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Current-voltage characteristics with several threshold currents in insulating low-doped $La_{1-x}Sr_xMnO_3$ (x=0.10) thin films

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Abstract: The current-induced resistive switching behavior in the micron-scale pillars of low-doped $La_{0.9}Sr_{0.1}MnO_3$ thin films using laser molecular-beam epitaxy was reported. It was demonstrated that the current-voltage curves at 120 K showed hysteresis with several threshold currents corresponding to the switching in resistance to metastable low resistance states, and finally, four closed loops were formed. A mode was proposed, which was based on the low-temperature canted antiferromagnetism ordering for a lightly doped insulating regime.

Keywords: current-induced resistive effect; manganites; voltage-current characteristic; rare earths

Phase separation is a character of the strongly correlated electronic systems. The effect of electric field on the transport behavior of the doped manganite has attracted much attention owing to its rich physics and great potential in developing electronic devices[1–9]. The majority of studies were carried out in charge-ordered perovskite manganites involving current injection into highly conducting filamentary paths[1] and characterized by a precipitous drop in resistance when the applied bias exceeded a critical value. In general, the accepted explanation to this effect is based on the assumption of creation of the percolation conduction in a mixed-phase state with intrinsic inhomogeneity.

In the doped $La_{1-x}Sr_xMnO_3$ oxides, the various properties rely on the competing balance between the electron-phonon coupling, the ferromagnetic double-exchange coupling, and the Coulomb interaction[10]. A cascade of magnetic and structural phase transformations is observed by changing both Sr-doped content x and temperature T[10]. Previous studies have shown that $La_{0.9}Sr_{0.1}MnO_3$ (LSMO) has a great advantage for practical applications[11]. Kawano et al. concluded that the magnetic ordering is a canted antiferromagnetism (CAF) rather than a spiral order for a lightly doped insulating regime (x<0.17)[12,13]. To enrich the intrinsic feature of mixed-valent manganites, it is important to study the effect of electrical-current on low-doping manganite oxides, which has been much less studied[14].

In this article, the effect of electric current on resistance of low-doped LSMO thin films was focused on. Inspired by the point contact to single ferromagnetic layer[15], a structure with a micron-scale pillar was fabricated. In the voltage-current (V-I) curves at low temperatures below the Curie temperature, several threshold currents have been observed with abrupt breaks of output voltage corresponding to switching in resistance to metastable states, and finally, four closed loops have been formed.

1 Experimental

LSMO (1000 nm) thin films were prepared on $SrTiO_3$ (001) substrates using a computer-controlled laser molecular-beam epitaxy (laser MBE)[11]. To study the resistive switching effect of LSMO, ellipse-like pillars with the active area of $3\times6\pi$ μm^2 were created by a mirco-fabrication patterning process. A top electrode layer of Ta (300 nm) was deposited to connect with LSMO for transport measurements. Fig.1 (a) and (b) present the cross-sectional and planar schematic illustrations of the sample, respectively. The structure is named as single layer pillar (SLP). The electrical transport properties of the SLPs were measured using the Physical Properties Measurement System (Model PPMS-

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14T) made in American Quantum Design Com.

2 Results and discussion

As shown in Fig.2, the resistivity of the sample is metallic for T_{CA} (125 K)<T<T_C (145 K), and it is in agreement with that reported by Urushibara[10]. The *V-I* characteristics of the SLPs were measured at 120 K under zero magnetic field. Figs.3 (a) and (b) present the *V-I* curve and the resistance ($R=V/I$) as a function of applied current for a 60 nm-thick SLP, respectively, and the closed loops are obtained symmetrically. At the forward threshold currents, I_{th1}=0.0036 μA and I_{th}=0.092 μA, the voltages drop abruptly, and the SLP shows switching in resistance to metastable low-resistive states. The SLP remains at the low-resistance states till V increases sharply at currents I_{th1}' and I_{th2}'. In the reverse scan, the resistance shows hysteretic behavior and then returns to the original value before switching. In addition, the resistance drop occurs only when the current is increased, which was also observed in our previous work[16].

