence of the discharge, pressure in the vacuum chamber and a number of other parameters.

The scheme of experimental device, photo and the characteristic of rough surfaces and technological modes of their reception are resulted.

**Keywords:** *VACUUM ARC, CATHODIC STAINS, ROUGHNESS OF METAL SURFACES.*

## THE STRUCTURE OF NITI SURFACE LAYERS AFTER THE TANTAL ION PLASMA ALLOYING

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The ion beam implantation is an effective method for the deposition of thin protective layers on the surface of NiTi alloys. The purpose of the given study is investigation of the surface layer structure of Ta-ion beam modified material on the micro- and nanoscale levels. The effect of the Ta-ion beam implantation on the surface layers was investigated using TEM on cross-section samples. The ion modification was performed on an ion implanter 'DIANA-3' using pulsed Ta-ion beams; the fluencies  $D = 3$  and  $6 \times 10^{17} \text{ cm}^{-2}$ ; the average accelerating voltage 80 KV and pulse repetition frequency 50 Hz. It was found that the modified surface layer is composed of an upper oxide sublayer and a lower-lying amorphous layer. The oxides of 20-30 nm thick is nanocomposite ceramic containing  $\text{TiO}_2$  and  $\text{Ta}_2\text{O}_5$ , which enhance the biocompatibility, non-toxicity and absorptive capacity of as-treated NiTi. The lower-lying amorphous layer of  $\leq 100$  nm thick includes two sublayers: an implanted Ta layer 30–40 nm thick and a lower-lying zone. The maximal Ta concentration is found to occur at depth 50–60 nm. The relative content of different oxides and elements distribution in modified surface layer with depth are determined by the treatment regime.

**Keywords:** *NiTi, Ion implantation, Surface layers structure, Oxides, Amorphous layer.*

## ADVANCED HARD NANOCOMPOSITE COATINGS: ROLE OF ENERGY

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The lecture is divided in five parts. The first part reports on the enhanced hardness, the thermal stability of nanocomposite coatings and the formation of the X-ray amorphous coatings with thermal stability and oxidation resistance above 1000 deg C using sputtering. The second part is devoted to flexible hard nanocomposite coatings with enhanced toughness and enhanced resistance to cracking. The principle of the formation of flexible hard coatings with enhanced resistance to cracking is explained [Musil J.: *Hard nanocomposite coatings: Thermal stability, oxidation resistance and toughness*, *Surf. Coat. Technol.* 207 (2012), 50–65, Musil J.: *Flexible hard nanocomposite coatings*, *RSC Advances* 5 (2015), 60482–60496]. It is shown that a key role in formation of the flexible coatings plays the energy delivered during their growth. As examples, the robust, flexible antibacterial coatings with long lifetime and the protective over-layers preventing to cracking of hard brittle coatings are given. Reported results can be used in the development of the flexible ceramic coatings, the surface strengthening of brittle materials, the prevention of cracking of functional coatings and the cracks formation on surfaces of bended materials. The fifth part explains the principle of the formation of nanocrystalline and crystalline films on unheated substrates. At the end, trends of next development of the advanced hard nanocomposite coatings with unique properties are outlined.

**Keywords:** *Advanced nanocomposite coatings, Unique properties, Role of energy.*

## FORMATION OF SURFACE TI-TA ALLOYS ON TINI SMA SUBSTRATE BY COMPLEX ION-PLASMA AND LOW ENERGY HIGH CURRENT PULSED ELECTRON BEAM TREATMENT

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The nearly equiatomic TiNi alloys are unique biomedical metallic materials due to combination of their properties – high level of superelasticity and high corrosion resistance. Two main important factors limiting their use are (i) high toxic nickel content; (ii) insufficient level of fatigue performance for TiNi vessel implants (stents, etc.). The aim of this work was to study the prospects for the use of combined ion-plasma and low energy high current pulsed electron beam treatments to create a thin (1–2 μm) barrier surface layers of nickel-free Ti-Ta superelastic alloys on the surface of TiNi substrate.

Electron-beam setup «RITM-SP» (Microsplyav, Russia) in combination with a magnetron setting was used for forming of the Ti-Ta surface alloy on the base of principle of additive technology. Integral «Ti-Ta SA» (SA – surface alloy) with thickness of ~1 μm was formed by repeating of electron beam melting of the thin Ti-30 at.%Ta layer (~ 50 nm) magnetron deposited on the TiNi substrate.

The chemical composition, structure and mechanical properties of the surface and near-surface layers of the Ti-Ta/TiNi composite alloy were investigated with the aid of SEM/EDS/EBSD, TEM/EDS/SAED, XRD and NTD techniques.

It is found that in the «Ti-Ta SA» the ratio of Ti:Ta is 65:35 and the nickel content is less than 10 at%. This layer consists of a (quasi-)amorphous matrix with nanophase/nanopores inclusions. We discuss mechanisms of formation amorphous-nanocrystalline structure of the synthesized layer on the base of the ternary Ti-Ta-Ni system.

This work was funded by a grant RSF № 15-13-00023 (18.05.2015).

**Keywords:** *surface modification, low energy high current pulsed electron beam, magnetron deposition, Ti-Ta and TiNi shape memory alloys, amorphous and nanophase structure.*



## VACUUM-ARC DEPOSITION OF METAL-LIKE CARBIDE COATINGS

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For the production of coatings vacuum-arc discharge existing in the vapors of the cathode material is frequently used. Metal-like carbides, built as an implementation phase of the carbon atoms in the crystal lattice of the transition metals, are widely used in many fields of modern technology.

Analysis of the plasma flux composition during the process of coatings deposition was carried out using emission spectral analyzer. On spectrograms spectral lines of the excited neutral atoms, singly and doubly charged metal ions and singly charged carbon ions were detected. Introduction of the benzene vapors into the plasma flux significantly modifies the emission spectrum, affecting the charge composition of the metal plasma and the concentration of the metal in the implementation of the plasma-chemical synthesis.

Deposited titanium carbide and zirconium carbide coatings have a well-formed crystalline structure, while on the diffraction patterns all the lines with maximum intensity are recorded. Phase diagrams of the systems of the transition metals titanium and zirconium with carbon are very similar to each other, thus they are characterized by only one carbide phase.

The use of vacuum-arc plasma sources allows synthesis of the transition metals carbides with constant phase composition and high adhesion. It was obtained that a significant part of the carbide phases of transition metals has a wide area of homogeneity and by controlling parameters of the plasma flux it is possible to regulate the properties of the formed coatings and to obtain coatings with high performance properties.

**Keywords:** *vacuum-arc discharge, coating deposition, plasma flux, carbide compounds.*

**COATING SYNTHESIS ON DIELECTRIC SUBSTRATES ASSISTED  
BY PULSED BEAMS OF HIGH-ENERGY GAS ATOMS**

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Coatings of titanium nitride and aluminum nitride have been deposited on glass and aluminum oxide substrates in a flow of metal atoms accompanied by high-energy gas atoms. The metal atoms are produced due to sputtering a flat rectangular magnetron target. The gas atoms with energy up to 25 keV are produced due to charge exchange collisions of ions extracted from the magnetron discharge plasma and accelerated by high-voltage pulses applied to a grid being parallel to the target. The metal atoms pass through the grid and deposit on the substrate. Conjunction of their trajectories with those of gas atoms bombarding the growing coating allows the coatings synthesis on complex shaped dielectric products planetary rotating inside a vacuum chamber. Mixing by high-energy gas atoms of the coating atoms and atoms of the substrate material in its surface layer substantially improves the coating adhesion.

**Keywords:** *coating, synthesis, adhesion.*

## TEXTURE AND MICROSTRUCTURE DEVELOPMENT IN RF MAGNETRON SPUTTER DEPOSITED HYDROXYAPATITE COATINGS

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The formation of dehydroxylated hydroxyapatite (HA) in the coatings deposited within radio frequency (RF) magnetron sputtering is considered as one of the obstacle of this method. The presence of OH-groups forming channels along c-axis in the hexagonal HA lattice is essential for HA structure formation. Absence or reorientation of OH-ions lead to structural changes, in particular to its decomposition and amorphization [1, 2]. Therefore, investigation of the influence of water content in the working atmosphere on the structure development of the RF-magnetron sputter deposited HA coatings is an urgent goal which is chased in this study. Furthermore, RF-magnetron sputtering is a line-of-sight deposition process where sputtered material is directed from a target towards a substrate. Therefore, the spatial arrangement of treated samples regarding the sputtered target is one of the parameters, which might influence the features of the formed films. This work was attempted to elucidate the fundamental aspects of RF-magnetron sputter deposition of HA thin films and to comprehend the relation between coating microstructure, texture and deposition conditions.

This work was supported by «Special Research Fund» (BOF) from Ghent University and the Russian President Fellowship MK-7907.2016.8, state-order NAUKA (#1359).

**Keywords:** *magnetron, sputtering, texture, hydroxyapatite.*

## PRODUCT SURFACE HARDENING IN NON-SELF-SUSTAINED GLOW DISCHARGE PLASMA BEFORE SYNTHESIS OF SUPERHARD COATINGS

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To prevent elastic and plastic deformation of products with thin superhard coatings and the coating brittle rupture, the product surface should be hardened before the coating synthesis. It can be carried out by plasma nitriding, because the nitrated subsurface really exhibits a high loadbearing capacity and fatigue strength. Customary the product heating by ions accelerated from the plasma by applied to the product bias voltage to a temperature of effective nitrogen thermodiffusion leads to overheating and blunting of the product sharp edges. To prevent the blunting it was proposed to heat the products with a broad beam of fast nitrogen molecules. The beam injection into the working vacuum chamber results in filling the chamber with quite homogeneous plasma suitable for nitriding. Immersion in the plasma of an electrode and increasing its potential up to 50–100 V initiates a non-self-sustained glow discharge between the electrode and the chamber. It enhances the plasma density by an order of magnitude and decreases its spatial nonuniformity to 5–10 %. When a product with sharp edges immersed in the plasma, for instance cutting tool, is isolated from the chamber, it is bombarded by plasma ions with energy corresponding to its floating potential, which is lower than sputtering threshold. Hence its sharp edges are sputtered by homogeneous beam of fast nitrogen molecules with the same rate as other parts of the surface. It leads to the cutting tool sharpening instead of blunting.

**Keywords:** *synthesis of superhard coatings, surface hardening, plasma nitriding, non-self-sustained glow discharge.*

## FEATURES OF DEFORMATION AND FRACTURE OF HOMOGENEOUS AND GRADIENT-LAYERED NANOSTRUCTURED COATING BASED ON TITANIUM NITRIDE DURING THE TRIBOLOGICAL TESTS

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The aim of this work is investigation of tribological properties and microstructural characteristics of deformation and fracture of the titanium nitride coatings doped with Al, Si, Cu or Al, Si, Cr, Mo, S with different structure type after deposition: with submicron and nanoscale columnar grains or combined structure comprising in addition to the previous surface nanocomposite layer. For both types of coatings the heterogeneous nature of the deformation, as in the surface plane of the coatings and perpendicular to it section was established. In the least deformed parts of the coatings a structure is maintained with an increase in comparison with the state after the deposition of elastic (in the nano-sized fragments) and elastic-plastic (on the size of subgrains) bending-torsion of the crystal lattice and the level of residual stress. The development of strain in the deeper layers of columnar coatings leads to the formation of single-phase areas of the nanocrystalline structure, and on the friction surfaces – amorphous or nanocrystalline heterophasic tribofilms. It was found that at small degree of wear the interfaces of layer structure and nanocrystalline surface layer are sites of crack initiation, whereas with increasing wear they are areas of preferential inhibition of radial cracks along the boundaries of the columnar crystals and propagation of the inclined cracks, intense branching which occurs at the nanocrystalline layer. The differences in the patterns of deformation and fracture of the investigated coatings reflect lower plastic coatings with MoS<sub>2</sub>, which is related with a higher dispersion of their structure.

**Keywords:** *single and gradient-layered coatings, tribological test, electron microscopy, defect structure.*

## MODERN TRENDS IN THE DESIGN COATINGS OF THE CONSTRUCTIONAL APPLICATION

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The paper presents a review of current methods for improving cohesive strength of the coatings made from amorphous carbon (DNG/AM type materials), nanocomposite coatings, given their comparatively high hardness ( $H\mu > 15\text{--}20$  GPa), wear resistance and low friction coefficient ( $\mu \leq 0.2$ ).

The main idea of their synthesis is thought to be self-organization of their microstructure during simultaneous nucleation of the growth islands of a number of mutually insoluble or slow-soluble phases.

The method for predicting the composition of an alloy consists in the selections of elements ensuring the following:

- Multiphase nature of coatings with little difference in the phase-formation heat
- Possibility of relaxation of internal stress concentrators at the phase boundaries and formation of nanocrystalline high-plasticity phases
- Decrease in grain-boundary sliding by the developed system of phase boundaries
- Doped with carbon, nitrogen or copper with the achievement of  $H\mu \approx 15\text{--}20$  GPa, the metal coatings (Zr, Hf, Nb, V, Y) with a low ( $E \sim 70\text{--}120$  GPa) modulus of elasticity
- Doped with carbon and nitrogen high entropy coatings
- Decrease in the elasticity modulus and minimum difference with the substrate (product) elasticity modulus.

The PVD methods deposition of the coatings typically used at  $T_s \leq T_m/3$  and combined with ion-plasma treatment using independent gas-ion sources of the PINK type and multi-elemental magnetron cathodes in the SPRUT and LEGEND facilities.

The paper discusses the results of investigations, which support the proposed approach to designing multi-elemental nanocomposite coatings, and principles for selecting their compositions.

**Keywords:** *cohesive strength, nanocomposite coatings, self-organization of the microstructure, approach to the selection compositions.*

## INFLUENCE OF REPETITIVELY-PULSED PLASMA IMMERSION LOW ENERGY ION IMPLANTATION TO TIN COATING PROPERTIES FORMATION

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Application of high frequency short pulse plasma immersion low energy ion implantation for titanium nitride coating deposition using vacuum arc metal plasma and hot-cathode gas-discharge plasma on R6M5 alloy was investigated.

Using of negative repetitively pulsed bias with amplitude of 2 kV, pulse duration 5  $\mu$ s and pulse frequency 100 kHz leads to 6.2 fold decrease of vacuum arc macroparticle surface density for macroparticles with diameter less than 0.5  $\mu$ m. Ion sputtering reduces the coating deposition rate approximately by 30 %.

It was found that with bias amplitude range from 1.1 to 1.4 kV and pulse duration 5  $\mu$ s yields to formation of coatings with average hardness 26 GPa and local values up to 40 GPa. This paper presents the results of experimental studies of adhesion, tribological properties and surface morphology of deposited TiN coatings.

**Keywords:** *titanium nitride coating, vacuum arc, negative high-frequency short-pulsed bias.*

## SAND-BLASTING TREATMENT AS A WAY TO IMPROVE THE ADHESION STRENGTH OF HYDROXYAPATITE COATING ON TITANIUM IMPLANT

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The sand-blasting (SB) and acid-etching (AE) treatments of titanium (Ti) implants are widely used prior the deposition of the hydroxyapatite (HA) coatings for the improvement of surface characteristics, thus increasing life expectancy of implants. Our previous study have assessed the effects of SB at different pressures on grain size, mechanical properties and surface wettability of radio frequency (RF) magnetron silver-containing HA coating and revealed that the coating microstructure could be designed by controlling the pre-treated Ti surface topography. However, the type, size and geometry of the sand particles are also important factors determining the result of the treatment. Therefore, in the current study, the effect of SB particle size (50 and 250–320  $\mu\text{m}$ ) on the surface structure, roughness, wettability, mechanical properties, and adhesion failure at the interface of RF magnetron deposited HA coating is studied.

**Keywords:** *sand-blasting, acid-etching, titanium, hydroxyapatite, biocomposite, adhesion.*



## ELECTROCONDUCTIVE GRAPHENE-HYDROXYAPATITE PVD TARGETS FOR MAGNETRON SPUTTERING

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To sputtering of dielectric target it is developed a number of devices operating at a higher frequency. Similar equipment is currently used quite successfully, but many users say that it have enough high cost and a certain «moodiness».

In MSTU «STANKIN» was developed a way to create new composite materials, containing in its composition graphene and the non-conductive matrix, in which it turns some various types of ceramics. The developed method allows several orders of magnitude to increase the conductivity. The method consists in the excellent combination of the methods of colloid (wet) mixing of the powders and spark plasma sintering.

Applying this technology we want to demonstrate on the example of creating a target of powdered calcium hydroxyapatite with the addition of graphene oxide intended for deposition of coatings on implants for the purpose of increasing their biocompatibility, which will meet modern requirements.

**Keywords:** *Magnetron target, Spark plasma sintering, Calcium hydroxyapatite, Graphene.*

**PHASE EQUILIBRIUM IN SYSTEM TI-SI-C-O AND SYNTHESIS  
OF MAX PHASES LAYERS IN VACUUM UNDER INFLUENCE  
ELECTRON BEAM**

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The new vacuum technology of protect coating formation on a basis of complex carbides is offered.

The thermodynamic modeling in system Ti-Si-C-O was executed with the computer system TERRA. The calculations were carried out in a temperature of 673–2473 K and in pressure range  $10^5$ – $10^{-4}$  Pa.

The sequence of the chemical transformations at MAX phase's synthesis, namely, the oxides → the silisides → the carbides is established.

Phase equilibriums in systems TiO<sub>2</sub>-Si-C are calculated. Fields of crystallization of all possible phases, and also influence of temperature and pressure upon their behaviors are established.

MAX phases coatings of a various thickness from 30 to 500 microns are generated. Mechanisms of complex carbides formation and coating on their basis for titanic alloy VT-1 are discussed.

**Keywords:** *MAX phases, coatings, Thermodynamic modelling, Electron beam, Treatment.*

## FEATURES OF PROCESSES OF ION-PLASMA FORMATION AND COMPARATIVE ANALYSIS OF THE PROPERTIES OF THE ANTI-FRICTION COATING TI-C-MO-S ON TITANIUM ALLOYS AND STEELS

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A new design-engineering trend in domestic manufacture is the slide bearings production, made of different alloys and of various purposes, with solid anti-friction coating. In this article specific techniques of magnetron ion-plasma formation of Ti-C-Mo-S anti-friction coating on VT-6, VT-14 titanium alloys and 40X, 20X13 hardened steels are provided and described. Application of integrated process of magnetron sputtering and assisting influence of gas-discharge plasma, generated by PINK, allows to maintain set-point coating synthesis temperature. It matters for hardened alloys – preventing tempering and durability properties loss. Additional operation of magnetron ion-plasma pre-doping of surface layer of substrate prior to coating deposition affords to make supportive hierarchically organized structure of substrate-coating composition. Combination of two mentioned technological methods enhances the controllability of coating properties.

Comparative researches on physical and tribological characteristics of this composition formed on surfaces of different materials were conducted. In the researches the following methods were used: methods of metallography and optical microscopy; friction tests using «CSEM High Temperature Tribometer»; method of measuring tracks depreciation using «Micro Measure 3D station»; examination coating and friction tracks structure using «Tescan Vega 3» scanning microscope. Distinctions in physical and tribological characteristics were figured out in dependence to substrate material. Interrelation between tribological characteristics and physical properties of substrate-coating composition was established and it is determined as by the substrate properties as well as by the parameters of surface pretreatment for coating deposition. Optimal receptions and pretreatment provides high coating adhesion; friction coefficient is about 0.1 and material wear resistance is increasing.

**Keywords:** *Slide bearing, Solid anti-friction coating, Ion-plasma coating, Magnetron sputtering, Friction tests.*

## INFLUENCE OF MICROSTRUCTURE AND SURFACE TOPOGRAPHY ON THE ELECTRICAL CONDUCTIVITY OF CU AND AG THIN FILMS OBTAINED BY MAGNETRON SPUTTERING

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Conductive thin films formation by copper and silver magnetron sputtering is one of the high technology areas at industrial production of solar energy converters, energy-saving coatings, flat panel displays and touch control panels due to their high electrical and optical properties.

Surface roughness and porosity, average grain size, internal stresses, orientation and crystal lattice type, the crystallinity degree are the main physical properties of metal films influence their electrical resistivity and conductivity.

Depending on the film thickness the dominant conduction mechanism can act bulk conductivity due to the flow of electron gas, and grain boundary conductivity.

This investigation assesses the effect of microstructure and surface topography on the electrical conductivity of magnetron sputtered Cu and Ag thin films using X-ray diffraction analysis, scanning electron and laser interference microscopy.

Highest specific conductivity (78.3 and 84.2 mega siemens per meter for copper and silver films at a thickness of 350 nm, respectively) are obtained with the minimum values of roughness and grain size as well as a high degree of lattice structuredness.

**Keywords:** *Copper, Silver, Thin films, Electrical conductivity, Roughness, Grain size, Magnetron sputtering.*

**SYNTHESIS OF SILICON-CONTAINING COATINGS  
BY TETRAETHOXYSILANE AEROSOL POLYMERIZATION IN PLASMA  
JET FORMED BY LOW-CURRENT PULSED DISCHARGE  
AT ATMOSPHERIC PRESSURE**

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The silicon-containing coatings ~100 nm thick on the metal and polymer samples were obtained at atmospheric pressure and room temperature using a liquid monomer input as a fine mist into a cold atmospheric plasma followed by plasma deposition of the coating. The spark discharge in a nitrogen flow in a coaxial electrode system was applied as a source of atmospheric pressure plasma stream. Tetraethoxysilane (TEOS) aerosol was formed by pneumatic nebulizer using argon as the carrier gas. The possibility of the coating deposition with the inhomogeneity of the thickness no more than a few percent at the surface area of ~100 cm<sup>2</sup> with a diameter of the plasma stream ~1 cm due to the blowing of the active mixture along the surface of the sample without special means moving the sample or plasma source was experimentally demonstrated. The coatings growth conditions at floating potential of the surface for metallic and polymeric substrates were defined. The composition of the formed coatings was investigated by FTIR-spectroscopy. Roughness and friction coefficient of the samples before and after coating deposition were measured by scratch-testing.

**Keywords:** *Cold atmospheric Plasma, Silicon-containing coatings, Aerosol-assisted plasma deposition.*

## CHARACTERIZATIONS OF NITROGEN-DOPED TITANIUM DIOXIDE FILMS PREPARED BY REACTIVE MAGNETRON SPUTTERING DEPOSITION

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Titanium dioxide ( $\text{TiO}_2$ ) and N-doped  $\text{TiO}_2$  films are very promising for applications as photocatalysts and bio-implants coatings due to their appropriate properties [1].  $\text{TiO}_2$  films can be fabricated by reactive magnetron sputtering method. The question about phase composition of deposited coating arises as  $\text{TiO}_2$  has three crystalline forms: anatase, rutile, and brookite. Anatase is known as an effective material for photocatalysis, whereas rutile is more chemically stable in the solutions and can improve the biocompatibility of implants.

This work presents the research results of the structural and phase change of  $\text{TiO}_2$  films deposited by reactive magnetron sputtering at various modes: different working gases ( $\text{Ar}+\text{O}_2+\text{N}_2$ ) and bias. The structure of the films was characterized by X-ray diffraction, Raman spectroscopy, and XPS surface analysis.

The data demonstrate that the main phase of the films is  $\text{TiO}_2$  despite the presence of nitrogen in its composition. Nitrogen incorporation initiates the increase of rutile volume fraction from 38 % to 68 % in the films during their growth. N-doping (like bias) acts on the microstructure of the films. The grain structure is crushed. Analysis of the results is carried out in the frame of the structure zone models (SZMs) which systematically categorize self-organized structural evolution during physical vapor deposition as a function of film growth parameters.

**Keywords:** *Magnetron, Sputtering,  $\text{TiON}$  films.*

## IMPROVEMENT OF THE MAGNETRON SPUTTERED COATING ADHESION THROUGH PULSED BOMBARDMENT BY HIGH-ENERGY IONS

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Comparative study of titanium nitride coatings deposition has been carried out, the growing coatings being uninterruptedly bombarded by ions with energy of about 100 eV or with ions accelerated by applied to the substrate high-voltage pulses. The pulses width was regulated from 10 to 50  $\mu$ s, their frequency – from 10 to 50 Hz and amplitude – from 5 to 25 kV. The study revealed that microhardness of 5–7- $\mu$ m-thick coatings synthesized on hard-alloy substrates with application to the substrates of 25 kV pulses rises from 2100 HV40 to 2900 HV40 when percentage of the nitrogen in mixture with argon increases from 15 % to 20 %. With a further increase of nitrogen percentage to 25 % and 30 % the microhardness slightly diminishes to 2800 HV40 and 2700 HV40, respectively. In contrast to golden coatings synthesized at an uninterrupted bias voltage of 100 V, the color of titanium nitride coating produced using high-voltage pulses is dark brown. The most striking difference of coating produced using high-voltage pulses applied to the substrates is possibility to form the transitional layer between the substrate and the coating, which defines its adhesion, at the room temperature without preliminary heating and activation. It was found using for the adhesion characterization a scratch-tester that critical loads of coatings synthesized using 25-kV pulses are 4 times higher than in the case of conventional nitride coatings synthesized at uninterrupted biasing of the substrates. When the pulses amplitude decreases to 5 kV, the critical loads and microhardness of the coatings diminish to conventional values.

**Keywords:** *magnetron, high-energy ions, coating, adhesion.*

## CALCIUM PHOSPHATE COATINGS MODIFIED WITH ZINC- OR COPPER-INCORPORATION ON Ti-40Nb ALLOY

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Materials used for implants should have not only high strength properties (yield strength, ultimate strength, fatigue strength, cycle life, wear resistance, etc.), but also low elastic properties, such as elastic modulus. Accordingly, the most promising research area in medical materials science is the application of  $\beta$ -titanium alloys with low elastic modulus, for example, Ti-Nb or Ti-Nb-Zr systems. To provide reliable osseointegration of bone tissue-implant interface integration, the implant surfaces are covered with bioactive calcium phosphate (CaP) coatings. During the last few decades, microarc oxidation (MAO) method is being widely used as electrical and chemical surface treatment for formation of oxide and CaP coatings on metals.

The influence of the microarc oxidation parameters as electrical voltage and electrolyte composition on the structure, properties and composition of CaP coatings modified with Zn- or Cu-incorporation on the Ti-40mas.%Nb (Ti-40Nb) alloy has been investigated. The linear growth of thickness, roughness, and size of structural elements with increasing process voltage has been revealed. It was shown that CaP coatings have low contact angles with liquids and, as consequently, high free surface energy. It indicates a high hydrophilicity. X-ray diffraction analyses showed that the coatings have X-ray amorphous structure. Increase in the process voltage leads to the formation of crystalline phases into the coatings such as CaHPO<sub>4</sub> and  $\beta$ -Ca<sub>2</sub>P<sub>2</sub>O<sub>7</sub>. The maximum Ca/P atomic ratio equaled to 0.6, and Zn or Cu contents equaled to 0.3 or 0.2 at.%, respectively.

**Keywords:** *Microarc oxidation, Calcium phosphate coatings, Ti-40Nb alloy.*



## THE DYNAMIC SUBLAYERS FOR IMPROVING THE ADHESION OF CVD DIAMOND FILMS ON COPPER

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The dynamic sublayers for improving CVD diamond coatings adhesion on copper substrates have been used. Variable thickness sublayers of Al/Cu/Cr, were sequentially deposited on a copper substrate. Aluminum layer was used as the dynamic melting sublayer, copper layer was used as carbon diffusion barrier and Cr layer was used as «new» substrate for polycrystalline diamond film synthesis. Influence of each sublayer thickness on the diamond film adhesion to copper substrate was studied. In addition, the effect of copper sublayer thickness on the aluminum carbonization was studied. The polycrystalline diamond films obtained were characterized by scanning electron microscopy (SEM) and X-ray diffraction (XRD). Element distribution by thickness of the sample was studied by Auger electron spectroscopy (AES).

