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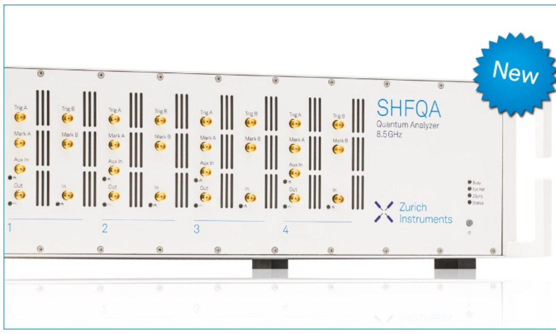

Magnetic-field- and bias-sensitive conductivity of a hybrid $Fe/SiO_2/p$-Si structure in planar geometry

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Pronounced magnetic-field- and bias-sensitive features of the transport properties of a $Fe/SiO_2/p$-Si hybrid structure in planar geometry at temperature variation are investigated. Comparative analysis of two $Fe/SiO_2/p$-Si samples, one with a continuous Fe film and the other with two electrodes formed from a Fe layer and separated by a micron gap, shows that these features are due to the metal-insulator-semiconductor (MIS) transition with a Schottky barrier near the interface between SiO_2 and *p*-Si. Resistance of such a MIS transition depends exponentially on temperature and bias. In the structure with a continuous ferromagnetic film, the competition between conductivities of the MIS transition and the Fe layer results in the effect of current channel switching between the Fe layer and a semiconductor substrate. Within certain limits, this process can be controlled by a bias current and a magnetic field. Positive magnetoresistance of the structures at high temperatures is determined, most likely, by disorder-induced weak localization. In the structure with the gap, negative magnetoresistance is observed at certain temperature and bias. Its occurrence should be attributed to an inversion layer formed in the semiconductor near the SiO_2/p-Si interface when MIS transition is in the inversion regime.
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I. INTRODUCTION

Study of the spin-polarized electron transport in hybrid multilayer nanostructures consisting of magnetic elements and nonmagnetic semiconductor layers[1] is an attractive and promising direction in spintronics. Such structures combine a huge potential of conventional semiconductor electronics and advantages of magnetic materials, whose transport properties can be controlled via spin states of electrons. In particular, it becomes possible to store, treat, and transfer information in one electron chip. The most interesting for both fundamental research and application are the silicon-based hybrid structures, which is no surprise, as the nearly perfect current silicon technology gives grounds for the development of elements with functionality broadened due to the use of spin degrees of freedom. Moreover, silicon is suitable for implementation of the coherent spin transport due to its enhanced spin lifetime and diffusion length. These properties are determined by low spin-orbit scattering and lattice inversion symmetry.[2–4]

At the same time, a great number of questions, both fundamental and technological, that concern the spin-dependent effects in the hybrid structures remain unanswered. These are injection of a spin-polarized current from a ferromagnetic (FM) metal to a semiconductor, detection of the spin transport in the structures, relaxation of the spin state in a semiconductor, and the effect of external factors, such as magnetic and electric fields and microwave and optical radiation, on the spin-dependent effects. The latter is of importance in searching for effective ways of controlling the spin-polarized transport.

We would like to emphasize two characteristic points regarding the silicon hybrid structures. First, the silicon semiconductor electronics is based on planar technology that imposes stringent requirements on the hybrid silicon structures; specifically, they must be compatible with this technology and based on the lateral transport. The second point concerns fundamental problems of injection/extraction of the spin-polarized current into/from a semiconductor. Seemingly, these problems can be solved by forming a ferromagnet/semiconductor interface whose resistance depends on spin polarization of an electron current.[5] The simplest way is to form tunnel junctions at this interface. Possibility of spin injection/detection via the tunnel contacts has been demonstrated recently.[6,7]

In view of the aforesaid, it is no surprise that the magnetic tunnel structures and hybrid structures with the tunnel junctions in current-in-plane (CIP) geometry, when a current flows along the interfaces, has attracted attention of researches. In this geometry, new physical phenomena involving electron spin are observed. For a $La_{0.7}Sr_{0.3}MnO_3$/depleted manganite layer/MnSi structure, current channel switching between conducting layers separated by a potential barrier was revealed.[8–10] The effect is controlled by a bias current, a magnetic field, and optical radiation. Since the conducting layers exhibit drastically different transport characteristics, the observed switching effect reflects in a nonlinear current-voltage characteristic and a bias-driven positive magnetoresistance attaining 400% in fields of no more than 500 Oe. Concerning the FM metal/insulator/Si tunnel hybrid structures, it was found that in very thin metal films on silicon substrates resistance of some structures

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experiences a sharp transition at 250–270 K, that has been attributed to current switching between the film and the silicon substrate separated by a SiO_2 potential barrier.[11] Channel switching can be controlled by temperature[12] and bias[13] variations. However, the established fact was not discussed. There is no agreement on whether the current flows via a semiconductor substrate volume or within a thin depleted layer at the interface between silicon and silicon oxide. Unanswered remains the question about the origin of the magnetoresistive effect in the FM metal/SiO_2/Si structures; it is still unclear whether it is related to injection of spin-polarized electrons in the silicon substrate.

