MAGNETO OPTICAL STUDIES OF YBCO THICK FILMS IN THE CRITICAL STATE

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Abstract: We present magneto optical studies of the critical state in $YBa_2Cu_3O_{7-\delta}$ (YBCO) thick films prepared using BaF_2 *ex-situ* post reaction process. A fractal-like propagation was observed as the magnetic flux entering the superconducting films, in striking contrast to the behavior expected of a uniform type II superconducting film in the critical state. However, by averaging the flux density over a certain length scale, we found that flux penetration can be described with the standard Bean critical state model. The temperature dependence of critical current density J_c was obtained by applying the Bean model to the averaged flux profiles, and found in good agreement with those obtained by direct transport measurements.

Key words: Magneto optical imaging (MOI), Critical current, Critical state, YBCO, Superconductor.

1. INTRODUCTION

The coated conductors by depositing $YBa_2Cu_3O_{7-\delta}$ (YBCO) thick films on flexible tapes are the second generation high temperature superconductors for large-scale applications. In last several years, impressive progress was reported in the development of the second generation wires carrying high critical current I_c over a long length [1]. Thick films are necessary for increasing the overall critical current carrying capability of a conductor and reducing the manufacturing cost. Understanding the correlation between J_c and the structural defects responsible for the flux pinning in the thick films is vital for improving current carrying capabilities of a coated conductor.

For thick YBCO films, the characterization of magnetic field B and temperature dependence of J_c by the standard transport measurement is rather difficult. This is due to the fact that YBCO thick films carry very high I_c, so that large dc current has to be applied to drive the superconducting films into the dissipating state, which usually results in excessive heating at the contacts. Hence, the transport J_c measurement of thick films is limited to the operating temperatures, where the sample can be immersed into liquid cryogen for effective cooling. For such reason, quantitative high-resolution magneto-optical imaging (MOI) technique becomes an excellent alternative tool for J_c measurement of the superconducting thick films [2]. In the MOI studies, the local magnetic field distribution was directly imaged via Faraday effect. By fitting the flux profile to certain critical state model, J_c of a superconducting film can be obtained. For a recent review, see reference [2]. Furthermore, the latest MOI technology enables us to visualize the local magnetic structure with high spatial and temporal resolution, which can provide valuable information on the interaction between the vortices and structural defects at a scale of μm.

In the present work, we prepared 1μm thick YBCO films on $SrTiO_3$ single crystal substrates using BaF_2 *ex-situ* post reaction process [3]. The BaF_2 processed YBCO films are known to produce relative large structural defects, yet have a very high J_c comparable to those made by the pulsed laser deposition (PLD). By imaging the flux distribution in the BaF_2 processed films, we can evaluate the role of these large structural defects played in the critical state. To our surprise, the flux propagation in these films showed the fractal-like behavior, in a striking contrast to what we would expect for a uniform film in the critical state. However, using the averaged flux profile, we were able to obtain J_c as a function of temperature for this film through fitting the flux front position via the standard Bean model. Furthermore, MOI determined J_c were found in a good agreement with those determined by the direct transport measurements.

2. EXPERIMENTAL DETAILS

Several 1 μm thick YBCO films were grown on single crystalline $SrTiO_3$ substrates by e-beam deposition of pre-cursors including BaF_2 and followed by *ex-situ* post reaction at 735 ^{0}C. The details can be found in the Ref. [3]. The resulting films had a sharp superconducting transition at $T_c \sim 91.5$ K. The dc transport J_c at 77 K and self-field was measured to be $\sim 1.2 - 2.5 \times 10^6$ A/cm^2. Both values of T_c and J_c for these films were comparable to the high quality films made by the *in-situ* PLD technique [4]. One piece of films was patterned into a circular disk with 5.0 mm in diameter using standard photolithography technique and studied by the MOI. One similar film was patterned into micro-bridges (20×120 μm^2) for the standard four-probes transport measurements, similar to those reported elsewhere [5].

MOI studies were performed on the same low temperature MOI station described earlier [6]. A high-resolution garnet MOI indicator film was placed directly onto the sample surface, with magnetic field always applied perpendicular to the film surface. The flux motion in the superconducting film was recorded via a digital camera with the arrangement of polarizer and analyser crossed at 90 degree at temperatures 4.2 K to 90 K under various sequences of applied field.

In order to compare J_c directly with the MOI measurement, transport J_c was measured in an exchange-gas cryostat equipped with a 9 T superconducting magnet. To avoid heating, a bi-directional pulse current sweep (10 ms) was used at high current level, and J_c was determined using the electric field criteria of 10 μV/cm.

