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Current-driven channel switching and colossal positive magnetoresistance in the manganite-based structure

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Abstract
The transport and magnetotransport properties of a newly fabricated tunnel structure *manganite/depletion layer/manganese silicide* have been studied in the current-in-plane (CIP) geometry. A manganite depletion layer in the structure forms a potential barrier sandwiched between two conducting layers, one of manganite and the other of manganese silicide. The voltage–current characteristics of the structure are nonlinear due to switching conducting channels from an upper manganite film to a bottom, more conductive MnSi layer with an increase in the current applied to the structure. Bias current assists tunnelling of a carrier across the depletion layer; thus, a low-resistance contact between the current-carrying electrodes and the bottom layer is established. Below 30 K, both conducting layers are in the ferromagnetic state (magnetic tunnel junction), which allows control of the resistance of the tunnel junction and, consequently, switching of the conducting channels by the magnetic field. This provides a fundamentally new mechanism of magnetoresistance (MR) implementation in the magnetic layered structure with CIP geometry. MR of the structure under study depends on the bias current and can reach values greater than 400% in a magnetic field lower than 1 kOe. A positive MR value is related to peculiarities of the spin-polarized electronic structures of manganites and manganese silicides.

1. Introduction

The intensive study of manganites with the perovskite-like structure was first motivated by the discovery of an unusual magnetic-field-driven resistivity decrease named the colossal magnetoresistance (CMR) effect. Close attention dictated by the perspectives of practical application has been focused on obtaining large magnetoresistance (MR) in low magnetic fields. Along with that, numerous research works have shown that manganites exhibit a rich variety of novel and intriguing features. Electric- and magnetic-field-driven nonlinear conductivity [1, 2], tunnel MR [3] and other effects of spin-dependent electron transport [4, 5] were found in the materials with manganite and manganite-based structures, which raises scientific issues and favours a new approach to spintronics. Recently the interest of researchers has turned to hybrid manganite/semiconductor structures where the classical Si- and GaAs-based semiconductors are used. On the one hand, such manganite-based devices are found to be compatible with current semiconductor technologies (in particular, a CMOS technology); on the other hand, these devices are expected to possess novel characteristics that could be useful for spintronics applications. As is known, the tunnel junctions and heterostructures containing ferromagnetic manganite and nonmagnetic semiconductor layers reveal anomalous conductivity [6], giant positive MR [7], a current-driven crossover from negative to positive MR [8] and a photoelectric effect [9]. For the manganite-based structures, all these phenomena were observed in current-perpendicular-to-plane (CPP) geometry, which is easier to analyse and, for this reason, traditionally used for studying the multilayer structures. However, sometimes using current-in-plane (CIP) geometry, when the current flows parallel to interfaces between different layers, is preferable, as it may provide new manifestations of the electron transport in the multilayer structures.

In a very thin metallic film deposited onto a Si substrate, switching conducting channels between the film and the Si inversion layer (a highly conducting region next to a native SiO_2 layer) was observed [10]. It can be controlled by changing the temperature [11] or by the bias current [12]. Since different conduction layers may have drastically different transport characteristics, the hybrid multilayer structures with CIP geometry can be perspective for practical applications. Fabrication of the structures with ferromagnetic layers lays grounds for expecting the development of spin-dependent effects in the transport properties and, as a consequence, possibilities of the effective magnetic-field control of the structure characteristics.

In this work, we report the transport and magnetotransport properties of the manganite- and Si-based layered structures. Transport measurements of the structure were performed in CIP geometry. Strongly nonlinear conductivity and significant positive MR in a low magnetic field have been found. We consider these phenomena to be related to switching the conducting channels between different layers of the structure and spin-dependent tunnelling of carriers through a potential barrier separating the channels.

2. Experimental details

For fabrication of a $La_{0.7}Sr_{0.3}MnO_3/Si/SiO_2$ structure, we chose pulsed-laser deposition with the use of $La_{0.7}Sr_{0.3}MnO_3$ (LSMO) and Si targets. The LSMO target was made of analytically pure oxides using a solid-state reaction technique with repeated grinding and sintering at 1200 °C for 24 h in air. Si and LSMO films as bottom and upper layers, respectively, were deposited onto a SiO_2 (0 0 1) substrate. During deposition, the substrate was kept at 500 °C. The process conditions were selected so that Si and LSMO thicknesses were about 5 nm and 500 nm, respectively. The as-deposited structure was annealed at 800 °C for 1 h in oxygen atmosphere.

