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Switching phenomena in $La_{2/3}Ca_{1/3}MnO_3/Eu_2CuO_4/La_{2/3}Ca_{1/3}MnO_3$ ramp-type junctions

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Abstract
Ramp-type junctions of p-type $La_{2/3}Ca_{1/3}MnO_3$ (LCMO) electrodes with n-type Eu_2CuO_4 (ECO) barriers have been fabricated by rf magnetron sputtering, photolithography and ion beam etching. A tunnelling effect was observed in junctions with colossal magnetoresistive materials. Interestingly, a discontinuity was observed in the I–V curves below the metal–insulator transition temperature (T_p) of LCMO electrodes. With increasing current, the voltage across the junction increases linearly at first, then deviates from linearity, then a discontinuity occurs and finally the voltage recovers its linearity. With changing temperature, the discontinuity in the I–V curves happens at the same voltage of 209 mV, but starts at different currents. The discontinuity starting current (I_c) decreases with increase of the temperature. The discontinuity disappears above T_p. There is a hysteresis near the discontinuity when the current increases and decreases. The discontinuity in the I–V curves could indicate a novel switching process. This switching phenomenon occurs only in the ferromagnetic metal state and strongly suggests a magnetism related effect. The physics of the switching process has not been understood yet, but it could be of interest for potential applications in spintronics devices.

Perovskite and its derivative oxides exhibit various thermal dynamics and electromagnetic properties, such as: ferroelectricity, high T_c superconductivity and colossal magnetoresistance (CMR). CMR in doped rare earth perovskite manganites has been a subject of considerable research interest in recent years [1]. In these materials, strong coupling between the spin, charge and orbital degrees of freedom results in a rich variety of electronic and magnetic properties, such as ferromagnetism with metallic conduction, and charge/orbital ordering, depending on the carrier concentration [2–5]. In structural aspects, CMR manganites show some similarities with high T_c superconducting cuprates (HTSC). The structural and physical interfaces of CMR/HTSC heteroepitaxial structures have interesting academic significance; for example, the investigation of nonequilibrium superconductivity due to the tunnelling injection of spin-polarized quasiparticles provides useful information on the superconducting mechanism related to spin-dependent electronic properties, and may also lead to novel devices [6]. $La_{2/3}Ca_{1/3}MnO_3$ (LCMO) shows the CMR effect and its carriers are p-type. Eu_2CuO_4 (ECO) can be made an n-type superconductor by partial doping with Ce^{4+}. Using these two materials, we tried to make a TMR junction to get high MR at low magnetic fields. Also we were able to make a novel diode, whose junction properties can be adjusted by magnetic fields. Recently, p–n junctions of perovskite oxides have been reported [7–10]. In this paper, we have fabricated ramp-type junctions of LCMO/ECO/LCMO by using photolithography and ion beam etching processes, and a novel switching phenomenon was observed in these junctions.

LCMO and ECO thin films were deposited on (100) $SrTiO_3$ (STO) substrates by using an off-axis rf magnetron sputtering technique [11]. The deposition gas was pure argon gas or a mixture gas of argon and oxygen. The sputtering pressure was $1–2 \times 10^{-1}$ mbar. The substrate temperature was 740–780 °C, measured by a k-type thermocouple inserted into the substrate heater. An rf power of 75 W was applied on the cathode, generating a power density of $\sim$4 W cm^{-2}. After deposition, the thin films were treated by *in situ* or *ex situ* annealing under an oxygen atmosphere at 700–1000 °C. The LCMO/ECO thin films were examined by x-ray energy dispersive analysis (EDAX), x-ray diffraction (XRD), surface profiling and scanning electron microscopy. Highly smooth thin films with good epitaxy were obtained for the junction preparations [11–13].

Ramp-type junctions of LCMO/ECO/LCMO were fabricated by photolithography and an ion beam etching process from high quality LCMO/ECO/LCMO thin films. The fabrication process is demonstrated in figure 1. First LCMO/ECO bilayers were deposited (figure 1(a)); then a ramp edge was formed by photolithography and ion beam etching (figures 1(b) and (c)); and then the barrier and top layers were deposited (figure 1(d)); finally ramp-type junctions of LCMO/ECO/LCMO were obtained by photolithography and ion beam etching (figures 1(e) and (f)). The junction areas are typically 5×10 and 5×20 μm^2, and the thickness of the barrier (ECO) is 5–30 nm.

