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Current-sensitive electroresistance and the response to a magnetic field in $La_{0.8}Ca_{0.2}MnO_3$ epitaxial thin films

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The influence of a transport dc current on the resistivity of $La_{0.8}Ca_{0.2}MnO_3$ epitaxial thin films and their response to a magnetic field has been investigated. We found that when the applied dc current exceeds a threshold value, the electric resistivity in these films could be significantly enhanced. Such observations are completely repeatable. More attractive is that the enhanced resistance turns out to be sensitive to a weak current in a wide temperature range from 10 to 300 K. Even a very small dc current could remarkably depress the high resistance, showing a colossal electroresistance (ER) effect. ER reaches ~1175% at temperatures lower than ~50 K, and ~705% at 300 K for a current changing from 0.72 to 10.5 μA. A highly nonlinear behavior of the *I*–*V* curves persists even to room temperature. Significant influence of the magnetic field on the electric transports was also observed. It is found that a low field of 0.25 T could remarkably affect the *I*–*V* curves, resulting in a considerable magnetoresistance (MR). © *2005 American Institute of Physics*.
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Colossal magnetoresistance (CMR) manganites have attracted much attention due to the interesting interplay between spin, charge, orbital, and lattice degrees of freedom in these materials. The large number of experimental and theoretical studies on these mixed-valent systems has brought out rich variety of phenomena of great interest. The closeness of the free energies of various competing electronic, magnetic, and orbital states causes multiphase coexistence in these systems.[1,2] The largest MR has been suggested to be associated with spatial inhomogeneity related to multiphase coexistence, which generically causes a sensitivity of physical properties to external perturbations. Many reports[3–5] proved that the balance of multiphase coexistence can be influenced not only by a magnetic field but also by an electric field or current bias. It has been observed[4] that an applied current could lead to a transition from the electrically insulating charge-ordered (CO) state to a ferromagnetic (FM) metallic state, even for $Y_{0.5}Ca_{0.5}MnO_3$ in which a large magnetic field (~40 T) has no effect on the charge-ordered state. Considering the strong effect of external perturbations on the balance of multiphase coexistence, it can be expected that a sufficiently large current flowing and the possible produced magnetic fields could thoroughly disturb the subtle balance of multiphase coexistence and then might induce a new equilibrium state of coexistence, in which various novel CMR characteristics might appear. In comparing with bulk samples, a current with a very high density could be easily applied to a micro-bridge of CMR thin films, thus the influence of high current density on the multiphase coexistence state can be studied.

In our previous study we reported that a giant ER near the T_c could be introduced by a current in epitaxial thin films of $La_{0.7}Ca_{0.3}MnO_3$ and $La_{0.85}Ba_{0.15}MnO_3$.[6] Further studies on the influence of electric currents on CMR manganites reveal that a current with a high density may significantly affect the balance of multiphase coexistence and cause a series of changes of transport properties, exhibiting unusual electroresistance (ER) effect.[7] Many experiments have indicated that metallic and insulating states coexist even for $La_{1-x}Ca_xMnO_3$, especially for the low-doped samples.[2,5,8,9] In this paper, we report the influence of large currents on the transport properties and the response to magnetic field in $La_{0.8}Ca_{0.2}MnO_3$ epitaxial thin films.

The present $La_{0.8}Ca_{0.2}MnO_3$ thin films were grown on single crystal substrates of $SrTiO_3$ with (100) orientation using pulsed laser deposition (PLD) technique under O_2 pressure of 1 mbar. The deposition temperature was 750 °C. The thickness is about 100 nm, controlled by deposition time. In order to avoid oxygen deficiency, a post-annealing at 800 °C for 1 h was made in air. The compositions of the films determined by energy dispersive x-ray analysis (EDAX) were very close to the stated compositions. The experiments of x-ray diffraction demonstrate that the grown films are highly epitaxial and of single phase. The temperature dependences of electric resistance were measured by using the standard 4-probe technique. In order to apply a current with high density, the films were patterned into a micro-bridge with the width of 50 μm and length of 200 μm using lithography technique. Silver contacting pads were evaporated on every sample and the current leads were connected to the silver pad using a MEI-907 supersonic wire bonder to obtain low ohmic contacts.

