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Bias-voltage-controlled ac and dc magnetotransport phenomena in hybrid structures

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ABSTRACT

We report some ac and dc magnetotransport phenomena in silicon-based hybrid structures. The giant impedance change under an applied magnetic field has been experimentally found in the metal/insulator/semiconductor (MIS) diode with the Schottky barrier based on the Fe/SiO$_2$/p-Si and Fe/SiO$_2$/n-Si structures. The maximum effect is found to observe at temperatures of 10–30 K in the frequency range 10 Hz–1 MHz. Below 1 kHz the magnetoresistance can be controlled in a wide range by applying a bias to the device. A photoinduced dc magnetoresistance of over 10^4% has been found in the Fe/SiO$_2$/p-Si back-to-back Schottky diode. The observed magnetic-field-dependent effects are caused by the interface states localized in the insula-tor/semiconductor interface.

1. Introduction

High expectations in spintronics are related to hybrid nanostructures comprising classical semiconductors and magnetic materials [1]. Whether are these expectations reasonable? On the one hand, the potential of magnetic structures (spin-valve and magnetic tunnel structures) which already find an increasing application in magnetic memory devices is well-known. The obvious advantages of such devices are high operation speed, nonvolatility, and high stability of their characteristics. On the other hand, semiconductor materials due to the properties controllable in wide ranges by temperature variation, doping with impurities, electric field and optical radiation determine the prospects for development of modern semiconductor technologies. It is not clear whether the integration of ferromagnetic (FM) materials and semiconductors will lead to the formation of novel concepts in spin-based electronics or just result in a simple combination of magnetic and semiconductor technology advantages.

Nowadays the main efforts of researches focus on solving the problems of spin injection, detection of the spin state and controlling that in semiconductors. This is the direct way to construct components for the signal processing and transmission in semiconductors using spin degrees of freedom. The possibility to control the orientation of electron spins and measuring spin currents by using special topologies of ferromagnetic elements or circularly polarized optical radiation was demonstrated in Refs. [2–5]. In addition, purely electric methods for controlling spin polarization in hybrid structures were proposed in literature available [6,7]. However, in our opinion, the advantages of semiconductors application in order to control the spin state and mutual transformation of the spin and charge currents in hybrid structures are still far to being exhausted. In the current investigation we have considered some ac and dc magnetotransport phenomena in silicon-based hybrid structures. We investigate ferromagnetic metal/insulator/semiconductor hybrid structures, which contain interface states localized near the insulator/semiconductor interface with the energy structure sensitive to an external magnetic field.

2. The ac magnetotransport phenomena in hybrid structures

First, we consider the Fe/SiO$_2$/p-Si (5 nm/1.5 nm/p-Si wafer) hybrid structure. To investigate the magnetotransport properties, a simple lateral device commonly referred to as a back-to-back Schottky diode (inset in Fig. 1) was fabricated. The bias-sensitive dc magnetoresistance in a high magnetic field was observed in this device [8]. The main contribution to the magnetoresistance of the structure is, most likely made by the processes occurring at the SiO$_2$/p-Si interface. This result stimulated us to address to

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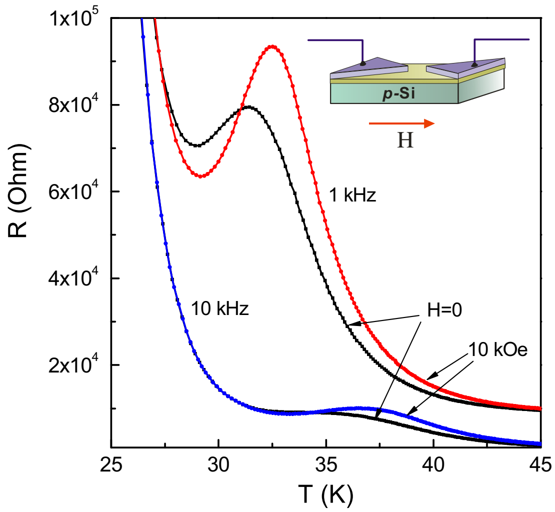

Fig. 1. The temperature dependences of real part of impedance R at various frequencies in zero and 10 kOe magnetic fields.

impedance spectroscopy [9] used for studying metal/insulator/semiconductor (MIS) structures.

