Journal of Applied Physics

Extremely large magnetoresistance induced by optical irradiation in the Fe/SiO_2/p-Si hybrid structure with Schottky barrier

Cite as: J. Appl. Phys. **114**, 093903 (2013); https://doi.org/10.1063/1.4819975
Submitted: 17 July 2013 . Accepted: 16 August 2013 . Published Online: 04 September 2013

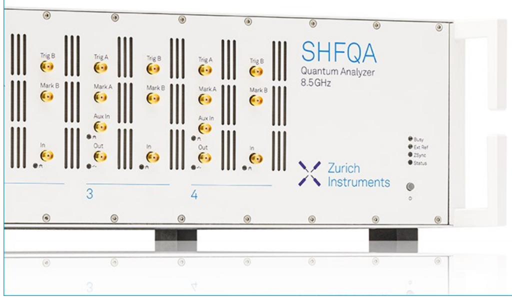
N. V. Volkov, A. S. Tarasov, E. V. Eremin, F. A. Baron, S. N. Varnakov, and S. G. Ovchinnikov

ARTICLES YOU MAY BE INTERESTED IN

Magnetic-field- and bias-sensitive conductivity of a hybrid Fe/SiO_2/p-Si structure in planar geometry
Journal of Applied Physics **109**, 123924 (2011); https://doi.org/10.1063/1.3600056

Extremely high magnetic-field sensitivity of charge transport in the Mn/SiO_2/p-Si hybrid structure
AIP Advances **7**, 015206 (2017); https://doi.org/10.1063/1.4974876

Frequency-dependent magnetotransport phenomena in a hybrid Fe/SiO_2/p-Si structure
Journal of Applied Physics **112**, 123906 (2012); https://doi.org/10.1063/1.4769788



AIP Publishing

JOURNAL OF APPLIED PHYSICS **114**, 093903 (2013)

Extremely large magnetoresistance induced by optical irradiation in the Fe/SiO$_2$/p-Si hybrid structure with Schottky barrier

N. V. Volkov,[1,2,a)] A. S. Tarasov,[1] E. V. Eremin,[1,2] F. A. Baron,[1] S. N. Varnakov,[1,2] and S. G. Ovchinnikov[1]
[1]*L.V. Kirensky Institute of Physics, SB RAS, Krasnoyarsk 660036, Russia*
[2]*Institute of Space Technology, Siberian State Aerospace University, Krasnoyarsk 660014, Russia*

(Received 17 July 2013; accepted 16 August 2013; published online 4 September 2013)

We report giant magnetoresistance (MR) effect that appears under the influence of optical radiation in common planar device built on Fe/SiO$_2$/p-Si hybrid structure. Our device is made of two Schottky diodes connected to each other by the silicon substrate. Photo-induced MR is positive and the MR ratio reaches the values in excess of 10^4%. The main peculiarity of the MR behavior is its strong dependence on the magnitude and the sign of the bias current across the device and, most surprisingly, upon polarity of the magnetic field. To explain such unexpected behavior of the MR, one needs to take into account contribution of several physical mechanisms. The main contribution comes from the existence of localized interface states at the SiO$_2$/p-Si interface, which provide the spots for the photo-current conduction by virtue of the sequential tunneling through them or thermal generation and optical excitation of mobile charges. External magnetic field changes the probability of these processes due to its effect on the energy states of the conduction centers. Two possible mechanisms that may be responsible for the observed dependence of magneto-resistance on the field polarity are discussed: the effect of the Lorentz force on moving carriers and spin splitting of electrons moving in the electrostatic potential gradient (Rashba effect). The most significant observation, in our opinion, is that the observed MR effect is seen exclusively in the subsystem of minority carriers transferred into non-equilibrium state by optical excitation. We suggest that building such magneto-sensitive devices based on this mechanism may set a stage for new types of spintronic devices to emerge.
[http://dx.doi.org/10.1063/1.4819975]

I. INTRODUCTION

Hybrid structures combining "classical" semiconductors and magnetic materials are expected to play major role in spintronics.[1] Are these expectations justified enough? On the one hand the high potential of the magnetic structures (spin valve structures, magnetic tunneling structures) is well recognized as they have already found their application in various memory devices. Advantages of these devices are obvious: high switching rate, fundamental non-volatility (independence on the energy supply), and their inherent high stability. On the other hand, the semiconductor material properties can be easily adjusted within wide range of values by varying the temperature, doping level, electric field, optical radiation intensity, which ultimately determines the high potential of the modern semiconductor technologies. But what can one expect conceptually new from combining ferromagnetic (FM) materials with semiconductors? Would it constructively interfere to yield an outstanding novel concept of the spin-based electronics or would this effort just end up with a group of stuck-together separate achievements of magnetic and semiconductor technologies?

Currently, many research efforts have their main focus on solution of the fundamental problem of spin injection, spin state detection and its controlled manipulation in semiconductors. This is a straightforward way to create the basic elements of signal processing and transmission in semiconductors by using the spin degree of freedom. Different approaches to control the electron spin orientation and to measure the spin currents using special topology of the ferromagnetic elements or by virtue of the circular polarized optical radiation have been shown recently.[2–4] Moreover, electrical creation and detection of spin polarization in silicon at room temperature by three-terminal Hanle measurement have been demonstrated.[5] Purely electric control of the spin polarization in hybrid structures has also been proposed.[6] Also we would like to mention the works of others reporting values of the MR effect in excess of 10^4%.[7,8]

We believe, however, that not all of the advantages of semiconductors have been utilized for the spin state control and for the spin-charge current mutual transformation in semiconductor hybrid structures. Here, we would like to draw attention to the well known fact that in semiconductor photodetectors, typically, the registration of the minority carriers is used. Absorbing a photon with the energy sufficient to cause interband transition in semiconductor creates the non-equilibrium electron-hole pair. When registering the electronic signal, it is required to detect the change of the carriers concentration. Obviously, all else being equal, it is easier to detect the concentration change of the minority carriers. So, the question arises, what if one could use this idea and apply it to the spin current control in semiconductors? For example, we could "work" with the spin degree of freedom of minority charge carriers, i.e., keep track of the spin