**Keywords:** *CVD synthesis, CVD diamond, dynamic sublayers.*

## TiC-BASED COATINGS DEPOSITION USING ELECTRIC DISCHARGED PLASMA

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The aim of this work was to research the possibility of using coaxial magneto plasma accelerator for TiC-coatings deposition on steel substrates. As a result, coatings with 0.01 m<sup>2</sup> area was deposited. They were researched using XRD, SEM and nanohardness on cross section of coating was measured. The influence of energy and carbon load on phase content, average hardness and microstructure is shown. It is established that the finest microstructure and average nanohardness is 15.3 GPa are achieved at energy  $W = 46.7$  kJ and carbon load 2.0 g.

**Keywords:** *Arc discharge, High speed plasma flow, Titanium carbide, Coating deposition.*

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**EFFECT OF VARIOUS METHODS AND CONDITIONS OF VACUUM  
ION PLASMA DEPOSITION ON SILICON COATINGS ADHESION**

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The paper presents the results of a study of adhesive properties of the silicon coatings obtained using various methods and conditions of vacuum preliminary ion-plasma treatment of the substrate surface to magnetron deposition. The experiments used pre-treatment (clearing) of the substrate surface by low-energy ion beams, high-energy ion beams, gas discharge plasma and plasma magnetron-sputtering system. Vacuum conditions (pumping method, pressure, etc.), substrate ion current density and the parameters (frequency and duration of pulses) of substrate bias voltage are varied. It was found a great effect of plasma immersion implantation processes to obtain high adhesion properties of coatings.

***Keywords:*** *Vacuum-plasma, Ion-plasma, Deposition, Coatings, Adhesion.*

## SOLID OXIDE FUEL CELL ANODE SURFACE MODIFICATION BY MAGNETRON SPUTTERING OF NiO/YSZ THIN FILM

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NiO/ZrO<sub>2</sub>-Y<sub>2</sub>O<sub>3</sub> (NiO/YSZ) anode functional layers (AFL) with a 20–60 vol.% NiO were deposited onto NiO/YSZ anode substrates by magnetron sputtering, followed by annealing in air at 1200 °C. The optimal conditions for NiO/YSZ deposition were determined. NiO content was varied by changing the oxygen flow rate during the sputtering process. The microstructure and phase composition of NiO/YSZ AFL were studied by SEM and XRD methods. NiO/YSZ films were fully crystallized and comprised of grains up to 200 nm in diameter after reduction in hydrogen. Anode-supported solid oxide fuel cells (SOFC) with a diameter of 20 mm including AFL, 5 microns-thick YSZ electrolyte and La<sub>0.6</sub>Sr<sub>0.4</sub>Co<sub>0.2</sub>Fe<sub>0.8</sub>O<sub>3</sub>/Ce<sub>0.9</sub>Gd<sub>0.1</sub>O<sub>2</sub> (LSCF/CGO) cathode were fabricated and tested. The electrochemical properties of SOFC were investigated as a function of NiO volume content in AFL. With an AFL introduced into anode/electrolyte interface, significantly enhanced SOFC performance was achieved.

**Keywords:** *Magnetron sputtering, Solid oxide fuel cell, Ni/YSZ anode, Anode functional layer.*

## STUDY OF GENERATION OF A WEAKLY IONIZED MEDIA FOR TWO-STAGE PULSED PLASMA SET FOR SPRAYING OF BIOCOMPATIBLE COATINGS

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Nowadays the using of two-stage pulsed plasma sets [1] for spraying is under consideration. A weakly ionized detonation wave (DW) is formed by gaseous detonation at the first stage. Additional acceleration of products takes place due to discharging of capacities during the second stage within coaxial electrode unit. The forming plasma channel expands with supersonic velocity and generate of shock wave. Particles which were injected before wave front are accelerated and transferred to substrate where they form a coating.

Note that the complications of the flows generation processes with particles can limit efficiency. As an example of this method spraying biocompatible coatings [2] from hydroxyapatite (HOA) was studied.

Based on CCDS 2000 equipment [3] the experimental set was design. Initial dispersion of HOA particles were varied from 4 to 105 nm. Piezometric sensors, schlieren photography and spectroscopy were used for flow characterization.

Data from the sensors indicated that strong DW takes place at the end of the barrel. The characteristic values of flow velocities approach of 2.1–2.4 km/s at duration time of the wave of 400–550  $\mu$ s. Pressure in the front is 25–30 atm. Schlieren photography allowed visualizing of the flow features. The spatial characteristics of the shock and detonation waves were defined. Spectroscopy showed that the injected particles were subjected to partial pyrolysis and ionization.

Samples of HOA coatings on carbon substrates were prepared. The coatings have high adhesion to the substrates.

Thus the detonation processes allow to generate media which is useful for spraying of biocompatible coatings.

**Keywords:** *Detonation wave, Plasma flows, Coating spraying, High current discharge.*

## THE PHENOMENON OF ARGON TRAPPING IN THE TUNGSTEN COATING

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Gas trapping during coating deposition could strongly affect the properties of the deposited films. In this paper the results of investigating argon trapping in tungsten layer during its deposition on a tungsten substrate are presented. The influence of deposition conditions: temperature of a substrate, deposition rate, secondary electron irradiation, working gas composition and composition of deposited layer on argon trapping is described. Argon trapping in the deposited films of tantalum and molybdenum, which have the same type of crystal lattice as tungsten, as well as close lattice constants, is considered.

The parameters of the experiments were as follows. The deposition rate varied from 0.5  $\mu\text{m/h}$  to 2  $\mu\text{m/h}$ . Argon was used as the main working gas for the target sputtering. The pressure of the working gas was equal to  $4 \cdot 10^{-2}$  Pa. The electron current density during deposition did not exceed 4 mA /cm<sup>2</sup>.

It is shown that electron irradiation of the deposited layer during the tungsten deposition leads to the increase of argon trapping in this layer. The amount of trapped argon also weakly depends on the temperature of substrate in the 800–1200 °C temperature range. No argon release from the deposited layer was registered below the temperature of 1200 °C. The addition of oxygen to the working gas weakly affects the amount of trapped argon. The argon trapping in tantalum layers was observed. In contrast, it was not detected in molybdenum films.

**Keywords:** *Tungsten, Coating, Deposition, Argon trapping.*

## ION IMPACT AT THE SUBSTRATE DURING HIGH POWER IMPULSE MAGNETRON DEPOSITION OF COPPER FILMS

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The parameters of high power impulse magnetron discharge were investigated in this work. Different operation regimes of the magnetron sputtering system: direct current (DC), mid-frequency (MF), high power impulse (HIPIMS) were realized by changing the pulse frequency from 100 Hz to 50 kHz and amplitude of the discharge current from 1 to 700 A at a fixed discharge power (500 W) and the pulse duration (20  $\mu$ s). As a result of the plasma probe measurements the dependencies of the parameters of ion and atom fluxes impacting at the substrate during coating deposition on the parameters of pulsed power were obtained. It is shown that the transition to HIPIMS regime occurs when the pulsed power density on the magnetron target is more than 100 W/cm<sup>2</sup>. In HIPIMS regime there is a significant increase in pulsed ion current density on the substrate (up to 160 mA/cm<sup>2</sup>) at decreasing the average value of ion current (up to two times), and the large decreasing (up to 10 times) of sputtering rate.

**Keywords:** *magnetron sputtering, HIPIMS, ion-to-atom ratio.*

**COATING OF A SUPPORT WITH SURFACE PRELIMINARILY TREATED  
WITH INTENSIVE FLOWS OF HIGH-SPEED ELECTRONS  
AND PLASMA USING A MAGNETRON**

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In recent years the radiation treatment (ion beams, low-power high-current electron beams or compressive plasma flows) of a material has become an effective tooling in modification of its properties and advancing of its operational characteristics. The treatment allows to increase microhardness, wear-resistance and modify the surface relief. The treatment also pursues an important task to strengthen the adhesion of materials of a film and a support under radiation treatment of the film-support systems.

The paper is devoted to study of the effect of preliminary radiation treatment of a surface on adhesion of the film-support system and its roughness.

Samples from brass and steel 8 were selected for the study. The samples were preliminarily treated in 2 ways with: 1. Compressive Plasma Flow (CPF). The discharge duration was  $\sim 100 \mu\text{s}$ . The speed of plasma products of the compressive flow was  $(4-7) \times 10^4 \text{ m/s}$ . The temperature of the compressive flow were 1–3 eV. 2. Low-Power High-Current Electron Beam (LPHCEB), impulse duration 2–3  $\mu\text{s}$  with the particle energy up to 30 keV.

The surface was treated in both modes of its smoothing or making it rougher.

The study demonstrated that preliminary treatment of samples and modes of treatment had a drastic effect upon adhesion of materials of a film and a support and final roughness of the film.

**Keywords:** *Radiation treatment, Adhesion, Coating.*



## THE PHASE AND ELEMENTAL COMPOSITION OF FILTERED ARC EVAPORATED TiAlN COATINGS USING SEPARATE CATHODES

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Ti-Al-N coatings are used to improve the functional characteristics of TiN such as hardness, friction coefficient, high temperature oxidation, and chemical stability. The widespread technologies for super-hard wear-resistant coatings are based on evaporation of the materials in a vacuum, which is called physical vapor deposition (PVD). Among the various PVD technologies, the vacuum-arc deposition (VAD) method is received the widest application on TiAlN coating deposition. But a lot of microdroplets are formed on the material surface during the deposition of coatings by the conventional vacuum-arc systems. For solving this problem are used plasma filters and changing Ti/Al ratio deposition.

TiAlN coatings were deposited by VAD using a separate aluminum and titanium cathodes. The bias voltage was kept constant at 1200 V. The total pressure in the vacuum chamber was  $5 \cdot 10^{-3}$  Pa. The ratio of Ti and Al plasma flows was determined by the arc currents (I). The deposition was carried out at constant arc currents  $I_{Ti} = 60$  A and  $I_{Al} = 70, 80, 90$  A.

In this work we investigate the layer by layer elemental and phase distribution of TiAlN coatings using Raman spectroscopy and glow discharge optical emission spectroscopy.

**Keywords:** *TiAlN, vacuum arc deposition, phase composition, elemental distribution.*

## TRIBOLOGICAL PROPERTIES OF ELECTRICALLY-CONDUCTIVE CU-MO-S COATINGS

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This paper is devoted to investigation of pulse magnetron Cu–Mo–S tribological coatings for electrocontact friction pairs, which operates in space environment.

Electrical resistivity of deposited Cu–Mo–S coatings, measured by four-point probe technique, is  $23 \cdot 10^{-8}$  Ohm·m.

Tribological test in argon atmosphere showed that Cu-Mo-S coatings decreases wear rate of copper friction pair in 38 times due to formation of transferred film on work surface of the counterface and the specimen. The transferred film changes wear mechanisms. The adhesive wear was dominant during wear testing of copper friction pair without coatings, while the fatigue wear was dominant during wear testing of copper friction pair with Cu-Mo-S coatings. The transferred film is like third body, which prevents from active metal contact of counterface and specimen and formation of strong molecular bonds. Secondary-ion mass spectrometry revealed that transferred film thickness decreased during friction. This fact gives evidence of transferred film degradation during friction. The degradation is coming from fatigue failure of surface layer. Debris with transferred film leaves from specimen and counterface surfaces under the action of reversed load and appearing local areas of active metal are smeared by remained on counterface film, which leads to decreasing of its thickness. When film achieved critical thickness and it was short of smearing, active metal of counterface is interacting with active metal of specimen and fatigue wear is changing on adhesive wear, which leads to extremely gross wear.

**Keywords:** *Pulse magnetron sputtering, Cu-Mo-S coatings, Solid lubrication, Electroconductive tribological coatings.*

## SYNTHESIS OF ALN FILMS VIA PEALD METHOD

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One of the most promising methods of thin film synthesis is atomic layer deposition (ALD). The method allows growing films of uniform and repeatable thickness and controlled chemical composition. Usage of plasma to increase reagent reactivity (PEALD – plasma-enhanced atomic layer deposition) allows drastic reduction of synthesis temperature and duration of ALD cycle.

Intent of current research is determining the possibility of synthesis of heteroepitaxial AlN films, which is especially important for such implementations as cold cathodes, buffer layers for high-quality material growth, dielectric and passivating layers in semiconducting device components, gas sensors, UV light-emitting diodes and photodetectors.

For AlN films deposition we used TFS-200 device with capacitively coupled plasma source, manufactured by Beneq (Finland). Films were grown on single crystal sapphire substrates of (0001) orientation at temperatures ranging from 210 to 280 °C. Film thickness grew linearly with an amount of growth cycles. Each PEALD cycle consisted of four steps: 1) Surface treatment with Al source vapor (trimethylaluminium), 2) Purging reactor with nitrogen, 3) Surface treatment with second reagent – nitrogen-hydrogen plasma, 4) Purging reactor with nitrogen.

It was found that at temperatures of 210–280 °C and at duration of plasma exposure (DPE) of more than 6 s, crystalline films with distinct (0001) orientation are grown. Specimens with highest crystallinity were grown at temperatures of 250–280 °C and DPE of 20–30 s. These films' refractive index was  $2.03 \pm 0.03$ , their XRD patterns showed (0002) and (0004) reflections at  $2\theta$  angles of 35.7 and 75.9°, characteristic to heteroepitaxial AlN films.

**Keywords:** Plasma, deposition, AlN films.

**THE INFLUENCE OF SUBSTRATE STRUCTURE ON ADHESION  
BEHAVIOR OF TIN AND TIAL<sub>3</sub>/TIALN COATING DEPOSITED  
BY VACUUM ARC PLASMA**

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The Influence of substrate structure on Adhesion Behavior of single layer TiN And multilayers TiAl<sub>3</sub>/TiAlN Coating Deposited By Vacuum Arc Plasma was investigated. Samples of austenitic steel with coarse and Ultra-fine grained structure. Samples were subjected to severe plastic deformation by torsion (HPT) for formation of the UFG structures. Samples was exposed to ion nitriding in a glow discharge before deposited coatings. Mechanical properties of the samples coated TiN And TiAl<sub>3</sub>/TiAlN was investigated. Multilayer intermetallic coatings TiAl<sub>3</sub>/TiAlN was obtained by simultaneous deposition with single component cathodes of Ti, Al and the rotation of samples in the vacuum chamber. The layers thickness were regulated in the range 5–250 nm by varying the rotational speed of desktop and spatial location of samples in vacuum chamber. The adhesion strength of the coatings was determined by ScratchTest. Effect of forming ultrafine structures have been investigated based on the adhesive strength.

**Keywords:** *Intermetallic coatings, Vacuum-arc plasma discharge, Multilayers TiAl<sub>3</sub>/TiAlN Coating, Scartchtest.*

## INVESTIGATION OF INFLUENCE OF STRUCTURE AND TIAL<sub>3</sub>/TIALN INTERMETALLIC COATINGS ON THE CORROSION BEHAVIOR OF MARTENSITIC STEELS

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Corrosive attack is one of the most frequent reasons of machine components failure. As is known part service properties substantially depend on surface layer state and structure, obtained after complete processing. Various coatings are widely used to improve service properties. It is also known that an intermetallic compounds are beneficial in many aspects. The coatings were deposited by vacuum arc plasma on martensitic steels substrate. An intermetallic compound was synthesized during the Ti-Al coating deposition. Phase composition and corrosion behavior of the coatings were investigated by means X-ray diffraction and electrochemical tests. Potentiodynamic curves in corrosive medium were made before and after coating deposition on heat-resistant high alloy steel. Corrosion currents were calculated using the potentiodynamic curves. General regularities of the steel corrosion were established using the potentiodynamic curves. Interdependence between surface state phase composition and corrosion rate was studied.

**Keywords:** *TiAl<sub>3</sub>/TiAlN intermetallic coatings, corrosion behavior, vacuum arc plasma.*

## DEPOSITION OF BN COATINGS BY REACTIVE MAGNETRON SPUTTERING OF BORON IN AR/N<sub>2</sub> MIXTURE IONIZED BY AN ELECTRON BEAM

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BN coatings were deposited by reactive magnetron sputtering of mono-component target in pulse DC regime (50 kHz, 10 ms) in gas mixture Ar/N<sub>2</sub> ionized by low-energy (100 eV) electron beam. The influence of current density of ion from beam plasma on the voltage of magnetron discharge and phase composition of the coatings was studied. It was shown that rise of ion current density from 2 to 19 mA/cm<sup>2</sup> under constant current of magnetron discharge leads to decrease of discharge voltage by several hundred V. According to results of IR spectroscopy, c-BN is the dominant phase in the coatings. It was determined that under electron beam current 2 A providing the ratio between ion current density  $j_i$  and neutrals flow  $j_a$  on samples surface  $\sim 6$ , BN coating contains significant amount of fullerene-like phase e-BN, that is reduced along with  $j_i/j_a$  ratio increase. In BN coatings deposited under magnetron sputtering of mono-component target in medium-frequency regime, e-BN phase was revealed for the first time.

**Keywords:** *BN coating, Reactive magnetron sputtering, Ion assistance, Electron beam.*

## A COMPARATIVE STUDY ON THE PROPERTIES OF CHROMIUM COATINGS DEPOSITED BY MAGNETRON SPUTTERING WITH HOT AND COOLED CATHODE

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The deposition of chromium thin films on stainless steel substrates was carried out by magnetron sputtering and two different operating conditions of the cathode were used, namely cooled target and hot target, the former being a sputtering process and the latter a combination of sputtering and evaporation processes of the target material. The characteristics of two families of chromium thin films such as thickness, hardness, topography, surface morphology and cross-section microstructure, crystal structure, elemental composition and corrosion resistance were assessed and discussed in relation to the different working conditions of the deposition system.

**Keywords:** Magnetron sputtering, Hot target, Evaporation, Chromium, High deposition rate.

## RADIATION PROCESSES AND PHENOMENA IN NANOCOMPOSITE COATINGS

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The development of technologies directly related to the radiation exposure to the various structures as specifically and spontaneously is actively conducted in recent years. Different protective coatings with the enhanced radiation stability are developed. In our work we propose a new concept of nanocomposite coatings as promising radiated resistant materials. The main idea of the work is connected with producing of a large number of the structural defects like grain boundaries that are effective absorbed primary and secondary defects formed after irradiation. The coatings for the experimental research were made by magnetron sputtering of metal (Zr, Al, Ti) and Si targets in the argon + nitrogen atmosphere. In this case a nanocomposite structure like amorphous  $\alpha$ -Si<sub>3</sub>N<sub>4</sub> matrix with embedded nanocrystalline particles of the metals nitrides ZrN, TiN, AlN was formed. The coatings were subjected to the ions (Xe<sub>2</sub><sup>+</sup>, Ar<sup>+</sup>, He<sup>+</sup>) irradiations with different energies and doses up to 10<sup>17</sup> ions/cm<sup>2</sup>. The unique nanocomposite structure allows to decrease in the primary defects number enhancing, in turn, the stability of the phase composition of the coatings under the irradiation.

**Keywords:** Radiation stability, Thin films, Nanocomposite materials.



## INTERRELATION BETWEEN MAGNETIC AND LUMINESCENT PROPERTIES OF ALUMINIUM OXIDE DOPED WITH COPPER AND CARBON

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The results of researches of structural, luminescent and magnetic properties nanopowders (NPs) of pure and carbon (copper)-doped aluminium oxide, obtained by the pulsed electronic vacuum evaporation are presented below. The suppression of the R-line ions  $\text{Cr}_3^+$  in photoluminescence spectra of all NPs is detected.

All NPs without an exception (pure and doped) showed room temperature ferromagnetism. The nature of the observed ferromagnetism is connected with high concentration of the structural defects, which are formed in NPs in the course of their synthesis by means of pulsed electronic evaporation in vacuum.

The correlation between concentration of structural defects (oxygen vacancies) and ferromagnetic behavior of nanopowders is presented. The correlation was established between dependencies of the ratio integral intensity of the yellow and the red bands of photoluminescence spectra and magnetization from carbon doping level

**Keywords:** *Nanopowders  $\text{Al}_2\text{O}_3\text{-C}$  and  $\text{Al}_2\text{O}_3\text{-Cu}$ , Photoluminescence, Ferromagnetism of non-magnetic nanopowders.*

**STRUCTURAL PROPERTIES OF NANOPOWDERS AND COATINGS  
OF ZINK OXIDE DOPED WITH CARBON PREPARED BY PULSED ELECTRON  
BEAM EVAPORATION**

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With the help of electron evaporation of mechanical mixtures of non-magnetic micron powders ZnO and carbon in vacuum with the subsequent annealing of evaporation products on air at the temperature of 773 K, single-phase crystal nanopowders ZnO-C were produced with the hexagonal wurtzite structure and low content of the carbon dopant not exceeding 0.25 %wt.

It is established that the doping ZnO with carbon stimulates primary growth of nanoparticles along the direction (002) in the coatings, which are formed at deposition of nanoparticles on cold glass substrates, it means that nanocrystals growth in coatings occurs in the same way as crystals growth in thin films, with growth anisotropy in the c- axis direction in wurtzite ZnO.

Change of morphology of coatings on the basis of ZnO by doping as a consequence of size change of the globule of the average size correlates well with the parameters of their specific surface area and change of the grains size from XRD data.

Element mapping has confirmed homogeneous distribution of carbon in ZnO when using the method of pulsed electron evaporation of powders mechanical mixtures.

**Keywords:** *Pulsed electron beam evaporation, C-doped ZnO nanopowders, C-doped ZnO coatings.*

## COMPUTER SIMULATION OF METAL WIRE EXPLOSION UNDER HIGH RATE HEATING

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Synchronous electric explosion of metal wires and synthesis of bicomponent nanoparticles were investigated on the base of molecular dynamics method. Copper and nickel crystallites of cylindrical shape were chosen as conductors for explosion. The embedded atom approximation was used for calculation of the interatomic interactions. Used potentials allow calculating with high accuracy the energy of structural defects, surface properties, elastic characteristics and some other properties. It is necessary for a correct and reliable simulation of electric explosion of metal wires. The periodic boundary conditions were used along the cylinder axis, while in the other directions a free surface was simulated. Heating of the nanowires was performed by scaling of the atomic velocities following a linear law while maintaining a Maxwell distribution. The high-rate heating led to explosive dispersion of the metal wires and formation of nanosized particles (atomic clusters). The influence of the distance between exploded metal wires and environment viscosity on the internal structure of formed nanoparticles was studied. As a result of the synchronous electric explosion of metal wires the bi-component nanoparticles with a block structure may be formed. The analysis of the internal structure, size, shape and phase composition of bi-component nanoparticles synthesized after metal wire explosion was carried out. The obtained results showed that the method of molecular dynamics can effectively be used to determine the optimal technological mode of nanoparticle synthesis on the base of electric explosion of metal wires.

The work was carried out at the support of RFBR Project No. 15-01-06585.

**Keywords:** *Electric explosion, Nanoparticle synthesis, Molecular dynamics.*

## PLASMA DYNAMIC SYNTHESIS OF IRON OXIDES IN A DISCHARGE PLASMA JET WITH POSSIBILITY TO CONTROL FINAL PHASE COMPOSITION

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Magnetite  $\text{Fe}_3\text{O}_4$  and epsilon iron oxide  $\epsilon\text{-Fe}_2\text{O}_3$ , having excellent frequency characteristics and high electrical resistivity, are considered as the most promising phases among all iron oxides for using in high-frequency equipment in order to increase the working frequency of the data transmission. Despite the large number of existing methods for synthesizing these materials, many of them do not provide obtaining both of these phases. Nonetheless, those methods, which allow doing that, suffer from such disadvantages as the process duration, the necessity to use expensive precursors and the low yield of the final product. In opposite to these methods, the plasma dynamic synthesis can provide the synthesis of necessary phases in one-step process. The process is implemented in an electrodischarge iron-containing plasma jet, which interacts with gaseous precursor (oxygen). The use of plasma jet allows obtaining nanoscale powdered products.

This work shows the results of the experiment series, where the influence of initial energy parameters on the final phase composition was studied. It is found that the plasma dynamic synthesis allows obtaining both magnetite  $\text{Fe}_3\text{O}_4$  and epsilon phase  $\epsilon\text{-Fe}_2\text{O}_3$  during one short-term process (less than 1 ms). It is also established that the final phase composition strongly depends on the initial parameters of the system. The increased energy parameters lead to the formation of the product with predominant content of epsilon phase, while lower parameters allow synthesizing magnetite phase. Thus, by changing energy parameters, it is possible to control the final composition in the considered system.

**Keywords:** *Electro discharge plasma, Plasma dynamic synthesis, Soft magnetic iron oxides, Energy parameters, Phase composition.*

## PLASMA DYNAMIC SYNTHESIS OF ULTRADISPERSED ZINC OXIDE AND SINTERING CERAMICS ON ITS BASIS BY SPS METHOD

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Zinc oxide is a well-known semiconductor material having good electrical, optical and catalytic properties. It can be used in different areas from cosmetics to drug delivery and biosensors. The synthesis of nanosized zinc oxide is an urgent task for obtaining ZnO-based ceramics with enhanced physical properties. This work shows the possibility to implement the plasma dynamic synthesis of zinc oxide in one short-term process (less than 1 ms) using an electrodischarge zinc-containing plasma jet, flowing into oxygen atmosphere. It allows synthesizing a mono-crystalline powder with particle size distribution from tens to hundred nanometers. The synthesized powdered product is investigated using by X-Ray diffractometry (XRD), scanning electron microscopy and high-resolution transmission electron microscopy. According to XRD, the obtained product consists of hexagonal zinc oxide with lattice parameters  $a = b = 3.24982 \text{ \AA}$ ,  $c = 5.20661 \text{ \AA}$  that is clearly confirmed by microscopy data.

This powder was used to produce a bulk ceramics sample on its basis by spark plasma sintering. The influence of sintering parameters on the structure of the resulting sample was studied. The optimal parameters were found which allows obtaining the more dense ceramics with a better microstructure. It was also found that the absence of exposure time after reaching the working temperature and pressure allows decreasing the porosity of ceramics.

**Keywords:** *Coaxial magnetoplasma accelerator, Zinc oxide, Ceramics, Spark plasma sintering.*

**THE PECULIARITIES OF CVD DIAMOND COATINGS SYNTHESIS  
IN ABNORMAL GLOW DISCHARGE PLASMA USING  
REPETITIVELY-PULSED MODE**

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We report about the features of polycrystalline diamond coatings CVD synthesis in repetitively-pulsed plasma of abnormal glow discharge. The discharge burning time was varied from a continuous one to 1 ms with proportional pauses. The dependences of growth rate and the phase composition of deposited diamond films on the durations of the discharge burning and pauses are presented. The mutual influence of two plasma filaments on each other and onto the substrate has unequivocally established. Raman spectroscopy, X-ray diffractometry and SEM were used for identification of phase composition and microstructure of deposited films. New data about the features of a pulsed discharge ignition and it's burning at high pressures ( $> 100$  Torr) is also presented.

**Keywords:** *CVD diamond coatings, Glow discharge plasma, Pulsed plasma.*

## CVD SYNTHESIS OF BN AND BCN COATINGS USING TRIMETHYLBORATE PRECURSOR

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We have studied the formation conditions of boronnitride (c-BN and a-BN) and B-C-N thin films deposited in abnormal glow discharge plasma using trimethylborate  $B(OCH_3)_3$  as a main boron source precursor. Effect of gaseous atmosphere composition and the discharge current-voltage characteristics on the phase composition of deposited coatings was investigated. The composition and structure of the coatings were investigated using Raman spectroscopy, X-ray diffractometry and SEM. Micro- and nanohardness of the films were also measured. Optical emission spectroscopy (OES) has been used to investigate the generation of active species in plasma during the deposition process.

**Keywords:** *CVD synthesis, Boronnitride, Boron carbonitride, Glow discharge plasma.*

## EFFECT OF PRECURSOR MASS ON PRODUCT PHASE COMPOSITION IN PLASMA DYNAMIC SYNTHESIS OF TUNGSTEN CARBIDE

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An interest in cubic tungsten carbide WC<sub>1-x</sub> results from its catalytic properties similar to those of platinum group metals and the synergistic effect between WC<sub>1-x</sub> and Pt in reactions of hydrogen evolution and hydrogen oxidation. However, according to the phase diagram of the W–C system, the cubic phase WC<sub>1-x</sub> only exists in a narrow range of temperature stability (about 2798–3058 K), which makes it difficult for being obtained. To date, there are different methods for synthesizing tungsten carbide powder with a low content of cubic phase that complicates the study of WC<sub>1-x</sub> properties. A direct plasma dynamic synthesis is known as one of the promising methods to produce WC<sub>1-x</sub>.

