Critical Current Density Enhancement in $YBa_2Cu_3O_{7-\delta}$ Thin Films by Twin Domains of $LaAlO_3$ Substrates

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***Abstract*—Magnetic flux penetration into a 0.2 μm-thick $YBa_2Cu_3O_{7-\delta}$ (YBCO) thin film grown on a crystalline $LaAlO_3$ (LAO) substrate was studied using magneto-optical imaging techniques. Enhanced critical current density J_c was observed at the location corresponding to twin domains on the underlying substrate. We attribute this J_c enhancement to increased pinning defects in the YBCO layer induced by the naturally formed nano-scaled surface roughness on the LAO substrate. Our results suggest that the substrate surface roughness might be helpful in J_c improvement of YBCO thin films grown on metal substrates by pulsed laser deposition.**

***Index Terms*—Flux pinning, magneto optical, superconductor, YBCO.**

I. Introduction

THICK films of $YBa_2Cu_3O_{7-\delta}$ (YBCO) deposited on flexible tapes are the second generation coated conductors for large-scale application of high temperature superconductivity [1]. Although remarkable progress has been made over the past few years [1], further improvement of critical current density J_c in thick films seems to be very challenging due to various growth related issues like loss of texture in the YBCO layer, where the quality of the metal substrates plays an important role. Two of the leading J_c limiting effects due to the buffered metal substrates are grain boundaries and substrate surface roughness. The grain boundary problem has been thoroughly studied using YBCO films grown on $SrTiO_3$ (STO) bi-crystal substrates [2]. However, the studies of substrate surface roughness effect are limited perhaps due to the difficulty to isolate the influence of substrate surface roughness from other effects including reaction of YBCO with buffered metal substrates.

Recently, Foltyn *et al.* reported enhanced J_c in YBCO films on electro-polished Hastelloy C276 substrates with nano-scaled smooth surface [3]. Their results highlighted the strong influence of the substrate surface roughness on J_c of YBCO thick films. However, it is not clear whether the smooth substrate surface or the improved texture of the buffer layer is the dominant reason for the enhancement in J_c. In order to determine the intrinsic effect of the substrate surface roughness, we focused on the YBCO thin films grown by pulsed laser deposition (PLD) on crystalline $LaAlO_3$ (LAO) substrates with naturally formed nano-scaled surface roughness. The choice of thin films here was to minimize various detrimental effects found in thick film processing, which varies from sample to sample. Strikingly, we observed a J_c enhancement by the surface roughness of the underlying LAO substrate, in contrast to the general degradation of J_c found in YBCO thick films earlier [1].

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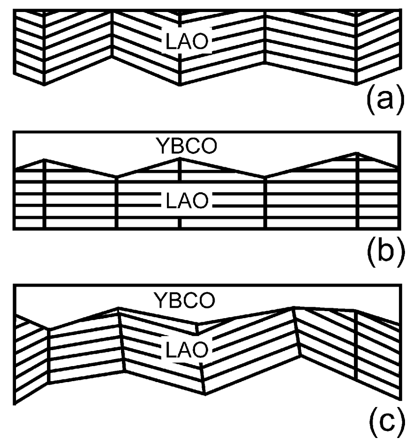

Fig. 1. Schematic drawing illustrating the formation of a nano-scaled corrugated interface between YBCO and LAO substrate. (a) (100)-cut and polished LAO at room temperature with natural twin domains; (b) YBCO films on LAO at high temperature (700°C–800°C), where (100) surface reconstruction leads to a triangular corrugation on LAO prior to the deposition of YBCO. (c) Formation of new twin domains in LAO during cooling to room temperature.

II. Experimental Details

A. Sample Preparation

Several c-axis oriented YBCO thin films with thickness $\sim 0.2\ \mu m$ were grown on crystalline LAO substrates by PLD. The substrates were heated to 790°C and an oxygen pressure of 100 mTorr was used during the deposition. The deposition time was about 5 minutes. After the deposition, the films were cooled to room temperature at a rate of 60°C per minute. Unlike STO substrates, LAO crystalline substrates are heavily twinned in its room temperature orthorhombic phase, as illustrated in Fig. 1(a). At 544°C LAO undergoes a structure transition to the high temperature cubic phase [4]. Fig. 1(b) illustrates the YBCO layer on LAO at high temperatures (700–800°C) during PLD, where the crystallographic (100) surface reconstruction leads to the corrugation of the LAO surface with a relief depth ~4.5 nm [5]. Fig. 1(c) illustrates the formation of new domain

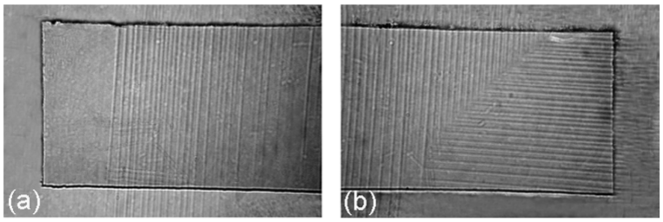

Fig. 2. Light microscope images of the 0.2 μm-thick YBCO film strip, demonstrating the nonuniform distribution of the substrate twin domains. (a) Light micrograph of the left end of the strip shows no visible LAO twin domains. (b) Light micrograph of the right end of the strip shows dense LAO twin domains.

structures when sample is cooled to room temperature. The selected sample used in MOI study has nonuniform distribution of twin domains in the LAO substrate, which makes it possible to compare the local J_c with or without the influence of substrate surface roughness under exactly the same conditions.

