Electric current-induced giant electroresistance in $La_{0.36}Pr_{0.265}Ca_{0.375}MnO_3$ thin films*

Yinghui Sun(孙颖慧)[1], Yonggang Zhao(赵永刚)[2,3], and Rongming Wang(王荣明)[1,†]

[1] *Beijing Key Laboratory for Magneto-Photoelectrical Composite and Interface Science, School of Mathematics and Physics, University of Science and Technology Beijing, Beijing* 100083, *China*

[2] *Department of Physics and State Key Laboratory of Low-Dimensional Quantum Physics, Tsinghua University, Beijing* 100084, *China*

[3] *Collaborative Innovation Center of Quantum Matter, Beijing* 100084, *China*

(Received 27 December 2016; revised manuscript received 22 January 2017; published online 20 February 2017)

The electroresistance (ER) of $La_{0.36}Pr_{0.265}Ca_{0.375}MnO_3$ (LPCMO) epitaxial thin film was studied under various dc currents. The current effect was compared for the unpatterned film and patterned microbridge with a width of 50 μm. The value of ER in the unpatterned LPCMO film could reach 0.54 under a 1-mA current, which is much higher than ER under 1 mA for the patterned weak phase-separated $La_{0.67}Ca_{0.33}MnO_3$ and $La_{0.85}Sr_{0.15}MnO_3$ microbridges with 50-μm width. More interestingly, for the patterned LPCMO microbridge, the maximum of ER can reach 0.6 under a small current of 100 μA. The results were explained by considering the coexistence of ferromagnetic metallic phase with the charge-ordered phase, and the variation of the phase separation with electric current.

Keywords: manganites, electroresistance, phase separation, percolation

PACS: 71.30.+h, 64.75.St, 75.47.Lx, 73.50.–h **DOI:** 10.1088/1674-1056/26/4/047103

1. Introduction

Because of the strong coupling between spin, charge, lattice, and orbital degrees of freedom, colossal magnetoresistive (CMR) perovskite manganites show a variety of electric and magnetic properties. They have been extensively studied due to their importance for both fundamental physics and potential applications.[1–3] In perovskite manganites, there exist different ground states with similar energy stability, depending on the balance of different interactions. Physical properties of manganites can be tuned by external disturbance, such as magnetic field,[4] pressure,[5] and illumination of light or x-ray,[6–10] due to the breaking balance of various interactions in the material.

The electric current effect on properties of CMR materials has also been reported, and it was shown that their resistances can be reduced under electric currents and/or electric fields, leading to the electroresistance (ER) effect and metastable states.[11–20] However, most of these previous reports focused on manganites with charge ordered state,[11] such as $Pr_{1-x}Ca_xMnO_3$ ($x = 0.3$, 0.4) single crystal,[21] polycrystalline bulk or films,[22,23] and $Pr_{0.7}Ca_{0.27}Sr_{0.03}MnO_3$ epitaxial films.[12] The ER and current-induced metastable states can be correlated with the phase separation scenario. The electric current was considered to lead to the melting of the charge ordered phase, i.e., a transition from the charge-ordered insulation (COI) state to the ferromagnetic metallic (FMM) state.[11,12,21,24] The transition is usually thought of as a percolative process with the domains of conducting FM eventually connected, which is accompanied by a large drop of resistivity. The ER effect has also been reported in the weak phase-separation systems, such as $La_{1-x}Ca_xMnO_3$ and $La_{0.67}Sr_{0.33}MnO_3$ films with different doping levels and thicknesses.[25–29] The research of electric current effect in different types of manganites is helpful for the study of mechanisms.

The previous investigation of current or field effect on epitaxial films of manganites with charge-ordered state is quite limited.[24,30] However, recent studies of current or field effect in LPCMO epitaxial films are rising again with different modulation and inspection in the phase separation picture.[31–37] Compared with $La_{1-x}Ca_xMnO_3$ and $La_{0.67}Sr_{0.33}MnO_3$ films, the current effect in LPCMO is expected to be distinct, because the intrinsic charge-ordered phase in LPCMO with a size in the mesoscopic range is easily modulated by electric current or field. In this work, we studied the current effect in $La_{5/8-y}Pr_yCa_{3/8}MnO_3$ epitaxial film with doping level of $y = 0.265$. The current effect was compared in unpatterned film and patterned microbridge with a width of 50 μm. The value of ER in unpatterned LPCMO film under the same current is much higher than those for patterned weak phase-separated $La_{0.67}Ca_{0.33}MnO_3$ and $La_{0.85}Sr_{0.15}MnO_3$ microbridges with 50-μm width. For the patterned LPCMO microbridge, the maximum of ER can reach 0.6 under a small

