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Switching of Current Channels and New Mechanism of Magnetoresistance in a Tunneling Structure

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Abstract—We have experimentally studied the transport properties of a planar $La_{0.7}Sr_{0.3}MnO_3$ (LSMO)/Mn-depleted LSMO/MnSi tunneling structure, in which the Mn-depleted LSMO layer plays the role of a potential barrier between the conducting layers of LSMO and MnSi. The measurements were performed in geometry with the current direction parallel to the planes of interfaces in the tunneling structure. It is established that the structure exhibits a nonlinear current–voltage characteristic and possesses a positive magnetoresistance, the value of which depends on the tunneling current. It is suggested that specific features of the transport properties of this structure are related to the phenomenon of current channel switching between the conducting layers. The switching mechanism is based on the dependence of the resistance of the tunneling junction between the conducting layers on the bias voltage and the applied magnetic field.

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Magnetic tunneling junctions and the phenomena of spin-polarized tunneling from ferromagnetic layers have been extensively studied in recent years [1]. This interest is related to both potential practical applications and a rich spectrum of new physical phenomena related to a relationship between the spin-polarized electron transport and the magnetic subsystem of low-dimensional structures. Tunneling junctions have been traditionally studied in geometry with the current perpendicular to the planes of interfaces in the tunneling structure. This geometry is simpler for a theoretical analysis and the interpretation of experimental results. However, the current-in-plane (CIP) geometry, in which the current is parallel to the planes of interfaces, is sometimes preferred for the practical purposes, in particular, in the case of ferromagnet/semiconductor hybrid nanostructures compatible with the traditional CMOS technology. In addition, this geometry can be expected to reveal new manifestations of the spin-dependent electron transport.

This Letter presents the results of an investigation, in which the transport properties of a tunneling structure have been measured in the CIP geometry.

The tunneling structure was manufactured using the method of pulsed laser ablation of $La_{0.7}Sr_{0.3}MnO_3$ (LSMO) and Si targets with deposition onto a (001)-oriented SiO_2 substrate. According to this, 5-nm-thick Si layer and 500-nm-thick LSMO layer were sequentially deposited onto the substrate heated to 500°C. The as-grown structure was immediately annealed in an oxygen-containing atmosphere at 800°C for 1 h. It was expected that this technological process must yield a structure, in which the lower layer of manganese monosilicide (MnSi) and the upper LSMO layer are separated by an interfacial layer of manganese-depleted LSMO ($LSM_\delta O$) with a thickness of about 5 nm (see the inset to Fig. 1). This composition profile must form due to a high coefficient of Mn diffusion in Si [2]. The $LSM_\delta O$ layer possesses dielectric properties and plays the role of a potential barrier between the conducting layers of LSMO and MnSi (electrodes).

According to the results of magnetic measurements, the manganite film exhibits a transition to the ferromagnetic (FM) state at a temperature of ~300 K. X-ray diffraction data show evidence for a predominant (110) orientation of the LSMO layer, but it is most probable that this layer is textured. The presence of boundaries, which separate crystalline grains and play the role of potential barriers, is confirmed by a low conductivity of the LSMO film and a large contribution of tunneling to the sample resistance. As for the lower layer, it is known that MnSi is characterized by metallic conduction and exhibits a transition to the FM state at about 30 K [3].

The transport properties of the samplers were studied using a Model 2400 SourceMeter (Keithley Instruments). The current-carrying contact pads were formed on the upper surface of the structure using a two-component silver-filled epoxide glue. The experimental geometry is schematically depicted in the inset to Fig. 1. The resistance was measured in the regime of stabilized current, while the current–voltage (I–V) curves were obtained in the current sweep regime. The magnetic field was applied in the plane of the structure. The sample temperature T was set and kept accurate to within 0.1 K in the entire range studied.

The experimental data can be conditionally divided into two parts, which refer to (i) nonlinear transport properties and (ii) the effect of a magnetic field on the conduction. Let us first consider features of the conduction in the absence of an external magnetic field. Figure 1 presents a series of I–V curves measured at various temperatures. As can be seen, all curves exhibit an almost linear initial portion. Then, at a certain threshold current (I_{th}), the slope sharply changes and, as the current I grows further, the voltage increases at a slow rate. This behavior is especially clearly pronounced at $T < 30$ K.