---

[a)] e-mail: volk@iph.krasn.ru.

state of a subsystem of the minority carriers. It is easy to create and vary their non-equilibrium concentration by the external optical illumination. At the same time, the spin polarization of the non-equilibrium photo-excited carriers can be effectively controlled by using the optical selection rules for circularly polarized light,[9] by combining the selection rules with photon energies[10] or even sub-picosecond electromagnetic pulses.[11]

Common photodetectors are built using diodes consisting of metal/insulator/semiconductor (MIS) structures with the Schottky barrier. Due to some reasons[12] we think that it is the hybrid Schottky barrier structures that are the most promising devices for the effective spin injection, detection and spin-filtering effect.[13–15] And here it is necessary to emphasize another important aspect of such structures, which is the presence of the localized interface states. These states assist the tunneling processes and may significantly affect the spin-dependent carriers transport.[16,17] Recently, we published some data that showed "magnetic" interface states were responsible for the alternate current (AC) magneto-transport properties of the Schottky barrier hybrid structures.[18] We also suggested that the interface states participating in optical transitions might be a key element in understanding of the relationship between the optical influence and the spin-dependent electronic transport of the non-equilibrium carriers.

The results of our investigation of the direct current (DC) magneto-transport properties of the Schottky barriers hybrid Fe/SiO$_2$/p-Si structure (which is set to operate in non-equilibrium state created by the optical irradiation), to some extent, confirmed our expectations. At the same time, several new unexpected phenomena have been uncovered, which are yet to be explained within the existing models. In this paper, we report two essential results obtained: the giant optically induced MR effect and also its strong anisotropy with respect to the direction of the external magnetic field applied.

II. EXPERIMENTAL DETAILS

To fabricate Fe/SiO$_2$/p-Si structure a p-doped silicon wafer with resistivity of $5\,\Omega\cdot$cm (a doping density of 2×10^{15} cm^{-3}) was used as substrate. The thicknesses of the SiO$_2$ and Fe layers were 1.2 nm and 5 nm, respectively. The details of structure preparation are given elsewhere.[19] The sample for study was a simple lateral device, well-known as a circuit with back-to-back Schottky diodes. To fabricated the device, two electrodes separated by a gap of 20 μm were formed from a continuous iron film on the structure's surface. The schematic illustration of the device is shown in the inset of Fig. 1(a). The desired topology of the electrodes was formed with a coordinatograph of original design using the wet-etching method. Ohmic contacts were formed on the top of Fe electrodes using two-component silver epoxy.

The transport properties were studied with an original facility based on a helium cryostat, an electromagnet, and a precise KEITHLEY-2400 current/voltage source meter. Resistance was measured in a DC mode at fixed value of the current and current-voltage characteristics were taken in a current scanning regime. A magnetic field was applied in the plane of the structures, and magneto-resistance measurements were carried out either at fixed value of the magnetic field or field was swept from -10 kOe to $+10$ kOe.

The optical effect was created using a laser diode with wavelength of 980 nm (hν = 1.26 eV). The sample was illuminated with linearly polarized light. Some measurements were also carried out with circularly polarized light, but no difference was observed in experiments using different polarization. In the experiments conducted one electrode of the device was illuminated through the 1 mm^2 window made as a special screen, while the other electrode was kept dark. Figures 1(a) and 1(b) schematically show the geometry of the experiment and the polarity of the bias current through device relative to the illuminated electrode.

III. RESULTS AND DISCUSSIONS

First, we briefly discuss the results obtained in the absence of magnetic field. Shown in Fig. 1(c) is the temperature dependence of the sample DC-resistance R ($R = V/J$) from dark measurements. Since the device is the back-to-back Schottky diodes its transport characteristics are symmetric

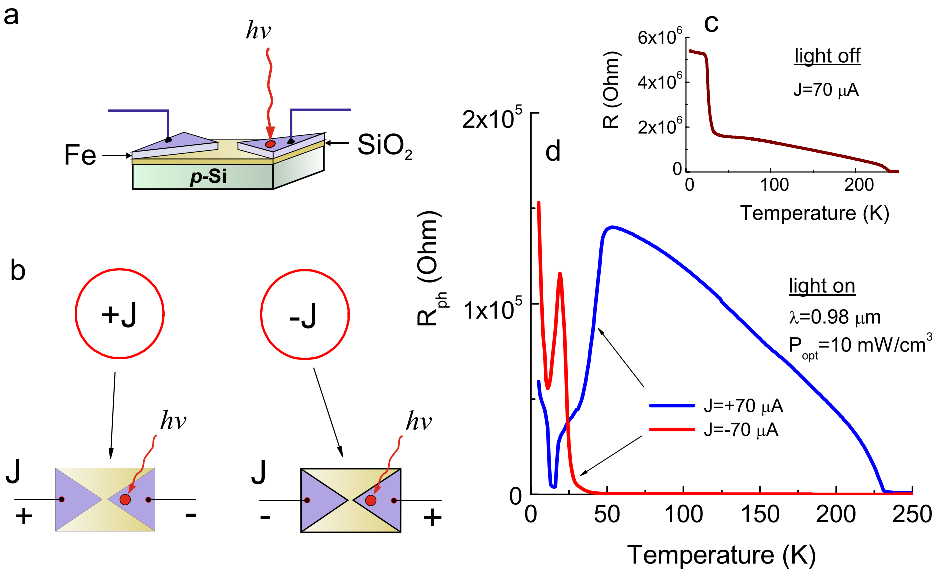


FIG. 1. (a) The schematic illustration of the back-to-back Fe/SiO$_2$/p-Si diode device, and (b) the measurement setup to study the photoinduced magnetoresistance. (c) Temperature dependence of the "dark" resistance R. (d) Temperature dependences of the resistance under optical radiation R_{ph} for different polarities of the bias current.