B. Sample Characterization

We patterned the 0.2 μm-thick YBCO thin film into a 5 mm $\times$ 0.8 mm strip in order to quantitatively determine the local J_c in our MOI study. Fig. 2(a) and (b) are the light microscopy images taken at the left and right ends of the YBCO film strip, respectively. The twin domains of LAO can be seen through the YBCO layer and continue to the area where the YBCO layer was etched off. The regular crossed-termination of twin domains is visible in Fig. 2(b). It is clear that there is no visible twin domain in the vicinity of the left end of the sample as shown in Fig. 2(a). In contrast, twin domains are abundant in other parts of the sample, which extend all the way to the right end [Fig. 2(b)]. This nonuniform distribution perhaps comes from the incomplete phase transformation of the LAO substrate. By measuring the flux pattern at the twin-free and twin-rich areas, we can quantitatively determine their different local J_c.

C. MOI Experiment

The MOI studies were performed on our low temperature MOI station described elsewhere [6]. A bismuth-doped iron garnet indicator film with in-plane spontaneous magnetization was placed onto the sample surface. The external magnetic field B_a is always applied perpendicular to the film surface. The magnetic flux distribution was recorded via a digital camera with the arrangement of polarizer and analyzer crossed at 90 degree at temperatures ranging from 4.2 K to superconducting transition temperature T_c. Brightness intensity in the images corresponds to the local flux line density.

III. Results and Discussions

A. Enhanced J_c by LAO Twin Domains

Fig. 3 shows the magnetic flux penetration pattern in the zero-field-cooled (ZFC) sample at temperature $T = 30$ K with various applied fields. Small pinholes or notches, indicated by the arrows in Fig. 3(a) due to fabrication and handling of the film, did not produce any significant change in the overall flux pattern. In general, a regular uniform flux penetration was always observed nucleating from the edges at temperatures from 4.2 K to a few degrees below T_c and the perpendicular applied field $B_a \leq 0.1$ T, which is consistent with the prediction of the Bean critical state model for a type II superconducting thin film.

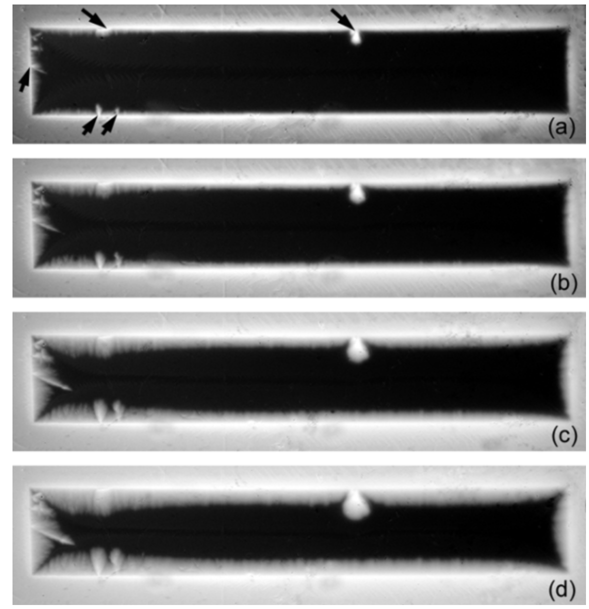

Fig. 3. Magneto-optical images of the zero-field-cooled (ZFC) 0.2 μm-thick YBCO thin film at temperature $T = 30$ K with the perpendicular applied field $B_a = 20\,\text{mT}$ (a), 30 mT (b), 40 mT (c), and 50 mT (d), respectively. The YBCO film was patterned into a 5 mm $\times$ 0.8 mm strip. Small pinholes or notches on the edges are indicated by the arrows.

In addition to the uniform flux pattern, the YBCO thin film also shows enhanced J_c in the areas corresponding to the twin domains of the underlying LAO substrate. It is clearly seen in the magneto-optical images shown in Fig. 3 that during the whole flux penetration process, the flux goes much deeper at the left end of the film than at the right end. Note that the right end of the film has dense twin structures on the LAO substrate as shown in Fig. 2. These MOI images indicate that the twin domains on the underlying LAO substrate enhance the J_c in the YBCO layer.

