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Out-of-plane tilted Josephson junctions of bi-epitaxial $YBa_2Cu_3O_x$ thin films on tilted-axes $NdGaO_3$ substrates with CeO_2 seeding layer

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Abstract

Bi-epitaxial heterostructures $YBa_2Cu_3O_x$(YBCO)/CeO_2/$NdGaO_3$ were prepared on tilted-axes $NdGaO_3$ substrates using laser ablation technique. The heterostructures were patterned for electrical measurements using photolithography and ion-beam milling. Electrical anisotropy of the YBCO film was tested on the ion-beam etched surface. Bi-epitaxial junctions with four different orientations of the bi-epitaxial border were fabricated and studied. The measured IV curves showed flux–flow behavior with critical current density 2.5×10^4 A/cm^2 for the twist-type junctions and 1.5×10^3 A/cm^2 for [1 0 0]-tilt type junctions.

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1. Introduction

Bi-crystal Josephson junctions of high-temperature superconductors (HTSC) with out-of-substrate plane tilt of crystallographic axes (sometimes called [1 0 0]-tilt junctions) have been studied extensively for the last five years (see, e.g., [1–3]). These junctions provide better electrical properties compared to ordinary bi-crystal junctions [1,2], and higher reproducibility of junctions parameters due to grains seeding on the bi-crystal boundary [3]. Application of the bi-epitaxial technique [3] removes some of the geometrical limitations on such junctions and allows combination of both out-of-substrate plane tilt and in-plane 45°-rotation of crystallographic axes [3] necessary for fabrication of Josephson junctions with equilibrium phase shift equal to π—the π-junctions—to be used in "quiet" qubit, one of the most promising qubit types [4].

The bi-epitaxial technique with out-of-substrate-plane tilt developed in [3] utilizes (1 1 0) $SrTiO_3$ substrates, providing a tilt angle of 45° only. The possibility of preparing bi-epitaxial thin films and structures for other tilt angles was demonstrated in [5], while Kim et al. [6] fabricated Josephson junctions for a tilt angle of 30° using miscut $SrTiO_3$ substrates. In both cases the seeding layer of fluorite crystal structure (CeO_2, Y:ZrO_2) provided *c*-oriented growth of HTSC $YBa_2Cu_3O_x$ (YBCO) independently of the substrate and seeding layer orientation. Similar effects were observed for other non-perovskite miscut substrates and seeding layers, for example, MgO [7]. As far as we know, bi-epitaxial junctions with out-of-plane tilt angle other than 45°, were not fabricated previously, though data

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obtained for bi-crystals showed best results for mutual axes tilt ~22° [2].

We manufactured bi-epitaxial tilted out-of plane (TOP) Josephson junctions of HTSC YBCO thin films grown on miscut $NdGaO_3$ substrates with seeding CeO_2 layer for the miscut angles 23–27°. TOP junction properties were studied for different grain-boundary in-plane orientations.

2. Experimental

The $NdGaO_3$ miscut substrates were formed by rotation of the substrate plane from the (1 1 0) crystallographic plane around the [0 0 1] axis of $NdGaO_3$. The substrate surface was polished using a specially developed chemical–mechanical process.

The YBCO thin films and CeO_2 seeding layers were deposited by laser ablation of stoichiometric ceramic targets. The details of the technique can be found elsewhere [8]. The parameters of the CeO_2 deposition (substrate temperature 800 °C, energy density on target 1.75 J/cm^2, total pressure 0.5 mbar, $p_{\mathrm{Ar}}/p_{\mathrm{O_2}} = 7/3$, deposition rate about 3 Å/pulse) were optimized to obtain smooth thin film of single orientation (0 0 1) CeO_2 ‖ (1 1 0) NGO on a standard (1 1 0) $NdGaO_3$ substrate.

The YBCO thin films deposition parameters (730 °C, 1.3 J/cm^2, 0.8 mbar, $p_{\mathrm{Ar}}/p_{\mathrm{O_2}} = 8/2$, 0.6 Å/pulse) were optimized to obtain the highest temperature of the superconducting transition T_c. Post-deposition annealing was performed at 450 °C in 800 mbar of oxygen for 1 h. All YBCO films showed T_c higher than 89 K and a narrow superconducting transition, proving good uniformity of the film.

The structural properties of thin films and multilayers were studied using X-ray diffraction technique, and the surface morphology was observed by SEM and AFM.

