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ANISOTROPY OF CRITICAL CURRENT DENSITY IN c-AXIS ORIENTED EPITAXIAL $YBa_2Cu_3O_{7-\delta}$ FILMS*

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The dependence of critical current density J_c on the angle α between the directions of the applied magnetic field H (which was rotated in the c-axis-I plane) and the in-plane current I was measured on a c-axis oriented epitaxial $YBa_2Cu_3O_{7-\delta}$ films at 81 K, with the magnetic field strength up to 6T. Analysis of the experimental results on the basis of the classical scaling law of pinning force shows that there exist simultaneously planar-pinning and volume-pinning mechanisms, and the contribution of volume pinning increases with decreasing α while that of the planar pinning decreases. We propose that the decrease of Lorentz-force-independent critical current density with increasing H for $H//I$ results from the suppression of superconductivity by the magnetic field. The fact that the contribution of volume pinning increases with decreasing α also arises from the suppression of superconductivity in CuO_2 plane by the magnetic field.

PACC: 7460J; 7460G; 7475

I. INTRODUCTION

High-T_c cuprate are the superconductors with highly anisotropic characteristics. For instance, their resistivity, upper critical field, pinning force, and critical current density show anisotropic behavior. Many experiments revealed that anisotropic G-L theory can well describe the properties of anisotropic superconductors, e.g., angular dependence of the upper critical field[1,2], resistivity[3,4] and critical current density,[5,6] etc., in three-dimensional (3D) anisotropic temperature region for high-T_c superconductors. If one introduces the anisotropic upper critical field in the Kramer's scaling law, the anisotropic pinning force[5,7] can then be well described. Nishizaki et al.[7,8] combined the Kramer's scaling law with Kim-Anderson critical state model and gave the critical current density in epitaxial c-axis-oriented YBCO thin film by the following formula:

$$J_c(H,\alpha) = \mathrm{ch}^p(1-h)^q/(H\sin\alpha + H_0)\ , \tag{1}$$

where α is the angle between the applied field and the current in a-b plane, H_o is generally considered as a constant, c is a variable parameter, and for YBCO thin film, $p \approx 0.5$, $q \approx 2$[7].

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In the case of $H//I$, J_c decreases with increasing H. In this paper, we suggest that H_0 does not keep constant, but is a function of H. By comparing the measured data of $J_c(H,\alpha)$ with Eq.(') (here we take $p = 0.5$, $q = 2$), it is expected that the field dependence of c and H_0 can be obtained, and their physical meaning will be also discussed in this paper.

II. EXPERIMENT AND RESULTS

High-quality c-axis-orientated YBCO thin film (t114) was prepared by high-pressure (p = 3 mbar) d.c. sputtering in pure oxygen atmosphere from planar and stoichiometric YBCO target (ϕ = 35 mm) onto a heated $SrTiO_3$ (100) substrate, as reported elsewhere[9]. The X-ray diffraction showed that no impurity phase peaks are present and the full width at half maximum (FWHM) of the rocking curve for the (005) diffraction peak is $\leq 0.3°$, indicating that the in-plane mosaic spread is of an order of $0.3°$, so that the film shows a very good epitaxial c-axis orientation. The ac-susceptibility measurement as a function of temperature shows superconducting transition temperature T_c = 91 K, and $\Delta T_c < 0.3$ K, defined by the temperature between $90\%\chi'_{ac}$ and $10\%\chi'_{ac}$. This is consistent with the result of electric measurement. We obtain J_c is 3.8×10^6 A/cm^2 at 77.3 K in zero magnetic field.

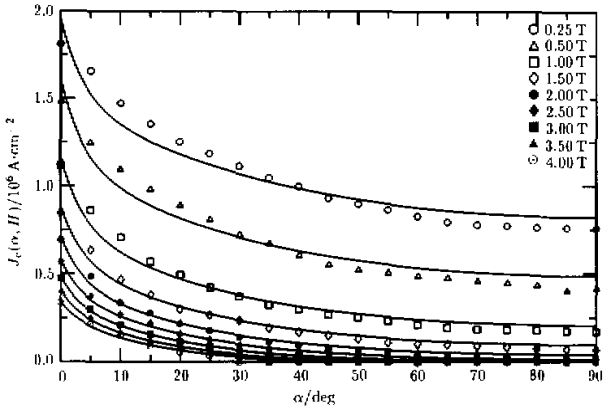

Fig. 1. Angular dependences of $J_c(H,\alpha)$. The solid lines are those fitted by Eq.(10) in the text.