Figure 1 presents the temperature dependent resistivity

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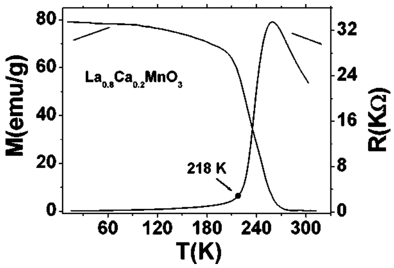

FIG. 1. The temperature dependent resistivity at zero field and magnetization measured under 100 Oe for a $La_{0.8}Ca_{0.2}MnO_3$ thin film.

without a magnetic field and magnetization measured under 100 Oe. It is found that the Curie temperature T_C of $La_{0.8}Ca_{0.2}MnO_3$ film is ~260 K, which is higher than that of its bulk material (~190 K).[10] Such a deviation is consistent with a previous report,[11] in which one found that the unit cell volume of $La_{0.8}Ca_{0.2}MnO_3$ film is much smaller than that of its bulk. It was suggested that the reduction in the unit cell volume due to strain effect would enhance the transfer integral of electron hopping between Mn^{3+} and Mn^{4+} and thus increase the T_c.[11]

We applied a dc current with high density at a specific temperature (~218 K), where *R* starts to increase in *R–T* curve (see Fig. 1), for a short duration δt and investigated the induced effect. The specific temperature ~218 K was chosen based on the following two considerations. First, the resistance at ~218 K is still small and the direct impact caused by self-heating effect should be weak. Second, the strong competition between different magnetic interactions at ~218 K, the start metal-like phase transforms to insulating-like phase, would enhance the influence of bias current on transport and magnetic properties. We found that an application of a suitable large dc current at such a manner would result in a strong increase of electric resistance in the whole temperature range from 10 to 300 K and, more important, the enhanced resistance is extremely sensitive to weak currents.

Figure 2 displays the temperature dependent resistance measured using a same small current of 0.01 mA for the states excited by currents of 4.7, 7.9, and 10.6 mA, respectively. The excitation currents are applied at 218 K for a same duration of 5 min. For comparison the *R–T* curve of the as-prepared state is also plotted. The state evolution with increasing the excitation current is manifested. One can find that an application of current of 4.7 mA could not cause any change of the transport properties. Increasing the excitation current from 4.7 to 7.9 mA results in a slight increase of resistivity, meanwhile, a small cusp at T_O (~140 K) is developed (see the details in the inset of Fig. 2). However, the enhanced resistance at this moment is found not sensitive to weak currents. Further increasing the excitation current to 10.6 mA (density, $\sim 2.1 \times 10^5$ Acm^{-2}) causes a remarkable increase of resistance in the whole temperature range from 10 to 300 K. The residual resistance has been significantly increased, but the resistance anomaly around T_C still remains and the position of the resistance peak T_P keeps unchanged. More attractive is that the significantly enhanced resistance in this case is extremely sensitive to weak currents. Even a very small dc current flow could remarkably depress the high resistance, resulting in a colossal ER effect. It is worthy to point out that all the observations are proved repeatable through our repeated experiments on several samples.

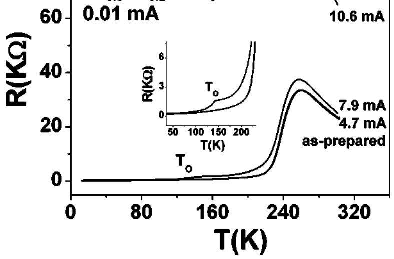

FIG. 2. The temperature dependent resistance of a $La_{0.8}Ca_{0.2}MnO_3$ thin film measured using a same small current of 0.01 mA for the states induced by dc currents of 4.7, 7.9, and 10.6 mA, respectively, applied at 218 K for δt =5 min. For comparison, the *R–T* curve of the as-prepared state is also plotted. Inset presents the details around T_O.

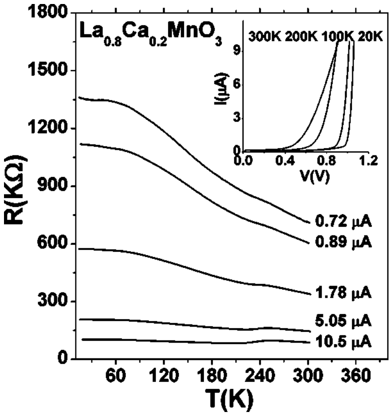

FIG. 3. The *R–T* dependences of $La_{0.8}Ca_{0.2}MnO_3$ thin films with different small currents for the state induced by a dc current of ~10.6 mA. Inset shows the isothermal *I–V* curves collected at different temperatures.

