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Dimensionality and Irreversibility Field in $YBa_2Cu_3O_7$ Films *

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In order to investigate the relationship between the flux pinning and dimensionality, the critical current density J_c for $YBa_2Cu_3O_7$ films was measured as a function of temperature, field and tilt angle between field and c-axis. The kink anomaly in the temperature dependence of J_c for B⊥c was observed as the dimensional crossover from 3D extrinsic pinning to 2D intrinsic pinning. The irreversibility field B_i for B//c was measured in fields up to 23T and estimated to be 90T at 30K using the scaling law of the pinning force densities. The enhancement of B_i from a power law $(1-T/T_c)^n$ with $n \approx 1.5$ for B//c was observed below 40K. This suggests the formation of the 2-dimensional pancake vortex in $YBa_2Cu_3O_7$.

KEYWORDS: intrinsic pinning, irreversibility field, critical current density, $YBa_2Cu_3O_7$ film, dimensional crossover

1. Introduction

The dimensionality in the crystal structure of superconductors affects to the critical current and the irreversibility field properties. Especially, the modulation of order parameter along c-axis which originated by the 2-dimensional(2D) layer structure gives rise to the 2D intrinsic pinning [1] for B⊥c and the 2D pancake vortex [2] for B//c. In the superconductors with the layer structure such as high-T_c superconductors, it is pointed out that the intrinsic pinning mechanism dose work for the magnetic field perpendicular to c-axis (B⊥c). The intrinsic pinning strength depends upon the anisotropy of crystal structure. Since the $YBa_2Cu_3O_7$ system has the smallest anisotropic properties among the high-T_c oxide superconductors, the intrinsic pinning should be not so strong at high temperature, while the J_c properties at low temperature show the field insensitive behavior which may be originated from the intrinsic pinning. Hence, the crossover from the extrinsic to the intrinsic pinning is expected in $YBa_2Cu_3O_7$. When the magnetic field applied parallel to c-axis (B//c), on the other hand, a concept of the pancake vortex was proposed by Clem et al. [2]. The coupling between pancakes along c-axis depends upon the anisotropy of the crystal structure and magnetic field. Hence, the dimensional crossover of the vortices from 3D (low field) to 2D (high field) was pointed out by Galzmann and Koshelef in high-T_c superconductors [2], where this crossover field is independent of temperature and depends upon the crystal anisotropy. In BSCCO system, the peak effect of the magnetization and enhancement of the irreversibility field B_i were attributed to such a dimensional crossover [4]. However, the B_i properties for $YBa_2Cu_3O_7$ has been investigated only near T_c because of the very high B_i values. This paper describe the experimental results of the critical current density J_c as the function of field, temperature and tilt angle between magnetic field and c-axis and the irreversibility field B_i for $YBa_2Cu_3O_7$ films in high magnetic fields up to 23T. We discuss the B_i and the flux pinning properties in relation to its dimensionality.

2. Experimental

1) Sample preparation

$YBa_2Cu_3O_7$ films were epitaxially grown on $SrTiO_3(100)$ single-crystalline substrate by the chemical vapor deposition (CVD) method using β-diketon metal chelates of Y, Ba and Cu.[5] During deposition, the temperature of substrate was kept at 850°C in the mixture gas of 10 Torr which consists of 67% Ar and 33% O_2. After the deposition, the temperature of films were slowly cooled down to the room temperature with the rate of 15°C/min in the O_2 atmosphere of 1 atm. These films have the strong c-axis orientation perpendicular to the substrates. CVD-$YBa_2Cu_3O_7$ films on $SrTiO_3(100)$ have no history effect of J_c [6] between increasing and decreasing magnetic field, indicating high-quality and single-crystalline films without weak-links at grain boundaries. The samples of 1-0.5μm in thickness used in this study were patterned into the shape of a bridge with dimensions of about 300 μm in width, 1 mm in length. The critical temperature T_c obtained by the R=0 definition in CVD-$YBa_2Cu_3O_7$ films is about 90 K.

