Magnetic field effects on the manganite junction with different electronic processes

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A manganite junction with two distinguishable electronic processes has been fabricated and its rectifying properties are experimentally studied. The current-voltage characteristics of the junctions are found to be dominated by leakage current and thermal current under low and high bias voltages, respectively. The responses of these two processes to magnetic field are found to be different, and the magnetoresistance (MR) of the junction arises mainly from the modification of magnetic field to leakage current. Although the MR shows a monotonic decrease with bias voltage (V), the MR-V dependence is different for the two processes. An approximately linear, yet slow, decrease of MR with V is observed for the leakage process, while an exponential reduction for the thermal one. These results show that the electronic processes undergoing in the junction can be identified based on the analysis of the MR-V relations. © *2007 American Institute of Physics*.
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By sandwiching a $SrTiO_3$ layer between $La_{0.9}Sr_{0.1}MnO_3$ and $La_{0.05}Sr_{0.95}TiO_3$, Sugiura *et al.* fabricated the first manganite *p-i-n* junction exhibiting an excellent rectifying behavior.[1] Tanaka *et al.* further demonstrated that the intermediate layer was unnecessary, and constructed a *p-n* junction simply using $La_{0.9}Ba_{0.1}MnO_3$ and Nb-doped $SrTiO_3$.[2] Subsequent studies show that, in addition to the excellent rectifying character, manganite junctions own a lot of amazing properties such as large magnetoresistance[3–5] (MR) and photovoltaic effects.[6] It has been reported that the junction resistance experiences a great change under magnetic field. Different from the manganite, the MR of the junction can occur in a wide temperature range well below the metal-to-insulator transition (MIT) of the manganite, and is strongly dependent of the current used by the measurement. Although it is natural to ascribe the MR effect of the junction to the manganite film, the detailed process undergoing in the former is not very clear at present. As a matter of fact, diverse mechanisms have been proposed for the MR of the manganite junctions. It has been suggested that it is the magnetic field-enhanced charge tunneling across the junction that leads to the MR.[4,5] This explanation seems to be consistent with the experiment result that the depletion width undergoes a reduction under magnetic field.[4] There is also a hypothesis that the buildup of an interfacial potential, due to the difference of the Fermi levels of the manganite and the electron-doped $SrTiO_3$, and the variation of this potential with external field should be responsible for the appearance of the MR.[3] However, the actual electronic processes in the junction may be much more complex than expected considering the fact that thermal current, tunneling current, and leakage current could coexist, though their contributions may vary with temperature and electric bias. A natural assumption is that the magnetic field affects these processes to different extents, and the observed MR is a combined effect. It is therefore highly desired to identify the MR effects associated with different electronic processes, which is basically important for a thorough understanding of the transport behaviors of the junction. In this letter we will present a comprehensive study on the rectifying behaviors of a manganite junction with two distinguishable processes. It is found that the MR of the junction arises mainly from the modification of leakage current by magnetic field, whereas the relative variation of thermal current is negligibly small.

The manganite heterojunction was fabricated by epitaxially growing $La_{0.67}Ca_{0.33}MnO_3$ (LCMO) film of ~100 nm in thickness on a 0.05 wt % Nb-doped (001) $SrTiO_3$ substrate (STON) by the pulsed laser ablation technique following the procedures: A LCMO layer of ~50 nm was first deposited at a temperature of ~600 °C then the remaining at ~720 °C, after an interruption (~20 min) for temperature increase and maintenance. The oxygen pressure was kept at ~100 Pa during the preparation. After the deposition, the sample was furnace cooled to room temperature in an oxygen atmosphere of ~160 Pa.

Resistive measurements were conducted by a superconducting quantum interference device magnetometer with the two-point technique being used. The lateral size of the junction is 1×1 mm^2, patterned by the conventional photolithography and chemical etching technique. Two Cu pads were deposited, respectively, on LCMO and STON as electrodes. The resistance is lower than 10 and 100 Ω for the Cu-STON and the Cu-LCMO contacts, respectively, evaluated by comparing the results of the four-point and two-point measurements. It is small compared with junction resistance, as will be seen below, and will not affect the quantitative analysis of the current-voltage (J-V) characteristics of the junction.