*Project supported by the National Natural Science Foundation of China (Grant No. 11604010), the Fundamental Research Funds for the Central Universities, China (Grant No. FRF-TP-15-097A1), and the Open Research Fund Program of the State Key Laboratory of Low-Dimensional Quantum Physics, China (Grant No. KF201611).

†Corresponding author. E-mail: rmwang@ustb.edu.cn

© 2017 Chinese Physical Society and IOP Publishing Ltd

current of 100 μA. The results were discussed based on the scenario of phase separation, by considering the coexistence of ferromagnetic metallic phase with the charge-ordered phase, and the variation of the phase separation with electric current.

2. Experimental

$La_{0.36}Pr_{0.265}Ca_{0.375}MnO_3$ (LPCMO) thin films with a thickness of ∼100 nm were grown on single-crystal substrates of $LaAlO_3$ (LAO) with (1 0 0) orientation by using the pulsed laser deposition (PLD) technique. Bulk target of LPCMO were synthesized using a conventional solid state reaction method. The stoichiometric amounts of La_2O_3, $CaCO_3$, Pr_6O_{11}, and MnO_2 powders with high purity were calculated and weighed according to the Pr doping level (0.265). La_2O_3 was baked at 800 °C for 2 hours before weighing, because it is reactive with moisture and CO_2 in air to form lanthanum carbonate and hydroxide hydrate. The powders of raw materials were mixed, ground, and calcined at 1000 °C∼1200 °C for 14 h repeatedly. The product was then finely ground, pressed into pellets and sintered at 1400 °C in air for another 24 h followed by furnace cooling. The target was used to prepare films in a PLD chamber. The films were deposited by using a 248-nm KrF excimer laser. The energy density is about 1.9 J/cm^2 with a repetition rate of 3 Hz. The size of LAO substrate was 3 mm×10 mm×0.5 mm. The substrate temperature was held at 780 °C under an oxygen pressure of 80-Pa during deposition. The film thickness was controlled about 100-nm according to the deposition rate. After deposition, the films were cooled down to 650 °C holding for 5 minutes, and then down to room temperature in oxygen with a pressure of 0.9 atm (1 atm = 1.01325×10^5 Pa).

X-ray diffraction (XRD) was performed by using a Rigaku D/max-RB x-ray diffractometer with a Cu K_α radiation. Powder XRD studies indicated that both the last powder and the target were essentially in single-phase. Some of the LPCMO films were patterned into bridge-shaped samples with a 50-μm width. The electrical resistance was obtained from both unpatterned and patterned samples with sputtered gold pads as the electrical contacts. A standard four-probe configuration for the dc current effect measurements was adopted using a Keithley 2400 SourceMeter and 2182 Nanovoltmeter. The separations between the voltage pads are about 80 μm for the unpatterned sample, and 50 μm for the patterned sample. The electrical measurements were done with a liquid-nitrogen-cooling system.

3. Results and discussion

3.1. Characterization of the polycrystalline LPCMO

XRD pattern of the polycrystalline pellet in Fig. 1 shows that the synthesized target was in single phase. The temperature-dependent resistance of the polycrystalline pellet was measured by four-probe configuration with indium as the electrical contact pads, as shown in the inset of Fig. 1. The peak at ∼ 210 K is related to the charge ordering temperature (T_{co}). The peaks at ∼ 150 K for the cooling process and at ∼ 175 K for the heating process are derived from the insulator–metal transition. The maximum slope of the resistance drop at ∼ 125 K is identified as the Curie temperature (T_C).[38] Below T_{co}, the resistance versus temperature (R–T) curves show a remarkable hysteresis for the cooling and heating processes, which is consistent with the first-order-type transition in a system with two-phase coexistence.[38,39] Our results are similar to the reported temperature dependence of resistivity of $La_{5/8-y}Pr_yCa_{3/8}MnO_3$ polycrystals ($0.25 \leq y \leq 0.275$), though the difference in the doping level ($y = 0.265$ in our case) and in the range of vertical axis. The identification of the two typical temperatures were also reported in single crystal $La_{5/8-y}Pr_yCa_{3/8}MnO_3$.[39] According to the electron microscopy, the sub-micrometer scale phase coexistence was directly observed in $La_{5/8-y}Pr_yCa_{3/8}MnO_3$.[38]