2) critical current density measurement

The critical currents were resistively measured by a 4-probe method and determined by use of a voltage criterion of 2 μV/cm. The current and voltage across the sample were obtained as a function of time using a digital oscilloscope. In order to protect the sample by avoiding self-heating, the transport current with a time duration of 500 ms was used. [7] The field angle θ was defined as the angle between the direction of the external field and the c-axis. The accuracy of the field angle in our system was within 0.5° The transport current was always normal to both c-axis and field directions. The temperature of the sample above 4.2 K was controlled by flowing He gas. The measurement at 4.2 K was carried out by directly

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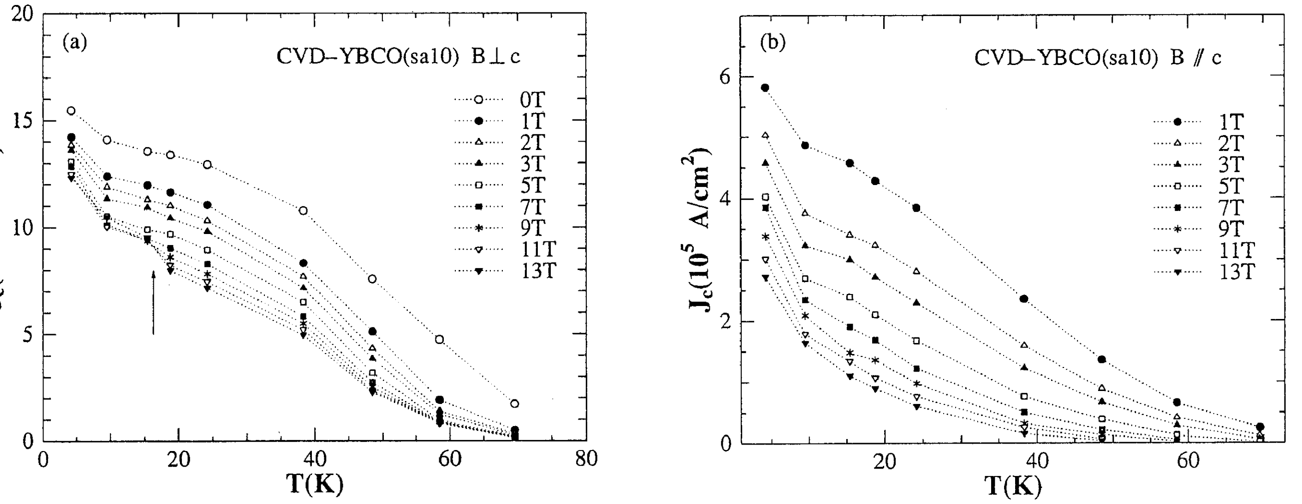


Figure 1. Temperature dependence of J_c at various fixed fields perpendicular to c-axis (a) and parallel to c-axis (b).

immersing the sample in liquid helium.

3) irreversibility field measurement

In order to determine the irreversibility field B_i, the field dependence of voltage was measured at a constant temperature and a constant current density of 10A/cm^2. The B_i values are determined as the field at which the voltage becomes 2μV/cm which is the same as the criterion of J_c. Therefore, the obtained B_i values correspond to the field where J_c=10A/cm^2 is attainable.

3. Results and discussions

1) Dimensional crossover of pinning

Figures 1 (a) and 1 (b) show the temperature dependences of J_c for B⊥c and B//c, respectively. A kink in the temperature dependence of J_c was observed around 17 K above 7 T for B⊥c as shown by arrow in Fig. 1(a). This kink was not observed for B//c as seen in Fig. 1 (b). We defined T_d as the temperature at which the kink appears. The T_d value of this film is about 17 K. The magnetic field dependence of J_c for B⊥c was performed at 15.4 and 18.8 K, which were selected as the temperatures just below and above T_d, respectively. The field dependence of J_c for B⊥c changes drastically at T_d as shown in Fig. 2. The J_c values at 18.8K just above T_d decreases monotonically with increasing field. However, at 15.4K just below T_d, J_c above 7 T does not depend on the external field within the experimental accuracy of our data. Similar anomaly with changing of the field dependence of Jc was also obtained for the other samples but at different temperature. Hence, the T_d value depends on the samples.

