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Two-dimensional properties of $GdBa_2Cu_3O_{7-\delta}$ epitaxial thin films

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The resistive transition of an epitaxial $GdBa_2Cu_3O_{7-\delta}$ thin film was measured in detail in a magnetic field up to 7.5 T. The field dependence of the activation energy revealed a crossover from a three-dimensional to two-dimensional (2D) vortex liquid induced by Lorentz force. The angular dependence of the characteristic temperature T^* exhibited a curve with a cusp at 0°, showing a 2D behavior. It was suggested that the 2D property of the epitaxial $GdBa_2Cu_3O_{7-\delta}$ thin film was due to the magnetic moment of the Gd^{3+} ion which suppresses the coupling of CuO_2 planes. [S0163-1829(97)05637-3]

I. INTRODUCTION

The high-T_c cuprate oxide superconductors may be schematically represented by a layered structure which consists of CuO_2 planes separated by insulating or weakly metallic layers. The copper oxide layers determine most of the physical properties of the system and are responsible for superconductivity. The physical properties of the high-T_c cuprate oxide superconductors, such as resistivity,[1–3] critical field,[3–6] and critical current density,[7] etc., are highly anisotropic and a crossover of dimensionality can occur.[8]

The roles of anisotropy and dimensionality in an electronic system are an important consideration for many properties and the understanding of these materials. A vast amount of experimental results showed that in the temperature region above 77 K an anisotropic, three-dimensional (3D) behavior is present for single crystals and epitaxial thin films of $YBa_2Cu_3O_{7-\delta}$ (YBCO),[9,10] and the field dependence[11,12] of the critical current density, magnetoresistance,[13] critical field, and irreversibility line,[13,14] as well as, the property of vortex lines[15] show a similar anisotropy. The temperature dependence of the fluctuation conductance near T_c showed a 2D-3D crossover for YBCO epitaxial thin films, but merely 2D behavior for the $GdBa_2Cu_3O_{7-\delta}$ (GdBCO) thin film.[16] The magnetoresistance study also showed a 2D behavior.[17]

In this paper we report experimental results on the resistive transition for epitaxial GdBCO thin films in magnetic fields up to 7.5 T.

II. SAMPLE

The c-axis oriented GdBCO epitaxial thin films used in this study were prepared by dc magnetron sputtering. The detailed process of preparation was reported elsewhere.[18] The superconducting transition temperature at zero resistance is 91.0 K. The critical current density is 5×10^5 A/cm^2 at 77 K and zero magnetic field.

The film with 640 nm thickness was patterned into a narrow bridge 30 μm in width and 40 μm in length. The current and voltage leads were attached by indium solder on silver terminals deposited onto the surface of the film.

III. EXPERIMENT

The resistive transition of the sample was measured in a variable temperature insert by a four-probe technique. The sample was held on a rotatable holder, so, the angle of the film surface with respect to direction of magnetic field could be varied with 0.1° resolution. The temperature was measured by a calibrated Rh-Fe resistance thermometer and was corrected for the effect of magnetic field. The magnetic field up to 8 T was supplied by a superconducting solenoid magnet system.

Figures 1(a), 1(b), and 1(c) plot the resistive transitions as a function of temperature at several constant magnetic fields up to 7.5 T for the configurations: (a) $H\parallel c$ and $H\perp J$, (b) $H\perp c$ and $H\perp J$, and (c) $H\perp c$ and $H\parallel J$, respectively. As is well known, the resistive transition in the magnetic field always exhibits a broadening induced by a magnetic field and the broadening increases with rising field for any configuration. It can be clearly seen from Fig. 1 that the broadening of resistive transition for $H\parallel c$ and $H\perp J$, as shown in Fig. 1(a), is much wider than that for $H\perp J\perp c$ as shown in Fig. 1(b), although there exists a net Lorentz force in all of them. However, the direction of Lorentz force F_L is different for two such configurations; $F_L\perp c$ for the former and $F_L\parallel c$ for the latter. This result shows that the intrinsic pinning is dominant in GdBCO thin films. Comparing Fig. 1(b) with 1(c), we can find that there is hardly any difference of broadening of resistive transition despite a net Lorentz force for the former but no macroscopic Lorentz force for the latter. Such a weak dependence of orientation of transport current relative to magnetic field has been observed in field dependence of critical current density[11,19,20] and the distinguishable interpretations have been proposed.[11,19,21–23]

