Thickness effect on pinning properties for GdBa$_2$Cu$_3$O$_{7-x}$ films deposited with RF sputtering

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Abstract. We studied the relationship between $J_C$ and $H$, direction and crystallization orientation of GBCO films grown by RF sputtering with different thickness which is 0.3 $\mu$m, 0.5 $\mu$m and 0.9 $\mu$m respectively. By de-convoluting the random pinning from the correlated pinning contributions, we find that all the three films exhibit a lower effective anisotropy parameter $\gamma = 3$ rather than $\gamma = 5$ in YBCO films. The thinnest film is the most anisotropic. The anisotropic scaling analysis reveals an enhanced random pinning for thick film the whole range of angles studied in the angle correlation $J_C$ curve. The $J_C$-thickness dependence analysis indicates that there is a certain threshold field $H_d$ and a certain thickness $d$ for magnetic decoupling.

1. Introduction

Based on the high-temperature superconductors (RE) Ba$_2$Cu$_3$O$_7$, second generation (2G) coated conductors have entered the stage of practical application, such as motors, transformers, and generators. High critical current density is a necessary condition in many practical applications. Increasing (RE) BCO film thickness is a simple method. However, researchers have found that the $J_C$ decreases with the increase of film thickness. Therefore, most $J_C$-thickness studies reported so far [1-5] were focused only on SF and 77 K, for identifying the reason why the $J_C$ decreases with the increase of film thickness. Little $J_C$-thickness studies of different $H$ field were found.

Additionally, the relationship between $J_C$ and magnetic field angle of YBCO films attracted many investigator’s interest. Many applications need low angular anisotropy of $J_C$. Most of papers have investigated the angular anisotropy of $J_C$ value of (Re) BCO samples by new artificial flux pinning methods[6-8]. But little attention was paid to researching $J_C$ angular anisotropy for pure GBCO samples with different thickness. Motivated by these studies, we have studied $J_C$ angular anisotropy of GBCO samples with different thickness between 0.2 and 0.7 T. In this paper, we present our experimental results.
2. **Experiment**

(Gd)BCO films are fabricated on CeO₂/YSZ/CeO₂/NiW substrates using RF Sputtering. Unless stated otherwise, the power is 50 w and the pressure of oxygen is 30 Pa. After deposition, all the films are annealing in 500 Torr oxygen for 50 min. Three films are fabricated with thicknesses 0.3 μm (sample A), 0.5 μm (sample B), 0.9 μm (sample C), respectively. The thickness is calibrated with KLA-Tencor P16 profiler. The deposition conditions are the same for the three films.

The four-probe method is used to measure Jc value of samples. Samples are prepared by chemical etching into 3 mm long and 2 mm wide. The Jc value angular dependence samples on the direction of magnetic field is measured at 0.2-0.7 Tesla 77 K. We collect the critical current density once every 5 degrees of rotation.

3. **Experiment result and discussion**

3.1. **Microstructure analysis**

The XRD results of the sample are shown in Figure 1. Aside from the peaks attributed to CeO₂/YSZ/CeO₂/NiW substrates, almost all the diffraction peaks are in the c-axis (00l) of GBCO. This indicates super high crystallinity for sample A and C. A small a-axis (200) peak of GBCO is found in sample B. A lack of c-axis (00l) peak of (Gd) BCO is found in sample A.

The out-of-plane textures for the (005) rocking curve and Phi scanning of a (103) peak are FWHM<1.6° and FWHM<3°, which indicating a good out-plane and in-plane texture as well.

4. **Field and angular-dependent Jc**

Figure 2 presents Jc with different film thickness for H=0 T, H//ab (H=0.5T) and H⊥c (H=0.5T). α is also shown in Figure 2 at the same time. The value of α obeys the relationship \( J_c \propto H^{-\alpha} \) between 0.1 and 1 T. We find the Jc decreases rapidly as the thickness of epitaxial GBCO films increasing from 0.3 to 0.9 μm for self-field H=0 T, H//ab (H=0.5T) and H⊥c (H=0.5T). And a low value of α value of 0.409 is obtained for sample B.

