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Anisotropic current-induced electroresistance effect in low-doped $La_{0.9}Sr_{0.1}MnO_3$ thin films

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Abstract

We have studied the giant negative electroresistance (ER) in strips and pillars of single-layer $La_{0.9}Sr_{0.1}MnO_3$ films fabricated by microfabrication patterning processes, and observed the different voltage–current (V–I) characteristics under current-in-plane (CIP) and current-perpendicular-to-plane (CPP) measurement modes, around room temperature. For the CIP mode, V–I curves show an asymmetry with jumps at the negative bias currents, while a symmetrical hysteresis against the polarity for the CPP one. The mechanism is illuminated in the letter. Furthermore, a large ER is obtained for both modes and the ER ratios increase monotonically with the temperature and bias current, suggestive of a promising potential in future device developments.

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Keywords: Manganites; Thin films; Electrical transport properties

1. Introduction

The doped manganites with a perovskite-type structure based on the $Re_{1-x}A_xMnO_3$ (Re = rare-earth ions, A = alkaline ions) have received much attention in recent years. Apart from understanding the basic mechanism underlying the colossal magnetoresistance (CMR) effects [1–3], much effort has been concentrated on obtaining a large room-temperature resistance change for the sake of their potential applications [4–7]. There are several reports on the effect of electric current on mixed-valent manganites, indicating that the electric current can reduce the resistivity dramatically and result in an electroresistance (ER) [8–17]. The effect has been explained in terms of the current-induced increase of the conducting phase in the phase-separated samples [11] or the effect of the magnetic field produced by the electric current [14].

In $La_{1-x}Sr_xMnO_3$ oxides, the various properties rely on the competing balance between three energy scales, the Jahn–Teller nature of the Mn^{3+} ions and so the electron–phonon coupling, the kinetic energy associated with the carrier delocalization leading to ferromagnetic (FM) double-exchange coupling and a metallic state, and finally the Coulomb interaction producing a charged localization and eventually ordering [18]. Interestingly enough, recent studies on $La_{0.9}Sr_{0.1}MnO_3$ (LSMO) have shown that this low-doped manganese oxide has a great advantage for practical applications at room temperature [6,7,19,20]. In this paper, we report on experiments concerning the

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electrical-current influence on resistivity of low-doped LSMO films. It is demonstrated that the current-induced ER effect depends on the different measurement modes, current perpendicular to plane (CPP) and current in plane (CIP). In particular, large dramatic ER values are reached for both modes. Here, ER is defined as $\Delta R/R_0 = (R_I - R_0)/R_0$, 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 strong dependence of resistance on a current near room temperature would be of great interest not only for fundamental physics but also for potential technological applications.

2. Experimental procedures

LSMO films with the thickness of about 200 nm were deposited on $SrTiO_3$ (0 0 1) (STO) substrates by the laser molecular beam epitaxy [21]. An in situ reflection high-energy electron diffraction (RHEED) system and charge coupled device (CCD) camera were used to monitor the growth process of the LSMO thin films. As shown in Fig. 1(a), the streaky and bright RHEED pattern clearly indicates that the films had a good crystallized structure

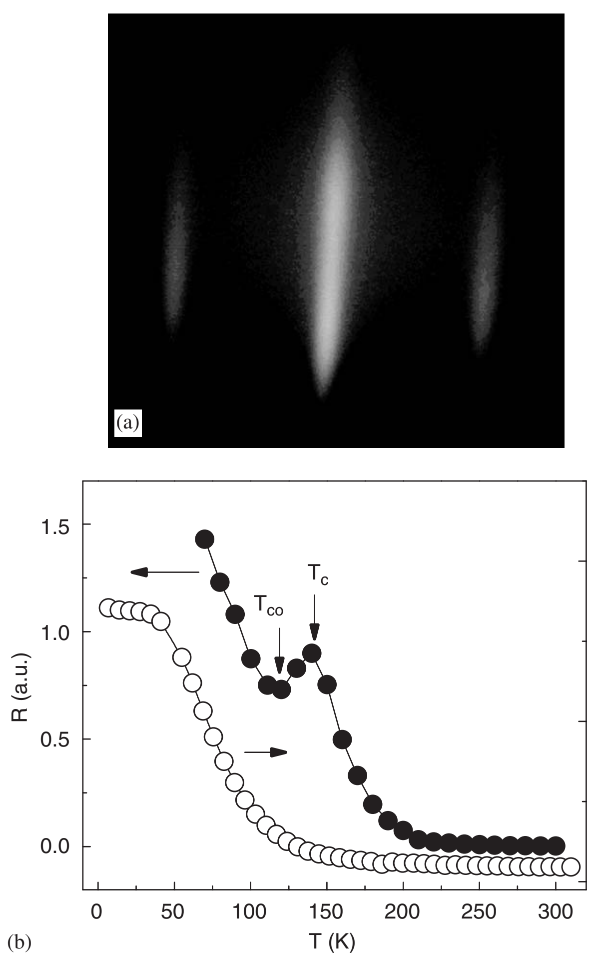

Fig. 1. (a) RHEED pattern of 200 nm LSMO film on STO (0 0 1) substrate, and (b) temperature dependence (heating) of the resistance R (T) and magnetization M (T) for LSMO film.