with respect to the bias current direction as they are determined by the type of the energy band diagram of the biased junctions. At high temperatures ($T > 240\,\mathrm{K}$) the sample resistance is $100 - 200\,\Omega$, and its sharp increase near 240 K is due to the presence of the Schottky barrier, which is consistent with the thermal electron emission theory.[18] At lower temperatures, the main contribution comes from the minority carrier generation-recombination processes assisted by the interface states localized near the SiO_2/(p-Si)-interface.[20] Presence of these states, which we believe are donor states, and their energy in this structure was determined by us earlier using the impedance spectroscopy technique.[17] The results obtained allow us to relate the increase of the resistance R at temperatures below $T_S \sim 50\,\mathrm{K}$ to the process of the holes capture/emission by the interface donor states depending on the Fermi-level position with respect to the energies of these donors.

The presence of the interface states also allows us to understand the peculiar features in the temperature dependence of the sample resistance (R_{ph}) when the light is on. The temperature dependences of the resistance of the MIS diodes biased with the current ($J = +70\ \mu\mathrm{A}$) is shown in Fig. 1(c). Here two curves correspond to different polarities of the bias current. Dramatic difference can be seen in the behavior of the diodes R_{ph} for the forward and reverse bias conditions. When temperature is below 240 K and the bias current set negative ($J = -70\ \mu\mathrm{A}$), the sample resistance decreases by several orders of magnitude approaching its room temperature value. However, starting from T_S, one can observe rapid growth of R. On the other hand, when the device was biased by positive current $J = +70\ \mu\mathrm{A}$ its resistance first remained high even below 240 K but then decreased sharply below T_S. We adopted our notations (see Fig. 1(b)) in a way that the positive bias current ($+J$) corresponds to the positive voltage on the non-illuminated electrode junction of the MIS device and, therefore, the voltage across the other junction corresponds to the forward bias region of that Schottky diode $J - V$ curve. However, if fed with the negative bias current ($-J$), the illuminated MIS junction will operate at the reverse bias condition. We believe that all optical processes take place near the interface of the Fe/SiO_2/p-Si MIS structure with the main contribution coming from the optical transitions assisted by the interface donor states. Qualitatively, the mechanism in charge of the $R_{ph}(T)$ behavior of the illuminated device under forward and reverse bias can be understood from Fig. 2. This figure shows schematically the band diagram of the device and principal carrier transport processes when it is illuminated.

For the $-J$ bias setup, the irradiated MIS junction is in the depletion mode (Fig. 2(a)). At high temperatures ($T > T_S$), the Fermi level energy E_F in semiconductor lies above the interface states. Optical excitation excites the electrons from these localized states to the conduction band from where they tunnel through the Schottky barrier into the free states of the FM metal. Thermal excitation of the holes then takes place at the interface donor sites, which excites the holes to the valence band and the whole cycle repeats. Considered mechanism provides high conductivity of the device. If one lowers the temperature then the Fermi-level crosses the donor states ($T < T_S$) and the holes are captured by the interface states. As a result, these centers become empty (ionized donor sites) and, therefore, cease to participate in the optical transitions no longer contributing to the sample photoconductivity. It is this mechanism that we believe is responsible for the sharp increase of the device resistance at temperatures below 50 K when the reverse biased structure is exposed to illumination. It should be noted that in this case the tunneling of electrons from the interface states into the FM electrode less probable due to the lack of the empty states in the metal. The only exception is the case of large bias when part of the interface states may be located lower than Fermi level in semiconductor but above the E_F in metal.

When we apply positive current bias to the irradiated MIS junction, it goes into enhancement mode and the surface concentration of the majority carriers (holes) increases (Fig. 2(b)). Now, it is obvious that after the optical excitation of electrons from the interface state levels occurred the thermal generation of holes from these levels into the valence band is no longer effective. Therefore, even at high temperatures,

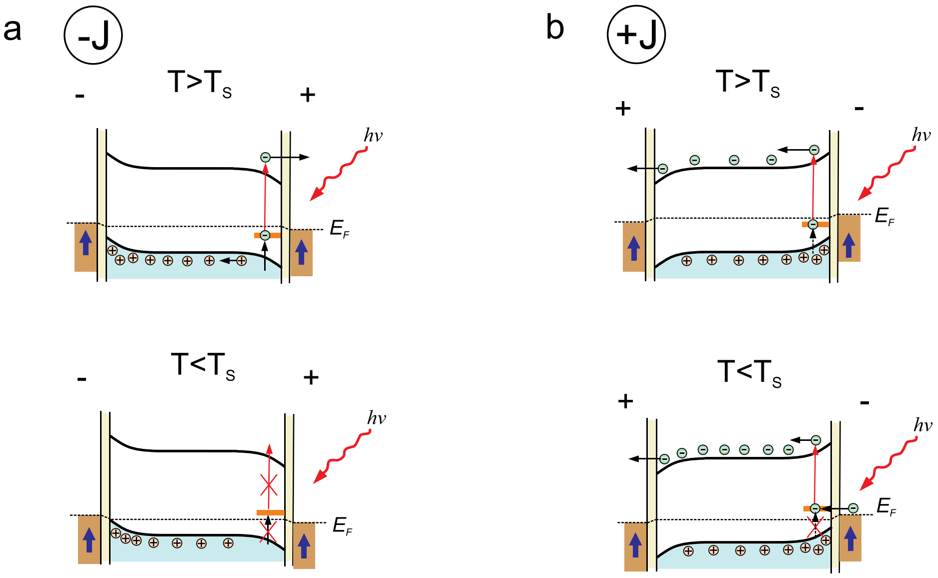


FIG. 2. Schematic diagram of principal carrier transport processes under optical irradiation in the back-to-back Fe/SiO_2/p-Si diode device. Illuminated MIS junction is under (a) reverse and (b) forward bias.

