Current-Induced Reversible Resistance Jumps in $La_{0.8}Ca_{0.2}MnO_3$ Microbridge *

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Two spatially confined $La_{0.8}Ca_{0.2}MnO_3$ (LCMO) microbridges with different widths, starting from a single LCMO film (3 mm×5 mm), are fabricated by optical lithography. A second new and robust metal-insulator transition (MIT) peak at about 75 K appears, in addition to the normal MIT at 180 K observed in the standard LCMO film. When the two bridges are processed by currents of high densities, interesting reversible resistance jumps are excited only around the new peak. A stronger dependence of resistance jump on current excitation is found for the bridge with a smaller width. The temperature driven transition between new excited multiple metastable states are involved to explain the interesting low-temperature ultra-sharp jumps.

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Colossal magnetoresistance (CMR) perovskite manganites are typical correlated electronic materials with inherent high degrees of inhomogeneity.[1] In these materials the strong coupling between lattice, orbital, charge and spin degrees of freedom gives rise to the well-known phenomena of electronic phase separation,[2] which is identified with the coexistence of various phases with close energy. Generally, the coupling and the competition between various states in single crystalline structure can cause great sensitivity of physical properties to external stimuli such as magnetic fields, strain and laser pulse. Among them, studying the effect of electrical current with high density is not only interesting for obtaining the complete view of strong electronic correlation in manganites, but also promising for applications in nonvolatile memory devices due to the electroresistance (ER) excited by the current.[3,4] Compared with technological limitation of generating high enough magnetic fields for disturbing the subtle balance of competing states, the current with high density has shown to be much easier to accomplish, since the desired microbridge can be fabricated with optical lithography. Moreover, the configuration of the microbridge may be seen as a natural route for obtaining spatial confinement, the substantial changes in the properties of mangnites should be expected. For example, interesting giant discrete steps in metal-insulator transition has been observed in $(La_{5/8-0.3}Pr_{0.3})Ca_{3/8}MnO_3$ wire.[5] In $La_{0.3}Pr_{0.4}Ca_{0.3}MnO_3$ film, re-entrant low-field magneto-resistance is shown due to the spatial confinement.[6]

Encouraged by the emergent phenomena after applying current on the microbridge, more research is continually expanding year by year. The physical behavior is different for different manganite systems. Remarkable changes of resistance in $La_{0.7}Ca_{0.3}MnO_3$ film[7] and asymmetric conduction in $La_{0.8}Ca_{0.2}MnO_3$ film[8] have been observed under the influence of currents with high densities. The electroresistance and current-induced metastable states can be induced in $Pr_{0.5}Sr_{0.5}MnO_3$ perovskite oxides.[9] Moreover, for $Nd_{0.7}Sr_{0.3}MnO_3$ the current processing even leads to a second metal-insulator transition at low temperature.[10] It is generally agreed that these effects are correlated with the phase separation scenario. However, the effect of electric current is still a hotly debated issue since decrease and increase of resistance were both observed. The physics behind this are far from being understood due to the strong electronic correlation character in manganites.

Therefore, in this work we choose a $La_{0.8}Ca_{0.2}MnO_3$ (LCMO) thin film, which usually has a stable phase-separated ground state, to thoroughly study the effect of high current density on the transport properties and to explore novel emergent behavior.

The $La_{0.8}Ca_{0.2}MnO_3$ film in thickness of ∼100 nm was grown on a $LaAlO_3$ (LAO) substrate (3 mm × 5 mm) by the pulsed laser deposition (PLD)

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technique. The deposition took place in a pure oxygen atmosphere of 40 Pa. During growth, the substrate temperature was maintained at 650°C. The energy of the laser beam was 400 mJ and the pulse frequency was 2 Hz. Film quality was verified by high resolution x-ray diffraction by using a Simens D5000 diffractometer. To apply a current with high densities, two microbridges have been fabricated from a single crystalline LCMO film by using photolithography. The length multiplied by width of two bridges is 40 μm by 80 μm and 40 μm by 40 μm, respectively. Silver (Ag) electrodes were deposited by thermal evaporation, and the current leads were made by using an MEI-907 supersonic wire bonder to obtain low Ohmic contacts. The four-probe method was adopted to measure the transport properties.

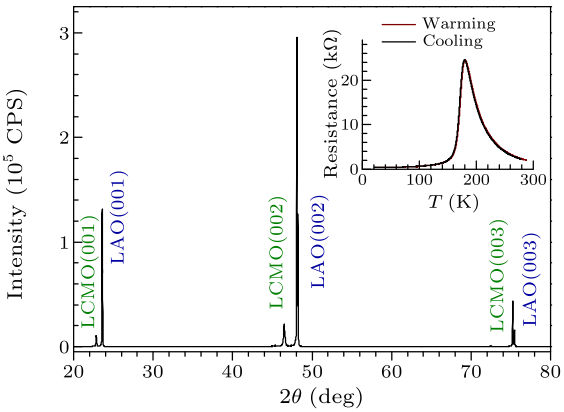

Fig. 1. High-resolution x-ray diffraction pattern of the LCMO film at room temperature. The inset shows the transport property of the corresponding film on cooling and heating process.