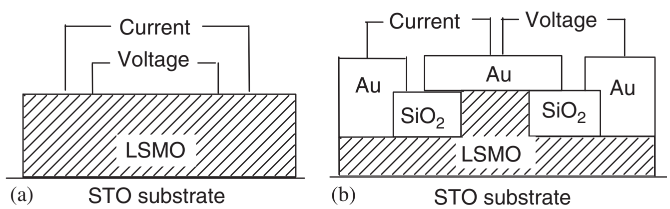

Fig. 2. The cross-sectional views of two samples and their measuring circuit configurations about four-probe technique.

and smooth surface. Fig. 1(b) presents the temperature dependence (heating process) of the resistance R (T) and magnetization M (T). The characteristic transition temperatures, occurring at $T_C \approx 145$ K and $T_{CO} \approx 125$ K, can be clearly appreciated and in agreement with those reported by Urushibara et al. [18], corresponding to, respectively, the onset of FM and metallic state and the temperature where carriers become localized and thus the resistivity strongly increase.

To measure the ER effect, the micro-fabrication patterning process was carried out for LSMO (200 nm)/STO samples. Sample 1 was patterned into strips of 100 μm in width and 1 mm in length by optical lithography and Ar ion-beam etching using chromium masks. For Sample 2, several ellipse-like pillars were created with the active area of $3 \times 6\pi\,\mu m^2$ and the thickness of about 60 nm. A 60-nm thick SiO_2 was used to insulate the sample, and a top electrode layer of Au (200 nm) was deposited for transport measurements. Fig. 2 presents the cross-sectional views of two samples and their four-probe circuit configuration. The point contacts are realized by ultrasonic soldering using gold line with the diameter of 20 μm. All measurements were performed in a DC current control mode using physical properties measurement system (PPMS) made by Quantum Design Inc., USA.

3. Results and discussion

Fig. 3(a) shows a series of V–I curves of Sample 1 taken at several temperatures, which display a strong anisotropy with respect to the direction of current. The resistance of the sample is much lower under the positive currents than that under the negative one. Giving an example, the output voltages under the currents of $\pm$ 0.25 mA are +18.8 and −32.3 V, respectively, at 300 K. Such an asymmetry in resistance may be attributed to phase separation and the coexistent FM phases with different orbital order as suggested in Ag–$La_{0.8}Ca_{0.2}MnO_3$ films by Hu and Gao et al. [15]. The most intriguing feature is that the jumps in the V–I curves appear at the negative current range. For instance at 300 K, in the forward and reverse direction, the jump occurs at threshold currents of −0.03 and −0.05 mA, respectively. The magnitude of the jump reduces gradually with temperature. Similar behaviors have been detected in different manganite systems [9,10,22,23]. The jump in $Pr_{1-x}Ca_xMnO_3$ is attributed to the collapse of the charge-ordered state induced by an electric field and the forming

