A Letters Journal Exploring the Frontiers of Physics

July 2007

EPL, **79** (2007) 27005
doi: 10.1209/0295-5075/79/27005

www.epljournal.org

# Current-processing–induced anisotropic conduction in manganite films

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received 11 March 2007; accepted 7 June 2007
published online 3 July 2007

PACS 75.47.Lx – Manganites
PACS 75.47.Gk – Colossal magnetoresistance
PACS 73.40.Ei – Rectification

**Abstract** – Current-processing–induced anisotropic conduction (CIAC) has been observed recently in $La_{1-x}Ca_xMnO_3$ ($x = 0.2$, 0.33) films. Here we report a more applicable and simple method, applying processing current at room temperature, to produce such anisotropic conduction. Using this method, we have examined $La_{1-x}Ca_xMnO_3$ ($x = 0.2$, 0.33), $La_{0.67}Sr_{0.33}MnO_3$, $Pr_{0.7}Ca_{0.3}MnO_3$, $La_{0.35}Pr_{0.32}Ca_{0.33}MnO_3$ and $La_{0.7}Ce_{0.3}MnO_3$ films grown on $SrTiO_3$ substrates, and found CIAC in all these films, showing CIAC is a fairly universal phenomenon for manganites. The method exhibits good ability to process samples of large resistance/size. We even got remarkable anisotropic conduction in a manganite film as long as 3 mm. Our effort provides a very simple method to prepare such samples, which will help to further researches in this field.



The magnetic and transport properties of the hole-doped manganites are sensitive to external perturbations, such as light illumination, magnetic field and electric current/field [1]. The study of the response of manganites to these external perturbations has been an effective way to reveal the nature of the physical processes in progress. It is an interesting topic that what will happen when the perturbation is extremely strong. Previous researches have shown that after applying a magnetic field up to 50 T, the physical properties of manganties have no obvious change [2]. Current, however, has a very different effect. Recently, an exotic current effect, current-processing–induced anisotropic conduction (CIAC), was observed in $La_{1-x}Ca_xMnO_3$ ($x = 0.2$, 0.33) films [3–5]. The film processed by a strong current exhibits a rectifying behavior, the resistivity is strongly bias dependent, like a *p-n* junction. Further research suggests that the anisotropy comes from the intrinsic change of $La_{1-x}Ca_xMnO_3$ [5]. Appearance of anisotropic conduction in an originally uniform system is amazing. Understanding this interesting phenomenon is important to both basic physics and potential applications of correlated electron materials.

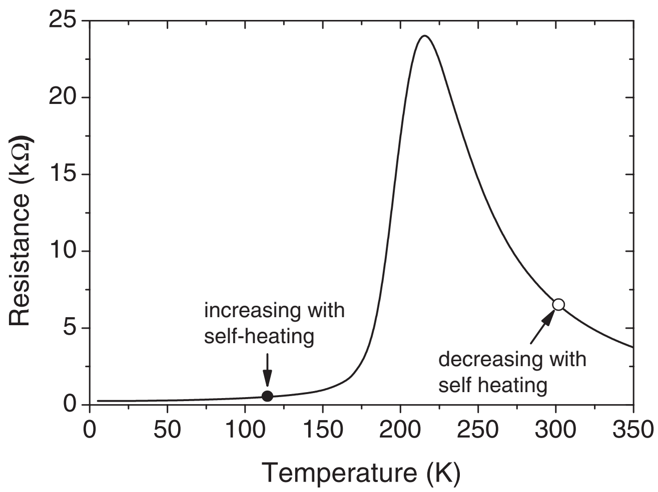


Fig. 1: Typical temperature-dependent resistance for a $La_{0.8}Ca_{0.2}MnO_3$ film with size of $50\,\mu m \times 50\,\mu m$ and thickness of $\sim 800$ Å.