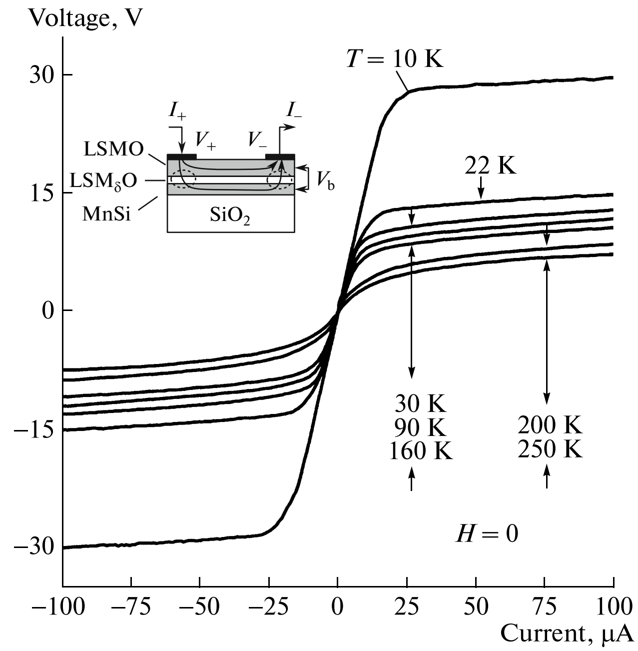

Fig. 1. I–V curves of the tunneling structure measured at various temperatures in the CIP geometry without an external magnetic field. The inset shows a schematic diagram of the sample structure (arrows indicate the possible current pathways).

We propose the following model to interpret the obtained I–V curves. In the given sample structure, the upper layer (LSMO) possesses a higher resistance than the lower (MnSi) layer. However, since the contact pads are formed on the upper surface and the lower layer is separated from the upper by a potential barrier, the current passes predominantly via the LSMO layer. This is confirmed by the linear $V(I)$ dependence observed at small currents, in agreement with what has to be expected for the manganite. An increase in the current I and, hence, in the voltage drop V between the contacts, leads to a redistribution of charges in the lower conducting layer. This, in turn, gives rise to a bias voltage V_b ($V_b \ll V$) on the tunneling junctions under the current-carrying contacts and the related increase in the tunneling current I_T through the potential barrier separating the upper and lower layers of the structure. Thus, the resistance R_T of the tunneling barrier decreases and the current begins to flow predominantly via the lower (silicide) layer, the resistance of which (R_S) is small compared to that (R_M) of the manganite film.

The upper inset in Fig. 2 shows an equivalent electric scheme of the tunneling structure in the CIP geometry. The current through this circuit is determined by the parallel connection of R_M and the series of R_T and R_S. According to this scheme, we have approximately described the I–V curves by assuming that R_S is small compared to R_T so that the charge transfer via the lower layer is fully determined by the tunneling current (I_T). This current was approximately described using the Simmons formula [4] obtained in the approximation of elastic electron tunneling through the potential barrier:

$$I_T = I_0\{\varphi_0\exp(-A\varphi_0^{1/2}) - (\varphi_0 + eV)\exp(-A(\varphi_0 + eV)^{1/2})\},$$

where φ_0 is the potential barrier height, A is a coefficient proportional to the barrier width Δx. The current through the upper layer was described according to the Ohm law as $I_M = V/R_M$, where R_M was determined from the temperature dependence of the sample resistance measured at $I = I_{th}$, that is, for the current passing almost entirely through the manganite film. The best fit was obtained for the following parameters: potential barrier width $\Delta x = 5$ nm (this value well agrees with the proposed structure composition); bias voltage $V_b \cong 3 \times 10^{-2}$ V; and the average potential barrier height varying from $\varphi_0 \cong 0.3$ eV at $T = 250$ K to $\varphi_0 \cong 0.8$ eV at $T = 5$ K.

Figure 2 gives an example of the experimental I–V curve approximated using the proposed model. The lower inset shows the temperature dependence of φ_0, which can be determined by changes in the electron structures of the tunneling junction components in the course of FM ordering [5]. Some manganites [6] exhibit an anomalously large change in the chemical potential below T_C, which is proportional to the square of the sample magnetization. Thus, the work

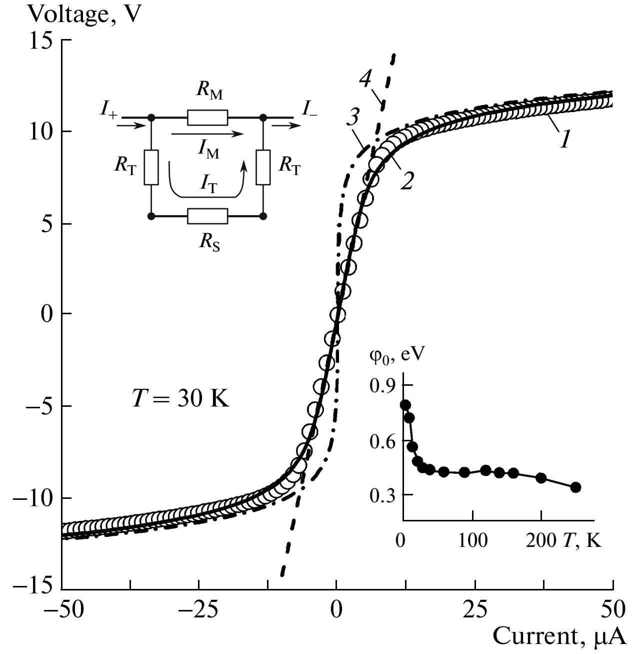

Fig. 2. Example of the experimental *I–V* curve of the tunneling structure in the CIP geometry at $T = 30$ K, approximated within the framework of the proposed model (with an equivalent scheme in the upper inset): (*1*) experimental points; (*2*) approximating curve; (*3*) *I–V* curve of the tunneling junction; (*4*) *I–V* curve of the manganite layer. The lower inset shows the temperature dependence of the average potential barrier height φ_0 in the structure, obtained for the tunneling current approximated by the Simmons formula.

