# Direct measurement of the interfacial barrier height of the manganite p–n heterojunction*

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A manganite p–n heterojunction composed of $La_{0.67}Sr_{0.33}MnO_3$ film and 0.05 wt% Nb-doped $SrTiO_3$ substrate is fabricated. Rectifying behavior of the junction well described by the Shockley equation is observed, and the transport properties of the interface are experimentally studied. A satisfactorily logarithmic linear dependence of resistance on temperature is observed in a temperature range of 150 K–380 K, and the linear relation between bias and activation energies deduced from the $R-1/T$ curves is observed. According to activation energy, the interfacial barrier of the heterojunction is obtained, which is 0.91 eV.

**Keywords:** manganite, heterojunction, interfacial barrier

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## 1. Introduction

Compared with the conventional semiconductor junction, manganite-based p–n heterojunctions are expected to exhibit much more powerful functions. Since Sugiura *et al.*[1] fabricated the first manganite p–i–n junction by sandwiching an $SrTiO_3$ layer between $La_{0.9}Sr_{0.1}MnO_3$ and $La_{0.05}Sr_{0.95}TiO_3$, manganite-based p–n heterojunctions have attracted considerable attention. Subsequent studies show that, in addition to the excellent rectifying characteristic, manganite junctions have a lot of amazing properties, such as strongly bias-dependent magnetoresistance,[2,3] magnetic-field-tunable photovoltaic effects,[4] and magnetic-field-tunable capacitance effects,[5] while a manganite-based transistor was fabricated successfully in 2011.[6]

It is obvious that the physical properties of the junction are mainly determined by an interfacial barrier. The direct information about the interfacial potential is therefore highly desired, especially for the manganite junctions that show emergent phenomena. Several successful attempts have directly measured the interfacial energy barrier in manganite junctions.[7–9] Based on the thermionic emission model for the Schottky diode, Postma *et al.*[10] analyzed the current–voltage characteristics of the (La, Sr) $MnO_3$/$SrTiO_3$:Nb junction and obtained a Schottky barrier of ∼0.65 eV, where (La, Sr) MnO3 was treated as a metal. Alternatively, Sawa[7] studied the $Pr_{0.6}Ca_{0.4}MnO_3$/SrTiO3:Nb junction in the frame of the conventional semiconductor theory and obtained a similar value of ∼ 0.70 eV for the interfacial barrier. Subsequent work by Sun[11,12] showed that the interfacial barrier can be deduced by analyzing the saturation current of the p–n heterojunction, and tuned by the hole density for the $La_{1-x}Ca_xMnO_3$/SrTiO3:Nb junctions, whereas it is insensitive to the metal-to-insulator transition and the change in resistivity is due to the variation of tolerance factor.

We notice that the previous work on the interfacial barrier of a manganite p–n heterojunction is mainly based on the analysis of the saturation current. However, the saturation current, which is obtained by linearly extrapolating the current-bias curve to the zero bias, cannot be measured directly. Usually, the obtained saturation current depends on the researcher's willing. Even from the same current-bias curve, the saturation currents obtained by different researches are distinctly different. Such deviations may bring errors to the analysis of the interfacial barrier. In this paper, we attempt to analyze the interfacial barrier of a manganite-based p–n junction composed of a $La_{0.67}Sr_{0.33}MnO_3$ (LSMO) film and a 0.05-wt% Nb-doped SrTiO3 (STON) substrate by directly measuring the resistance of the heterojunction. The rectifying behavior of the junction is well described by the Shockley equation. The relation between junction resistance and temperature is similar to that of the traditional gapped semiconductor, and the interfacial barrier of the heterojunction, which is 0.91 eV, is obtained.

## 2. Experiment

The LSMO/STON junction was fabricated by epitaxially growing LSMO film of the thickness of ∼200 nm on the (001) 0.05-wt% Nb-doped STON single crystal substrate by the pulsed-laser deposition (PLD) technique. The temperature of the substrate was kept at 750 °C and the oxygen pressure at 60 Pa during the deposition. The as-deposited sample was furnace cooled to room temperature in an oxygen atmosphere of 160 Pa. As shown by the X-ray diffraction data (not shown in

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this paper), only the $(00l)$ peaks of the LSMO film and STON substrate are observed, indicating that the LSMO film is clean single phase and highly textured. The magnetic–paramagnetic transition of LSMO film occurs at 380 K and the film is metallic below 380 K, which is consistent with that of the reported LSMO film.

The electrical measurements of the junction were performed in the two-probe configuration. To obtain a good electric contact and avoid the effect of current distribution in the junction,[13] three copper electrodes (one on the LSMO film and two on the STON substrate) were deposited. The LSMO film and copper electrodes were subsequently patterned into squares of a size of 1 mm×1 mm by the conventional photolithography and chemical etching technique. The Cu–STON and Cu–LSMO contacting resistances are both lower than 1 Ω at room temperature. Here we explain why the Cu is selected as the electrode material. The Cu can be deposited on LSMO and STON by PLD conveniently, and it can adhere to LSMO and STON strongly. The contact between Cu–LSMO may be regarded as a metal–metal contact, and the contact resistance can be ignored. Usually, the contact resistance between Cu and STON is very large. A special technology was adopted to remove the Cu–STON contact resistance. Finally, the contact resistance is small and will not affect the quantitative analysis of the transport properties of the junction.