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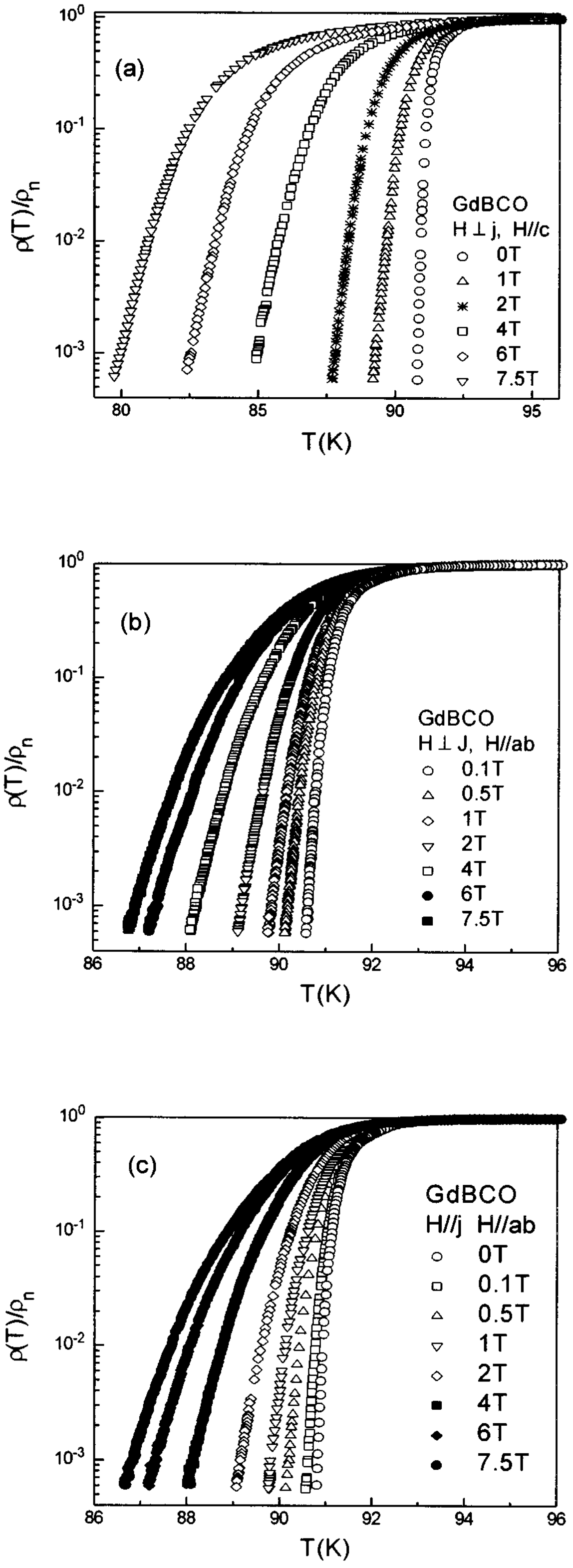

FIG. 1. The resistive transitions as a function of temperature at several constant magnetic fields up to 7.5 T for the configurations: (a) $H \| c$ axis and $H \perp J$, (b) $H \perp c$ axis and $H \perp J$, and (c) $H \perp c$ axis and $H \| J$.

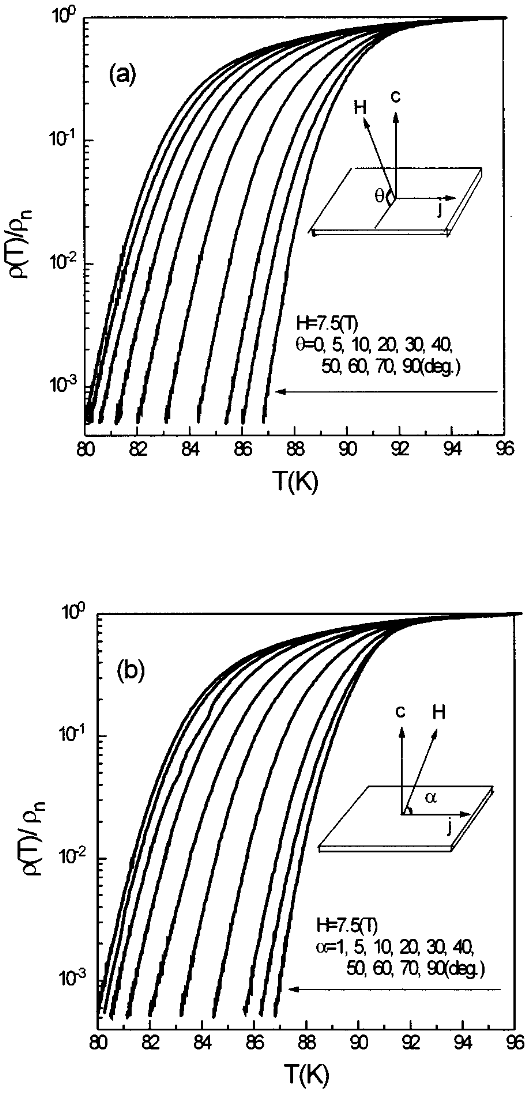

FIG. 2. The resistive transition as a function of temperature at the magnetic field of 7.5 T for various angles θ (a) and for various angles α (b). The angles θ and α were defined in the insets of (a) and (b), respectively.