The film was patterned into a narrow bridge whose typical dimensions were 20 μm wide, 100 μm long and 300 nm thick. The silver leads were attached by indium solder on Ag terminals deposited on the YBCO. The electric measurements were performed using a standard four-probe technique. The critical current density J_c was determined by the 1 μV voltage criteria. Film was held on a sample holder consisting of a worm-gear driving system, with which the angle between the direction of the external magnetic field and the ab plane of

the film can be adjusted conveniently, and the resolution of the angle is 0.1°. The magnetic field up to 10 T was supplied by a water-cooled magnet system, and the temperature of the sample was measured by a calibrated Rh-Fe resistance thermometer, corrected for the effect of magnetic field.

Figure 1 shows the critical current density J_c as a function of α from 0^o to 90^o under different various magnetic fields at 81 K. There are maxima of J_c at $\alpha = 0°$, and J_c decreases monotonously with increasing α, till $\alpha = 90°$, where J_c becomes minimum.

III. DISCUSSION

For conventional type-II superconductors, the Kramer's scaling law of pinning force is as follows[10]:

$$F_p = c(T)h^p(1-h)^q \,, \tag{2}$$

where $h = H/H_{c2}$ is the reduced field, p and $q = 2$ are fit parameters, and $p = 0$ for volume pinning mechanism, $p = 0.5$ for planar pinning mechanism, and $p = 1$ for point pinning mechanism. For anisotropic superconductors, Kramer's scaling law is corrected as follows[8]:

$$F_p = c(T,\alpha)h^p(\alpha)[1-h(\alpha)]^q \,. \tag{3}$$

Generally, $c(T,\alpha)$ is irrelevant to α due to the weak relationship between $c(T,\alpha)$ and α; $h(\alpha) = H/H_{c2}(\alpha)$ and $H_{c2}(\alpha)$ is the anisotropic upper critical field.

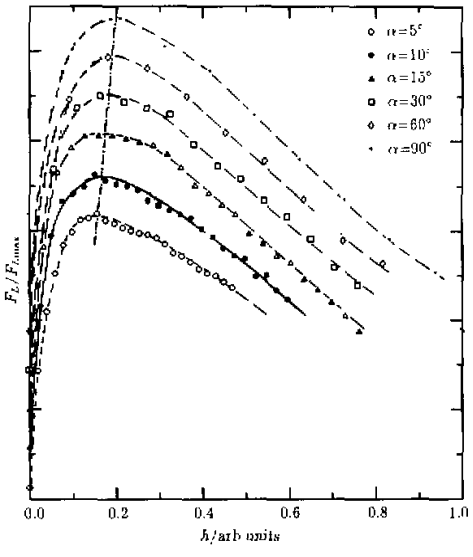

Fig. 2. Reduced Lorentz force vs. reduced field. Except for $\alpha = 5°$, each curve is moved upward a proper distance along the vertical axis.

Figure 2 plots the reduced Lorentz force F_L/F_{Lmax} as a function of the reduced field $h(\alpha) = H/H_{c2}(\alpha)$. The angular dependence of $H_{c2}(\alpha)$ is described by the effective mass models:

$$H_{c2}(\alpha) = H_{c2}(90^\circ)\sqrt{\sin^2\alpha + \epsilon^2\cos^2\alpha}\,, \tag{4}$$

where $\epsilon = H_{c2}(90^\circ)/H_{c2}(0^\circ) = 1/6$ and $H_{c2}(90^\circ) = 4\,\mathrm{T}$ are the measured values. $F_L = J_c\sin\alpha$ is the Lorentz force, it can be expressed as

$$F_L = \mathrm{ch}^p(1-h)^2\,, \tag{5}$$

with c and p being fit parameters. For $\alpha = 90^\circ$, p is about 0.5, and it decreases with increasing α. At the same time, the reduced field which is corresponding to the maximum Lorentz force (pinning force) will also decrease. The reason for this will be discussed later.