The LCMO film shows a MIT at ~245 K. Magnetic field depresses the resistivity of the film, and a field of 5 T can produce a MR of ~90% (not shown). These behaviors are similar to those of the bulk LCMO.[7] Figure 1 shows the current-voltage characteristics of LCMO/STON, measured under different temperatures below 360 K. Excellent rectifying behaviors characterized by strongly asymmetric J-V curves against electric polarity are observed. The current is

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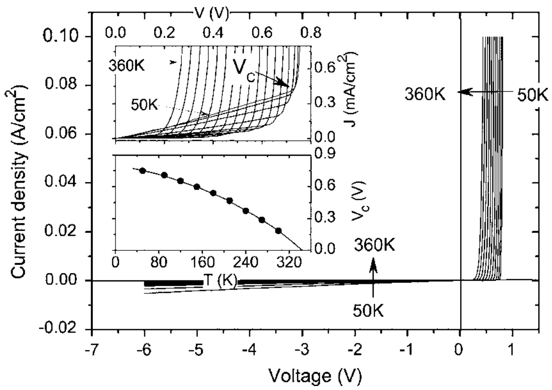

FIG. 1. Current-voltage characteristics of the manganite junction LCMO/STON measured under different temperatures below 360 K. Top inset: a close view of the *J*-*V* curves that show two electronic processes. Bottom inset: variation of V_c with temperature.

tiny in the zero-bias limit and remains small as the reverse bias increases, whereas it grows steeply with voltage in forward direction. Decrease in temperature has no obvious effects except for a nearly rigid shift of the *J*-*V* curves along the *V* axis. Although these behaviors are similar to those observed in other manganite junctions, a careful analysis indicates the occurrence of two different processes. As can be seen from the positive branch of the *J*-*V* curves, the current increases first slowly then rapidly against bias voltage, with a definite delimitation between the two processes at $V=V_c$ (top inset of Fig. 1). The *J*-*V* relation is essentially linear below V_c when temperature is low, which reveals the Ohmic character of the junction resistance, and slightly deviates from linearity as the temperature approaches 230 K. In contrast, an exponential relation between *J* and *V* is observed above V_c, $J \propto J_s \exp(eV/nk_BT)$ when $eV \gg nk_BT$, where k_B is Boltzmann's constant and *n* the ideality factor ($n=1$ for a perfect *p*-*n* junction). These results indicate that the charge leaking dominates the electronic process of the junction in the low bias range. However, thermal current grows at a much higher speed with bias voltage than the leaked one and exceeds the latter for $V>V_c$. As expected, V_c exhibits a monotonic decrease with temperature, and only the thermal process is visible above 330 K (bottom inset of Fig. 1). Figure 2 shows a decomposition of a typical *J*-*V* curve into two *J*-*V* branches for the two different electronic processes, respectively. The inset of Fig. 2 presents the ratio of the leakage to thermal

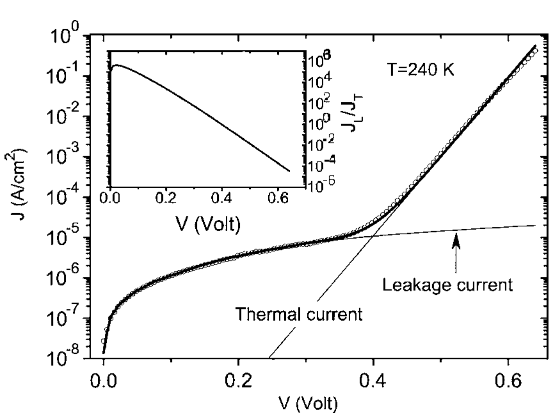

FIG. 2. Decomposition of a typical current-voltage curve obtained at $T=240$ K. Thin lines represent leakage current and thermal currents, thick line a combination of the two currents, and symbols the experimental results. The inset plot displays the leakage to thermal current ratio: J_L=leakage current and J_T=thermal current.