The structure was investigated by x-ray diffraction using a Brucker D8 ADVANCE diffractometer and by scanning electron microscopy (SEM) using a JEOL JSM-6460 electron microscope. SEM images of the LSMO film showed the absence of any noticeable microstructure. The x-ray diffraction pattern shows (0 0 *l*) fundamental peaks of the SiO_2 substrate and LSMO satellite peaks, whose positions are consistent with a (1 1 0) dominant orientation of the LSMO film. These data indicate that the LSMO layer has either an epitaxial character or a (1 1 0) texture. There are no peaks related to Si or any silicide compound in the pattern. Magnetization of the structure measured with a Physical Property Measurement System (PPMS, Quantum Design, USA) showed that at about 300 K the LSMO film undergoes a transition to the ferromagnetic state. At the same time, the temperature range of the transition is considerably extended, which apparently suggests the inhomogeneous distribution of the composition in the film volume.

Transport measurements were performed with a precise Keithley-2400 current/voltage source-meter. Ohmic contacts to the upper LSMO film were made of silver epoxy. For MR measurements in a constant-current mode, both two- and four-probe methods were used. Voltage–current characteristics were obtained by applying dc current and measuring the voltage in both contact geometries. We did not see any noticeable difference between the results obtained by the different measuring methods. In all the measurements, the magnetic field induced by an electro-magnet was in the film plane. In order to obtain data at different temperatures, we used a helium cryostat, which allowed fixing the sample mount temperature with accuracy of 0.05 K within the entire temperature range under study.

3. Results

We studied resistance and MR of the structure in the temperature range from 4.2 to 300 K. The resistance value and the MR behaviour appeared to be dependent, to a large extent, on the measuring current I. At a bias current I lower than some threshold value I_{th}, which is about 10 μA, the temperature dependence of resistance is typical of strontium manganites with a nonstoichiometric composition on oxygen or with a low doping level [13]. Figure 1(*a*) presents a low-temperature region of this dependence at bias currents of 2 and 60 μA with and without a magnetic field. At small bias currents, the structure exhibits negative MR (see figure 1(*b*)), as could be expected for a manganite film. MR is observed in a wide temperature range, down to the lowest temperature values, which suggests the contribution of tunnelling MR; a characteristic resistance drop in weak magnetic fields at low temperatures (see figure 2) also evidences this. In other words, despite the x-ray diffraction and electron microscopy data, the manganite film does contain certain boundaries working as potential barriers.

The behaviour of resistance and MR of the structure at bias currents over the threshold I_{th} appeared surprising (figure 1). Firstly, the measuring current increasing leads to a decrease in the resistance of the structure. Secondly, the bias current exceeding the threshold value causes suppression of the MR effect in the high-temperature region of $T > 30$ K (figure 2) and at $T < 30$ K positive MR arises, which reaches a much higher value than the negative MR value observed at $I < I_{th}$. The most surprising fact is that saturation of the positive magnetoresistive effect, i.e. reaching its maximum value, for $T < 20$ K is observed in weak magnetic fields <1 kOe (figure 3). According to the magnetic-field dependences, at these fields the magnetization of the structure reaches the saturation (inset in figure 3).

In order to explore the nonlinear transport properties and the influence of the magnetic field on these properties, we obtained the voltage–current (V–I) characteristics under the applied magnetic field varying between 0 and 10 kOe over the temperature range 5–300 K. To minimize heating, the bias current was swept in a range not exceeding the limit

