Current channel switching in the manganite-based multilayer structure

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Abstract. The transport properties of the structure $\text{La}_{0.7}\text{Sr}_{0.3}\text{MnO}_3$/depleted manganite layer/$\text{MnSi}$ have been studied. The depleted manganite layer serves as a potential barrier between the ferromagnetic conducting $\text{La}_{0.7}\text{Sr}_{0.3}\text{MnO}_3$ and MnSi layers by forming a magnetic tunnel junction. The study in the CIP (current-in-plane) geometry has revealed the effect of current channel switching between the manganite layer and the manganese silicide layer with higher conductivity. The effect is controlled by bias current, magnetic field, and optical radiation. Such switching is responsible for the features of the transport properties and the magnetoresistive and photovoltaic effects in the structure.

1. Introduction

In recent years, the effects of the spin-polarized electron transport in magnetic tunnel structures have been intensively studied [1]. This is related not only to perspectives of practical application but to a rich variety of novel physical phenomena resulted from the tight interrelation of the spin-polarized current and a magnetic subsystem of the low-dimensional structures. Tunnel junctions have been traditionally investigated in the current-perpendicular-to-plane (CPP) geometry which simplifies the theoretical analysis and interpretation of experimental results. At the same time, the current-in-plane (CIP) geometry is often preferable for applications such as fabrication of hybrid nanostructures ferromagnet/semiconductor compatible with a traditional CMOS technology. Also, new manifestations of the spin-dependent transport can be expected. In this study, the results of the CIP-geometry investigation of the transport and magnetotransport properties and the photovoltaic effect in the tunnel structure are reported.

2. Experimental details

The tunnel structure was prepared by pulse laser sputtering onto a SiO$_2$ (001) substrate using $\text{La}_{0.7}\text{Sr}_{0.3}\text{MnO}_3$ (LSMO) and Si targets. The technological process described in detail in [2] yielded the structure of the following composition (bottom inset in figure 1): the bottom layer (~ 5 nm) of manganese monosilicide MnSi, the top layer (~ 500 nm) of a LSMO film and a manganite layer (~ 5 nm) depleted in manganese at the interface (LSM$_{\delta}$O). The LSM$_{\delta}$O layer is dielectric and serves as a
potential barrier between two conducting electrodes MnSi and LSMO. The manganite film transfers to the ferromagnetic state at about 300 K and possesses of conductivity typical of the La_{0.7}Sr_{0.3}MnO_3 composition but with the considerable tunnel contribution at low temperatures which is related to the film microstructure. MnSi is characterized by metal conductivity and transfers to the ferromagnetic state at 30 K.

The transport properties of the structure were studied in the CIP geometry with a precise KEITHLEY-2400 current/voltage source-meter. Ohmic contacts were formed on the top of the structure with the use of two-component silver epoxy. The experimental geometry is illustrated in figure 1 (top inset). Resistance was measured in the current stabilization regime and the current-voltage-current ($V-I$) characteristics were taken in the current scanning regime. The external magnetic field was applied in the plane of the structure. In order to keep the sample temperature accurate to 0.1 K, a helium refrigerator with optical windows was used. A semiconductor laser ($\lambda = 0.98 \mu m$) and an incandescent lamp and a monochromator provided the optical effect. The entire surface of the structure, except for the contact area, was exposed.

3. Results and discussions

We will report the results obtained at temperatures below 30 K, i.e., when both electrodes of the structure are ferromagnetic. Figure 1 presents the $V-I$ characteristics of the structure taken at different temperatures in zero magnetic field. The initial portion of the dependences is nearly linear; then, at some critical value of bias current $I_{th}$ the slope of the curves drastically changes and with the further increase in current $I$ via the structure voltage $V$ on the structure starts slowly increasing. Such a behavior of the $V-I$ characteristics is explained as follows. The top LSMO layer has higher resistance as compared to the bottom MnSi layer. However, since the current contacts are formed at the top layer and the bottom conducting layer is separated from the manganite film by the potential barrier, current flows mainly in the top layer, which is characterized by the linear $V-I$.
characteristic. Indeed, the linear $V-I$ characteristic portion corresponds to small $I$ values. The increase in $I$ and, consequently, in $V$ causes charge redistribution in the bottom conducting layer. This, in its turn, leads to the occurrence of bias voltage $V_b$ on the tunnel junctions under the current contacts and the related increase in tunnel current $I_T$ via the potential barriers separating the top and bottom layers of the structure. As a matter of fact, resistance $R_T$ of the tunnel junctions decreases and the current starts flowing mainly in the bottom layer whose resistance $R_S$ is small as compared to resistance $R_M$ of the manganite layer.