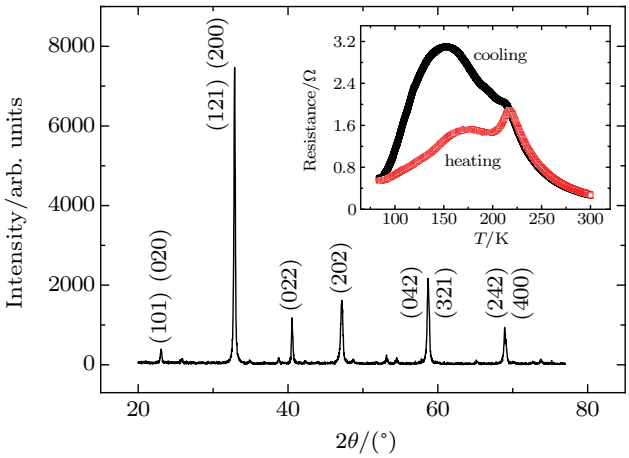


Fig. 1. (color online) XRD of the polycrystalline pellet. Inset: The temperature-dependent resistance of the polycrystalline pellet during cooling (black) and heating (red) processes.

3.2. Characterization of the LPCMO thin films

XRD pattern of the θ–2θ scan for LPCMO thin film in Fig. 2 shows that besides the reflections from the substrates and (00ℓ) peaks of LPCMO, no other peaks are visible with the intensity axis on a logarithmic scale within 20° ∼ 55° (2θ), indicating the films are in single phase and well epitaxially c-axis oriented. The film is under compressive strain induced by the substrates, because the pristine in-plane lattice parameter of LPCMO (pseudocubic structure with $a = 3.85$ Å)[40] is larger than that of LAO (rhombohedral structure with $a =$ 3.788 Å). The out-of-plane lattice parameter of the film is about 3.865 Å, calculated from the position of the diffraction peak 2θ with Bragg diffraction equation. This value verifies the compressive strain in the LPCMO film due to LAO.

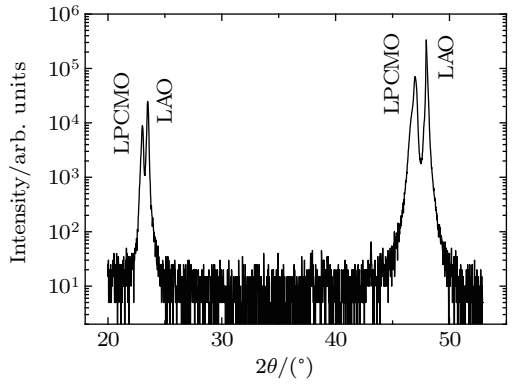


Fig. 2. XRD pattern of the θ–2θ scan for the LPCMO epitaxial film deposited on LAO substrate.

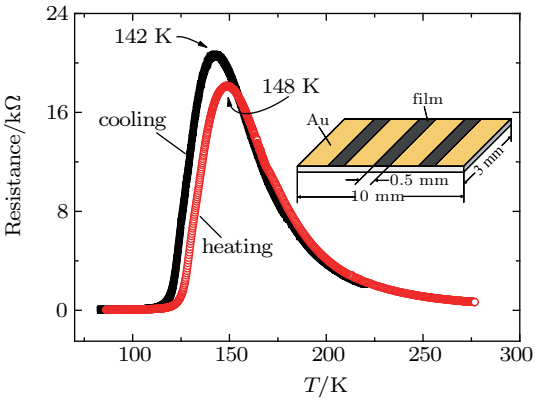


Fig. 3. (color online) Temperature dependence of resistance for the unpatterned LPCMO film under cooling and heating processes. The applied dc current was 0.1 μA during the measurement. The measurement configuration is shown in the inset. The separation between the voltage pads is about 0.5 mm.