In this study, we report the results of CIP-geometry investigations of two types of the Fe/SiO_2/p-Si structure. In the first case, an iron film was continuous; in the second case, two electrodes separated by a micron gap were formed from this film. The transport and magnetotransport properties of both structures were studied in planar geometry. The aim of the study was to clarify the mechanisms responsible for the features of the transport and magnetotransport properties of the FM metal/insulator/semiconductor hybrid structures.

II. EXPERIMENTAL

The structures Fe/SiO_2/p-Si were fabricated as follows. As a substrate, a *p*-doped silicon wafer *p*-Si(100) with a resistivity of 5 Ω·cm (a doping density of 2×10^{15} cm^{-3}) was used. The substrate's surface was precleaned by chemical etching and prolonged annealing at temperatures of 400–650 °C. This yielded an atomically clean silicon surface; the process was controlled by high energy electron backscattered diffraction. Next, the substrate was exposed in aqueous solution of H_2O_2 and NH_4OH (in the ratio 1:1:1) at 60 °C for 30 min. During the exposure, a SiO_2 layer with a thickness of ~2 nm was formed at the substrate's surface. The thickness was controlled by spectral ellipsometry.

Iron thin films were deposited at room temperature by thermal evaporation. A background vacuum of 6.5×10^{-8} Torr was used and the sputtering rate was 0.25 nm/min. Thickness of the Fe layer was controlled *in situ* with an LEF-751 high-speed laser ellipsometer. We obtained the structures with Fe film thicknesses of 5, 8, and 12 nm. The main experimental results will be presented for the samples with 5-nm-thick iron, because the effects of interest are the most pronounced in this case.

Quality of the films was controlled by force microscopy and transmission electron microscopy. Atomic force images of the structure surface were taken before and after deposition of the Fe film. Roughness analysis shows that the mean surface roughness of a silicon wafer with the only native SiO_2 layer is 0.12 nm; the roughness value for the surface of the Fe film deposited over the SiO_2 layer is 0.58 nm. As we will show below, in our experiments the main processes are determined by the Fe/SiO_2/p-Si tunnel junction; therefore, the most important are the parameters determining quality of the Fe/SiO_2 and SiO_2/p-Si interfaces. Figure 1(a) presents a TEM cross section micrograph. One can see that where the structural composition includes the single-crystal silicon substrate, the amorphous SiO_2 layer, and the polycrystalline Fe film.

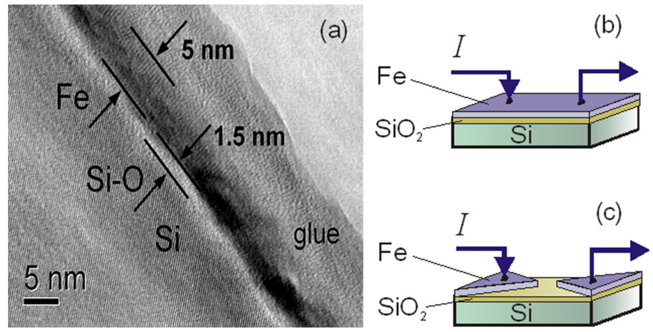

FIG. 1. (Color online) (a) The TEM cross section micrograph of the Fe/SiO_2/p-Si structure. Schematic illustration of the experimental geometry used for transport measurement of the «continues-film structure» (b) and «gap-film structure» (c).

To investigate the transport properties of the samples in CIP geometry, rectangles with typical dimensions of 3×8 mm^2 were cut out from the structure. Two samples were studied. The first sample, hereinafter referred to as the continuous-film structure, contained a continuous ferromagnetic film. On the top of the structure, i. e., on the Fe film, Ohmic contacts were formed using two-component silver epoxy. The spacing between the contacts was 4 mm. The experimental geometry is illustrated in Fig. 1(b). The second sample was a simplest lateral device fabricated from the structure. On the structure's surface, two electrodes separated by a gap of 20 μm were formed from a continuous iron film [Fig. 1(c)]. Below, we will call this sample the gap-film structure. The desired topology of the electrodes was formed with a coordinatograph of original design using the wet-etching method.

The transport properties of the samples were studied with a Physical Property Measurement System (PPMS-9, Quantum Design) and 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 and current-voltage characteristics were taken in a current scanning regime. A magnetic field was applied either in the plane or along the normal to the structures. The magnetic properties were studied using an MPMS-5 SQUID magnetometer (Quantum Design).