A very useful route to gain deeper insight into the nature of CIAC is to examine the influence of current processing for a wide variety of manganites, particularly for the typical systems such as $La_{1-x}Sr_xMnO_3$, $Pr_{1-x}Ca_xMnO_3$, $(La_{1-y}Pr_y)_{1-x}Ca_xMnO_3$ and $La_{1-x}Ce_xMnO_3$. $La_{1-x}Sr_xMnO_3$ is the most canonical

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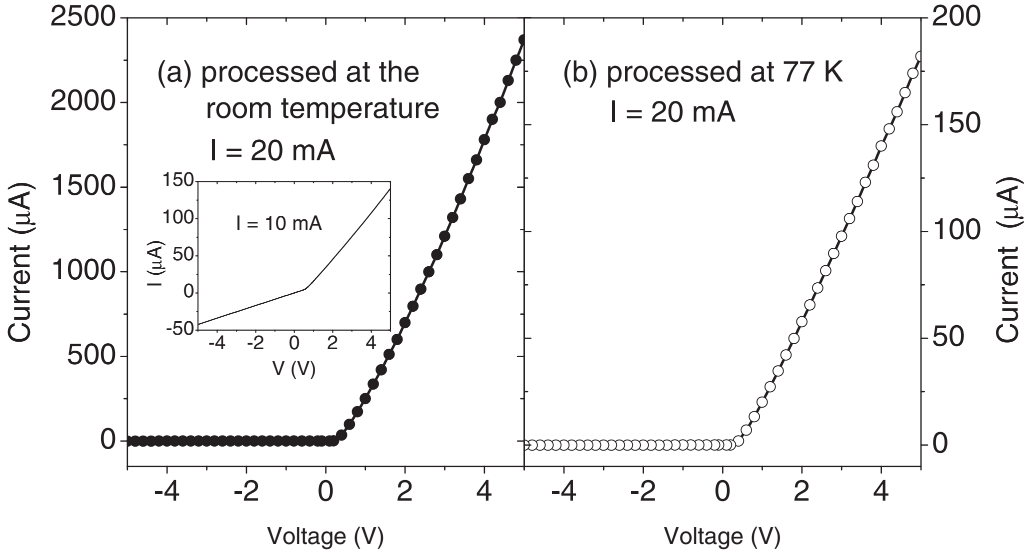


Fig. 2: Current-voltage relations at the room temperature for $La_{0.8}Ca_{0.2}MnO_3$ films processed at (a) room temperature and (b) 77 K. The size of the films is $50\,\mu m \times 300\,\mu m$ and the thickness is $\sim 800$ Å. The magnitude of the processing current is 20 mA. In the inset of panel (a) we also give the result for a film processed with a much smaller current, 10 mA.

double-exchange system because it has the largest one-electron bandwidth and accordingly is less affected by the electron-lattice interaction and Coulomb correlation [1]. $Pr_{1-x}Ca_xMnO_3$ is unique because it has a narrow one-electron bandwidth and shows an insulating behavior over the whole doping composition ($x$) range [6]. $(La_{1-y}Pr_y)_{1-x}Ca_xMnO_3$ is well known for its large-scale phase separation [7]. $La_{1-x}Ce_xMnO_3$, different from others, is doped by tetravalent cation, but recent researches showed that its major carriers are still holes [8].

However, there seems to be a huge difficulty keeping us from examining CIAC in a wide range. Previously it was believed that the current-processing is most effective near or below Curie temperature ($T_C$), where the metallic-insulating transition occurs. A common method used in refs. [3–5] is applying current at a temperature lower than $T_C$. Figure 1 shows a typical temperature-dependent resistance for a $La_{0.8}Ca_{0.2}MnO_3$ film (size: $50\,\mu m \times 50\,\mu m$; thickness: $\sim 800$ Å). To successfully process this film, a typical current needed is $\sim$10 mA. The self-heating effect is severe, and the film is thus heated toward, at last may through, $T_C$. During the processing the resistance of the film increases for self-heating, and a larger power (current $\times$ resistance) is thus needed to maintain the constant current, which will in turn accelerate heating. Therefore, to successfully perform the process, the peak resistance of manganite film can not be large. Unfortunately, $(La_{1-y}Pr_y)_{1-x}Ca_xMnO_3$ shows extremely large resistivity near $T_C$, and $Pr_{1-x}Ca_xMnO_3$ even shows no $T_C$. Therefore it is impossible to process them by the reported method. In addition, to avoid the resistance to be too large, the length of the film has to be limited to a small value, which causes inconvenience in characterizing.