## 3. Results and discussion

To investigate the rectifying property of the heterojunction, the current–bias ($I$–$V$) characteristics are measured under various temperatures, as shown in Fig. 1(a). The junction exhibits an excellent rectifying property, as demonstrated by the strong asymmetry of the $I$–$V$ curves against the polarity of the electrical bias. The current is negligibly small and remains tiny in the initial stage of the application of electrical bias in both directions, but grows rapidly when the bias voltage exceeds a threshold value of direction dependence. In the forward direction, the threshold is a few tenths of a volt. However, the current is still tiny in the reverse direction until the bias reaches 6 V, indicating that the heterojunction has an excellent anti-breakdown ability, which shows that the potential acts as a diode. As temperature decreases, the $I$–$V$ curve exhibits a simple expansion along the $V$-axis as occurring in the conventional p–n junctions.

Based on semiconductor theory, the $I$–$V$ relation of an idealized p–n junction can be described by the Shockley formula, as follows:[14,15]

$$I \approx I_0 \exp(eV/nk_{\mathrm{B}}T) \qquad (1)$$

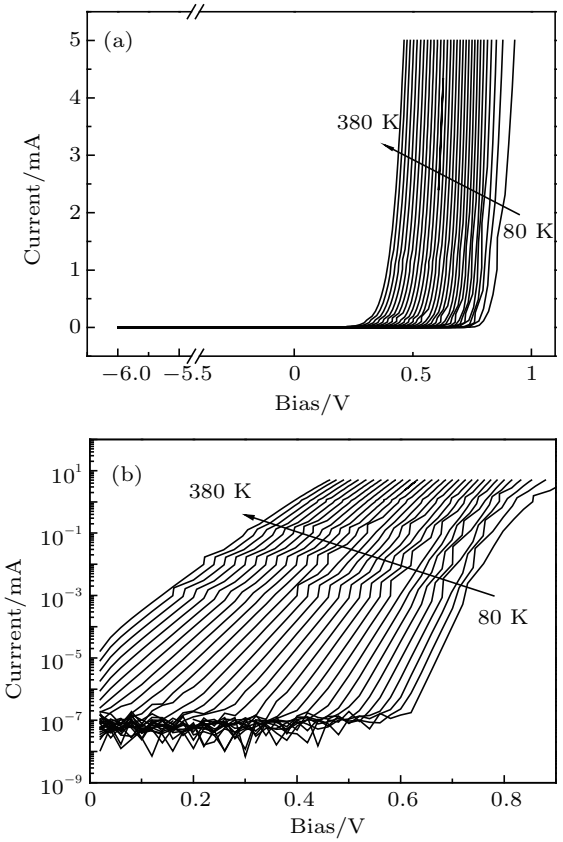



**Fig. 1.** Current–voltage characteristics (a) and logarithmic (b) plot of the characteristics of LSMO/STON junctions measured at temperatures between 80 K and 380 K.

for $eV > nk_{\mathrm{B}}T$ in the forward direction. Here, $k_{\mathrm{B}}$ is the Boltzamann constant, $n$ is the ideality factor, and the prefactor $I_0$ the reverse saturation current, which is related to interfacial barrier. It is obvious that the precondition that the heterojunction can be regarded as an idealized p–n junction requires that the $\log(I)$–$V$ relation should be linear. Fortunately, this condition is satisfied by the present junction. As is shown in Fig. 1(b), an excellent linear dependence of $\log(I)$ on $V$ is observed in a temperature range from 150 K to 380 K. The saturation current $I_0$ obtained as an intercept on the $y$ axis of the extrapolated $\log(I)$–$V$ relation is quite small, say $\sim 2.7 \times 10^{-11}$ A for $T = 300$ K, which indicates the high quality of the junction and the negligible leakage current. This is consistent with the fact that the ideality factor $n$ (shown in Fig. 2), where $n$ is determined by the slope of the $\log(I)$–$V$ curve, is pretty small, varying between 1 and 1.2 in a temperature range from 160 K to 380 K ($n$ is expected to be unity for an idealized p–n junction). That the ideality factor is very close to 1 implies that the thermal emission is the dominating means of a carrier to overcome the interfacial barrier, which makes it possible to obtain the interfacial barrier by measuring the resistance of the heterojunction directly.