In Figs. 2(a) and 2(b), we plot the resistive transition as a function of temperature for various angle θ and α at a constant magnetic field of 7.5 T, respectively. Where θ is the angle between direction of magnetic field and film surface, as shown in the inset of Fig. 2(a), and α is the angle between magnetic field and transport current, as shown in the inset of Fig. 2(b). It can be seen that the broadening behavior of resistive transition in Figs. 2(a) and 2(b) is almost identical. This indicates further a weak orientational dependence of magnetic field relative to transport current. From the experimental results in Figs. 1 and 2, we can conclude that the behaviors of resistive transition broadening are mainly dominated by the orientation of magnetic field with respect to crystal axis rather than to the direction of transport current.

IV. ANALYSIS AND DISCUSSION

A. Field dependence of activation energy

The standard technique to extract the activation energy U for vortex motion from the resistivity data is to plot the relation of $\ln \rho$ vs $1/T$ for different magnetic fields. Our experimental result in Fig. 1 shows a good agreement with the Arrhenius plot for resistivity below $0.01\rho_n$. In Fig. 3, we

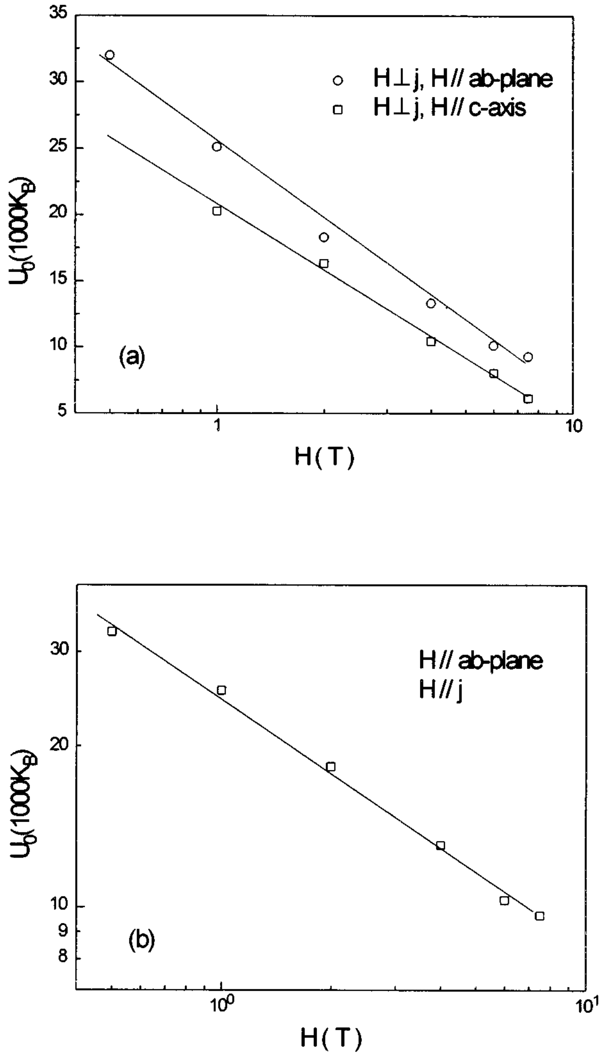

FIG. 3. The activated energy U for vortex motion as a function of magnetic field H, (a) for $H\|c$ axis and $H\perp J$, and for $H\perp c$ axis and $H\perp J$, and (b) for $H\perp c$ axis and $H\|J$.