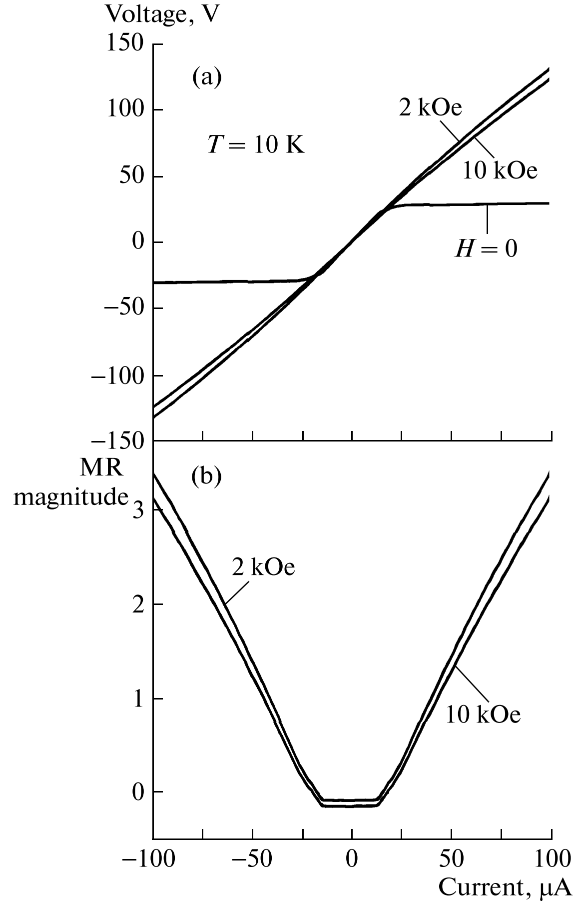

Fig. 3. LSMO/$LSM_\delta O$/MnSi tunneling structure: (a) *I–V* curves measured in the CIP geometry at $T = 10$K in the absence of an external magnetic field ($H = 0$) and with an applied magnetic field of $H = 2$ and 10 kOe; (b) plots of the MR magnitude versus bias current for $H = 2$ and 10 kOe.

function of the LASMO layer upon the transition to the FM state increases as compared to that of the interfacial $LSM_\delta O$ layer (remaining in the nonmagnetic state), which plays the role of the potential barrier. As a result, φ_0 increases with the magnetization of LSMO, which explains the behavior observed at high temperatures. The growth in φ_0 at temperatures below 30 K is naturally explained by an increase in the work function of the MnSi layer upon its transition to the FM stage at $T \sim 30$ K.

The results of measurements of the *I–V* curves in an external magnetic field *H* showed that the influence of this field at $T > 30$ K is manifested only for $I < I_{th}$. The effect of *H* in this interval of currents is fully determined by the magnetoresistance (MR) of the LSMO film. The MR is negative and its absolute value is independent of the probing current, which is typical of manganites. For $I > I_{th}$, the sample exhibits switching so that the current begins to flow predominantly via the lower (silicide) layer. Since MnSi does not possess significant MR, while the current via tunneling junctions at $T > 30$ K is independent of *H*, the MR effect for $I > I_{th}$ at $T > 30$ K is not observed. At $T < 30$ K, the silicide layer exhibits magnetic ordering and the entire structure represents a magnetic tunneling junction. The current through this junction depends on the mutual orientation of magnetizations (M_M and M_S, respectively) in the LSMO and MnSi layers.

As can be seen from the data in Fig. 3a, the effect of the negative MR at $T < 30$ K for $I < I_{th}$ is still retained, but a strong influence of *H* is additionally manifested in the *I–V* curves for $I > I_{th}$. Indeed, at $T = 10$ K, this dependence already becomes linear in a field of $H =$ 1 kOe, which can be interpreted as the reverse switching of the current channel from the lower to upper layer of the structure as a result of increase in the resistance R_T of the tunneling junction in the applied magnetic field. Indirect evidence for this scenario is the negative MR (typical of the manganite film) observed for $I > I_{th}$ (see the MR curves for $H = 2$ and 10 kOe in Fig. 3b).

Thus, there are several possibilities to control the switching of current channels in a magnetic tunneling structure in the CIP geometry. The bias voltage (cur-