The x-ray diffraction pattern collected at room temperature is used to check the crystallization of the LCMO film. As shown in Fig. 1, in addition to the reflections from LAO (00l) and LCMO (00l), no peaks from any other impurity phases or randomly oriented grains are observed. The out-of-plane lattice constant of the LCMO film calculated from the (002) peak is ∼3.90 Å. Compared with the LCMO bulk value of 3.88 Å, the elongated c-axis parameter suggests tensile strain in the out-of-plane direction and compressive strain in the plane are realized, due to the 2% lattice mismatch between LCMO and LAO substrates. The inset of Fig. 1 shows the temperature dependence of resistance for the LCMO film measured with the standard four-probe method. There is no obvious difference in resistance between warming and cooling curves. Typical insulator-to-metal transition (MIT) at 180 K expected in CMR manganites is shown.

Optical lithography was used to pattern two microbridges with an appropriate geometry. The pictures of the two bridges are shown in Fig. 2(c). Overall, the resistance is promoted and the original MIT at 180 K is broadened compared with that of the LCMO film, due to the reduced dimension. The R–T curve on cooling also matches well with that on heating. Interestingly, a second new and robust MIT peak at about 75 K appears, in addition to the MIT at 180 K, as shown in Fig. 2. The re-emergence of MIT has also been observed in $La_{0.3}Pr_{0.4}Ca_{0.3}MnO_3$ micro-bridge[6] and $(La_{5/8-0.3}Pr_{0.3})Ca_{3/8}MnO_3$ wire,[11] where the spatial confinement in the wire geometry plays a vital role. Furthermore, the current processing could also induce the second metal–insulator transition.[10] Shen *et al.*[12] suggested that the wire geometry forces the electronic channel to pass across both high and low resistive domains and can be modeled as a serial resistive network. For lightly doped $La_{0.8}Ca_{0.2}MnO_3$, there is a strong competition between the ferromagnetic metal (FM) state and the ferromagnetic charge ordered insulator (CO) state at low temperature. By spatially confining the film to micrometer scale, the number of partially insulating and partially metal phase clusters is limited, thus the transport properties are more sensitive to the size, shape and phase distribution of clusters. Thus the new peak at about 75 K could be explained based on the arguments of Shen *et al.*[12] such that some of the accumulating metallic and insulating phase may be comparable with the width of microbridge and the electrons are forced to pass through both the regions with different resistances. However, it can be found that the resistance at 75 K is much larger than that in the wider bridge. We thought that the random arrangement of FM state and CO state and the strong sensitivity to any external disturbance could be the possible reason. More detailed exploration shall be conducted in the future.

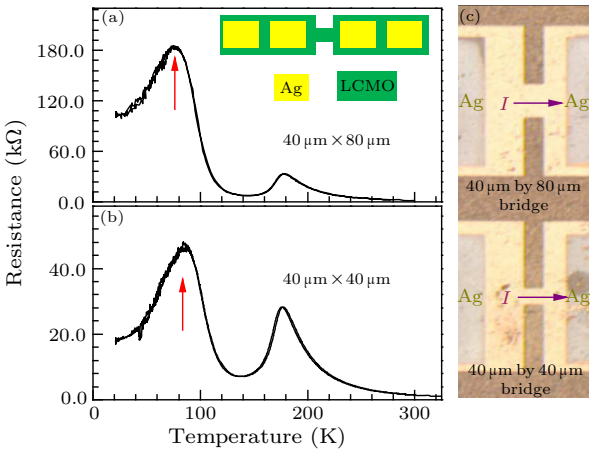

Fig. 2. The temperature dependence of resistance for (a) 40 μm by 80 μm bridge and (b) 40 μm by 40 μm bridge. The four-probe configuration used to measure all the R–T curves is shown in the inset of Fig. 2(a). The pictures of the two bridges are shown in (c).

Compared with the transport measurements on

the single film, the measurement on the microbridge is indeed a more effective probe to disclose the vital information about the formation and distribution of phases in a manganite system. As we can see, the exact material composition that exhibits the anomalous peak at low temperature is different from one to another in many studies, while the common nature is such that all the studied materials belong to a perovskite manganite system. Quantitatively, it is the phase coexistence and phase separation, induced by electron correlation, that give rise to the new anomalous peak at low temperatures, when the material is subjected to an external stimulus such as spatial confinement or current processing.

