Current-Induced Resistive Effect in $Cu/MgO/La_{0.9}Sr_{0.1}MnO_3$ Trilayers on $SrTiO_3$ (001) Substrates *

FENG Jia-Feng(丰家峰)[1], ZHAO Kun(赵昆)[2,3**], HUANG Yan-Hong(黄延红)[2], ZHAO Jian-Gao(赵见高)[1], LÜ Hui-Bin(吕惠宾)[2], HE Meng(何萌)[2], HAN Xiu-Feng(韩秀峰)[1], ZHAN Wen-Shan(詹文山)[1]

[1] *State Key Laboratory for Magnetism, Beijing National Laboratory for Condensed Matter Physics, Institute of Physics, Chinese Academy of Sciences, Beijing 100080*

[2] *Key Laboratory of Optical Physics, Beijing National Laboratory for Condensed Matter Physics, Institute of Physics, Chinese Academy of Sciences, Beijing 100080*

[3] *International Center for Materials Physics, Chinese Academy of Sciences, Shenyang 110016*

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$Cu/MgO/La_{0.9}Sr_{0.1}MnO_3$ pillars are fabricated on $SrTiO_3$ (001) substrates by the micro-fabrication patterning processes. Their electric transport properties have been measured in the temperature range from the temperature smaller than the Curie one to 300 K. At 125 K there emerges abrupt breaks of output voltage in voltage–current (V–I) curves, corresponding to switching in resistance to metastable states, and finally two closed loops are formed with double threshold biases. Around room temperature the V–I characteristics are non-ohmic and show some gradual hysteresis when sweeping the current in a round-trip scan. A large current-induced resistive change $\Delta R/R_0$, $\sim -63.2\%$, is obtained under a current density of 1.0×10^4 $A cm^{-2}$. Especially, $\Delta R/R_0$ depends linearly on the applied current and is independent of the applied magnetic field. The current-induced resistive effect should be of interest for various applications such as switching and field effect devices.

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The doped manganite $La_{0.9}Sr_{0.1}MnO_3$ (LSMO) is a low-temperature ferromagnetic insulator and a high-temperature paramagnetic one, and its Curie temperature (T_C) is about 145 K.[1] No obvious colossal magnetoresistance (CMR) in LSMO has been detected due to the insulating characteristic near T_C. Since LSMO can serve as a p-type doped manganite, it can make of epitaxial *p-n* junctions with an *n*-type semiconductor,[2−6] and large positive magnetoresistance (MR) in a low magnetic field has been observed in the p–n junctions.[4−6] However, if LSMO is replaced by $La_{0.8}Sr_{0.2}MnO_3$, the MR ratio is very low.[6] In addition, similar results have been found in p–n junctions made of $La_{0.9}Te_{0.1}MnO_3$/Nb-doped $SrTiO_3$.[7] All these suggest that such doped manganites as LSMO and $La_{0.9}Te_{0.1}MnO_3$ may present some fancy phenomena if we design some special structures with them.

In this Letter, current-induced resistive effect is discovered in pillars of Cu/MgO/LSMO. There appears to be two breaks of output voltage in voltage–current (V–I) curves below T_C, which corresponds to switching to metastable low resistance states, and finally two closed loops are formed. Furthermore, around room temperature the V–I characteristics are non-ohmic with some hysteresis, and large current-induced resistive effects are induced.

LSMO (100 nm) thin films were prepared on the insulating $SrTiO_3$ (001) substrate by a computer-controlled laser molecular-beam epitaxy (laser-MBE).[6] The x-ray diffraction measurements show the thin films were grown epitaxially from the substrate. To avoid reaction and diffusion between LSMO and common metal at the interface, a thin MgO layer with the thickness of about 0.5 nm was sputtered on LSMO by magnetron sputtering with an MPS-4000-HC7 system made by ULVAC in Japan. Subsequently, a Cu (10 nm) layer was deposited on MgO to protect it from possible damage. Thereafter, the micro-fabrication patterning processes were carried out as follows: two 40-μm-wide bottom electrodes were created by optical lithography and Ar ion-beam etching; then four ellipse-pillar-like pillars with the active area of $3\times6\pi$ μm^2 and the thickness of about 60 nm were defined using the same conditions as the first one. To insulate the sample, a 60-nm-thick SiO_2 layer was deposited by dc rf magnetic sputtering and selectively removed by lift-off. Finally, a top electrode layer of Cu (200 nm) was deposited to make a connection with pillars for transport measurements. Here LSMO (100 nm) serves as pillars and bottom electrodes simultaneously. The cross-sectional schematic of the sample and the circuit configuration about four-probe technique are presented in Fig. 1, and an output voltage V can be obtained when a current I is applied on the pillars. All measurements were performed us-