The experimental temperature dependences of the real part of impedance R at different frequencies in zero magnetic field and in a field of 10 kOe are shown in Fig. 1. Hence, the existence of the impedance peak with the frequency-dependent position and amplitude is observed. In addition, the peak parameters appear to be magnetic-field-dependent.

The peaks presence in the temperature dependences of the real part of the impedance is not surprised if one considers that the metal/insulator/semiconductor (MIS) junction with a Schottky barrier at the SiO_2/p-Si interface [8] determines all the transport properties features of the structure. Such features observed in real MIS structures [9] result from recharging of interface states and impurity centers localized at the oxide/semiconductor interface.

Since the features of the ac transport properties are determined by recharging of the interface centers at the SiO_2/p-Si interface, the magnetotransport effects result from magnetic-field-induced rearrangement of the energy structure of these centers. Having used the approximation proposed in a study [9] it was established that the magnetic field shifts energy levels of the interface states upward relative to the top of the valence band by 20 meV, which directly affects the recharging processes [10].

The next structure that was under investigations is the Fe/SiO_2/n-Si hybrid structure where n-Si is used instead of p-Si. In this structure another experimental geometry was utilized. The impedance spectra of the MIS diode were investigated in a two-probe configuration. The schematics of the device and measuring setup are shown in the inset in Fig. 2. One probe connected to the top of the Fe electrode by a two-part silver-filled epoxy adhesive; the other probe connects to the substrate backside by a barrier-free Al–Ga contact.

The impedance of the device was observed to be strongly influenced by magnetic field on in the narrow temperature range 10–30 K. Within this range, as shown in Fig. 2, the intense peak in the temperature dependence of the real part of the impedance exists. As it mentioned above, the occurrence of peaks in the $R(T)$ dependences for this MIS structure is caused exclusively by a recharging delay of the interface states localized near the insulator/semiconductor interface [11].

Fig. 3 shows one can implement positive or negative magnetoresistance or even the alternating magnetoresistive effect at certain H depending on the temperature. The behavior $R(H)$ depends on what the peak part in $R(T)$ the system is at $H=0$. This position, in its turn, is entirely determined by the temperature.

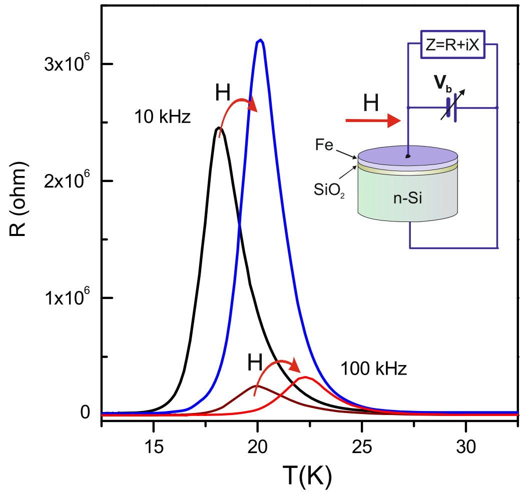

Fig. 2. Temperature dependences of the real part of the impedance at 10 and 100 kHz in zero magnetic field and in 10 kOe. Inset: a schematic of the device and the measurement setup.

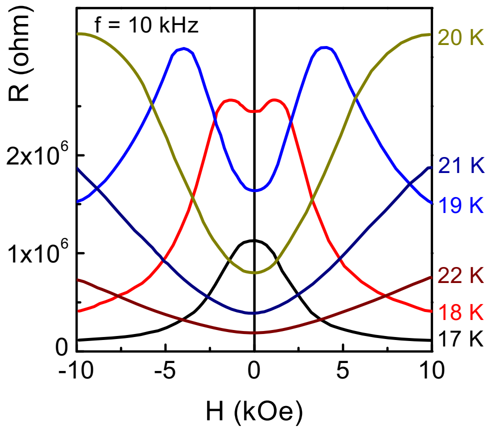

Fig. 3. The real part of the impedance vs magnetic field at different temperatures ($f=10$ kHz).