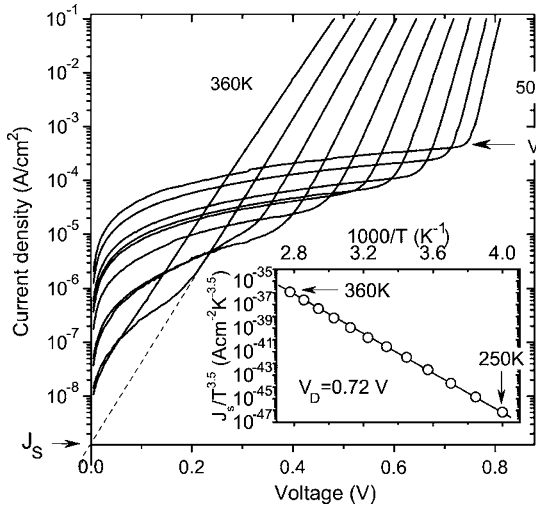

FIG. 3. Semilog plot of the characteristics of LCMO/STON showing the determination of saturation current. Dashed line is a guide for the eye. The inset plot displays saturation current as a function of reciprocal temperature, based on which the built-in potential is determined.

current. The exponential decrease of this ratio with bias voltage is obviously a consequence of the increase of thermal current.

The appearance of leakage current indicates the presence of interfacial defects such as pin holes, anionic or ionic vacancies, and dislocations, through which charge leaking takes place. However, a further analysis indicates that the interfacial barrier is not affected by charge leaking. Based on the formula $J_s \propto T^{3.5}\exp(-eV_D/k_BT)$ (Ref. 8) and with the use of the saturation current J_s obtained by simply extrapolating the log *J*-*V* curve for $V>V_c$ to $V\to 0$ (Fig. 3), the built-in potential V_D is estimated to be ~0.72 V (inset of Fig. 3). This is a result similar to that obtained for other junctions with only a simple thermal process.[9]

It would be instructive to investigate the respective response of the two processes to magnetic field. Figure 4 exemplifies the typical current-voltage curves measured with and without magnetic field, respectively. Magnetic field is found to modify the first process significantly, resulting in a great increase of leakage current. A simple calculation shows that the maximum $J(H=5\text{ T})/J(0)$ ratio is ~3.3

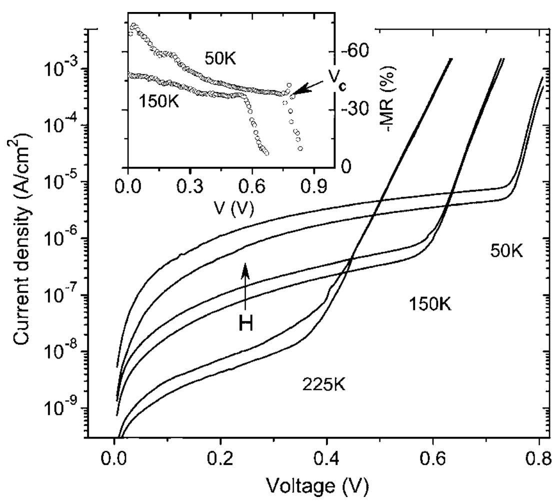

FIG. 4. Current-voltage characteristics with and without magnetic field for selected temperatures. The inset plot shows the magnetoresistance as a function of bias voltage.

[$MR=J(0)/J(H)-1\approx-65\%$], occurring at $T=50$ K, the lowest temperature of the present measurement. Different from the LCMO film, for which significant MR appears around the temperature where the MIT occurs, the MR of the junction takes place in a wide temperature range below 240 K, and increases with the decrease of temperature. In contrast, the field effect on thermal current is rather weak in the whole temperature range concerned, and the modest $J(H=5\ \mathrm{T})/J(0)$ ratio is only $\sim$1.06. This result reveals the insensitivity of J_s to magnetic field. A remarkable observation of the present work is the complex, yet strong, electric bias dependence of the MR of the junction. As shown by the inset plot in Fig. 4, the MR takes its maximum value in the zero-bias limit, and decreases first slowly then rapidly with bias voltage. A rigid corner at $V=V_c$, which delimitates the two processes, can be clearly seen. The weak bias dependence of the MR in the range of $V<V_c$ reveals the deviation from an idealized ohmic character of the leakage process. This is found to be a general feature of the leakage process, and could be ascribed to weak electric link. It is further found that an exact MR-V relation for $V<V_c$ cannot be obtained because of the slight variation of the detailed J-V relation with repeated measurements. This could also be a signature of weak electric link.