The temperature dependences of the junction resistance and I–V curves of the LCMO/ECO/LCMO ramp-type junctions were measured by a standard DC four-probe method using a closed-cycle cryogenerator. The sampling current was monitored by measuring the voltage across a resistance of 100 Ω in series. A Pt resistance thermometer was used to measure the temperature of the sample.

Figure 2 shows the temperature dependence of the resistance of an LCMO/ECO/LCMO ramp-type junction. The sampling current was less than 50 μA across the junction. The junction exhibits a semiconducting behaviour at high temperature and a transition from semiconductor to metal occurs at 245 K. We call the transition temperature the peak temperature T_p. The transition from semiconductor to metal is strongly related to the transition from paramagnet to ferromagnet. That is consistent with the behaviour of a single LCMO layer. It is indicated that the coupling between the bottom and top electrodes is effective.

The I–V curves below T_p show the same character. A typical I–V curve is shown in figure 3. This I–V curve was obtained from an LCMO/ECO/LCMO ramp-type junction at 120 K. With increase of the current, the voltage cross the junction increases linearly first, then deviates from its linearity, then a discontinuity occurs and finally the voltage recovers its linearity. It is clearly seen that when the current increases there is a discontinuity in the I–V

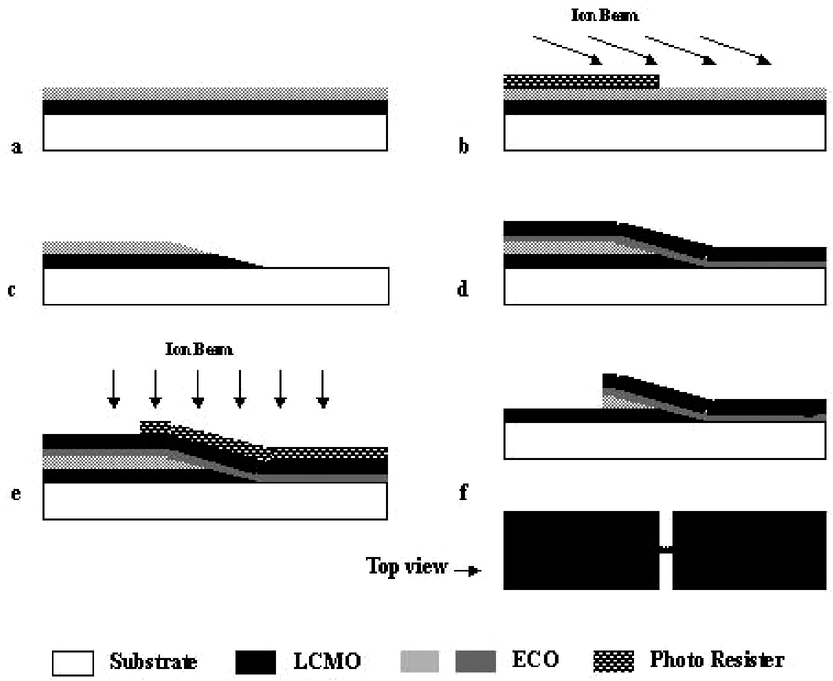

Figure 1. A schematic diagram of the fabrication process for LCMO/ECO/LCMO ramp-type junctions.

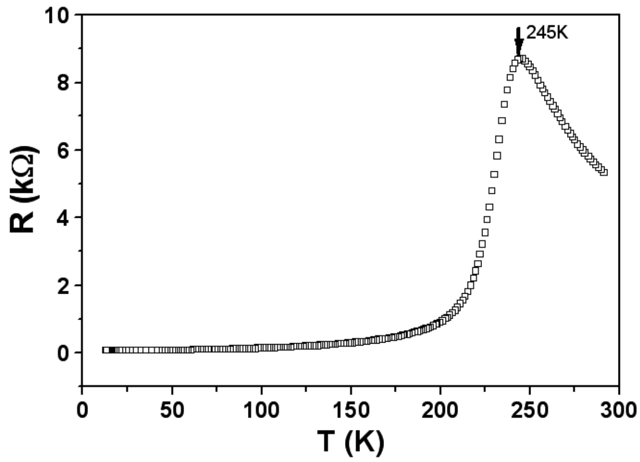

Figure 2. The temperature dependence of the resistance across the junction of a typical LCMO/ECO/LCMO ramp-type junction.