Figure 3 shows the angular dependence of $J_c(\theta)/J_c(90°)$ at 13 T for various temperatures. The angular dependence of J_c has a broad minimum at θ=0° (B//c) and a cusped maximum at θ=90° (B⊥c). The anisotropy of J_c in the

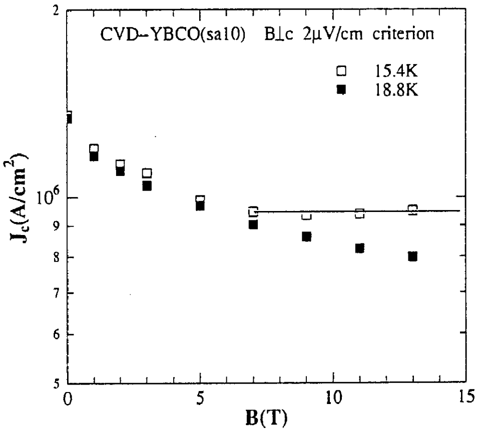


Figure 2. Comparison of field dependence of J_c at 15.4 and 18.8 K for B⊥c.

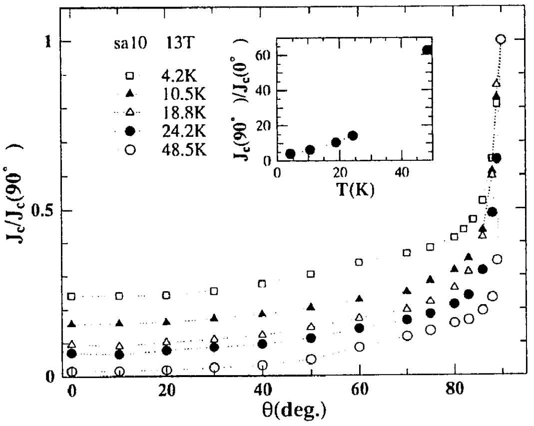


Figure 3. Angular dependence of $J_c/J_c(90°)$ at 13 T. The inset shows $J_c(90°)/J_c(0°)$ vs temperature.

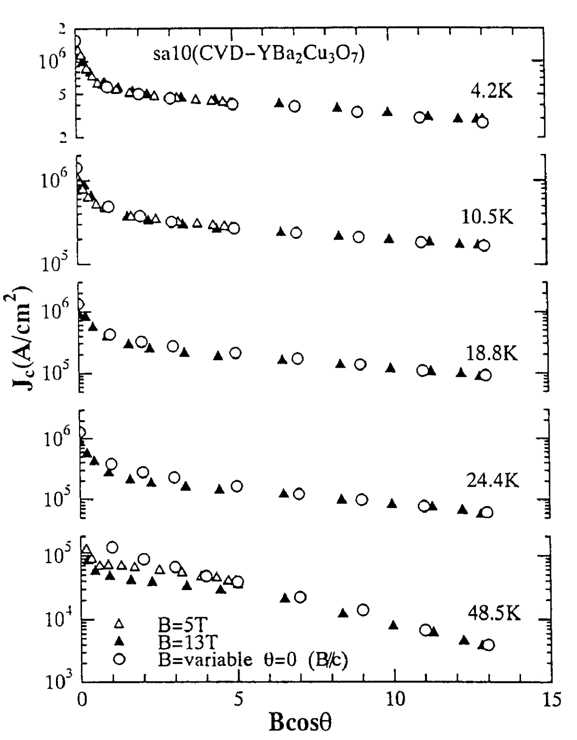


Figure 4. J_c vs Bcosθ replotted from J_c vs θ and the field dependence of J_c for B//c.

form of $J_c(90°)/J_c(0°)$ increases with temperature as shown in the inset of Fig. 3.