The detailed microstructures of BaF_2 processed YBCO film have been reported earlier [3]. Large structural defects are known present in these films. Round and rectangular shaped precipitates (either Y_2O_3 or CuO) have a physical size ranging from 0.05 μm to 0.40 μm. Since the size of these precipitates is orders of magnitude higher than the superconducting coherence length of YBCO, they are not considered as the effective pinning sites. Instead, they may simply act as roadblocks along the supercurrent path. The individual magnetic response of these precipitates can not be studied by the current MOI system, since their size is substantially below the spatial resolution of MOI, ~1μm. Furthermore, these precipitates can be completely screened out by the superconductors surrounding them.

3. MOI RESULTS AND DISCUSSIONS

Fig. 1 is a sequence of MOI images taken during a field cycle at 40 K, showing magnetic flux penetration into the zero-field-cooled YBCO thick film. Note that only a portion of the YBCO film was observable due to the limited size of the garnet indicator film relative to the YBCO disk. The image brightness represents the local flux density. The arrow in the figure indicates the edge of the YBCO disk. The respective images were taken at applied magnetic field B_a = 12.5, 25, 37.5, and 50 mT during a field increasing process. It is clear that the magnetic flux structure shown in Fig. 1 is remarkably different from what you would expect from a microscopically uniform type II superconductor in the critical state [2]. Instead, a fractal-like flux propagation pattern was observed. The scale of the break-up structures is in the order of tens of μm. Detailed analysis of this flux penetration pattern and its correlation to the structural defects will be discussed elsewhere. In fact, the same kind of flux structure was observed at all temperatures from 4.2 K to 90 K.

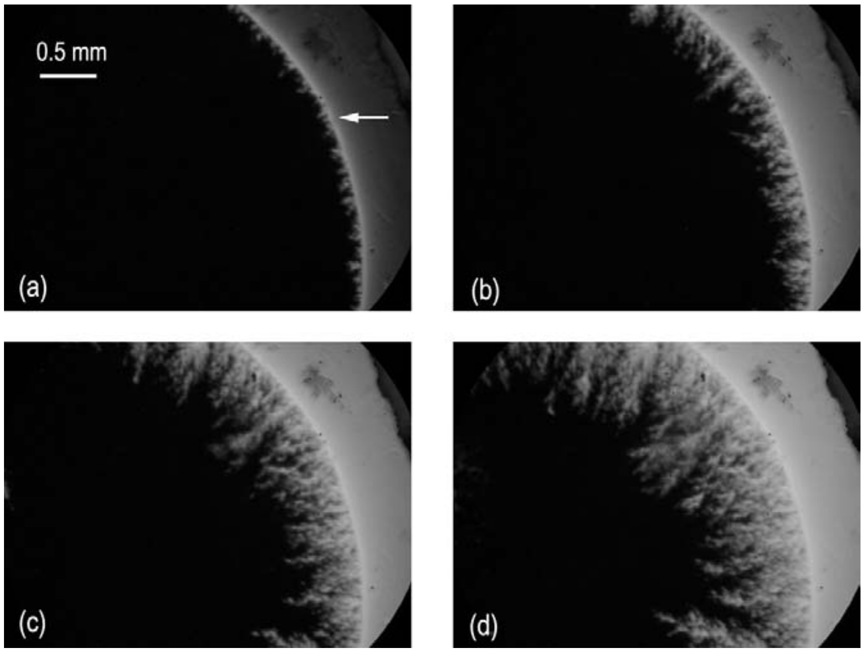

Figure 1. Magneto-optical images of magnetic flux penetration into a zero-field-cooled YBCO thick film circular disk at 40 K, where the arrow indicating the disk edge. The respective images were taken at B_a = 12.5 mT (a), 25 mT (b), 37.5 mT (c), and 50 mT (d).