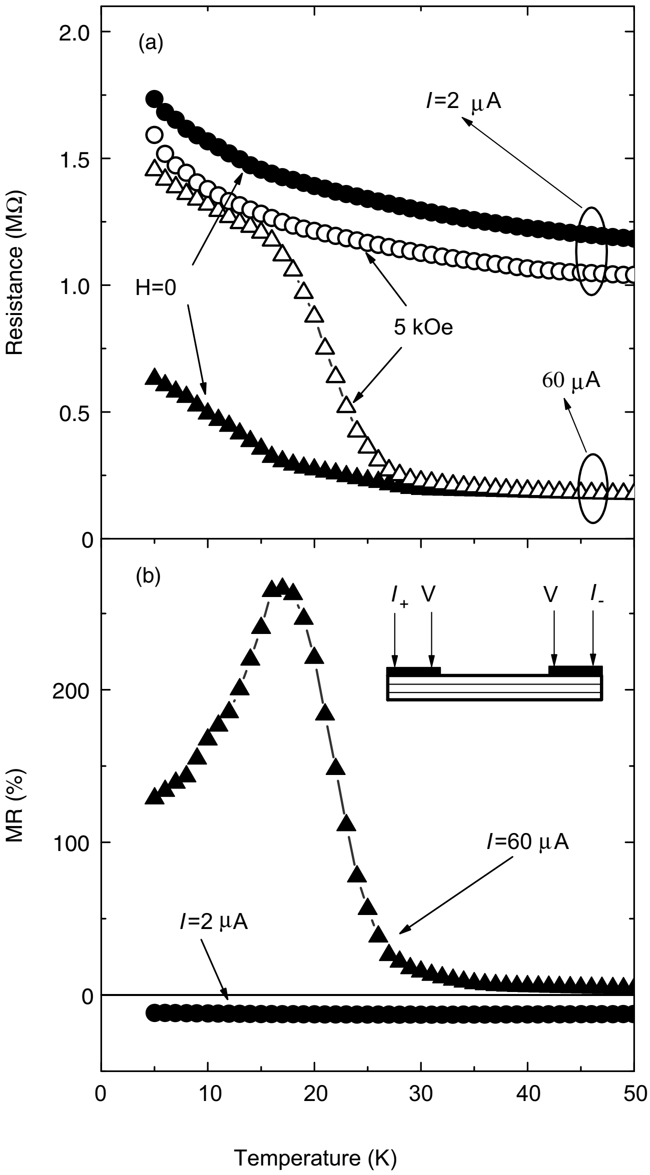

Figure 1. (*a*) Resistivity of the structure measured as a function of temperature at the bias currents $I = 2\,\mu$A and $I = 60\,\mu$A in zero and 5 kOe magnetic fields. (*b*) Temperature dependence of MR measured at the bias currents $I = 2\,\mu$A and $I = 60\,\mu$A in a magnetic field of 5 kOe. The inset shows the experiment geometry.

0.1 mA. The typical V–I characteristics taken at different temperatures are presented in figure 4. In the absence of the external magnetic field the voltage–current characteristics appear strongly nonlinear over the entire temperature range. At low currents, $I < I_{th}$, the V–I curves are linear; near I_{th} they sharply change their slope, which is related to a decrease in the resistance of the structure; at high currents the curves become linear again but with a slope strongly different from the initial part of the dependences.

The applied magnetic field appreciably changes the behaviour of the V–I curves (figure 5). At the initial linear part of the dependences, the changes correspond to the presence of the negative MR characteristic of the manganite materials; the MR value is independent of the bias current. At $I > I_{th}$, the situation changes. In the temperature range from 300 to about 30 K the curve part corresponding to the high-current area does not undergo any noticeable changes in the magnetic field, i.e. the MR effect is suppressed by the bias current, $I > I_{th}$. However, at temperatures below 30 K the magnetic field strongly affects the behaviour of the V–I curves in the high-current area. The applied magnetic field causes a sharp change in the slope of the dependences; the step of the curves straightens as the magnetic field increases and the temperature decreases. For instance, at 5 K in a field of 2 kOe the V–I dependence becomes nearly linear over the entire current range. Thus, at low temperatures the structure possesses the positive MR effect induced by the bias current; near I_{th} the crossover from negative to positive MR occurs. The positive

