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BROADENING OF RESISTIVE TRANSITION AND IRREVERSIBILITY LINE FOR EPITAXIAL $YBa_2Cu_3O_{7-\delta}$ THIN FILM*

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The broadening of resistive transition of c axis oriented epitaxial YBCO thin film has been measured for three configurations: (1) $H//c$ and $H \perp I$; (2) $H//ab$ plane and $H \perp I$; (3) $H//ab$ plane and $H//I$ in magnetic field up to 8 Tesla(T), and for different angle θ of magnetic field relative to the ab plane with $H = 4$T. The results obtained indicate that the broadening of resistive transition is mainly determined by the angle θ, but is hardly related to the angle α made between magnetic field and tran sport current in ab plane. This means that the broadening of resistive transition is not determined by flux motion drived by apparent Lorentz force. An expression of angular dependence of irreversibility line has been given.

PACC: 7460E; 7460G; 7475; 7410

I. INTRODUCTION

The broadening of resistive transition induced by magnetic field is one of the important characteristics in high-T_c superconductors, and is generally described by the thermally activated flux motion.[1-6] The layered structure and the short coherent length are considered as two crucial elements which determine the characteristics of high-T_c superconductors.[7] As a result, the broadening of resistive transition induced by magnetic field and its anisotropy is one of some new phenomena which are hardly observed in conventional superconductors. Much information in the mixed state of type Ⅱ superconductor can be obtained from the measurement of $R(T)$ broadening in an applied field, e.g., the activation energy for flux creep and the irreversibility line, etc. In this article, we report the experimental results about $R(T)$ broadening and the angular dependence of irreversibility line for YBCO epitaxial thin film.

Ⅱ. EXPERIMENTAL

The c-axis-oriented YBCO epitaxial thin film was prepared by DC magnetron spputtering. X-ray diffraction showed that no impurity-phase peaks appeared and the full width

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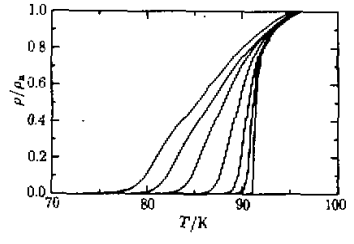
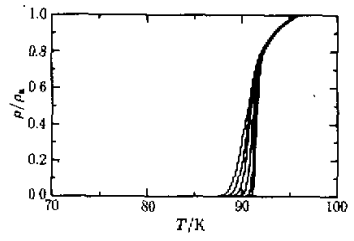
at half maximum of the rocking curve for (005) diffraction peak was less than 0.3°. This indicates that the film is of good c-axis-orientation. AC susceptibility measurement as a function of temperature gives $T_c = 91.6\,K$ and $\Delta T_c < 0.3\,K$, and the critical current density J_c is $3.8 \times 10^6\,A/cm^2$ at 77.3 K in zero magnetic field. The thin film with a thickness of 300 nm was patterned into a narrow bridge, 20 μm wide and 100 μm long. Silver leads were attached on Ag terminals deposited on the film by indium solder. Electrical measurements were performed by using a standard four-probe technique. The film was held on the sample holder consisting of a worm-gear system, where the angle between the field H and the film surface could be adjusted conveniently and the resolution of the angle was 0.1°. The magnetic field up to 10 T was supplied by a water-cooled magnet system. The temperature of the sample was measured by a calibrated Rh-Fe resistance thermometer and corrected for the effect of magnetic field.

III. RESULTS AND DISCUSSION

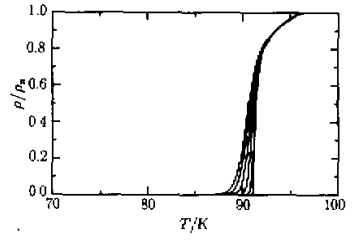
A. The $R(T)$ broadening of epitaxial YBCO thin film



(a) $H//c$ and $H \perp J$. $H = 0, 0.5, 1, 2, 4, 6, 8$ T.



(b) $H//ab$ plane and $H \perp J$. $H = 0, 0.5, 1, 2, 4, 6, 8$ T.



(c) $H//ab$ plane and $H//J$. $H = 0, 1, 2, 4, 6, 8$ T.

Fig. 1. The resistive transition of sample t114 in various magnetic fields for the configurations.

