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The scaling property of the critical current density for layered structure superconductors

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Abstract. The dependence of the critical current density J_c upon the reduced field h and the angle α between the current and the applied magnetic field has been experimentally studied for a $YBa_2Cu_3O_{7-\delta}$ (YBCO) epitaxial thin film in the 3D temperature region. An expression for J_c for layered structure superconductors is given. The results are discussed on the basis of the idea of a combined vortex lattice. It is pointed out that the influence of a layered structure on the critical current of YBCO thin films cannot be neglected at small angles.

1. Introduction

In recent years, the dependence of the critical current density J_c upon temperature, applied magnetic field and the angle between the direction of the applied field and the ab plane for high-T_c superconductors, especially for YBCO, has been extensively studied [1–3]. Some characteristics of the anisotropy of J_c can be summarized as follows [2–6]. (1) In the angular dependence of J_c, the maximum value of J_c appears under an applied field parallel to the ab plane; there exists a good symmetry of J_c with respect to the c axis or the ab plane at low temperatures and high applied fields, but an asymmetry of J_c appears at high temperatures and low applied fields. (2) The anisotropy of J_c increases with increasing H. (3) In some experiments, a small peak of J_c was observed under an applied field along the c axis. Many theoretical models, including the effective mass model [7], intrinsic pinning model [8, 9] and 2D model [10], have been proposed to explain the J_c characteristics for high-temperature superconductors. Recently, we have proposed a scaling formula of critical current density for anisotropic superconductors based on the classic Kramer scaling law and effective mass model [11, 12]. It can be used to describe well the dependences of the critical current density on applied field and angle, but there exists a certain deviation in the small-angle range. In this work, the dependences of the critical current density upon reduced field and angle have been experimentally studied. An expression that can be used to describe the dependence of the critical current density on applied field and angle for YBCO thin films in the small-angle region has been proposed. It is pointed out that the influence of a layered structure on J_c characteristics for YBCO at small angles cannot be negligible, even in the 3D temperature region.

2. Experiment

A high-quality c-axis-orientated YBCO thin film was prepared by d.c. magnetron sputtering. X-ray diffraction shows that no impurity phase peaks appear, and the full width at half maximum of the rocking curve for the (005) diffraction peak is less than 0.3°. This shows that the film is of good c-axis orientation. The a.c. susceptibility measurement as a function of temperature gives $T_c = 91\,K$ and $\Delta T_c < 0.3\,K$. The J_c is $3.8 \times 10^6\,A\,cm^{-2}$ at 77.3 K in zero magnetic field. The film of thickness 300 nm was patterned into a narrow bridge, 20 μm wide and 100 μm long. The silver leads were attached on silver terminals deposited on the film by indium solder. The electrical measurements were performed using a standard four-probe technique. The critical current density J_c was defined as a current density at which a voltage of 1 μV appeared. The film was held on the sample holder, consisting of a worm-gear system with which the angle between H and the film surface could be adjusted conveniently; the resolution of the angle was 0.1°. A magnetic field up to 10 T was supplied by a water-cooling magnet system. The temperature of the sample was measured by a calibrated Rh–Fe resistance thermometer and corrected for the effectiveness of the magnetic field.

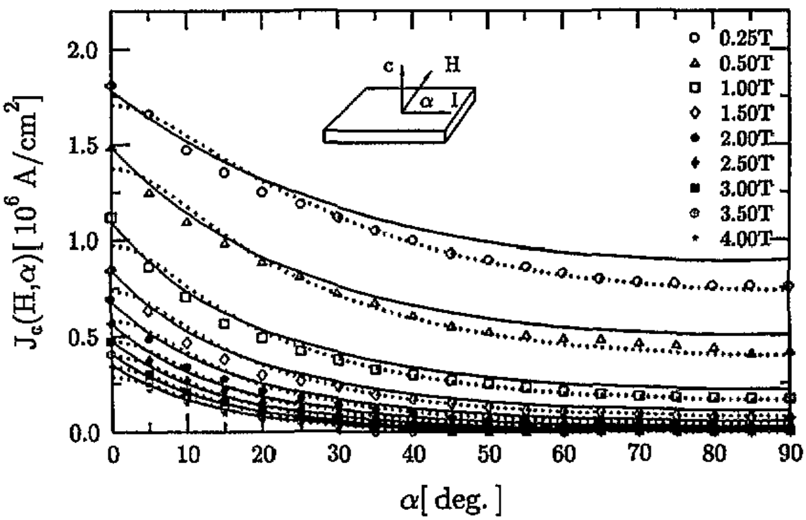

Figure 1. The angular dependence of the critical current density $J_c(H, \alpha)$ at 81 K for YBCO epitaxial thin films. The full curves and dotted curves are those calculated by (4b) and (4a), respectively. The inset shows the configuration for the measurement.

