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# Manipulating metal-to-insulator transition temperature in manganite–titanate junction by reverse electrical bias

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**Abstract**
The metal-to-insulator transition (MIT) is a prominent feature of manganites and also occurs in a few manganite junctions. In this study we prepared $La_{0.67}Sr_{0.33}MnO_3$/1 wt% Nb-doped $SrTiO_3$ junctions and detected their MIT temperature ($T_{MIT}$) at different reverse biases. We show that $T_{MIT}$ can be significantly modulated from 150 to 260 K when the bias voltage increases from −0.3 to −2.0 V. This phenomenon could be a combined effect of charge tunnelling across the junction and the reduction of film thickness of $La_{0.67}Sr_{0.33}MnO_3$.

## 1. Introduction

Doped manganites of the type $R_{1-x}A_xMnO_3$ ($R$ = rare-earth and $A$ = alkaline-earth elements) have attracted much attention because of their rich fundamental physics and potential applications [1]. A prominent feature of these materials is the existence of a metal-to-insulator transition (MIT) accompanying a ferromagnetic–paramagnetic transition [1]. The ability to control the MIT temperature ($T_{MIT}$) may find use in electronic devices and therefore should be of great interest. It has been well known that the magnetic field can suppress spin disorder at around $T_{MIT}$, driving $T_{MIT}$ to higher temperatures. However, the variations of $T_{MIT}$ are usually less than 50 K even under strong fields up to several tesla, which severely limits its practical utility. According to the phase diagram of manganites [2], the modulation of the carrier concentration affect the double exchange interaction, leading to a variation of $T_{MIT}$. In general, the field effect is used to modulate the carrier concentration in conventional semiconductors. However, no significant variation in $T_{MIT}$ is found for the manganites even under a strong electric field [3, 4]. To date, a simple and practical modulating technique for $T_{MIT}$ is still desired.

It has been proved that $T_{MIT}$ is different for manganite films of different thicknesses [5, 6]. It is possible that the magnetic and electronic properties of the films vary with the distance from the film–substrate interface, and if $T_{MIT}$ of different distances from the interface can be directly detected, the modulation of $T_{MIT}$ is realized naturally. A previous work suggests that manganite junction could be a suitable sample for relevant studies. In fact, electrical bias modified MIT has been observed in a few junctions [7–9]. For example, Tanaka *et al* [7] achieved a $T_{MIT}$ from 290 to 340 K by increasing the bias voltage from +1.0 to +1.8 V in the $La_{0.9}Ba_{0.1}MnO_3$/Nb-doped $SrTiO_3$ junction. Lang *et al* [8] observed that $T_{MIT}$ decreases from ∼200 to ∼120 K when the bias voltage increases from +0.1 to +0.6 V in a p–i–n junction composed of $La_{0.7}Ca_{0.3}MnO_3$, YSZ and Si. Unfortunately, the applied electric bias, and therefore the modulation of $T_{MIT}$, is strongly limited because of low built-in interfacial potential of the junction, which is generally less than 1 V [10]. In this study, we report on the modulation of $T_{MIT}$ by a reverse electrical bias in $La_{0.67}Sr_{0.33}MnO_3$ (LSMO)-based junctions. A remarkable advantage of the reverse bias is that it can be

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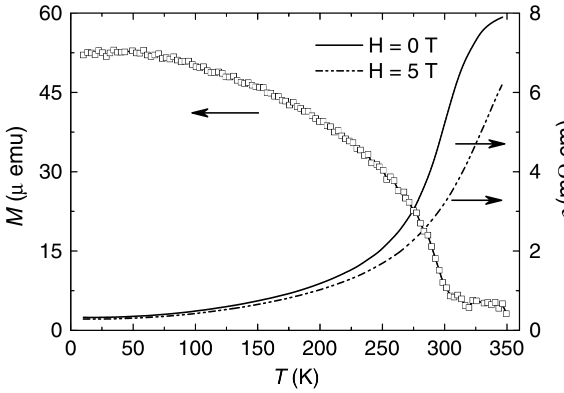


**Figure 1.** Temperature dependence of magnetization ($M$) and resistivity ($\rho$) of a 5 nm LSMO film on $SrTiO_3$ substrate.

much larger than the forward bias, therefore producing a much stronger effect on $T_{MIT}$. We have examined junctions based on LSMO films with different thicknesses (5, 10, 20, 60 nm) and found a distinct modulation of $T_{MIT}$ in all these junctions. As a typical example, here we have demonstrated the result for the 5 nm LSMO-based junction, in which the largest modulation was achieved.