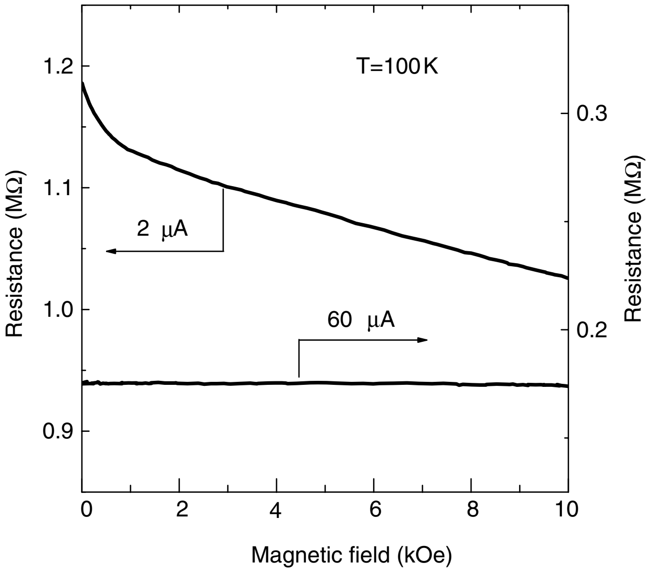

Figure 2. Magnetic field dependence of resistance at 100 K for the two different bias currents $I = 2\,\mu$A and $I = 60\,\mu$A.

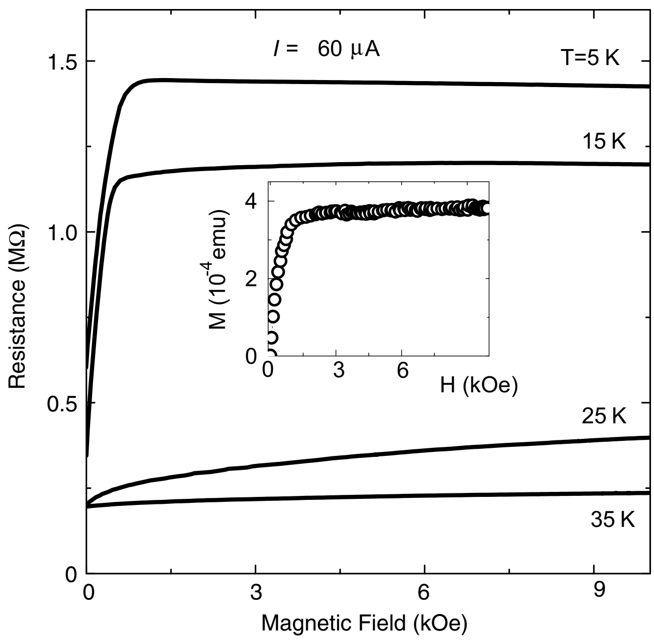

Figure 3. Magnetic field dependence of resistance at different temperatures for the bias current $I = 60\,\mu$A. The inset shows the field dependence of magnetization for the structure.

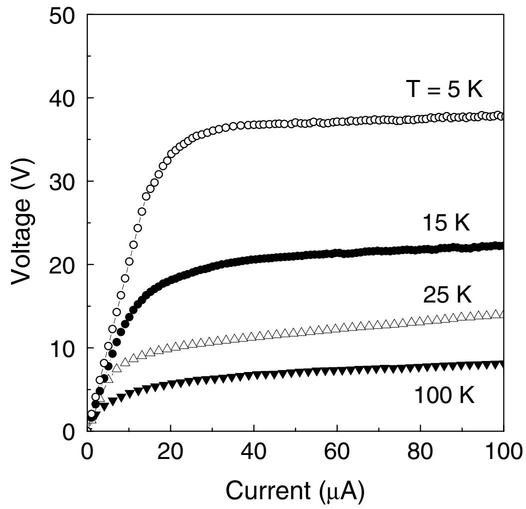

Figure 4. V–I curves at different temperatures in a zero magnetic field.

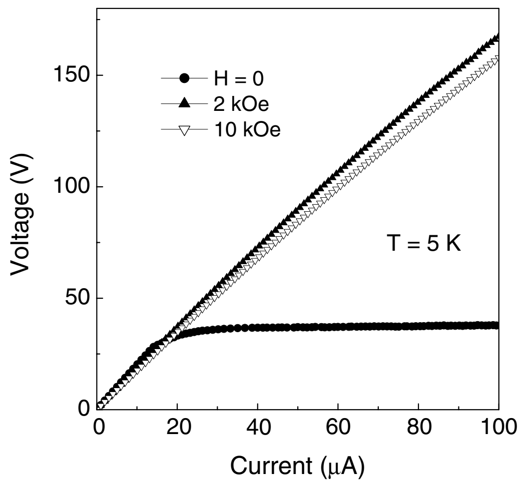

Figure 5. V–I curves for different applied magnetic fields at 5 K.

