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Fabrication and *I–V* characteristics of *p–n* junctions composed of high-T_c superconductors and La-doped $SrTiO_3$

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Abstract

We have fabricated heterojunction structures comprising *p*-type high-T_c superconductor (YBCO) and *n*-type La-doped $SrTiO_3$ (La-STO). (001) and (110) oriented-YBCO thin films were prepared on the (001) and (110)-oriented La-STO substrates, respectively, with the pulsed laser deposition technique. X-ray diffraction measurements confirm that the (001) and (110) YBCO thin films are epitaxially grown on the substrates. The fabricated junctions with both orientations show rectifying *I–V* characteristic, but their behavior are rather different depending on the orientation. The threshold voltages in the forward bias region increase with decreasing temperature.

Keywords: Heterostructure; Oxide; La-STO; YBCO

1. Introduction

Transition-metal oxides exhibit various intriguing physical properties [1]. Colossal magnetoresistive manganites and superconducting cuprates, so-called, strongly electron correlated materials, are well known examples. These properties are highly sensitive to changes in the external electric and magnetic fields, light, and carrier concentration. Accordingly, with heterointerface structures composed of the transition-metal oxides, we are able to control the physical properties, as well as develop new functional devices. Indeed, various heterojunctions using perovskite oxides have been fabricated, and their observed properties are expected to be useful in new exotic functional devices [2–7], which cannot be achieved by conventional semiconductors.

We are greatly concern about *p–n* junctions with a heterointerface of transition-metal oxides. Electron-doped $SrTiO_3$ (STO) is often used for *n*-type conductor. A small amount of electron doping into STO makes the material conductive and furthermore superconducting at low temperature [8–10], while a stoichiometric sample is a band insulator with an indirect band gap of 3.2 eV [11,12]. Another interesting property of this material is photo-active. Under ultraviolet light illumination, large photocarriers (photocurrent) are generated [13]. Besides, the broad and structureless greenish luminescence around 500 nm is emitted below 110 K [14,15]. Therefore, *n*-type STO is a promising material for the component of the *p–n* junction.

High-T_c superconducting $YBa_2Cu_3O_{7-\delta}$ (YBCO) is well suited for the *p*-type conductor. Its electronic structure can be controlled by adjusting the doped carrier concentration. In addition, its crystal and electronic structures show large anisotropies. Thus, the physical properties of *p–n* junctions composed of YBCO with different orientations and carrier concentrations should be interesting.

In this study, we have fabricated heterojunctions comprising a *p*-type $YBa_2Cu_3O_{7-\delta}$ (YBCO) high-T_c superconductor and an *n*-type La-doped $SrTiO_3$ (La-STO) substrate. We deposited (001) (CuO_2 plane parallel to substrate plane) and (110)-oriented (CuO_2 plane perpendicular to substrate plane) YBCO thin films on the La-STO substrates. X-ray diffraction measurements confirm the epitaxial growth of the film. Current versus voltage (*I–V*) characteristics measurements for the (001)- and (110)-

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oriented junctions show the rectifying properties. We also found anisotropic junction properties depending on the orientation of the YBCO thin films.

2. Experiments

(001) and (110)-oriented YBCO thin films were prepared on the (001) and (110) La-STO substrates, respectively, with pulsed laser deposition (PLD) technique. We used 0.075 wt.% La-doped STO substrate as an n-type conductor for the fabricated junctions. About 500 Å (001) YBCO thin film was deposited at 740 °C under 0.4 Torr oxygen atmosphere. (110) YBCO film was fabricated using a self-buffer method [16], in which the film was first deposited at 540 °C and then at increasing temperatures up to 740 °C under oxygen partial pressure of 0.6 Torr. To control the carrier concentration, both thin films fabricated here were annealed at 400 °C for 20 min changing the oxygen partial pressure from 10^{-5} to 760 Torr. The crystallinity and lattice parameters of the thin film were investigated by X-ray diffraction. The film resistivity was measured by a conventional four-probed method. For the I–V characteristics measurements, Au electrodes were evaporated on the surfaces of YBCO and mechanically polished La-STO. This polishing process reduces the Schottky barrier with Au electrode. The device size was 2×2 mm^2.