The $R(T)$ broadening curves of epitaxial YBCO thin film for different magnetic field configurations and in various magnetic fields have been measured, as shown in Fig. 1. The $R(T)$ transition is very steep in zero field and the broadening of the resistive transition in

the applied field appears for any configulations. Figure 1(a) shows the $R(T)$ broadening for $H//c$ ($\theta = 90°$), $\Delta T_c \approx 17.5\,\mathrm{K}$ when $H = 8\,\mathrm{T}$, assuming $R(T_c(H)) = 0$, where ΔT_c is defined as the interval between the zero resistance temperatures for $H = 0$ and for $H = 8\,\mathrm{T}$. Figures 1(b) and 1(c) show the behavior of $R(T)$ broadening for $H//ab$ plane and $H \perp I$ (i.e., $\theta = 0°$) and for $H//ab//I$ (i.e., $\alpha = 0°$), respectively. The $R(T)$ broadening induced by magnetic field can hardly be distinguished for these two configurations, for example, their ΔT_c are 4 K at $H = 8\,\mathrm{T}$. Under the same magnetic field, the ratio of $R(T)$ broadening ΔT_c for configuration of $\theta = 90°$ to that for configuration of $\theta = 0°$ or $\alpha = 0°$ is about 3–4, and this ratio expands with increasing magnetic field. The results mentioned above indicate that the $R(T)$ broadening depends mainly on the relative direction between H and crystal axis, not the relative direction between H and I. The $R(T)$ broadening ΔT_c for different configurations in various fixed magnetic fields is given in Table 1.

Table 1. The $R(T)$ broadening ΔT_c for different configurations in various magnetic fields.

H/T	0.5	1	2	4	6	8
$\theta = 90°$	1	2.5	6.4	10.4	14	17.5
$\theta = 0°$	0.3	0.8	1.7	3.1	3.7	4.35
$\alpha = 0°$		0.9	1.6	2.7	3.6	4.7

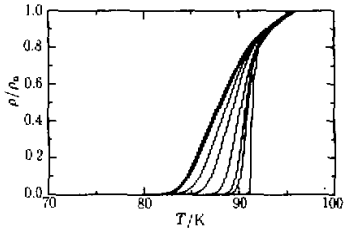


Fig. 2. The resistive transition of sample t114 for different angle θ under the field of $H = 4\,\mathrm{T}$, $H \perp J$. $\theta = 0, 5, 15, 30, 45, 65, 80, 90$ deg.

When ΔT_c is defined as the temperature interval between $10\%\rho_n$ in a zero magnetic field and that in a non-zero magnetic field, where ρ_n is the normal state resistivity at the onset, the ratio of $R(T)$ broadening ΔT_c is about 5–6. It is about 5–7 when $50\%\rho_n$ is taken as a criterion. The ratio of $R(T)$ broadening expands with the increase of resistance value taken as the criterion. However, the ratio of $R(T)$ broadening is nearly the same for $\theta = 0°$ and for $\alpha = 0°$ whatever the criterion is. The above results further indicates that the $R(T)$ broadening depends mainly on the relative direction between the magnetic field and the crystal axis, not the relative direction between the magnetic field and the current. This implies that the Lorentz force plays only a secondary role.

Figure 2 shows the curves of $R(T)$ broadening of resistive transition for different angle θ under the magnetic field of $H = 4\,\mathrm{T}$, where the $R(T)$ broadening increases rapidly with increasing angle θ for $\theta < 65°$, and increases slowly with increasing angle θ for $\theta > 65°$.

B. The H-T relation with different criterion of ρ/ρ_n

According to experimental results shown in Fig. 1, the upper critical field, $H_{c2}(T)$, can be determined by different criterion of ρ/ρ_n, and the H_{c2}-T relation can be obtained. Figure 3

shows the relation between $\lg H_{c2}$ and $\lg(1-t)$ with $\rho = 0$, where $t = T_c(H)/T_c(0)$, $T_c(H)$ is the zero resistance T_c in the magnetic field H and $T_c(0)$ is that for $H = 0$. The upper critical field obtained by using the criterion of zero resistance is essentially an irreversibility field, so the relation of H-T represents the irreversibility lines. It can be seen from Fig. 3 that $\lg H$ vs $\lg(1-t)$ curves are linear, and their slopes approach to 3/2 for three configurations. Therefore, the relation of H-T can be expressed by a universal equation

$$H = H_0(1-t)^{\mu} . \tag{1}$$

However, the constant H_0 is different for different magnetic field configurations, e.g., $H_0^c = 87\,\mathrm{T}$ and $\mu = 1.46$ for $\theta = 90°$, $H_0^{ab} = 526\,\mathrm{T}$ and $\mu = 1.53$ for $\theta = 0°$ and $\alpha = 0°$.