3. Results and discussion

The critical current density J_c was measured as a function of angle α from 0 to 90° at 81 K under a magnetic field up to 6 T; the results are plotted in figure 1, where α is the angle between the magnetic field H and current I, as shown in the inset of figure 1. $J_c(\alpha)$ peaks appear near $\alpha = 0°$; J_c then decreases with increasing α and is a minimum at $\alpha = 90°$.

Figure 2 shows a linear relation of $(1-h)^2/J_c$ as a function of the reduced field $h = H/H_{c2}$. It can be expressed by the equation

$$(1-h)^2/J_c = K(\alpha)h + h_0. \tag{1}$$

The slope of the straight lines, $K(\alpha)$, is a function of α, as shown in figure 3, and there exists a characteristic angle $\alpha \approx \tan^{-1}(\epsilon)$ in the angular dependence of $K(\alpha)$. The $K(\alpha)$ increase

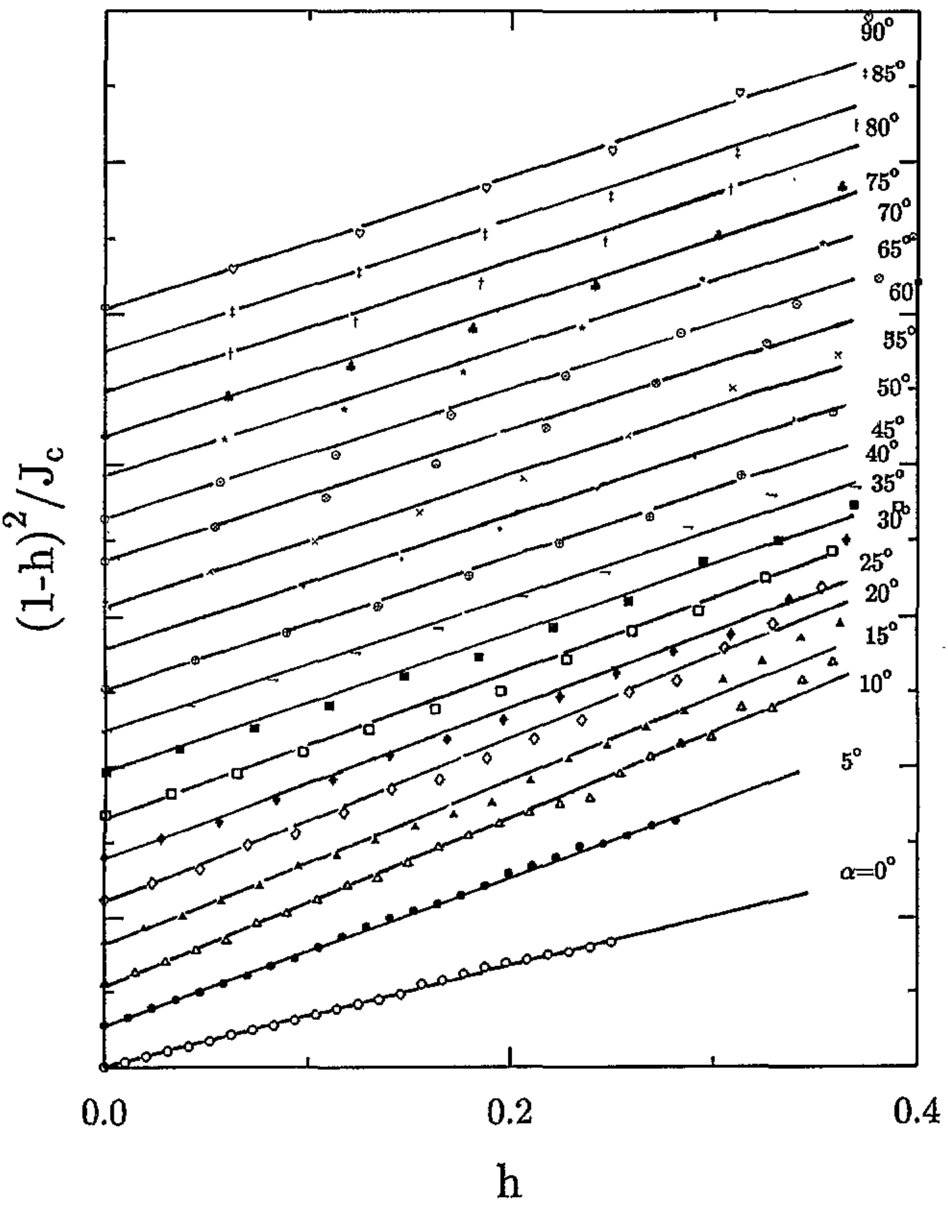

Figure 2. $(1-h)^2/J_c(H,\alpha)$ against h at various α. In order to show them clearly, every line is translated a distance along the direction of the vertical axis.