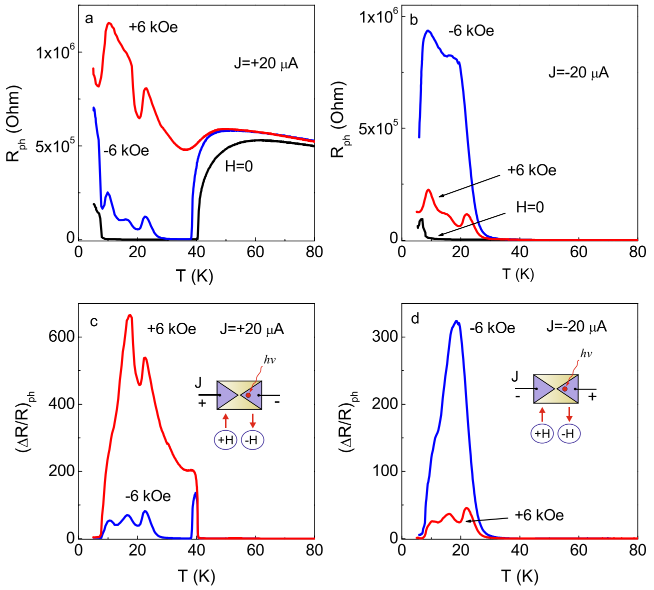


FIG. 3. Temperature dependences of the resistance under optical radiation R_{ph} at bias current of $+20$ μA (a) and -20 μA (b) for zero magnetic field, positive and negative fields of $+6$ kOe and -6 kOe. Appropriate temperature dependences of the magnetoresistance $(\Delta R/R)_{ph}$ measured at positive (c) and negative (d) bias current.

one can observe low photoconductivity. One might expect that at lower temperatures, the interface energy states should appear above the E_F and capture the holes, which would completely stop their participation in the optical transitions. Then one would observe even in stronger increase of the resistivity below T_S. However, experiments reveal that the resistance quickly drops at $T < 50\,\mathrm{K}$. To explain this experimental result, we have to assume that there appears an additional effective channel for the electrons (that tunnel from the metal electrode) capture by positively charged centers. This occurs when Fermi level in metal aligns with the interface state levels. We believe that the increase of the structure photo-conductivity is due to the two-step process of, first, tunneling the electrons (or their thermal generation from the valence band) onto the interface states and, second, their light-assisted optical excitation to the conduction band.

Of cause, the model we present here is only qualitative and ignores many details of the resistivity change (due to illumination) of the explored device. Nevertheless, it is entirely consistent with the conclusions regarding the nature of the interface states obtained recently from the measurements data of the impedance of the Fe/SiO$_2$/p-Si structure.[17] One should notice that the resistance behavior of the illuminated sample at low temperatures reflects the behavior of the density of interface states distribution function, which explains the non-monotonous behavior of $R_{ph}(T)$. It is also obvious that within our model one should observe the dependence of the photo-conductivity upon the magnitude of J because bias current changes the alignment between the Fermi level and the interface energy levels. Indeed, as we will see further, changing the bias current J strongly affects both the character of the photoconductivity and the photo-induced MR effect, which is the primary subject of our investigation.

Shown in Fig. 3 are low temperature dependences of $R_{ph}(T)$ obtained under the optical irradiation both with the magnetic field off and on set at $H = \pm 6$ kOe. Also shown are corresponding dependences of photoinduced MR $(\Delta R/R)_{ph} = \lfloor R_{ph}(H) - R_{ph}(0) \rfloor / R_{ph}(H)$ on temperature (with $R_{ph}(0)$ and $R_{ph}(H)$ the resistances under optical irradiation at zero and applied field, respectively). Results are obtained for $J = +20$ μA (Figs. 3(a) and 3(b)) and $J = -20$ μA (Figs. 3(c) and 3(d)) because it is these values of the bias current that yield the maximum effect of the magnetic field on the resistance behavior. Looking at these results we, first, notice the giant photo-induced MR effect. When placed in magnetic field of $H = 6$ kOe the MR $(\Delta R/R)_{ph}$ it measures up to a few tens of thousands percent. And we also find that in the absence of illumination this MR effect completely vanishes. Second surprising result is extremely high sensitivity of this photo-induced MR effect to the polarity of magnetic field. Here, the field is applied in the plane of device and orthogonal to current J.

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. 4(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.[19] When the light is turned on 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 discussed above. The voltage increase at certain values of J is related 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. Obviously, this saturation current value depends on the

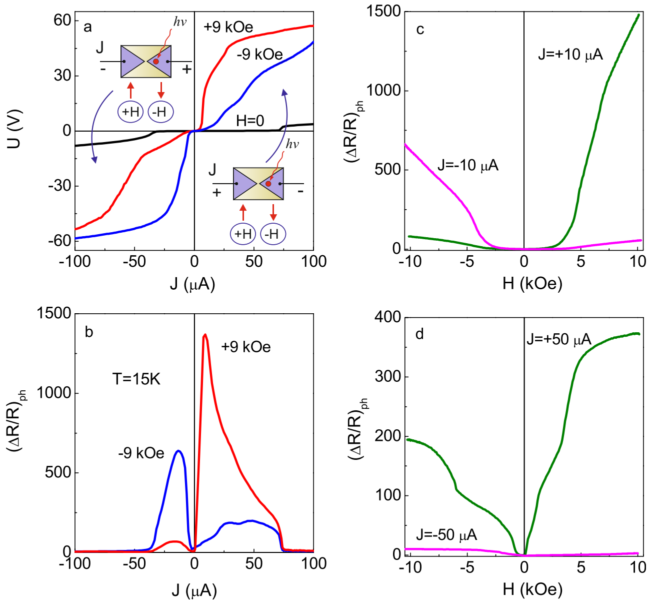


FIG. 4. (a) Voltage-current characteristic of the device measured under optical irradiation for zero magnetic field, positive and negative fields of $+9$ kOe and -9 kOe. (b) Appropriate plots of the magnetoresistance $(\Delta R/R)_{ph}$ vs bias current for positive and negative magnetic fields. $(\Delta R/R)_{ph}$ as a function of magnetic field for positive and negative bias currents of $+10$ μA and -10 μA (c), $+50$ μA and -50 μA (d).

optical illumination power P_{opt}. Indeed, the measurements show (to be published later) that with the increase of P_{opt} the feature of interest shifts to a higher current J. Starting from small values of the current, the applied magnetic field of any polarity (though to a different extent), result in more rapid growth of U. Thus, positive magneto-resistance appears for all values of J regardless of its sign (see Fig. 4(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.

