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Measure the barrier height of manganite p–n heterojunction by activation energy measurement

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The barrier height of the manganite based p–n heterojunction is identified from the activation energy. The $La_{0.35}Pr_{0.32}Ca_{0.33}MnO_3$/Nb-doped $SrTiO_3$ p–n heterojunction is fabricated by the pulse laser deposition technology. The junction shows good rectifying behavior which can be well described by the Shockley equation. A satisfactorily logarithmic linear dependence of resistance on temperature is observed, and also the relation between bias and activation energy (E_A) deduced from the $R-1/T$ curves is linear. As a result, the interfacial barrier of the heterojunction is obtained by extrapolating the Bias $-E_A$ plot to Y axis, which is 0.95 eV.

1. Introduction

Since Sugiur and collaborators fabricated the first manganite p–i–n junction that showed satisfactory rectifying properties under a wide temperature range [1], manganite-based p–n heterojunctions have attracted lots of attention with regard to their basic physics as well as applications [2–4]. Manganite-based heterojunctions are typical systems composed of Mott insulators and they possess diverse properties absent in conventional junctions, such as excellent rectifying properties, bias-dependent magnetoresistance [5,6], magnetocapacitance effect [6], peculiar photoelectronic behaviors [7–9], and temperature-dependent photovoltaic effect [10]. In the scenario of the buildup of a built-in voltage due to the interlayer diffusion of holes and electrons between p-type manganites and n-type doped $SrTiO_3$ and the variation of this potential with external fields, these behaviors can be understood qualitatively. It is obvious that the direct information about the interfacial potential is highly desired. This will allow us to gain an intuitive image about the effect of the resistive/magnetic transition of the manganite, which is especially important for the understanding of the diverse behaviors of the manganite junction. Several successful attempts have been made for the measurement of the interfacial barrier in manganite junctions [11–13]. Based on the analysis of the current–voltage dependence, the interfacial barrier of a $La_{0.67}Sr_{0.33}MnO_3/SrTiO_3$:Nb junction (0.01 wt%Nb) is deduced by Postma [14], which is about 0.94 eV. Similar studies were also performed by Sun and collaborators [15], and the interfacial barrier was found to be about 0.8 eV for the p–n heterojunctions composed of various manganites.

It is noticed that the previous work on the interfacial barrier of a manganite p–n heterojunction is mainly based on the analysis of the reverse saturation current J_0, where J_0 was obtained as the intercept in the J-axis of the extrapolated $\log(J)-V$ relation, which requires that the relation between J and V should be logarithmic linear in a broad temperature range. In fact, an obvious deviation from linearity at low temperature was observed which can be ascribed to the increase in tunneling current [15]. And also the obtained saturation current, which is obtained by linearly extrapolating the current–bias curve to the zero bias, is usually depends on the researcher's willing.

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Even for a same current–bias curve, the saturation currents got by different researches are different greatly. Such deviations may bring the errors to analyze the interfacial barrier. In an attempt to ascertain a more accurate interfacial barrier value and to avoid the effect of tunneling current. In this paper we will perform the possibility of analyzing the interfacial barrier of a manganite based p–n junction by directly measure the activation energy of the interfacial resistance. The rectifying behavior of the heterojunction can be well described by the Shockley equation. A satisfactory logarithmic linear dependence of resistance on $1/T$ is observed and simultaneously a very satisfactory line dependence of activation energy on the bias is also observed. Therefore, the interfacial barrier of the junction is obtained, which is 0.95 eV.

2. Experiment

A p–n heterojunction composed of a $La_{0.35}Pr_{0.32}Ca_{0.33}MnO_3$ (LPCMO) film and 0.05 wt% Nb-doped $SrTiO_3$ (STON) substrate was fabricated by epitaxially growing the LPCMO film on STON single crystal substrate with (001) orientation by the pulsed laser deposition technique. The temperature of the substrate was kept at 730 °C and the oxygen pressure at 100 Pa during the deposition. The thickness of the LPCMO thin film is about 200 nm controlled by the deposition time. The resulting sample was furnace cooled to room temperature in an oxygen atmosphere of 160 Pa after deposition. As is shown by the X-ray diffraction data (not shown in this paper), only the (00*l*) peaks of the LPCMO film and STON substrate are observed, indicating that the LPCMO film is clean single phase and highly textured.