In this letter, we report a much more applicable current processing method, simply applying current at the room temperature, to produce anisotropic conduction in manganite films. Our results revealed that employing current processing near or below $T_C$ is not necessary. Above room temperature, the resistivity of most manganites decreases with self-heating, therefore large processing current is easy to be applied. $La_{1-x}Ca_xMnO_3$ ($x = 0.2$, 0.33), $La_{0.67}Sr_{0.33}MnO_3$(LSMO), $Pr_{0.7}Ca_{0.3}MnO_3$(PCMO), $La_{0.35}Pr_{0.32}Ca_{0.33}MnO_3$(LPCMO) and $La_{0.7}Ce_{0.3}MnO_3$ (LCeMO) films had been processed, and anisotropic conductance appeared in all these films, showing CIAC is a fairly universe phenomenon for manganites. Using this method, we also got anisotropic conductance in a $La_{0.67}Ca_{0.33}MnO_3$ film as long as 3 mm.

All films were grown on (100) $SrTiO_3$ substrates by the pulsed laser deposition technique. During the deposition, the typical temperature is 720 °C, and the typical oxygen pressure is 80 Pa. The film thickness is controlled by the deposition time. In the X-ray diffraction $\theta$-$2\theta$ scan, only $(00l)$ peaks of the manganite films and $SrTiO_3$ substrates were observed, confirming good quality of these films. The films were patterned by the conventional lithography technique into microbridges with widths of $50\,\mu m$, $100\,\mu m$, and $200\,\mu m$.

A Keithley 2400 source meter (voltage limit 210 V) was used to provide constant current. To facilitate heat-diffusion, the samples were mounted on an aluminum radiator using silver paste. A typical process lasted for $\sim$1 minute. We define the direction of the processing current as the forward one.

In fig. 2 we compared the results for $La_{0.8}Ca_{0.2}MnO_3$ films (width: $50\,\mu m$; length: $300\,\mu m$; thickness: $\sim 800$ Å)