Patterning of the YBCO thin film and CeO_2 seeding layer was done by photolithography and ion-beam etching techniques. The etching voltage and current were set to minimal values providing discharge stability (300 V, 10 mA, beam diameter—25 mm) to decrease the damage introduced into the films by ion bombardment. The etching depth of the seeding layer was determined by pre-calibrated etching rate and etching time, while YBCO thin film removal was checked by simple two-point measurement.

3. Results

Detailed results of our study of YBCO thin film structure, growth mechanisms, and electrical properties on miscut $NdGaO_3$ substrates can be found elsewhere [9]. Briefly, the YBCO thin films grow in agreement with the epitaxial relations $\langle 1 0 0\rangle_Y\ (0 0 1)_Y \parallel [0 0 1]_N\ (1 1 0)_N$ for all studied angles, except for the special case of $(1 2 0)_N$ substrate (miscut angle 18.4°).

CeO_2 growth on miscut $NdGaO_3$ substrate and dependence of the YBCO growth on CeO_2 seeding layer will be published in [10]. For all deposition parameters the YBCO film grew textured with the axis of texture $\langle 1 0 0\rangle_Y \parallel [0 0 1]_N$ and single main orientation of the $[0 0 1]_Y$ axis. At low deposition rate the $[0 0 1]_Y$ axis aligned with the substrate normal, so the film grew *c*-oriented.

On Fig. 1 the X-ray diffraction rocking curves in wide angular range [5] are shown for 2θ angles 69.4° (corresponding to CeO_2 (0 0 4) Bragg reflection, top curve) and 54.9° (YBCO (0 0 7) peak, bottom curve) for a sample with partially removed CeO_2 seeding layer. Two YBCO peaks can be seen: left, aligned with the (1 1 0) $NdGaO_3$ reflection; and right, aligned with the substrate normal **n**. On a bare $NdGaO_3$ substrate only the first peak can be seen, while on the CeO_2-covered substrate only the right one is present.

The Bragg diffraction angle during this measurement was set to $2\theta = 54.9°$, corresponding to the *c* lattice constant of the tilted-axes YBCO film (11.7 Å). The Bragg diffraction angle for the *c*-oriented part is different ($2\theta = 55.15°$, $c = 11.65$Å), so the intensity of the corresponding peak on the scan is smaller than at the optimal Bragg angle. The actual volume of the two parts of the film is equal.

To test the electrical properties of the film and of bi-epitaxial junctions of different types we fabricated the structure shown in Fig. 2. The $NdGaO_3$ substrates with miscut angle 23.4° and 26.6° were covered with 300 Å CeO_2 as a seeding layer. Part of the seeding layer (Γ-shaped, light grey on Fig. 2) was milled-off, and after removal of photoresist the YBCO thin film was deposited all over the substrate surface. The YBCO thin film was patterned using ion-beam etching to form four long lines (*l*1–*l*4, Fig. 2), two of which were situated on the seeding layer while two other were on

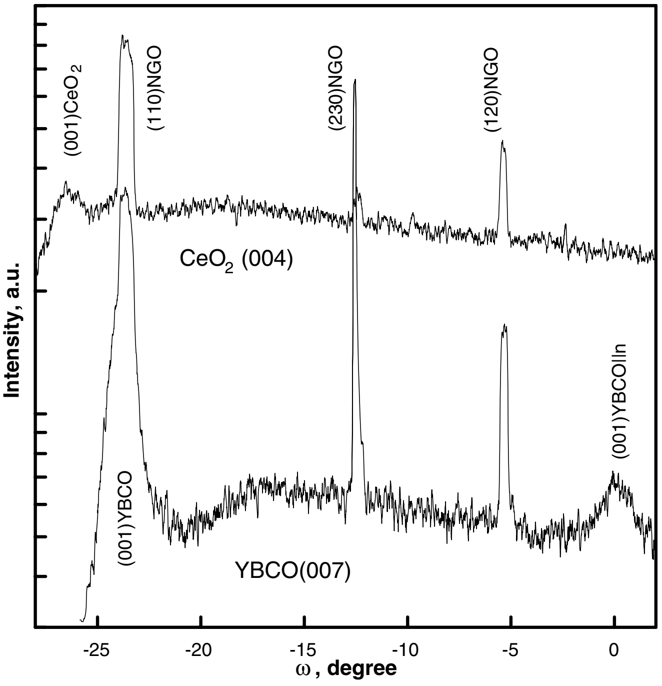

Fig. 1. Rocking curves in a wide angular range taken from epitaxial heterostructure $YBCO/CeO_2/NdGaO_3$ on miscut substrate. The CeO_2 seeding layer is partially removed by ion-beam milling. Zero ω angle corresponds to the substrate plane, miscut angle 23.4°.