## 2. Experimental details

The junction was prepared by growing an LSMO film about 5 nm in thickness on a 1 wt% Nb-doped (0 0 1) $SrTiO_3$ (STON) substrate using the pulsed laser ablation technique. During deposition, the oxygen pressure was kept at 50 Pa, and the temperature was kept at 750 °C. The details of the fabrication process have been described elsewhere [11]. X-ray diffraction reveals epitaxial growth of a (0 0 1)-oriented LSMO film. The atomic force microscopy image reveals a smooth surface and the root-mean-square roughness is ∼0.2 nm. The area of the junction is 1 mm$^2$. To make a direct comparison of the junction, an LSMO film on the (0 0 1) $SrTiO_3$ substrate was also prepared under the same conditions. The Curie temperature of the film is ∼300 K (figure 1), much lower than that of the bulk LSMO (∼350 K), which could be due to the reduction of the film thickness.

## 3. Results and discussion

Transport measurements of the junction were performed by the two-electrode method and good rectifying behaviours were observed (figure 2). In the forward direction, the current increases abruptly when the bias voltage exceeds a threshold. The current versus voltage ($I$–$V$) curves shrink monotonically along the $V$-axis with increasing temperature. In the reverse direction, the current is small when $|V|$ is low and increases quickly with the reverse bias when $|V|$ exceeds 1. This phenomenon is known as soft breakdown [10, 12] and will be explained later. The reverse $I$–$V$ curves change with temperature in a much complex manner (figure 2 and its inset), implying the presence of different temperature dependences of junction resistance when the bias voltage varies.

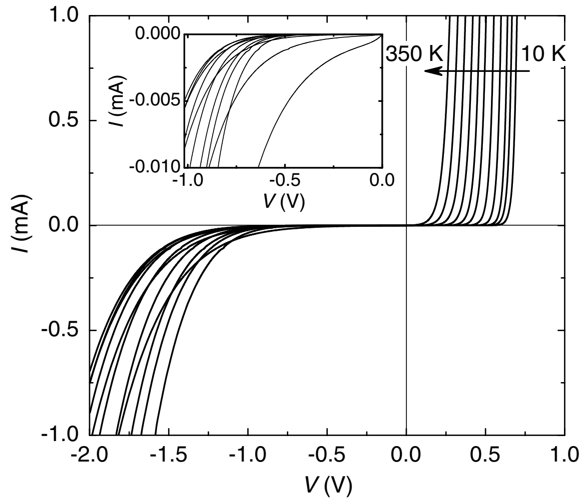


**Figure 2.** $I$–$V$ relations of the LSMO/STON junction. The inset shows a magnification of the $I$–$V$ relations in the reverse direction.

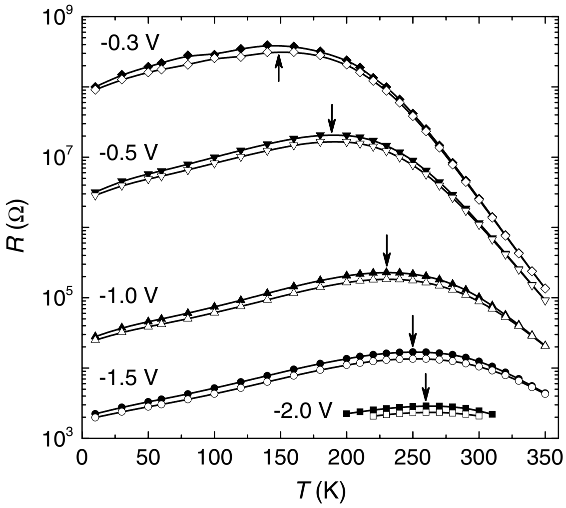


**Figure 3.** Temperature dependence of the junction resistance of the LSMO/STON junction at various biases under 0 T (filled signals) and 5 T (empty signals) magnetic fields.

The temperature dependence of the junction resistance ($R_j = V/I$) for the reverse direction is shown in figure 3. In a bias range from −0.3 to −2.0 V, all $R_j$–$T$ curves exhibit MIT and the $T_{MIT}$ can be modified between ∼150 and ∼260 K. This result indicate the possibility of modulating $T_{MIT}$ in a simple manner. Compared with that of STON, the resistive property of LSMO is much more sensitive to temperature. It is therefore a natural assumption that the MIT can be exclusively ascribed to the LSMO film. It should be mentioned that no MIT in the reverse direction has ever been reported in the junctions whose substrates are lightly doped, partially because of the extremely large $R_j$ in this direction [7]. In addition to the increase in $T_{MIT}$, a large reverse bias leads to a drastic decrease of $R_j$. When the bias increases from −0.3 to −2 V, the peak $R_j$ reduces from $\sim 4 \times 10^8$ to $\sim 3 \times 10^3\ \Omega$, over five orders of magnitude. It is instructive to note that the electrical bias effect on the junction is similar to that of the magnetic field on the manganite.

