Crossover of thickness dependence of critical current density $J_c(T,H)$ in $YBa_2Cu_3O_{7-\delta}$ thick films

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Critical current density J_c as a function of temperature T and magnetic field H was studied for high quality $YBa_2Cu_3O_{7-\delta}$ (YBCO) films with thickness $d=0.2$, 1, and 3 μm by means of magnetization measurements of a circular disk in perpendicular field. We found that the thickness dependence of $J_c(H)$ for the YBCO thick films crossovers at high fields for $T>50$ K, where the 0.2-μm-thick film carries significantly lower $J_c(H)$ than the 3-μm-thick film at high fields, even though the zero- or low-field J_c for the 0.2-μm-thick film is more than twice the value for the 3-μm-thick film. © *2004 American Institute of Physics.* [DOI: 10.1063/1.1737067]

Thick films of $YBa_2Cu_3O_{7-\delta}$ (YBCO) deposited on flexible tapes (so-called coated conductors) are considered to be the key candidate for the large scale application of high temperature superconductor. In the last several years, remarkable progress was reported in the development of these "second generation" wires carrying critical current I_c exceeding 200 A over a long length at 77 K.[1] The immense effort for further improvement generally falls into two categories: (1) enhance grain alignment and connectivity, and (2) produce thicker films with sustainable high J_c. Thick films are necessary for reducing the manufacturing cost. Understanding the dependence of J_c on the film thickness d is vital to gaining the insights for improving the total current carrying capabilities of a coated conductor. Toward this goal, extensive studies have been reported to investigate the d dependence of J_c in YBCO thick films, as well as some studies on the thin films less than 500 nm thick,[2] for example, excellent reports exist describing the consistent d dependence of J_c in thick YBCO films on single crystalline and buffered metallic substrates.[3] As in these studies, transport $J_c^{\mathrm{Tr}}(\mathrm{LN}_2)$ at the self-field in the liquid nitrogen temperature is usually the only parameter used for characterizing the performance of the coated conductors manufactured by various methods.[3,4] However, applications of the coated conductors in the motors, magnets, and transformers require thorough knowledge of the properties of the conductor in the wide range of temperatures and magnetic fields. Unfortunately, a comprehensive set of this type of data is not yet available as a function of d. This is due to the difficulty, in part, in dealing with excessive heating during the dc transport measurements of thick films. Thus, it is the purpose of this work to provide the first and comprehensive analysis of $J_c(T,H)$ as a function of d for a set of high quality YBCO films produced by pulse-laser deposition (PLD). The choice of this set of PLD films on single crystalline $SrTiO_3$ substrates is to provide a baseline data that can be compared with similar data taken for coated conductors. We found a high-field performance crossover in these films at elevated temperatures in relation to the thickness, namely the thicker films performed better than the thinner films at high fields, while the opposite was observed at low fields.

Three high quality epitaxial YBCO films, 0.2, 1.0, and 3.0 μm thick, were prepared on 1×1 cm^2 $SrTiO_3$ substrates by the PLD under similar conditions described elsewhere.[5] The transport J_c^{Tr} of similarly processed films was measured using the standard four probe configuration on narrow strips (240 μm$\times$6 mm) at liquid nitrogen temperature, and they are 5.2, 3.2, and 2.0×10^6 A/cm^2 for $d=0.2$, 1.0, and 3.0 μm, respectively. For magnetization measurement of $J_c(T,H)$, each film was patterned into circular disks with an identical diameter of 5.3 mm using a standard photolithography technique. To ensure the uniformity of the entire area of the films, we performed high resolution magneto-optical imaging (MOI) studies on all films using MOI imaging station described elsewhere.[6] Uniform flux penetration and trapping were observed for all films at various temperatures between 4.2 K and T_c ($\geqslant 90$ K). Examples were shown in Fig. 1, which were taken on the same area of a 3.0-μm-thick film at 4.2 K, where brightness intensity is proportional to the local magnetic field ($\perp$ film surface).[6] Figure 1(a) shows flux pen-