The aim of this work is to find the optimal amount of tungsten precursor to obtain cubic tungsten carbide with a high purity by plasma dynamic method. The synthesized products were examined by X-ray diffraction (XRD) and transmission electron microscopy (TEM). The XRD patterns showed that the main phase was cubic tungsten carbide with negligible content of hexagonal tungsten carbide W<sub>2</sub>C and pure tungsten W. According to a quantitative analysis of synthesized products, which were obtained using masses of initial tungsten equal to 1.0, 0.7, 0.6 and 0.5 g, the yield of WC<sub>1-x</sub> phase was 84, 89, 95 and 92 % (wt.), respectively. The results of TEM displayed that the synthesized powders consist of crystallites, having sizes less than 100 nm (WC<sub>1-x</sub>), and a carbon matrix. This carbon was not detected in XRD due to its presence like an amorphous phase.

**Keywords:** *Plasma dynamic synthesis, Electrodischarge plasma, Cubic tungsten carbide, Nanoscale powder.*



**TEMPLATE SYNTHESIS OF ZNO NANOCCLUSERS IN SiO<sub>2</sub>/Si STRUCTURE**

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The results on creation of zinc oxide nanoprecipitates in a-SiO<sub>2</sub>/Si template by methods of chemical and electrochemical deposition have been presented. Nanoporous SiO<sub>2</sub> has been created by swift <sup>132</sup>Xe ions irradiation at DC-60 cyclotron (Astana, Kazakhstan) with the subsequent etching in 4 % HF aqueous solution. Afterwards, the Zn-based nanoparticles were precipitated in nanoporous a-SiO<sub>2</sub>/Si templates by means of chemical and electrochemical deposition.

As it has been found, filling the template pores by chemical deposition requires a long time (7 days). The electrochemical deposition (ECD) is more convenient and reproducible for Zn precipitation in a-SiO<sub>2</sub>/Si templates. It is possible to modify the precipitates size varying ECD time in the interval of 1 to 7 min.

The analysis of differential PL spectra allows us to assume that the oxidation of metal precipitates takes place during the Zn deposition process. PL spectrums analysis proves, too, that VZn is dominating defect in Zn oxide precipitates deposited in a-SiO<sub>2</sub>/Si templates by ECD and CD methods. The VAC measurements have revealed an existence of p-n transition «n-ZnO/p-Si».

**Keywords:** *SiO<sub>2</sub>/Si, Etched ion tracks, Template synthesis, Chemical deposition, Electrochemical deposition, Zinc oxide.*

## SHI IRRADIATION INDUCED SHAPE AND SIZE TRANSFORMATION IN ZN NANOPARTICLES EMBEDDED IN SiO<sub>2</sub>

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We present results on the influence of swift heavy ion irradiation on Zn nanoparticles embedded in amorphous SiO<sub>2</sub>. SiO<sub>2</sub> layer with thickness of 600 nm was thermally grown on Si substrate. The samples cut from this wafer were implanted with Zn ions (150 keV,  $7.5 \cdot 10^{16} \text{ cm}^{-2}$ ) at room temperature. A part of implanted samples were annealed in air at 700 °C for 60 min. It has been found from RBS measurements that the shape of experimental profile of zinc distribution in as-implanted SiO<sub>2</sub> layer and simulated one (SRIM 2013) are the similar. Annealing results in insignificant zinc redistribution in depth of implanted layer. A slight decrease of impurities concentration due to diffusion to the surface has been revealed. TEM data give the evidence of formation of Zn nanocrystals with size of 3–5 nm during «hot» implantation. Annealing leads to the growth of Zn-based nanocrystals size to 12–16 nm.

As-implanted with Zn as well as annealed samples were irradiated with 200 MeV-132Xe ions to a fluence of  $5 \cdot 10^{12}$  and  $2 \cdot 10^{14} \text{ cm}^{-2}$  at T = 300 °C. It has been found that Xe ion irradiation induces an increase in the size of nanocrystals and their shape elongation along the SHI beam direction. The results of Raman scattering and PL have been discussed.

**Keywords:** Irradiation by swift heavy ions, Zn nanocrystals, Ion implantation.

**THE PECULIARITIES OF STRUCTURAL MODIFICATIONS  
OF CVD POLYCRYSTALLINE DIAMOND COATINGS BY HEAVY DOPING  
WITH BORON**

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We report about the features of structural modifications of CVD polycrystalline diamond coatings by heavy doping with boron. This coatings were deposited in abnormal glow discharge plasma with the addition of a dopant (boron) in different concentrations. Coatings with different structure and phase composition from lightly to heavy doped were obtained. Raman spectroscopy, X-ray diffractometry Hall's method, four-point probe method and SEM were used for identification of obtained composition and microstructure of deposited films.

**Keywords:** *CVD diamond coatings, Glow discharge plasma, Doping, Structure, Modification.*

## HIGHLY SELECTIVE DEPOSITION OF CVD DIAMOND ON SI WAFERS BY USING A COMBINED TECHNIQUE OF PHOTOLITHOGRAPHY AND ION ETCHING

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We report the development of a new technique of high selective deposition of polycrystalline diamond films on monocrystalline silicon wafers. This technique based on the deposition of desired pattern by using standard photolithography with addition of a nanodiamond suspension in photoresist, and the subsequent ion etching the surface of wafer. Ion etching is allows to remove the remaining parasitic nanodiamond particles in areas where the diamond film should not grow. Etching was carried out with 3.5 keV argon ions generated with closed drift ion source. Diamond films were deposited in selective regions using high-current glow discharge PACVD reactor. The effects of the nanodiamond concentration in photoresist and the thickness of etching layers on the nucleation density of diamond were also investigated. This technique is much simpler than those that are currently in use (eg selective oxidation method), and is very promising for the development of different microelectronic devices, displays, sensors, etc.

**Keywords:** *CVD diamond coatings, Glow discharge plasma, Selective deposition, Structure.*

## SYNTHESIS OF SILICON CARBIDE NANOPOWDERS IN FREE FLOWING PLASMA JET WITH DIFFERENT ENERGY LEVELS

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Silicon carbide (SiC) due to its attractive properties such as high hardness and mechanical strength, low density, good wear resistance, together with excellent mechanical and chemical stability at high temperatures is widely used for producing abrasive materials, different kinds of wear- and heat-resistant ceramics. Different methods have been applied for obtaining silicon carbide nanoparticles and nanostructures but these methods do not allow to synthesize an optimal product. Plasmadynamic method is based on the use of a coaxial magnetoplasma accelerator (CMPA) as a plasma jet generator. The present paper reports the way of implementing plasmadynamic method by synthesis in a free flowing hypersonic plasma jet. The study was primarily concerned with investigating effect of changing plasma energy on a silicon carbide nanopowder. A supplied energy  $W$  was 11, 16, 21, 28 kJ at experiments with a charging voltage of 2.0, 2.5, 3.0, 3.5 kV respectively. Crystalline silicon and amorphous carbon black powders were used as precursors. The hypersonic plasma jet flowed into the argon atmosphere of working chamber. The powders synthesized by plasmadynamic method were analyzed without any pretreatment by X-ray diffraction, scanning (SEM) and transmission (TEM) electron microscopy. The results showed that the synthesized products mainly consist of  $\beta$ -SiC. Silicon carbide content increases (up to  $\sim 92\%$  mass) and particle sizes remain constant ( $\sim 60$  nm) with increasing plasma energy (11–28 kJ). Prisms with a triangular base which form the majority of the product were identified as crystals of silicon carbide.

**Keywords:** *Silicon carbide, Nanopowder, X-ray diffraction, Transmission electron microscopy.*

## PLASMADYNAMIC SYNTHESIS OF TI-B NANOPOWDERS

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Titanium diboride TiB<sub>2</sub> has many attractive properties including high hardness, high elastic modulus, high melting point and high temperature oxidation resistance. The outstanding physical and mechanical properties of TiB<sub>2</sub> allow for various applications across many areas, e.g. military, aerospace or automotive applications. The present paper reports a novel way of direct and quick making nanodispersed Ti-B phases out of amorphous boron powder (B) and crystalline titanium (Ti). A hypersonic plasma jet was generated by a coaxial magnetoplasma accelerator. An amorphous boron powder was placed axially into a plasma formation zone as a precursor of a chemical reaction. After emergence of the discharge a plasma jet was accelerated by an own magnetic field and the magnetic field of external inductor. The accelerated plasma jet flew to a working chamber filled with argon. Accelerator was powered by a capacitive energy storage, the level of released energy reached  $W_r = 33.5$  kJ. The synthesized powders were analyzed by the X-ray diffraction (XRD) method. The XRD analysis showed that the products mainly contain boride of titanium and diboride of titanium. The preferential content of borides in the products compared with diboride is explained by the certain ratio of boron and titanium for respective phases in accordance with the Ti-B state diagram – 20 % of boron in the system. The products contain pure titanium, so this fact and the absence of pure boron in the products demonstrate the redundancy of titanium in the system.

**Keywords:** *Titanium diboride, Titanium boride, X-ray diffraction.*

## SILICA NANOPARTICLES PRODUCED BY DC ARC PLASMA FROM SOLID RAW MATERIALS

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At the present time due to the increasing need for nanosized oxides with especial properties to modify different materials the problem of effective production technology developing is particularly relevant. There are a broad range of nanoparticles synthesis methods such as sol-gel, laser ablation, mechano-chemical, plasma and flame processes. Each of them has some prospects and constraints, but top-priority direction of investigations is creation of anhydrous, low-waste and economical technology, such as plasma-chemical synthesis.

Silica nanopowder is one of the most widely applied additives in industry. As a rule, it helps to increase mechanical and chemical properties of materials. But nowadays there are not so many works concerned with using low-cost solid raw materials for production nanosilica.

The paper presents the investigations results of plasma synthesis of silica nanopowder from different solid raw materials under atmospheric conditions. Scanning Electron Microscopy, Dynamic Light Scattering, Energy-dispersive X-Ray Spectroscopy were carried out for characterization of product. It is shown the possibility of obtaining polydispersed silica nanoparticles with spherical shape.

**Keywords:** *Plasma, Silica nanopowder, Sublimation.*

## 700 KEV ELECTRONS IRRADIATION INFLUENCE ON MAGNETIC AND LUMINESCENT PROPERTIES OF VARIOUS NANOPOWDERS OF METALS OXIDES PRODUCED BY PULSED ELECTRON EVAPORATION

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With the help of pulsed electron evaporation were produced the nanopowders  $\text{Al}_2\text{O}_3$ ,  $\text{SiO}_2$ ,  $\text{SeO}_2$  and YSZ ( $\text{Gd}_2\text{O}_3\%$   $\text{Y}_2\text{O}_{3.8}$ ) with the high specific surface, the nanopowders were further irradiated with electrons energy 700 keV, pulse duration 60 ns on the pulsed repetitive accelerator URT-1 within 15 and 30 minutes.

Magnetic and cathodoluminescent characteristics of the unirradiated and irradiated nanopowders were measured.

It is established that irradiation by electrons does not influence significantly initial magnetization of samples.

To the contrary, obvious correlation between intensity of the pulsed cathodoluminescence and time (dose) of irradiation is found in the most part of oxides. There was a reduction of cathodoluminescence intensity after irradiation.

Luminescent properties stronger reflect transformation of structural defects in NP after impact on them with pulsed electron beam in comparison with corresponding changes of the magnetic response NP.

**Keywords:** *Nanopowders  $\text{Al}_2\text{O}_3$   $\text{SiO}_2$   $\text{CeO}_2$  and YSZ, Pulsed electron beam irradiation, Pulsed cathodoluminescence, Ferromagnetism of non-magnetic nanopowders.*



**PLASMA-CHEMICAL SYNTHESIS OF CARBON NANOTUBES  
AND FULLERENES TO CREATE FROST-RESISTANT COMPOSITE  
BUILDING MATERIALS**

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This paper considers method of synthesis of fullerenes and carbon nanotubes at atmospheric pressure. Carbon evaporates into the plasma arc, and then condenses on the reactor walls. Carbon nanotubes and fullerenes contained in the composition of the condensate. Helium is used as the buffer gas. The paper discusses the method of synthesis of helium at a pressure of 105 Pa. Also shows the dependence yield of fullerenes and carbon nanotubes on the buffer gas pressure changes. It was found that an increase in helium pressure increases yield of higher fullerenes (C70) in the coal condensate.

The obtained fullerenes and nanotubes find their application in the modification of construction materials. The use of carbon nanomodifiers in the modification of the construction is promising since their introduction significantly improves the physico-mechanical properties using a small quantity of additives.

Carbon nano-modifier changes the structure of water, creating around their directionally oriented particles of hydrated shell, which lead to the change of rheological characteristics of cement paste. The particles of the carbon nano-modifier serve as centers of crystallization of hydration products of cement, which accelerates the process of hydration and hardening of cement, especially in the initial stages of hardening. With the introduction of the carbon nano-modifier decrease the porosity of cement stone, which leads to high strength and frost-resistant indicators of the modified cement.

**Keywords:** *Carbon, Fulleren, Nanotube, Composite building materials.*

**THE FORMATION OF CARBON NANOFIBERS  
ON A FERROCENE-CONTAINING CHLORINATED POLYMER SURFACE INDUCED  
HIGH-POWER ION BEAM TREATMENT**

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Fast surface thermal processing is of great interest from the point of view of transformation of polymer materials with low melting temperature to carbon structures. The objective of this investigation is to study the possibility of forming a carbon nanostructure on the surface of polymer using a high-power ion beam (HPIB). We investigated the effect of HPIBs on layers chlorinated polyvinylchloride containing ferrocene as a catalyst. Irradiation was performed on a Temp accelerator by the ion beam (70 % C<sup>+</sup> and 30 % H<sup>+</sup>) with energy  $E \approx 200$  keV, duration  $\tau = 60$  ns, and a current density range of 20–100 A/cm<sup>2</sup>. The surface morphology and the sample composition were studied using scanning electron microscopy and transmission electron microscopy. It was established that an HPIB with a current density of 100 A/cm<sup>2</sup> incident on the surface results in the formation on the surface of the polymer material of layers of carbon nanofibers with an average diameter of 80 nm and a length of up to 10  $\mu$ m. A possible mechanism of the observed phenomenon is discussed.

**Keywords:** *Ion, beam, Polymer, Carbon, Nanofibers.*

## SHS-PROCESS IN THE MIXTURE OF TI, AL, C POWDERS INITIATED BY PULSED ELECTRON BEAM

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Using a pulsed electron beam (with an energy of 15 keV, a pulse duration of 200  $\mu$ s, energy density of  $\sim 40$  j/cm<sup>2</sup>) SHS-process of synthesis of nanolaminates (initial porosity of 40 %) in the powder mixture of 3Ti-Al, 1.1–1.8 C composition was initiated.

The phase composition and microstructure of the synthesis products was investigated using diffractometer DRON-UM1 (Ka), optical (AXIOVERT 200M, Carl Zeiss) and scanning electron (SEM 515, Philips) microscopes.

The synthesized phases: Ti<sub>3</sub>AlC<sub>2</sub> and TiC. Long elongated plate – Ti<sub>3</sub>AlC<sub>2</sub>-phase, rounded particles – TiC-phase.

**Keywords:** *Pulsed electron beam, Shs-process, Structure, Mixture of powders.*

## EXPERIMENTAL INVESTIGATION OF RESISTANCE TO PARTICLES IMPACT OF COATINGS ON THE BASIS OF AL-SI-N SYSTEM

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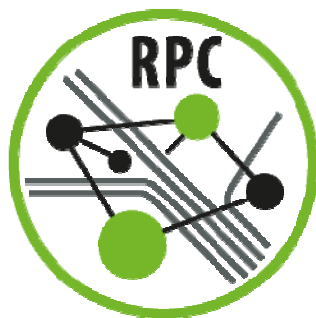
Active exploration of space and the need to develop of spacecrafts, capable to operate in extreme conditions of outer space, requires the development of new construction materials and technologies of their production. Impact of micrometeoroids with spacecraft is important factors capable to cause an erosion of a surface and local destructions. Various optical spacecraft elements on suffer from micrometeoroids more. One way of solving this problem can be deposition of protective coatings on basis of the Al-Si-N characterized by a high degree of transparency in the visible spectrum and a high level of mechanical properties on the optical parts spacecraft system. The aim of this work is to study the structural-phase state and mechanical properties of magnetron coating on the basis of Al-Si-N system, as well as their impact on the stability of the quartz glass samples to the impact of iron microparticles moving at a speed of 5–8 km/s.

The results of X-ray showed that the nanocrystalline Al-Si-N coating with different thickness having phase AlN (hcp) is formed on the surface of the quartz glass under pulsed magnetron sputtering technique. Coatings of Al-Si-N system are characterized by a high degree of transparency (80 %) in the visible wavelength range. Study crater formation on the surface of the samples as a result of the bombardment them of high speed iron particles have shown that increasing of the Al-Si-N coating thickness from 1 to 10 micrometers can decrease the surface density of craters of quartz glass 4 times.

**Keywords:** *Magnetron deposition, Protective coating, Structure-phase state, Microhardness, optical properties, Crater density.*



**17<sup>th</sup> International Conference  
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Physical principles of radiation technologies

Radiation defects: structure, formation, properties

## PHOTO- AND THERMOLUMINESCENCE OF HIGHLY IRRADIATED ANION-DEFECTIVE ALUMINA CRYSTALS

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Anion-defective alumina (ADA) crystals are widely used in TL and OSL personal dosimetry and in environmental radiation monitoring. However, recent researches show that ADA crystals are also promising for measuring high and ultrahigh doses up to 1,000 kGy. This work is devoted to investigations of a changing of TL and PL properties of ADA crystals under high-dose irradiation. The methods of UV and VUV spectroscopy were used to measure PL and PLE spectra in samples exposed to high-dose of gamma-rays and nanosecond electrons beam.

Significant changes in luminescent and dosimetric properties of ADA crystals are observed after exposure to high doses. In the PL and PLE spectra, alongside with emission bands of F and F<sup>+</sup>-centers, which are created by oxygen vacancies, additional bands emerge. They are caused by aggregate F<sub>2</sub>-type centers in different charge states. At the same time high-temperature TL peaks appear, which are associated with deep traps. The concentration of such deep centers increases as a result of radiation-induced transformations of luminescence centers.

Several methods can be used for high-dose dosimetry by means of ADA crystals. TL yield of high-temperature peaks can be registered in the 550–850 K range. High doses were successfully measured by using PTTL and TA-OSL methods. It was also shown that ultrahigh doses can be registered due to the effect of high dose sensitization of ADA crystals. Our studies show that ADA crystals can be used as multipurpose detectors of ionizing radiations with the measurement range of  $10^{-6}$ –10<sup>6</sup> Gy.

**Keywords:** *alumina, photoluminescence, irradiation*



## CRYSTAL GROWTH AND SCINTILLATION PROPERTIES OF BaCl<sub>2</sub> DOPED WITH Eu<sup>2+</sup> IONS

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Inorganic scintillators are used for the detection of ionizing radiation and are widely applied in such areas as physics, medicine, geology and others. Of these, alkaline earth halide scintillators have received great attention during the past few years due to their high light yield close to the theoretical limit. In this work we consider the problem of obtaining single crystals BaCl<sub>2</sub> doped with divalent Eu and study their scintillation and optical properties.

In crystal growing special attention was paid to the preparation of raw materials. For removing water and hydroxyl groups the reactants in stoichiometric amounts were placed into the quartz ampoule and then were slowly heated in vacuum. The modes of drying materials were selected according to differential scanning calorimetry spectroscopy.

The crystals were grown from the melt by the vertical Bridgman technique in the multizone thermal facility. The growth rate was 1mm/h and the temperature gradient about 15 C/cm. Excitation, emission and absorption spectra were measured for the obtained crystals. The photoluminescence spectra of crystals showed broad emission bands centered around 408 nm. Their excitation spectra showed two peaks at 280 and 350 nm, respectively. According to the spectra obtained Eu is included in the lattice in the divalent state. The light yield of our sample obtained from the X-ray luminescence spectrum is around of 50,000 photons / MeV. Further research will be aimed at improving the optical characteristics of crystals BaCl<sub>2</sub>:Eu<sup>2+</sup>.

This work was supported by RFBR (project # 15-02-06514 and project # 16-32-00198).

**Keywords:** *Inorganic scintillators, Crystal growing, Luminescence.*

**SPECTROSCOPY OF BABRI CRYSTALS DOPED WITH  $\text{Eu}_2^+$** 

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Spectra of photo- and X-ray luminescence crystal BaBrI activated by different concentrations of  $\text{Eu}_2^+$  ions were measured. Luminescence spectra confirm that europium is part of BaBrI lattice in the divalent state with its characteristic transitions 5d–4f. The excitation and emission spectra, show that with increasing concentration of europium, emission intensity increases, and as a result, increased light output.

We calculated relative light output BaBrI crystals with different concentrations of europium. The calculation was made based on the ratio of the area of the spectrum of X-ray luminescent crystal BaBrI:Eu to the area of the spectrum of the crystal CaF<sub>2</sub>:Eu. It is known that the light output of the crystal CaF<sub>2</sub>:Eu 0,3 % of 19000 ± 1000 photons/MeV. The greatest light yield of about 81,000 photons/MeV have crystals with a high content of europium 7–8 mol.%.

The absorption spectrum of the crystals BaBrI:Eu was first obtained in this work for low concentrations of europium. The spectrum shows a double peak associated with the fd-absorption in  $\text{Eu}_2^+$ . On the absorption spectrum of the band gap  $E_g$  was evaluated. For crystals BaBrI:Eu  $E_g$  is 5.1 eV.

The decay curves of the time show that the crystals BaBrI activated by different concentrations of  $\text{Eu}_2^+$  the largest contribution comes from the fast component, about 60–70 %, the slow component contributes 30–40 %. At low concentrations of europium slow component makes a significant contribution. The decay time in BaBrI crystals depends on the concentration of the activator.

This work was supported by RFBR (project # 15-02-06514).

**Keywords:** *absorption spectra, decay time. X-ray luminescence. photoluminescence.*

## LUMINESCENCE OF ULTRAFINE MAGNESIUM OXIDE CERAMICS WITH DEEP TRAPS

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The luminescence properties of wide-gap insulators are largely determined by charge transfer processes between different types of localized defect states, in particular, associated with deep traps. The deep traps occur in many wide-gap oxides. In particular, they are present in magnesium oxide. Many aspects of their influence on the luminescent properties of this material are studied insufficiently and require further investigations.

This paper deals with the study of luminescent properties, related to the presence in material the deep trapping centers, in ultrafine magnesium oxide.

Ultrafine anion-defective magnesium oxide ceramics were synthesized from pressed nanopowder at high temperature (1100–1400 °C) in vacuum in the presence of carbon for increase the luminescence output due to thermochemical coloration. The decisive influence of F-type centers associated with oxygen vacancies in different charge states on spectral-luminescent properties of the samples under study was confirmed by luminescent spectroscopy techniques. During the investigation of deep trap thermoluminescence (TL) in anion-defective magnesium oxide the tunneling mechanism of charge carriers' recombination was found. The absent of the temperature dependence of TL decay kinetics and hyperbolic law of TL intensity variation with time confirm this mechanism experimentally. The effect of TL sensitization in 380 K peak, associated with the competitive interaction between the main and deep traps which capture the carriers of the same sign, was found. The proposition about the hole nature of traps associated with the observed TL peaks in the samples under study, was made on the base of TL spectra analysis and literature data.

**Keywords:** *oxide, thermoluminescence, high dose, deep traps.*

**THERMALLY STIMULATED TRANSFORMATIONS OF LUMINESCENCE CENTERS  
IN ANION-DEFECTIVE CORUNDUM AND THEIR CORRELATION  
WITH HIGH-TEMPERATURE TL**

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Using samples of anion-defective corundum ( $\alpha\text{-Al}_2\text{O}_3\text{-}\delta$ ) with different titanium impurity concentrations we have carried out a comprehensive study of thermoluminescence (TL) in an extended temperature range of 300–950 K, changes in the concentrations of active centers and their photoluminescence as a function of annealing temperature up to 1400 K, and corresponding thermally stimulated changes in the TL spectra and TL yields. The study has enabled us to establish the following regularities:

- The course of the thermally stimulated conversion  $F - F^+$  in the 300–1400 K region and substantial change in its efficiency near 850–950 K depend on the presence or absence of a high-temperature TL peak and, consequently, on the concentration of the titanium impurity;
- The thermally stimulated processes are subject to a substantial influence of not only F and  $F^+$  centers but also of other more complex centers such as types  $\text{Al}i^+$  and  $F_2$ ;
- TL yield in the main dosimetric peak at 450 K depends not only on the degree of filling of the hole trap, emptied near 830 K, but also on the interaction of F type centers with more complex ones.

In general, the comprehensive data that we have obtained on changes in the concentrations of F,  $F^+$ ,  $\text{Al}i^+$ ,  $F_2$  and unidentified centers, their PL yields, TL spectra, acquired TL-sensitivity under step annealing in the 300–1400 K range, and their comparison with TL curves provide a new perspective on the issue of the TL properties of  $\alpha\text{-Al}_2\text{O}_3\text{-}\delta$  crystals.

**Keywords:** *anion-defective corundum, high-temperature thermoluminescence, anion vacancies.*

## HIGH-TEMPERATURE THERMOLUMINESCENCE OF ANION-DEFICIENT CORUNDUM AND ITS CONNECTION WITH TI IMPURITY

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It was found [A.I. Surdo et al., *Rad. Meas.*, 2016, V. 90, p. 192–195] that the thermoluminescence (TL) response in TLD-500 detectors based on anion-deficient single crystal of corundum is proportional dose- in the high-temperature peak at 830 K. Where continuous irradiation is used, such response is proportional to a dose up to 2 kGy. The TL spectrum in the peak at 830 K was also studied [A.I. Surdo et al., *Rad. Meas.*, 2016, V. 90, p. 192–195] to reveal, along with intense luminescence with  $h\nu_{em} = 4.1$  eV whose nature is not known precisely. Preliminary research showed that the TL peak at 830 K is only found in a part of TLD-500 detectors. The objective of this study is detection in TLD-500 detectors of possible correlations of TL yield in the peak at 830 K with the content of intrinsic and impurity defects.

It has been found that, as Ti concentration (CTi) in the TLD-500 detectors is increased from the detection threshold of  $\sim 7$  ppm to 21 ppm, the TL yield in the peak at 830 K decreases to undetectable values. On the other hand, study of samples at constant CTi and decreasing anion deficiency CF determined from total concentration of  $F^+$  and F centers shows the TL yield at 830 K to drop essentially as well. Comparative studies of concentration variations of F,  $F^+$  and  $F_2$  centers in samples free of peak and with a TL peak at 830 K were carried out additionally with step-by-step annealing within a range between 300 K and 1400 K.

**Keywords:** *anion-deficient corundum, high-temperature thermoluminescence, Ti impurity.*

## RADIOLUMINESCENT PROPERTIES OF $Ce_3^+$ DOPED ALUMINIUM OXYNITRIDE

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Powdered samples of  $AlON:Ce_3^+$  with spinel structure were prepared by standard sol-gel method using aluminium isopropoxide  $Al(OiPr)_3$ , aluminium nitride  $AlN$  and  $CeO_2$  as starting materials. The rare-earth ions concentrations vary from 0.01 to 1.0 at. %. [1, 2].

X-ray luminescence spectra (Fig. 1) of samples were measured at room temperature in the wavelength range of 200–1000 nm. For all the samples, bands are located at 375–500 nm with maximum at 450 nm and can be assigned to 5d-4f-transitions of dopant ions.

The pulsed cathodoluminescence decay kinetics were measured in the maximum of the most intense spectral band of each sample. The resulting curves were approximated by exponential expression with two components. Decay times vary from 28 to 56 ns for «fast» component and from 394 to 486 ns for «slow» component.