In conventional type-II superconductors, Lody *et al.*[11,12] proposed that the critical current density in the case of magnetic field non-normal to transport current is:

$$J_c(H,\alpha) = A_p/(H\sin\alpha + H_0)\,, \tag{6}$$

where A_p is pinning force parameter, H_0 is generally a constant in higher magnetic field range. This relation deviates largely from the experimental results for high-T_c YBCO superconducting thin film[8]. The reason why $J_c(H,\alpha)$ in high-T_c superconductors does not obey Eq.(6) in higher magnetic field range has already been analyzed in Ref.[8], and a formula of Lorentz-force-dependent $J_c(H,\alpha)$ for anisotropic superconductors is proposed,

$$J_c(H,\alpha) = \mathrm{ch}^{\frac{1}{2}}(1-h)^2/(H\sin(\alpha) + H_0)\,. \tag{7}$$

First we analysis Eq.(7)briefly: (1) When $\alpha = 0^\circ$, Eq.(7) becomes $J_c(H,0^\circ) = \mathrm{ch}^{\frac{1}{2}}(1-h)^2/H_0$, and $J_c(H,0^\circ)$ has a maximum at $h = 1/5$. However, the experimental results indicate that $J_c(H,0^\circ)$ also decrease monotonously with increasing H, as shown in Fig.3. This means that Eq.(7) cannot be used to describe the magnetic field dependence of critical current density in the Lorentz-force-independent case (just as pointed out in Ref.[8], Eq.(7) is the description of the critical current density in the Lorentz-force-dependent case). If Eq.(7) is simply corrected by the following method, i.e., H_0 is treated as a function of H, then the corrected Eq.(7) can be used to describe the magnetic field dependence of the critical current density in the Lorentz force-independent case. (2) In fact, Eq.(7) represents a planar pinning mechanism.[8,2] However, our experimental results indicate that the planar pinning mechanism, i.e., $p = 0.5$, dominates only when $\alpha = 90^\circ$[13], while $\alpha < 90^\circ$, $p < 0.5$, it is shown that the pinning behavior in the material cannot be simply described by planar pinning. Therefore, we suggest that the parameter c in Eq.(7) should also be considered to be a function of H. Then we can further get the corrected form of Eq.(7).

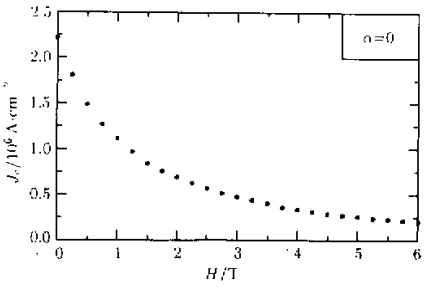

Fig. 3. *The critical current density as a function of magnetic field for YBCO thin film for H//I at 81 K.*

As mentioned above, we take c and H_0 as variable parameters, then fit the experimental data by Eq.(7), as shown in Fig.1 by solid lines. It can be seen that the fitted results are in good agreement with the experimental data, in particular, in the case of higher magnetic fields.

According to Eq.(1), the experimental data of $J_c(H,\alpha)$ have been fitted for magnetic field H ranging from 0.25 T to 4 T and the field dependences of c and H_0 are shown in Figs.4 and 5, respectively. Further study shows that they can be expressed simply by

$$c = c_0 H^{-\mu} , \tag{8}$$

where $c_0 = 8.439 \times 10^5$, $\mu = 0.2202$, and

$$H_0 = b_0 + kH \tag{9}$$

with $b_0 = 0.0333$, $k = 0.1167$. Substituting Eqs.(8) and (9) into Eq.(7), we get

$$c_0 H^{-\mu} h^{\frac{1}{2}}(1-h)^2 = J_c(H,\alpha)[H\sin\alpha + (b_0 + kH)] . \tag{10}$$