Figures 4(c) and 4(d) show dependence of $(\Delta R/R)_{ph}$ versus H for high ($J = \pm 50\ \mu$A) and low ($J = \pm 10\ \mu$A) values of bias current. Again, we notice the asymmetry of the MR effect with respect to both the bias current sign and the magnetic field sign. Here, the surprising fact is totally different behavior of $(\Delta R/R)_{ph}$ for small and large bias currents J. For $J = \pm 10\ \mu$A sweeping the magnetic field we see gradual slow growth of $(\Delta R/R)_{ph}$ for low field H and rapid growth above 3 kOe. For $J = +10\ \mu$A and $H = 10$ kOe $(\Delta R/R)_{ph}$ reaches 1.5×10^5 % and there is no saturation. Contrary to that for $J = \pm 50\ \mu$A a rapid growth of $(\Delta R/R)_{ph}$ starts immediately from $H = 0$ then at $H = 5 - 7$ kOe the growth slows down and then the MR effect saturates at higher field. The maximum value of $(\Delta R/R)_{ph}$ in this case is less than 4×10^4 %.

Measurements were also carried out in geometry with current and magnetic field vectors pointing in the same direction. In this case, the character of discussed above dependences in magnetic field slightly changes, but the asymmetry with respect to the sign of J and H still remains.

In the literature there are few works dedicated to investigation of the influence of the optical radiation on the magnetoresistive properties of the magnetic nanostructures. The influence of light on the magnetoresistance was discovered in magnetic tunneling structure $La_{0.7}Sr_{0.3}MnO_3$/depleted manganite layer/MnSi.[21] The effect is attributed to the photon generated electron-hole pair in (interband transition) in dielectric layer. For the hybrid structure $La_{2/3}Ca_{1/3}MnO_3$/n-Si the increase of MR is found (from 0.54% to 18%) when exposed to optical radiation.[22] It is suggested that radiation generates photocarriers in both $La_{2/3}Ca_{1/3}MnO_3$ manganite and Si, which influences the tunneling current and also on the spin-polarized current from the manganite electrode side.

In our case, we see that photo-response of the explored device to the external magnetic field variation is rather complex and depends on many parameters. We do not exclude the possibility that several mechanisms are present concurrently and they contribute differently under the illumination of the MIS junction, being forward or reverse biased. Nevertheless, we try to analyze possible scenarios of change of transport properties due to simultaneous action of optical and magnetic fields. Taking into account, our photoconductivity model and analyzing the influence of magnetic field, it is natural to propose that the key role in the optically induced MR effect is played by localized interface states.

First, let us consider the case of negative bias current $-J$ (irradiated MIS junction is reverse biased Fig. 2(a)). The appearance of the positive magnetoresistance may be understood if one suggests that magnetic field shifts the energy levels up. Indeed, at certain temperature, the Fermi-level approaches the energy levels of the interface states. As long as they are below E_F, they participate in optical transitions and photo-electrons provide high conductivity through the MIS device. Due to the energy shift in magnetic field, the interface state levels emerge higher than Fermi level E_F and capture the holes, thereby, falling out of the photoelectrons generation process (Fig. 5(a)). Then the conductivity of the junction and the whole device decreases (R_{ph} increases).

Relative position of E_F with respect to the interface state levels depends also on the bias voltage across the junction. The transport properties measurements are carried out with stabilized current fed into illuminated MIS junction. The question of redistribution of potentials in the device by changing the bias current in this case appears non-trivial. We suppose that the current increase shifts the interface state levels up with respect to Fermi level E_F. This is possible because the photocurrent increase through the junction must result in equalization of potentials of semiconductor bulk and the metal electrode. Therefore, one should expect that by lowering T the growth of H and J would accompany each other. And, indeed, the experiments show that. First of all given small shifts one has to provide strong magnetic field in order to cross the localized states with E_F and have them fell out of the "game." On the contrary, at large bias, some of the levels already reside above E_F while the rest start crossing E_F starting from small H. This is confirmed by Figs. 4(c) and 4(d). At small bias current J, the rapid growth of the relative

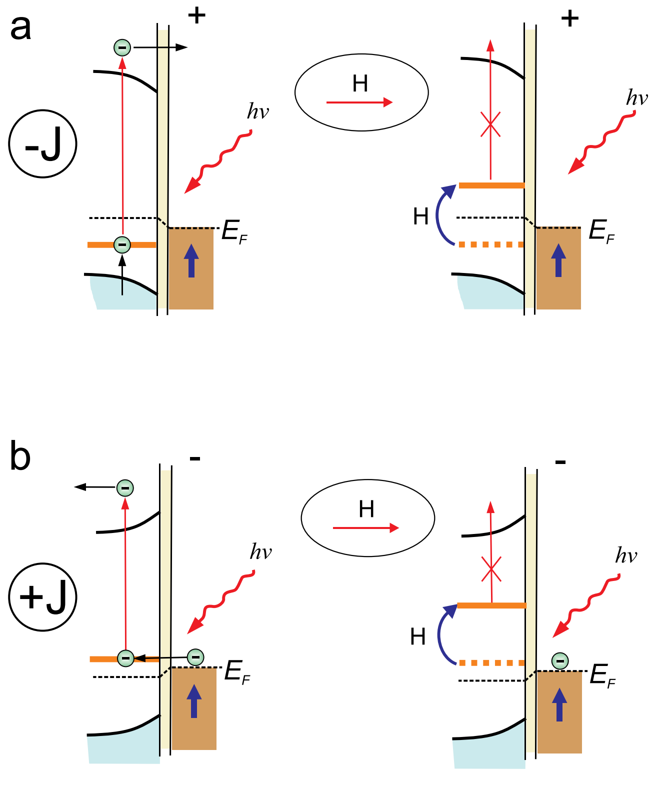


FIG. 5. Schematic energy-band diagrams of the MIS junction including the interface states, which demonstrates the change of the photocurrent as a result of shifting the interface state levels in magnetic field; irradiated MIS junction is at reverse (a) and forward bias (b).