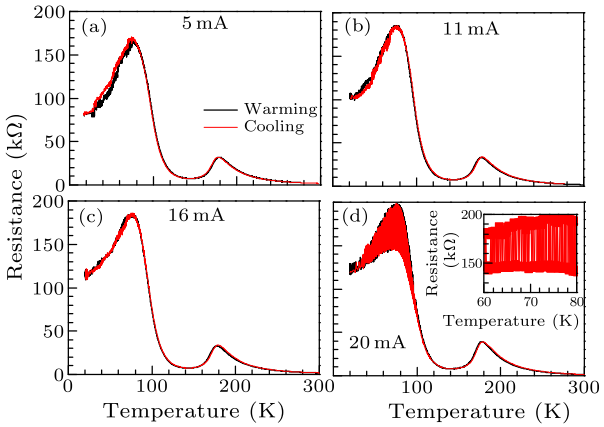

Fig. 3. The R–T curves measured with a current of 1 μA subsequent to (a) 5 mA, (b) 11 mA, (c) 16 mA and (d) 20 mA current processing with durations of 10 min for 40 μm × 80 μm microbridge at room temperature. The inset of (d) shows the enlarged area around 75 K.

As is well known, the configuration of the microbridge is beneficial to acquire the current with high density. Thus the evolution process of the state with the increase of the applied current is further studied. We measured the R–T curve in cooling and warming processes with a current of 1 μA after each current excitation. The duration of current excitation was fixed for 10 min and magnitudes varied from 5 mA to 20 mA. For the two studied microbridges, great changes appear when the dc current was applied up to a critical value. The dependence of resistance on temperature for 40 μm × 80 μm microbridge measured after current processing is shown in Fig. 3. The data are repeatable for cooling and warming processes, which indicate that the Joule heating effect is irrelevant to our results.[13] Compared with the initial state (no current processing, see Fig. 2(a)), the R–T curve shows slight changes except for some increased residual resistance when the excitation current increases from 5 mA to 16 mA. However, when the processing current increases to 20 mA, the residual resistance increases further and the magnitude of high temperate MIT increases too. Moreover, for the MIT at 75 K, an interesting resistance ultra-sharp jump develops around the peak when the excitation current increases up to 20 mA.

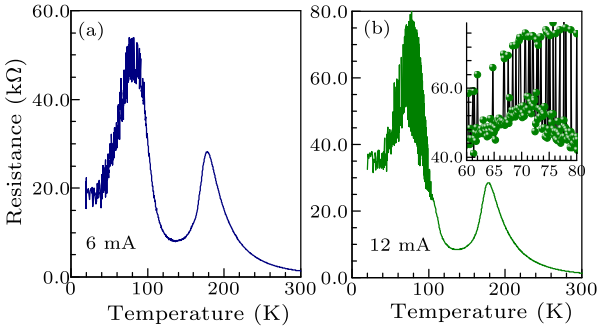

Fig. 4. The R–T curves for LCMO 40 μm×40 μm microbridge measured with a small dc current of 1 μA after being excited by (a) 6 mA and (b) 12 mA for 10 min. The inset in (b) shows the enlarged area around 75 K. For clarity, we only show the warming process.

For another narrower, i.e., 40 μm×40 μm bridge, the overall corresponding resistance behaviors after current excitation are similar to those in the 80 μm bridge, while the resistance jump is more sensitive to the applied current. As indicated in Fig. 4(a), a current of 6 mA could already excite the low temperature resistance jump. The size of jump is dramatically enhanced with further increasing the processing current (see Fig. 4(b)). To the best of our knowledge, these kinds of current-induced multi-jumps have never been reported. For $La_{0.8}Ca_{0.2}MnO_3$ composition, at low temperatures, there is a strong competition between the FM state and the CO state. An applied critical current will shift such an intricate balance. The increased residual resistance could be seen as indirect evidence for the rearrangement of FM and CO states induced by the current. When the applied current is larger than a critical value, it seems that new multiple metastable states are excited, which are coexisting with the original FM and CO states. The CO state has a much larger resistance than the FM state even though their compositions are the same. The temperature may drive the transition between these local metastable states with obvious different resistances, resulting in the ultra-sharp transition. The resistance modulation here shows the behavior is quite different from that reported by Hu *et al.* in Ref. [4] in which it was found that a novel state with an enhanced electroresistance could be induced by a suitable large current in $La_{0.8}Ca_{0.2}MnO_3$ microbridges grown on $SrTiO_3$ substrates. In our case, the $LaAlO_3$ substrate, with much larger lattice mismatch with the film, has been used. Cui *et al.*[14] has also demonstrated that rich spectra of exotic properties and unexpected states could be modulated by large strain engineering. Therefore, it is reasonable to believe that a higher degree of complexity can be achieved in the present system.

In summary, an additional new MIT peak appears at low temperature for the $La_{0.8}Ca_{0.2}MnO_3$ bridges studied. The low temperature MIT is considerably more sensitive to the applied large current density than the high temperature one. A giant resistance jump is observed around the new low temperature MIT when the current is increased to a critical value.

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