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Superposed forward current–voltage characteristics in $TbMnO_3$/*n*-Si and $TbMnO_3$/*p*-Si heterostructures

Yimin Cui *, Rongming Wang

Physics Department, Beijing University of Aeronautics and Astronautics, Beijing 100083, People's Republic of China

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ABSTRACT

$TbMnO_3$/*n*-Si (*n*–*N*) and $TbMnO_3$/*p*-Si (*p*–*n*) heterojunctions were fabricated under identical conditions. Good rectifying characteristics were found with almost the same forward current–voltage behavior in a temperature range from 150 to 300 K. Such intriguing superposed rectifying behaviours at the interfaces between $TbMnO_3$ and Si of two different doped types can be explained by a similar Schottky barrier diode behavior with its current–voltage dependence generally dominated by only one type of carrier. This work will favor both electronic transport analysis and future device applications.

1. Introduction

Multi-ferric materials are of great technological importance as promising candidates in a wide range of applications due to their unique properties [1–4]. It is well-known that the *p*–*n* junction has been widely used as a basic element in various semiconductor devices. Several groups have constructed *p*–*n* junctions by combining multi-ferric films with other semiconductor materials and found good rectifying and other interesting properties [5–9]. As one of a few candidates for magnetoelectric materials, $TbMnO_3$ (TMO) has attracted considerable interest in recent years [10–13]. In our previous work, we have fabricated a TMO/Nb doped $SrTiO_3$ heterojunction with good rectifying property [9]. For technical applications, it is important to use Si wafers as the substrate. Here, we report the successful fabrication of heterojunctions of TMO/*n*-Si and TMO/*p*-Si which show interesting rectifying properties.

2. Experiment

The heterojunctions were fabricated simultaneously by growing TMO thin film on *n*-type Si (resistivity is about 0.02 Ω cm) and *p*-type Si (about 12.5 Ω cm) single crystal substrates using pulsed laser deposition. TMO bulk target was synthesized using the conventional solid state reaction method, which was already described in Ref. [17]. The distance between the target and the substrate is 5 cm. Prior to the deposition, the substrates were chemically cleaned with acetone and ethanol, and fixed in a deposition chamber which was protected by pure argon. When the chamber was vacuumized to 1×10^{-4} Pa, the substrates were heated and kept at 750 °C, then in several seconds the chamber was pumped with high purity oxygen to 40 Pa and just at the same time the deposition began. The laser intensity was approximately 2 J/cm^2 with a repetition rate of 3 Hz. The film's thickness was about 100 nm, controlled by the deposition time. After deposition the chamber was vented with high purity oxygen to 1×10^4 Pa and then the substrates were cooled down to room temperature. A gold pad of 0.8 mm^2 was sputtered on TMO thin film as top electrode and the bottom electrode was In film (1 mm^2) pressed onto Si substrate. The layouts of the devices are illustrated in the insets of Figs. 1 and 2 with two voltage polarities, respectively. The current–voltage (*I*–*V*) curves were measured by applying an increasing pulsed dc voltage with a width of 0.5 s and an interval of 10 s between the two sequent pulses. Room temperature X-ray diffraction (XRD)was used to characterize the TMO film structure on the Rigaku D/Max-RB diffractometer in the 2θ range 20°–80° with step size of 0.02 using Cu Kα radiation.

3. Results and discussion

The upper inset of Fig. 1 shows the XRD pattern of TMO films on *n*-Si and *p*-Si substrates with clear (112) and (224) peaks of TMO, indicating epitaxial TMO film formed on *n*-Si and *p*-Si substrates.

Shown in Fig. 1 are the *I*–*V* curves of the TMO/*n*-Si junction, which show good rectifying behavior in a temperature range from 150 to 300 K. The *I*–*V* curves reveal critical voltages i.e. diffusion voltage (V_d)

* Corresponding author.
E-mail address: cuiym@buaa.edu.cn (Y. Cui).