As in the previous case, the shift of the $R(T)$ features in a magnetic field and, consequently, the giant magnetoimpedance (GMI) phenomenon in the Fe/SiO_2/n-Si-based MIS diode should be considered from the viewpoint of the magnetic field effect on the energy structure of the interface states localized near the SiO_2/n-Si interface.

In addition, the dc bias voltage V_b influence of the impedance was revealed. This effect can be clearly observed in the frequency dependences of the real part of the impedance (Fig. 4). The applied voltage $V_b < 0$ reduces R in the low-frequency region. The negative bias leads to the formation of an area depleted of electrons in the surface layer of the MIS structure. This area operates as an additional dielectric layer, reducing the total capacitance of the structure. At increasing frequency the bias influence of the real part of the impedance decreases. The frequency dependences for $V_b = -5$ V and $V_b=0$ coincide at frequencies close to 1 MHz.

It is noteworthy the magnetoresistance strongly increases (Fig. 5) that in the low-frequency region at an applied bias. In particular, it increases approximately from 50% to 290% at a frequency of 100 Hz At higher frequencies MR do not change noticeably by the V_b bias. We define the magnetoresistance as $MR = 100\%(R(H) - R(0)/R(0))$.

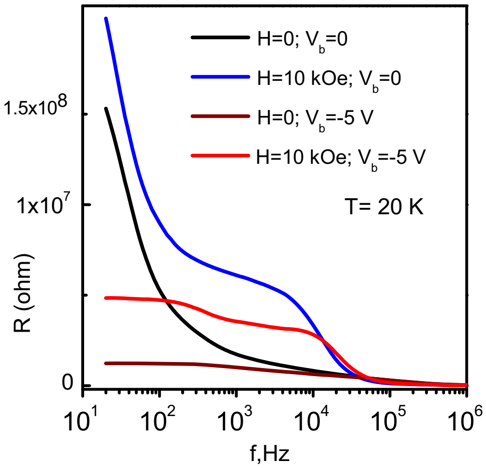

Fig. 4. Impedance at 10 kOe for zero bias and a bias of −5 V as a function of frequency ($T=20$ K).

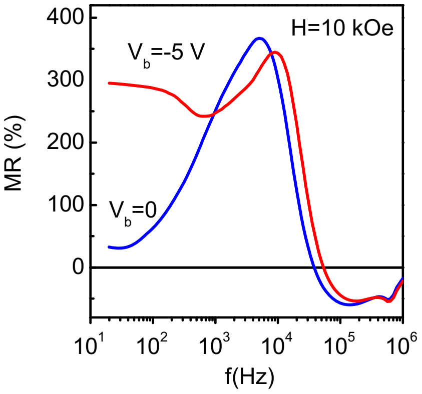

Fig. 5. Magnetoimpedance at 10 kOe for zero bias and a bias of −5 V as a function of frequency ($T=20$ K).

Therefore, one may conclude that the magnetoimpedance effect implemented due to the interface states presence at SiO_2/Si interface which participate in recharging under an ac voltage applied to the structure. The impurity centers at the SiO_2/n-Si interface most likely form with the Fe ions participation that can diffuse through the thin SiO_2 layer [12,13]. The effect of a magnetic field consists mainly in influence of the energy levels of the interface states.

3. The dc magnetotransport phenomena in the hybrid structures under optical irradiation

The other magnetoresistive effect to be elucidated in this study is the giant magnetoresistive (MR) effect caused by optical irradiation to the Fe/SiO_2/p-Si back-to-back Schottky diode. It has two specific features: the huge photoinduced MR effect, which can exceed in several times 10^4% at the field $H=6$ kOe, and the extremely high sensitivity of the photoinduced MR effect to the field polarity.