In the 2D pinning model such as the intrinsic pinning one, angular dependence of J_c with respect to the field direction is described by the field component parallel to the c-axis as follows [1]:

$$J_c(\theta,B) = J_c\,(B\cos\theta). \qquad (1)$$

Figure 4 shows the relationship between J_c and Bcosθ, where

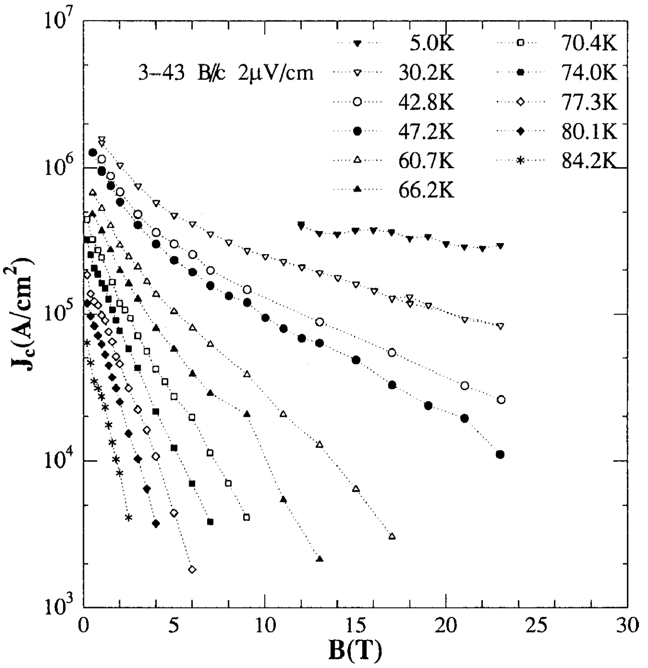
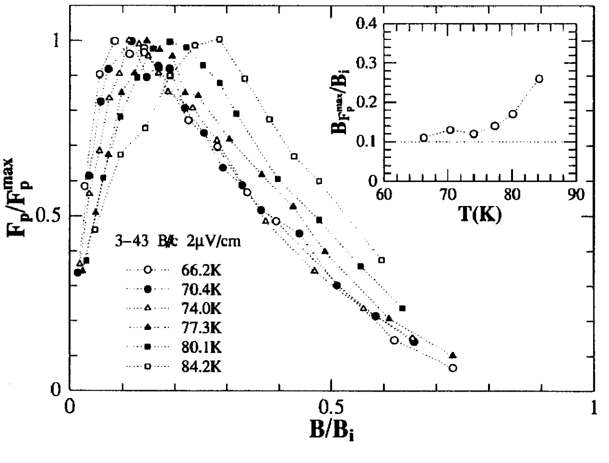


Figure 5. Field dependence of J_c for B//c at various temperatures.

Bcosθ corresponds to the c-axis component of the applied magnetic field. In the case of B//c (θ=0°), the open circles represent the field dependence of J_c for B//c. Note that the Bcosθ dependence of J_c replotted from J_c vs θ measurements (open and closed triangles) is in good agreement with the field dependence of J_c for B//c at 4.2 and 10.5 K below T_d. This means that the angular dependence of J_c is described by only c-axis component of the magnetic field. On the contrary, J_c derived from the angular dependence at 18.8, 24.4 and 48.5K above T_d is different from J_c for B//c . Thus, in the high temperature region above T_d, the J_c value is not described by the c-axis component of field. Hence, the experimental results indicate that 2D pinning is dominant below T_d, and the conventional 3D pinning works above T_d. Therefore, T_d corresponds to the crossover temperature of the flux pinning from 3D (extrinsic pinning) to 2D pinning (intrinsic pinning). This dimensional crossover which strongly depends on the flux pinning mechanism is different