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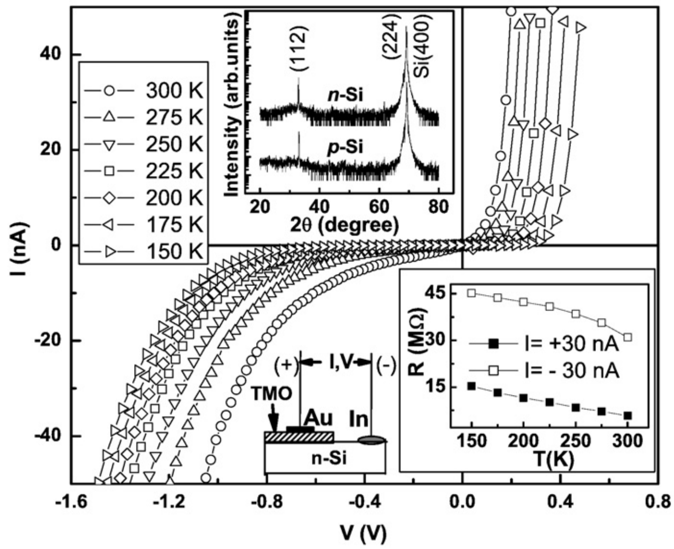

Fig. 1. The *I–V* curves of the TMO/*n*-Si junction in a wide temperature range from 150 to 300 K. The inset is layout of the TMO/*n*-Si heterojunction. The upper inset of Fig. 1 shows the XRD pattern of TMO films on *n*-Si and *p*-Si substrates. The lower inset of Fig. 1 shows the temperature dependence of the junction resistance at forward and backward currents of 30 nA.

and breakdown voltage (V_b), at which the current *I* starts to increase rapidly at forward and reverse bias, respectively. Although it is difficult to extract the precise values of V_b and V_d from our experimental *I–V* curves, it is still clear that V_b and V_d both increase with decreasing temperature monotonically. The lower inset of Fig. 1 shows the temperature dependence of the junction resistances at forward and backward currents of 30 nA, which both increase slightly and almost linearly with decreasing temperature.

Fig. 2 shows the *I–V* curves of the TMO/*p*-Si junction measured at different temperatures, which exhibits better rectifying properties. While V_b increases quickly with decreasing temperature, indicating a large reverse resistance especially at low temperature, the diffusion potential V_d varies little at different temperatures, as shown in Fig. 2.

For a comparison, the resistances as functions of temperature for the two junctions at a forward current of 10 nA are shown together (lower inset of Fig. 3). It was noticed that the two curves are nearly the same, with obviously the same diffusion potential V_d. The intriguing rectifying behaviours are observed in Fig. 3 for both two heterojunctions at 300 K as well as 200 K. Identical forward properties but with remarkably different backward properties are clearly seen. This phenomenon was reproducible by repeated experiments.

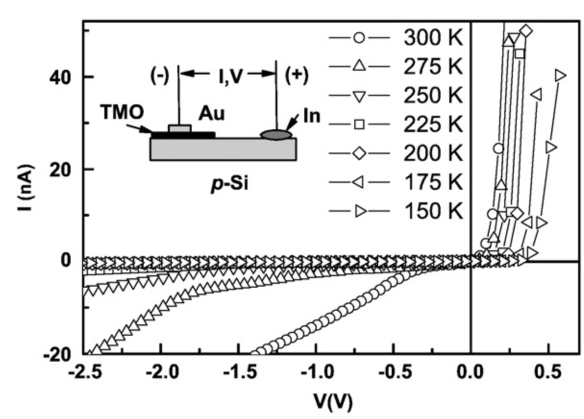

Fig. 2. The *I–V* curves of the TMO/*p*-Si junction measured at different temperatures in a temperature range from 150 to 300 K. The inset is layout of the TMO/*p*-Si heterojunction.