Insensitivity of the thermal current to magnetic field was also observed in the $La_{0.7}Sr_{0.3}MnO_3$-based junction. As reported by Nakagawa *et al.*,[4] the MR of this junction is negligibly small without significant charge leaking. However, the thermal current was found to increase greatly when oxygen vacancies exist in the manganite film. It is believed that in this case charge tunneling dominates the behavior of the junction because of the reduction of depletion width, and magnetic field affects the charge tunneling by modifying the thickness of depletion layer. Similar results are obtained for the LCMO/STON junction if significant oxygen deficiency occurs for LCMO (not shown). The reason for this is not clear. It is possible that oxygen deficiency in the manganite film affected adjacent STON layer.

As for the sudden drop of MR above V_c, it could be a consequence of the increase of thermal current. It is easy to obtain that $MR\approx-\Delta J_L/J_T(H)-\Delta J_T/J_T(H)$ for $V>V_c$, where J_L and J_T are leakage and thermal currents, respectively, and $\Delta J=J(H)-J(0)$ is the variation of J under magnetic field. This result actually implies an exponential decrease of MR with V noting the relation of $\Delta J_T/J_T=\exp[(1/n_0-1/n_H)eV/k_BT]\exp(-e\Delta V_D/k_BT)-1$, where ΔV_D is the change of V_D under magnetic field, and n_0 and n_H are the ideality factors without and with magnetic field, respectively. It is therefore obvious that the drastic decrease of MR with V is a typical feature of the thermal process. A strong bias dependence is also expected when MR takes place as a result of the variation of depletion width under magnetic field, which will affect the charge tunneling of the junction. These analyses reveal that the MR behavior of the junction is a combined effect and the fingerprints of different electronic processes can be identified from the MR-V relation.

Stepwise J-V curves are unusual for the LCMO-based junctions. It is possible that the low deposition temperature impedes the epitaxial growth of the LCMO film, resulting in considerable interfacial defects. The density of interfacial defects could not be high noting the large junction resistance, $\sim 1.7\times10^5\ \Omega$ at $T=50$ K and larger at lifted temperatures. In fact, the effective area of the interfacial defects can be estimated based on a simple consideration. It is reasonable to assume that the low-bias resistance of the junction is mainly determined by the depleted LCMO layer near the interface, which could be the thickness of $L\approx10$ nm considering the presence of a conductive deadlayer.[10] A simple calculation based on the relation $R=\rho L/S$ gives the effective area of $S\approx5\times10^5\ \mathrm{nm}^2$ of the interfacial defects adopting the resistivity $\rho\approx10^2\ \Omega\,\mathrm{cm}$ for the depletion layer and $R\approx1.7\times10^5\ \Omega$ the junction resistance.

As discussed above, interfacial defects may be the channel for charge leaking. This implies that the MR for $V<V_c$ could be mainly determined by the depleted LCMO layer near the interfacial defects. Because of the presence of the STON layer that is insensitive to magnetic field, the MR of the junction is usually smaller than that of the LCMO film. As shown by the present work, the maximum MR is $\sim$90% for the LCMO film and $\sim$65% for the corresponding junction. A larger MR is expected in the LCMO/STON junction with a higher Nb content, which reduces the depletion width of STON, thus the corresponding resistance. Leakage current may always exist in the manganite junctions, though its effect is unobvious when the junction has a high quality interfacial structure. This implies that the stepwise MR-V relation observed here could be a general feature of the manganite junction.

In summary, a manganite junction with two distinguishable electronic processes has been fabricated and its rectifying properties are experimentally studied. The current-voltage characteristics of the junctions are found to be dominated by leakage current and thermal current under low and high bias voltages, respectively. The responses of these two processes to magnetic field are found to be different, and the MR of the junction arises mainly from the modification of magnetic field to leakage current. Although the MR shows a monotonic decrease with bias voltage (V), the MR-V dependence is different for the two processes. An approximately linear, yet slow, decrease of MR with V is observed for the leakage process, while an exponential reduction for the thermal one. These results show that the electronic processes undergoing in the junction can be identified based on the analysis of the MR-V relations.

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