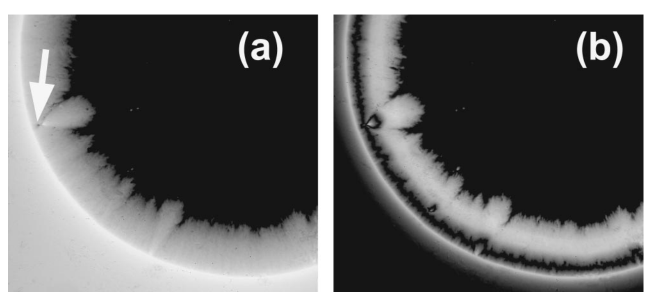

FIG. 1. Magneto-optical images of the same area of a 3.0-μm-thick YBCO disk (O.D.$=5.3$ mm) at 4.2 K; (a) flux penetration into the disk at external field $\mu_0H_{\mathrm{ext}}=0.1$ T applied to the zero-field-cooled sample; (b) flux trapping in the remnant state after μ_0H_{ext} was reduced from 0.1 T to zero. Small pinholes (indicated by the arrow) are due to fabrication/handling of the disk, which does not produce significant change in the overall pattern.

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etration into the disk at external field $\mu_0 H_{\mathrm{ext}} = 0.1$ T applied to the zero-field-cooled sample; whereas Fig. 1(b) shows flux trapping in the remnant state after $\mu_0 H_{\mathrm{ext}}$ was reduced from 0.1 T to zero. Small pinholes, as indicated by the arrow, were due to fabrication/handling of the disk, which did not produce any significant change in the overall pattern. It was evident that all three films were very uniform, as determined by the intensity profiles along the radius and the local field distribution around the circumference of the disks. Note the roughness displayed at the flux front is the result of intrinsic fractal behavior mostly related to the random distributed flux pinning centers, other than the film's physical roughness.[7]

To obtain $J_c(T,H)$, we measured the hysteresis loop of each disk in a Quantum Design SQUID magnetometer with $H_{\mathrm{ext}} \perp$ film surface at various temperatures. The value of $J_c(T,H)$ reported throughout this letter was magnetically determined by applying the standard Bean model to the magnetic hysteresis, via $J_c(H) = (3/2R)\Delta M(H)$, where R is the radius of the circular disk, and $\Delta M(H)$ is the width of the hysteresis at a given H.[8] As noted by Shantsev *et al.*[9] the expression is valid for any given field-dependent $J_c(B)$ except for very low field of $\mu_0 H \leqslant \mu_0 J_c(0) d/2$ ($\approx 4-40$ mT at 77 K for our films).

The values of zero field J_{co}^M for all YBCO films were determined by fitting the magnetization measured field dependence of $J_c(H)$ in the low field regime $[\mu_0 J_c(0) d/2 \leqslant \mu_0 H \leqslant 0.15\ \mathrm{T}]$ with several theoretical models to account for the self-field effect. The details have been reported elsewhere.[10] We found that the Kim model[11] $J_c(H_{\mathrm{ext}}) = J_{\mathrm{co}}/(1 + H_{\mathrm{ext}}/H_0)$ provided a good fit to the $J_c(H)$ data. Such determined J_{co}^M at 77 K are 4.3, 3.2, and 2.5×10^6 A/cm^2 for $d = 0.2$, 1.0, and 3.0 μm, respectively. The agreement between J_{co}^M and J_c^{Tr} at the liquid nitrogen temperature was very good. It should be noted that the self-field effect on J_c^{Tr}, generated by the transport current at the patterned strips at 77 K, is small ($\sim$ a few mT at 77 K). Further estimation based on the self-consistent solution proposed by Buleavskii *et al.*[12] and the Kim model $J_c(H)$ showed that self-field in the transport measurement produced less than 10% reduction of J_{co} at 77 K for these films. Therefore, both J_{co}^M and J_c^{Tr} should be quite close to J_{co} for these YBCO films at theoretical zero field. The thickness dependence of J_{co} for these films was found to be consistent with the previous published results.[3] In this low field regime, the thinner the film, the higher $J_c(T,H)$ at all temperatures. Though there are some explanations given to the observed $J_{\mathrm{co}}(d)$ behavior in the literature based on the microstructure of the thick films, the mechanism is still a subject of intense discussions.