The experimental geometry and polarity of the bias current through the sample relative to the irradiated electrode are schematically shown in the inset of Fig. 6. In the experiments we irradiated only one of the electrodes through a window in a special screen with a diameter of 1 mm. The temperature dependence of resistance R_{ph} upon irradiation of one of the MIS junctions (MIS diodes) at the same bias current $J=70$ μA of two different polarities is presented in Fig. 6. First of all, fundamentally different behaviors of R_{ph} upon irradiation of the MIS junction under the forward and reverse bias attracts attention. This can be explained by the presence of the impurity and interface states in the Fe/SiO_2/p-Si structure [10,11,14]. These energy states take a part in the photogeneration processes of electrons to the conduction band, the thermal hole generation to valence band and electron capture tunneled from metal electrode.

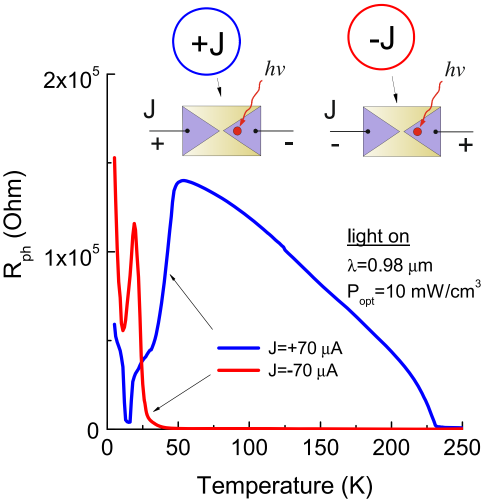

Fig. 6. Temperature dependences of the resistance under optical radiation R_{ph} for different polarities of the bias current. Inset: a schematic of the device and the measurement setup.

As it is mentioned above, the MR effect is sensitive to the magnetic field polarity. In Fig. 7 are shown dependences of

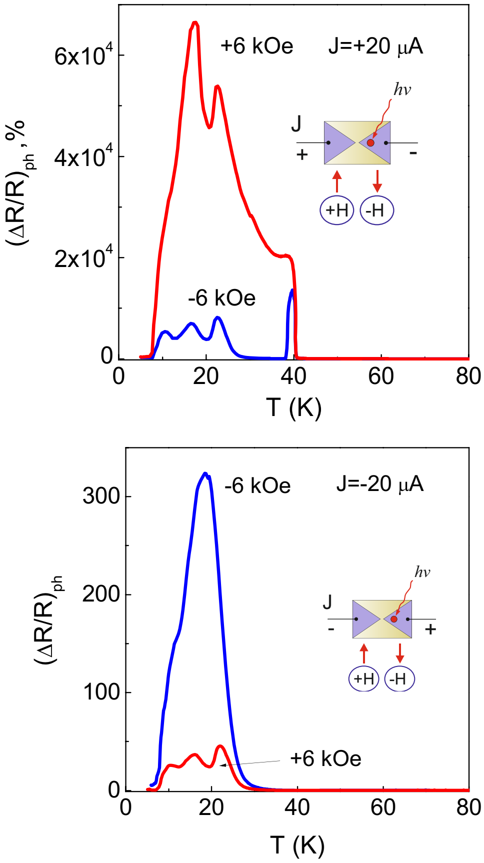

Fig. 7. Temperature dependences of magnetoresistance R_{ph} under optical radiation for different polarities of magnetic fields and bias currents. Inset: schematic of the device and measuring setup.