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** Email: kzhao@aphy.iphy.ac.cn

ing a physical property measurement system (PPMS) by a standard four-probe technique with a current-perpendicular-to-plane (CPP) geometry in a dc current mode. A Keithley 2400 SourceMeter was selected as the current source and a Keithley 2182 NanovoltageMeter as the output voltage reading instrument. To minimize the influence of Joule heating, the measuring current was kept smaller than 10 mA, and the interval time between two data was selected to be 10 s to effectively eliminate the heating effect. All the pillars show similar current-induced resistive effects.

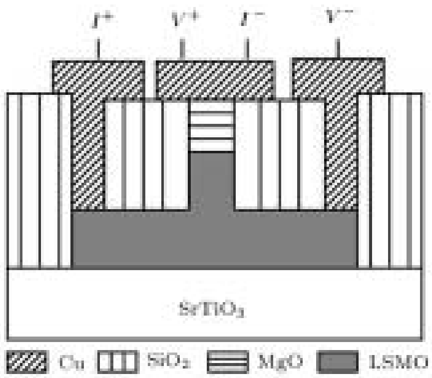

Fig. 1. The cross-sectional schematic of the sample and the measuring circuit configuration about four-probe technique.

Figure 2 (a) shows the V–I characteristic of a pillar at 125 K, and two symmetrical closed loops are obtained. When the loop starts emerging at a threshold current $I_{\rm th1}$, V falls down abruptly corresponding to a switching in resistance to metastable state, and the pillar remains at the low resistance state till the V increases sharply at another threshold current $I_{\rm th2}$. If a magnetic field ($\mu_0 H$) is applied parallel to the pillar surface, $I_{\rm th1}$ and $I_{\rm th2}$ augment irregularly and the loop area becomes smaller gradually with increasing $\mu_0 H$, as shown in Figs. 2(b) and 2(c). In particular, the loops in the V–I curve disappear completely under a field of 4 T. Furthermore, similar interesting phenomena are attained in the curve of resistance R versus $\mu_0 H$ at 125 K, as shown in Fig. 3. Two abrupt breaks of the resistances emerge at $\pm$(1.5–2) Tesla after a treatment under a magnetic field applied parallel to the surface of the pillar, suggesting that more ferromagnetic domains come forth abruptly and lead to a steep drop in resistance.[8]

Nonlinearity in the V–I curves and the resistance jump at a threshold bias are also reported by other groups,[9–13] which can be explained by phase separation concomitant percolation conductivity by filamentary paths. In contrast, two threshold currents with $I_{\rm th1} < I_{\rm th2}$ appear when sweeping forward bias up or backward one down in our case. A simplified model can be given on the origin of the resistivity jumps. Based on our magnetization measurement, the LSMO (100 nm) thin film shows an in-plane magnetic anisotropy, suggesting that the magnetic moment $\boldsymbol{m}_1$ in the bottom LSMO electrode is in the ab plane and perpendicular to the [001] direction. The moment $\boldsymbol{m}_2$ in the LSMO pillar may be parallel to the [001] axis, $\boldsymbol{m}_2 \perp \boldsymbol{m}_1$, if its c-axis magnetocrystalline anisotropy field is larger than demagnetization one. Upon application of a current I, the conduction electrons are spin-polarized and are forced to move forward whether or not their spin is parallel to neighbouring localized spin which will align themselves to some degree with the magnetic field induced by the bias current. Note that the current-induced magnetic field is perpendicular to the c-axis not only in the LSMO electrode but also in the LSMO pillar. When I exceeds $I_{\rm th1}$, a low resistance state arrives to indicate $\boldsymbol{m}_2 // \boldsymbol{m}_1$, which enhances the transfer of spin-polarized electrons. After the metastable state another high resistance state is reached at $I = I_{\rm th2}$, suggesting $-\boldsymbol{m}_2 \perp \boldsymbol{m}_1$. Although