The flux density is highly non-uniform. However, if averaged either along the radius or over small portion of the circumference (e.g 10 degree) at any given distance away from the center, they looked quite regular similar to those observed in the YBCO thick films grown by the PLD [2, 7]. In fact, we found that the magnetic flux density profile along the radius averaged over the area covered by the MOI indicator film (~ 60^o region) can be fitted well by applying the standard Bean model to a circular disk [8]. An example was shown in Fig. 2. The symbols were for the averaged flux density profiles at two applied fields of 25 mT (open circle) and 64 mT (open diamond) taken at T = 40 K, while the solid curves are the respective calculated results. The theoretical profiles were calculated from the Bean model. In the theoretical calculation, we considered a type II superconducting disk of radius R and uniform thickness d, where $d << R$. We assumed either that $d \geq \lambda$, where λ is the London penetration depth, or, if $d < \lambda$, that $\Lambda = 2\lambda^2/d << R$, where Λ is the two-dimensional screening length, and that the lower critical field H_{c1} is small enough to be neglected. Under these assumptions, we used the analytical solutions for the field distribution in terms of B_a/B_d via the Bean model given in Reference 2 and 8. B_d is the characteristic magnetic field given by $B_d = \mu_0 J_c d/2$, and J_c is assumed to be B-independent in the Bean model. The calculated results at 40 K (shown as lines in the Fig. 2) were obtained using B_d = 51.2 mT determined through the fitting of the flux front position to be described in the next section.

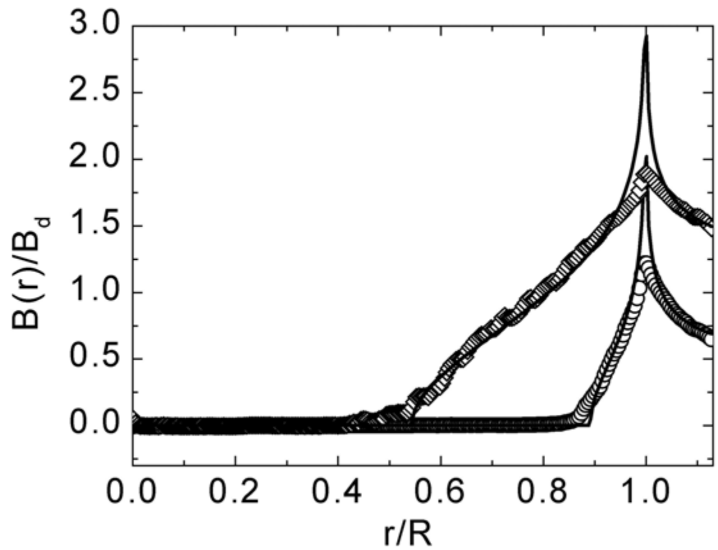

Figure 2. The magnetic flux density profiles of the zero-field-cooled YBCO thick film circular disk at T = 40 K, under the applied magnetic fields B_a of 25.6 mT (open circle) and 64 mT (open diamond). The solid lines are the calculated ones with B_d = 51.2 mT (see text).

The experimentally determined profiles are in good agreement with the theoretical profiles based on the simple Bean model except near the edge of the film. This discrepancy is mainly due to the limited magnetic field measuring range of the garnet indicator film and the thickness effect, which was not corrected in the calculation [2]. In perpendicular field orientation (i.e. $B_a \perp$ sample surface), the local flux density is very high near the edge of the film due to the extremely high demagnetization factor for films, and thus can be easily over the measurable range of the indicator film. For the finite thickness of the samples and garnet film, the sharpness of local field profile was reduced in the captured images [only stray field was actually recorded in the MOI images]. For more precise determination, all relevant distances should be considered. Nevertheless, other than at the area near the edge, there is a good agreement between experimentally measured profiles and the calculated ones based on the Bean model with a constant value of J_c.

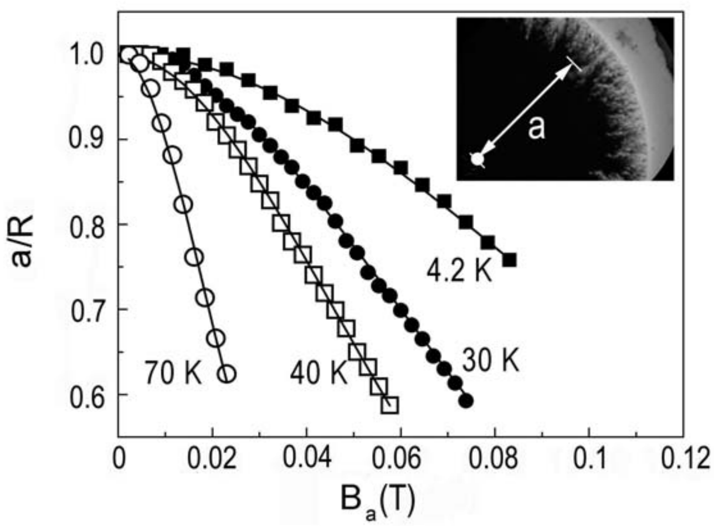

Figure 3. The flux front position as a function of applied magnetic fields at T = 4.2, 30, 40, and 70 K respectively. The inset shows the definition of the flux front position, the averaged distance measured from the center of the disk to the flux front.