Using the Simmons formula [3] for $I_T$ approximation and the dependence $I_M=V/R_M$ for the current over the manganite layer ($R_M$ values were obtained experimentally at $I \perp I_b$), we described the experimental $V-I$ characteristics with good accuracy (bottom inset in figure 1). The best fitting results were obtained for the potential barrier width $\Delta x=5$ nm and height $\phi_b$ changing with temperature from $\phi_b \approx 0.45$ eV at $T=30$ K to $\phi_b \approx 0.79$ eV at $T=5$ K. The variation of the mean height of the potential barrier may result from the variation of the MnSi electronic structure during the transition to the ferromagnetic state at $T_C \approx 30$ K [4].

The $V-I$ characteristic study in magnetic field $H$ showed that for $I < I_{th}$ both above and below 30 K small negative magnetoresistance is observed whose behavior typical of manganites and value is independent of $I$ (figure 2). This should be expected since at small $I$ the current channel goes almost completely in the LSMO layer. At $I > I_{th}$, when the current channel switches to the bottom layer of the structure, the $H$ effect cardinally changes. Magnetoresistance becomes positive and its value grows with $I$ and reaches 350% at $T=10$ K, $I=100$ $\mu$A, and $H=1$ kOe. The bottom inset in figure 2 demonstrates that the resistance change in such a field nearly stops, i.e., the magnetoresistive effect saturates. Note that the $V-I$ characteristics with a sharp kink at $H=0$ become practically linear in magnetic field. Such a behavior can be explained by reverse current channel switching from the bottom to the top layer under the action of magnetic field. Thus, one can suggest the following scenario. In the absence of magnetic field, due to the magnetostatic interaction between the ferromagnetic layers, magnetizations $\mathbf{M}_M$ and $\mathbf{M}_S$ of the manganite and manganese silicide layers, respectively, which lie in the plane of the structure are antiparallel. In this case, resistance $R_T$ of the tunnel junctions is minimum and at $I > I_{th}$ the current in the structure flows in the bottom MnSi. The applied magnetic field tends to orient $\mathbf{M}_M$ and $\mathbf{M}_S$ parallel. Resistance $R_T$ of the junctions increases and becomes higher than resistance $R_M$ of the manganite film and even at $I > I_{th}$ the current starts flowing mainly in the top manganite layer whose $V-I$ characteristic is linear. Here we should make an assumption that, in our case, the layers forming the magnetic electrodes in the structure are ferromagnets of different type. As is known, only for the magnetic tunnel junction where one electrode is MASC (majority spin carriers) and the other is MISC (minority spin carriers), the junction resistance at parallel orientation of the electrode magnetization will be higher than that at antiparallel one [5].

One more interesting result is the effect of optical radiation on the transport properties of the magnetic tunnel structure in the CIP geometry (figure 3). The photoinduced variations in the transport properties of the structure are reversible and tend to saturation at the radiation power densities $P>20$ mW/cm². The changes are observed over the entire $V-I$ characteristic. The $V-I$ characteristic obtained under the action of radiation is similar to that without radiation, but the current value at which the sharp $V-I$ characteristic kink occurs, which corresponds to current channel switching, is considerably lower; as a result, voltage $V$ on the structure contacts drops. In magnetic field, the character of the photoinduced changes is the same, but the value of the effect increases. With an increase in power, the $V-I$ characteristics resulted from the effect of optical
radiation in magnetic field approaches the dependences obtained in zero magnetic field. One can see in the inset in figure 3 that light suppresses the magnetoresistive effect.

The study of spectral dependences shows that the photovoltaic effect is threshold, i.e., it appears only at $h\nu > 1.17\ eV$. The analysis of the results obtained under the different conditions makes it possible to conclude that the mechanism of interband light absorption in the dielectric spacer of the structure works [6]. This process makes an additional (aside from tunnel) contribution from the photogenerated carriers to the total current via the junction, thus controlling current channel switching between the top and bottom layers of the structure. The action of light both with and without magnetic field leads to the occurrence of switching from the top low-conductive layer to the bottom high-conductive one already at small $I$. Consequently, after such switching the $V-I$ characteristic branch goes much lower, or corresponds to smaller $V$, as compared to the situation when optical radiation is absent.

**4. Summary**

We have demonstrated the possibility of controlled current channel switching between different layers of the magnetic tunnel structure in the CIP geometry.

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