The first term on the right side of Eq.(10) is Lorentz force and the second one $J_c(H,\alpha)(b_0 + kH)$ should be the "non-Lorentz-force", which is the driving force for flux motion. And the term on the left side of Eq.(10) corresponds to the pinning force: $F_p = c_0 H^{-\mu} h^{\frac{1}{2}}(1-h)^2 = c_0 H_{c2}^{-\mu}(\alpha) h^{\frac{1}{2}-\mu}(1-h)^2$. The relationship between c and H shows that Eq.(7) cannot describe our experimental data. If we add a correct factor $(-\mu)$ in the exponent of $h^{\frac{1}{2}}$, it will be almost in agreement with the pinning force (in fact it is a Lorentz force) calculated by Eq.(1) as mentioned before, i.e., p in Eq.(5) is a constant between 0 (corresponding to volume pinning) and 0.5 (corresponding to planar pinning). This indicates that there exist both planar pinning and volume pinning in our sample under our experimental conditions.[13]

When $\alpha = 0$, we have $F_p = c_0 H_{c2}^{-\mu}(0^\circ) h^{\frac{1}{2}-\mu}(1-h)^2 = J_c(H,0^\circ)(b_0 + kH)$. According to the critical state model, $J_c(H,0^\circ)(b_0 + kH)$ is the Lorentz-force-independent driving force

for flux motion. This would imply that the applied magnetic field plays a role to suppress the superconductivity. Similarly, when α is not equal to zero, the component of the magnetic field parallel to J may also play a role to suppress the superconductivity. Similarly, when α is not equal to zero, the component of the magnetic field parallel to J may also play a role to suppress the superconductivity; in fact, it results from the decrease of the flux pinning potential U_p with increasing field. If we consider it as a driving force for flux motion, it corresponds to $J_c(H,\alpha)(b_0 + kH)$.

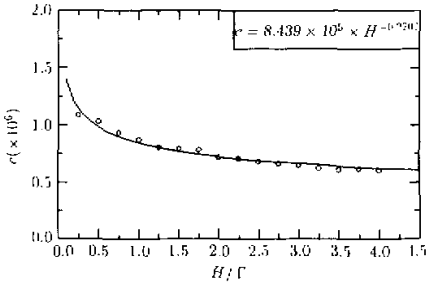

Fig. 4. The relationship between the fitting parameters c and H.

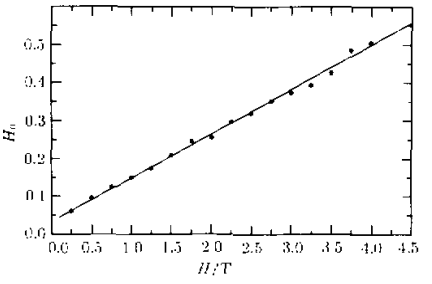

Fig. 5. The relationship between the fitting parameters H_0 and H.

Additionally, p decreases with decreasing α as mentioned above. This means that the component of volume pinning increases with decreasing α. It can also be interpreted as the suppression of the superconductivity by the component field parallel to J, which reduces the magnitude of the order parameter in CuO_2 plane. On the other hand, some defects become the point pinning centers in strong superconductivity due to strong proximity effect. However, when the superconductivity is suppressed by the magnetic field, it becomes weak, and the proximity effect also becomes weak; these defects may be spread to become the volume pinning centers, thus leading to the macroscopic enhancement of volume pinning. At the same time, the enhancement of the modulation of the superconducting order parameter by the Josephson current related to the component of the field parallel to J leads the intrinsic pinning to become weaker.

IV. CONCLUSION

By analyzing and fitting the angular dependence of the critical current density at 81 K, we find that, there exist both volume-pinning and planar-pinning mechanisms in our $YBa_2Cu_3O_{7-\delta}$ epitaxial film. On the basis of the scaling law of the pinning force in the classical critical state model, it is expected that the volume pinning enhances, while the planar pinning weakens, with increasing α, the angle between H and J in a-b plane. We suggest that the quantitative transformation of pinning mechanism results from the suppression of

the superconductivity by the field component parallel to J. The decrease of Lorentz-force-independent critical current density with increasing field also results from the suppression of the superconductivity by the magnetic field.

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