**Keywords:** *Aluminium oxynitride, rare earth ions, X-ray luminescence, pulsed cathodoluminescence, phosphor.*

**THE RECOMBINATION RADIATION OF ELECTRON-HOLE LIQUID IN DIAMOND***EVGENIY LIPATOV, DMITRII GENIN AND VICTOR TARASENKO**Institute of High Current Electronics, Russia**lipatov@loi.hcei.tsc.ru*

The recombination radiation of drops of electron-hole liquid (EHL) in the diamond is observed in cathodoluminescence and photoluminescence spectra at temperatures low than 200 K and peak densities of non-equilibrium charge carriers more than  $(0.3-1.0) \times 10^{18} \text{ cm}^{-3}$ . The EHL band consists of three phonon components: TA-, TO- and TO+O-component at 5.249, 5.211 and 5.075 eV, respectively. After reaching the critical EHL concentration of charge carriers the dominant TO-component of EHL band begins to appear like a long-wavelength shoulder of TO-component of the free exciton band. A further increase in carrier density leads to an increase in intensity EHL band. A surface layer of the specimen is defective, that in the bulk. Therefore, the absorption of incident radiation in a thin layer hampers condensation EHL compared with volume absorption. EHL condensation results in displacement of the FE band intensity maximum on the temperature dependence to higher temperatures up to 220 K, which can be interpreted as a decline in the condensation of excitons in EHL drops at lower temperatures. In this context the critical value of the condensation temperature of the EHL is not established and, presumably, takes values in the range of 160–220 K. In this regard, the phase diagram of the existence of the EHL requires clarification.

**Keywords:** *diamond, recombination, electron-hole pair, exciton, electron-hole liquid, electron-hole plasma, photoluminescence, cathodoluminescence, KrCl-laser.*

## KINETIC CHARACTERISTICS OF THE LUMINESCENCE OF INDUSTRIAL YAG PHOSPHORS

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This paper reports the quantitative luminescence decay kinetics characteristics of YAG phosphors powders after pulsed optical and electronic excitation. Two components found in the decay kinetics. Nanosecond decay component, about 60 ns, approximately the same for all investigated phosphors upon photoexcitation. Differences luminescence decay kinetics characteristics of the phosphors different prehistory are discussed.

**Keywords:** *phosphor, yttrium aluminum garnet, kinetic characteristics.*



## PREPARATION AND STUDING OF POLYMERIC NANOCOMPOSITES CONTAINING CDSE/CDS NANORODS

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Nanohybrid composites comprising polymeric organic compounds and semiconductor nanoparticles, such as quantum rods, are of great importance for various functional materials potentially promising for lasing, informational displays, light-emitting diodes, solar cells etc [N. Osada, T. Oshima, S. Kuwahara, T. Toyoda et al. // *Phys. Chem. Chem. Phys.* – 2014. – V.16 – P. 5774–5778]. However, despite of great interests, the achievement of uniform distribution of quantum rods in a polymer host and long-term stability of the composites still a challenge.

In this work, colloids of CdSe/CdS quantum rods (diameter of 2.5–4 nm, length of 40–60 nm, covered with a non-polar organic shell comprising hexadecyl of phosphonic acids) in various polymers (polystyrene, dimethyl silicone and polymethylmethacrylate) are prepared and spectral and kinetic characteristics for the colloids are studied using pulse spectrometry [V.I. Oleshko, S.S. Vil'chinskaya // *The 7th International Forum on Strategic Technology, Proceedings of IFOST.* – 2012. – V.1 – P. 304–307].

It is revealed that uniformity of distribution of quantum rods, position of PL maximum and decay strongly affected by the polymer host used. The most homogeneous distribution of nanorods is found in dimethyl silicone polymer host which is apparently attributed to the similarity in aliphatic nature of both NPs shell and polymer chains.

**Keywords:** CdSe/CdS nanorods, polymeric nanocomposites, photoluminescence.

## PULSE CATHODOLUMINESCENCE KINETICS OF LITHIUM ORTHOBORATE CRYSTALS

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Present research is devoted to investigation of lithium gadolinium orthoborate (LGBO) crystal by means of pulse cathode luminescence (PCL). For interpretation of experimental data on PCL kinetics we applied mathematical model of tunneling electron transfer. We investigated LGBO in two forms: single crystal and crystal-fiber, both crystals were doped with cerium impurity. It was revealed that the cathodoluminescence intensity is considerably higher in comparison with photo- and x-rays induced luminescence intensity. Also, the PCL decay kinetics has certain peculiarities that cannot be explained in terms of a simple mechanism of  $4f \rightarrow 5d$  transition in trivalent Ce ions in energy range of 2.5–3.4 eV.

In accordance with this alternative mechanism of PCL excitation the short-lived trapped electron centers (in the form of neutral Li atom) surrounded by tetravalent Ce ions occur after nanosecond electron beam exposure. After electron tunneling between Li and tetravalent Ce centers (recharging of the impurity ions) the short-lived trivalent Ce impurity centers in the excited state are formed. De-excitation leads to an additional contribution to the luminescence band of trivalent Ce ions.

**Keywords:** *lithium gadolinium orthoborate (LGBO), pulse cathode luminescence (PCL), tunneling electron transfer.*

## LUMINESCENCE SPECTROSCOPY OF OXYFLUORIDE CRYSTALS

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The class of oxyfluoride crystals with general formula AMOF are attractive compounds for developing new noncentrosymmetric crystals having ferroelectric and ferroelastic properties.

The aim of this research is study of luminescence properties of  $K_3WO_3F_3$ ,  $CsZnMoO_3F$ ,  $Rb_2KTiOF_5$  single crystals and ceramics with the usage of the method of time-resolved spectroscopy. We wish to identify some general patterns of PL excitation mechanism and defining the role of radiation induced defects of the crystal structure in the processes of energy transformation.

These samples were grown and certified (Raman scattering and XRD analysis) in the Institute of Geology and Mineralogy SB RAS (Novosibirsk, Russia).

In all studied samples, we observe intrinsic luminescence with a Stokes shift of 1.5–2.0 eV. The emission bands have a characteristic PL excitation spectra, PL yield is temperature dependent. The intrinsic luminescence of tungstates (molybdates) is usually ascribed to the radiative relaxation of exciton-like excitations localized on  $WO_6$  octahedra or  $WO_4$  tetrahedra. In these compounds there are anion sites with mixed oxygen/fluorine occupancy. Therefore, different octahedra form with different distortion. Two emission centers of exciton-like origin, with distinct relaxation time, different types of such octahedra were found. The time-resolved luminescence spectroscopy technique was applied to distinguish these centers, proving itself as a sensitive method to study the character of lattice distortion. Apart from intrinsic luminescence, the PL of defect-related centers was found in samples irradiated by fast electrons. The role of shallow charge carrier traps in the low-temperature luminescence was revealed.

**Keywords:** *Luminescence, exciton, oxyfluoride, tungstates, molybdates,  $K_3WO_3F_3$ ,  $CsZnMoO_3$ ,  $FRb_2KTiOF_5$ , AMOF,  $WO_6$  octahedra,  $WO_4$  tetrahedra, irradiation defect.*

## THE STUDY OF INORGANIC SCINTILLATING MATERIALS

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Inorganic scintillating materials are widely used in detectors for diverse applications ranging from high energy physics to nuclear medicine. Better understanding of the various scintillation mechanisms has led to innovative new materials for both gamma-ray and neutron detection, and the concept of scintillator design and engineering has emerged, whereby materials are optimized according to the scintillation properties needed by specific applications. Although certain incremental improvements may still be achieved in each property the main challenge then becomes to find a scintillator material that has the correct combination of properties to match the needs of a given application rather than to find a scintillator with a single outstanding characteristic.

In this paper the procedure for measuring the temporal characteristics and light output of inorganic scintillating materials excited by  $\beta$ - ,  $\gamma$ - , and  $\alpha$ -particles from radioactive sources is described. Results of measurements of characteristics are presented for ~40 scintillating compounds including cerium-doped yttrium silicate and scandium borate; europium-doped strontium phosphate; cerium-doped strontium silicate, calcium silicate and magnesium calcium silicate; etc. Upon- and -excitation, cerium-doped scandium borate gives the highest light output with a fluorescent lifetime of  $40 \pm 4$  ns. The highest light output for -excitation was from cerium-doped yttrium aluminum perovskite, with a fluorescent lifetime of  $29 \pm 3$  ns.

**Keywords:** *Inorganic scintillating materials, detector, gamma-ray, neutron detection.*

## THERMAL QUENCHING OF LUMINESCENCE IN NANOSTRUCTURED MONOCLINIC ZIRCONIUM DIOXIDE

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The luminescent properties of zirconium dioxide ( $ZrO_2$ ) are studied intensively due to its application as laser hosts, optically active layers in photoluminescence (PL), cathodoluminescent and electroluminescent devices. Despite on large quantity of publications, the luminescent properties of  $ZrO_2$  are investigated insufficiently. In particular, the mechanisms of thermal quenching of luminescence and connection of this effect with thermoluminescent (TL) properties of material are poorly studied.

The purpose of this work was to examine thermal quenching of luminescence in nanostructured  $ZrO_2$ .

We used  $ZrO_2$  samples in a form of compacts, produced from nanopowder (40–65 nm). TL was excited by a pulsed electron beam with 130 keV energy.

In PL spectra a wide non-elementary band centered at 480 nm was observed. PL was quenched in this band in a temperature range of 300–450 K. Two peaks were registered on the TL curve – A at 400 K, and B at 500 K. For both peaks, a tendency of lightsum to decrease with a growing heating rate was observed. Theoretical lightsum dependences on the heating rate were obtained using the TL curves that were calculated by general order kinetic formula, with a Mott factor taken into account. The analysis of theoretical and experimental dependences of TL peaks lightsum on heating rate shows that the thermal quenching of luminescence in nanostructured  $ZrO_2$  is not described by intracenter mechanism. It is suggested that the thermal ionization of excited states of  $F^+$ -centers takes part in the mechanism of luminescence quenching of the material under study.

**Keywords:** *Zirconium dioxide, Thermal Quenching, Thermoluminescence.*

## THERMOSTIMULATED LUMINESCENCE OF RADIATION DEFECTS IN KCL, KBR AND KI CRYSTALS AT ELASTIC AND PLASTIC DEFORMATION

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By the method of absorption spectroscopy the efficiency of radiation defects formation in alkali halide crystals was studied (Shunkeev K., Babin V., Bekeshev A., Elango A., Kalder K., Vasilchenko E., Zazubovich S. J. Lumin. 76-77, 502 (1998)). However, by the absorption spectrum of radiation defects due to the limited sensitivity compared with luminescent spectroscopy is not possible a detailed study of the deformation-stimulated processes. In this regard, thermally stimulated luminescence (TSL) of radiation defects at elastic and plastic deformation was applied in alkali halide crystals. In the absence of deformation the dominant peaks in TSL are corresponded to the three halogen molecule.

After elastic deformation low temperature peaks of TSL, corresponding to F<sup>'</sup>-, Vk- and Vf-centers became dominant. After plastic deformation peaks of TSL, corresponding to the three halogen molecule became dominant.

Elastic deformation contributes to the increase in concentration of low-temperature F<sup>'</sup>-, Vk- and Vf-centers, and plastic – of high temperature – centers (peaks of TSL in KCl at 360K, in KBr at 365k, in KI at 340k, composed by divacancies created by plastic deformation. At elastic deformation unrelaxed interstitial halogen atoms are converted into Vk- and Vf-centers, due to this fact the long-range interaction is absent, the result of which are the the three halogen molecule.

**Keywords:** *Thermally stimulated luminescence, radiation defects, elastic and plastic deformations.*

## DEFORMATION STIMULATED LUMINESCENCE IN KCL, KBR AND KI CRYSTALS

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Currently, strengthening of the intensity of luminescence in alkali halide crystals (AHC) at lattice symmetry lowering is discussed as a promising direction for the development of scintillation detectors [Babin V., Bekeshev A., Elango A., Kalder K., Shunkeev K., Maaros A., Vasilchenko E., Zazubovich S. *J. Phys.: Condens. Matter* 11, 2303 (1999)].

In this regard, for the study of anion excitons and radiation defects in the AHC anion sublattice at deformation crystals with the same sizes of cations and different sizes of anions were chosen.

In the X-ray spectra of KCl at 10 K is clearly visible the luminescence at 3.88 eV; 3.05 eV and 2.3 eV. Luminescence at 3.05 eV is corresponded to the tunneling recharge [F\*, H]. Luminescence at 3.88 eV is quenched in the region of thermal destruction of F'-centers and characterizes tunneling recharge of F', Vk-centers. In KCl at 90 K the luminescence of self-trapped excitons (STE) is completely absent.

In KBr at deformation not only STE luminescence, but also deformation stimulated luminescence at 3.58 eV, corresponding to tunneling recharge of F', Vk-centers.

In KI crystal at 10 K and 90 K at deformation enhances only STE luminescence. Thus no deformation luminescence bands, unlike KBr and KCl crystals [Shunkeyev K., Zhanturina N., Aimaganbetova Z., Barmina A., Myasnikova L., Sagimbaeva Sh., Sergeyev D. *Fiz. Nizkikh Temp.* 42 (7), 738, (2016)].

**Keywords:** Deformation stimulated luminescence, Self-trapped excitons, tunneling luminescence.

## LUMINESCENT DIAGNOSTICS OF LED HETEROSTRUCTURES BASED ON INGaN/GaN

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GaN-technologies are developing dynamically and are considered the most promising in the field of high-power optoelectronic devices. Requirements for optical, electrical and mechanical characteristics of the structures based on GaN, rise. At the same time the need for effective methods of research and diagnostics of the materials increases.

In this paper we studied the cathodoluminescence (CL) and photoluminescence (PL) characteristics of LED heterostructures based on InGaN/GaN grown under different technological conditions, with the aim of obtaining the experimental basis for the development of effective methods of heterostructures diagnostics.

As the samples were used blue LED heterostructures based on GaN grown by metalorganic vapor-phase epitaxy on sapphire. The active region of the samples consisted of multiple InGaN quantum wells and GaN barriers.

CL of heterostructures was excited by high-current electron beam (pulse duration 15 ns, energy density 0.05–0.5 J/cm<sup>2</sup>). PL was excited by two sources: a nitrogen laser ( $\lambda = 337.1$  nm, pulse duration 10 ns, the level of optical excitation  $\sim 10$  kW/cm<sup>2</sup>) and Xe lamp (pulse width 2  $\mu$ s, equivalent power 75 kW).

In the luminescence spectra of the samples in addition to the main blue band of quantum wells InGaN/GaN we registered a number of emission bands in UV, green, yellow and red ranges. Dependences of the luminescence spectral composition on the source and the level of excitation were detected. The observed features of radiative recombination in LED heterostructures can be a basis for the creation of diagnostic methods of these materials.

**Keywords:** *luminescent diagnostics, LED heterostructures, InGaN/GaN, high-current electron beam, cathodoluminescence, photoluminescence.*



## THERMALLY STIMULATED LUMINESCENCE PROCESS IN (LI, NA)F:ME CRYSTALS UNDER THE ELECTRON IRRADIATION

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The TSE and TSL of some compounds based on (Li, Na)F:Me crystals irradiated with different doses of soft (150 keV) and hard electron beams (10 MeV) have been investigated in the framework of the collaboration between the Ural Federal University and the National Academy of Sciences KR, where the (Li, Na)F:Me crystals were grown by Kyropoulos method. It has been proved that the NaF:Sc crystals are the most efficient OSL and TSL sensors for 150 keV soft electron beams. In the TSL spectra of NaF:Sc crystals, peaks at 99, 143 and 181 °C of about equal intensity can be clearly seen. The TSE curves show a prominent intensity, especially for high fluence irradiation dose ( $1.5 \times 10^{14}$  eV/cm<sup>2</sup>). In the TSE spectra peaks are recorded at 74, 124, 144, 183, 206, 240, 290 and 375 °C, the predominant being the one at 183 °C. Highly efficient OSL and TSL sensors for 10 MeV electrons energy were proved to be NaF:Li; NaF:1Li, 0.1Cu; LiF:0.3Cu and LiF:1Cu crystals. NaF:Li crystals evidence TSE maxima at 163, 237, 285 and 322°C, the peak at 237 °C being dominant also in the spectrum where Cu is added as activator (NaF:1Li, 0.1Cu sample). The composition of NaF: Li and NaF: Li, Cu is important in view of working media for TSE high energy and high doses radiation dosimetry to control radiation modifications induced on the centers of functional materials.

To this regard, in June 2016 a patent application was submitted (№ 2016121282) using crystals having NaF 98.3-98.9, LiF 1-1.5, CuCl<sub>2</sub> 0.2-0.3 composition (mol.%).

**Keywords:** *Luminescence, TSE and TSL processes, luminescence centers, scintillators.*

## PULSE CATHODOLUMINESCENCE OF CERAMIC $\text{Al}_2\text{O}_3/\text{MgO}$ COMPOSITE

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Aluminum and magnesium oxides are radiation-resistant materials. Their luminescent properties are intensively studied. Synthesis of ceramic  $\text{Al}_2\text{O}_3/\text{MgO}$  composite with different concentrations of MgO allows one to see its luminescent properties as a result of two processes: doping of  $\text{Al}_2\text{O}_3$  with magnesium ions and formation of a new phase of aluminum – magnesium spinel ( $\text{MgAl}_2\text{O}_4$ ).

A method of high-temperature solid-state synthesis in vacuum was used to obtain anion-defective ceramics of  $\text{Al}_2\text{O}_3/\text{MgO}$  composite while MgO was varying from 0.01 up to 99.99 weight percent. The synthesis temperature was changed from 600 up to 1,400 °C. XRD method was applied for phase analysis. Pulse cathode luminescence (PCL) was excited with a pulse electron beam with duration of 2 ns, electron energy of 130 keV and current density of 60 A/cm<sup>2</sup>.

It was found that a band with the maximum at 2.4 eV was registered in the PCL spectrum in the samples synthesized at 1,000–1,200 °C. This band is presumably associated with the formation of oxygen vacancies forming F-centers in spinel phase ( $\text{MgAl}_2\text{O}_4$ ). Increasing synthesis temperature up to 1,400 °C leads to growing PCL in the bands of 3 eV and 2.7 eV in the samples with low and high MgO contents respectively. The 3 eV band is observed due to formation of F-centers in  $\text{Al}_2\text{O}_3$ . The band with the maximum at 2.7 eV is caused by luminescence of F<sup>+</sup>-centers in  $\text{MgAl}_2\text{O}_4$ .

The synthesized  $\text{Al}_2\text{O}_3/\text{MgO}$  composite is highly radiation-resistant, since the absorbed dose in PCL excitation was 30 kGy.

**Keywords:** *ceramic composite, aluminum-magnesium spinel, cathode luminescence.*

## LUMINESCENCE CENTERS IN NANOLAYERS OF FLUORIDE CRYSTALS WITH EMBEDDED AG IONS

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Results of studies luminescent centers originated from irradiation of fluoride crystals with silver ions are presented. The samples were irradiated with ion beam of fluencies varied in the range  $2 \times 10^{13}$ – $10^{18}$  ions/cm<sup>2</sup> and 150 keV energy. Photoluminescence spectra of the samples were measured under excitation with a picosecond laser of 375 nm wavelength. It was found that at fluencies of  $2 \times 10^{13}$  ions/cm<sup>2</sup> the peak of the spectrum lies at a wavelength less than 400 nm, with a shift of the peak position towards 600 nm at increasing of the influence up to  $2 \times 10^{13}$  ions/cm<sup>2</sup>. A photoluminescence of the samples doped with Eu<sup>2+</sup> ions was not recorded. When excitation the irradiated CaF<sub>2</sub> crystal by a radiation of 357 nm wavelength, a glow of a surface layer appears with position of the band's peak at 600 nm wavelength. With excitation by radiation of 270 nm wavelength, the layer glows with peak of the band position at 400 nm. These results permit us to argue that the irradiation CaF<sub>2</sub> crystal by silver ions resulted in formation two types of luminescence centers in a surface layer of the crystal, so that the first one can be attributed to formation of the molecular clusters  $n \cdot \text{Ag}^+$  ( $n = 3$ – $6$ ) and the second is attributed to formation of the silver nanoscale particles. The irradiated KCl crystals, as a result of excitation by a laser radiation, exhibit a photoluminescence band with a peak at 573 nm.

**Keywords:** *luminescence centers, nanoscale particles, fluoride crystals.*

## LUMINESCENCE OF LITHIUM-PHOSPHATE-BORATE GLASSES DOPED WITH $Tb_3^+$ AND $Pr_3^+$ IONS

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The oxide glass doped with rare-earth ions (REI), as active media in optoelectronics; as scintillation materials for imaging radiation fluxes; UV-Vis radiation converters are widely used. Simplicity of synthesis of glassy materials, the ability to manufacture optical elements of any shape and size, relatively low cost, possibility to incorporate impurities, changes in the composition of the host and high optical homogeneity makes them an alternative to single crystals.

In this work glasses of composition  $Li_2O-B_2O_3-P_2O_5-CaF_2$  (LBPC) doped with  $Tb_3^+$ ,  $Pr_3^+$  and co-doped  $Pr_3^+/Tb_3^+$  ions with different concentration of  $Pr_3^+$  ions from 0.2 to 1 wt % was studied. The samples at the Institute for Single Crystals of National Academy of Sciences of Ukraine (Kharkov) were synthesized. Optical analysis of these glasses has been carried out based on the measurements of absorption, excitation and emission spectra.

For all investigated samples occurs luminescence in «blue-green» region spectra. The radiative transitions occur from the excited states  $5D_3$ ,  $5D_4$  to the ground state  $7F_j$  in terbium ions. It was found that quenching process can occurs when the concentration of  $Pr_3^+$  increase from 0.2 to 1 wt% at main luminescence bands of terbium ions. The decay kinetics of luminescence glasses excited electrons beams was studied in detail. The mechanism of energy transfer between  $Tb_3^+$  and  $Pr_3^+$  ions are discussed.

**Keywords:** *glasses, scintillators, rare earth ions, luminescence decay kinetics.*

## LUMINESCENCE POTASSIUM SULPHATE CRYSTALS DOPED WITH $\text{Sn}^{2+}$ IONS

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The aim of this paper is to study some spectral-luminescent properties of sulfates activated stannous ions. The paper presents the photoluminescence excitation spectra of crystal  $\text{K}_2\text{SO}_4\text{Sn}^{2+}$ . In this spectrum, peaks are observed at 240 nm and 260 nm. Depending on the field of radiation monitoring in the excitation spectra has a «shoulder» or a short-wave or long-wave wing on the optical band. Thus, the presence of two bands photoluminescence excitation suggests that  $\text{K}_2\text{SO}_4$  formed two types of impurity luminescence center differing immediate surroundings.

**Keywords:** *potassium sulphate, photoluminescence, optical band.*

## LUMINESCENCE OF LiF CRYSTALS DOPED WITH URANIUM

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Absorption spectra were measured in the range from 195 nm to 5 microns, luminescence excitation spectra in the range of 200–400 nm, the luminescence in the 400–550 nm, and the decay kinetics pulsed cathodoluminescence LiF crystals doped with uranium.

Introduction of the activator (U) and the co-activator (OH) shown in occurrence of additional absorption in the range 260–320 nm. The IR spectrum in crystals containing OH, distinguished characteristic absorption bands at  $3725\text{ cm}^{-1}$ . In crystals with an activator (U) are observed in the bands  $3550\text{--}3580\text{ cm}^{-1}$ , which are responsible, probably, OH ions in the activator. The activated crystals observed with co-activator additional band at  $3342\text{ cm}^{-1}$ .

The activated crystals luminescence observed in the field of 470–520 nm when excited by harsh and UV radiation. Type of luminescence spectra depend on the activator concentration and the presence of the co-activator.

The luminescence is excited in the region below 370 nm UV light (Figure 1). At low concentrations of activator luminescence excited by radiation mainly in the bands at 230 and 270 nm. At high concentrations of the activator and co-activator in the presence of luminescence excited in the overlapping bands of approximately equal intensity at 220, 270 and 340 nm. Apparently, coactivators (OH) is introduced always in the synthesis of the crystal in air with the uranium and the excitation band of 340 nm in the centers responsible related to OH in the activator.

**Keywords:** *photoluminescence, cathodoluminescence, luminescence centers.*

## LUMINESCENT PROPERTIES AND MORPHOLOGY OF $ZnWO_4$ POWDERS SYNTHESIZED BY HYDROTHERMAL METHOD

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$ZnWO_4$  powders were synthesized by hydrothermal method followed with calcination process. It was used for the synthesis of zinc acetate  $Zn(NO_3)_2 \cdot 6H_2O$   $Na_2WO_4 \cdot 2H_2O$  and sodium tungstate. The synthesized phosphors were characterized by Raman spectra, scanning electron microscopy (SEM), photoluminescence excitation and emission spectra, cathodoluminescence spectra and luminescence decay kinetics. The results showed that the obtained phosphors have monoclinic wolframite structure. The particle size was about 100 micrometer. The phase structure of  $ZnWO_4$  powders changed after the annealing. It was shown that the excitation and luminescence spectra of the synthesized powders are such as the spectra measured for single crystals. Upon excitation at UV light 300 nm was obtained blue emission band at 486 nm (FWHM 0.71 eV) corresponding to tungstate groups. Luminescence intensity and time decay are grown with increase of annealing temperature from 100 to 400 °C. The morphology of particles, phase structure, luminescent properties of the synthesized phosphor are discussed.

**Keywords:** zinc tungstate, luminescence, hydrothermal synthesis, scintillators, phase structure.

## SPECTRAL CHARACTERISTICS OF THE LUMINESCENCE OF INDUSTRIAL YAG PHOSPHORS

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The results of studies of quantitative characteristics of photo- and cathodoluminescence of YAG phosphors are presented. The results of studies of quantitative characteristics of photo – and cathodoluminescence of YAG phosphors are presented. Spectral characteristics of the luminescence of phosphors tested are independent of excitation method. Some differences in the characteristics of fully explained by the difference of excitation power. Spectral and kinetic characteristics of investigated luminescence phosphors have similar but the elemental composition of the phosphor varies greatly. This suggests that the luminescence centers in the investigated phosphors are similar. A variation of the elemental composition achieved by the formation of similar emission centers in all investigated phosphors differ, possibly trapping efficiency of electronic excitations. This suggests that the elemental composition, including activators, not directly determine emission characteristics of the phosphor. Radiative characteristics determined not only by the elemental composition of the matrix but also introduced in the synthesis of imperfection, primarily related to the intrinsic defects.

In the synthesis of the phosphor in the form complex defects with luminescence centers in them, including in its membership structure of intrinsic defects. Complex defects mentioned in [L.A. Lisitsyna, V.M. Lisitsyn, *Composition nanodefects in doped lithium fluoride crystals, Phys. of Solid State. 55 (2013) 2297–2303*] nanodefects have a large capture cross section of the electronic excitations, the high efficiency of excitation energy transfer to the emission center.

**Keywords:** Cathodoluminescence, Photoluminescence, Phosphor, Spectral.



## RADIATION DEFECTS IDENTIFICATION BASED ON THE PROPERTIES OF THEIR PHOTOLUMINESCENT TRAJECTORIES

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The aim of the study is to explore the possibilities of spectroscopic differentiation of the individual types of luminescent defects created by radiation in condensed matter, on the basis of a comparison of generalized numerical characteristics of the photoluminescence intensity quantum trajectories measured on single defects by the methods of scanning confocal fluorescence microscopy in the mode of spatial-selective time-correlated single photon counting. The unique luminescence measuring technologies with extremely high sensitivity used in this work provide the possibility of exploring single radiation defects. These technologies able to revolutionize the radiation physics of solids, which depth of research so far had been limited to mostly dealing only with defect ensembles. One of the problems in this field of science is the difficulty of identifying numerous types of intrinsic defects and intrinsic-impurities defects created by radiation in crystalline and amorphous media. In contrast to atomic gases or rare earth impurities with their optical transitions in the inner electron shells, the huge electron-phonon and electron-vibrational homogenous broadening of spectral lines leading to transformation of these lines into broad bands are observed for condensed matter. This significantly limits the capabilities of commonly used methods of absorption and fluorescence spectroscopy in research of condensed matter. The report proposes a new spectroscopic criteria based on the characteristics of the quantum trajectories of the luminescence intensity of individual radiation defects, providing new opportunities for their identification.