Surprising results from the present studies are the magnetic field dependence of J_c of these films in the high field regime. To provide a detailed view, we present our $J_c(T,H)$ data of all three films in 3D plots shown in Fig. 2, where J_c was plotted in the log scale, and the lines drawn through either $J_c(T)$ or $J_c(H)$ are a guide to the eye for illustrating the sharp drop of $J_c(T,H)$. The shaded are on the $T-H$ plane is the region where the value of J_c falls below 200 A/cm^2. If $J_c = 200$ A/cm^2 was used as the criteria for the irreversibility temperatures T_{irr}, the boundary line surrounding the shaded area may be regarded as the usual irreversibility line $T_{\mathrm{irr}}(H)$, and the shaded area would represent the magnetic reversible region, where the films lost their ability to carry any meaningful amount of supercurrents. At low temperatures below 50 K, $J_c(H)$ behavior is essentially the same for all three films at fields up to 5 T. As T increases above 50 K, the difference in the behavior of $J_c(H)$ at high fields becomes evident. The accelerated decrease of $J_c(H)$ at high fields becomes much more pronounced in the 0.2-μm-thick film [Fig. 2(a)] than that in the 3-μm-thick film [Fig. 2(c)]. This results in a much wider reversible region [or lower $T_{\mathrm{irr}}(H)$ line] for the 0.2-μm-thick film. It is quite remarkable that the irreversible field H_{irr} for the 0.2-μm-thick film (≈ 2 T) is only half that for the 3-μm-thick film (≈ 4 T) at 77 K, even though J_{co} for the 0.2-μm-thick film is about twice that for the 3-μm-thick film at the same temperature.

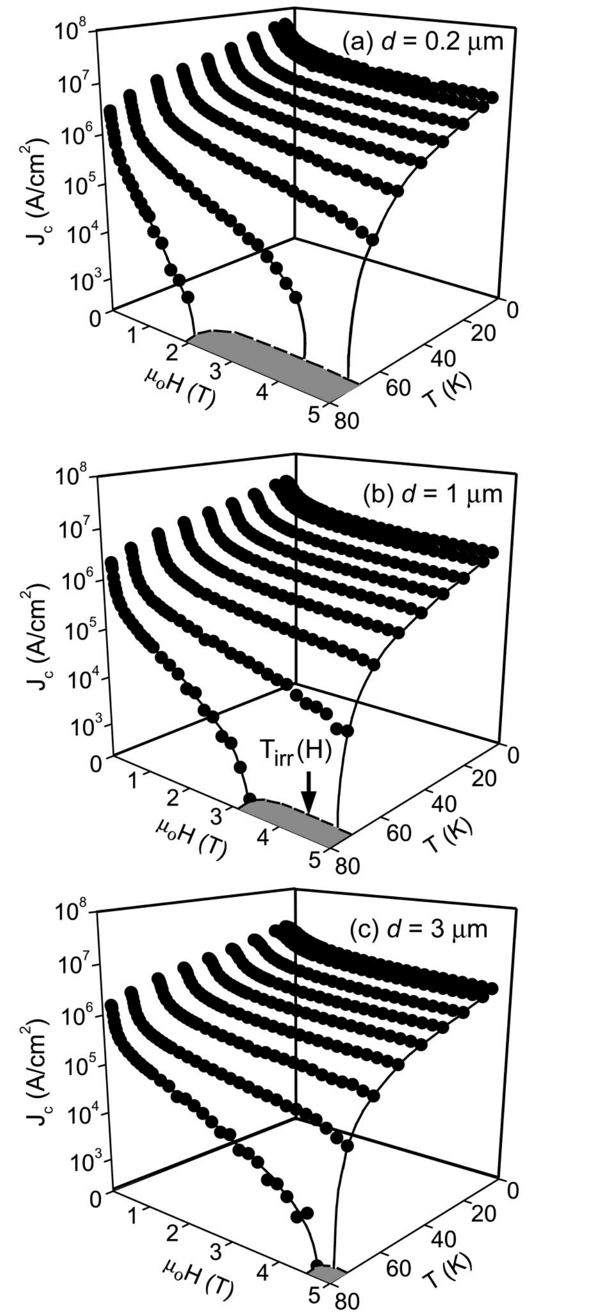

FIG. 2. $J_c(T,H)$ for three YBCO films are plotted in log scale in 3D, the lines drawn through either $J_c(T)$ or $J_c(H)$ are the guide to eye for illustrating the sharp drop of $J_c(T,H)$. The shaded area on the $T-H$ plane is the magnetic reversible region bounded by the irreversibility line $T_{\mathrm{irr}}(H)$.