rapidly with increasing α for $\alpha < \tan^{-1}\epsilon$, and decrease for $\alpha > \tan^{-1}\epsilon$, i.e. there exists a peak of $K(\alpha)$ at $\alpha \approx \tan^{-1}\epsilon$. The $K(\alpha)$ become constant when $\alpha > \tan^{-1}(d/\xi)$, where $\epsilon = \sqrt{m_{ab}/m_c} = H_{c2}^c/H_{c2}^{ab} = 1/6$ is the measured value of the anisotropic parameter of the material, d is the space distance of layers and ξ is the coherence length in the ab plane. The inset in figure 3 shows the relation $k = \partial[(1-h)^2/J_c]/\partial H$ against α [11]. Because $h = H/H_{c2}(\alpha) = H\epsilon_\alpha/H_{c2}^c$, we have $K = H_{c2}^c k/\epsilon_\alpha$, where $\epsilon_\alpha = \sqrt{\sin^2\alpha + \epsilon\cos^2\alpha}$ is the angular dependence parameter, and $H_{c2}^c(81K) \doteq 3.95(T)$. A characteristic function that can describe both the characteristics of K and k is as follows:

$$K(\alpha) = \begin{cases} K & \alpha \geqslant \tan^{-1}(d/\xi) \quad (2a) \\ K'(\sin\alpha + \epsilon\cos\alpha)/\epsilon_\alpha & \alpha < \tan^{-1}(d/\xi) \quad (2b) \end{cases}$$

or

$$k(\alpha) = \begin{cases} K/H_{c2}^c\epsilon_\alpha & \alpha \geqslant \tan^{-1}(d/\xi) \quad (3a) \\ K'/H_{c2}^c(\sin\alpha + \epsilon\cos\alpha) & \alpha < \tan^{-1}(d/\xi) \quad (3b) \end{cases}$$

where $K = 11.57 \times 10^{-6}$ and $K' = 10.19 \times 10^{-6}$ are constants. In figure 3, the full curve is fitted by (2*b*). The full and dotted curves in the inset of figure 3 are fitted by (3*b*) and (3*a*), respectively.

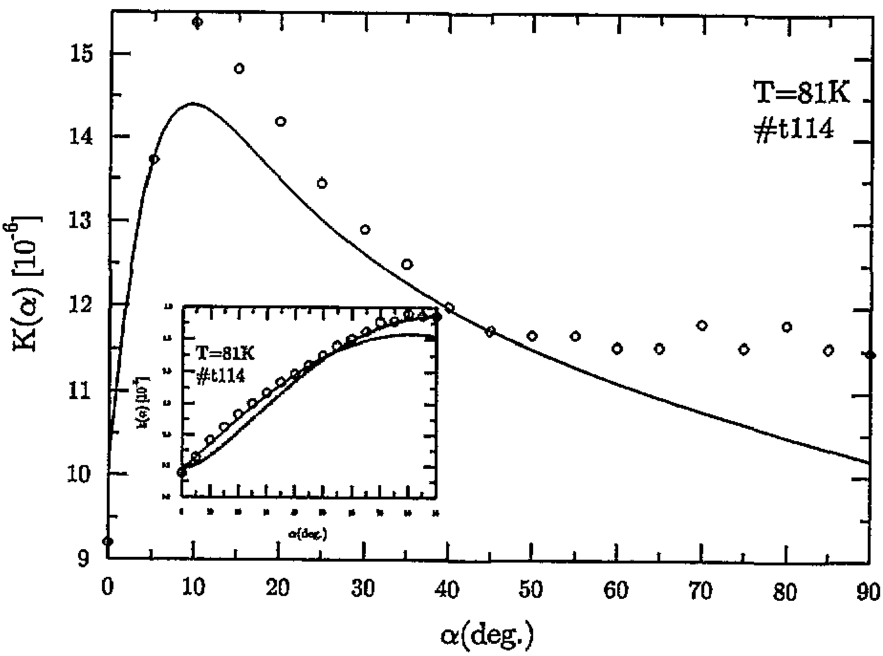

Figure 3. $K(\alpha)$ against α. The full curve is calculated by (2b). The inset shows $k(\alpha)$ against α; the full curve is that calculated by (3*b*) and the dotted curve is that calculated by (3*a*).

Substituting (2) into (1) we have

$$J_c(H, \alpha) = \begin{cases} c(1-h)^2/(\epsilon_\alpha H + H_0) & \alpha \geqslant \tan^{-1}(d/\xi) \quad (4a) \\ c'(1-h)^2/[(\sin\alpha + \epsilon\cos\alpha)H + H_0'] & \alpha < \tan^{-1}(d/\xi) \quad (4b) \end{cases}$$

where $c = H_{c2}^c/K$ and $c' = H_{c2}^c/K'$.