**Keywords:** *Luminescence, color center, quantum trajectory, crystal, radiation, excitation, lifetime, triplet, singlet, confocal microscopy, photon counting, spectroscopy.*

## ION BEAM EXCITATION OF TXRF YIELD FORMED BY PXWR

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Total external reflection of X-ray exciting flux on the studied surface (TXRF analysis) method is characterized by X-ray fluorescence excitation of the material surface layer with thickness 3–5 nm. The method is featured by very small background intensity and has not need in the matrix correction introduction. Moreover, fluorescence lines intensities are connected with atomic concentration in the surface layer, linearly, and method can be used as the effective quantitative procedure for the concentration analysis of superlow pollutions concentration. But TXRF and XRF analysis diagnostics at gamma, X-ray and electron excitation is characterized by very low efficiency at light elements determination in materials. This methodical disadvantage can be compensated by application of ion beam excitation of X-ray fluorescence (PIXE-method). At the same time, PIXE method reflects the element composition of the studied material volume.

In our work we elaborated the experimental scheme for TXRF measurements in conditions of characteristic fluorescence excitation by high energy proton beams. The scheme is build on base of the planar X-ray waveguide-resonator (PXWR) with specific design. PXWR in this scheme is formed by Be polished with hole in its centre and surface of studied target. Slit clearance between Be reflector and target surface ( $s = 0.15$  mkm) selects characteristic fluorescence yield from the surface target layer with thickness 3–5 nm. So, we realized new method for surface material diagnostic characterized by high efficiency for the light element determination. Its features in conditions of Sokol-3 ion beam analytical complex application are discussed.

**Keywords:** *TXRF, Ion beam analysis, waveguide-resonator, X-ray fluorescence.*

## OXIDE FILMS STATE ANALYSIS BY IR SPECTROSCOPY BASED ON THE SIMPLE OSCILLATOR APPROXIMATION

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Stabilization of structure-phase state in a wide temperature range is one of the most important problem of improving properties of oxide compounds. As such, the search of new effective methods for obtaining of metal oxides with desired physic-chemical, electro-physical and thermal properties and their control is important and relevant.

The aim of this work is identification features state of the oxide films of some metals Be, Al, Fe, Cu, Zr on the metal surface of the polycrystalline samples by infrared spectroscopy.

To identify the resonance emission bands algorithm of IR-spectra processing was developed and realized on the basis of table processor EXCEL-2010, which allow to reveal characteristic resonance bands successfully and identify inorganic chemical compounds.

In frame of simple oscillator model resonance frequencies of normal vibrations of water and some inorganic compounds: metal oxides – Be, Al, Fe, Cu, Zr were calculated and characteristic frequencies for different states (aggregate, deformation, phase) were specified.

By means of IR-spectroscopy fundamental possibility of revealing oxides films on metal substrate features state is shown, that allow to develop and optimize technology of production of the oxide films with desired properties.

**Keywords:** *IR-spectroscopy, oxide films, simple oscillator.*

**SYNTHESIS AND STUDY OF PHOTOPHYSICAL PROPERTIES  
OF NEW SENSORS ON NITROAROMATICS COMPOUNDS BASED  
ON PYRIMIDINE AND DEVELOPMENT OF PORTABLE DETECTOR  
OF EXPLOSIVES**

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The design and synthesis of artificial sensors capable to detect rapidly the chemical explosives is prevalent and current research topic. The most common explosives are nitroaromatic compounds (NACs). NACs have received great attention in last decades due to global terror threats and to their high toxicity to the environment. Various analytical methods have been developed for sensitive detection of nitroaromatic compounds. Among the physical methods, photoluminescence based chemosensors that exploit sensitive fluorescence quenching by nitroaromatic derivatives have been investigated extensively for both vapor and solution phases at low concentrations with high sensitivity and selectivity.

Currently, the most promising sensors for nitroaromatic explosive compound are materials based on carbazole and triphenylamine. The theoretical calculations showed the possibility of using such systems as the sensors. We have carried out the synthesis of the wide number of similar compounds containing different donor (carbazole and triphenylamine) deputies and various PI-linkers. On the basis of fluorescence titration it were determined the constants of Stern-Folmer and detection limits of some model nitroaromatics explosives with use of synthesized fluorophores. The most sensitive compounds were used to create prototypes of new sensors for the instrument [1, 2].

As a result, the device was designed on the basis of this sensor material, sensitivity dependences of the material sensor in interaction with TNT vapors were revealed. The quantitative evaluation of luminescence intensity quenching under the HE vapors influence was determined. This device has been done in collaboration with the Plant «Promautomatika» and subsidiary company «Intermolecular system of security» (Ekaterinburg, Russia).

**Keywords:** *nitroaromatic explosive fluorescence quenching device for vapor detection.*

## DTG-4 – SINGLE CRYSTAL THERMOLUMINESCENT DETECTORS

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Single crystal detectors DTG-4 (LiF:MgTi) have been developed for application in thermoluminescence dosimetry in the Institute of Geochemistry SB RAS more than 30 years ago. The crystal growth technology has also been developed. The crystals were grown from fused high purity powder of LiF by Stockbarger method and have been activated with MgF<sub>2</sub> and TiO<sub>2</sub>.

The thermoluminescent properties of obtained detectors DTG-4 are similar to that of well known powder detector TLD 100. However, single crystal DTG-4 possesses well known advantages against its powder competitor/analogue TLD 100 – those are greatly improved reusability and reduced chemiluminescence. The latter allows to lower significantly own background of detector, which is very important when low radiation doses are detected.

Detectors made with developed technology have linear indications in the dose range of  $5 \times 10^{-5}$ –1 Sv, radiation resistance up to 100 Sv and allow over 500 cycles of usage. This makes them appropriate for applications in personal dosimetry.

In this paper we report a comparison of properties of thermoluminescent detectors DTG-4 made and studied in 1986 and in 2016. Experiments reveal identical properties of detectors. Also DTG-4 produced in 1986 were re tested in 2016, i.e. after thirty year conservation. Surprisingly, own loss of sensitivity of detectors investigated after such a long period of time has not been observed. The fading derived is only 5 % per year. It is due mainly to loss of information which occurs during storage of irradiated detectors.

**Keywords:** *DTG-4, LiF:MgTi, thermoluminescence dosimetry.*

## DETERMINATION OF ORIENTATION OF RADIATION INDUCED QUANTUM SYSTEMS IN ANISOTROPIC CRYSTALS BY THE SPATIAL-MODULATION METHOD

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Important properties of crystalline optical materials depend on the orientation of the quantum systems which are contained in them and interact with the radiation. Therefore, the development of crystalline optical elements for different purposes need to have data about their orientation. Therefore, various methods for determining the orientation of color centers in crystals exist [P.P. Feofilov «*Polyarizovannaya lyuminesentsiya atomov, molekul i kristallov*», M: Gos. izd-vo fiz.-mat. lit-ry, 1959, str. 198–219; M.Ye. Springis «*Primeneniye metoda polarizatsionnykh otnosheniy dlya issledovaniya tochechnykh defektov v kristallakh  $\alpha$ -Al<sub>2</sub>O<sub>3</sub>*» – *Izvestiya AN Latv. SSR, Seriya fiz. i tekh. nauk*, 1980, №4, str. 38–46; E.F. Martynovich «*Tsentry okraski v lazernykh kristallakh*», – *Irkutsk: Izd-vo Irkut. un-ta*, 2004. – str. 150–155]. Effect of spatial modulation of photoluminescence intensity of anisotropic crystals under laser excitation theory [E.F. Martynovich, G. Petite, V.P. Dresvianskiy, A.A. Starchenko, *Appl. Phys. Lett.* 84 (2004) 4550] developed in this work. The correspondence between the depth of modulation of the luminescence intensity and the orientation of the dipole moments quantum transitions was determined. The new method of determining the orientation of the quantum systems developed and tested. This method allows to determine the orientation of the quantum systems in anisotropic crystals different crystallographic point groups, as well as crystals with the induced anisotropy.

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**Keywords:** *laser, photoluminescence, color centers, anisotropic crystals, orientation, quantum systems, depth of modulation.*

## DESIGN OF COLLIMATION SYSTEM FOR GAMMA PROBE

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Studies using radiometric medical devices involve the creation of systems of collimation of gamma radiation. This paper considers problem of gamma-ray collimation system and discussed importance of creating set collimators for gamma probe radiometric device (gamma-locator). Gamma probe radiometric system planned to be used in nuclear medicine in vivo in our research work. It is shown that cylindrical type collimators for gamma probe should be used in observational studies of distribution of radiopharmaceuticals. In that work collimators cylindrical type for given values of investigated objects, for example their size and depth, were designed and manufactured . Using set of collimators working with gamma probe in phantom study, conducted on the original simulators for pilot assessment of the spatial and angular resolution, was made optimal set of collimation systems for prototype.

**Keywords:** *radiometric, radiopharmaceutical, collimator, radionuclide.*

## PROGRAM MODELING OF THE PHOTOLUMINESCENCE CHARACTERISTICS OF RADIATION-INDUCED DEFECTS IN ANISOTROPIC CRYSTALLINE MEDIA

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A program for modeling dependence of the luminescence intensity of radiation defects and the depth of its spatial modulation in anisotropic crystals of various parameters which determine the characteristics of the exciting radiation, and crystal contained therein luminescence centers.

The program is based on the semiclassical theory of vector interaction of laser light with an anisotropic crystalline medium containing luminescence centers with different orientations. The program is written in C++ in the environment Borland C++ Builder development.

The following relationships can be calculated using the program:

- the luminescence intensity dependence from the angle of rotation of the electric vector of about the optical axis;
- dependence of the luminescence intensity from angles which determine the direction of the transition dipole moments;
- dependence of the luminescence intensity from angles defining direction of observation of the luminescence;
- the luminescence intensity dependence from the crystal distance along the wave vector;
- dependences the depth of the spatial modulation of the luminescence intensity from different angles which determine direction of the field vectors and the orientation of the luminescence centers.

The program has been tested experimentally. Comparison with experiment has shown the adequacy of the results obtained with the help of the developed program. There are opportunities to use the program for the design and development of new applications.

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**Keywords:** *program modeling, radiation-induced defects, luminescence, transition dipole moments, anisotropic crystals, orientations.*



## NUMERICAL SIMULATION OF THE EFFECT OF LASER RADIATION ON MATTER IN AN EXTERNAL MAGNETIC FIELD

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The experimental study of thermonuclear plasma should be accompanied by the construction of multi-level radiation and gas-dynamic computing models that adequately describe processes in the active zone of impulsive thermonuclear reactor. Thus, calculation-theoretical methods are an important element in the development process of concept of magneto-inertial fusion (MIF). You will recall that MIF system is a pulsed thermonuclear setting, where a cylindrically or spherically symmetric thermonuclear target placed in the seed magnetic field is compressed by the powerful laser beams or shells of all kinds, including gas, liquid and metal shells, plasma liners formed by the merger of high-speed plasma jets, etc. It is obvious that the developed mathematical models and methods of computing target plasma dynamics of MIF require in this case obligatory verification on the basis of comparing to the reliable computation and experimental data of physical experiment.

Results of computational modeling are presented. Calculations carried out for the Nd laser radiation for forming rectangular shape (impulse duration = 10 ns). The radiant flux value is  $q_{\text{las}} = 2 \times 10^{14} \text{ W/cm}^2$ . A thin metallic cylindrical shell material is Al.

This research has been supported in part by grant No. 13.79.2014/K from the Ministry of Education and Science of the Russian Federation.

**Keywords:** *Magneto-inertial fusion, Numerical method, Radiation magnetohydrodynamic simulation.*

**PHOTOCHROMIC EFFECT IN PR DOPED FLUORIDE CRYSTALS****TATYANA SIZOVA<sup>1</sup>, ROMAN SHENDRIK<sup>1</sup> AND VALERIYA VESLOPOLOVA<sup>2</sup>***<sup>1</sup>Federal state budgetary institution of science A.P. Vinogradov Institute  
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Both irradiation and additive colouration of alkaline-earth fluorides doped with trivalent lanthanides result in the formation of divalent ions or photochromic (PC) centres. Trivalent ions (Y, La, Ce, Gd, Tb, and Lu) with low third potential ionization are not reduced to the divalent state; instead, they form photochromic centers. Crystals in which they are present become coloured on exposure to light; the process may be reversed by heating. Optical dichroism studies have identified the centre as a complex of a dopant ion (La, Ce, Gd, Tb, Lu) with low third ionization potentials and an anion vacancy, containing two trapped electrons. Hayes proposed the formation of PC centres in irradiated Pr-doped CaF<sub>2</sub>, however, these centres do not observed. Nevertheless, formation of Pr<sub>2</sub><sup>+</sup> centres in irradiated CaF<sub>2</sub> crystals was found in several papers. In this article, we found photochromic effect in irradiated Pr-doped CaF<sub>2</sub>. Optical absorption spectra of photochromic centers, the thermal destruction in crystals of CaF<sub>2</sub> doped PrF<sub>3</sub> have been studied at temperatures 300–600 K. We show that X-ray irradiation at 300 K cause to the formation of PC<sup>+</sup> centers in Pr doped CaF<sub>2</sub> crystals. At temperatures in the ranges 350–450 K PC<sup>+</sup> centers are transformed into PC centers. All color centers destruct by heating of the crystals to ~600 K. The mechanism of formation PC centres will be discussed.

The reported study was funded by RFBR according to the research Project no. 16-32-00198 \_mol\_a.

**Keywords:** *photochromic centre, fluoride, praseodymium.*

## CREATION AND EXCITATION OF Ti:Al<sub>2</sub>O<sub>3</sub> LAYER AT BOMBARDMENT OF SAPPHIRE CRYSTAL BY ELECTRON- Ti<sup>n+</sup>-ION BEAMS

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The capture by electron-beam and effective collective acceleration of Ti<sup>n+</sup> ions is found at a pinching of the electron-beam (300 keV) formed at hot plasma in vacuum at explosive emission of the sharp titanium (Ti) cathode. Electron-Ti<sup>n+</sup>-ion beams formed by method of effective collective acceleration of Ti<sup>n+</sup> are used for bombardment of sapphire crystal.

Energy of Ti<sup>n+</sup> ions as a result of collective acceleration on the pinched electron-beams can too exceed the energy of formation of defects in sapphire. Thus, a doping process of sapphire crystals by Ti<sup>3+</sup> ions can occur at electron-Ti<sup>n+</sup>-ion-beam bombardment.

Al<sub>2</sub>O<sub>3</sub> crystal was irradiated at the distance of 0,5 cm from the sharp Ti-cathode. Sapphire crystal after irradiation was investigated at using of the optical microscope with laser excitation (450 nm). It is determined that in Al<sub>2</sub>O<sub>3</sub> crystal the electron-Ti<sup>n+</sup>-ion beams is induced the alloy Ti:Al<sub>2</sub>O<sub>3</sub> layer in which the Ti<sup>3+</sup> photoluminescence is observed visually in the red range at laser excitation (450 nm). For confirmation of visual researches the single-pulse spectrum of cathodoluminescence (CL) of implanted Ti:Al<sub>2</sub>O<sub>3</sub> zone of crystal is measured. The CL spectrum of the alloyed Ti:Al<sub>2</sub>O<sub>3</sub> layer induced by electron-Ti<sup>n+</sup>-ion beams corresponds to the spectrum of luminescence of Ti<sup>3+</sup> centers and to the intrinsic luminescence in synthesized Ti:Al<sub>2</sub>O<sub>3</sub>.

Thickness of Ti<sup>3+</sup> luminescence layer (0,5–0,8 microns) was investigated on the optical microscope which corresponds to depth of the Ti<sup>n+</sup>-ions penetration in Al<sub>2</sub>O<sub>3</sub>. It is known that Ti<sup>n+</sup> ions with energy ~10 MeV penetrates in Al<sub>2</sub>O<sub>3</sub> crystals on the depth of 0,8 microns.

**Keywords:** *sapphire, luminescence, Ti-implantation.*

## EXPLOSIVE RADIATION SOURCES FOR ANALYTICAL SPECTROSCOPY

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The high-current electron beams impact to the energy materials under certain experimental conditions, leads to the explosion initiation, which is accompanied by an intensive radiation. The emission spectra of explosive decomposition products of furazanotetrazin dioxide (C<sub>2</sub>N<sub>6</sub>O<sub>3</sub>, FTDO) and of the heavy metals azides were measured and identified in [1–2].

The purpose of investigation is to explore the possibility of explosive radiation source using for analytical spectroscopy.

The investigation objects were salt BaCl<sub>2</sub> and SrCl<sub>2</sub>. The FTDO pressed powder tablets were used for vaporization, atomization and emission spectra excitation. The samples in form of a powder or a compressed tablet were placed on the explosive tablets surface. The pulsed electron accelerator (250 keV, 15 ns) was served as the source of the explosion initiation.

The intensive lines of metals (Na, K, Ba, Sr) and series of BaCl and SrCl molecular bands were found in the total spectra of samples explosion plasma.

The research results indicate the possibility of the explosive energy using for solid samples evaporation, atomic and molecular emission spectra excitation. The benefits of the explosive radiation source include a high level of thermal capacity, providing heating of any substance to tens of thousands degrees, rapidity and cost-effectiveness.

**Keywords:** *explosive radiation sources, analytical spectroscopy, explosive decomposition spectra, high-current electron beams, explosion plasma spectra.*

## METHODS FOR RADIATION AND ECOLOGICAL RESEARCH OF BUILDING LANDS AND ANALYSIS

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It's known that radon and its radioactive decay products are major cause of background radiation in houses and industrial buildings. Therefore, before the construction process it's necessary to make an investigation. However, at present time, there is no uniform method for estimation of the radon risk of territories. Abroad as a criterion of radon risk is widely used «geogenic radon potential» (GRP). The determination of the value of GRP requires different sets of input values (such as concentration of radium in the soil, radon porous activity, gas permeability of soils, soil geological properties) and different measurement methods. In Russia, radon risk of building lands is estimated by measuring the value of radon flux density (RFD) by using storage chamber method. This paper presents an analysis of different methods for estimating radon risk of territories, also presents the result of measurements of RFD by different methods. Researches have shown that the existing approaches to the assessment of radon risk have significant drawbacks, because it does not allow to reliably determine the amount of radon coming from the soil surface.

**Keywords:** *Radon, Radon flux density, Radon porous activity.*

**ION IRRADIATION BEHAVIOR OF NANOSTRUCTURED TI-SI-N FILMS****VLADIMIR UGLOV<sup>1</sup>, SERGEY ZLOTSKI<sup>1</sup> AND VLADIMIR SKURATOV<sup>2</sup>**<sup>1</sup>*Belarusian State University, Belarus*<sup>2</sup>*Joint Institute for Nuclear Research, Russia**uglov@bsu.by*

Structure and phase composition of the films based on transition metal nitrides can be significantly improved by addition of silicon. Such thin films are potential candidates for radiation-tolerant materials due to high density of interfaces which act as efficient sinks and recombination sites for radiation-induced point defects. The effects of the irradiation (360 keV Xe<sub>2</sub><sup>+</sup>, dose of  $5 \cdot 10^{16} \text{ cm}^{-2}$ ) on the structure, phase composition of nanocomposite TiSiN and multilayered TiN/SiN thin (1.5 μm) films deposited by magnetron sputtering were studied. It has been found that the nanocomposite films are corresponding to particles of titanium oxide in an amorphous matrix SiN<sub>x</sub>. As for multilayer TiN/SiN they are X-ray amorphous. It was found that annealing of nanocomposite and multilayered films does not lead to a change in its phase composition, which testifies to the high thermal stability of phase composition. It was found that irradiation by Xe ions does not lead to a change in the phase composition of the nanocomposite TiSiN films. For multilayer coating TiN/ZrN irradiation also does not result a change in X-ray amorphous state. Studies of a surface microstructure have revealed the formation of blisters only in multilayer films. In the paper the mechanisms of radiation resistance of nanocomposite and multilayered Ti-Si-N films are discussed.

**Keywords:** *Ion irradiation, nanocomposite, blisters formation, phase composition.*

**PIC CODE KARAT SIMULATIONS OF COHERENT THZ SMITH-PURCELL RADIATION FROM DIFFRACTION GRATINGS OF VARIOUS PROFILES**

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Generation of coherent THz Smith-Purcell radiation by single electron bunch or multi-bunched electron beam was simulated for lamellar, sinusoidal and echelette gratings. The dependences of the C SPR intensity of the corrugation gratings depth were investigated. The angular and spectral characteristics of the C SPR for different profiles of diffraction gratings were obtained. It is shown that in the case of femtosecond multi-bunched electron beam with 10 MeV energy sinusoidal grating with period 292  $\mu\text{m}$  and groove depth 60  $\mu\text{m}$  has the uniform angular distribution with high radiation intensity.

***Keywords:*** *Coherent THz radiation, Smith-Purcell radiation, PiC simulation.*

## LITHIUM FLUORIDE FILMS CONTAINING COPPER NANOPARTICLES AS A PROMISING MATTER FOR MEMRISTOR CELL

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Thin composite films were produced on a glass substrate by a common usage of thermal evaporation of the lithium fluoride sample and magnetron sputtering of a copper target. The absorbance spectrum of the film exhibits the bands characteristic of the copper nanoparticles. It was shown that there is a current about of  $10^{-14}$  A between electrodes placed on the opposite surfaces of the film at absence an applied bias. When the applied voltage increased up to  $10^{-2}$  V then the current increased dramatically up to  $10^{-5}$  A and the subsequent voltage increase resulted to a gradual increasing of the current up to  $10^{-3}$  A at the voltage of 0.4 V. Hence, these films exhibit a memristor effect. The volt-ampere curve of the film varied significantly at varying of time of the copper deposition and hence the nanoparticles content/size in the film. These results show that the films under the researches can be considered as a promising matter for memristor cell.

**Keywords:** *copper nanoparticles, lithium fluoride film, memristor cell.*



## INVESTIGATION OF LASER HEATED SPOTS ON THE SURFACE OF CARBON STEEL

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Laser heat treatment is the surface process (not voluminous in contrast to other thermal hardening processes). The feature of laser radiation is high energy density and low radiation exposure time that provide high-speed heating and cooling of the workpiece.

We investigate the local divided spots after laser radiation on the surface of carbon steel – the microstructure on the surface and the influence of the spot matrix on the properties of steel under tension.

**Keywords:** *laser heated spots, carbon steel, metal structure.*

**DISCHARGE-MECHANICAL METHOD OF ROCK DESTRUCTION**

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On the basis of mechanical and electric-pulse destruction methods discharge-mechanical method of solid rocks destruction is developed. Early studies of this method for deep drilling are executed. It is shown that owing to destruction by discharges of a surface of rock destruction productivity in comparison with traditional mechanical methods significantly increases.

**Keywords:** *Electric-pulse method, Discharge, Breakdown, Rock, Destruction, Deep drilling.*

**UV EXCILAMP INACTIVATION OF HELMINTH EGGS OF IN WASTEWATER*****EVGENIY LIPATOV, EDWARD SOSNIN, VICTOR TARASENKO AND SERGEY AVDEEV****Institute of High Current Electronics SB RAS, Russia**lipatov@loi.hcei.tsc.ru*

The inactivation of helminth eggs *Opisthorchis felinus*, *Hymenolepis diminuta* and *Toxocara canis* in the wastewater of treatment plants of Tomsk region using combined UV irradiation by excilamps at 282 and 222 nm was demonstrated. At the surface dose 25 mJ/cm<sup>2</sup>, only 15 % of the eggs remained in the wastewater after treatment. At the same time 85 % of the helminth eggs lost the shell integrity and destroyed. It is proposed to use this method for wastewater deworming of small treatment plants with productivity up to 200 m<sup>3</sup>/day.

**Keywords:** *excilamp, helminthes eggs, inactivation, wastewater, deworming, ultraviolet.*

**HEAT LOSSES OF ENERGY EXCITATION IN PHOSPHOR***YANGYANG JU, V. M. LISITSYN AND S. A. STEPANOV**National Research Tomsk Polytechnic University, Russia  
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In this paper, showed the results of heat losses in phosphor-converted LEDs (hereinafter chips) during spectrum conversion. The limit values of the luminous efficacy for LEDs are evaluated.

**Keywords:** *phosphor, spectrum conversion, heat losses.*

## KINETIC FEATURES OF ENERGETIC MATERIAS' CHAIN AND THERMAL EXPLOSION INITIATED BY LASER PULSE

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The aim of the present work is to find out the readily executable experimental approaches of the explosion decomposition nature of primary and secondary explosives initiated by laser pulses determination. The main task is to compare the experimental kinetics of the silver azide single crystals and pentaerythritol tetranitrate (PETN) doped with metal nanoparticles pressed pellets explosion in the conditions of pulsed laser initiation.

The basic distinctive features of the different samples explosive decomposition are concerned on the time delay absence and observation of under-threshold effects in the case of PETN-based composites. On the contrary, in the case of silver azide single crystals the time delay is always pronounced while the under-threshold effects are not observed. We showed that the differences found out are explained in terms of different mechanisms of the explosion initiation. A criterion that allows one to discern the mechanisms of chain and thermal (the micro hot-spot type) explosion initiation in the conditions of laser pulse influence was suggested.

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**Keywords:** *thermal explosion, chain reaction, laser initiation, petn, silver azide.*

**CRITICAL PARAMETERS OF THERMAL EXPLOSION  
MICRO HOT-SPOT MODEL**

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The main tasks are to calculate the dependencies of the explosion reaction initiation critical parameters on the metal nanoparticles radius and specific heat in terms of the model [Kalenskii A. V., Zvekov A. A., Anan'eva M. V., Zykov I. Yu., Kriger V. G., Aduev B. P. // *Combustion, Explosion, and Shock Waves*. – 2014. – Vol. 50. No. 3. 333–338] and to determine the influence of the thermophysical constants of the nanoparticle on the stages of the reaction in hot-spots initiation and development. The dependencies of the critical energy density and hot-spot critical temperature on the nanoparticles' radius of 12 metals in PETN were calculated. The critical energy density was calculated with the relative uncertainty 10–12.

For the radii 10 nm the critical energy density tends to a limit that does not depend on the nanoparticles specific heat. The reaction initiation modes at the energy densities a little higher than the threshold ones were studied. The analytical equations for the critical parameters of the explosion initiation on the nanoparticles' radii on the volumetric heat capacity of metal as well as the critical hot-spot temperature were derived. We showed that that an invariant exists giving a link between the critical energy densities and the typical time of the reaction initiation.

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**Keywords:** *hot-spot model, petn, critical parameters.*

## MECHANISM OF HOT SPOTS FORMATION IN PENTAERYTHRITOL TETRANITRATE UPON EXCITATION BY THE FIRST HARMONIC OF A NEODYMIUM LASER

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Currently, several alternative models of laser initiation of «pure» (without specially introduced impurities) samples of pentaerythritol tetranitrate (PETN) have been proposed. The most widespread model is thermal hot-spot initiation model.

The purpose of this work is to explore the mechanism of the formation of «hot spots», which are formed in the samples of «pure» PETN under pulsed action of the first harmonic of Nd-laser.

The work presents first results of experimental studies of spatial, temporal and amplitude characteristics of luminescence, which appears under irradiation of a «pure» and carbon black doped pressed samples of PETN and neutral samples (MgO, Cu) by the first harmonic of the Nd-laser ( $\lambda = 1064$  nm,  $\tau = 16$  ns). It was found that on the surface of all studied solids at the instant of irradiation the micro plasma spot was formed («hot spot»), which characteristics are determined by absorbing irregularities on the surface of the irradiated targets and the parameters of the laser radiation.