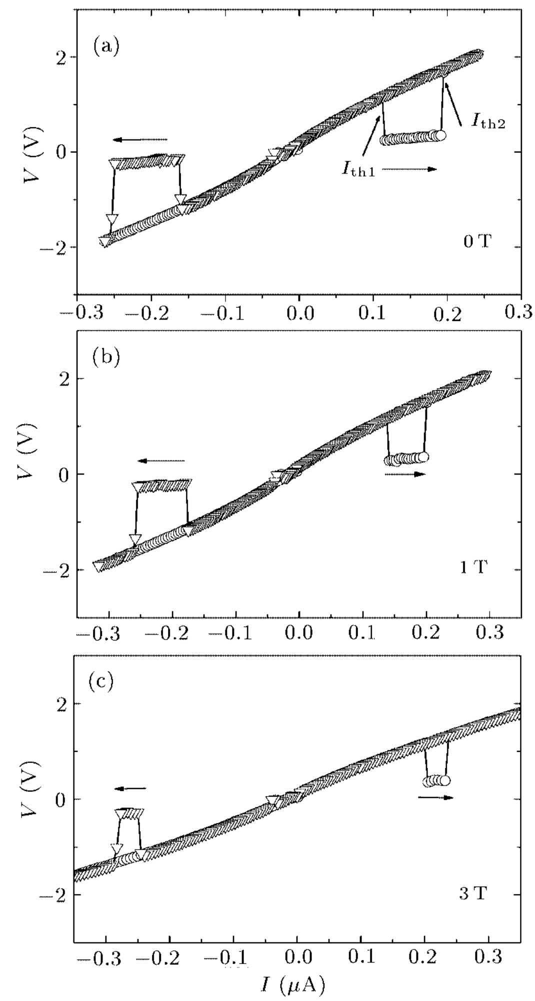

Fig. 2. V–I characteristics of a Cu/MgO/LSMO pillar under different magnetic fields at 125 K. Arrows show the scan directions. $I_{\rm th1}$ and $I_{\rm th2}$ denote the two threshold currents under forward biases.

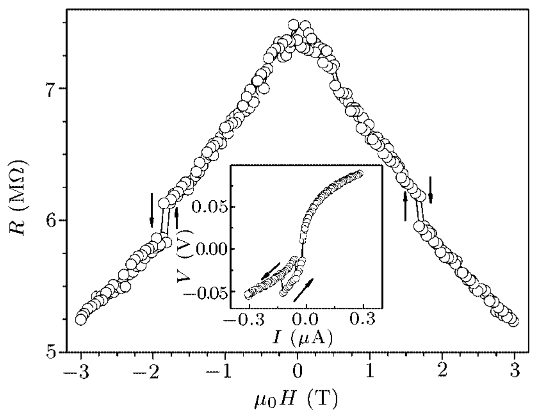

Fig. 3. Resistance R of a Cu/MgO/LSMO pillar as a function of magnetic field $\mu_0 H$ at 125 K under a bias current of 0.2 μA. Inset: the V–I characteristic of an LSMO pillar at 125 K.

the switching of the magnetization in the pillar is a rough sketch, it is reasonable that magnetocrystalline anisotropy may play an important role for this effect. Further study on this nature is in the progress.

Compared with the present trilayer pillar, an LSMO single layer pillar displays an asymmetric V–I curve (inset of Fig. 3) and similar resistance jump behaviour under backward biases to Ref. [14]. As a barrier, the 0.5-nm MgO layer is very thin, suggesting that the tunnelling and pinhole effects through MgO layer coexist in the system. It is unclear why inserting a thin barrier results in a feature of double threshold biases. An assumption of the formation of filamentary conducting paths in manganites may be responsible for the anomalous behaviour.[12]

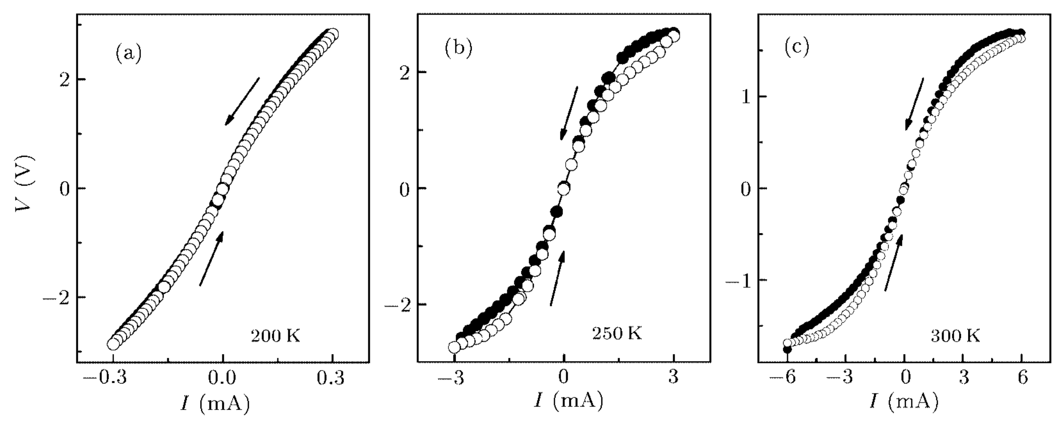

Fig. 4. The V–I curves of a Cu/MgO/LSMO pillar under zero magnetic field at (a) 200 K, (b) 250 K and (c) 300 K, respectively.