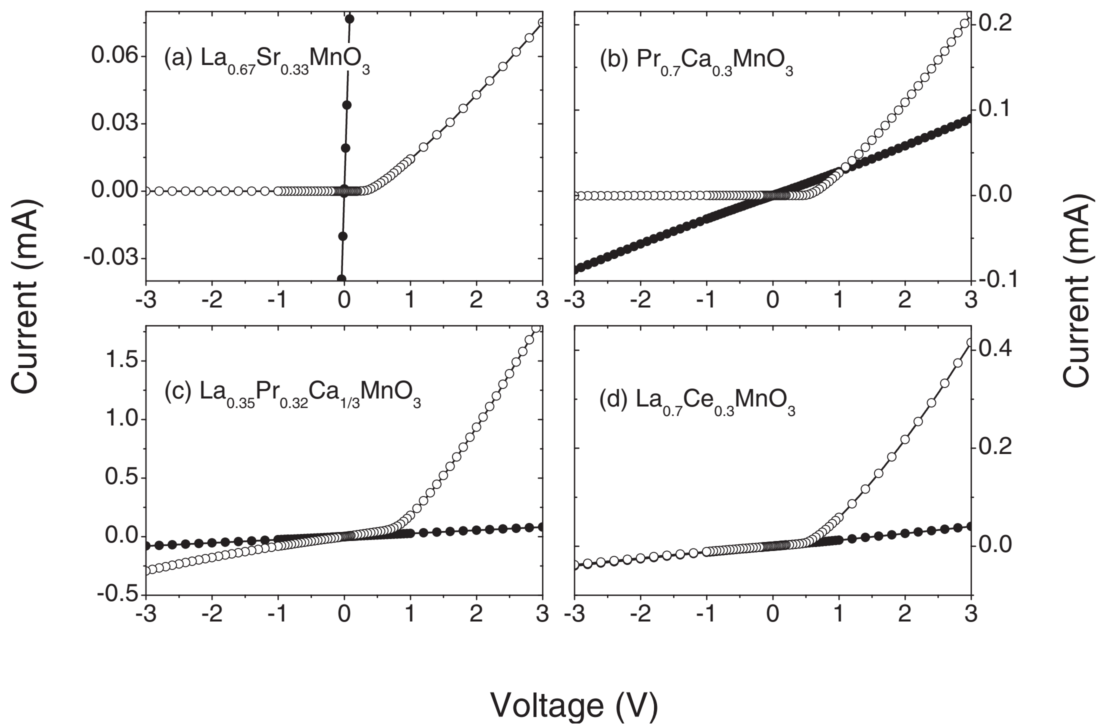


Fig. 3: Current-processing–induced anisotropic conduction in (a) $La_{0.67}Sr_{0.33}MnO_3$, (b) $Pr_{0.7}Ca_{0.3}MnO_3$, (c) $La_{0.35}Pr_{0.32}Ca_{0.33}MnO_3$, and (d) $La_{0.7}Ce_{0.3}MnO_3$ films. Filled and empty signals represent the data before and after processing, respectively.

processed at the room temperature and at 77 K, respectively. In both cases the processing current is 20 mA ($5.0 \times 10^5$ A/cm$^{-2}$), and the current-voltage ($I$-$V$) curves were measured at room temperature. Strongly anisotropic conduction appeared in both cases, characterizing by the extreme asymmetry of the $I$-$V$ curve, like a horizontal line upwards bended at $\sim 0.18$ V. Although the forward current for the film processed at the room temperature is relatively large, the main characteristics for the two curves are essentially the same, showing that processing samples at the room temperature is an equivalent method to produce CIAC.

In the following we examined the CIAC effect in a wide variety of manganites by processing the corresponding films at the room temperature. Figure 3 shows typical results for LSMO, PCMO, LPCMO, and LCeMO films. The density of the processing current is $1.3 \times 10^5$ A/cm$^{-2}$, $4.2 \times 10^4$ A/cm$^{-2}$, $5.0 \times 10^5$ A/cm$^{-2}$, and $1.0 \times 10^5$ A/cm$^{-2}$ for LSMO, PCMO, LPCMO and LCeMO, respectively. For comparison, the $I$-$V$ relation before processing for each film was also given (filled signals). Remarkable CIAC appears in all these films, showing it is a fairly universal phenomenon for manganites. If we define the voltage where the largest bend occurs as the threshold voltage ($V_T$), from fig. 3 we can see that $V_T$ for LSMO, PCMO, LPCMO, and LCeMO are 0.34 V, 0.55 V, 0.74 V, and 0.54 V, respectively. However, besides the type of manganites, $V_T$ also varies with other factors such as processing current. In the inset of fig. 2(a) we also give the $I$-$V$ curve for a $La_{0.8}Ca_{0.2}MnO_3$ film processed with a current of 10 mA. The decrease of the magnitude of the processing current shifts $V_T$ from 0.18 V to 0.59 V. Moreover, the asymmetry of the $I$-$V$ curve becomes much weaker.