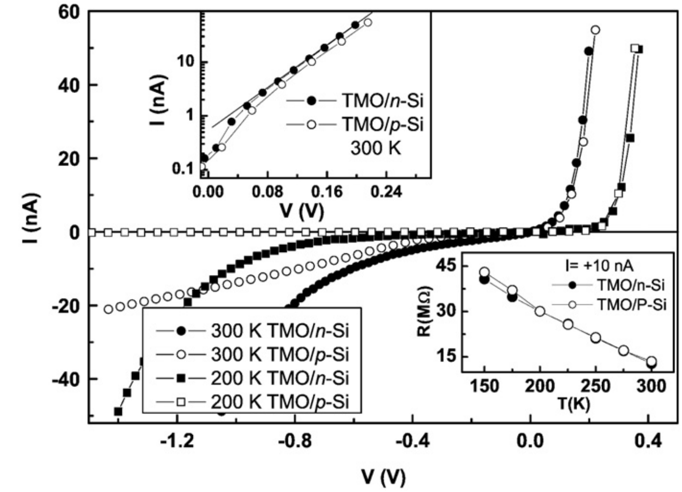

Fig. 3. The *I–V* curves for the two heterojunctions at 300 K and 200 K. The lower inset is the two junction resistances at forward current of 10 nA in the temperature range of 150–300 K. The upper inset is the two log(*I*)–*V* lines of forward-biased current.

The measured resistance of the heterojunction is the sum of all the resistances through all the current paths from top to bottom electrodes, including the contact resistance of Au/TMO, resistance through TMO thin film, the junction resistance of TMO/Si, resistance of part Si substrate, and the contact resistance of Si/In. Our *I–V* characteristic measurements show that Au/TMO contact is ohmic and Si/In contacts are nearly ohmic, which are shown in Fig. 4. Therefore the observed nonlinearity of *I–V* curves in Figs. 1 and 2 should come from the two TMO/Si junctions.

The rectifying *I–V* characteristic of the junctions usually originates from the band bending, i.e., the built-in potential at the interface. Due to the two different doping types, the Fermi level of the *n*-Si should be near the bottom of the conduction band whereas that of the *p*-Si should be above the top of the valence band. The stoichiometric TMO was reported to be an insulator [14]. Moreover, unlike the $LaMnO_3$ compound, bulk TMO prepared even in air does not show any more oxygen greater than 3 atoms per unit cell [15]. Since oxygen was introduced into the growing chamber with pressure of less than 1 atm during the cooling process, oxygen vacancies and other defects could well appear in as-prepared TMO thin films at the interfaces, which

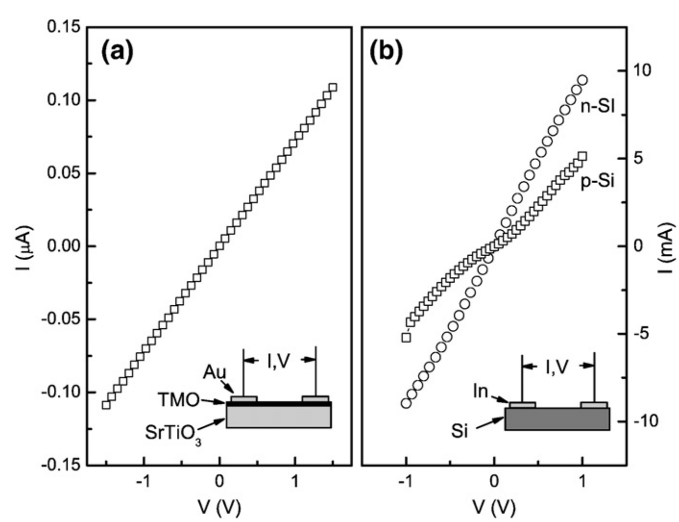

Fig. 4. The *I–V* curves for Au/TMO contact (a), and In/Si contacts (b) at room temperature, insets are the layouts of the measurements.