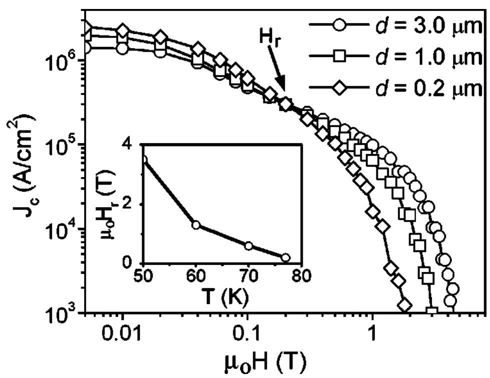

FIG. 3. A log–log plot of $J_c(H)$ at 77 K for three YBCO films with various thickness *d*. The crossing-point H_r is indicated by an arrow. The inset shows H_r as a function of *T*.

The crossover behavior is illustrated clearly when the $J_c(H)$ curves are plotted as a function of H in a log–log plot at elevated temperatures as shown in Fig. 3 for 77 K. All $\log J_c$-vs-$\log H$ curves appear to come together and cross at the same points. The crossover field was defined as H_r, ($\sim$0.2 T at 77 K) and increased with decreasing temperatures as shown in the inset. The $\log J_c$–$\log H$ curves for the 1- and 3-μm-thick films showed slight kinks at H_r and suggested $J_c(H)$ was controlled by different mechanism above and below this field.

We give a very brief account of one possible explanation for this phenomenon, while a detailed discussion will be given elsewhere. This crossover behavior is believed to be related to the role of the surface currents I^s playing in superconducting films under perpendicular fields in the critical state, where the total current I^t consists of surface current I^s and bulk current I^b. I^s is determined by the curvature of magnetic flux lines, whereas I^b is due to the spatial variation of the vortex lines directed perpendicular to the films and is determined by the bulk pinning in the film.[13] At low fields, I^s is very large due to the extremely high demagnetization factor for the films, and hence dominates I^t of the films. This results in J_c for thinner films at low fields to be much greater than that for thicker ones since the volume fraction occupied by I^s is much greater in the former than in the latter. For the fact that I^s diminishes at moderate fields, J_c of the films at high fields is then controlled by I^b. The transition from the dominated I^s in I^t to I^b in I^t explains the crossover of all $\log J_c$–$\log H$ curves at H_r shown in Fig. 3. Although analytical calculations of $I^s(H)$ are not available, it was experimentally demonstrated that $I^s(H)$ decreases rapidly for fields beyond the "full penetration fields" in a YBCO thin film.[14] On the other hand, the mechanism for the J_c^b increase with increasing film thickness at high fields is not so obvious. However, it is perhaps reasonable to expect that the thicker films have tendencies to amplify any defects at the initial growth stage, and thus likely to have more flux pinning sites. The above supposition suggests that the thickness dependence of the self-field transport J_c^{Tr} widely used in the literature is perhaps a simple manifestation of the surface currents whose contribution to the total J_c decreases with an increase in the thickness of the films. This indicates a need for measuring J_c at higher fields in order to assess the bulk J_c of the YBCO films, associated with the bulk flux pinning.

In summary, we presented a detailed study of temperature and magnetic field dependence of $J_c(T,H)$ in YBCO thick films as a function of film thickness. A high-field J_c crossover of these YBCO films was observed in the elevated temperatures as the thickness changed from 0.2 to 3 μm. Through this study, we demonstrated that a detailed measurement of $J_c(T,H)$ is necessary for assessing the bulk pinning strength of YBCO films. The fact that the 3-μm-thick YBCO film actually carries higher value of J_c at fields over 0.2 T at 77 K than the thin films is of immense importance for the coated conductors used in the applications operated in high fields and at the elevated temperatures. This result suggested that the approach of pursuing a thicker layer of YBCO to improve the overall current carrying capacity of a coated conductor is, in fact, a step in the right direction.

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[1] For a comprehensive review, see, *Next Generation High Temperature Superconducting Wires*, edited by A. Goyal (Plenum, New York, 2003).

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