Similar results are obtained if a current was applied to the SLPs with different thickness. It is noted that four closed switching loops appear in the *V-I* curves, and two threshold

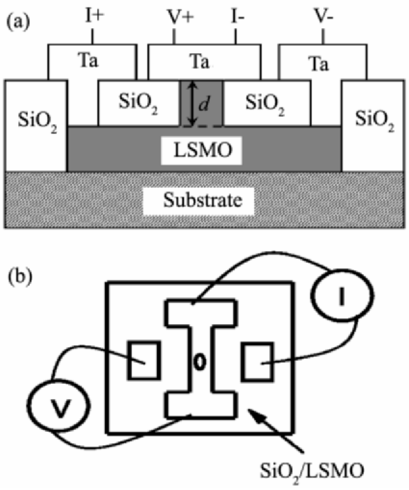

Fig.1 Cross sectional (a) and planar (b) views of the measuring circuit configuration. *d* denotes the thickness of SLP

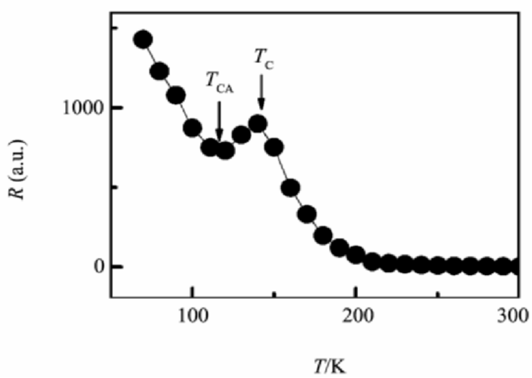

Fig.2 Temperature dependence of the resistance of an SLP

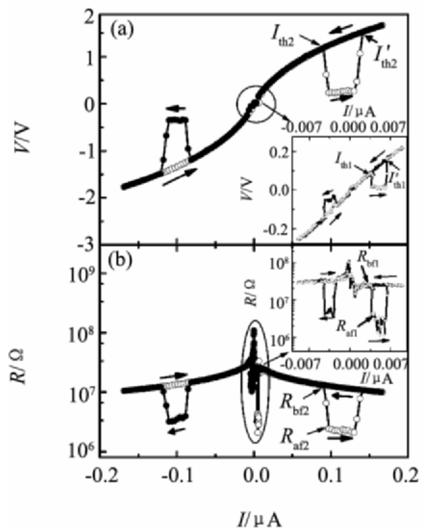

Fig.3 *V-I* characteristic (a) and the corresponding *R-I* curves (b) of a 60 nm thick SLP at 120 K. The insets in (a) and (b) show the close view at low current. I_{th}s and I_{th}'s denote the threshold currents at the switchings, R_{bf}s and R_{af}s the resistances before and after the switching at I_{th}s

currents I_{th1} and I_{th2} set in when the forward bias current sweep across the SLP, which is very different from the resistance drop at only a threshold bias reported by other groups[1-4]. Such switching behavior cannot be simply ascribed to the percolation conduction alone.

Fig.4 shows the DR/R value and the threshold current I_{th} as a function of the thickness (d) of the SLP. Here, $DR/R=(R_{bf}-R_{af})/R_{af}$, R_{bf}, and R_{af} denote the resistances before and after the switching at I_{th} (see Fig.3(b)). We note that both DR/R and I_{th} strongly depend on the SLP thickness. With the increase of d from 15 to 180 nm, the I_{th1} decreases from 0.02 to 0.002 μA, as well as the I_{th2} from 0.3 to 0.016 μA. As for the first switch at the I_{th1}, DR/R increases from 30% to 2300% and from 10% to 2000% for the second one at the I_{th2}.

On the basis of the experimental observation mentioned above, there are several possible consequences for the switching effect. The first one is the contacting effect between common metal Ta and LSMO. An experiment just without the LSMO pillar (d=0) was carried out, and no switching effect was found in the *V-I* characteristics, suggesting that the additional contact resistances existing between the Ta and the LSMO layer make a negligible contribution to the switching behavior. In addition, this experiment also remove the possible contribution of the bottom electrode LSMO to the switching effect because the current density of bottom electrode is sufficiently low and the magnetization reversal driven by spin-polarized current is difficult[15]. However, when a SLP mentioned above is introduced, the spin-momentum transfer could be observed. In particular, when we choose other metals as the top electrode layers[16,17], the same switching effect occurs. These facts suggest that the present behavior is as a result of the intrinsic factor of LSMO.