III. RESULTS

Initially, the aim of the comparative analysis of the samples (the continuous-film and gap-film structures) was to clarify the mechanisms of current channel switching and the origin of the magnetoresistive effect in the hybrid structures in CIP geometry. Here, of fundamental importance is that in the continuous-film structure the switching effect should be determined by the competition of the transport properties of the ferromagnetic film and the Fe/SiO_2/p-Si tunnel junction upon temperature variation, whereas in the gap-film structure, independent of temperature, the current path near the gap is forced to go from the ferromagnetic film through the tunnel junctions to the volume of the semiconductor wafer or to the inverse layer near the SiO_2/p-Si interface.

The temperature dependences of resistance R for the continuous-film structure are shown in Fig. 2 (the Fe film thickness is 5 nm). The dependences were measured in zero magnetic field and in the field $H = 90$ kOe at the bias current $I = 1$ μA. The main feature in the resistance behavior is a sharp jump at 250–200 K. As the previous authors, we attribute this feature to switching a current channel between the semiconductor substrate and the iron film. At high temperatures ($T > 250$ K), $R$of the Fe/SiO_2/p-Si tunnel junction is lower than that of the ferromagnetic film and the current flows mainly in the semiconductor substrate. Below 250 K, R of the tunnel junction starts rapidly growing; at 200 K, the current path in the upper iron film becomes more favorable, since R of the iron film appears lower than that of the tunnel junction between the iron layer and the semiconductor wafer. The temperature range 250–200 K is a transition area. With increasing Fe layer thickness, the amplitude of the R variation rapidly decreases and so does R of the entire structure over the entire temperature range. It would be reasonable to attribute such a behavior simply to an increase in conductivity of the Fe film with increasing thickness of the latter. The current channel switching in the FM metal/insulator/semiconductor structure will be considered in more detail below. Regarding the influence of the magnetic field, the noticeable positive magnetoresistance $MR = [R(H) - R(0)]/R(0)$ is observed only at high temperatures ($T > 200$ K), i.e., before complete switching of the current channel to the upper film. Figure 3 shows the temperature dependence of MR. The MR value monotonically grows with decreasing temperature; however, below 250 K, when the current channel switching starts, MR rapidly decreases. In this temperature region, the dependence of MR on the bias current is determined by the fact that with increasing I the transition area where the current channel switching occurs is displaced toward higher temperatures (see the inset in Fig. 2).

The experimental results obtained for the gap-film structure is an additional argument for the scenario at which current channel switching occurs between the semiconductor

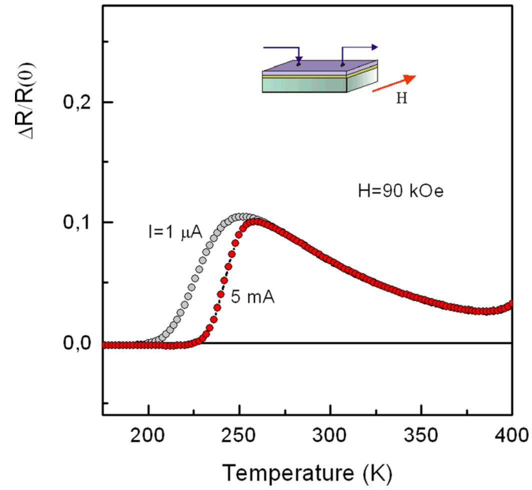

FIG. 3. (Color online) Magnetoresistance of the «continues-film structure» as a function of temperature at bias currents of $I = 1$ μA and $I = 5$ mA; magnetic field is $H = 90$ kOe.

substrate and the ferromagnetic film in the continuous-film structure. As one could expect, the behavior of resistance of the gap-film structure at $T > 250$ K repeats qualitatively that of the continuous-film structure (Fig. 4). However, below 250 K, R starts growing exponentially and, already at $T = 100$ K, attains the value of about 10^5 Ω, which implies the rapid growth of R of the Fe/SiO_2/p-Si tunnel junction. Similar to the case of the continuous-film structure, the region of the rapid R growth starts at increasingly higher temperatures, as the measuring current increases (see the inset in Fig. 4). The temperature dependence of MR of the gap-film structure repeats qualitatively the behavior of MR of the continuous-film structure, although exceeds the latter by a factor of more than two quantitatively (Fig. 5). With a decrease in temperature, the monotonic growth changes for the sharp drop of the MR value at the same temperatures where the sharp growth of R of the gap-film structure starts. This suggests that a decrease in MR of the continuous-film structure below

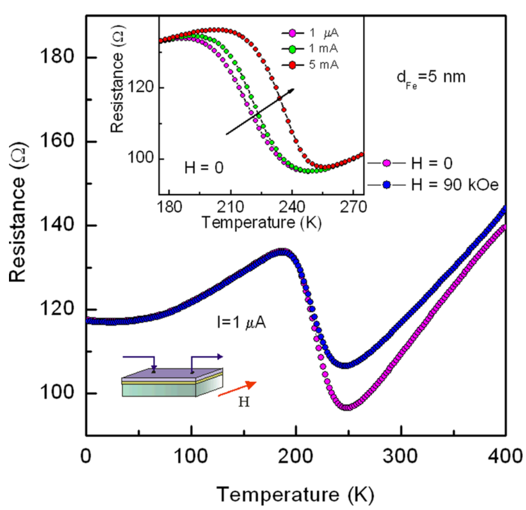

FIG. 2. (Color online) Temperature dependences of the resistance of the «continues-film structure» at magnetic field $H = 0$ and $H = 90$ kOe; bias current is $I = 1$ μA. The inset shows dependencies at various bias currents near transition region.