resistance $(\Delta R/R)_{ph}$ starts in strong field only, while at large bias current, it appears much earlier, practically at zero magnetic field. The maximum value of the relative resistance change in magnetic field $(\Delta R/R)_{ph}$ in the last case is smaller, as expected. The temperature dependence of resistance R_{ph} is also consistent with the model, in particular, at zero field. The R_{ph}-growth (at low temperature) corresponds to the moment when the interface centers energy levels begin crossing the Fermi level. When decreasing the temperature, this effect starts to appear earlier in case of higher bias current (Fig. 1(d)) than in case of small bias current (Fig. 3(c)).

Now let us turn to the situation when the irradiated MIS transition is located on the forward region of the $J - V$ characteristic $(+J)$. Schematic diagram of the principal carrier transport process in this case is shown in Fig. 2(b). The shifts of the interface centers levels to higher energy in magnetic field, as in the previous case, allow one to explain the appearance of positive values of $(\Delta R/R)_{ph}$. Low resistance of device at low temperatures (under illumination) is realized by turning on the tunneling channel between the interface states and the electrode metal when all of them align with respect to the metal Fermi-level. Magnetic field shifts the levels higher than E_F in metal so that they turn off from the tunneling process and, thereby, turn off from the process of the photo-electrons generation (Fig. 5(b)). Thus, the device conductivity decreases in magnetic field (R_{ph} increases).

As for the dependence on the bias current, the experimental data indicate that the current increase again causes upward shift of the localized interface states energy relative to E_F, as it should be the case when increasing the negative voltage bias (negative potential at the metal electrode) across the junction.

We remind that the phenomenon of the giant magneto-impedance found in the same back-to-back Fe/SiO_2/p-Si diode device may also be explained within the mechanism, which assumes the localized states energies up-shift with respect to the valence band edge in magnetic field.[17] Moreover, the up-shift of the energy levels of impurities in magnetic field had been also observed earlier in doped semiconductors, for example, in p-type Si[7] and n^--type GaAs.[23] Possible causes of such behavior had been discussed and the following models proposed: (1) shrinkage of the impurity center wave function caused by magnetic field; (2) splitting of the impurity band into lower and higher sub-bands. The first case corresponds to the change in the overlap of the impurity-bound electronic wave function in the semiconductor bulk, which influences the conductivity through the impurities states. The second case is related to formation of the impurities bands. We believe that in our experiment we are facing completely different situation, namely, the conductivity mechanism includes only the interface states at the SiO_2/p-Si boundary.

From the impedance spectroscopy data, we found that the magnetic field of 10 kOe must shift the interface energy levels by at least 20 meV. This is a large value in comparison with, say, Zeeman splitting, which for $S = 1/2$ and field of 10 kOe is only 0.1 meV. What kind of mechanism may account for such large shift of electronic interface states energy? It is not very clear at this point. One possible explanation may be that the interface states energy levels split due to exchange interaction with d-electrons in the FM electrode close to the interface[24] or/and exchange interaction with localized magnetic centers in the SiO_2. In general, appearance of ferromagnetic centers in the oxide (SiO_2) is expected when processing the FM/SiO_2/Si MIS structures with 3d FM metals.[25] The external field action, in this case, may cause magnetization of FM or polarization of localized magnetic centers. And the effective exchange interaction with the interface states may be either ferromagnetic or antiferromagnetic, the latter being more relevant to our situation. One can draw certain analogy with the effect of giant Zeeman splitting in semiconductors with magnetic impurities,[26] with only difference that that case corresponds to the spin-splitting of the conduction band electrons while ours is for the localized electronic states. Let us estimate some typical values of related parameters. For the solid solution of magnetic ions (Mn) in $Cd_{0.9}Mn_{0.1}Te$ if one sets the polarization (in external magnetic field) of Mn-system to be 10% of total population then Zeeman splitting will be about 10 meV, which is comparable to what is observed in our case.

Of cause, we should not rule out possible contribution of the spin-dependent tunneling through the SiO_2 potential barrier into the FM electrode of photo-excited electrons. This process is defined by the spin polarization of the photoelectrons and the details of the spin split density of states (DOS) in the FM. The spin polarization of the photoelectrons can be controlled by external field, exchange interaction with magnetic impurity centers and circularly polarized light. With regards to the optical phenomena revealed in our experiments, we do not find noticeable effects of incident light polarization (linear, left or right circular), so we cannot claim optical polarization of conduction electrons. Exchange interaction with d-electrons of the FM electrode or with magnetic centers may result in large spin-splitting of electron sublevels in conduction band and, hence, may create high spin polarization. Thus, the contribution to the MR from the spin dependent tunneling current between the semiconductor and FM electrode may be substantial.