MR value depends on the bias current value: when $T = 15$ K and $I = 60\,\mu$A, the structure shows the MR of 250%, but at $I = 100\,\mu$A it increases up to 420%. It must be noted that in the temperature region 20–30 K, which may be characterized as a transition region, the complete saturation of the positive MR effect is not observed up to a magnetic field of 10 kOe, while at lower temperatures the saturation occurs already at fields of about 1 kOe with a slight smooth decrease in the effect value as the field further increases.

4. Discussion

From our point of view, the observed behaviour of the transport and magnetotransport properties, despite the CIP geometry of the experiments, cannot be explained only by the properties of the manganite film, which is on top in the structure. The experimental results may be interpreted under the assumption that at the technological stage an additional high-conductive layer is formed, whose conductivity exceeds that of the manganite film. This layer is separated from the manganite film by a potential barrier, and, under certain conditions, switching a conducting channel between the upper manganite film and this conducting layer becomes possible. Since the properties of the two channels can be generally different, such switching, as we see in the experiment, is able to change substantially the transport properties of the structure.

First, let us consider a possible mechanism of the formation of the additional conductive layer in our structure. As is known, manganese ions reveal high interstitial diffusivity in silicon facilitating the formation of stable bulk Mn–Si phases [14]. In a number of works devoted to Mn growth on a Si substrate, the Mn trend to for silicide formation was reported [15, 16]. The metal–silicon reaction occurs already at room temperature and further enhances by annealing at temperatures up to 400 °C leading to the surface being completely covered with a homogeneous silicide film. Thus, we may reasonably suggest that, during deposition of the manganite film, manganese ions from its boundary layer diffuse into a thin silicon layer formed at the previous stage of the process; as a result, the Mn–Si compound is formed. The latter, most probably, is a manganese monosilicide MnSi, which is the only Mn–Si compound possessing a metallic type conductivity and a ferromagnetic order below ∼30 K [17]. Just below this temperature the structure under study starts revealing the features of magnetoresistive properties and, as we discuss below, the conductive ferromagnetic state plays a crucial role in the mechanism of positive MR of the structure. Owing to diffusion of a part of manganese ions into the silicon layer, the manganite film region adjacent to MnSi experiences manganese deficit and, as a consequence, forms a dielectric layer working as a potential barrier between the top manganite film and the bottom conductive layer (figure 6).

Now consider the behaviour of the transport properties of such a tunnel structure under different conditions. We start with the case of temperatures above 30 K. When the current applied to the structure is small, $I < I_{th}$, the resistance of the tunnel junctions separating two current paths is high. The potential barrier prevents tunnelling a carrier into the high-conductive MnSi layer, so the current is completely carried by the upper manganite layer. This determines the transport and magnetotransport properties of the structure at a low bias current, specifically, a linear current–voltage characteristic and negative MR independent of a bias current.

The enhancement of bias current and, thus, a potential on the current contacts leads to redistribution of carriers in the high-conductive MnSi layer (see figure 6). As a result, the bias voltage V_b on the tunnel transition under the current electrodes grows, which, in its turn, causes an increase in the probability of tunnelling a carrier through the potential barrier. When the bias current exceeds I_{th}, tunnelling the carriers across the depletion manganite layer (potential barrier) establishes a low-resistance Ohmic contact between the current-carrying electrodes and the conducting MnSi layer. Thus, the current path is switched from the manganite film to the MnSi layer. A characteristic sharp kink of the current–voltage characteristics corresponds just to this switching of a conducting channel. One more result that evidences switching is the absence of the negative MR at $I > I_{th}$, which would be inevitably observed if the current flowed in the manganite film.