plot U as a function of H for the configuration: (a) $H\|c$, $H\perp J$; and $H\perp c\perp J$; (b) $H\perp c$, $H\|J$. We find that for configuration (a), the field dependence is essentially logarithmic in the magnetic field up to 7.5 T investigated, as observed in YBCO/PrBCO multilayers film[24,25] and α-MoGe thin film.[26] Since a ln H dependence of the activation energy is often observed in superconductors, such as YBCO/PrBCO multilayers and α-MoGe thin film where the vortices are in the 2D region, this simple fact suggests that our GdBCO sample is in quasi-2D state. However for the configuration of $H\perp c$ and $H\|J$, in which there is no macroscopic Lorentz force, the field dependence of the activation energy follows a power law, $U(H)\propto H^{-\alpha}$, with the exponent α=0.53, as shown in Fig. 3(b). The power law in the field dependence of the activation energy was often observed in 3D regime of vortex. The comparison of the result in Fig. 3(b) with that in Fig. 3(a) shows that the Lorentz force acting on the vortex line may induce a crossover of vortex from 3D to quasi-2D vortex liquid. Qiu *et al.*[27] observed a crossover from 3D at low temperature to 2D vortex liquid state regime at high temperature in the field dependence of the activation energy for YBCO thin films. Eltsev, Holm, and Rapp[28] observed a crossover from 3D at high field to 2D at low field and argued that the ln H dependence of activation energy was in quantitative agreement with a model for thermal activation of vortex-antivortex pairs. The crossover of the vortex dimensionality suggests different mechanisms for activated vortex motion.

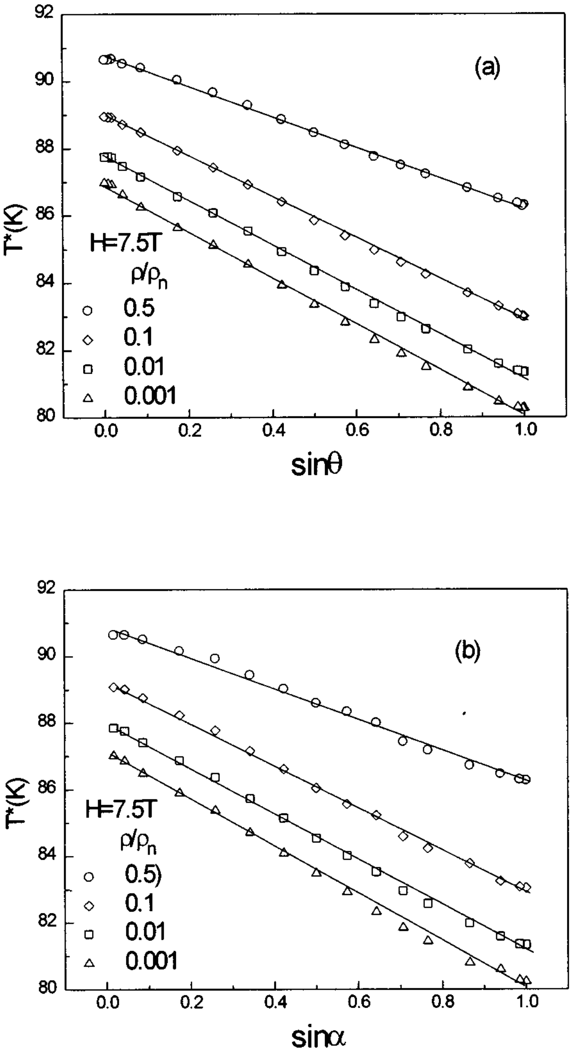

FIG. 4. The dependence of T^* on the angle sin θ (a) and sin α (b) at magnetic field of 7.5 T.

B. Angular dependence of T^*

In the measurement of resistive transition in magnetic field the onset of resistivity was usually used to measure critical field H^* and characteristic temperature T^*. The $H^*(T)$ or the $T^*(H)$ is essentially a irreversibility line (IL) due to the onset of resistivity as a result of flux motion. The data obtained from Fig. 2(a) could be plotted as the dependence of T^* on the angle θ at magnetic field of 7.5 T, as shown in Fig. 4(a). In fact, we have taken ρ/ρ_n=0.001, 0.01, 0.1, and 0.5 as the criteria to define T^*, where ρ_n is the extrapolated normal-state resistance. From Fig. 4(a) it can be clearly seen that the dependence of T^* on sinθ exhibits good linearity although there were distinct slopes for different criteria. The relation implies that the dissipation occurring in GdBCO thin films is only related to the magnetic field com-

TABLE I. The values of $T^*(0)$, $H_{\parallel}^*(0)$, and ε for criteria $\rho/\rho_n = 0.5$, 0.1, 0.01, and 0.001.

ρ/ρ_n	$T^*(0)$ (K)	$H_{\parallel}^*(0)$ (T)	ε
1/2	91.60	126.18	0.180
0.1	91.10	82.64	0.284
0.01	90.95	69.05	0.345
0.001	90.84	62.54	0.380

ponent parallel to the c axis, i.e., the dissipation is merely determined by motion of pancake vortex in CuO_2 planes. It is a typical 2D behavior, as predicted by Kes *et al.*[29] We find a similar behavior in the relation of T^* vs $\sin\alpha$, obtained from Fig. 2(b), as shown in Fig. 4(b).