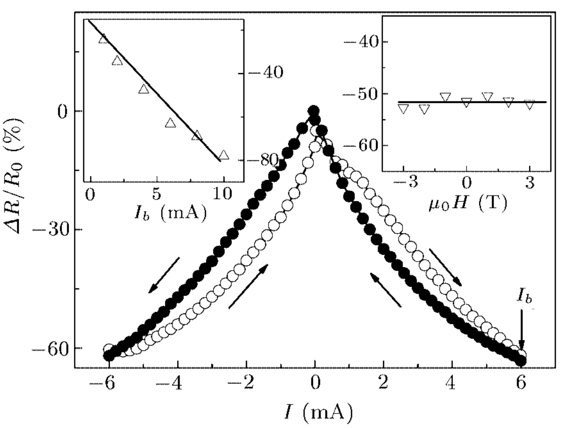

Fig. 5. The $\Delta R/R_0$ ratio at 300 K varying with bias current I under zero magnetic field based on Fig. 4(c). The left inset shows the I_b dependence of $\Delta R/R_0$, and the right one the field dependence. Here I_b denotes the largest bias current applied in the V–I hysteresis curve.

With the increase of temperature, no voltage jump is observed in the V–I curve above T_C ($\sim$ 145 K). As shown in Fig. 4, the V–I characteristics above 200 K is non-ohmic and shows some gradual hysteresis when sweeping the current in a round-trip scan. It is clear that the hysteresis area depends on the temperature. Current-induced resistive change $\Delta R/R_0$ [$\Delta R/R_0 = (R_I - R_0)/R_0$] at room temperature based on Fig. 4(c) is presented in Fig. 5, where R_I is the resistance with the applied current I and R_0 is obtained by extrapolating R_I defined as V–I to the zero-current limit. The $\Delta R/R_0$ ratio is as large as about -63.2% for $I_b = 6$ mA, where I_b denotes the largest bias current applied in the V–I hysteresis curve. Furthermore, $\Delta R/R_0$ is modulated simply by the bias current I_b, and a linear dependence is observed at 300 K (left inset of Fig. 5), in contrast to the results observed in a polycrystalline $Nd_{0.5}Ca_{0.5}MnO_3$ film by Ponnambalam *et al.*[9] and in a heteroepitaxial $CeO_2/La_{0.67}Ca_{0.33}MnO_3$ film structure by Fors *et al.*[14] One point worthy of special attention is that the $\Delta R/R_0$ is steady with respect to the applied magnetic field as illustrated in the right inset of Fig. 5. Such results are observed in the temperature range from 200 K to 400 K, suggesting a potential technological application.

Although the resistance of LSMO is expected to decrease with the increase of the temperature alone in the insulating case, the change of about $70\,\Omega\cdot\mathrm{K}^{-1}$ at 300 K estimated from the resistance data is less by about two orders of magnitude than that of about $4000\,\Omega\cdot\mathrm{mA}^{-1}$ observed at $I_b = 10\,\mathrm{mA}$. Thus simple Joule heating cannot account for the observation of the effect of bias current on the resistivity switching. The nature of this effect at room temperature may relate to percolation conduction by filamentary paths among the insulating regions.[15] When the current applied on the sample increases gradually, more filamentary paths appear and an improved percolation conduction arrives, corresponding to a gradual reduction in resistance. Such a feature with a strong change in resistance under the application of an electric current might be of interest of fundamental physics and of great technological potential for CMR thin films.

In summary, micro-fabricated Cu/MgO/LSMO pillars are studied in the temperature range from the temperature smaller than the Curie one to 300 K. Below T_{C}, symmetrical closed loops in the V–I curves are observed with a feature of double threshold biases, which corresponds to a switching in resistance to metastable low-resistive state. Around room temperature the V–I characteristics are non-ohmic and show some gradual hysteresis, from which a large current-induced resistive change $\Delta R/R_0$ of about -63.2% is obtained under a current density of $1.0\times10^4\,\mathrm{Acm}^{-2}$ at 300 K. Furthermore, $\Delta R/R_0$ depends linearly on the applied current I_b and is independent of the applied magnetic field. The current-induced resistive effect described here may have potential technological applications in switching and other devices.

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