Figure 3 displays the temperature dependent resistance measured using small currents for the state induced by 10.6 mA with a density of $\sim 2.1 \times 10^5$ Acm^{-2}. One can see that the enhanced resistance is highly sensitive to weak currents for temperature from 10 to 300 K. The obtained ER reaches ~1175% at low temperatures <50 K, and ~705% even at 300 K for the current changing from 0.72 to 10.5 μA. Inset of Fig. 3 shows the isothermal *I–V* curves collected at different temperatures. It is found that the nonohmic behavior persists up to the room temperature. We also investigated the influence of a magnetic field on the transport properties. Figure 4 presents the compared *I–V* curves measured at room temperature in zero and 0.25 T. The applied magnetic field is in the direction parallel to the current. The strong influence of a low magnetic field on the *I–V* curves is obvious. Inset of Fig. 4 is the deduced magnetoresistance (MR) from the two *I–V* curves. Considerable MR at small currents can be observed.

The interesting phenomena could not be explained simply by the escape of oxygen caused by self-heating effect. We studied vacuum annealing effects for the as-prepared films. The results are very similar to a previous report.[12]

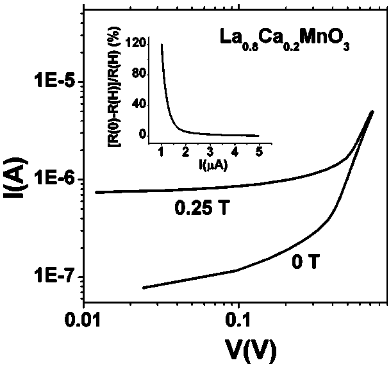

FIG. 4. The compared *I*–*V* curves of a $La_{0.8}Ca_{0.2}MnO_3$ thin film measured at room temperature in zero and 0.25 T magnetic field for the state induced by a dc current of ~10.6 mA. Inset displays the deduced magnetoresistance (MR) from the two *I*–*V* curves.

Simply annealing in a vacuum could only cause a shift of the position of peak resistance to lower temperature and make the resistance increase. No similar phenomena as described in Fig. 3 were observed at all.

The mechanism of percolative phase separation is taken into account in the interpretation of the observed phenomena. It has been demonstrated that metallic FM and insulating CO states coexist in a broad range of phase space even for $La_{1-x}Ca_xMnO_3$[2,5,8,9] and the insulating phase in phase separation is the $x=1/2$-type CO state. Applied electric field (or current) may perturb the coexistence and set-up filamentary currents across insulate region, and intense local magnetic fields might be induced by the current flow, which may in turn further influence the phase coexistence. Therefore, it is possible that a quite large current flow thoroughly breaks down the balance of multiphase coexistence in the initial state and induces a new state with new coexistence of the phases. Actually, the developing of *R*–*T* curve shown in Fig. 2 reflects the modulation process of the large current on the coexistence. The small cusp developed by 7.9 mA may indicate a start of the perturbation of the coexistent multiphase in the initial state. Continuously increasing the excitation current to a critical value (e.g., $I_c=10.6$ mA for present sample) may significantly change the relative volume of metallic and insulating phases. The reduction of the electron conduction with decreasing temperature from ~220 K (Fig. 2) for the case of 10.6 mA can be a result of the volume increase of the insulating phase. An abundance of insulating domains would lead to poor connection of minority FM domains and enhance the residual resitivity remarkably. A key factor is that the newly formed multiphase coexistence is metastable compared to the as-prepared initial case, behaving more sensitive to the external perturbations. A small current or magnetic field could strongly influence the formed coexistent multiphases, leading to a colossal ER or MR. It is intriguing that the newly formed metastable states are still robust. All their transport properties could persist even exposing the sample in air at room temperature for a long time. Such a feather would be of great technological interest. Here, we merely present a primary analysis based on the picture of percolative phase separation. For thoroughly understanding the formation and nature of such novel states induced by a critical current, further detailed investigations are still required.

ACKNOWLEDGMENTS

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