The effect of «burning out» of absorbing irregularities with multi-pulse irradiation of the studied target was detected. Analysis of the results suggests that the cause of the formation of «hot spots» in the studied materials is the low-threshold optical (electric) breakdown, developing in local (defective) regions of solids in the electric field of the electromagnetic wave.

The possible types of the «defects» responsible for a near-surface laser plasma formation are discussed.

**Keywords:** *Pentaerythritol tetranitrate, laser radiation, hot spots.*

## 2D/3D OPENMP PARALLEL COMPUTING OF TiC COMBUSTION SYNTHESIS

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This paper analyzes the ignition and propagation of the combustion front during the exothermic TiC combustion synthesis in the case of a cylindrical sample and a cubic made of Titanium and carbide particles when the thermo-physical properties are either constant or temperature dependent. The heat supply is prescribed on several sides or surfaces of the physical domain. A one step kinetics is used to handle the exothermic synthesis  $Ti^+C^- > TiC$  in a solid phase and leads to the computation of the conversion rate. A coupling with a non-linear heat equation taking into account the heat generated by the kinetics and the two allotropic phase-changes is considered. An explicit finite-volume discretization of the overall system is constructed and analyzed mathematically. A discrete maximum principle and the computation of the stability condition over the time-step are rigorously established when the thermo-physical properties are either assumed constant or temperature and conversion rate dependent.

The inhouse numerical software is parallelized using openmp thanks to pragmas inserted into the code. The speedup obtained on a intel quad core is computed for several 2D/3D uniform tensorial grids. The induction time and the fraction of unreacted material are systematically computed. The contribution of the furnace's temperature, the heat capacity, phase changes are carefully analyzed.

2D/3D animations showing the propagation pattern are presented.

**Keywords:** *TiC Combustion Synthesis, Induction time, Evolution of the fraction of unreacted material, 2D/3D combustion propagation's pattern, Explicit Finite-Volume scheme, parallel programming, Openmp, Speedup.*



## OPTIC PROPERTIES OF GOLD NANOPARTICLES AT DIFFERENT TEMPERATURES

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The target of the present work is to calculate the temperature dependencies of gold nanoparticles' in potassium bromide matrix scattering and absorption efficiencies with variation of wavelength and nanoparticles' radius. The Mie theory, which applicability to these tasks solution was proved in [Kalenskii A.V., Zvekov A.A., Nikitin A.P., Ananeva M.V., Aduiev B.P.// *Optics and Spectroscopy*. – 2015. Vol. 118. – No. № 6. – pp. 978–987], was used in the optic properties calculations. The temperature dependencies of refractive indexes presented as a set of Lorentz oscillators with additional term describing free electron gas interaction with electromagnetic field were applied to temperature influence modeling.

The spectral dependencies of absorption and scattering efficiencies of electromagnetic radiation by gold nanoparticles with radii from 10 to 150 nm in the temperature range 300–1000 K were calculated. It was elucidated that temperature increasing makes the scattering efficiency of gold nanoparticles decrease. The absorption efficiency decreases as temperature rises for small particles in the area of plasmon resonance absorption. In other conditions the temperature augmentation causes the absorption efficiency increasing. The maximal relative increasing of the gold nanoparticles' absorption efficiency is observed in the infrared region where the albedo of single scattering is close to unity.

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**Keywords:** *gold nanoparticles, Mie theory, temperature dependencies.*

**A HOT-SPOT MODEL OF THERMAL EXPLOSION THAT TAKES INTO  
ACCOUNT NEODYMIUM LASER PULSE MULTIPLE SCATTERING***ALEXANDER KALENSKII<sup>1</sup>, ALEXANDER ZVEKOV<sup>2</sup> AND ANDREY NIKITIN<sup>2</sup>*<sup>1</sup>*Kemerovo State University, Russia*<sup>2</sup>*Federal Research Center of Coal and Coal Chemistry, Russia  
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The aim of the present work is to calculate the optic properties including the radiance increasing factor and critical energy densities of pentaerythritol tetranitrate (PETN) – aluminum nanoparticles explosion initiation considering the multiple scattering influence. The methods of optic properties calculation of a transparent matrix – metal nanoparticles composites were described in [Zvekov A. A., Kalenskii A. V., Aduiev B. P., Ananyeva M. V. // *Journal of Applied Spectroscopy*. – 2015. – Vol. 82. №. 2. – pp. 213–220]. The optic properties of individual nanoparticles were calculated using Mie theory. The optic properties of a composite slab concerned on multiple scattering were calculated in terms of spherical harmonics approach. The calculations were performed to the wavelength 1064 and 532 nm matching the first and second harmonics of the neodymium laser.

The radiance increasing coefficient for the nanoparticles with radii from 30 to 210 nm at the depth 100 μm is varied from 1.213 to 3.335 at the wavelength 1064 nm. The multiple scattering consideration allows one to improve the agreement between theory and the experiment. The effect is essential when one compares the critical laser initiation conditions of transparent explosives containing metal nanoparticles at different wavelength. The radii ranges where the critical energy density is minimal are determined predominantly by the radii of nanoparticles with maximum absorption efficiency.

This work was supported by the grant of Russian Federation President (MK-4331.2015.2) and the Ministry of Science and Education of the Russian Federation (Research project No. 3603, task No. 2014/64).

**Keywords:** *aluminum nanoparticles, petn, multiple scattering, radiative transfer.*

## THE CRITICAL PARAMETERS OF THE THERMAL EXPLOSION MICRO HOT-SPOT MODEL DEPENDENCE ON THE PULSE DURATION

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The micro hot-spot model was suggested for lead azide laser initiation features interpretation. One of the model assumptions was independence of the light absorption efficiency factor on the nanoparticles radius and the radiation wavelength. The calculations of the critical energy density  $H_c$  with the pulse duration  $t_i$  variation were carried out in terms of the micro hot-spot model [Kalenskii A.V., Zvekov A.A., Ananeva M.V., Zykov I.Yu., Kriger V.G., Aduiev B.P. // *Combustion, Explosion, and Shock Waves*. – 2014. – Vol. 50. – № 3. – P. 333–338]. For the nanoparticles' ensemble including at least one nanoparticle with each possible radius value the optimal nanoparticle's size decreases as a square root of the decreasing pulse duration. At the same time the calculated critical energy density of the explosion initiation  $H_c$  also decreases tending to zero that was referred as the small particles' paradox.

In terms of the updated micro hot-spot model the dependencies  $H_c(t_i)$  for the systems lead azide – lead nanoparticles and pentaerythritol tetranitrate – aluminum nanoparticles were calculated. The incorporation of the absorption efficiency factor dependence on the nanoparticles' radius changes the initiation criterion in the limit of the short pulse durations. This criterion becomes the critical energy density matching the experimental results. The conclusion was made that taking into account of this dependence is sufficient for the paradox solution.

This work was supported by the grant of Russian Federation President (MK-4331.2015.2) and the Ministry of Science and Education RF (Research project No. 3603, task No.2014/64).

**Keywords:** *hot-spot model, laser initiation, lead azide, Mie theory, small particles' paradox.*

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**OPTICAL PROPERTIES OF WIDEBAND METAL OXIDE – ENERGETIC MATERIAL INTERFACES**

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Using laser irradiation for direct initiation of high density energy materials opens up new opportunities in design safe optical detonators by removing primary explosive from the devices. Precise tuning of sensitivity to initiation of detonation via photo-excitation appears challenging because all secondary explosives are insulators with the band gap of 4–8 eV. We report here results of our combined experimental and theoretical study, and propose feasible mechanisms of photocatalytic decomposition of explosives triggered by the laser excitation with the energy of 1.17–2.3 eV and the wavelength of 1064–532 nm. Our approach considers tuning the optical absorption via the controlled modification of the electronic structure of the explosive-metal oxide interfaces.

**Keywords:** *photoexcitation, charge-transfer transition, energetic material.*

## USING CARBONYL PHOTOINITIATORS FOR ACHIEVING TUNABLE OPTICAL SENSITIVITY OF PETN

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Photo decomposition of wide gap dielectric PETN ( $E_{\text{gap}} \sim 7$  eV) doped with 9, 10-phenanthrenequinone (PQ) was triggered by irradiating samples with the laser beam with  $E \sim 2.33$  eV. DFT modeling was employed to study optical properties of the pristine compounds and their mixture as well as for modeling decomposition mechanism on ground state and the lowest triplet potential energy surface. It was revealed that PQ molecule absorbs light in the range 1.9–2.4 eV. The excited PQ molecule abstracts hydrogen from the PETN which triggers subsequent barrierless cleavage of O-NO<sub>2</sub> bond. This reaction requires 9 kcal/mol, and proceeds with the heat release of 37.6 kcal/mol.

**Keywords:** *carbonyl photoinitiators, laser ignition, PETN.*

**LASER IGNITION OF COATED PETN BY MILLISECOND DURATION PULSES**

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Thermal initiation of PETN, coated with a thin layer of CuO, was performed by laser millisecond duration pulses. The dependence of the threshold of launching the exothermic reaction on the thickness of the light absorbing coating was studied. It has been found that the formation of the focus of the exothermic reaction does not always lead to the initiation of the entire sample. An analytical model describing the initiation of the exothermic decomposition reaction in the surface layer of the sample was developed. The effectiveness of the initiation of the explosion decreases with the increase in the thickness of the absorbing layer. This may be due to energy consumption for thermal decomposition of CuO forming Cu<sub>2</sub>O.

**Keywords:** *laser initiation, absorbing layer, copper (II) oxide, heat transfer simulations.*

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## DYNAMIC REGIMES OF CONDENSED SYSTEMS IGNITION BY RADIATION HEAT FLUX

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Characteristics of ignition of the condensed systems when heating by an external heat flux (conductive, convective, radiation or the mixed) are necessary for development of initiation systems of explosives and high-energy materials, at an assessment of fire and explosion hazard of substances and in some other practical problems.

Now rather explicitly characteristics of ignition of the condensed systems when heating are studied by a constant heat flux, that is in the so-called static mode of heating. In actual practice, in particular, when inflaming a charge of the solid propellants rocket engine, combustible materials in the conditions of the fire, etc., ignition is carried out at the dynamic modes of heating by a variable (time dependent) heat flux.

The experimental study of characteristics of ignition of the condensed systems by a radiation heat flux it was carried out in the majority of works at constant value of heat flux at the induction period. The dynamic modes of ignition were considered by a convective and radiation heat flux in available literature in publications that is bound, apparently, to technical complexity of carrying out correctly experiments.

The technique and results of the experimental study of characteristics of ignition of the condensed systems by a radiation heat flux at the dynamic modes of heating are presented in this report.

This work was supported by the Ministry of Education and Science of the Russian Federation under Agreement No. 14.577.21.0157 of 11.28.2014 (unique identifier RFMEFI57714X0157).

**Keywords:** *Dynamic regime, ignition, heat flux.*

**IGNITION BY LASER RADIATION AND COMBUSTION  
OF COMPOSITE SOLID PROPELLANTS****VLADIMIR ARKHIPOV<sup>1</sup>, NIKOLAY ZOLOTOREV<sup>1</sup> AND ALEXANDER KOROTKIKH<sup>2</sup>**<sup>1</sup>*Research Institute of Applied Mathematics and Mechanics, Russia*<sup>2</sup>*National Research Tomsk Polytechnic University, Russia**leva@niipmm.tsu.ru*

The report presents measurement techniques for the recoil force, gasification time of products outflow from burning surface, burning rate of composite solid propellants (CSPs) with sampling of condensed combustion products (CCPs) to determine their size distribution, chemical and phase compositions, as well as the experimental study results of ignition and combustion of CSPs based on AP, an inert binder and aluminum ultrafine powder (UFP) type Alex, containing additives of iron and boron. It was found that the partial replacement 2 wt. % of Alex by iron UFP in CSP decreases the ignition time 1.3–1.9 times under initiation by CO<sub>2</sub>-laser in the air at the range of heat flux density 55–220 W/cm<sup>2</sup> and increases the recoil force of gasification products outflow by 27 % in the period of stationary combustion and increases the burning rate 1.3–1.4 times at the range of nitrogen pressure 2.0–7.5 MPa. At the partial replacement 2 wt. % of Alex by boron UFP in CSP the ignition times are decreased 1.2–1.4 times, the recoil force of gasification products outflow is increased by 9 % and the burning rate of CSP does not change in the above pressure range.

This work was supported by the Ministry of Education and Science of the Russian Federation under Agreement No. 14.577.21.0157 of 11.28.2014 (unique identifier RFMEFI57714X0157).

**Keywords:** *Laser radiation, solid propellants, ignition delay time.*



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## **HOT-SPOTS LASER INITIATION OF THE ENERGETIC MATERIALS BY KILOWATT AND MEGAWATT POWER PULSES**

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Composite energetic materials explosion probability and induction period dependence on exposure was measured. Mixture of PETN with Al nanoparticles (ALEX, V-ALEX) and carbon black was used in experiments. Initiation of the explosion was carried out by using YAG: Nd laser LDPL1500 (1064 nm, 532 nm, 10 ns, MW) and Yb fiber laser IRE-Polus YLR-150/1500-QCW-AC (1070 nm, 20 ms, kW). Difference between the effectiveness of each additive for initiation by MW and kW sources of laser radiation was shown.

***Keywords:*** *laser initiation, hot spots, PETN.*

**CALCULATION OF SPHERICAL INCLUSION'S HEATING TAKING  
INTO ACCOUNT THE ABSORPTION CROSS SECTION OF A PARTICLE  
AND WAVELENGTH OF LASER RADIATION**

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The modeling and numerical calculation of a laser heating of the absorbing inclusion placed in a transparent matrix of explosive is carried out. The inclusion with spherical shape with  $R_0$  radiuses in the range from  $10^{-5}$  to  $10^{-2}$  cm are used. Duration of a laser pulse changed ranging from  $10^{-9}$  to  $10^{-3}$  with allowed to investigate process in approach adiabatic and quasistationary the heating modes.

The object of research is the pressed powders of tetranitrate of pentaerythritol (PETN) and azid of lead. In calculations, dependence of absorption cross section of particles from the laser wavelength  $\lambda_0$ , the particle's radius  $R_0$  and complex index of refraction  $n_0$  according to Mi's theory was considered. The discrete set of wavelengths was used: 354,7 nm; 532 nm; 1064 nm and 10600 nm.

It has been shown for particles with same radius, there is a characteristic duration laser pulse at which the maximum heating reached.

The maximum of heating is displaced towards particles with great values of  $R_0$  with increase of laser pulse duration. The maximum of heating corresponds the assumed border dividing the adiabatic and quasistationary modes of heating.

Feature of the accounting of absorption cross section is that in this case temperature of small size inclusions sharply decreases. It leads to sharp reduction of heat in the thermal center which is formed near small size inclusions and respectively to sharp reduction of their reactionary ability in the course of explosive decomposition.

***Keywords:*** modeling, spherical inclusion, PETN, absorption cross section, Mie theory.

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**THE INFLUENCE OF AMMONIUM PERCHLORATE ON THE ACTIVITY  
OF ALUMINUM POWDERS OF DIFFERENT PARTICLE SIZE**

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The thermal decomposition of ammonium perchlorate in freely poured mixtures with aluminum nanopowder and micron powders of different particle size, as well as the influence of ammonium perchlorate thermal decomposition products on the activity parameters of aluminum powders were investigated in the paper. It was found that ammonium perchlorate had decomposed at heating in the studied mixtures with aluminum powders at a lower temperature than the aluminum began to oxidize. At the same time, the ammonium perchlorate thermal decomposition products reduced the activity parameters of all investigated aluminum powders.

**Keywords:** *ammonium perchlorate, aluminum powder, micron powderd, nanopowder, activity parameters, freely poured mixture, thermal decomposition.*

**SPECTRAL AND KINETIC FEATURES OF COMPOSITES  
EXPLOSIVES – ULTRAFINE METAL AND COAL PARTICLES  
LASER INITIATION**

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The spectral and kinetic features of pentaerythritol tetranitrate (petn) composites containing 0.1 wt% Fe (80 nm), 0.2 wt% Al (100 nm), 0.1 wt% Ni (150 nm) or 0.1 wt% of lignite coal (750 nm) explosion glow were studied. The initiation was performed with a YAG-Nd<sub>3</sub> laser operating in the Q-switch mode (1064 nm, 14 ns). All the experiments were done with the energy density 2 J/cm<sup>2</sup> which is substantially higher than critical one for each of the sample types.

The explosion glow is observed in the microsecond time range and is concerned on the products evolved during the chemical reaction glow. The spectra at the pulse end are not described with Plank formula. The maximums in the spectra are seen at the wavelength 420 nm. Thus this glow is predominantly luminescent one. We believe that the glow arise as a luminescence of excited nitrogen dioxide molecules formed after O-NO<sub>2</sub> bond scission, which is the weakest in the petn molecule.

The explosion glow after the pulse on the stage of the reaction propagation is the thermal one as it is fairly described with the Plank formula. The character temperature values determined for the studied composites explosion were 3400 K (petn-Al and petn-Fe), 4300 K (petn-Ni), 3200 K (petn-lignite).

The work was supported by the Ministry of Science and Education of the Russian Federation (project 3603, task 2014/64).

**Keywords:** *petn, metal nanoparticles, laser initiation, spectroscopy, explosion glow.*

## LASER INITIATION OF COMPOSITES BASED ON PETN AND ULTRAFINE COAL PARTICLES

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Coal is a multicomponent natural substance which main components concentration may vary for the individual particles and gross sample. Its combustion contains several stages including the matrix decomposition, volatiles' evolution, volume and structure of the col particle changes and so on. The main task was to elucidate the efficiency of coal particles as additives making the critical energy density of pentaerythritol tetranitrate (petn) laser initiation with nanosecond duration decrease.

The primary results of the experiments on petn containing different two types of coals (lignite and bituminous coal) are presented. The measured critical energy densities ( $H_{cr}$ ) are and kinetics of the petn composites containing coals in the conditions of neodymium laser initiation (1064 nm, 14 ns) in the coal mass fracture range 0–5 weight % are presented. We showed that the minimal critical energy density of the composites' explosion initiation equal to  $H_{cr} = 1.1 \text{ J/cm}^2$  is observed for the same mass fraction of the coal 0.5 weight % regardless the coal type.

The results obtained demonstrate that the coal submicron particles are prospective additives for the explosive sensitivity to laser pulses regulation. The subsequent determination of the optimal coal type and particles' size is planned now in order to get an idea how the chemical composition and the laser initiation threshold are linked.

The work was supported by Russian Science Foundation (project 15-13-10043).

**Keywords:** *laser ignition, petn, coal.*

**EFFECT OF ELECTRIC FIELD ON THE EXPLOSIVE SENSITIVITY  
OF SILVER AZIDE**

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In this paper studied the effect of the weak and super weak electric (from 1 mV / cm to 100 V / cm) fields on speed of a chemical reaction in a silver azide. It is shown that weak electric field can be considered as a «catalyst» of a chemical reaction and as «inhibitor» of a chemical reaction, and, hence, as an instrument of control of stability and reactionary ability of the «energy-saturated» of materials. Influence of the super-weak electric fields on the process of explosive decomposition of materials (explosion was initiated with the help pulse duration of 10 ns, the first harmonic (1064 nm) YAG: Nd laser and contact electric field by intensity 300 KV/m) was shown in this work. The practical significance of the work is determined by possibility of the use of the obtained experimental data for the purposeful change of reactionary ability of explosive materials. The work is one of the first attempts of development of effective methods of management of explosive sensitivity of explosives by means of the weak electromagnetic fields.

**Keywords:** *silver azide, electric field, explosive sensitivity.*

## INFLUENCE OF THE THICKNESS OF FLAT CRYSTALS ON THE CRITICAL TEMPERATURE OF THERMAL EXPLOSION OF LEAD AZIDE

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Reaction of thermal decomposition of lead azide is heterogeneous [P.G. Fox, R.W. Hutchinson // *Energetical Materials*, V. 1. – New York: Plenum Press, 1976; P. G. Fox // *J. Solid State Chem.* – 1970. – Vol. 2. – No. 4. – P. 491–502; M.M. Chaudhri, J.E. Field // *J. Solid State Chem.* – 1975. – Vol. 12. – No.1-2. – P. 72–79; A.V. Khanef // *Russian Journal of Physical Chemistry.* – 2001. – Vol. 75. – No. 1. – P. 14–17]. Thermal explosion of lead azide occurs after an acceleration period, caused by a topochemical autocatalysis. When the lead nuclei are overlapped, the kinetics of the decomposition of lead azide is described by the equation of the shrinking volume. Thermal decomposition parameters of lead azide from [A.V. Khanef // *Russian Journal of Physical Chemistry.* – 2001. – Vol. 75. – No. 1. – P. 14–17] were used for the calculation of the critical temperature of a thermal explosion of lead azide. On the bases of the Semenov ignition criteria, a system of equations for the calculation of the critical ignition temperature is derived T. The results of the calculations are consistent with experiments [M.M. Chaudhri, J.E. Field // *J. Solid State Chem.* – 1975. – Vol. 12. – No.1-2. – P. 72–79].

**Keywords:** *lead azide, thermal explosion, critical temperature.*

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**INFLUENCE OF THE ENERGY FLUENCE AND THE ALUMINUM LAYER THICKNESS  
ON THE IGNITION DELAY TIME OF EXPLOSIVE MATERIALS  
BY A LASER PULSE**

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System of three equations of thermal conductivity for three-layer system: glass – aluminum layer – explosive material have been numerically solved. Metal layer, absorbing the energy of the laser pulse, heats up the glass and the explosive material. The melting of the aluminum layer and the explosive material was taken into account. PETN, HMX, RDX, and TATB were selected as explosive materials. The thickness of the aluminum layer was varied between 100 and 500 nm. It was determined that the thicker the metal layer is the longer the ignition time delay of the explosive materials by laser pulse. It is caused by fact that the thickness of the skin layer, in which the electromagnetic wave is absorbed at the constant energy fluence, significantly smaller than the thickness of the aluminum layer. In this case, more time is needed for the heating of the cold part of the layer with an increase of its thickness. Calculations shown that the larger the energy fluence of the laser pulse the shorter the ignition time delay of the explosive materials at fixed thickness of the aluminum layer.

**Keywords:** *aluminum layer, explosive material, laser pulse.*



## THE EFFECT OF DIFFUSION OF ACTIVE PARTICLES ON THE IGNITION OF EXPLOSIVE MATERIALS BY A PULSED ELECTRON BEAM

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In [G.A. Ivanov, A.V. Khanef // *Russian Journal of Physical Chemistry B.* – 2013. – Vol. 7. – No. 6. – P. 741– 747] the radiation-thermal mechanism of PETN initiation was discussed. Physicochemical principle of the mechanism is that the part of the electron beam energy is used for the formation of active particles, which becomes seeds for the autocatalytic reaction of the thermal decomposition of explosive materials. In this work the equations of heat conductivity with Arrhenius source of heat and the equation of the level of conversion with the autocatalytic reaction are expanded with the equation of diffusion of active particles. The lifetime of active particles has two components: 1 – characteristic time of deactivation of particles; 2 – characteristic lifetime of particles in autocatalytic reaction. System of these equations have been analyzed and numerically solved in this work. It was shown that the ignition delay time is increased when the diffusion of particles from the electron absorption area is taken into account.

**Keywords:** *active particles, autocatalytic, diffusion, electron beam, ignition.*

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**EFFECT OF ALUMINUM PARTICLES DISPERSITY ON CHARACTERISTICS  
OF AMMONIUM PERCHLORATE—ALUMINUM COMPOSITION  
LASER IGNITION**

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Ammonium perchlorate–aluminum compositions taken in stoichiometric ratio were ignited in air with 1.06- $\mu\text{m}$  1-ms-long laser pulses. The ignition energy threshold, and ignition delay were measured for samples at various dispersity of Al.

The causes of the difference in examined compositions sensitivity to the influence of laser radiation is considered from the perspective of the thermal theory.

**Keywords:** *pyrotechnic composition, laser radiation, ignition, ammonium perchlorate.*

## RESONANCE ABSORPTION OF LASER RADIATION GOLD NANOPARTICLES IN A POLYCRYSTALLINE MATRIX OF PETN

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Laser initiation of explosives is now being increasingly used in new and innovative technologies, such as in the military, explosion welding metals, etc. Crucial issue is the security of working with explosives, for which you want to use explosives with low sensitivity to mechanical stress, shock, static electricity and electromagnetic interference. One way of solving the problem – the undermining of standard explosives with the help optical detonators composed lacking initiating explosives, instead of the currently used electric detonators. Therefore we need to develop ways to control the sensitivity of explosives, which will provide low thresholds laser initiation while maintaining high thresholds for other methods of exposure. To solve this problem, focused fundamental research of the mechanism of laser initiation of explosives.

This paper presents the results of a study by optical and opto-acoustic spectroscopy explosive new composite material based on polycrystalline sample of PETN containing gold nanoparticles. Opto-acoustic spectroscopy is applied for the first time to study the optical properties of explosive systems. The formation of spherical gold nanoparticles in a polycrystalline matrix was confirmed by optical spectroscopy – the observation of the spectrum of the optical plasmon resonance absorption with a maximum at 532 nm. Position band in these samples is explained by a theoretical simulation based on Mie theory. This set is a good correlation of experimental data with the results of numerical calculations.

The reported study was funded by RFBR according to the research project № 16-33-00510 mol\_a.

**Keywords:** *plasmon resonance absorption, PETN, gold nanoparticles.*

**ABNORMAL PHOTO-THERMAL EFFECT OF LASER RADIATION ON HIGHLY DEFECT OXIDE BRONZE NANOPARTICLES AT SUB-THRESHOLD ABSORPTION****PAVEL GULYAEV<sup>1</sup>, MARGARITA KOTVANOVA<sup>1</sup> AND ALEXANDER OMELCHENKO<sup>2</sup>**<sup>1</sup>*Ugra State University, Russia*<sup>2</sup>*Institute of Laser and Information Technologies Russian Academy of Sciences, Russia*  
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The mechanism of abnormal photo-thermal effect of laser radiation on nanoparticles of oxide bronzes (Gulyaev et al. 2012. *Nanotechnologies in Russia*, 7 3, 127-131. DOI: 10.1134/S1995078012020097) has been proposed in this paper. The basic features of observed effect are: a) sub-threshold absorption of laser radiation at the excitation of donor-like levels realized by superficial defects of oxide bronze nanoparticles; b) non-radiative inter band transition of energy of excitation on the deep triplet levels and c) consequent recombination occurring at the Plasmon absorption. Acceptor levels were generated by thermally intercalation K or Na atoms to the octahedral crystal structure of TiO<sub>2</sub> in the wave SHS combustion. The prepared oxide bronzes of the non-stoichiometric composition Na × TiO<sub>2</sub> and K × TiO<sub>2</sub> were examined by high resolution TEM, and then grinded in a planetary mills with powerful dispersion energy density up to 4000 J / g. This made it possible to obtain nanoparticles about 50 nm with high surface defect density (10<sup>17</sup>–10<sup>19</sup> cm<sup>-2</sup>) at a depth of 10 nm). The observed high photo-thermal effect of laser radiation on the defect nano-crystals after its impregnation into cartilaginous tissue exceeds 7 times in comparison with the intact ones.

The reported study was funded by RFBR according to the research project No. 15-42-00106.

**Keywords:** *photothermal effect, sub-threshold absorption, nanoparticle, oxide bronzes, superficial defects, SHS, IR-laser radiation.*

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## SIZE EFFECT OF LEAD AZID INITIATION BY CO<sub>2</sub> LASER RADIATION

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Explosive decomposition energy threshold for PbN<sub>6</sub> were estimated in case of CO<sub>2</sub> laser exposure. Dependence between Ignition threshold and laser beam diameter on the pressed powders surface was determent.

Laser beam was formed on the sample surface by the projection method. The beam size varied from 0,01 to 6 mm. Detonation probability curves were defined for each size. The Ignition threshold value were estimated from that curves. Explosive decomposition delays and process progress times were registered in the surface area.

Size effect in case of CO<sub>2</sub> laser exposure is similar to the case of 1.06 μm laser radiation wavelength exposure in quality manner. The results were discussed from the perspective of diffuse scattering in transparent explosives powders.