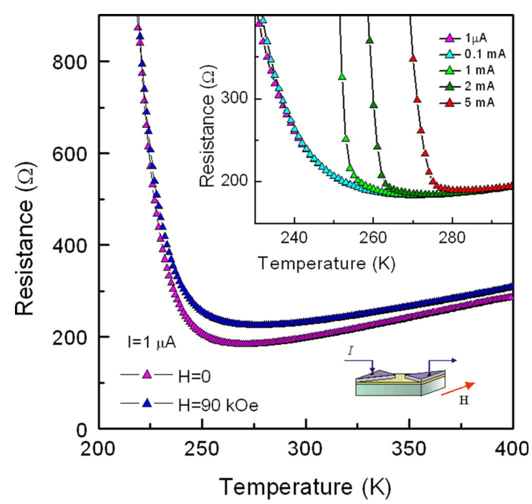

FIG. 4. (Color online) Temperature dependences of the resistance of the «gap-film structure» at magnetic field $H = 0$ and $H = 90$ kOe; bias current is $I = 1$ μA. The inset shows dependencies at various bias currents near temperature range related to rapid growth of the resistance.

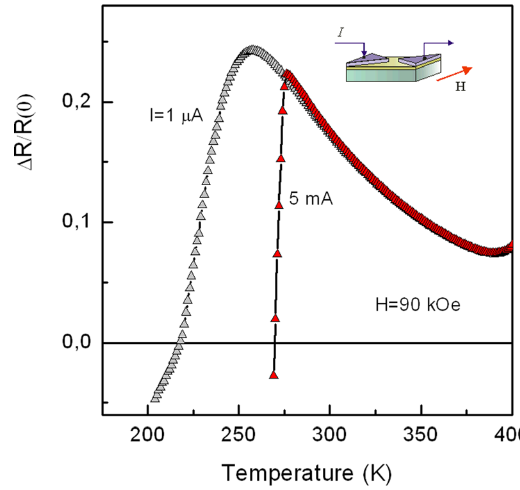

FIG. 5. (Color online) Magnetoresistance of the «gap-film structure» as a function of temperature at bias currents $I = 1$ μA and $I = 5$ mA; magnetic field is $H = 90$ kOe.

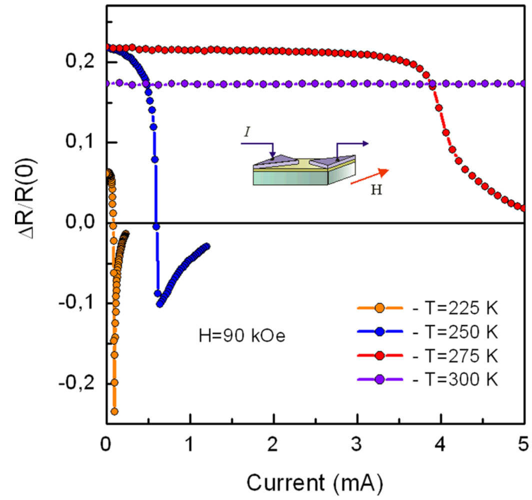

FIG. 7. (Color online) Magnetoresistance of the «gap-film structure» as a function of bias current measured at various temperatures and for magnetic field $H = 90$ kOe.

250 K is not that much related to current channel switching between the substrate and the upper film, but is determined by the mechanisms that cause the sharp growth of resistance of the Fe/SiO_2/*p*-Si tunnel junction. It is noteworthy that there is a region of negative *MR* at low temperatures, which was not observed for the continuous-film structure.