In general, different pinning mechanisms leads to various values of the exponent α. In our case, we have obtained values of α ~0.7 for A, C samples, and α ~0.4 for B sample. This result implies different pinning mechanisms. From the XRD results in Figure 1, we speculate that a mixed a-axis with c-axis orientation of sample B leads to low α value, and the different thickness is not the origin of the different α value.
The $\theta$ value at 0.5T for all three films is shown in Figure 3(a) and (b). The $cJ$ decreases in all directions with increasing thickness. To compare the relative increase in $cJ$ for three samples, angular dependence data of normalized $cJ$ are presented in Figure 3(b). We will see that the ratio of $(cJ \text{ in } H//ab)/(cJ \text{ in } H//c)$ is about 2.21, for sample A, whereas it is around 1.73 and 1.69 for samples B and C, respectively. The result indicates more strong anisotropy for sample A, which will be discussed carefully in the next part.

For further studying the flux pinning mechanism of the three samples, we measure the angular dependence of $J_c$ under different magnetic fields. Then a modified “Tachiki and Takahashi model” with expression $\alpha = 0.5 - \alpha 0.5 \cos \theta$ is used to fit our data. As shown in Figure 4. In the formula, $\alpha$ is related to IFD. We get $\alpha \sim 0.1$ for sample A, $\alpha \sim 0.25$ for sample C, while $\alpha = -0.35$, $\alpha = -0.25$, $\alpha = -0.2$ at 400 MT, 500 MT, 600 MT for sample B, respectively. The different $\alpha$ values indicate different pinning mechanisms. The FLL with different structural defects and thermal conditions[9, 10] maybe one possible reason for different $\alpha$.

Figure 2. The $J_c(0T, 77K)$, $J_c(H//c)$ at $H=0.5T$, $J_c(H \perp c)$ at $H=0.5T$, and $\alpha$ are presented as a function of film thickness.

Figure 3. Angular dependence of $J_c$ at 77K, 0.5 T for all three films. in general, $J_c$ increases in all directions as thickness decreases. (b)normalized $J_c$ for all the three samples.

The $J_c(\theta)$ value at 0.5T for all three films is shown in Figure 3(a) and (b). The $J_c(77K, 0.5T)$ decreases in all directions with increasing thickness. To compare the relative increase in $J_c$ for three samples, angular dependence data of normalized $J_c$ are presented in Figure 3(b). We will see that the ratio of $(J_c \text{ in } H//ab)/(J_c \text{ in } H//c)$ is about 2.21, for sample A, whereas it is around 1.73 and 1.69 for samples B and C, respectively. The result indicates more strong anisotropy for sample A, which will be discussed carefully in the next part.

For further studying the flux pinning mechanism of the three samples, we measure the angular dependence of $J_c$ under different magnetic fields. Then a modified “Tachiki and Takahashi model” with expression $J_c(\theta) = J_c(0)\left(1 + \alpha \cos \theta\right)^{1/2}$ is used to fit our data. As shown in Figure 4. In the formula, $\alpha$ is related to IFD. We get $\alpha \sim 0.1$ for sample A, $\alpha \sim 0.25$ for sample C, while $\alpha = -0.35$, $\alpha = -0.25$, $\alpha = -0.2$ at 400 MT, 500 MT, 600 MT for sample B, respectively. The different $\alpha$ values indicate different pinning mechanisms. The FLL with different structural defects and thermal conditions[9, 10] maybe one possible reason for different $\alpha$. 
Anisotropic behavior analysis

Many authors [11-13] used Blaster’s scaling approach to distinguish the random pinning contribution from \(J_c(\theta)\) with the contributions of correlated pinning. The correlated pinning are most obvious for \(H//ab\)-planes or the c-axis. However, by this method, the curve indicative of random defect contribution is obtained subjectively. Unusually, in order to let the curve passes through \(J_c(\theta)=J_c[H_c(\theta)]\) as soon as possible, ones just make an approximation. Thus, extracting the random pinning contribution is a very hard work.

Recently, T. Aytug et proposed a simpler way to study the anisotropic characteristic of YBCO films. They used a cure to describe random defect contribution for \(J_c\). The curve has a smooth maximum along \(H//ab\), any other peaks outside this curve are representative for “correlated pinning”. [14] The details of the procedure were described in their article [14].

For the case considered here, \(B~(400mT—600mT)\), the scaled field \(B_c(\theta)\) indeed remains within the observed power-law regime \((J_c \propto B^\alpha)\) [14], where \(\alpha\) values are shown in Figure 1(\(\alpha=0.712, 0.409, 0.73\) for all three samples) respectively. Figure 5 shows the scaling plots at 77.3 K for the samples. We can make a few observations on these plots.

\[
J_c(\theta) = J_c(\theta)\cos^\alpha(\theta).
\]

Figure 4. The \(J_c(\theta)\) for all three films, at 77 K and 400 mT, 500 MT, and 600 MT. ((a), (b) and (c) corresponding to samples A, B, C, respectively.) solid lines are fits as expression \(J_c(\theta) = J_c(\theta)\cos\theta\^{(\theta+\alpha)}\).