Figure 3 shows the temperature dependences of resistance for the unpatterned LPCMO film under the cooling and heating processes, respectively, and the inset is the measurement configuration. The applied dc current was 0.1 μA during the measurement. The R–T curves of the sample reveal a sharp metal–insulator transition (MIT) and a remarkable hysteresis in the cooling and heating processes. The resistance peak appears at about 145 K. This behavior is similar to the results of $La_{0.4}Pr_{0.27}Ca_{0.33}MnO_3$ film grown on LAO substrate[41] and $La_{0.268}Pr_{0.4}Ca_{0.33}MnO_3$ film grown on (110) $NdGaO_3$ substrate.[42] The existence of the remarkable hysteresis of R–T curves is claimed to be a typical phenomenon in phase separation system.[24,34,41,42] A strong hysteresis was also observed in the variation of resistance with external magnetic field in the ultrathin $La_{1-x}Ca_xMnO_3$ film.[26] This hysteresis indicates the coexistence of FMM and COI states in LPCMO films, because the CO transition is a first order phase transition.[38] It is noted that for the case of thin films, there are no observable peaks around 210 K in the R–T curves and with reduced hysteresis compared to that in bulk, which is similar to the R–T behaviors of LaPrCaMnO thin films grown on $LaAlO_3$.[32,41] The strain might be responsible for the different R–T behaviors between bulk and thin films. In epitaxial thin films, the biaxial strain induced by lattice mismatch has a great influence on their electrical transport properties. For example, both the metal–insulator transition and the phase separation can be affected by strain.[28,43] However, strong supportive evidence is still needed.

3.3. Electric current-induced electroresistance

3.3.1. Current effect on the unpatterned films

Figure 4(a) shows the temperature dependences of resistance for the unpatterned LPCMO film under different dc currents. The temperature of the resistance peak (T_p) of this film is about 145 K, comparable to the results of $La_{0.4}Pr_{0.27}Ca_{0.33}MnO_3$ film grown on LAO reported in the literature.[41] The applied currents are 1, 200, 500 μA, and 1 mA, with the corresponding current densities of 0.33, 66.7, 1.67×10^2, 3.33×10^2 A/cm^2, respectively. Figure 4(a) shows that T_p of LPCMO film remains nearly unchanged with increasing electric current, however, the peak resistance drops remarkably. This insensitivity of T_p to current differs from the dependence of T_p on magnetic field as the magnetic field shifts T_p to higher temperatures.[17] This phenomenon can be attributed to the current-induced electroresistance effect.[13–18] Electroresistance (ER) is defined as ER $=$ $(R(1\ \mu A)-R(I))/R(1\ \mu A)$, where $R(I)$ and $R(1\ \mu A)$ stand for the film resistance measured with current I and 1-μA current, respectively. The heating power in this sample is smaller than that in $La_{0.67}Ca_{0.33}MnO_3$ epitaxial films[17,26] where the heating is minor. The key point in this experiment is that the heat produced by the current can be quickly diffused and is averaged by the four large Au pads.

The temperature dependences of ER for this LPCMO film under different currents are shown in Fig. 4(b). Its ER increases with increasing current, and has a peak value at about 130 K with a very narrow full width at half maximum (FWHM). At 130 K, the value of ER could reach 0.54 under a 1-mA current (the current density 3.33×10^2 A/cm^2). This value is larger than ER under 1 mA for patterned $La_{0.67}Ca_{0.33}MnO_3$ (ER $=$ 0.27)[26] and $La_{0.85}Sr_{0.15}MnO_3$ (ER $=$ 0.44) microbridges with 50-μm width as shown in Fig. 5(b). In Figs. 4(a) and 4(b), the studied LPCMO film is unpatterned, therefore the average current density is about 1/60 compared to those in the patterned $La_{0.67}Ca_{0.33}MnO_3$ and $La_{0.85}Sr_{0.15}MnO_3$ microbridges. This means that in the strongly phase-separated LPCMO films with COI and FM coexistence, a relatively small current density can induce remarkable ER. The reason is that COI state in the strongly phase-separated LPCMO is fragile and more easily affected by the external stimuli. On the other hand, in the film with inhomogeneous phase domains, the current will follow the path of low resistance forming a uniform distribution.[37] Therefore, the real current density would be much higher than the calculated average one.