**Keywords:** *lead azide, laser ignition, size effect, carbon dioxide laser.*

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**CHARACTERISTICS OF CAPILLARY DISCHARGE CHANNEL AND ITS EFFECT  
ON CONCRETE SPLITTING OFF BY ELECTRO-BLASTING METHOD**

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The research results of concrete splitting off of the free surface by borehole electro-blast with the discharge initiation by the wire explosion have been presented with the shock and pressure wave dynamics depending on the spatiotemporal distribution of electrical power deposition in plasma channel. The electrical characteristics of plasma channel initiated by exploding wire in polyethylene capillary have been investigated. It has been shown the significant dependence of the stress-wave profile on the pressure pulse wave shape on the borehole wall which is determined by the rate of electrical energy release in the plasma channel and is weakly depended on the time of energy release (at given rate of its release).

**Keywords:** *capillary discharge, splitting off, borehole electro-blast, wave dynamics, plasma channel.*

## COMPOSITIONAL DEPENDENCE OF THERMAL, OPTICAL AND MECHANICAL PROPERTIES OF OXYFLUORIDE GLASS

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Tungsten oxyfluoride glasses are characterized by their low phonon energy. This is due to the presence of fluoride ions that have low phonon energy also the formation of low phonon energy  $WO_6$  units. So Oxyfluoride glasses based on  $WO_3-BaF_2-RF$ , where  $RF = LiF, NaF$  or mixed ( $LiF-NaF$ ) have been prepared by melt quenching technique. The density and molar volume of the prepared glasses show a decrease with the increase of  $RF$  instead of  $WO_3$  content. The decrease in molar volume may be also due to the change of  $W-O$  bond length that changes from 0.3269 to 0.3505 nm in case of  $r(W-O)_4$  and increases from 0.2312 to 0.2528 nm for  $r(W-O)_6$  with the change in  $RF$  content. The glass transition temperature  $T_g$  is found to decrease with increasing  $RF$  content. The Optical energy gap for these glasses decreases from 3.450–3.155, 3.325–3.200 and 3.350–2.700 eV for WBL, WBN and WBNL glasses respectively. The refractive index increases with the addition of heavy polarizable fluorides. The decrease of the elastic moduli and microhardness of these glasses may be due to the decrease in density and the depolymerization effect. The poisson's ratio increases with increasing  $RF$  content due to the structural changes and formation of (NBOs) and (NBF) units.

The aim of this work is to prepare a glass host with low phonon energy to be an efficient host with good luminescence properties when doped with rare earth ions. And introduce a study of its structural, thermal, optical and mechanical properties.

**Keywords:** *glass, activation energy, linear thermal expansion, Urbach energy, refractive index, Elastic moduli.*

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**THE STUDY OF ABLATION OF HETEROGENEOUS TARGETS UNDER  
THE ACTION OF YTTERBIUM FIBER LASER RADIATION**

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The paper reports about the results of research of powerful ytterbium fiber laser radiation impact on inhomogeneous targets. The targets were the samples of pressed oxides micropowder and the samples of porous ceramic sintered from nanopowder. The dynamic of the laser plume from the surface of such targets was studied with a method of high-speed shooting. It was shown that laser plume consists of target material plasma at the beginning stage. At the later stage laser plume consists of a mixture of vapor and droplets.

We carried out the numerical study of the interaction of ytterbium laser radiation of with the above-mentioned targets. The results show the presence of local regions where the magnitude of electromagnetic field intensity is more than an order greater than the average value. In our opinion, just in these areas the heating of the target, which leads to melting and evaporation, is initiated.

The obtained results are very useful for the development of technologies of nanopowder production by laser evaporation.

**Keywords:** *Laser ablation, laser plume, nanopowder.*



## USING ROUSE-FOWLER MODEL TO DESCRIBE RADIATION-INDUCED ELECTRICAL CONDUCTIVITY OF NANOCOMPOSITE MATERIALS

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Significant interest in nanocomposite materials such as (polymethylmetacrilate) PMMA with CdS and CdSe nanoparticles arises from their extensive use in microelectronic and optic devices. It is important to consider the possibility of using these devices under increased radiation (space, nuclear engineering, etc.). Therefore study of the nanocomposites radiation resistance is a crucial important and relevant task.

Phenomena related to radiation-induced electrical conductivity of polymers are best described by Rouse-Fowler model. Nanocomposite materials are characterized by existence of additional centers of localization in bandgap. Energy spectrum of these centers depends on shape, size and concentration of nanoparticles.

Using Rose-Fowler model this work studies radiation-induced electrical conductivity of PMMA+CdS nanocomposite material against intensity and exposure time of gamma-ray, concentration and size of nanoparticles. Research has found an energy spectrum of localized states induced by CdS nanoparticles. Irradiation process has shown that conductivity depends on the size and concentration of nanoparticles. Concentration increase of CdS nanoparticles with 2 nm in radius results in electrical conductivity that exceeds the value of pure PMMA. While concentration increase of CdS nanoparticles with 5 or 10 nm in radius results in electrical conductivity decrease with the value less than the one of pure PMMA. After irradiation conductivity returns to its original state of equilibrium and the relaxation rate grows with the size reduction of nanoparticles.

**Keywords:** *nanocomposite, quantum dots, Rouse-Fowler model, radiation-induced electrical conductivity.*

## INFLUENCE OF PRELIMINARY IRRADIATION BY GAMMA-QUANTA ON DEVELOPMENT OF CATASTROPHIC FAILURES DURING OPERATION OF IR-LEDs

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Infrared wavelength range light-emitted diodes (IR-LEDs) operate under conditions of various ionizing radiation, which leads to combined action of ionizing radiation, and long operating time factors limited their efficiency.

As a result of the preliminary investigation we have established that reliability of the LEDs and, therefore, their lifetime are limited by catastrophic failures (CFs).

Previously our research results of preliminary irradiation by neutrons influence on changes of IR-LEDs characteristics and on probability of development of catastrophic failures during their further operation have been presented in [*Gradoboev A.V., Orlova K.N., Asanov I.A., Salchak Y.A. // ISROS 2014: Proceedings of the International Symposium on Reliability of Optoelectronics for Systems, Toulouse. – 2014. – P. 1–7*]. By-turn only investigation results of preliminary irradiation by gamma-quanta influence on reliability Of LEDs have been considered in [*Gradoboev A.V., Simonova A.V., Orlova K.N. // E-MRS Spring Meeting 2016, Lille, France. Symposium BB.12.7. – 2016*].

Hence, the purpose of this paper is research the influence of  $^{60}\text{Co}$  gamma-quanta preliminary irradiation on catastrophic failures development of IR-LEDs during long operating time. Matter of research is IR-LEDs based on double AlGaAs heterostructures. Irradiation has realized by  $^{60}\text{Co}$  gamma-quanta in passive power mode. Reliability indices have assessed at results of step-by-step tests.

Consequently the investigation was determined that preliminary  $^{60}\text{Co}$  gamma-quanta irradiation of dose less than  $1 \cdot 10^5$  Gy has increased useful lifetime. However, increase of irradiation dose leads to decrease of LEDs reliability and reduction of lifetime.

Main causes of observable investigation results are discussed.

**Keywords:** LED, AlGaAs, reliability, gamma-quanta, catastrophic failures.

## THE INFLUENCE OF ION IRRADIATION ON THE PROPERTIES OF CERAMIC SILICON CARBIDE

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Silicon carbide SiC is a wide-band semiconductor material promising for high-power, high-temperature and radiation-resistant electronic devices. That stimulates study of the influence of the various kinds of radiation on the characteristics of SiC and of devices based on it. In this paper the structural, electrical and optical characteristics of the ceramic silicon carbide before and after irradiation by carbon and hydrogen ions in regimes of high-power ion beams and high-intensity short-pulse implantation were studied. Electrical and optical characteristics of ceramics before and after irradiation are determined by the influence of biographical and radiation defects whose energy levels localized in band gap and distributed continuously. A predominant activation component of conduction of p-type with participation of shallow acceptor levels is complemented by hopping mechanism of conduction. The influence of radiation defects having deep levels in the band gap on properties dominates after short-pulse implantation of ions. A new material with higher content of Si and changed electronic structure and properties is formed in surface layer of ceramics after the impact of the high-power ion beams.

**Keywords:** *silicon carbide, conduction, optical absorbtion, localized states, high-intense pulsed ion beams, ion implantation.*

**ULTRAFAST MELTING OF POLYSTYRENE COLLOIDAL CRYSTALS  
INVESTIGATED IN PUMP-PROBE EXPERIMENTS  
AT X-RAY FREE ELECTRON LASER**

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Periodic mesoscopic materials have a high potential for a wide variety of applications such as multi-dimensional photonic crystals, light manipulation, communication technology, sensors, and future optical computing. The possibility to manipulate the properties of photonic crystals by applying stress, pumping energy, or varying temperature opens new highly potential applications. Self-assembled colloidal crystals present a promising bottom-up approach towards the fabrication of photonic materials.

The ultrafast melting of polystyrene (PS) colloidal crystals formed by self-assembly of sub-micrometer colloidal spherical particles was studied with picoseconds time resolution in pump-probe experiments at x-ray free electron laser at Linac Coherent Light Source (LCLS) in Stanford, USA at the x-ray pump probe (XPP) beamline. The x-ray Bragg peak parameters, such as integrated intensity, peak position, radial and azimuthal widths were analyzed as a function of time. For these parameters time constant of exponential decay were determined. Our analysis has revealed two time scales in relaxation dynamics of colloidal crystals. One time is on the order of few tens picoseconds and second, slower on the order of few hundred picoseconds.

Recent theoretical calculations of pumped infrared (IR) laser pulse interaction with a PS colloidal particle reveal full ionization of atoms after the IR pulse and hot electron plasma formation. Therefore, in the experiment plasma crystals in air were formed. The ultrafast dynamics of the plasma crystals will be studied in our future work.

**Keywords:** *x-ray free electron laser, colloidal crystals, pump-probe experiment.*

## **SURFACE MODIFICATION OF PET-TRACK MEMBRANES BY LOW-TEMPERATURE PLASMA AND GAMMA RADIATION**

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Nuclear tracks membranes (TM) from polyethylene terephthalate (PET) have a chance to be used in medicine [E.O. Filippova, V.V. Sokhoreva, and V.F. Pichugin, *Petroleum Chemistry*, V. 54, pp. 669-672 (2014)]. The sterilization is a mandatory procedure in this case.  $\gamma$ -irradiation is widely used for sterilization of medical grafts. In addition, application of low-temperature plasma has both antimicrobial and surface modifying effects.

These are defined the aim of the work: investigate the effects of low-temperature plasma and  $\gamma$ -irradiation in sterilization doses on the structure and properties of PET TM.

TMs were prepared by  $40\text{Ar}^{+8}$  ions ( $E = 41 \text{ MeV}$ ) irradiation of PET film and subsequent etching in NaOH solution. Low-temperature atmospheric plasma with  $2 \text{ W/cm}^2$  of power density used.

The results of the experiment showed that action of low-temperature plasma leads to reconstruction of TM surface: 15-fold increase in its roughness takes place (parameter Ra increases from 0.25 mm to 3.30 mm; surface energy increase more than 4 times by virtue of polar component, surface hydrophilicity increases while negative  $\xi$ -potential decreases.

I – irradiation in sterilizing dose (1 kGy and 10 kGy) of plasma treated TM restores the roughness to the value of 1.3 initial one and increases the value of negative  $\xi$  – potential up to 36 %. Effect of  $\gamma$  – irradiation is similar to those of low doses.

***Keywords:*** polyethyleneterephthalate, plasma, gamma-irradiation.

## LOCAL MECHANICAL STRESS RELAXATION OF IN GUNN DIODES IRRADIATED BY PROTONS

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Local mechanical stresses may be introduced into the active layers of Gunn diodes during the manufacturing process, for instance, when ohmic contacts forming or thermocompression assembling. Relaxation of mechanical stresses during operation and / or under the influence of ionizing radiation can lead to failure of devices based on Gunn diodes.

The purpose of this paper is research local mechanical stress relaxation in active layers of Gunn diodes during strict thermocompression assembling mode, further thermal annealing and proton irradiation.

Matters of research are 3 cm band Gunn Diodes based on n<sup>+</sup>-n-n<sup>+</sup>-n<sup>++</sup> GaAs epitaxial structure by standard sandwich technology using thermocompression assembling in metal-ceramic body with upper crystal mounting.

Two groups of Gunn diodes are produced. Optimal thermocompression assembling mode is used in first group. Strict thermocompression assembling mode (higher temperature and pressure) is used in second group.

The basic parameters of Gunn diodes for observable group and their changes are presented at further thermal annealing, irradiated by protons of 65 MeV and in storage.

Probable causes of observable phenomena are discussed. In conclusion the main results of research are formulated.

**Keywords:** *Gunn diodes, thermocompression assembling, mechanical stresses, relaxation, proton irradiation.*

## EFFECT OF TEMPERATURE ON RESISTANCE OF LEDS BASED ON ALGAAS TO 60CO GAMMA RADIATION

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The paper presents the results obtained in the study of the change in the parameters of IR LEDs based on AlGaAs double heterostructures under <sup>60</sup>Co gamma irradiation with regard to irradiation temperature.

The study indicated several consecutive stages of LED emissive power lowering under ionizing radiation. Increased temperature during gamma irradiation enhances radiation resistance at the first stage due to radiation-stimulated defect annealing, which reduces relative contribution of the first stage to the overall emissive power lowering.

It was found that in exposure at temperature more than 400 K, the first stage of LED emissive power lowering is completely eliminated. At the second stage, increase in resistance is caused by the decreased relative contribution of the less stable first stage to the overall emissive power lowering. The maximum resistance of LEDs to gamma radiation depends on radiation resistance of metal–semiconductor contacts.

**Keywords:** *LED, radiation resistance, gamma-quanta, temperature.*

## BEHAVIOR OF AL-SI-N NANOSTRUCTURED COATINGS UNDER THE IONS ( $\text{He}^+$ , $\text{Ar}^+$ , $\text{Xe}_2^+$ ) IRRADIATION

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The results presented in this work are devoted to the study of radiation damage in nanostructured coatings based on Al-Si-N system formed by magnetron sputtering. The coatings were synthesized with a different silicon concentration which was varied in the range from 6 to 30 at. %. The nitrogen atoms efficiently interact with aluminum ones resulting in formation of a crystalline phase of aluminum nitride h-AlN. When adding silicon atoms, the h-AlN grains growth is blocked silicon nitride layer providing a nanocomposite structure formation. The thickness of the coating was about 1  $\mu\text{m}$ . The formed Al-Si-N coatings were irradiated with  $\text{He}^+$ ,  $\text{Ar}^+$  and  $\text{Xe}_2^+$  ions up to dose of  $5 \times 10^{16}$  ions/cm<sup>2</sup>. The structure as well as phase composition of the as-deposited and irradiated coatings were investigated by means of both atomic-force microscopy and x-ray diffraction.

The obtained results showed the dependence of the Al-Si-N structure on Si content. Indeed, the coating containing 6 at. % of Si are characterized by a nanocomposite structure (h-AlN nanocrystals surrounded by amorphous a-SiN<sub>x</sub> matrix) whereas the coatings with 30 at. % of Si become fully amorphous. The results of structure analysis showed that addition of Si atoms to the AlN nitride structure enhances its structure under the ions irradiation.

**Keywords:** nanostructured coatings, Al-Si-N composite, ion irradiation, radiation stability.



**TRACE TRANSFORM INVARIANTS OF HIGH-VELOCITY ENERGY EMISSIONS  
FROM THE SURFACE OF TUNGSTEN MICRODROPLETS  
AT BREAKUP IN THE PLASMA JET**

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The paper presents analysis of registered emission tracks in air-argon plasma flow during breaking up of tungsten microdroplets produced by DC arc. This new physical effect of optical emission involves two stages. First one includes thermionic emission of electrons from the surface of melted tungsten droplet of 100–200  $\mu\text{m}$  size and formation of charged sphere of 3–5 mm in diameter. After it reaches breakdown electric potential it collapses and produces spherical shock wave and luminous radiation. The second stage includes previously unknown physical phenomenon of narrowly directed energy jet with velocity exceeding 4000 m/s from the surface of tungsten droplet. The luminous spherical collapse and high-velocity jets were registered using CMOS photoarray operating in global shutter charge storage mode. Special features of CMOS array scanning affects formation of distinctive signs of registered tracks, which stay invariant to trace transform (TT) with specific functional. The series of concentric circles were adopted as primitive object models (patterns) used in TT at the spherical collapse stage and linear segment of fixed thickness – at the high-velocity energy jet stage. The two invariants of physical object – motion velocity and optical brightness distribution in the motion front, were adopted as desired identification features of tracks. The analytical expressions on relation of 2D TT parameters known from CMOS scanning algorithm and physical object motion invariants were obtained. Equations for spherical collapse stage correspond to Radon–Nikodym transform.

The work was supported by the Russian Foundation for Basic Research: Grants No. 15-42-00106 and 15-48-00100.

**Keywords:** *luminescence recording tracks, invariants, trace transform, electric breakdown, tungsten microdroplet, thermionic emission, high-velocity jets.*

## PROTON-IRRADIATION TECHNOLOGY FOR HIGH-FREQUENCY HIGH-CURRENT SILICON WELDING DIODE

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Main fundamental parameter that determines rectifier diode frequency except its geometry is minor charge carrier lifetime in active regions and its spatial distribution. Lifetime value depends on characteristics of recombination centres in semiconductors, such as energy level in forbidden zone, electrons and holes capture cross sections and concentration. An optimum and stable in time recombination centres distribution in welding diode structure will provide needed fast and soft reverse recovery characteristics, low forward voltage drop, low leakage, low power losses and temperature swing during working cycle, high reliability. In this work an optimum proton irradiation regimes were determined to provide more than 20 kHz frequency, very high softness factor up to 5, leakage current lower than 1  $\mu\text{A}$  for 50 mm diameter 7 kA/400 V nano-Ag sintered welding diode Al/Si/Mo structure. Silicon diode with such parameters very suitable for high frequency resistance welding machines of new generation for robotic welding. Today there is no welding diode with such parameters on the global market.

**Keywords:** *silicon, welding diode, proton irradiation, deep level, high frequency, high current, soft reverse recovery, resistance welding, carrier lifetime, working cycle, welding machine.*

**PROPERTIES OF COMPOSITE WITH THE DIFFERENT CONTENTS  
OF POLYTETRAFLUOROETHYLENE NANOPOWDER IRRADIATED  
BY ELECTRONS**

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Polytetrafluoroethylene (PTFE) is known as a polymer having their unique physical, chemical and other properties and it is the most inert material among all the polymers with respect to aggressive media. In this work, we conducted studies on the effect of electron radiation on properties of a composite in which the filler used ultrafine powder of PTFE with a particle size of 0.5–1  $\mu\text{m}$ , with concentrations of 5 and 50 %. The samples were irradiated by the electrons in the accelerator of electrons ELA-2 with the energy of 2 MeV, the intensity  $I = 0,3 \text{ mA/cm}^2$ , the irradiation dose  $D = 20 \text{ kGy}$  and 50 kGy and irradiation temperature  $T = 20 \text{ }^\circ\text{C}$ . Inputting of 5 % PTFE filler, results in the formation of structural elements having the fuzzy boundaries in the form of large, round and elongated spherulites with uncertain orientation. Additional inputting of the filler into the polymer blend up to 50 % provides a significant change in the structure, leading to formation of the densified homogeneous supramolecular structure in the composite. The image analysis shows that irradiation by the dose of 20 kGy leads to the growth of agglomerations and their compaction, by increasing the dose up to 50 kGy is observed the appearance of crystal formations in the form of spherulites and fibrils with clear boundaries. However, for the sample with the concentration of powder 50–50 % is noticed a violation of the orderness of formations and the beginning the process of amorphization.

**Keywords:** *polymer, composite, material, nanopowder, microscope, radiation, electron, concentration, structure.*

## ELECTRODEPOSITION OF CONIFE COATINGS IN THE X-RAYS FIELD

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In this study we report the experimental results of researches kinetics electrodeposition, a structure formation of ternary CoNiFe alloys coating onto the low-carbon steel 08kp in the presence of the X-rays, using reverse of current until deposition during 5 minutes. These alloys are currently being considered as materials with the excellent soft magnetic properties. It is obtained relations of deposit rate, current efficiencies, element and phase compositions, physical and protective properties of CoNiFe coatings are formed from sulfate baths with respect of cathode current densities (0,5–3 A/dm<sup>2</sup>). It is shown that, the CoNiFe coatings formed by the electrochemical method involving exposure of the X-rays are characterized by more perfectly morphology surface with less developed surface geometry then reference coatings. The effect of the X-ray irradiation on the electrodeposition of CoNiFe coatings promotes to formatting alloys with increased electropositive component and uniformly distribution elements through the film thickness and surface. The observed variations in the morphology and element composition of exposed samples may be explain by the primary structure destruction of electrolytes and as a result the radiolysis transformations taking place in solutions in the X-ray irradiation and by the dependences of radiolysis products from type and concentration of components in these electrolytes. It should be noted, in the X-ray irradiations coatings formed with higher specific magnetization with respect of reference samples due to variations of the elemental composition of CoNiFe coatings deposited in the X-rays.

**Keywords:** *Electrodeposition, X-rays, Radiolysis, Structure, Kinetic.*

## STRUCTURE OF THE ZNCO AND ZNNI ALLOYS MODIFIED BY LASER BEAMS

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The experimental results of researches of the laser radiation treatment (wavelength 532 nm) on the evolution microstructure, elemental composition of the ZnCo and ZnNi alloys are presented. The coatings were electrodeposited from additive-free sulfate electrolytes. Deposition has performed with a preliminary reverse onto low-carbon steel at controlled temperature. Current density was equaled  $2 \text{ A/dm}^2$ . The coatings were irradiated by laser beams generated by the Lotis laser with a 70 Ps pulse duration. The specific power of the pulse was varied from  $5 \cdot 10^6 \text{ W/cm}^2$  to  $2 \cdot 10^9 \text{ W/cm}^2$ . It is obtained that the surface relief, the elemental composition and phase composition of the ZnCo and ZnNi alloys after laser irradiation change with respect of modes and irradiation regimes. It is found the dependences of the elements composition of the specific power of the pulse.

**Keywords:** *Electrodeposition, ZnNi, ZnCo, laser irradiation, elemental composition, surface morphology.*

## ATOMISTIC SIMULATIONS OF ELECTRONIC EFFECTS DURING SWIFT HEAVY ION IRRADIATION

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Radiation effect in materials have gotten new perspectives since the high energy accelerators have become available for modification of material properties. The shift towards the high irradiation energies highlighted the importance to consider the energy deposition via electronic stopping power. The exciting effects in high energy regimes brings together the lattice and electronic subsystems in a single interplay, while historically they were considered almost independent on one another. When irradiation energies exceed 1 MeV/amu, the energy is almost never lost on nuclear stopping power. However, these high-energy heavy ions are seen to leave behind well-recognizable footprints in the lattice – micron-long and nanometer-wide damage regions in a material – known as «tracks».

In our group we use and develop one of the favorite models to explain the track formation via a so-called inelastic thermal spike. We present a two-temperature molecular dynamics (TTMD) study, which is suitable to simulate the damage production in 2D and 3D materials.

We obtain a good quantitative agreement between the TTMD model and experiments and explain the origin of the track radii saturation with the electronic stopping power,  $S_e$ . Furthermore, by moving away from the commonly used free electron gas approximation for the excited electrons, we build a more realistic two-temperature description for band-gap materials for track simulations, resulting in a fitting parameter-free model. Our simulations explain the origin of the experimental discrepancy in 3D materials and provide the insight in damage formation in 2D materials.

***Keywords:*** radiation, high-energy heavy ions, track, inelastic thermal spike.

**COMPLEX DEFECTS IN SCINTILLATION CRYSTALS****VIKTOR LISITSYN<sup>1</sup>, LIUDMILA LISITSYNA<sup>2</sup> AND ELENA POLISADOVA<sup>1</sup>**<sup>1</sup>*National Research Tomsk Polytechnic University, Russia*<sup>2</sup>*Tomsk State University of Architecture and Building, Russia*  
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The existing models assume that the defects are distributed evenly in the crystal lattice. The defect as a dopant is an elementary unit with specific properties independent of the system it is located in. This assumption is supported by studies of radiation induced processes in crystal phosphors with a perfect structure and low concentration of the dopant. However, in real crystal phosphors used in practice the concentration of defects, dopants is large, and the crystal structure is complicated and imperfect. Therefore, we can assume that the defects are incorporated in these crystals in synthesis, in the form of complex systems. The complexes should represent the dopant entered with other impurities, often in the form of hydroxyl groups, oxygen, particularly if the synthesis is carried out in air, intrinsic lattice defects, which compensate the difference in the charge and elastic stresses in the region of the dopant.

**Keywords:** *nanodefects, scintillators, luminophores.*

## PHOTOPHYSICAL PROCESSES AND ACCUMULATION OF ENERGY OF INTENSE FEMTOSECOND LASER RADIATION IN DIELECTRIC CRYSTALS

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The object of research is the formation of the luminescent point defects in alkali-halide crystals under the action of high intense femtosecond laser pulses and the processes of energy accumulation, transfer the energy to the recombination centers and its decay.

The physical model of the interaction processes of intense femtosecond laser radiation with wide-band crystals of lithium fluoride as an example, including the self-focusing and multiple filamentation of laser radiation is formed on the basis of experimental and literature data.

It is shown that the axial dependence of the energy accumulated crystal under the influence of individual femtosecond laser pulses or a small series has a «ragged», nonmonotonic character. The length of the tracks (trace of the filament), filaments induced in the crystal, as well as their diameters increase with increasing number of laser pulses, and axial dependence of the energy stored smoothed. The saturation effect of the stored light sum is detected. The spectra of thermally stimulated luminescence (TSL) of LiF crystal at different temperatures measured during thermoluminescence process show that the  $F_2$  centers – are centers of emission in the TSL. We can assume that the kinetic particles are interstitial fluorine ions (I-centers). They split off from X3-centers as a result of their thermal decay at the I-centers and X20 molecules. I-centers, recombining with  $F_3^+$  centers can form  $F_2$  centers in the excited state, i.e. in the excited emission centers, which provide a characteristic emission spectrum of  $F_2$  centers, emitted in the form of thermostimulated luminescence.

**Keywords:** *femtosecond, laser, pulses, energy, accumulation, luminescence.*



## FEATURES OF RADIATION DEFECT FORMATION IN LITHIUM-FLUORIDE CERAMICS

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In order to establish the processes of radiation defect formation in ceramic samples of lithium fluoride we studied the optical absorption spectra of initial and irradiated samples of ceramics and the relaxation of induced spectra over time after irradiation with high-current pulses of accelerated electrons. The results were compared with data of similar studies, carried out for the original single-crystal samples. Spectral-kinetic characteristics of the photoluminescence of irradiated ceramic samples when excited of luminescence by picosecond laser pulses in the spectral range of the absorption of induced color centers from 370 to 640 nm are studied.

For the first time, the moment of diffusion-controlled tunneling recombination  $F_2^+$  – color centers with the formation of  $F_2$  – color centers after irradiation of ceramic sample with X-rays was registered by confocal scanning fluorescence microscopy during the registration of single color centers. The obtained results show that during irradiation the basic kinetic particles, responsible for the formation of the luminescent aggregate color centers in optical ceramics, as well as in single crystals are anion vacancies and  $F_2^+$  centers.

Studies have shown that the efficiency of defect formation in ceramics is lower than in the single crystal. The concentration of the  $F_2^+$  – centers in ceramics after completing all the relaxation processes is 3 times higher than in a single crystal. This is caused by that the grain boundaries and dislocations are the obstacles for the kinetic particles, providing the transfer of charge and mass during radiation exposure and subsequent relaxation.