To provide insight into the nature of this phenomenon, we also measured the *V-I* characteristics of $La_{0.7}Sr_{0.3}MnO_3$ SLP, and no switching was observed. Thus, a simplified model is proposed according to the CAF ordering of LSMO at low temperature[12,13]. Fig.5 illustrates schematically the origin of this switching behavior. As shown in Fig.5 (a), the magnetic order is homogeneous before switching. *A* denotes the CAF states in the bottom electrode below the dashed line, which can be as a static region[15]. *B* denotes the free CAF states,

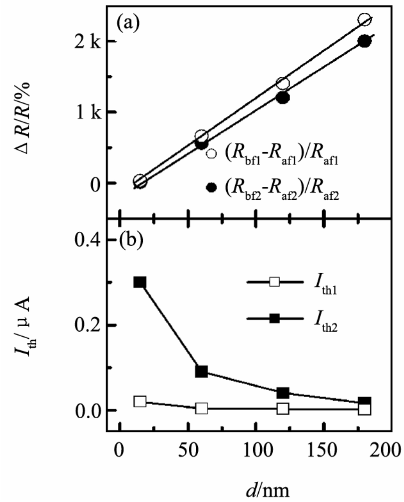

Fig.4 *DR/R* value (a) and the threshold current I_{th} (b) as a function of the SLP thickness *d*

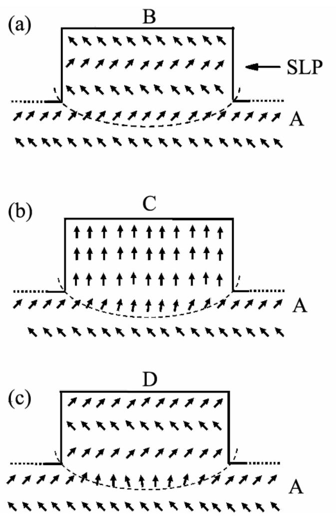

Fig.5 Cross sectional schematic illustration of the model related to the switching behavior for (a) $I<I_{th1}$; (b) $I_{th1}<I<I'_{th1}$; (c) $I'_{th1}<I<I_{th2}$. *A* is the "static" CAF state of the bottom electrode. *B*, *C* and *D* denote the "free" magnetic states at $I<I_{th1}$, $I_{th1}<I<I'_{th1}$ and $I'_{th1}<I<I_{th2}$, respectively. The arcate dashed line marks the boundary between the free and static regions

which are mainly in the SLP and some in the bottom electrode above the dashed line due to the exchange coupling. It is reasonable that the state *A* remains fixed on the spin-momentum transfer process, whereas the state *B* is sensitive to the spin-polarized current[15]. A ferromagnetic state *C* may be easily obtained by the current injection due to the spin-momentum transfer from spin-polarized carriers to a ferromagnetic SLP between the electrodes (Fig.5(b)) [15,18] and then enhances the transfer of spin-polarized electrons resulting in a low resistive state when the applied current exceeds I_{th1} (see the inset of Fig.3(b)). It may be easy for another spin-canted state *D* different from *A* in the SLP to arrive at I'_{th1} after the first metastable state (Fig.5(c)) because the canted feature is intrinsic in LSMO[12,13], corresponding to the higher resistive state. With the increase of the bias current, the second switching at I_{th2} appears again owing to the emergence of the state C. This rough sketch suggests a process of B→C→D→C→B under forward bias currents in the SLP.

From the analysis mentioned above, it is the spin-momentum transfer that is responsible for the switching effect, although the current densities in the SLPs are about one order of magnitude lower than those in Ref.[18]. Currently, it is not clear why no switching to low resistive states is observed above I'_{th2}. The reason may be that a local magnetic field induced by very large currents strengthened the exchange coupling between the free and static regions[19], leading to the difficult transfer of the states.

3 Conclusion

In summary, the *V-I* characteristics was studied in pillars of single-layer LSMO thin films on STO substrates. It is demonstrated that the *V-I* curves at 120 K showed hysteresis with several threshold currents corresponding to the switching in resistance to metastable low-resistance states. A mechanism, based on the low-temperature CAF state, was proposed. The suggested model is fairly simplified, and further studies on the real origin of multithreshold bias currents are highly expected.

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