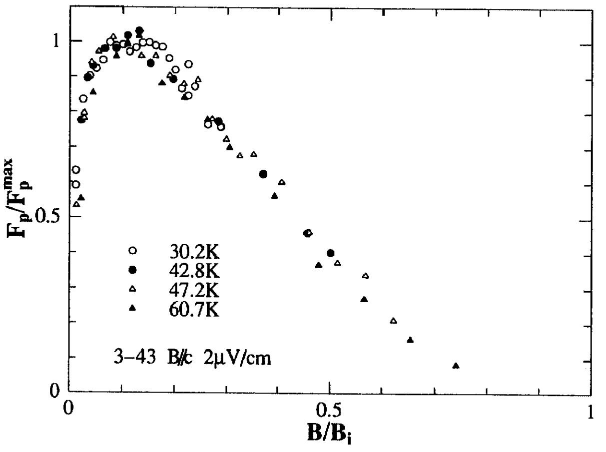


Figure 6 F_p/F_p^{max} vs. B/B_i in a high temperature region. Inset shows temperature dependence of $B_{F_p^{max}}/B_i$ above 66K.

Figure 7 F_p/F_p^{max} vs. B/B_i in a low temperature region below 61K, using the estimated B_i values.

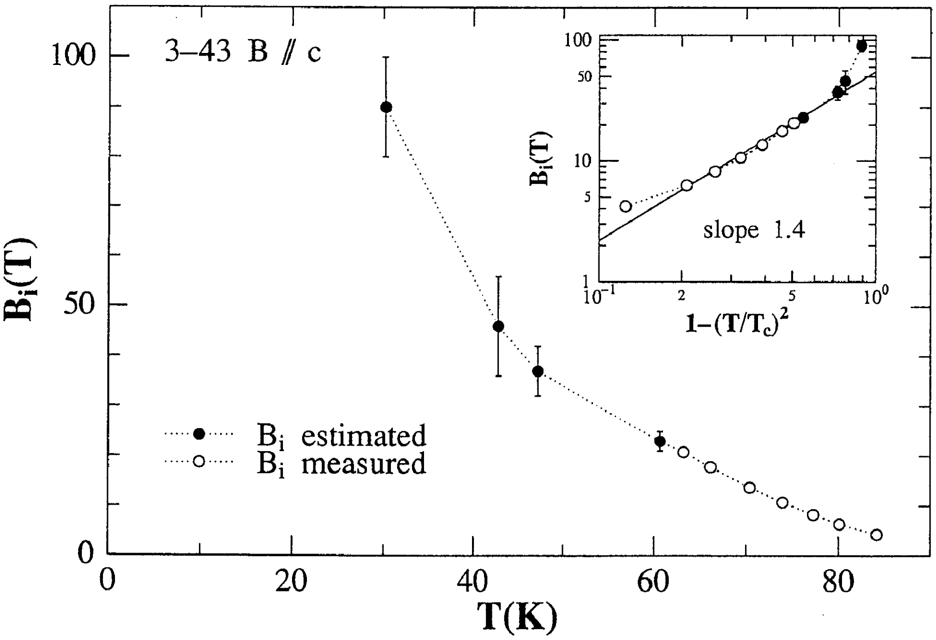


Figure 8 Temperature dependence of B_i. Inset shows B_i vs $(1-(T/T_c)^2)$.

from that expected from the Lawrence-Doniach model. Since the dimensional crossover of pinning showed here is closely associated with the relative strength between the 3D pinning and 2D one, the crossover temperature should change from sample to sample. In the results of other samples, we have obtained the sample dependence of T_d [9]. These T_d values decrease with increasing 3D pinning strength. This results also suggested that the anomaly appeared at T_d is due to the dimensional crossover from the 3D extrinsic pinning to the 2D intrinsic one.