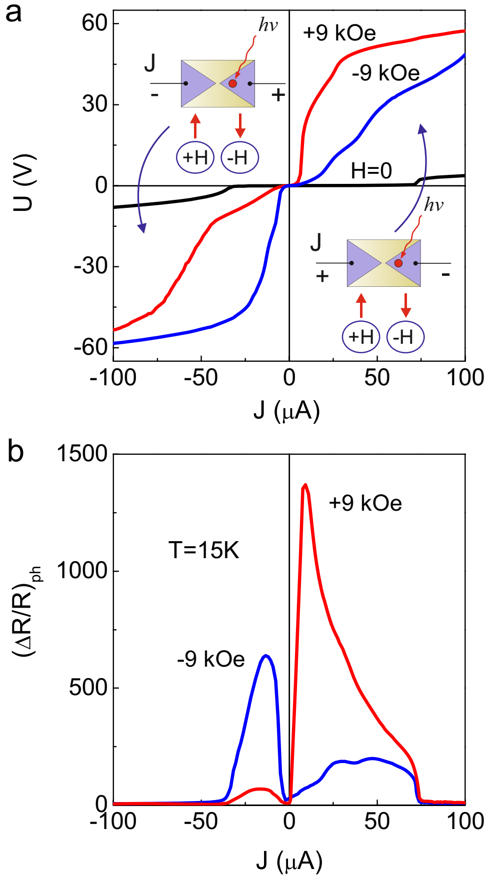

Fig. 8. (a) Voltage–current characteristic of the device measured under optical irradiation for zero magnetic field, positive and negative fields of +9 kOe and −9 kOe. (b) Appropriate plots of the magnetoresistance vs bias current for positive and negative magnetic fields.

photoinduced MR ($(\Delta R/R)_{ph} = [R(H)_{ph} - R(0)_{ph}]/R(0)_{ph}$) on temperature (with $R(0)_{ph}$ and $R(H)_{ph}$ the resistances under optical irradiation at zero and applied field respectively). Results obtained at +20 μA and −20 μA the bias currents are shown in Fig. 7 because ones yield the maximum effect of the magnetic field on the resistance behavior.

The asymmetry of the device photo-response with respect to the sign of the bias current *J* and the sign of magnetic field is clearly demonstrated in *J*–*V* characteristics shown in Fig. 8(a). Dark low-temperature *J*–*V* curves are symmetric and have typical shape of the reverse biased tunneling MIS diode. The tunneling conductivity mechanism is realized, likely, assisted by the interface states [8]. At the irradiation of one of the device MIS junctions at $H=0$ the conductivity increases, which we believe is due to the mechanism of photoconductivity through the interface states. The voltage increase at certain values of *J* relates to the current saturation, which is determined by the concentration of the non-equilibrium carriers, i.e. by generation-recombination rate of photo-excited electrons. Starting from small values of the current, the applied magnetic field of any polarity (though to a different extent), result in faster growth of *U*. Thus, positive magneto-resistance appears for all values of *J* regardless of its sign (see Fig. 8 (b)). Although, as seen in the figure, the value of $(\Delta R/R)_{ph}$ strongly depends on the sign and value of the bias current. At high current *J* the photo-induced MR effect is suppressed and practically vanishes.

In order to explain the high sensitivity of the photoinduced magnetoresistive effect to the sign of *H* it is necessary to employ additional mechanisms of the magnetic field influence of the electron transport. Such mechanism can be the Lorentz force that affects moving carriers and additionally contributes to the total magnetoresistance [15]. When a carrier moves in a magnetic field, it experiences a force that deflects it in a specific direction, which depends on the direction of *H* and the direction of motion. In our case, at $+J$, photoelectrons move from one MIS junction to the other along the SiO_2/p-Si interface. Magnetic fields of different polarities deflect the electron trajectories either toward this interface or in the semiconductor volume. Due to different recombination rates of photoelectrons near the interface and in the semiconductor volume, the photocurrent values are different for the positive and negative polarity of a magnetic field. At $-J$, according to our model, holes move along the SiO2/p-Si interface, i.e., in the same direction as electrons at $+J$; hence, the contribution to the magnetoresistance will be of the opposite sign. This behavior was observed in our experiment.

4. Summary

We demonstrated the giant magnetoimpedance effect in the hybrid Fe/SiO_2/p-Si Fe/SiO_2/n-Si MIS structures. It was shown the effect is due to the presence of the interface states at the SiO_2/Si interface, which participate in the recharging processes under the action of an ac-voltage applied to the structure. Also we found the giant magneto-resistance effect in the Fe/SiO_2/p-Si back-to-back Schottky diodes device under the influence of the optical radiation. Observed positive magneto-resistance is strongly influenced by the magnitude and sign of applied bias current through the device and, unexpectedly, to a high degree, depends on polarity of magnetic field.

Acknowledgments

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