Study of the $I - V$ characteristics shows that they are linear for the continuous-film structure over the entire temperature range, except for the transition area 200–250 K, where current channel switching occurs. Even in this area, the $I - V$ characteristics deviate from linear dependences insignificantly. For the gap-film structure, the $I - V$ characteristics are fundamentally different. While at temperatures above 300 K they stay linear (for I up to 5 mA), at lower temperatures they have a kink (Fig. 6) typical of the systems with the current saturation. Although the $I - V$ characteristics show no complete saturation, they approach it with a decrease in temperature and the characteristic voltage at which the transition to the current saturation occurs (the kink in the dependences), also rapidly drops. The comparative analysis of the $I - V$ characteristics with and without magnetic field yielded the dependence of the magnetoresistive effect on the bias current. We got a surprising result (Fig. 7). In the initial (linear) portion of the $I - V$ characteristics, the *MR* value is nearly independent of I. Meanwhile, in the current region where the dependences transfer to the current saturation mode, the *MR* value starts rapidly decreasing. Moreover, while at high temperatures (the dependence at $T = 275$ K in Fig. 7) the *MR* simply approaches zero from the side of the positive values, at lower temperatures (the dependences at $T = 250$ and $T = 225$ K in Fig. 7) in the transition area the portion of negative magnetoresistive appears. This portion in the $MR(I)$ dependence represents a sharp peak, which becomes more intense and narrow with decreasing temperature. With increasing I, *MR*, having passed through the peak value, approaches zero, but from the side of the negative values this time. In any case, one may conclude that the *MR* value can be changed by choosing the I value and the transition of the gap-film structure to the current stabilization regime suppresses the magnetoresistive effect. Typical field dependences of R are given in Fig. 8. In the initial portion, positive *MR* at small I values grows following the quadratic dependence ($\sim H^2$); then, there is an inflection point, after which *MR* increases proportional to the square root of the magnetic field value ($\sim\sqrt{H}$). Note here that such a behavior remains up to 350 kOe. (We obtained the results using a facility equipped with a pulse magnetic field source). Negative *MR*, which is implemented at a certain I value, grows in its absolute value monotonically, almost linearly, with H. Comparing the field dependences of *MR* for the gap-film structure and the continuous-film structure, one can see that they have a similar character and differ only in value. Certainly, here we speak only about the positive magnetoresistive effect; for the continuous-film structure, there is no negative magnetoresistance portion.

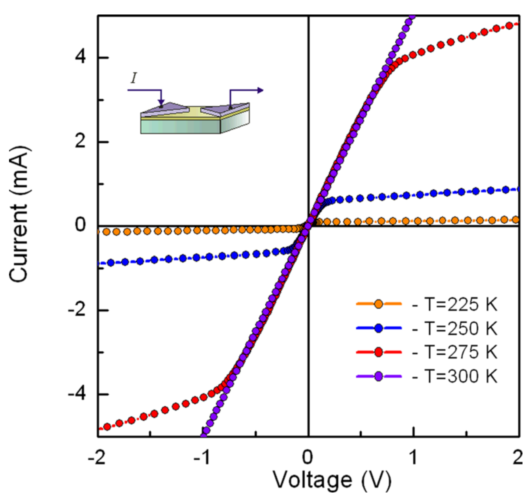

FIG. 6. (Color online) Current–voltage characteristic curves of the «gap-film structure» measured at various temperatures.

IV. DISCUSSION

The presented experimental data allow us to conclude that the observed features of the transport and magnetotransport

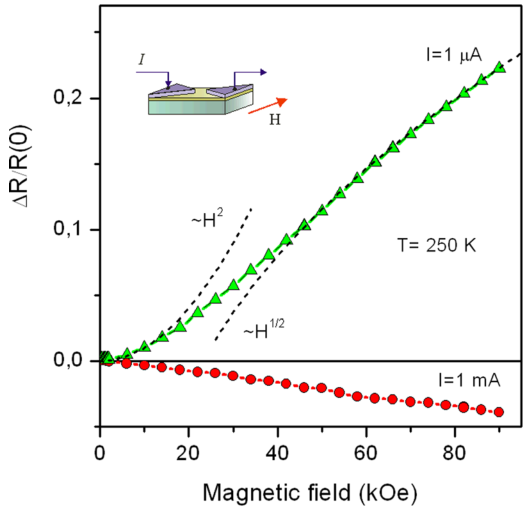

FIG. 8. (Color online) Field dependence of magnetoresistance of the «gap-film structure» at $T = 250$ K measured at bias currents $I = 1$ μA and $I = 1$ mA; dashed lines are approximations by dependencies following H^2 and $\sqrt{H}$.

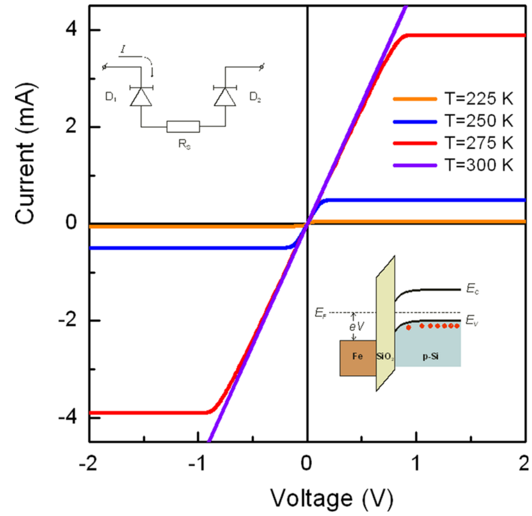

FIG. 9. (Color online) Current–voltage characteristic curves of the «gap-film structure» calculated in the framework of the equivalent scheme (see top inset) for various temperatures. Bottom inset: Energy band profile of the Fe/SiO_2/p-Si transition at reverse bias (positive voltage on metal).

properties of both continuous-film and gap-film structure are determined by the processes occurring upon current flowing via the Fe/SiO_2/*p*-Si tunnel junction. Such a junction is, in fact, a MIS diode, whose energy band diagram is well-known.[14] However, the specific type of this diagram and, of course, the $I-V$ characteristics of the junction depend on many factors, such as a semiconductor doping level, a width of the insulating layer, a barrier height at the metal/insulator interface, and the distribution of electron states. We are interested in the variation in the properties of the junction with temperature and bias current.