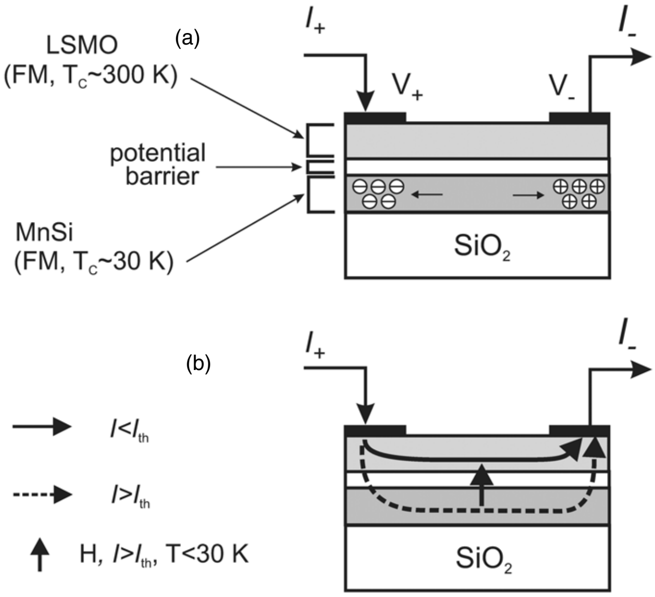

Figure 6. (*a*) Schematic view of the structure formed in the technological process. (*b*) Schematic representation of switching the conducting channels between LSMO and MnSi layers; at $I < I_{th}$ the current flows in the manganite film; at $I > I_{th}$ current is mostly carried by electrons in the MnSi layer; when $I > I_{th}$ and $T < 30$ K, the current flow reverts to the LSMO film by applying the magnetic field.

It should be noted that the channel switching effect was observed earlier, mainly in the hybrid structures containing the so-called inversion layer at the Si–SiO_2 interface [10]. The switching effect occurred at a temperature change due to the principally different temperature behaviour of the transport properties of two current channels. Also, in a limited temperature region current-driven switching was observed, which was revealed on changing the temperature of switching between the channels at the change in the applied current [12]. We demonstrated for the first time the possibility of controlling the switching between two channels of the electron transport in a thin-film system by the applied current in a wide temperature range, even when switching at a temperature change is absent.

The layered structure with the inversion Si layer usually exhibits a large positive MR caused by high mobility of electrons in this layer and originates from the Lorentz force acting on electrons [12]. In our case, a fundamentally new mechanism of positive MR is implemented, which has never been discussed in the literature. This mechanism is based on the phenomenon of spin-dependent transport. The above-mentioned scenario of controlled switching of a current path between two channels works, generally, even at temperatures below 30 K; but, along with that, a principally new fact arises: the high-conductive MnSi layer undergoes a transition to the ferromagnetic state (the manganite film becomes ferromagnetic at much higher temperatures). In this case, the probability of tunnelling carriers through the potential barrier should depend on the spin-polarized electronic structure in the manganite film and the MnSi layer and, ultimately, on the relative orientation of magnetizations of the layers. In fact, the magnetic tunnel junction comprising two ferromagnetic electrodes separated by a thin insulating tunnel barrier is implemented in the structure below 30 K. The density of current through the potential barrier $J_{\uparrow\uparrow}$ ($J_{\uparrow\downarrow}$) for the parallel (antiparallel) orientation of magnetization of the ferromagnetic electrodes is determined now by the details of the spin-up and spin-down density of state (DOS) near the Fermi energy E_F:

$$J_{\uparrow\uparrow} \propto [\rho_1^{\uparrow}(E_F) \cdot \rho_2^{\uparrow}(E_F + eV_b) + \rho_1^{\downarrow}(E_F) \cdot \rho_2^{\downarrow}(E_F + eV_b)],$$

$$J_{\uparrow\downarrow} \propto [\rho_1^{\uparrow}(E_F) \cdot \rho_2^{\downarrow}(E_F + eV_b) + \rho_1^{\downarrow}(E_F) \cdot \rho_2^{\uparrow}(E_F + eV_b)].$$