**Keywords:** *ceramics, laser, pulses, defect formation.*

## REAL-TIME STUDY OF RADIATION DAMAGE IN $Al_2O_3$ AND LiF INDUCED BY HIGH ENERGY HEAVY IONS

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In the present report we review the results of real-time ionoluminescence (IL) characterization of structural defects in  $Al_2O_3$  and LiF single crystals under heavy ion irradiation in a broad range of nuclear and electronic stopping powers. In-situ experiments were carried out using (1–3) MeV/amu Ar, Kr, Xe and Bi ion beams. To monitor the lattice disorder in alumina and lithium fluoride, the luminescence of F-type centres have been used. It was found that the dose dependent defect-related emission in both materials exhibits two stages, which are associated with irradiation regimes of (i) isolated and (ii) overlapped ion tracks. It was also shown that swift heavy ion (SHI) track region overlapping may induce relaxation of mechanical stresses in the irradiated layer. The build up and accumulation of mechanical stresses in  $Al_2O_3$  was studied by exploiting a piezospectroscopic effect through the shift of the Cr emission lines.

The real-time IL measurements were followed by postradiation examination with high resolution transmission electron microscopy (HRTEM) and laser confocal scanning microscopy (LCSM). The LCSM technique was employed for depth resolved studies of F-type aggregate centers in LiF and evaluation of mechanical stresses across SHI irradiated layers in  $Al_2O_3$ . Optical effects of SHI irradiation will be discussed considering our recent HRTEM data on ion track morphology and latent track interference in  $Al_2O_3$ .

**Keywords:** high energy heavy ions, radiation damage, latent tracks, LiF,  $Al_2O_3$ .

## THEORETICAL MODELLING OF THE STRUCTURE OF ZR-RICH LEAD ZIRCONATE-TITANATE

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In this work we report the development and application of a novel algorithm for structural modelling of complex multiphase systems. The method allows for prediction of phase composition of studied solids, for example, systems like well-known ferroelectric perovskites PZT, PMN-PT, PZN-PT, which are widely used in piezoelectric industry applications.

The developed approach is similar to well-known multiphase Rietveld method, however, it is based on first principle results of structural optimization and, therefore, uses completely different set of fitted parameters, which makes it appropriate for using in combination with other atomic structure simulation methods, as Rietveld refinement and Reverse Monte Carlo approaches.

We applied our method for description of phase composition of piezoelectric material  $\text{PbZr}_{1-x}\text{Ti}_x\text{O}_3$  (PZT) at  $x = 0.4$  and  $x = 0.3$ . The compositions are close to material's morphotropic phase boundary (MPB) and are characterized by complex multidomain/multiphase structures, as shown by recent controversial single or two phase structural models. Our procedure successfully fitted the structure of the samples, as shown by good agreement between modelled and experimental pair distribution function (PDF) curves. The structure of  $\text{Pb}_{1-x}\text{Zr}_x\text{TiO}_3$  at Zr-rich compositions is shown to be essentially multiphase, which is in line with recent theoretical and experimental investigation, however, our model includes much more local structures to reproduce the experimental PDF curve over the wide range of distances (from 0 Å up to 50 Å). We discuss the obtained variety of phases and show that it could be a consequence of partial preservation of long-range order in the Zr rich PZT, which was previously unreported.

**Keywords:** *lead zirconate titanate, piezoelectric material, structure modelling.*

## INTRODUCING HYDROGEN U-CENTERS INTO ALKALINE EARTH FLUORIDES BY THE ADDITIVE COLORATION

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Additive and radiation coloration is a powerful tool for creation of thermally stable color centers in crystals and converting the valence state of the impurity ions, which is important in the development of new laser and holographic media.

The processes of unintentional formation of hydrogen ions in the crystals of alkaline earth fluorides with calcium vapor additive coloration are studied. The colored crystals shows ultraviolet absorption bands at 7.8, 7.0, 6.025 eV, for CaF<sub>2</sub>, SrF<sub>2</sub>, BaF<sub>2</sub>, respectively, previously identified as a band of hydrogen ions. As a result of X-ray irradiation additively colored crystals at room temperature the hydrogen ions jump into interstitial position losing an electron. Interstitial hydrogens was detected by the paramagnetic resonance.

The diffusion of hydrogen, was studied by splitting a cylindrical sample to disk and then gradually fleshing out the outer part of the disc. The concentration of hydrogen ions decreases exponentially with increasing depth. Hydrogen diffused into the crystal at a speed considerably less than the speed of conventional additive coloration. The process of hydrogen penetration into the crystals was studied by a color change with the depth of the crystal also. The inner part is more deeply colored because of the competition between the color centers and the hydrogen centers.

It is assumed that the formation of the hydrogen atmosphere take place during the pyrolysis of the organic impurities in an autoclave at high temperatures. Further, hydrogen enters the anionic vacancy of fluoride crystals, grabbing electron and forms hydrogen ion on anion site.

**Keywords:** *additive, coloration, hydrogen.*

## PATTERN ASSISTED STRUCTURE SEARCH (PASS) APPROACH FOR MODELING COMPLEX DEFECTIVE STRUCTURES

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This paper presents a novel approach for predicting and modelling complex defective structures like nanoparticles, grain boundaries, surfaces and interfaces. The new approach can be called Pattern Assisted Structure Search (PASS) as it relies on the use of structural patterns. PASS algorithm successively applies a set of patterns to perform «search- and-replace» operations in the complex structure until it becomes energetically favourable.

The new approach has been applied to find the smallest stable configurations of toroidal carbon nanoparticles (nanotori) and to model grain boundaries in polycrystalline silicon. We have found stable carbon nanotori with the number of atoms of 136, 138, 148, 162, 164, 166, 168, 336. Their electronic structure and properties were studied with B3LYP density functional. The correlation between the number of atoms and total energy has been revealed and compared to that of fullerenes. We propose a criterion for determining the stability of the structures obtained.

Application of PASS method to the low-angle tilt grain boundaries in polycrystalline silicon allowed to establish the structural elements comprising these boundaries. Their relative stability and comparison with experimentally observed structures will be discussed.

**Keywords:** *Pattern assisted structure search (PASS), Toroidal carbon nanoparticles (nanotori), B3LYP.*

## AB INITIO MOLECULAR DYNAMICS SIMULATION OF POINT DEFECTS IN $\text{CaF}_2$ AND $\text{LaF}_3$ CRYSTALS.

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Rare-earth fluoride crystals are promising materials in a variety of potential applications including scintillators and ionic conductors. Despite more than half-century history of investigations, the structure and properties of intrinsic defects and elementary excitations in these crystals are not yet established. In these paper we applied ab initio molecular dynamics to study anion vacancy, F-centres, Vk-centres and self-trapped excitons (STE) in  $\text{LaF}_2$  and  $\text{CaF}_2$  crystals.  $\text{CaF}_2$  has been selected for the purpose of computational method verification as it is very well studied.

We used periodic plane-wave density functional theory (DFT) as implemented in VASP code. PBE functional with DFT+U correction has been applied in order to obtain the right degree of hole state localization. The choice of U and J parameters will be discussed and justified.

The molecular dynamics of Vk-centre and STE has been studied in the temperature range between 50 and 450 K. It was possible to observe different thermally activated processes as STE reconfigurations and Vk-centre diffusion. It turns out that axial translation of Vk-centre has much lower energy barrier than its reorientation.

The STE demonstrates frequent reconfigurations, i.e. jumps between its neighbouring configurations. Interestingly, this process is very sensitive to the axial stress applied to the crystal.

It is found that anion vacancy in  $F_2$  position of  $\text{LaF}_2$  crystal lattice is 0.75 eV more stable than that in  $F_1$  position which makes the vacancy in  $F_2$  sublattice predominant.

The vacancy induces considerable lattice distortion with nearest neighbours displacements up to 0.5 Å.

**Keywords:** *DFT+U, Vk-centres, self-trapped excitons,  $\text{LaF}_2$ ,  $\text{CaF}_2$ , intrinsic defect, molecular dynamics.*

## ACCUMULATION OF COLOR CENTERS IN LiF CRYSTALS DOPED WITH METAL OXIDES

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The processes of accumulation of color centers ( $F^-$ ,  $F_2^-$ ,  $F_3^-$ ,  $F_2^+$  centers and  $F^-V_k$ -pairs) in «pure» LiF crystals and those doped with metal oxides ( $TiO_2$ ,  $WO_3$  and others) have been studied after irradiation by nanosecond electron pulse series with an average energy of 250 keV in the temperature range of 20–300 K. The effect of impurities on accumulation was analyzed with respect to the capture of electron-hole pairs and Frenkel defects generated by electron pulse by pre-irradiation and radiation defects.

**Keywords:** *lithium fluoride, color centers, accumulation, metal oxides.*

## EMBEDDED CLUSTER CALCULATIONS OF RARE-EARTH IMPURITIES AND INTRINSIC DEFECTS IN $\text{LaF}_3$ CRYSTALS

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Rare-earth impurities (Sm, Eu) in tysonite phase  $\text{LaF}_3$  crystal have been studied in embedded cluster approach at the hybrid density functional (BHLYP) level and with correlated electronic structure methods. Our approach allows to account for deformable and polarizable crystalline lattice.

First, anion vacancy and  $\text{F}^-$  centres were calculated. The fluoride vacancy in  $\text{F}_2$  sublattice possesses the total energy 0.85 eV lower than that in  $\text{F}_1$  sublattice. In both vacancies F-centre is formed upon electron trapping. The lattice deformation caused by the vacancy is large and unusual. In order to establish the origin of such deformation we have analyzed the phonon spectrum of  $\text{LaF}_2$  for the presence of soft modes and possible influence of orthorhombic crystalline phase existence on the «softness» of  $\text{LaF}_3$  lattice.

Then  $\text{Sm}_2^+$  and  $\text{Eu}_2^+$  defective complexes with neighbouring anion vacancy were calculated. The lattice deformation is found to be predominantly due to the presence of vacancy.

The ground and excited states of  $\text{Sm}_2^+$  – vacancy defects were further studied with multi-determinant CASSCF approach including scalar relativistic effects and spin orbit coupling. The experimental optical absorption spectrum of this defects has a peculiar peak at  $16000 \text{ cm}^{-1}$  which is absent in excitation spectrum. The intensity of this peak show linear dependence on the Sm impurity concentration. It has been found from calculation results that lowest vacancy states appear about this energy of  $16000 \text{ cm}^{-1}$ . The excited 4f6 levels of Sm ion are situated below, while its 4f5d levels appear above  $20000 \text{ cm}^{-1}$ . These results agree with experimental data.

**Keywords:** *rare-earth ions,  $\text{LaF}_3$ , embedded cluster, quantum chemistry, spin-orbit coupling.*



**DEFECT STRUCTURE STUDY OF NEUTRON, HEAVY-ION  
AND ELECTRON IRRADIATED BERYLLIUM OXIDE***MAXIM PETRENKO, IGOR OGORODNIKOV AND VLADIMIR IVANOV**Ural Federal University, Russia  
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The main purpose of present study are pristine and Zn-doped BeO single crystals. The samples were irradiated by electrons, neutrons and heavy ions. Spectra of X-Ray induced luminescence and optical absorption were obtained before and after irradiation for all the samples studied. Thermoluminescence of BeO crystals in the temperature range of 6–600 K was also studied. Low-temperature thermoluminescence (TL) glow curves and spectra of X-ray induced luminescence were studied for Zn-doped and pristine crystals.

Neutron and heavy-ion irradiation leads to creation of color centers in beryllium oxide single crystals. We discuss the origin of these defects and compare the spectra obtained in present study with the spectra obtained for additively colored samples of beryllium oxide single crystals.

**Keywords:** *Beryllium oxide, Luminescence, Low-temperature thermoluminescence, Defect structure, Color Centers.*

## OPTICAL STUDY OF BABRI AND BACLI CRYSTALS DOPED WITH RARE-EARTH IONS

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Luminescence and scintillation properties of BaBrI and BaClI doped with Eu and Ce ions (0.05–8 %) are reported. The luminescence of the BaBrI:Eu<sup>2+</sup> crystals under lamp excitation in UV wavelength range peaked at about 415 nm. The excitation spectrum of luminescence of BaBrI:Eu<sup>2+</sup> crystals contains wide structureless band in 240–400 nm wavelength range. Available luminescence is attributed to 5d-4f transitions in Eu<sup>2+</sup> ions.

The X-ray excited luminescence (XEL) spectra present one broad band emission with maxima at about 412 nm in BaBrI:Eu<sup>2+</sup> and 425 nm in BaBrI<sup>-</sup>Eu<sup>2+</sup> crystals. Light yield of obtained crystals of BaBrI:5%Eu is 74000 ph/Mev and BaClI:5%Eu – 60000 ph/Mev (was estimated from XEL spectra). In the XEL spectrum of BaBrI<sup>-</sup>Ce<sup>3+</sup> the most intense bands at 368 and 394 nm correspond to transitions from 5d state to terms of Ce<sup>3+</sup> ions.

We measured thermostimulated luminescence (TSL) of crystals doped with Eu<sup>2+</sup> and Ce<sup>3+</sup> ions. We observed several complex peaks within 150–250 K region in Eu<sup>2+</sup> doped crystals. These peaks can be attributed to thermal liberation of electrons from perturbed F(Br<sup>-</sup>) centers upon recombination with the holes trapped by Eu ions. Crystals doped with Ce<sup>3+</sup> ions demonstrate high temperature complex TSL peak at 280 K. The peak can be related to shallow traps. The intervals of the emission decrease are correlated with TSL peaks. Therefore, we can assume that trapping centers contributed to energy transfer from primary electrons and holes to Eu<sup>2+</sup> and Ce<sup>3+</sup> ions.

This work was supported by RFBR (project # 15-02-06514).

**Keywords:** *Scintillator, Halides, Single crystal growth, Luminescence.*

## RADIATION DAMAGE CAUSED BY LIGHT AND HEAVY SWIFT IONS IN CALCIUM FLUORIDE SINGLE CRYSTALS

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The study is devoted to a comparative investigation of radiation damage in oxygen-free calcium fluoride single crystals caused at 295 K by 0.23-GeV Xe ions (DC-60, Astana), 2.38-GeV Bi ions (UNILAC, GSI, Darmstadt) or 100-keV hydrogen ions (KIIA 500 kV implanter, Helsinki). Radiation-induced optical absorption (RIOA) was measured from 1.5 to 10.5 eV in a step-to-step regime after preheating of the irradiated samples to different temperatures. In addition, the thermally stimulated luminescence was measured during linear heating (2 K/s) of preliminary irradiated crystals.

The annealing of a complex wide RIOA band in visible range ( $\sim 2.2$  eV), tentatively associated with different F-type aggregates and calcium colloids, mainly occurs at 400–600 K. The band at  $\sim 6.5$  eV can be ascribed to trihalide quasi-molecules. Only high-dense ion-irradiation creates a complex RIOA band at  $\sim 9.7$  eV which cannot be induced by X-rays (W, 50 kV, 15 mA) and 100-keV protons. In our opinion, this band can be partly ascribed to electronic excitations localized near complex radiation damages. The joint action of shock waves and the decay/recombination of radiation-induced electronic excitations is considered to be responsible for the creation of novel defects with complex structure under Xe or Bi irradiation. The cracking and fracturing of calcium fluoride single crystals into pieces with (111) faces is especially efficient in the samples irradiated with Bi ions. The estimation of the contribution of bismuth nuclei specificity (extremely high nuclear spin of 9/2, electrical quadrupole moment of  $-0.4$ , etc.) to radiation damage needs further analysis and still lies ahead.

**Keywords:** *Swift ion irradiation, Calcium Fluoride, Radiation-induced optical absorption, Thermally stimulated luminescence.*

## AFM AND TEM STUDY OF HILLOCK-LIKE DEFECTS INDUCED BY SWIFT HEAVY IONS ON AL<sub>2</sub>O<sub>3</sub> SURFACE

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High energy heavy ions induce nanosized hillock-like defects on surface of variety materials including such radiation resistant insulators as aluminium oxide. Most of corresponding experimental data on this material concern on the AFM studies of the hillock parameters as a function of incident electronic stopping power [*S. M. Ramos et al., Nucl. Instr. Meth. B143 (1998) 319; V.A. Skuratov et al., Surface and Coating Technology 196 (2005) 56*]. In this report we present and discuss the results of complementary AFM and high resolution XTEM examination of hillock morphology on surface of single crystalline Al<sub>2</sub>O<sub>3</sub> irradiated with swift (1.2–3 MeV/amu) Xe and Bi ions. It was found that hillocks are crystalline in nature. At the same time the hillocks overlapping may trigger amorphization process in irradiating material.

**Keywords:** *Heavy ion irradiation, Hillock, Al<sub>2</sub>O<sub>3</sub> crystal, XTEM, AFM.*

## STUDY OF DEFORMATION DEPENDENCE FROM TIME IN POLYETHYLENE TEREPHTHALATE FOR DIFFERENT STATIC LOADS AND IRRADIATION DOSES

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In connection with the widespread use of polymeric materials the volumes of their production have been steadily increasing. World production of plastics increases two times every fifteen years. Moreover, the fastest growing market today is polyethylene terephthalate. Polyethylene terephthalate is a polymer that has revolutionized the world of packaging, radically changing the situation in the world market in the field of production. Industrial polyethylene terephthalate of 90-micrometers thick was selected as the test material. The length of material to be tested was 7 cm and the working part was 5 cm, width – 0.5 cm. The dependence of deformation from  $t$  was recorded. Irradiation of samples was carried out using ELU-6 linear electron accelerator with energy of 2 MeV in air. Irradiation dose was equal to 50 and 100 kGy. Samples of the films were placed at the distance of 40 cm from the output window of the accelerator. The material temperature was 23 °C and the relative humidity was 55 %. Complex experiments were conducted on the deformation dependence from time for different static loads and irradiation doses: 1 = 7; 2 = 10; 3 = 11; 4 = 12; 5 = 14 MPa. It was found that the deformation of the material depends strongly from time and static load. Irradiation of PET samples results in significant improvement in the flexibility, and a significant increase in strain (more than 100 % compared with non-irradiated material), which is associated with degradation of the polymer chains. However, strength is virtually unchanged.

**Keywords:** *temperature, static load, time, electrons, dose, polyethyleneterephthalate, strain, deformation.*

## THERMAL CONVERSION OF COLOR CENTERS IN LITHIUM FLUORIDE CRYSTALS UNDER LASER EXCITATION

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Dielectric crystals with induced aggregate color centers are the gain medium of tunable lasers and passive laser shutters, photosensitive storage materials for multilayer and volumetric fluorescent recording media and are widely used in other applications of science and technology. To achieve the required functional characteristics of these materials in some cases, it is necessary to use special technologies providing optical and thermal transformation of color centers.

Here, the results of the photothermal transformation of color centers in lithium fluoride crystals are presented. We have carried out the temperature dependence of the luminescence intensity of some types of color centers during the annealing process under the constant CW laser irradiation ( $\lambda_{\text{ex}} = 405 \text{ nm}$ ).

The data presented show that with the temperature increasing the decay of  $F_2$  and  $F_3^+$  color centers occurs. Moreover, the decrease rate of the concentration of different centers is different. The  $F_3^+$  centers are destroyed much faster and when the temperature reaches  $290 \text{ }^\circ\text{C}$ , they are destroyed almost completely.  $F_2^-$  color center annealing occurs at a slower rate and takes place up to the  $415 \text{ }^\circ\text{C}$ .

In the temperature range from  $390$  to  $440 \text{ }^\circ\text{C}$  the photoluminescence spectra show high-temperature band increase with a maximum at  $510 \text{ nm}$ .

The continuous exposure with the laser excitation accelerates the transformation of the centers. It can be explained by the fact that in addition to the thermally activated processes in the ground state of the centers we have activation processes in excited states populated under laser irradiation.

**Keywords:** photoluminescence, color centers, lithium fluoride, annealing.

**FIRST PRINCIPLES CALCULATIONS OF CO IMPURITIES IN  $\text{MgF}_2$  CRYSTALS**

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$\text{MgF}_2$  crystals have unique properties of luminescence, laser, magnetism and crystal-field interactions, when doped with some transition-metal ions. In particular, Co-doped  $\text{MgF}_2$  is known as a still promising laser material, which could be operated at room temperature in spite of a very reduced fluorescence quantum efficiency [R. Moncorgé. Laser materials based on transition metal ions. *Opt. Mater.* (2016) doi:10.1016/j.optmat.2016.05.060]. Thus the clear understanding of the non-radiative multiphonon relaxations between the  $4T_2$  and the  $4T_1$  ( $4F$ ) emitting- and ground states of  $\text{Co}_2^+$  requires the detailed knowledge of the atomic and electronic structure of Co-doped  $\text{MgF}_2$ .

The ab initio calculations represent a powerful tool to study the behaviour of dopants in  $\text{MgF}_2$  crystals. In the present study we employ the linear combination of atomic orbitals approach and the hybrid exchange-correlation functionals as implemented in CRYSTAL14 computer code [R. Dovesi *et al*, *Int. J. Quantum Chem*, 2014, 114, 1287–1317]. We demonstrate the role of basis set optimization, i.e. of the exponents of Gaussian-type orbitals, and the amount of exact exchange to fully reproduce the bulk properties of un-doped and doped  $\text{MgF}_2$  in comparison with the existing experimental literature. In particular, the band gap value appeared to be much sensitive to the approach chosen. Such careful calculations allowed us to properly treat the magnetic properties of Co ions in  $\text{MgF}_2$ , as well as its atomic and electronic structure.

**Keywords:** *ab initio calculation, Co-doped  $\text{MgF}_2$ , multiphonon relaxations.*

## RADIATION EFFECTS IN NANOCRYSTALLINE TiZrN FILMS IRRADIATED BY HIGH ENERGY IONS

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Investigation of the behavior of nanomaterials exposed to radiation is very important as applied to the development of promising components for fission and synthesis reactors of a new generation (fast neutron reactors, high-temperature gas reactors, thermo-nuclear reactors, etc.). The presence of the high density of interfaces in nanomaterials acting as the sinks for radiation defects allows predicting the improved radiation stability of such materials. One of the perspective groups of these nanomaterials includes coatings on the basis of the transitional metal nitrides obtained by the physical vapour deposition. In this paper, swift Xe and Bi ion irradiation effects in nanocrystalline TiZrN coatings as a function of ion fluence are reported. Nitride films of different thickness (1 and 4  $\mu\text{m}$ ) synthesized by vacuum arc-vapour deposition in nanocrystalline state were irradiated with 167 MeV Xe and 695 MeV Bi ions to fluences in the range  $1 \times 10^{12}$ – $1,83 \times 10^{14}$   $\text{cm}^{-2}$  (Xe) and  $10^{12}$ – $10^{13}$   $\text{cm}^{-2}$  (Bi) and studied using XRD techniques. No evidence of amorphization due to high level ionizing energy losses has been found. XRD examinations revealed no changes in phase composition of nanocrystalline TiZrN films irradiated with high energy Xe and Bi ions proving very high resistivity of this material against fission fragment impact. It was found that the radiation damage accumulation results in increase of compressive stress level in TiZrN films. The measurements of lattice parameter have revealed nonmonotonic dependence of the stress level in irradiated samples on ion fluence.

**Keywords:** Ion irradiation, residual stress, nanocrystalline films, phase composition.



**SELF-TRAPPED EXCITON CONFIGURATION IN TITANIUM OXIDE***MICHAEL BOTOV, ALEXEY KUZNETSOV AND ALEXANDER SOBOLEV**Ural Federal University, Russia**scibma@gmail.com*

Presented work is devoted to theoretical investigation of possible self-trapped exciton (STE) configuration in titanium oxide (anatase) crystal. Our study is based on ab-initio calculations performed in CRYSTAL09 program package by means of Hartree-Fock and hybrid functional B3LYP30 (with 30 % of exact exchange) methods. Atoms were described by their full-electron basis set. Charge density distribution of presented defect configuration and its geometry relaxation were obtained. All calculations were carried out using periodic boundary conditions and full relaxation of supercell. STE luminescence energy was found to be 3.50 eV for HF and 2.26 eV for B3LYP30.

**Keywords:** *exciton, HF, B3LYP, luminescence, TiO<sub>2</sub>, anatase, ab initio.*

**ON REAL CRYSTAL STRUCTURE OF THE ANION-DEFICIENT CORUNDUM**

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Anion-deficient single crystals of corundum ( $\alpha\text{-Al}_2\text{O}_3\text{-}\delta$ ) grown by Stepanov's method under reducing conditions are widely used for the manufacture of radiation detectors of the type TLD-500. Two types of these single crystals were investigated by scattering of thermal neutrons ( $\lambda = 1.57 \text{ \AA}$ ) at  $T = 300 \text{ K}$ . The first type (or  $\alpha\text{-Al}_2\text{O}_3\text{-}\delta$ ) as grown crystal was with a concentration of anion vacancies  $\sim 10^{17} \text{ cm}^{-3}$ . The second type obtained by the same synthesis was annealed at  $T = 1970 \text{ K}$  for 70 hours in oxygen atmosphere to restore the «natural» structure state of corundum or  $\alpha\text{-Al}_2\text{O}_3$ . In it concentration of anion vacancies was less than  $10^{12} \text{ cm}^{-3}$ . The neutronographic research was carried out on D7b multichannel diffractometer (IVV-2M reactor, Zarechny, Sverdlovsk region, Russia).

The fine features of the structural state of bulk  $\alpha\text{-Al}_2\text{O}_3\text{-}\delta$  crystals, belonging to perspective detector materials, are considered for the first time by thermal neutron diffraction at  $T = 300 \text{ K}$ . In full, neutron scattering picture obtained on fragmented part allows to suppose that anion vacancies, being concentrated mostly in fragments, result in the highest vacancies content on the boundaries of the fragments. The other finding implying twinning effect is presented by additional knots in reciprocal space. Because of intensity relations of quasi-twin indications do not repeat main structure intensity relations, existence of substructure characterized by lower symmetry built on the lack of anions may be assumed. Annealing of  $\alpha\text{-Al}_2\text{O}_3\text{-}\delta$  crystals in  $\text{O}_2$  atmosphere leads to form modulated superstructure of displacement type.

**Keywords:** *anion-deficient corundum, crystal structure, neutron scattering.*

## RELATIONSHIP THE PROCESSES OF THE RADIATION DEFECT FORMATION AT PROTON IRRADIATION WITH MARKOV CHAINS

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Development of physical and mathematical models, computational algorithms, objects of study allows us to describe many phenomena.

We examine the processes of radiation defect formation in solids irradiated by protons and the features of computer simulation of cascade-probability functions (CPF) and radiation-induced defects, the establishment of the relation of these functions with Markov chains and Markov processes. In the interaction of charged particles with matter on the way their movements are continuous energy losses, which lead to a strong dependence of the energy spectra of incident particles themselves and primary knocked atoms from the depth of penetration. The interaction path on PVA formation essentially depends on the energy. We have developed a physical model of the interaction of the charged protons with materials. The mathematical models of the cascade-probability functions were presented, taking into account the loss at proton irradiation. There were conducted the CPF calculations depending on the number of interactions and the depth of particle penetration. It was presented a calculation model of PVA spectra and concentration of radiation defects, the calculations were produced. It was shown the relationship of the processes of the radiation defect formation at proton irradiation with Markov chains. The recurrence relations, from which the analytical expressions for the cascade-probability functions are derived, there were obtained from the Chapman-Kolmogorov equation. The expression for the spectrum of PVA can also be written in the form of the Chapman-Kolmogorov equation. The integrand contains a product of probabilities, which are the transition probabilities for the Markov chain.

**Keywords:** *cascade-probability functions, defects, model, Markov processes, Mileage of interaction.*

## STUDY OF COMBUSTION OF COAL-WATER SLURRY AT NATURAL GAS IGNITION

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This article presents the results of research into the processes of combustion of coal-water slurries (CWS) of the cake obtained electric discharge method, as well as considering the possibility of their practical application for burning in the boiler furnace.

Presented thermodynamic calculations burning of CWS at different temperatures. Also studied the dynamics of CWS combustion burner layout thermal imaging method, followed by mapping- and 3D-modeling of temperature fields.

Development of technologies for thermal waste cake is promising because it is a waste coal, and thanks to its high moisture content, the same as coal-water fuel.

***Keywords:*** *coal cake, the burner, the temperature field, thermodynamics.*

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