First, let us discuss the gap-film structure. The planar geometry in which we studied the transport properties suggests that the current path goes through the Fe/SiO_2/*p*-Si junction, then the *p*-Si semiconductor substrate volume and, finally, the *p*-Si/SiO_2/Fe junction. In terms of the equivalent circuits, the gap-film structure is two MIS diodes, D_1 and D_1, separated by resistance R_S and connected in series toward each other (see the top inset in Fig. 9). Thus, regardless of the bias current sign, the $I-V$ characteristic of the gap-film structure in CIP geometry will be determined by the type of the energy band diagram implemented at the reverse bias on the junction (positive voltage on the metal) or, in other words, by a back branch of the $I-V$ characteristic of the MIS diode. The bottom inset in Fig. 9 presents the schematic of the energy diagram of the MIS diode with the Fe film (the work function for Fe is $\chi = 4.7$ eV) at high reverse bias. It is important that, apart from the potential barrier formed by the insulating SiO_2 layer, at the SiO_2/*p*-Si interface the Schottky barrier is formed, whose properties change drastically upon bias variation. At small bias values, the majority carrier (hole) current is the main. With increasing reverse bias, the surface region of the semiconductor becomes depleted with the majority carriers. At a certain bias value, the inverse mode is implemented, when the current via the junction goes out on a plateau and does not change with further increase in bias. In this case, the current value is limited by a rate of generation of the minority carriers (electrons) in the semiconductor volume. The general expression for the current via the meta/insulator/semiconductor junction can be written as[14]

$$I = S_{eff} D_T(U) A^* T^2 \cdot \exp\left[-\frac{e\varphi_s(U) + (E_c - F) + eU}{k_B T}\right] \times \left[\exp\left(\frac{eU}{k_B T}\right) - 1\right]. \quad (1)$$

This expression is identical to the conventional formula for thermal electron emission in the case of the Schottky barrier, except for the $D_T(U)$ factor that represents the probability of tunneling via a rectangular barrier (insulator). In Eq. (1), S_{eff} is the effective square of the insulator/semiconductor interface, through which tunneling occurs; A^* is the Richardson constant equal to $120(m_p^*/m_0)$ A/(cm·K)^2 (m_p^*/m_0 is the relative effective mass of holes); E_c is the energy corresponding to the conduction band bottom; F is the Fermi energy; and $\varphi_s(U)$ is the surface potential. For the reverse branch, the surface potential is $\varphi_s(U) \cong U + U_k$, where U_k is the contact potential difference. Using the actual values of the parameters for the structure under study and assuming, for certainty, that $D_T(U) \cong 1$, we calculated the $I-V$ characteristics at different temperatures and the temperature dependences of resistance for the gap-film structure within the proposed equivalent scheme. For R_S, we employed the temperature dependence obtained from the experimental data by extrapolation of the high-temperature portion of the $R(T)$ dependence in Fig. 4. With regard to the exponential temperature dependence of R [Eq. (1)], the contribution of the Schottky barrier to the impedance of the structure at high temperatures is negligible. Figure 9 demonstrates the calculated $I-V$ characteristics for the gap-film structure taken at different bias values. It can be seen that the dependences repeat all the main features observed in the experimental curves. This is, first of all, the current saturation of the dependences and the changes in the curves with temperature. Of course, it is hard to get good quantitative agreement between the calculated and experimental curves. In particular, similar to our case, the experimental

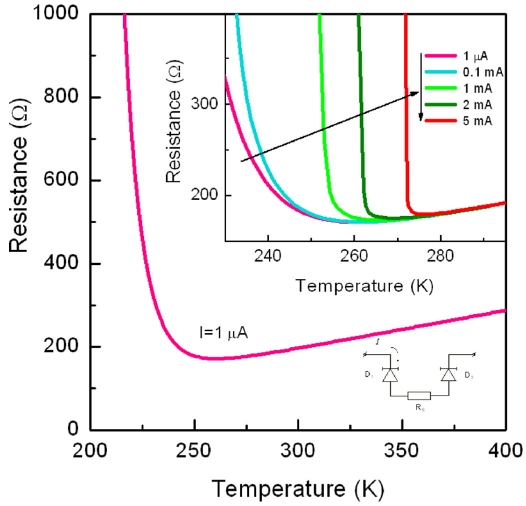

FIG. 10. (Color online) Temperature dependences of the resistance of the «gap-film structure» calculated in framework equivalent scheme (see bottom inset) for bias current $I = 1\ \mu$A. The top inset shows dependencies calculated for various bias currents near temperature range related to rapid growth of the resistance.