Here $\rho_1^{\uparrow}(E)$ and $\rho_1^{\downarrow}(E)$ are the spin-up and spin-down DOS in the LSMO layer; $\rho_2^{\uparrow}(E)$ and $\rho_2^{\downarrow}(E)$ are those in the MnSi layer. The relative change in the conductivity of the magnetic tunnel contact on changing the orientation of magnetizations of the electrodes from antiparallel to parallel is determined as TMR $= J_{\uparrow\uparrow}/J_{\uparrow\downarrow} - 1 = 2P_1P_2/1 - P_1P_2$, where $P_i = (\rho_i^{\uparrow} - \rho_i^{\downarrow})/(\rho_i^{\uparrow} + \rho_i^{\downarrow})$, $i = 1, 2$ is the degree of polarization of ferromagnetic electrodes 1 and 2. It should be taken into account that ferromagnets can be of two types; one of them have majority spin carriers (MASCs), $\rho_i^{\uparrow}(E_F) > \rho_i^{\downarrow}(E_F)$ (the carriers' spins are mainly parallel to magnetization) and the other have minority spin carriers (MISCs), $\rho_i^{\uparrow}(E_F) < \rho_i^{\downarrow}(E_F)$ (the spins are mainly antiparallel to magnetization). A tunnel junction where both electrodes are either MISC or MASC exhibits negative MR (TMR < 0). Only for a tunnel junction with one MISC and one MASC ferromagnetic electrode, the MR is positive (TMR > 0) [18].

Apparently, the aforesaid takes place in our structure. In a zero magnetic field, magnetizations of the two ferromagnetic electrodes are predominantly antiparallel, owing to the magnetostatic interaction between the ferromagnetic layers with in-plane magnetization. In this case, the junction resistance is minimal and at $I > I_{th}$ the current flows in the bottom channel in the structure, i.e. in the MnSi layer. When magnetic field is applied, magnetizations of the ferromagnetic layers tend to parallel orientation. This leads to the increase in the tunnel junction resistance; when the latter becomes higher than the manganite film resistance, switching of the current channels occurs and the current begins flowing mainly in the manganite film. It should be emphasized that in the switching mechanism two sequence tunnel junctions (under each current electrode) are equipped, which makes the characteristics of switching by both bias current and magnetic field more sharp. The facts that are evidence of the above-mentioned scenario are: (1) the field-induced reconstruction of the nearly linear current–voltage characteristic expected for manganites of this composition; (2) the occurrence of the negative MR effect typical of a manganite in magnetic fields exceeding the field in which switching of the current channels occurs; (3) positive MR saturation and saturation of the film magnetization occur in the same magnetic fields. Thus, aside from current control, control of switching of the current channels in the structure by the external magnetic field becomes possible. As a matter of fact, a fundamentally new MR mechanism is implemented associated with switching between the different current channels in the film structure by the external magnetic field. We see that, using this switching, large MR can be realized in relatively small magnetic fields.

Since the value and the sign of the tunnel contact magnetization are determined by spin polarization of the ferromagnetic electrodes, we would like to make a few comments regarding the spin-polarized electronic structure of two different ferromagnetic electrodes for the system under study. Hole-doped manganites are considered to have a majority spin state at E_F and to possess very high spin polarization [19]. As for the ferromagnetic MnSi, we, unfortunately, failed to find any data on the direct measurements of spin polarization of this material in the literature; however, the DOS calculation for thin films shows considerable spin polarization up to 45% at E_F with the predominant minority spin component [20]. Our investigations provide indirect experimental confirmation of these results and make us pay attention to the Mn/Si systems as candidates for spintronic applications.

5. Conclusion

In summary, we have observed current-controlled switching of the conductance channels in a structure consisting of conductive manganite and MnSi layers separated by a potential barrier. The switching mechanism is based on the dependence of the tunnel junction resistance on a bias value. At low temperatures ($T < 30$ K), when both layers are in the ferromagnetic state, two current channels appear separated by magnetic tunnel junctions. This allows controlling the resistance of the junctions and, consequently, switching between the current channels in the structure by the magnetic field. Since the transport properties are strongly different, such switching induced by magnetic field makes it possible to implement a new mechanism of MR. The positive MR value is related to the fact that LSMO is a MASC ferromagnet, while MnSi has MISCs.

Acknowledgments

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