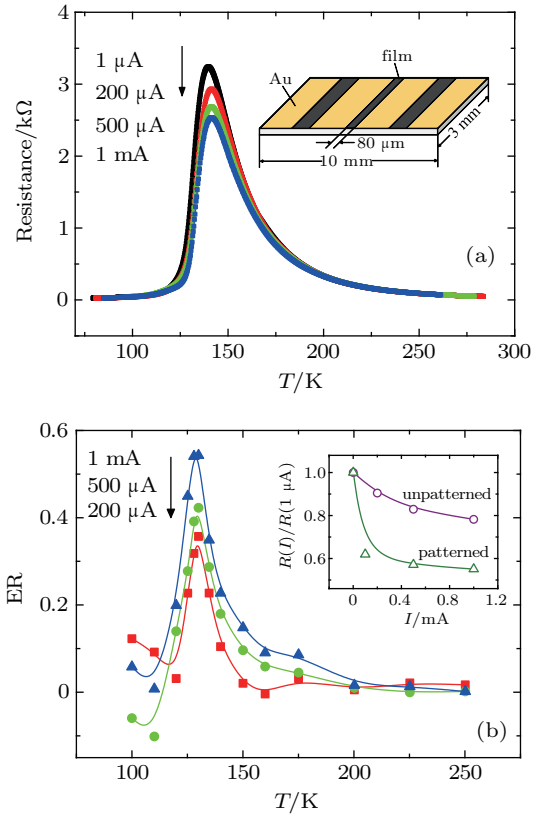


Fig. 4. (color online) (a) Temperature dependence of resistance for the unpatterned LPCMO film under different dc currents. The currents are 1, 200, 500 μA, and 1 mA, with the corresponding current densities of 0.33, 66.7, 1.67×10^2, 3.33×10^2 A/cm^2, respectively. The measurement configuration is shown in the inset. The separation between the voltage pads is about 80 μm. (b) Temperature dependence of electroresistance (ER) under different currents. Inset shows the normalized peak resistance variation with current for the unpatterned and patterned LPCMO film.

3.3.2. Current effect on patterned films

We also studied the current effect for the patterned LPCMO microbridge with a 50-μm width. Temperature dependences of resistance under different dc currents are shown in Fig. 5. No sharp drop or upturn of resistance is observed as reported in the confined LPCMO with narrower wire dimensions of about 1 μm.[44,45] and 10 μm.[32,40] When the applied current is 100 μA, the heating effect is not distinct, because T_p is unchanged compared with that under 1 μA. The local temperature increase ΔT of the film induced by overheating can be evaluated as a function of the applied electric current (I) by the expression of $\Delta T(T,I) \approx 2P_l/\kappa_{sub} = 2I^2R(T+\Delta T)[l\kappa_{sub}]$, where P_l is the power dissipated per unit length of the sample, κ_{sub} is the thermal conductivity of the substrate, R and l are the resistance and length of the sample, respectively.[46] It is found that, under 100 μA, the maximum ΔT is about 0.6 K at 135 K, and 0.3 K at 130 K. Therefore, Joule heating is a minor effect under this current and the observed ER is an intrinsic effect. The peak resistance drops more remarkably as compared with that in Fig. 4(a), which is verified by the normalized peak resistance decrease with current for the unpatterned and patterned films in the inset of Fig. 4(b). The peak resistance displays an exponential decay with a faster decay rate for the patterned films. However, when the applied current is larger than 500 μA, the heating effect becomes obvious that we can observe the decrease of T_p. The maximum ΔT is estimated about 14 K at 135 K under 500 μA, which is not negligible. When the applied current reaches 1 mA, the measured R–T behavior indicates the local overheating is high and not negligible. Compared with the unpatterned films, the current density enhances by about 60 times under the same applied currents. When the applied current is 100 μA, the maximum ER is about 0.6, as shown in the inset of Fig. 5. This value is even larger than that for the unpatterned film under 1 mA current. The ER shoulder between 145 K and 200 K is probably related to the two-phase coexistence.