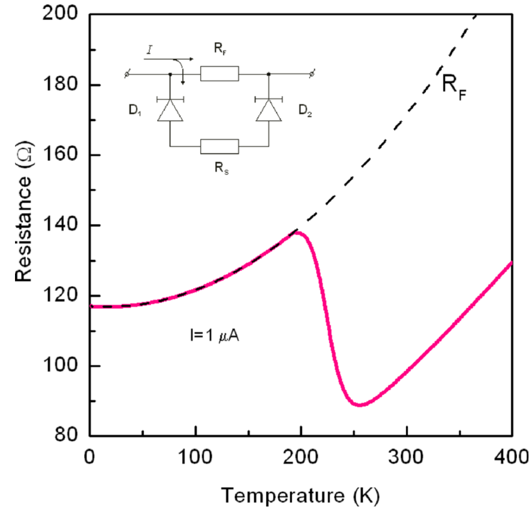

FIG. 11. (Color online) Temperature dependences of the resistance of the «continuous-film structure» calculated in framework equivalent scheme (see inset) for bias current $I = 1\ \mu$A.

values of the reverse current for MIS diodes most frequently appear higher than the calculated values and the reverse branch of the $I - V$ characteristics does not saturate. According to these facts, there are other reverse current components that were not taken into account Eq. (1).[14] In our case, for better quantitative coincidence between the calculated and experimental curves, we used fitting parameter S_{eff}, which, in reality, is always different from the actual electrode square. The calculated temperature dependences of resistance of the gap-film structure (Fig. 10) also reproduce well all the features of the experimental resistance behavior. Thus, the above analysis convinces us that our model captures the most relevant details responsible for the features of the transport properties of the gap-film structure; specifically, the Schottky barrier at the SiO_2/p-Si interface and the change in its state with bias and temperature plays a key role.

Obviously, the features in the behavior of resistance of the continuous-film structure can also be explained within the proposed mechanism. Following the results reported previously, above we interpreted these features by the effect of current channel switching between the iron film and the substrate. In fact, it would be more correct to speak about current redistribution between the iron film and the semiconductor substrate with varying resistance of the Schottky barrier at the SiO_2/p-Si interface. The actual picture of this redistribution can be obtained with the use of the equivalent circuit of the continuous-film structure (the inset in Fig. 11). The calculated temperature dependence of resistance for $I = 1\ \mu$A is shown in Fig. 11. For simplicity, we used the dependence obtained by extrapolation of the low-temperature portion of the experimental curve for the continuous-film structure as a temperature dependence of resistance R_F of the Fe film (Fig. 2), since at low temperatures the current evidently flows only in the iron film. Emphasize once again that we did not intend to get good quantitative agreement and wanted merely to make sure that the model was chosen correct. Indeed, comparing the calculated and experimental dependences, one can see that the proposed mechanism describes well the features of the transport properties of the continuous-film structure.

Now, let us briefly discus the magnetoresistive properties of the structures. When starting the investigations, we were interested generally in whether or not the magnetoresistance mechanism driven by the spin-dependent electron transport across the Fe/SiO_2/*p*-Si interfaces is implemented in simplest hybrid structures. The analysis shows that this mechanism is not revealed explicitly, although in the $R(H)$ dependence for both continuous-film and gap-film structure has a maximum with the center at $H = 0$, whose width is limited by the range of the magnetic field (from -1 up to $+1$ kOe) coinciding with the area of magnetization reversal of the Fe film. The observed changes are insignificant; here, the magnetoresistive effect does not exceed 0.1%. Possibility of spin-dependent tunneling will be argued later on, after we present the results of investigations of the structures with ferromagnetic electrodes of special topology[15] formed from the upper ferromagnetic layer.

Now, pass to magnetoresistance in the magnetic fields higher than the saturation field of the Fe film. The magnetoresistive effect for the continuous-film and gap-film structure behaves similarly, i.e., it is based on the same mechanisms. An exception is the temperature range below 250 K, where the gap-film structure exhibits a negative *MR* portion at certain bias currents. It is most probable that the main contribution to magnetoresistance of the structures is made by the processes occurring in the semiconductor (either in its volume or at the SiO_2/*p*-Si interface). At high temperatures ($T > 250$ K), the $R(H)$ dependence at the initial portion, i.e., up to $H \sim 20$ kOe, is satisfactorily approximated by the dependence $R(H) = R_0 + aH^n$ with $n \cong 2$, whereas, at high magnetic fields ($H \geq 30 \div 35$ kOe) the $R(H)$ dependence varies as $\sqrt{H}$. Similar dependences were observed previously for the ferromagnet/SiO_2/p-Si hybrid structures. Authors explain the magnetoresistive effect differently. It was suggested[13] that large positive magnetoresistance is related to high mobility of electrons in a Si inversion layer and originates from the Lorentz force affecting the electrons. In fact, when there are several types of carriers with different effective masses and, may be, relaxation times, in a material, the magnetoresistance will be positive and proportional to H^2 in weak magnetic fields, while in strong magnetic fields magnetoresistance tends to saturation[16] (in our experiments, there was no saturation up to 350 kOe). Exceptions are the materials with complex Fermi surfaces, where the *MR* saturation is not observed; however, in this case, there should be strong anisotropy of the magnetoresistive effect, which was not found in our experiments. Other authors[12] assume the presence of impurity localized states in the semiconductor, which facilitate hopping conductivity. Consequently, the effect of a magnetic field can be explained in the framework of the hopping magnetoresistance model developed by Shklovskii and Efros.[17] The magnetic field shrinks the localized wave functions of the impurity electrons in the direction perpendicular to the field direction. The wave function overlapping decreases leading to a decrease in the probability of hopping and, consequently, an increase in resistance. However, in the case of hopping magnetoresistance, resistance should increase exponentially, which is inconsistent with the experimental dependences.