Early, Tinkham[30] proposed a 2D model (curve with cusp at 0°). According to this 2D model, we have

$$T^* = T^*(0)\frac{H}{H_{\parallel}^*(0)(\sqrt{\sin^2\theta + 4\varepsilon^2\cos^2\theta} - \sin\theta)/2\varepsilon^2\cos^2\theta}, \tag{1}$$

where $T^*(0)$ is the characteristic temperature at $H = 0$, $H_{\parallel}^*(0)$ the critical field for $H \parallel c$ at 0 K, H a constant equal to the applied magnetic field, and $H = 7.5$ T in this work, $\varepsilon = H_{\perp}^*/H_{\parallel}^* = \sqrt{m_{ab}/m_c}$ anisotropy parameter. The values of $T^*(0)$, $H_{\parallel}^*(0)$, and ε for criteria $\rho/\rho_n = 0.5$, 0.1, 0.01, and 0.001 obtained from the above experimental data were listed, respectively, in Table I. For comparison of Eq. (1) with the experimental results, the data in Fig. 4(a) were replotted in Fig. 5 showing that the data could be approximately described by the Tinkham model, as shown by the solid line in Fig. 5. For the relation of T^* vs α, the experimental data also have similar behavior. Such a curve with cusp at 0° in the relation of H^* vs θ was observed for $Bi_2Sr_2CaCu_2O_y$ (Refs. 31 and 32), $YBa_2Cu_3O_{6.6}$,[33,34] respectively.

From the above results, it can be clearly seen that the 2D behavior of the vortex for the GdBCO epitaxial thin films has been observed in the field dependence of the activation energy and the angular dependence of T^*. In the layered structure superconducting system, a crossover from a 3D to a decoupled quasi-2D vortex liquid is possible under some circumstance such as magnetic field and temperature, etc. However, the problem is why YBCO exhibits a 3D behavior and GdBCO reveals a 2D property in the temperature above liquid nitrogen. It was well known that the GdBCO was isomorphic to YBCO and they had almost identical lattice constant. However an important difference between them was that the Gd^{3+} ion had a magnetic monument equal to $8.0\mu_B$ and the Y^{3+} ion was nonmagnetic. From such a simple fact we suggest that the 2D behavior of the vortex in the GdBCO epitaxial thin films might be due to the magnetic moment of the Gd^{3+} ion which suppresses the coupling of CuO_2 planes.

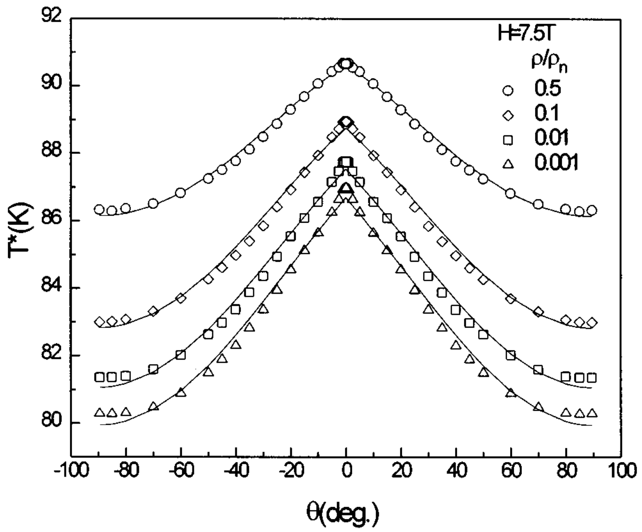

FIG. 5. The dependence of T^* on the angle θ.

V. CONCLUSION

We have systematically measured the resistive transition of the epitaxial GdBCO thin films in magnetic field up to 7.5 T. The field dependence of the activation energy exhibits a 2D behavior, i.e., it follows $U_0 \propto -\ln H$, for $H \perp c$ and $H \parallel c$ with $H \perp J$, and a 3D behavior, i.e., it follows $U_0 \propto H^{-\alpha}$, for $H \perp c$ and $H \parallel J$, showing a crossover from 3D to 2D vortex liquid induced by the Lorentz force. The angular dependence of the characteristic temperature T^* at the magnetic field of 7.5 T exhibits a curve with cusp near 0° showing a 2D property and can be approximately described by the Tinkham 2D model. Two-dimensional behavior of the vortex liquid is suggested to be due to the magnetic moment of Gd^{3+} which suppresses the coupling of the CuO_2 planes.

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