Comparing (4) with experimental results, it is found that (4*a*) can describe the behaviour of $J_c(H, \alpha)$ in the large-angle region, as shown in figure 1 by dotted curves, and (4*b*) is in good agreement with the experimental results in the small-angle region, as shown in figure 1 by the full curves.

Figure 4 plots the dependence of J_c upon H for various α. The full curves are those calculated by (4*b*) and the dotted curves are those calculated by (4*a*). From figure 4, a range in which (4*a*) and (4*b*) are suited to describe J_c behaviour, respectively, can be seen clearly.

It is found that (4*a*) is essentially a formula for J_c for anisotropic superconductors, as given in [11, 12]. However, (4*b*) exhibits distinctly different behaviour from (4*a*) and we call it the formula for critical current density for layered structure superconductors.

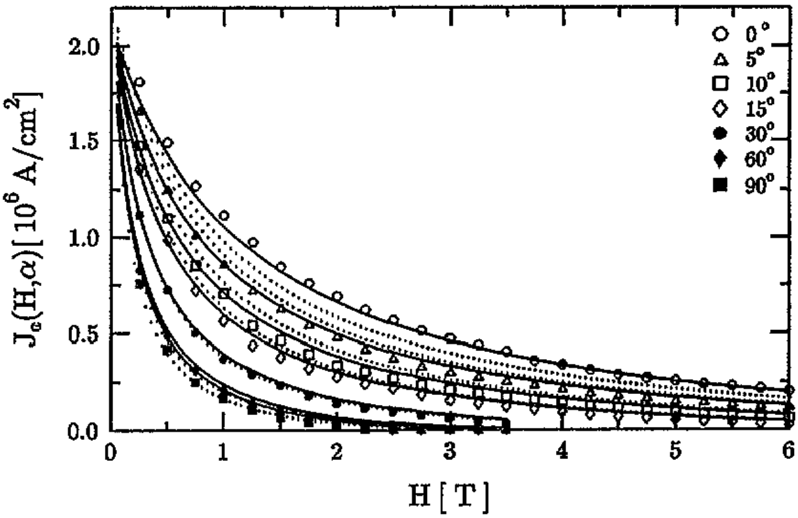

Figure 4. $J_c(H, \alpha)$ against H of sample t114 at 81 K at various α. The full curves are those calculated by (4*b*). The dotted curves are those calculated by (4*a*).

For strongly layered structure superconductors, the field components parallel and perpendicular to the CuO planes can penetrate independently and set up a combined vortex lattice made up of co-existing Abrikosov ($\perp$ *ab* plane) and Josephson ($\parallel$ *ab* plane) vortices [10, 13, 14]. We extend the idea to other layered structure superconductors, such as YBCO, and, based on this, we discuss the experimental results.

According to the idea of combined vortex lattices, a pure Josephson vortex lattice exists at $\alpha = 0°$ and in the small-angle range approaching zero due to lock-in transition then, in the range $0 < \alpha < \tan^{-1} \epsilon$, with increasing α the variation of the Josephson vortex lattice is negligible, and the Abrikosov vortex lattice starts and is rapidly enhanced. Therefore, the variation of the effective strength of the applied field is determined predominantly by the change of the perpendicular component (the Abrikosov vortex lattice). The experimental results show that the $K(\alpha)$ increase rapidly with increasing angle α. When $\alpha > \tan^{-1} \epsilon$, the screening currents shift from Josephson to the planes, and the increase of the perpendicular component becomes slower with increasing α. Consequently, there is a characteristic angle $\alpha = \tan^{-1} \epsilon$ which corresponds to the angle of maximum $K(\alpha)$. The experimental results also show that a $K(\alpha)$ peak appears at this angle. Furthermore, when the angle α increases over $\tan^{-1}(d/\xi)$, the screening current mainly flows in the planes and the Josephson vortex lattice disappears. The flux lines therefore become rectilinear objects in the direction of applied field. As a result, the material can be regarded as an anisotropically continuous medium, which can be described by anisotropic GL theory.

4. Conclusion

A formula for the dependence of J_c upon the applied field and angle for layered structure superconductors has been proposed, based on $J_c(H, \alpha)$ experimental results. It indicates that there exists a combined vortex lattice in YBCO thin films in the small-angle range. This means that the layered structure cannot be negligible, even in the 3D temperature region. The relation of J_c with H and α for YBCO thin films in the 3D temperature region can be well described by combined formulae for anisotropic superconductors and for layered structure superconductors.

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