A field of 5 T depresses the peak $R_j$ by ∼20%, essentially independent of the bias voltage, but has no significant influence

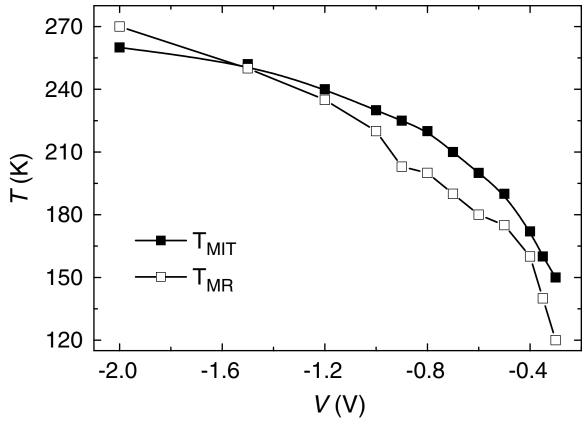


**Figure 4.** Bias dependence of $T_{MIT}$ and $T_{MR}$ of the LSMO/STON junction.

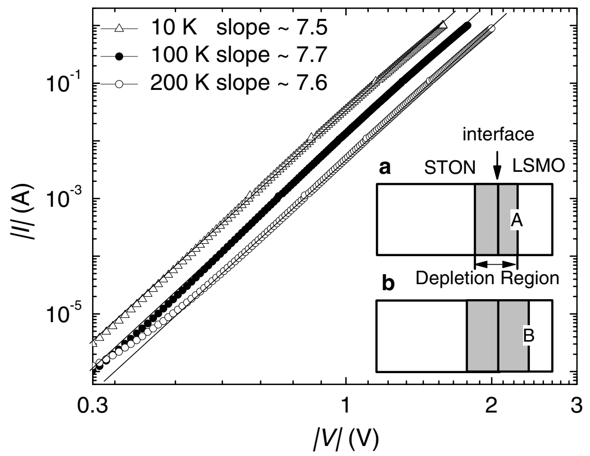


**Figure 5.** $|I| - |V|$ characteristics in the reverse direction of the LSMO/STON junction plotted in logarithm coordinates. Thin lines are guide for eyes. The insets schematically show the distribution of the depletion region.

on $T_{MIT}$ (figure 3). The temperature corresponding to the maximum magnetoresistance ($T_{MR}$) nearly coincide with $T_{MIT}$ (see figure 4), which can be regarded as an evidence of the responsibility of the LSMO film for the MIT of the junction.

To get a further understanding of the observed $T_{MIT}$ modulation, an analysis of the conduction mechanism of the junction under reverse bias is necessary. Figure 5 shows the presence of linear $\log|I|$–$\log|V|$ relations in a wide reverse bias range, with a nearly constant slope of ~7.6, regardless of temperature. This result follows a power law with the bias, which is a signature of tunnelling [12]. The breakdown of the LSMO/STON junction at a relatively low bias is also a signature of the tunnelling effect (figure 2) [10].

In a p–n junction the tunnelling current is mainly determined by the thickness of the depletion layer and the state density near the depletion region on both the p- and the n- sides [10, 12]. A previous study [11] revealed that the depletion layer of the manganite junction with high carrier concentrations is only several nanometres in width, and a considerable part of it is distributed in the manganite side. A similar situation may occur in the current LSMO/STON junction. Since the physical properties of STON are relatively insensitive to temperature, the LSMO layer near the depletion region will determine the conduction behaviour of the junction. Accordingly, the MIT of the junction could originate from the variation of the density of states due to the MIT of the LSMO layer. In the inset of figure 5 we schematically show the distribution of the depletion region. Increasing the reverse bias will lead to the enlargement of the depletion region and push the boundary in LSMO from A to B, away from the interface. Due to the thickness effect [5, 6], the layer located at B will have a higher $T_{MIT}$ than the layer at A, and this accounts for the increase in $T_{MIT}$ of the junction.

This simple model can also explain the variation of $T_{MIT}$ under a positive electric bias observed by Lang *et al* [8] noting the fact that the forward bias can reduce the depletion width [10]. In the case of the $La_{0.9}Ba_{0.1}MnO_3$/Nb-doped $SrTiO_3$ junction, $T_{MIT}$ of the $La_{0.9}Ba_{0.1}MnO_3$ film increases with decreasing film thickness [13], which explains the increase in $T_{MIT}$ of the junction with the forward bias. It should be pointed out that this model gives only a qualitative explanation. The manganites are different from conventional semiconductors due to the strong coupling between spin, charge and lattice degrees of freedom [1] and the significant temperature dependence of depletion width. The physical process undergoing in the junction could be much more complex, and a thorough understanding of it requires further work.

## 4. Summary

We have achieved significant modulation of $T_{MIT}$ in LSMO/STON junctions by tuning the reverse bias. The modulation was realized by detecting $T_{MIT}$ of the LSMO layers with different distances away from the interface, instead of changing the intrinsic magnetic order. This study provides a simple and practical method to modulate $T_{MIT}$. By optimizing the doping level of the substrate and the physical properties of the manganite film, larger modulation could be expected.

## Acknowledgments

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