curve, and when the current decreases the discontinuity still appears but shifts to a lower current value. The inset of figure 3 is a magnified figure. It is shown that before the discontinuity appears the voltage increases nonlinearly with the current, clearly suggesting a tunnelling effect in the ramp-type junctions. I–V curves at different measuring temperatures are presented in figure 4. It is observed that the current (I_c) at which the discontinuity happens decreases with

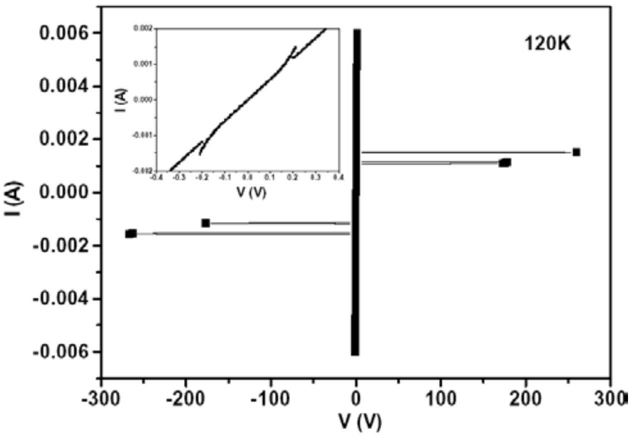

Figure 3. An I–V curve of a LCMO/ECO/LCMO ramp-type junction at 120 K. The inset is a magnified figure.

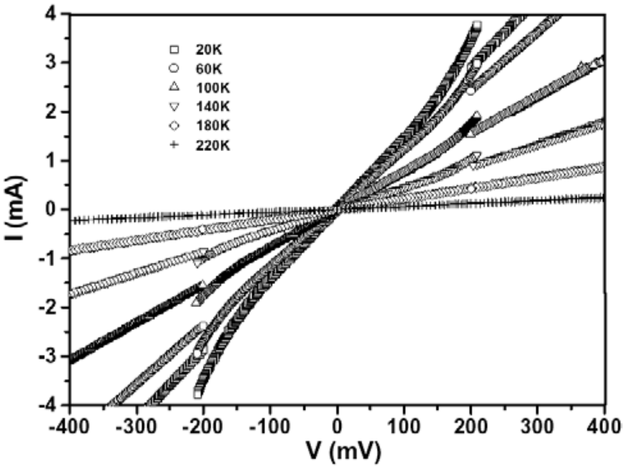

Figure 4. I–V curves at different measuring temperatures for an LCMO/ECO/LCMO ramp-type junction.

increase of the temperature, and the discontinuity disappears around T_p. The dependence of I_c on temperature is plotted in figure 5. It is found that the discontinuity happens at the same voltage of 209 mV at different temperatures. Although we cannot understand the physics of this discontinuity, the discontinuity could indicate a novel switching process. It is found that this switching phenomenon occurs only in the ferromagnetic metal state, strongly suggesting a magnetism related effect, and could have potential application in spintronics devices.

Recently, studies on the effect of the electric field or the electric current on the CMR materials have attracted great research interest. Colossal electroresistance and strong current induced abrupt resistance jumps have been reported. Wu *et al* [14] reported a large electroresistance in field effect configurations with CMR channels, and ferroelectric PZT or dielectric STO gates. Current switching of resistive states was observed by Tulina *et al* [15] in point contacts of normal metal and manganite single crystal and by Sun [16] in some manganite magnetic trilayer junctions. Gao *et al* [17] reported a significant change in the ratio of the peak