Electric measurements were performed using the cryostat system of a SQUID magnetometer. We added an external electrical equipment for applying and measuring the bias voltage and current through the device. To get a good electric contact and to avoid the effect of current distribution in the junction, three copper electrodes, one on LPCMO and the other two on STON were deposited. The manganite films and electrodes were subsequently patterned into squares of the size of 1×1 mm^2 by the conventional photolithography and chemical etching technique. The contacting resistance is lower than 1 Ω/10 Ω between Cu and STON/manganite films, evaluated by comparing the four-point and the two-point results. It is quite small compared with the junction resistance as will be seen below, so it will not affect the quantitative analysis of the electrical transport behavior.

3. Results and discussions

Fig. 1 shows the resistance and magnetization of the LPCMO film as a function of temperature measured along the film plane. The film is metallic below T_p ~152 K and semiconductive above T_p. The simultaneous occurrence of metal-semiconductor transition and magnetic transition indicates a strong correlation between these two processes, which is a typical feature of a colossal magnetoresistance effect (CMR) material.

To have a general impression on the transport behaviors, the temperature-dependent current–voltage characteristics

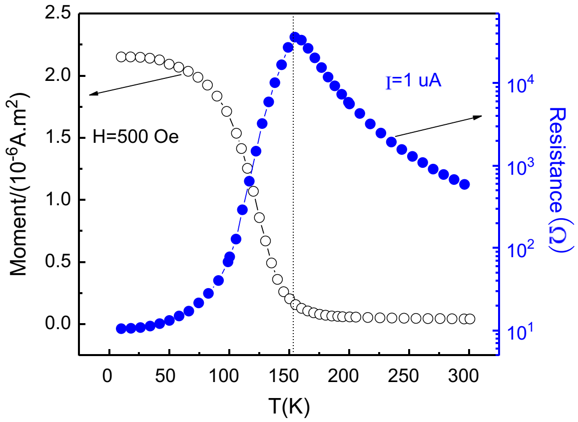

Fig. 1. Resistance and magnetization of the LPCMO film dependent on temperature (thin line marks the simultaneous occurrence of resistive and magnetic transition).

of the LPCMO/STON junction are presented in Fig. 2a. The junction shows an excellent rectifying behavior, as demonstrated by the strong asymmetry of the *J*–*V* curves against the polarity of the electric bias. The value of *J* rises quickly in the forward direction when the bias voltage exceeds a threshold value below 1 V, while it is negligible small in the reverse direction up to the bias voltage 6 V, indicating that the heterojunction has an excellent anti-breakdown ability, which shows the potential application of the heterojunction as a diode. As the temperature increases, the *J*–*V* curves shift along the *V* axis to the low bias voltage direction as occurred in the conventional junctions. In other manganite junctions, the rectifying behavior has also been reported, except for the difference of the threshold voltage [11,14].

To obtain the information of the interfacial potential, the *J*–*V* curves have been further analyzed. Based on the semiconductor theory, the *J*–*V* relation of a idealized p–n junction can be described by the formula $J \approx J_0 \exp(eV/nk_BT)$ in the forward bias direction when $eV \gg nk_BT$. Where n is the ideality factor, k_B the Boltzamann contact and the pre-factor J_0 is the reverse saturation current density. It is obvious that the precondition to regard our heterojunction as an idealized p–n junction is that the log(*J*)–V relation should be linear. Fortunately, this condition is satisfied by the present junction. Fig. 2b is the log(*J*)–V plots for the temperatures from 50 K to 360 K. Well linear log(*J*)–V relations are observed for all the temperatures in a wide bias range. The value of the ideality factor n (shown in Fig. 3), where n is determined by the slope of the log(*J*)–*V* curve, is pretty small, varying between 1 and 1.4 in the temperature range from 100 K to 360 K (n is expected to be unity for an idealized p–n junction). That the ideality factor is 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 activation energy of interfacial resistance.

The dependence of resistance of the heterojunction on temperature measured under various biases is shown in Fig. 4. When the resistance data is plot logarithmically vs $1/T$, the resistance and $1/T$ is well logarithmic linear. The dependence