Figure 5. \(J_c(\theta)\) for (Gd) BCO films at (77 K, 1 T) with different film thickness. the solid lines are random pinning for \(J_c\).
The first is that by de-convoluting the random pinning from the correlated pinning contributions, it is found that the random pinning exhibits $\gamma = 3$ rather than $\gamma = 5-6$ in pure YBCO, as shown in Figure 5(a), (b), and (c) for all the three samples. This value $\gamma = 3$ has been found for YBCO films [11, 15]. However, there was still a strong random pinning left. Such small anisotropy maybe attributed to the effect of strong random pinning.

The second observation is that this method describes our data well for angles $\theta$ up to 150° for sample C, 135° for sample B and 120° for sample A, respectively. In another word, random pinning contribution obviously increases for thicker film (C) compared as thinner film (A). This is certified by the high ($J_c$ in H//ab)/ ($J_c$ in H//c) value for sample A in Figure 4. The normalized values of $\left(\frac{J_c^{RD}(\theta)}{J_c^{RD}(\theta = 180^\circ)}\right)$ value of the three films for a given field and angle can also conclude this result.

Now, we begin to analyze the ab-correlated pinning. First we normalize the ab correlated pinning by the formula $\delta J_c^{\text{nd}}(\theta) = \left[J_c(\theta) - J_c^{\text{nd}}(\theta)\right]/J_c^{\text{nd}}(\theta = 180^\circ)$. Then, we observe that correlated pinning increases with enhancing film thickness from 0.3 to 0.9 $\mu$m between 120 to 205 degrees, as shown in Figure 6.

![Figure 6](image)

**Figure 6.** $\delta J_c^{\text{nd}}(\theta) = \left[J_c(\theta) - J_c^{\text{nd}}(\theta)\right]/J_c^{\text{nd}}(\theta = 180^\circ)$ normalized $J_c$ at H//ab for the (Gd) BCO A, B, C samples. The sample A exhibits the largest $\delta J_c(\theta)$.

Better crystallinity of the thinner sample maybe a possible reason for above result. This has been published earlier for YBCO films[16, 17]. However, According to C. Tarantini al’s research, the reduction of $\gamma$ from 5 to 3 corresponds to disorientation angles $\theta = 30^\circ$ [18]. Such a large disorientation angles is impossible. So, this imply that better crystallinity cannot be the main mechanism reducing $\gamma$. The second possible reason is that extended defects may exist along the ab-plane. They maybe strong pinning sources along the ab-plane.

6. Jc-thickness dependence analysis

The interlayer magnetic coupling is a main factor for $J_c$ reducing effect with thick HTS film. [19] This has been indeed observed in this experiment. Figure 7 (a) shows an interesting “magnetic decoupling” results. Jc reducing effect becomes more obviously as H near $H_d$(700mT). This is in accord with the authors’ conclusion[19].
Figure 7(b) shows the Jc-thickness plots for samples at different H fields. The monotonic decreasing Jc-thickness is often observed for samples with different thickness at 77 K reported earlier. But in Figure 7(b), the monotonic decreasing Jc-thickness is changed. They almost coincide when the film increases to 0.9 μm thickness. The result indicates that the H influence on Jc is more insignificant when film becomes thicker. In other word, there is a certain threshold thickness d for Jc-H behavior, above d, all Jc-H curves of the sample with different H coincide well.

7. Conclusions
In conclusion, the value of (Jc in H//ab)/(Jc in H//c) for sample A, B and C indicates that the thinnest film exhibits the most Jc angular anisotropy. With the anisotropic scaling approach, it is determined that the thickest film sample C has bigger random pinning effect compared as sample A and B. Furthermore, the sample A exhibits a strong anisotropy at H // the ab-plane, which implies strong pinning sources exists along ab-plane. The Jc-thickness dependence analysis indicates that there is critical magnetic field H_d for magnetic decoupling. At the same time there is a certain threshold thickness d for Jc-t behavior, above d, all Jc-H curves coincide well with different H for all the samples.

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