The dependences of resistance of the heterojunction on temperature measured under various biases are shown in Fig. 3. The resistivity increases monotonically and smoothly

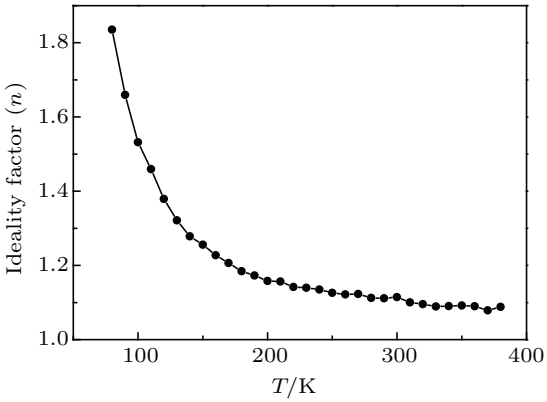



**Fig. 2.** Dependence of ideality factor $n$ on temperature.

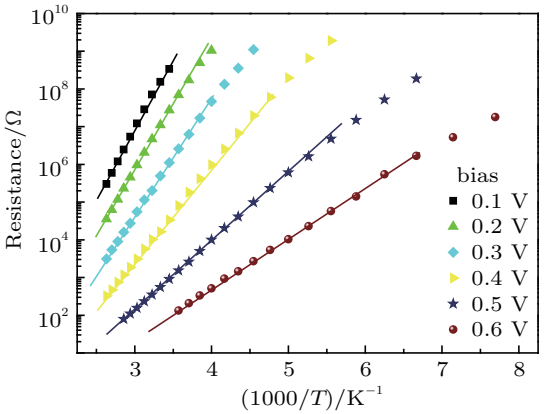



**Fig. 3.** (color online) Dependences of resistance of LSMO/STON heterojunction on $1/T$ measured under various bias voltages. The solid lines are guides for the eye.

with the decrease of temperature with the increase of bias. However, when the resistance data are a plot of logarithmically versus $1/T$, the resistance and $1/T$ is well logarithmically linear. The present $R$–$1/T$ relation of the heterojunction is similar to that of the traditional gapped semiconductor. Both of which can be described by the formula $R = R_0 \exp(E_A/k_B T)$, where $E_A$ is the activation energy, which implies that the heterojunction and semiconductor have similar basic physical transport properties. Carriers must overcome a barrier to take part in the transport process by thermal emission. The carriers in the semiconductor need to overcome the energy gap between the valence and conduction band. However, in the heterojunction they must overcome the interfacial barrier, which is an important and complex parameter of a junction. The $E_A$ values of present heterojunction under various measured bias voltages can be deduced from the slopes of $R$–$1/T$ curves, as shown in Fig. 3. As shown in Fig. 4, a satisfactory linear dependence of activation energy $E_A$ on the bias is observed. The interfacial barrier of the junction is obtained by extrapolating the $E_A$-bias line to zero bias, which is 0.91 eV, and is slightly larger than that of the manganite heterojunction obtained by analyzing the $I$–$V$ curves[11,12] and less than that obtained by the technology of photo resistance.[16]

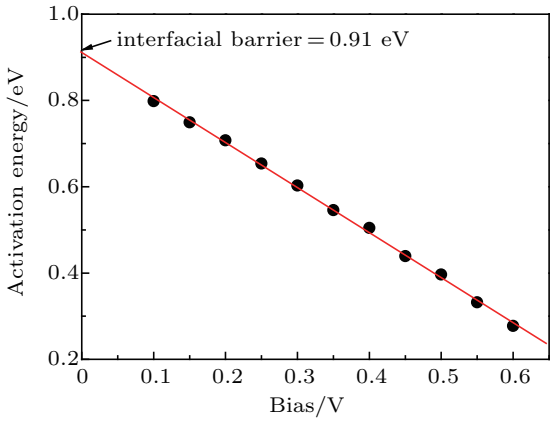



**Fig. 4.** (color online) Linear relation between activation energy and bias ($E_A$-bias). The interfacial barrier is obtained to be 0.91 eV by extrapolating the line to zero bias.

On the other hand, if the LSMO/STON heterojunction is treated as a metal–semiconductor contact Schottky junction, then its current–voltage relation is described by the function[14]

$$I = I_s \exp\left(\frac{eV}{k_B T}\right) = CT^2 \exp\left(\frac{e(V - V_D)}{k_B T}\right),$$

where the prefactor $C$ is a constant and $V_D$ is the interfacial barrier. Comparing with the exponential factor, the factor $T^2$ changes very slowly, so it can be ignored. Then, the resistance of the junction is $R \propto \exp[e(V_D - V)/k_B T]$ under a fixed bias voltage. It is clearly seen that the activation energy deduced from the ln($R$)–$1/T$ curve is $e(V_D$–$V)$, which is consistent with the experimental results.

By analyzing the saturation current of the heterojunction, the interfacial barrier is also obtained to be 0.85 eV, which is slightly less than that from the resistance measurement. This difference may be ascribed to the measurement error of saturation current.

## 4. Summary

In the present paper, a manganite p–n heterojunction LSMO/STON is fabricated by using the PLD technology and the transport properties of the interface are experimentally studied. The rectifying behavior of the junction is well described by the Shockley equation. A satisfactory logarithmically linear dependence of resistance on temperature is observed in a temperature range of 150 K–380 K, and the relation between the bias and activation energy which is deduced from the $R$–$1/T$ curve is linear. According to the $E_A$-bias curve, the interfacial barrier of the heterojunction is obtained to be exactly 0.91 eV.

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