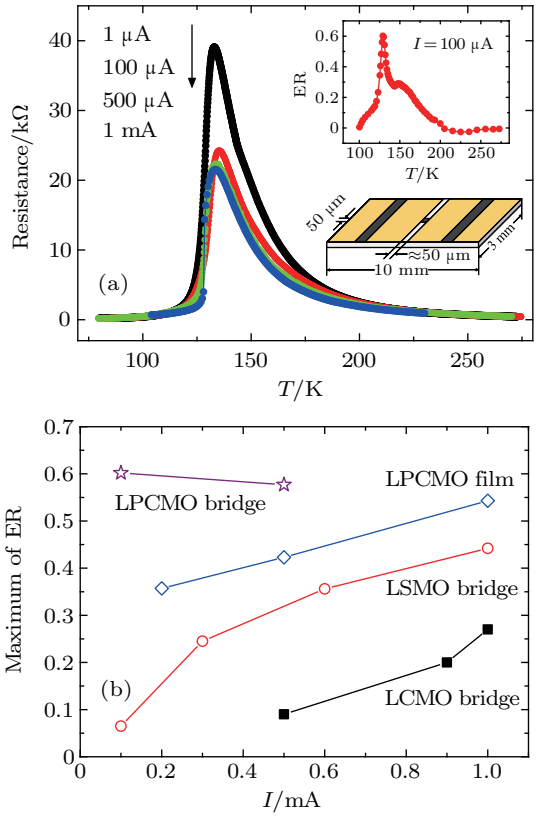


Fig. 5. (color online) (a) Temperature dependences of resistance for the patterned LPCMO film under different dc currents. The currents are 1, 100, 500 μA, and 1 mA, with the corresponding current densities of 20, 2.0×10^3, 1.0×10^4, 2.0×10^4 A/cm^2, respectively. The upper inset shows the temperature dependences of ER under different currents. The lower inset shows the measurement configuration for the patterned LPCMO film. The four yellow rectangular parts are deposited gold for contact and the black parts are the patterned LPCMO films. The size of the LPCMO microbridge is 50 μm ×50 μm. (b) The maximum values of ER under different dc currents for $La_{0.67}Ca_{0.33}MnO_3$ (LCMO), $La_{0.85}Sr_{0.15}MnO_3$ (LSMO), LPCMO microbridges, and unpatterned LPCMO film, respectively.

For LPCMO, where replacing La^{3+} with smaller Pr^{3+} increases the effective Jahn–Teller coupling by reducing the hopping matrix element and decreases the bandwidth. LPCMO is sensitive to the internal chemical pressure and ex-

ternal disturbance, indicating the balance of various interactions determines its electronic ground states. If La^{3+} is fully replaced by Pr^{3+}, the FMM state disappears because of the reduced bandwidth and only the COI state is observed at low temperature.[47] However, at low Pr doping levels, the COI state becomes less stable relative to the FMM state and finally collapses into a two-phase state revealing metal–insulator transition with the percolative mechanism below charge-ordering temperature T_{co}. Electron microscopy results showed that LPCMO is phase-separated into a sub-micrometer-scale mixture of insulating regions with charge ordering and metallic, ferromagnetic domains.[38] Powder neutron diffraction measurement showed mesoscopic ($\geq$ 1000 Å) phase separation in LPCMO. When the temperature decreases down to $T_{co} \sim$ 210 K, Mn^{3+} and Mn^{4+} ions orderly distribute in the lattice space. When an external magnetic field is applied, charge-ordered state can be melted, changing from the charge crystal to charge liquid, accompanied by the transition from the antiferromagnetic to ferromagnetic states. Meanwhile, the resistance is reduced remarkably. The magnetic field used to melt the CO state is usually quite large, typically about 12 T for the melting of CO states in $Pr_{1-x}Ca_xMnO_3$. The melting of CO state is first-order phase transition, happening with distinct hysteresis and metastable states. The charge ordering state is fragile and can be switched from insulator to metallic state by pressure, magnetic and electric field, or light irradiation. Under a magnetic field, the melting of the CO state usually corresponds to huge magnetoresistance. Previous reports of current effect are focused on manganites with charge-ordered state, such as $Pr_{0.7}Ca_{0.3}MnO_3$ single crystal, $Pr_{1-x}Ca_xMnO_3$ ($x = 0.3$, 0.4) polycrystalline bulk and films, $Pr_{0.7}Ca_{0.27}Sr_{0.03}MnO_3$ epitaxial films. The electric current can lead to the melting of the charge ordered phase. Because of the competition of CO and FM states, the proportion of conductive FM states would be enhanced under electric current or field. When the proportion of FM states increases to a certain threshold, the percolation routes for current are formed. Therefore, the resistivity is remarkably reduced, corresponding to distinct ER. The value of ER is larger in LPCMO film even though the current density is only about 1/60 compared with the effect in weak phase-separated manganite films.