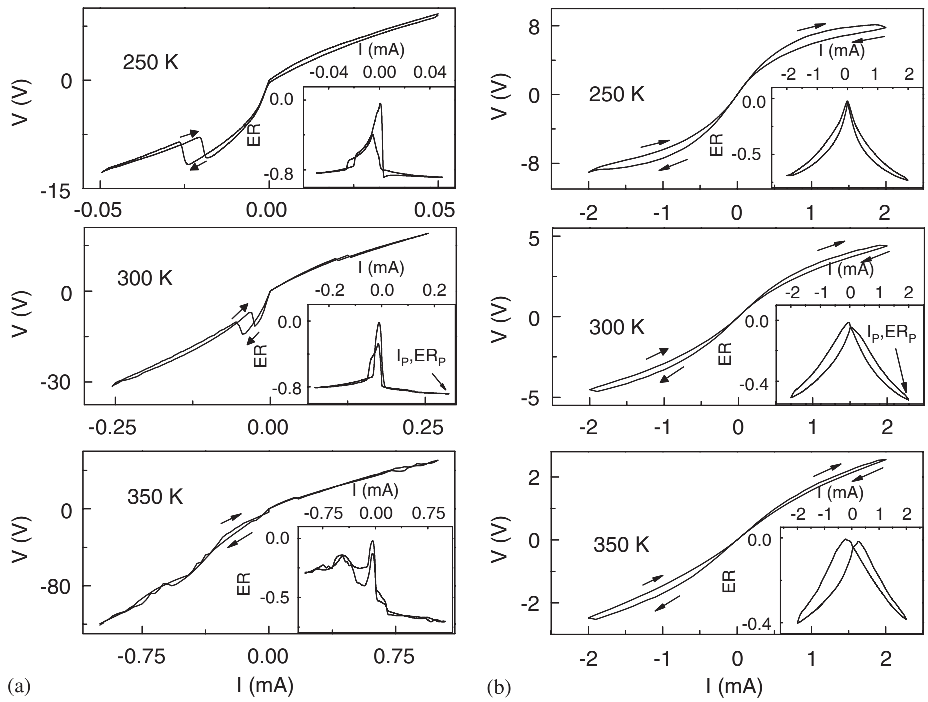

Fig. 3. The *V–I* hysteresis loops of (a) Sample 1 and (b) Sample 2 under zero magnetic field at 250, 300 and 350 K, respectively with arrows indicating the direction of the sweep. Insets show the corresponding ER curves at different temperatures. ER_P denotes the ER value at a peak current I_P.

of the FM clusters [9,10,22]. Tokunaga et al. [23] have suggested that their observations in $(La_{0.7}Pr_{0.3})_{0.7}Ca_{0.3}MnO_3$ are due to current-induced collapse of the phase separation through a local heating. It is found the jumps of resistance are associated with the inhomogeneous feature in the doped manganites as discussed in Refs. [9,10,22,23]. The jump in our case will be discussed later. Furthermore, large ER is attained from the *V–I* hysteretic curves as shown in the insets of Fig. 3(a). At 300 K, ER can reach −87.7%, denoted as ER_P at $I_P = 0.25$ mA, which is the largest bias current applied in the *V–I* curves. Similar results are observed at 250 and 350 K.

Different from that of Sample 1, the *V–I* behavior of Sample 2 is symmetrical against the polarity (see Fig. 3(b)), and the voltage in forward-scan mode is always larger than that in the backward-scan one. It is clear that the hysteretic characteristic becomes weak gradually with increasing temperature. In particular, the ER_P values reach −73.2%, −52.3% and −40.2% for 250, 300 and 350 K, respectively, at $I_P = 2\,mA$ (see the insets of Fig. 3(b)).

The effect for different measuring modes reveals that the resistance of LSMO is sensitive to current as presented in other manganites [11,22–24]. As reviewed in Figs. 4(a) and (b), the ER_P values increase with temperature at a fixed current and bias current at a fixed temperature. It is ascertained that the ER effects are not attributed to local heating. Give an example of Sample 2, the resistance change, $\sim 70\,\Omega\,K^{-1}$ at 300 K estimated from the resistance data, is much smaller than that observed, $\sim 4000\,\Omega\,mA^{-1}$ at $I_P = 10$ mA. Thus, simple Joule heating cannot account for the present work, quantitatively at least.

Fig. 5 presents the current dependence of the magnetoresistance (MR) of Sample 2 under different magnetic fields. Here MR is defined as $(R_{IH}-R_{I0})/R_{I0}$, where R_{IH} and R_{I0} denote the resistances under a fixed current *I* with an applied magnetic field *H* and without it. It is found that the MR ratio increases with *H*, indicating that the FM phase may exist even around room temperature which was confirmed by our magnetic loop measurement (see the inset of Fig. 5). Such a phenomenon agrees with the fact that the FM clusters were found to exist up to $2T_C$ [25]. In addition, the ER effect is strongly correlated with the MR effect as reported in Ref. [14]. A rough estimation shows that 1-nm-wide filamentary path biased with a current of 1 mA can produce a magnetic field of about 10 kOe [14], thus, it is evident that the MR values will monotonically reduce with increasing current as displayed in Fig. 5.

According to the percolation model, local electric fields perturb the coexistence of phases of the different electric densities and set up filamentary currents across nonconductive regions. Current flow through space, limited within the filamentary regions, induces an intense local magnetic field, which may in turn further polarize the ferromagnetic regions. It is noted that our data is obtained around room temperature, suggestive of magnetic and electronic phase separation can persist above T_C as discussed by Causa et al. [26].