It is obvious that models mentioned above cannot explain the strong sensitivity of the photo-induced MR effect to the sign of magnetic field. One needs to consider some additional mechanism of the field influence on the electron transport. And here there are not many possibilities that we could think of. First of all, additional contribution to the MR effect can come from Lorentz forces acting on energetic carriers.[27] When carrier moves in a magnetic field, it experiences a force that deflects it in a specific direction. This direction depends on the direction of H and the direction of motion. In our case, at $+J$ the photoelectrons move from one MIS junction to another along SiO_2/p-Si interface of the device. Magnetic field of different polarity deflects electron trajectories either towards the interface or into the bulk of semiconductor. Due to different recombination rates of the photoelectrons near interface and in semiconductor bulk, the photocurrent value will be different for positive and negative polarity of magnetic field (see Fig. 6). At negative bias current $(-J)$ according to our model holes move along the SiO_2/p-Si interface (in the same direction as electrons move

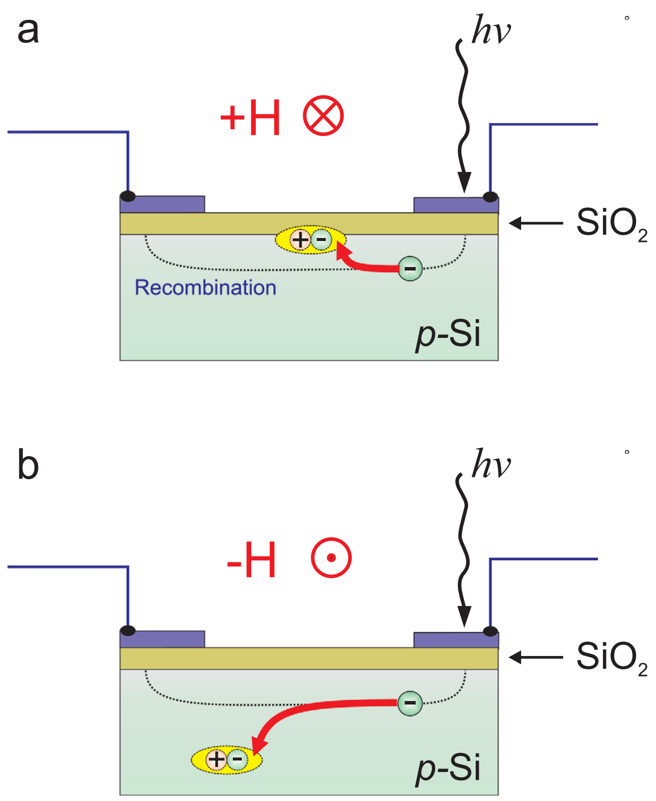


FIG. 6. Schematic illustration of carrier transport processes in the device with allowance of the Lorentz force at positive (a) and negative (b) magnetic field.

when the bias current is positive) and, hence, their contribution to the MR will have the opposite sign. It is this behavior that we observe in our experiment (see Fig. 4).

The explanation just provided seems quite reasonable but several questions remain. For instance, why would the influence of the magnetic field (dependence on the sign of magnetic field) show up only at $T < 40\,\mathrm{K}$ while, at the same time, the electron (at positive bias current $+J$) and hole (at negative bias current $-J$) current along the SiO$_2$/p-Si interface would flow even at higher temperatures?

This implies one needs an alternative explanation for the MR dependence on the applied field sign, which is more sophisticated and takes into account the carriers spin degree of freedom. Here we are talking about the Rashba spin splitting effect,[28] which has been recently shown to play significant role at the interfaces between Si and some materials.[29,30] Lifting the spin degeneracy via the Rashba effect occurs when moving electron experiences the electrostatic potential gradient. In our case, the electric field appears at the space charge region in semiconductor near the boundary with SiO$_2$. Interface states may be the source of the electric field as well. Roughly speaking, one may think of a process in which (due to Rashba spin-orbital coupling at the semiconductor/dielectric interface) the number of electrons with spin facing one direction increases and the spin current flows. Curiously this happens in the absence of external magnetic field and the influence of the field on MR effect is due to remagnetization of FM electrodes, which play the role of spin injector and detector. Dependence upon the sign of magnetic field is believed to be due to the asymmetry of electrons motion with different polarization direction injected into the semiconductor. Certainly, in order to see the MR mechanism based on Rashba splitting, one needs to run more tests and satisfy many requirements.[31] Therefore, here, we only point out at mere possibility of such mechanism taking place while detailed discussion of its possible contribution to the photo-induced MR effect in the circuit with back-to-back Schottky diodes is beyond the scope of this report. In conclusion, we also would like to note that other than the mechanisms related to the Lorentz force and Rashba spin-orbital coupling we do not see any other explanations of the dependence of the magneto-transport properties of our structure (or another magnetic or non-magnetic structure) under investigation upon the magnetic field polarity.

IV. CONCLUSION

We demonstrated 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. To explain these effects, we considered several possible physical mechanisms. The main contribution to MR is believed to be due to the presence of localized interface states near or at the SiO$_2$/p-Si interface. These states participate in the optical transitions and in the recharging processes involving both the carriers' excitations from the valence band and the tunneling from the FM electrode. The effect of magnetic field is due to the interface states energy shift with respect to the Fermi level. The physical mechanism behind the change of the energy structure of the interface centers in magnetic field was attributed to the spin-splitting. The magnitude of the spin-splitting exceeds typical value of the Zeeman splitting, which we suggest is due to the exchange interaction between the interface centers and the ferromagnetic electrode or magnetic centers in the dielectric layer. Observed dependence of the MR effect on polarity of magnetic field may be explained by one of two possible mechanisms taking into account either charge or spin degree of freedom of carriers: (1) change of the charge carriers trajectory in the magnetic field due to the Lorentz force; (2) electron spin-splitting when moving in the electrostatic potential gradient due to Rashba effect. More importantly, for the first time, we observed the MR effect in the hybrid structure, which is determined by behavior of subsystem of minority carriers in semiconductor under non-equilibrium state created by optical pumping. We suggest that hybrid devices exercising such working principle may provide a new concept of operation of the semiconductor based spintronic devices.