4. Conclusion

In summary, we studied the electroresistance effect of $La_{0.36}Pr_{0.265}Ca_{0.375}MnO_3$ (LPCMO) epitaxial thin film under various dc currents. The current effect was compared in unpatterned film and patterned microbridge with a width of 50 μm. The value of ER in unpatterned LPCMO film could reach 0.54 under a 1-mA current, which is much higher than ER under 1 mA for patterned weak phase-separated $La_{0.67}Ca_{0.33}MnO_3$ and $La_{0.85}Sr_{0.15}MnO_3$ microbridges with 50-μm width. More interestingly, for the patterned LPCMO microbridge, the maximum of ER can reach 0.6 under a small current of 100 μA. The results were explained by considering the coexistence of ferromagnetic metallic phase with the charge-ordered phase, and the variation of the phase separation with electric current. The research of electric current effect in different types of manganites is helpful for the study of magnetoelectric coupling and the development of devices based on electric-current/field modulation.

References

[1] Salamon M B and Jaime M 2001 *Rev. Mod. Phys.* **73** 583
[2] Prellier W, Lecoeur P and Mercey B 2001 *J. Phys.: Condens. Matter* **13** R915
[3] Dagotto E 2005 *Science* **309** 257
[4] Tokura Y, Kuwahara H, Moritomo Y, Tomioka Y and Asamitsu A 1996 *Phys. Rev. Lett.* **76** 3184
[5] Moritomo Y, Kuwahara H, Tomioka Y and Tokura Y 1997 *Phys. Rev. B* **55** 7549
[6] Miyano K, Tanaka T, Tomioka Y and Tokura Y 1997 *Phys. Rev. Lett.* **78** 4257
[7] Kiryukhin V, Casa D, Hill J P, Keimer B, Vigliante A, Tomioka Y and Tokura Y 1997 *Nature* **386** 813
[8] Lee H J, Kim K H, Kim M W, Noh T W, Kim B G, Koo T Y, Cheong S W, Wang Y J and Wei X 2002 *Phys. Rev. B* **65** 115118
[9] Chaudhuri S, Pandey N K, Saini S and Budhani R C 2010 *J. Phys.: Condens. Matter* **22** 275502
[10] Cui Y M, Liu W and Wang R M 2013 *Phys. Chem. Chem. Phys.* **15** 6804
[11] Rao C N R, Raju A R, Ponnambalam V, Parashar S and Kumar N 2000 *Phys. Rev. B* **61** 594
[12] Srivastava S, Pandey N K, Padhan P and Budhani R C 2000 *Phys. Rev. B* **62** 13868
[13] Markovich V, Rozenberg E, Yuzhelevski Y, Jung G, Gorodetsky G, Shulyatev D A and Mukovskii Y M 2001 *Appl. Phys. Lett.* **78** 3499
[14] Gao J, Shen S Q, Li T K and Sun J R 2003 *Appl. Phys. Lett.* **82** 4732
[15] Debnath A K and Lin J G 2003 *Phys. Rev. B* **67** 064412
[16] Ma Y Q, Song W H, Dai J M, Zhang R L, Yang J, Zhao B C, Sheng Z G, Lu W J, Du J J and Sun Y P 2004 *Phys. Rev. B* **70** 054413
[17] Zhao Y G, Wang Y H, Zhang G M, Zhang B, Zhang X P, Yang C X, Lang P L, Zhu M H and Guan P C 2005 *Appl. Phys. Lett.* **86** 122502
[18] Wu T, Ogale S B, Garrison J E, Nagaraj B, Biswas A, Chen Z, Greene R L, Ramesh R, Venkatesan T and Millis A J 2001 *Phys. Rev. Lett.* **86** 5998
[19] Sun J R, Liu G J, Zhang S Y, Zhang H W, Han X F and Shen B G 2005 *Appl. Phys. Lett.* **86** 242507
[20] Zhai Z Y, Xie Q Y, Chen G B, Wu X S and Gao J 2016 *Chin. Phys. Lett.* **33** 056103
[21] Asamitsu A, Tomioka Y, Kuwahara H and Tokura Y 1997 *Nature* **388** 50
[22] Parashar S, Ebenso E E, Raju A R and Rao C N R 2000 *Solid State Commun.* **114** 295
[23] Stankiewicz J, Sese J, Garcia J, Blasco J and Rillo C 2000 *Phys. Rev. B* **61** 11236
[24] Pandey N K, Lobo R and Budhani R C 2003 *Phys. Rev. B* **67** 054413
[25] Hu F X and Gao J 2004 *Phys. Rev. B* **69** 212413
[26] Zhang X L, Zhao Y G, Sun Y H, Gao S N, Lang P L, Zhang X P and Zhu M H 2006 *J. Magn. Magn. Mater.* **306** 55
[27] Sun Y H, Zhao Y G, Zhang X L, Gao S N, Lang P L, Zhang X P and Zhu M H 2007 *J. Magn. Magn. Mater.* **311** 644
[28] Sun Y H, Zhao Y G, Tian H F, Xiong C M, Xie B T, Zhu M H, Park S, Wu W and Li J Q 2008 *Phys. Rev. B* **78** 024412
[29] Sun Y H, Zhao Y G, Zhu M H, Xie B T and Wu W B 2012 *J. Appl. Phys.* **112** 023908