Different from that in CIP mode, the *V–I* hysteretic curves in CPP one shows symmetry and no jump, and the resistance decreases gradually with increasing current in both bias polarities. Such a distinctive behavior in the *V–I* characteristics for two measuring modes should be

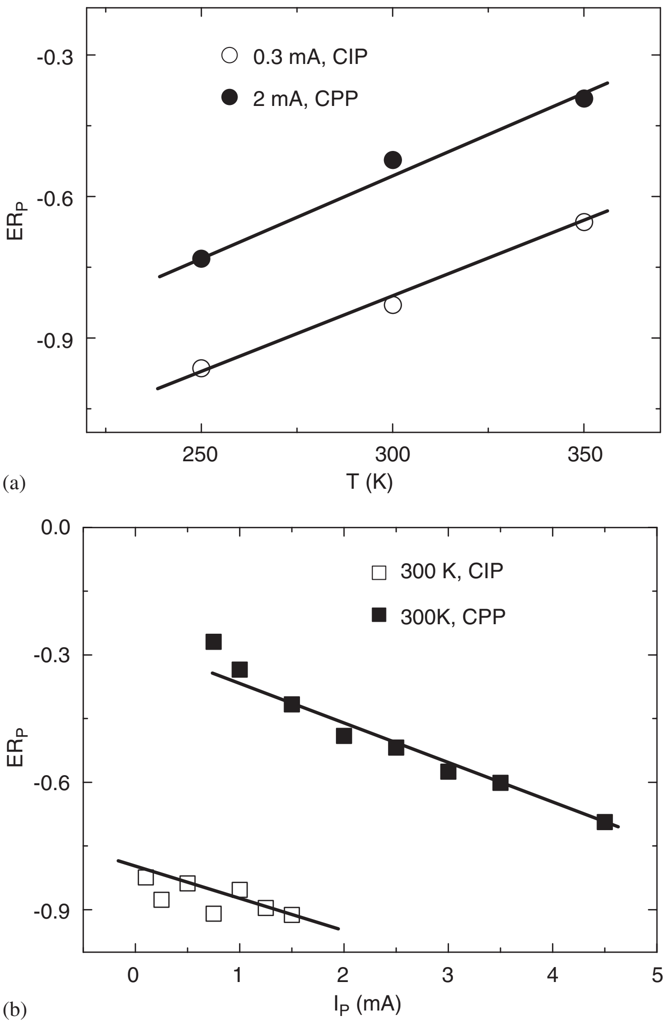

Fig. 4. ER_P as functions of (a) temperatures at 2 and 0.3 mA and (b) peak current I_P at 300 K for different measurement modes.

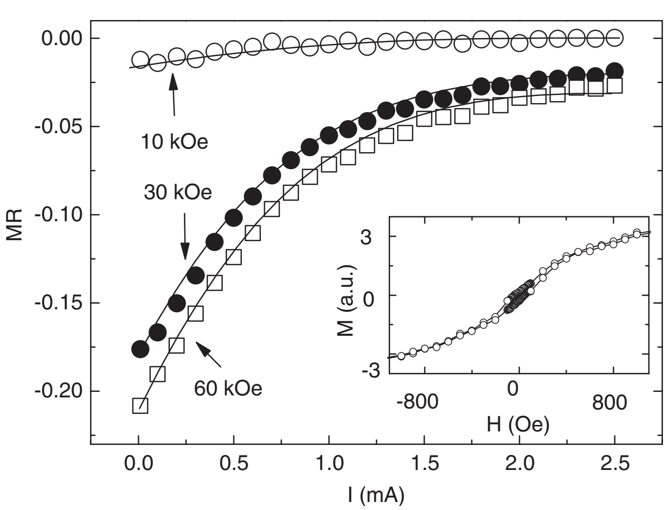

Fig. 5. Bias current dependence of MR at several magnetic fields for Sample 2 at 300 K. The inset shows the magnetic loop of LSMO film at 300 K.

attributed to the anisotropic transport properties of LSMO in *a–b* plane and *c*-axis, suggesting that two FM phases with different orbital order exist between them [15]. It is known that a Jahn–Teller distorted orthorhombic phase dominates in LSMO around room temperature [27]. The distorted degree of the phase may be altered by a spin-polarized current. The low-doped LSMO shows a FM coupling in *a–b* plane and a weak antiferromagnetic interplane coupling in *c* axis [28]. At a threshold current, the planar FM coupling may cause the resistance to drop abruptly due to the magnetic clusters rearranging and merging together with the increase of the electron transfer, which corresponds to a jump in the output voltage.

4. Conclusion

In summary, the *V–I* characteristics of LSMO films have been carried out under CIP and CPP measuring modes around room temperature. The former shows an asymmetry with jumps at negative bias current, while the latter gives a symmetrical hysteresis. A large ER is obtained for both, and the ER ratios increase with temperature and bias current. 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.

Acknowledgments

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