2) Irreversibility field

Figure 5 shows the field dependence of J_c for B//c at various temperatures. The J_c values at 1T are 9.8 x 10^4 A/cm^2 at 77.3K and 1.6 x 10^6 A/cm^2 at 30.2K for B//c. Flux pinning force density F_p is obtained using the relationship $F_p = J_c \times B$. Figure 6 shows the normalized flux pinning force F_p/F_p^{max} near T_c as a function of B/B_i in high temperature region, where F_p^{max} is the maximum pinning force density. The peak field $B_{F_p^{max}}$ in the F_p-B curve decreases with decreasing temperature. The temperature dependence of $B_{F_p^{max}}/B_i$ is shown in the inset of Fig. 6. The $B_{F_p^{max}}/B_i$ value decreases with temperature in the higher temperature region and then saturates to about 0.1 at low temperature. This means that F_p/F_p^{max} would be scaled by B/B_i at low temperature. Assuming that the scaling relation of F_p/F_p^{max} holds and $B_{F_p^{max}}/B_i \approx 0.1$, the B_i values at lower temperature is estimated from the $B_{F_p^{max}}$ values. Figure 7 shows the normalized flux pinning force F_p/F_p^{max} as a function of B/B_i at low temperature below 61K, using the estimated B_i values. The good scaling suggests that the our assumption of $B_{F_p^{max}}/B_i \approx 0.1$ is reasonable.

Figure 8 shows the directly measured irreversibility fields below 23 T and the estimated B_i ones above 30T. The B_i values are proportional to $(1-(T/T_c)^2)^{1.4}$ in the temperature range above 40K and then rapidly increase below 40 K. It has been reported by many groups that the temperature dependence of B_i is proportional to $(1-(T/T_c)^2)^{3/2}$ near T_c. [8] Our result is in good agreement with these results as shown in the inset of Fig. 8. On the other hand, the enhancement of B_i below 40K have not been reported before, because the B_i value in the $YBa_2Cu_3O_7$ system is too large to be directly observed. The similar enhancement of B_i at low temperature was reported for Bi-Sr-Ca-Cu-O and PBCO/YBCO. [4, 10] This anomalous behavior of B_i has been attributed to a dimensional crossover from 3-dimensional to 2-dimensional vortex structures. [4] Galzmann and Koshelef pointed out that this dimensional crossover field is given theoretically by $B_{cr} \approx \phi_0/s^2\gamma^2$, where ϕ_0 is the flux quantum, s the layer spacing and γ the anisotropic parameter. [3] Kishio et al. proposed that the change of temperature dependence of B_i comes from the dimensional crossover of flux line for $Bi_2Sr_2Ca_1Cu_2O_{8+x}$ single crystals. [4] For $YBa_2Cu_3O_7$ system, the B_{cr} value is calculated to be about 56T using s = 11Å and $\gamma = 5.5$. This B_{cr} value is very similar with the field at which the B_i increases rapidly from $(1-(T/T_c)^2)^{3/2}$. Therefore, the enhancement of B_i as shown in Fig. 8 may be due to the diemensional crossover of vortices. The present paper is the first report on the enhancement of B_i for $YBa_2Cu_3O_7$, which is ascribed to the dimensional crossover.

4. Conclusion

We found two different dimensional crossover effects for different field direction of B//c and B⊥c, which are originated from the layer crystal structure.

The kink in the temperature dependence of J_c for B⊥c in the CVD-$YBa_2Cu_3O_7$ film was found at T_d. It is made clear that the 2-dimensional pinning behaves below T_d, and the 3-dimensional pinning become dominant above T_d. The kink can be explained as the dimensional crossover point of the pinning from 3D to 2D.

On the basis of the scaling law of the flux pinning force, the B_i value at low temperature down to 5K was estimated. We found that the B_i value is proportional to $(1-(T/T_c)^2)^{1.4}$ at high temperature and enhanced below about 40K. This behavior is very similar to the Bi-Sr-Ca-Cu-O system and may be attributed to the 2D-3D crossover of vortices.

Acknowledgments

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