ACKNOWLEDGMENTS

This study was supported by the Russian Foundation for Basic Research, Project No. 11-02-00367-a; Presidium of the Russian Academy of Sciences, program Quantum Mesoscopic and Disordered Structures, Project No. 20.8; the Division of Physical Sciences of the Russian Academy of Sciences, program Spin Phenomena in Solids Nanostructures and Spintronics, Project No. II.4.3; the Siberian Branch of the Russian Academy of Sciences, integration projects nos. 43, 85 and 102; Project of the Russian Ministry of Education and Science N 02.G25.31.0043.

[1] J. Fabian, A. Matos-Abiague, C. Ertler, P. Stano, and I. Žutić, Acta Phys. Slov. **57**, 565 (2007).

[2] I. Zutic, J. Fabian, and S. Das Sarma, Rev. Mod. Phys. **76**, 323 (2004).

[3] O. M. J. van't Erve, A. T. Hanbicki, M. Holub, C. H. Li, C. Awo-Affouda, P. E. Thompson, and B. T. Jonker, Appl. Phys. Lett. **91**, 212109 (2007).

[4] I. Appelbaum, B. Huang, and D. J. Monsma, Nature (London) **447**, 295 (2007).

[5] S. P. Dash, S. Sharma, R. S. Patel, M. P. de Jong, and R. Jansen, Nature (London) **462**, 491 (2009).

[6] S. Datta and B. Das, Appl. Phys. Lett. **56**, 665 (1990).

[7] J. J. H. M. Schoonus, F. L. Bloom, W. Wagemans, H. J. M. Swagten, and B. Koopmans, Phys. Rev. Lett. **100**, 127202 (2008).

[8] H.-J. Jan and I. Appelbaum, Appl. Phys. Lett. **97**, 182108 (2010).

[9] S. J. Steinmuller, C. M. Gürtler, G. Wastlbauer, and J. A. C. Bland, Phys. Rev. B **72**, 045301 (2005).

[10] H. Kurebayashi, S. J. Steinmuller, J. B. Laloë, T. Trypiniotis, S. Easton, A. Ionescu, J. R. Yates, and J. A. C. Bland, Appl. Phys. Lett. **91**, 102114 (2007).

[11] J. Watzel, A. S. Moskalenko, and J. Berakdar, Appl. Phys. Lett. **99**, 192101 (2011).

[12] R. Jansen, Nature Mater. **11**, 400 (2012).

[13] Y. Ando, K. Hamaya, K. Kasahara, Y. Kishi, K. Ueda, K. Sawano, T. Sadoh, and M. Miyao, Appl. Phys. Lett. **94**, 182105 (2009).

[14] S. E. Andresen, S. J. Steinmuller, A. Ionescu, G. Wastlbauer, C. M. Guertler, and J. A. C. Bland, Phys. Rev. B **68**, 073303 (2003).

[15] S. A. Crooker, M. Furis, X. Lou, P. A. Crowell, D. L. Smith, C. Adelmann, and C. J. Palmstrøm, J. Appl. Phys. **101**, 081716 (2007).

[16] M. Tran, H. Jaffres, C. Deranlot, J.-M. George, A. Fert, A. Miard, and A. Lemaitre, Phys. Rev. Lett. **102**, 036601 (2009).

[17] R. Jansen, A. M. Deac, H. Saito, and S. Yuasa, "Injection and detection of spin in a semiconductor by tunneling via interface states," http://arxiv.org/abs/1203.4034 (preprint).

[18] N. V. Volkov, A. S. Tarasov, E. V. Eremin, A. V. Eremin, S. N. Varnakov, and S. G. Ovchinnikov, J. Appl. Phys. **112**, 123906 (2012).

[19] N. V. Volkov, A. S. Tarasov, E. V. Eremin, S. N. Varnakov, S. G. Ovchinnikov, and S. M. Zharkov, J. Appl. Phys. **109**, 123924 (2011).

[20] M. A. Green, F. D. King, and J. Shewchun, Solid-State Electron. **17**, 551 (1974).

[21] N. V. Volkov, C. G. Lee, P. D. Kim, E. V. Eremin, and G. S. Patrin, J. Phys. D: Appl. Phys. **42**, 205009 (2009).

[22] Z. J. Yue, K. Zhao, H. Ni, S. Q. Zhao, Y. C. Kong, H. K. Wong, and A. J. Wang, J. Phys. D: Appl. Phys. **44**, 095103 (2011).

[23] T. W. Hickmott, Phys. Rev. B **46**, 12342 (1992).

[24] L. V. Lutsev, A. I. Stognij, and N. N. Novitskii, Phys. Rev. B **80**, 184423 (2009).

[25] M. Kanoun, R. Benabderrahmane, C. Duluard, C. Baraduc, N. Bruyant, A. Bsiesy, and H. Achard, Appl. Phys. Lett. **90**, 192508 (2007).

[26] J. Cibert and D. Scalbert, "Diluted Magnetic Semiconductors: Basic Physics and Optical Properties," in *Spin Physics in Semiconductors, Springer Series in Solid-State Sciences*, edited by M. I. Dyakonov (Springer-Verlag Berlin Heidelberg 2008), p. 157.

[27] S. Joo, T. Kim, S. H. Shin, J. Y. Lim, J. Hong, J. D. Song, J. Chang, H.-W. Lee, K. Rhie, S. H. Han, K.-H. Shin, and M. Johnson, Nature **494**, 72–76 (2013).

[28] Y. A. Bychkov and E. I. Rashba, JETP Lett. **39**, 78 (1984).

[29] A. Takayama, T. Sato, S. Souma, T. Oguchi, and T. Takahashi, Nano Lett. **12**, 1776 (2012).

[30] I. Gierz, T. Suzuki, E. Frantzeskakis, S. Pons, S. Ostanin, A. Ernst, J. Henk, M. Grioni, K. Kern, and C. R. Ast, Phys. Rev. Lett. **103**, 046803 (2009).

[31] R. Winkler, *Spin–Orbit Coupling Effects in Two-Dimensional Electron and Hole Systems*, No. 191 in Springer Tracts in Modern Physics (Springer, Berlin, 2003).