From our present and previous results [3,5] it can be seen that CIAC can appear in a wide variety of manganites and in the whole temperature range, which is different from magnetoresistance induced by magnetic field [1] and electroresistance induced by electrical field [9]. CIAC seems to have weak dependence on the electronic properties of manganites, and thus it can hardly be explained in a picture based on phase separation and any other existing mechanisms. Current-processing induced change in crystalline structure and topologic distribution may play an important role in determining the anisotropic conduction. Compared with magnetic and electric fields, current has a much violent role, accompanied by severe Joule heating. In the previous report [5] we proposed that the overheating and directional migration of oxygen near the grain boundaries may account for CIAC. In that scenario, the transport behavior of the manganite film will be determined by the conduction of the grain and the interfacial structure, and the strongly bias-dependent property may mainly origin from the latter. It is important

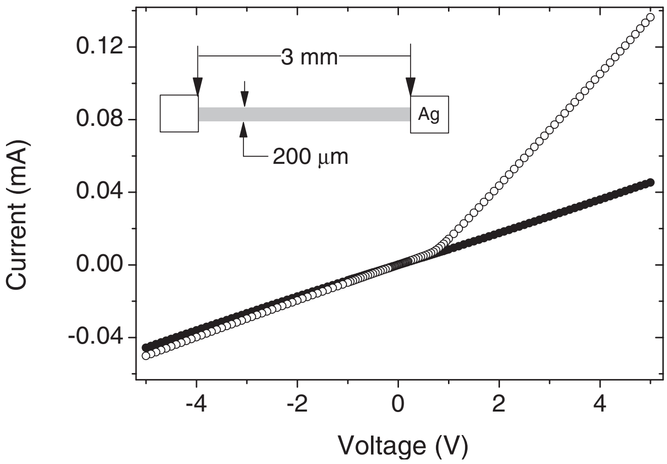


Fig. 4: Current-processing–induced anisotropic conduction in a $La_{0.67}Ca_{0.33}MnO_3$ film with size as large as $200\,\mu m \times 3\,mm$. The film thickness is $\sim 380$ Å. The processing current is 11 mA. Filled and empty signals represent the data before and after processing, respectively.

to note that both the forward and backward resistances of the processed films can be either smaller or larger than the corresponding original resistances, depending on the type of manganites and the magnitude of the processing current (figs. 2 and 3). Obviously the change of the boundary will increase the total resistance. To explain the fact that the resistance of the processed film can be much smaller than the original film, another local overheating effect should be considered. Because of phase separation, a current prefers to flow through manganites in filamentary conduction paths [1,10]. An application of large current will cause heating along conduction paths, decrease their resistivity, and in turn much more current will concentrate on these paths. Previous researches had revealed that strong current can cause enhance of conduction of manganite [11,12]. For current-processed films, it is possible that the enhance of conduction partly retains when the current is withdrawn, since the processing current is extremely strong.

Finally, we report our effort to produce CIAC in manganite film of large size. In fig. 4 we present our result on a $La_{0.67}Ca_{0.33}MnO_3$ film. The thickness, width and length of the film are 380 Å, $200\,\mu m$ and 3 mm, respectively (fig. 4, inset). The resistance of the film at room temperature is $\sim$120 kΩ. Thus it is impossible to directly apply a strong current to process the film, considering that the voltage limit of the source meter is 210 V. As an alternative, we began with relatively small current to heat the sample, and thus decrease the resistance of the film (fig. 1). Then we gradually added the magnitude of the processing current. At last, designed current was applied. As shown in fig. 4, a current of 11 mA produced remarkable anisotropy in the film. The $V_T$ is $\sim 0.71$ V. This value is close to other samples (fig. 3), though the length of $La_{0.67}Ca_{0.33}MnO_3$ film is one order of magnitude larger than that of other films. This fact suggests that the CIAC cannot be treated in the picture that the anisotropy distributed evenly through the film and the observed anisotropy is the superposition of each part.

In summary, our studies showed that CIAC is a fairly universal phenomenon for manganite films. The anisotropy can be easily produced by processing samples at room temperature, independent of $T_C$. Further researches are highly needed to understand the mechanism underneath this interesting phenomenon. Our effort provides a very simple method to prepare such samples, which will help further researches in this field. In addition, considering their resemblance with manganites, CIAC might appear in other complex oxides, such as cobaltites and high-temperature superconductor oxides.

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This work has been supported by the National Natural Science Foundation of China and the National Fundamental Research of China.

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