4. COMPARISON OF J_C DETERMINED BY THE MOI AND TRANSPORT MEASUREMENT

The temperature dependence of J_c for these films was obtained by a simplified method using the standard Bean model with field-independent J_c, through the fitting of the flux front position a in a superconducting disk, via formula [2, 8],

$$a/R = 1/\cosh(B_a/B_d) \quad (1)$$

Fig. 3 is the plot of the averaged flux front position as a function of applied field measured at various temperatures. The solid lines are the corresponding fits according to Eq. 1, with a fitting parameter B_d. The inset to Fig. 3 shows the definition of flux front position a, which is the averaged distance from the center of the disk to the flux front over the entire 60^o observable region. For a given set of a and B_a, B_d is obtained as a fitting parameter, and in term used for calculating the corresponding J_c. As shown in Fig. 3, for all temperatures, the agreement between the measured flux front position and fitting curves is excellent, which suggests that using a field independent J_c is a reasonable approximation in the low field region of MOI.

In Fig. 4, we plotted J_c as a function of T determined either by MOI, or by transport measurement at various fields, together. The open symbols are transport J_c at external field B_a = 0, 0.1, 0.5, 2 and 9 T respectively. Transport J_c were measured only at high temperatures in self-field or low fields, or at low temperature with large external magnetic field to avoid sample heating. As shown in Fig. 4, MOI-determined J_c is very close to the transport J_c at the self-field. The good agreement demonstrates that MOI is a reliable technique for determining J_c in a thick superconducting film, particularly at the low field region, to complement the conventional transport measurement.

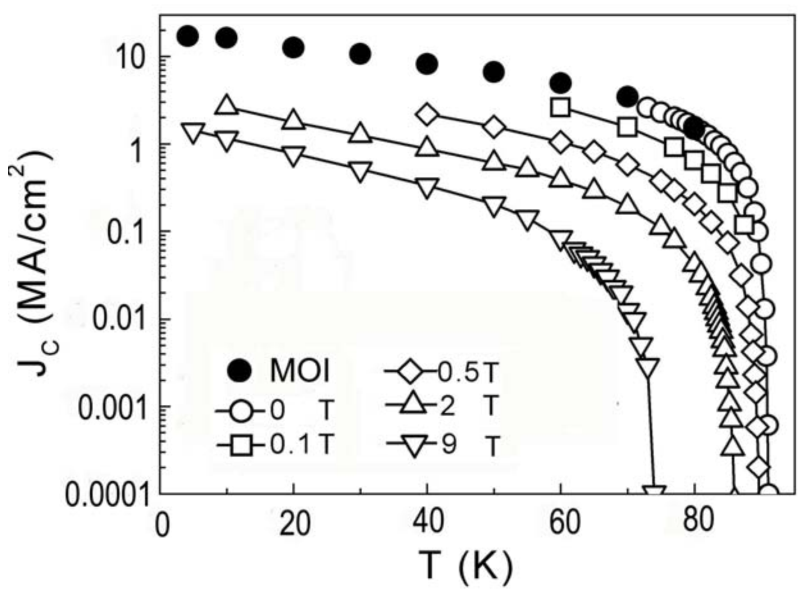

Figure 4. Temperature dependence of J_c of the YBCO thick films obtained by magneto optical imaging and transport measurements. The solid circles are the MOI data, while the transport data (open symbols) were obtained at self-field, 0.1, 0.5, 2, and 9 T respectively.

5. CONCLUSION

In conclusion, we report our magneto optical imaging studies of BaF_2 processed YBCO thick films in the critical states. We observed a non-uniform, fractal-like flux penetration pattern. Though locally non-uniform, the averaged flux density profiles were found to follow the Bean critical state model. The critical current density J_c as a function of temperature was obtained through fitting the flux front position via the standard Bean model, and found in a good agreement with those determined by the direct transport measurements. The MOI images revealed an interesting flux propagation pattern in the BaF_2 processed YBCO thick films, which could provide important information as how flux lines interact with the large structural defects presented in this type of films. Further investigation is being performed to clarify the correlation between the observed flux penetration pattern and defects in the films.

*QL's (contacting author) e-mail: qiangli@bnl.gov. The work at Brookhaven National Laboratory was supported by the U. S. Dept. of Energy, Division of Materials Sciences, Office of Basic Energy Science, under contract No. DE-AC-02-98CH10886.

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