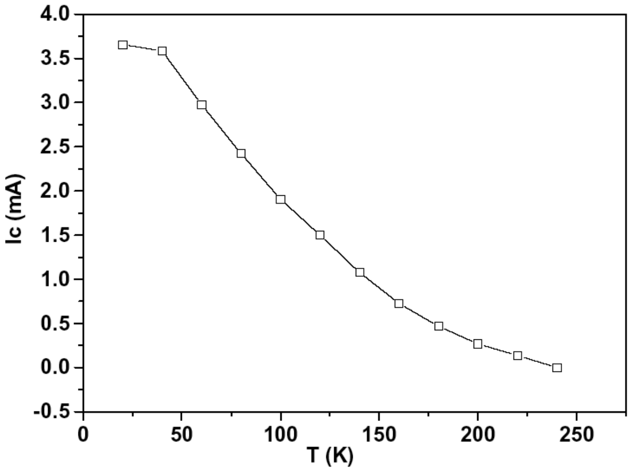

Figure 5. The dependence of I_c on temperature.

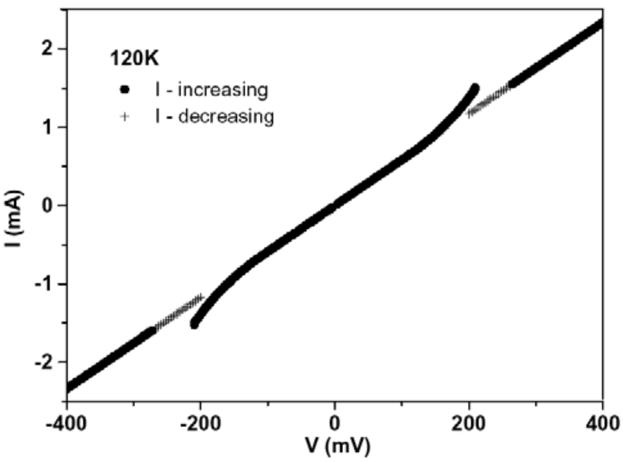

Figure 6. A hysteresis I–V loop near the discontinuity when the current increases and decreases.

resistance at different applied currents in thin films of $La_{0.7}Ca_{0.3}MnO_3$ and $La_{0.85}Ba_{0.15}MnO_3$. The physics behind those phenomena has not been understood up to now. It could be due to the phase instability and the spin transfer caused by the electric current.

There is a hysteresis near the discontinuity when the current increases and decreases (see figure 6). The I–V curves were symmetrical when the current direction was reversed. To eliminate the heating effect, we measured the I–V curves of several cycles continuously. There is no detectable change from cycle to cycle (see figure 7).

In summary, ramp-type junctions of $La_{2/3}Ca_{1/3}MnO_3/Eu_2CuO_4/La_{2/3}Ca_{1/3}MnO_3$ have been fabricated successfully. A tunnelling effect was observed in junctions with colossal magnetoresistive materials and a discontinuity was observed in the I–V curves. On changing the temperature, the discontinuity in the I–V curves happens at the same voltage of 209 mV, but starts at different currents. The discontinuity starting current decreases with the increase of temperature. The discontinuity disappears above the T_p. The discontinuity in the I–V curves

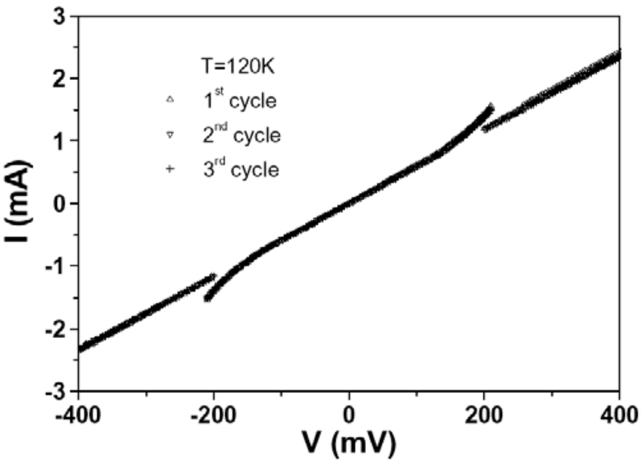

Figure 7. I–V curves with three cycles of an LCMO/ECO/LCMO ramp-type junction.

could indicate a novel switching process. This switching phenomenon suggests a magnetism related effect and could have potential application in spintronics devices.

Acknowledgment

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