B. Temperature Dependence of J_c

In order to quantitatively evaluate this J_c enhancement, we determined the local J_c at both left end twin-free region and right end twin-rich region by measuring their corresponding flux front positions. The flux front position a was defined as the distance from the flux front to the central line of the strip. According to Bean model for a thin film strip with perpendicular magnetic field, J_c can be estimated from a via the following formula, $2a/w = 1/\cosh(B_a/B_d)$, where w is the width of the strip, and B_d is the characteristic field given by $B_d = \mu_0 J_c d/2$ [7]. Fig. 4(a) and (b) are the enlarged view of the flux penetration patterns at the left and right ends of the ZFC sample at $T = 30$ K with $B_a = 40$ mT. The left end flux front position a_1 and right end flux front position a_2 were found to be equal to 0.23 mm and 0.28 mm, respectively, in the 0.8 mm wide strip. This corresponds to $B_d = 34.8$ mT for the left end and $B_d = 45.5$ mT for the right end. Hence, J_c is found to be equal to $2.8 \times 10^7\ \text{A/cm}^2$ and $3.6 \times 10^7\ \text{A/cm}^2$ at the left and right end of the strip at 30 K, respectively. It is remarkable that the increase in local J_c due to the substrate surface roughness can

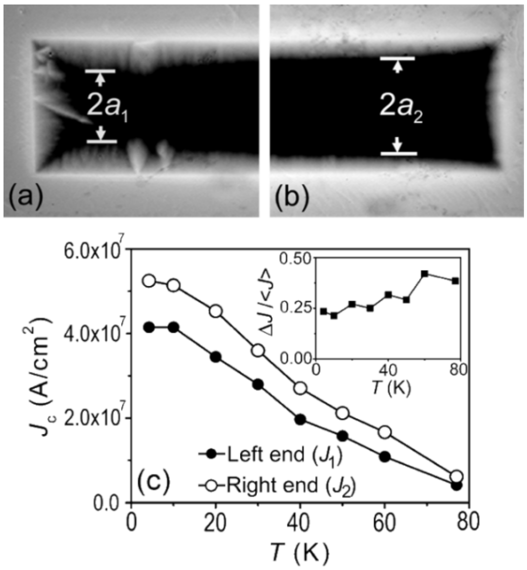

Fig. 4. The critical current densities determined by measuring the flux front positions. (a) and (b): the enlarged view of the flux pattern on the left and right ends of the sample, where the corresponding flux front positions a_1 and a_2 are sketched. (c) The temperature-dependent local critical current densities at the left end (J_1) and right end (J_2). The inset shows the temperature dependence of the relative J_c enhancement.

be as large as 25% at 30 K. The temperature dependences of the local critical current density at the left end (J_1) and right end (J_2) of the film are shown in Fig. 4(c). The relative enhancement $\Delta J/\langle J\rangle \equiv 2(J_2 - J_1)/(J_1 + J_2)$ at various T from 4.2 K to 77 K is shown in the inset of Fig. 4(c). The J_c enhancement is in general >25% and slightly increases as T increases.

C. Twin Boundary Pinning in YBCO Single Crystals vs. Substrate Surface Roughness Induced Pinning in YBCO Thin Films

Our observation of J_c enhancement in YBCO thin films by the substrate twin domains can be very tempting for a comparison with the earlier MOI studies on the effect of twin boundaries in the YBCO single crystals on flux motion. In unidirectional twinned YBCO single crystals, Duran and coworkers reported that flux penetrated faster along the twins [8]. This study was in contrast to the experiment by Vlasko-Vlasov *et al.* [9], who showed that twin boundaries are not channels for easy flux penetration but planar pinning barriers near which vortices were concentrated, giving rise to guided vortex motion. In a careful experiment using high quality YBCO single crystals, Welp *et al.* showed that flux moved easily along the twins, but was hindered across the twins [10].

Unlike YBCO single crystals, YBCO films are heavily twinned due to the complicated microstructures of thin films. The twin boundaries in YBCO films are generally bundled, and crossed 90 degree with each other all around the film. They appear to be "isotropic" to the macroscopic flux patterns. In the particular case of YBCO films on LAO substrates, the twins in the YBCO layer are not correlated with the twins of the LAO substrate. Therefore, the J_c enhancement is not likely the result of additional twin boundaries inside the YBCO films created by the epitaxial growth on the partially twinned LAO substrates. Instead, the enhanced J_c is more likely due to the increased pinning defects in the YBCO layer induced by the nano-scaled surface roughness of the LAO substrate. However, the exact types of the pinning defects induced by this LAO surface roughness are not known and further microstructure studies are clearly desirable. One possible type of defect is the antiphase boundary that has been observed in YBCO films grown on vicinal STO (001) substrates by Ch. Jooss *et al.* [11]. They found a 30% flux pinning enhancement due to the antiphase boundary, which is comparable to the J_c enhancement observed in this work. Obviously, it is an inviting area for future research.

IV. Conclusion

In conclusion, we have studied the flux pinning characteristics in superconducting YBCO thin films grown on crystalline LAO substrates. The correlation studies of MOI and surface analysis revealed a surprising enhancement of J_c induced by the surface roughness of the LAO substrate. This result suggests that the nano-scaled surface roughness of the metal substrate can be advantageous in improving the flux pinning in YBCO coated conductors, if the same microstructure of a YBCO thin film can be maintained throughout the entire thickness of a YBCO layer.

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