3. Results and discussion

2θ–θ X-ray diffraction measurements reveal that the (001)-oriented YBCO thin films with various doping levels are grown on the La-STO (001)-oriented substrates. The obtained films show good crystallinity and superconducting transition temperatures (T_c) are 0, 53, 83, and 90 K. Based on a T_c-to-δ diagram of bulk YBCO samples [17], these T_c's correspond to the oxygen contents 6.0, 6.5, 6.8, and 7.0, respectively. Fig. 1 shows lattice parameter c of the thin films determined from the (00l) diffraction peak as a function of the oxygen content. The lattice parameter c of the film changes linearly from 11.815 to 11.676 Å , with increasing the oxygen content. This behavior is quite similar to that observed in bulk YBCO [17]. We can thus control the doped carrier concentration by changing the partial oxygen pressure during cooling in the deposition process.

The (110)-oriented YBCO thin films were confirmed to be grown on the (110)-oriented La-STO substrates. Only (hh 0) diffraction peaks of YBCO are observed in the 2θ–θ measurements. In order to analyze the thin film structure in detail, ϕ- and reciprocal space-mapping of the X-ray diffraction were performed. Fig. 2(a) presents ϕ-scan X-ray diffraction of the (005) peak of the (110)-oriented YBCO thin films with T_c~50 K. Only two peaks along the (001) azimuth of the La-STO substrate are observed at ϕ=0 and 180°, indicating that the thin film has two-fold symmetry in the in-plane direction. Therefore, the c-axis of the YBCO thin film is completely aligned with the (001) direction of the (110) substrate.

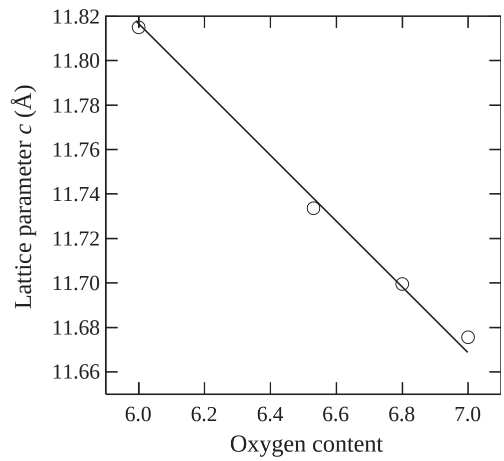

Fig. 1. Variation in lattice parameter c as a function of oxygen content, which is determined by T_c-to-δ diagram of bulk YBCO samples [17].

The logarithmic intensity contour plots of the (330) reciprocal mapping shown in Fig. 2(b) reveal the epitaxial relationship that the (110) plane of YBCO thin film is parallel to the (110) plane of La-STO substrate. In addition, the (400) reciprocal mapping in Fig. 2(c) shows three peaks, which are identified as La-STO(400), YBCO(400) and YBCO (040). The very weak intensity observed for the YBCO(040) strongly indicates that the obtained orthorhombic YBCO film has a little twin structure and that the a-axis of the film is almost aligned along the a-direction of the substrate.

Fig. 2(d) shows the variation in the lattice parameters a and b for the (110) YBCO thin films as a function of the oxygen content. The film annealed under an oxygen pressure of 10^{-5} Torr shows tetragonal symmetry (a=b). Orthorhombic YBCO phases are appeared when the films are deposited in an oxidizing atmosphere. The difference between a and b increases with the carrier concentration.

Fig. 3 shows the I–V characteristics at 290 and 5 K of the heterostructures composed of the (001) and (110)-oriented p-type YBCO with T_c~50 K and n-type La-STO. The temperature dependence of the resistivity of the YBCO film measured by the conventional four-probe method is shown in the inset. Transport properties in the Au/La-STO interface are often complicated and strongly depend on the surface treatments of junctions [18,19]. In our study, though Schottky barrier-like behavior is observed in our Au/La-STO interface, the threshold voltage of our Au/La-STO junction was very small and the large leak current was appeared. This means that the observed I–V curves shown in Fig. 3 originate from the interface properties of YBCO/La-STO. Rectifying properties of the fabricated junctions with (001) and (110) orientation are evident. In the (001) junction (Fig. 3(a)), the threshold voltage (V_{th}) at 290 K in the forward bias region is 1.65 V. At 5 K, it increases to 2.03