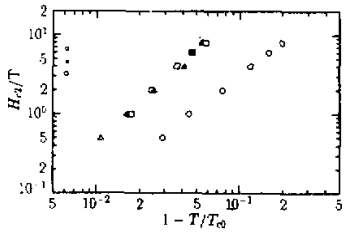


Fig. 3. Curves of $\lg H_{c2}$ vs $\lg(1-t)$ by using the criterion of $\rho = 0$. ○: $H \perp ab$ plane, $H \perp J$; △: $H//ab$ plane, $H \perp J$; □: $H//ab$ plane, $H//J$.

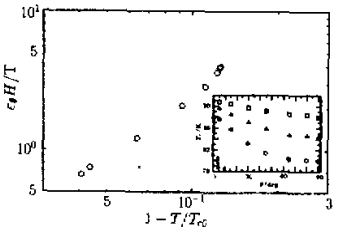


Fig. 4. Curve of $\lg(\varepsilon_\theta H)$ vs $\lg(1-t)$ obtained by using the criterion of $\rho = 0$. $H \perp J$.

Figure 4 shows the curve of $\lg(\varepsilon_\theta H)$ vs $\lg(1-t)$, where $\varepsilon_\theta = \sqrt{\sin^2\theta + \varepsilon^2\cos^2\theta}$ is the angular dependence parameter and $\varepsilon = (m_{ab}/m_c)^{1/2} = H_{c2}^c/H_{c2}^{ab} = 1/6$ is the measured value. It can be approximately expressed as

$$\varepsilon_\theta H = H_0^c(1-t)^{3/2} , \tag{2}$$

where $\varepsilon_\theta H$ is, in fact, the effective field. This result indicates that the angular dependence of irreversibility line agrees with the description of effective mass model.

Putting ε_θ into H_0 in Eq. (1), i.e., $H_0(\theta) = H_0^c/\varepsilon_\theta$, we have an anisotropic irreversibility line of the form

$$(1-t) = [H/H_0(\theta)]^{2/3} . \tag{3}$$

The inset in Fig. 4 shows the dependence of T_c upon angle θ at $H = 4\,\mathrm{T}$ obtained by using the criteria $\rho/\rho_n = 1/2$, 10% and zero, respectively, where T_c decreases monotonously with increasing angle, θ. Figure 5 shows the curves of ΔT_c vs $H(\sin\theta + \varepsilon\cos\theta)$ in the cases of $\rho/\rho_n = 1/2$ and 10%. The broadening of resistive transition in Fig. 5 can be expressed by

$$\Delta T \propto H(\sin\theta + \varepsilon\cos\theta) . \tag{4}$$

IV. CONCLUSSION

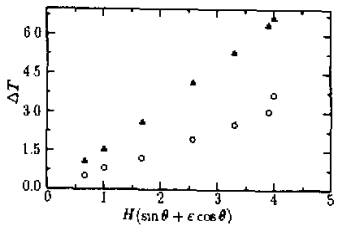


Fig. 5. Curves of ΔT vs $H(\sin\theta + \varepsilon\cos\theta)$ for $\rho/\rho_n = 1/2$ (○) and 10% (△) in the magnetic field of $H = 4$ T.

There exists the broadening of resistive transition induced by non-Lorentz force except for that induced by Lorentz force driving flux motion in an applied field. For the configuration of $\alpha = 0°$, i.e., with the current parallel to the magnetic field, there is not any Lorentz force driving flux motion, but the $R(T)$ broadening in this configuration is equal to that in $\theta = 0°$ configuration in which Lorentz force driving flux motion is present. Just as observed in our experiment, the large anisotropy of the broadening of resistive transition in an applied field means it is an intrinsic property of the YBCO oxide superconductors. The anisotropic two-dimensional electronic structure implies that the anisotropic broadening of resistive transition may be relevant to the fluctuation of two-dimensional superconductivity in an applied field. The dependence of the broadening ΔT_c upon the angle between the applied field and the crystal axis or plane indicates that the $R(T)$ broadening depends on the reduced field, not the absolute value of the applied field. The angular dependence of irreversibility line is in agreement with the description of the effective mass model.

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