Finally, to explain the observed magnetoresistive properties, we may address to the theory,[18] where positive magnetoresistance is implemented in a weakly disordered medium with regard of the electron interaction. A silicon crystal (substrate) doped with boron can be considered as a medium where carriers have random potentials, which is formed by means of the random distribution of impurities over a crystal volume. This theory predicts the $\sqrt{H}$ dependence within the strong-field limit and the H^2 dependence at weak fields. This seems to be consistent with the experimental dependences of resistance on a magnetic field. The theory predicts also that the crossover point should take place near $H = k_B T / g\mu_B$; i.e., at $T = 300$ K the change in the type of the dependence should be observed at $H \cong 22$ kOe. This value is quite consistent with the experimental data.

Concerning the temperature behavior of magnetoresistance, the sharp drop of the effect value below 250 K can be attributed simply to the sharp growth of resistance of the Schottky barrier at the SiO_2/*p*-Si interface and, consequently, to reduction of the relative contribution to resistance of the structure of a semiconductor volume or an inversion layer where the magnetoresistive effect is implemented. At the same time, the occurrence of the negative magnetoresistance at appropriate temperature and bias evidences a different mechanism of the magnetic field effect on conductivity. Here, a key role is apparently played by the fact that the negative magnetoresistance occurs at the transition to the current saturation mode upon reverse bias of the MIS structure. Recall that this situation corresponds to the inversion regime, when conductivity of the transition is determined by minority carriers (electrons) and this crossover from the hole-dominated to electron-dominated transport apparently drives the variation in a character of the magnetoresistive effect. Note that such a behavior of magnetoresistance in the ferromagnet/SiO_2/*p*-Si structures was observed by us for the first time. Additional studies are required to clarify a specific mechanism, but we already may conclude that the contribution to the negative magnetoresistance is made by a thin inversion layer at the SiO_2/*p*-Si interface and not by a semiconductor volume. Therefore, it is not improbable that the ferromagnetic state of the upper layer of the structure also plays its role in the magnetoresistance mechanism in the inversion regime. To make a more definite conclusion on the observed positive magnetoresistance is still difficult.

V. CONCLUSION

We have investigated the transport and magnetotransport properties of the Fe/SiO_2/*p*-Si hybrid structure in planar geometry. It has been shown that the features of the transport properties are controlled by the MIS junctions with the Schottky barrier formed at the SiO_2/*p*-Si interface. Resistance of the MIS junction depends on temperature, value and direction of bias, which determines the features of the temperature behavior of resistance of the structure and the dependence of resistance on the current flowing through the structure. In the case of the structure with a continuous ferromagnetic film, the features of the transport properties observed in current-in-plane geometry are related to the effect of current channel switching between the ferromagnetic film and the semiconductor substrate and the MIS junction is a structure's basic element that drives current channel switching. For the structure with two electrodes formed from the Fe layer and separated by a micron gap, the sharp growth of resistance of the MIS junction with decreasing temperature leads to the sharp growth of resistance below 250 K. Varying the bias current, one may control resistance of the MIS junction within certain limits and, consequently, shift the temperature range where the sharp resistance growth starts.

To explain the effect of positive magnetoresistance in the structures under study at temperatures above 250 K, we proposed a few possible mechanisms related to the processes occurring during current passage in the semiconductor volume; however, we still find difficulty in drawing the final conclusion. Additional investigations are needed. In the case of a structure with the gap, the crossover of magnetoresistance from positive to negative is found under choosing temperature and bias. The negative magnetoresistance takes place when the MIS junction passes to the inversion regime, where the transport properties start being determined by minority carriers (electrons). The occurrence of the negative magnetoresistance should be attributed to the inversion layer formed in a thin layer at the SiO_2/*p*-Si interface. It is not inconceivable that a certain role is played here by the ferromagnetic state of the upper layer and spin-dependent tunneling of electrons across the SiO_2/*p*-Si interface of the structure.

The results of our investigations may be useful for solving the topical problems of spin injection and detection of spin polarization of charge carriers in the ferromagnet/insulator/semiconductor hybrid structures.

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