[30] Babushkina N A, Belova L M, Khomskii D I, Kugel K I, Gorbenko O Y and Kaul A R 1999 *Phys. Rev. B* **59** 6994
[31] Jeen H and Biswas A 2013 *Phys. Rev. B* **88** 024415
[32] Cui L M, Li J, Wang J, Zhang Y and Zheng D N 2014 *Chin. Phys. B* **23** 097103
[33] Wang J F, Zhou Y, Cao D, Yu S J, Jiao Z W and Gao J 2015 *J. Phys. D: Appl. Phys.* **48** 175302
[34] Wang J F, Cao D, Zhou Y, Wang X Y, Chen M G and Gao J 2015 *J. Alloys Compd.* **649** 819
[35] Wei W G, Zhu Y Y, Bai Y, *et al*. 2016 *Phys. Rev. B* **93** 035111
[36] Liu Y B, Sun J R and Shen B G 2013 *J. Appl. Phys.* **114** 193704
[37] Shen J, Ward T Z and Yin L F 2013 *Chin. Phys. B* **22** 017501
[38] Uehara M, Mori S, Chen C H and Cheong S W 1999 *Nature* **399** 560
[39] Kiryukhin V, Kim B G, Podzorov V, Cheong S W, Koo T Y, Hill J P, Moon I and Jeong Y H 2001 *Phys. Rev. B* **63** 024420
[40] Ward T Z, Liang S, Fuchigami K, Yin L F, Dagotto E, Plummer E W and Shen J 2008 *Phys. Rev. Lett.* **100** 247204
[41] Wu T, Ogale S B, Shinde S R, Biswas A, Polletto T, Greene R L, Venkatesan T and Millis A J 2003 *J. Appl. Phys.* **93** 5507
[42] Jeen H and Biswas A 2011 *Phys. Rev. B* **83** 064408
[43] Jin S, Tiefel T H, McCormack M, O'Bryan H M, Chen L H, Ramesh R and Schurig D 1995 *Appl. Phys. Lett.* **67** 557
[44] Zhai H Y, Ma J X, Gillaspie D T, Zhang X G, Ward T Z, Plummer E W and Shen J 2006 *Phys. Rev. Lett.* **97** 167201
[45] Singh-Bhalla G, Selcuk S, Dhakal T, Biswas A and Hebard A F 2009 *Phys. Rev. Lett.* **102** 077205
[46] Lavrov A N, Tsukada I and Ando Y 2003 *Phys. Rev. B* **68** 094506
[47] Hwang H Y, Cheong S W, Radaelli P G, Marezio M and Batlogg B 1995 *Phys. Rev. Lett.* **75** 914