Magnetoresistance and a crossover from activated to diffusive dissipation in the mixed state for $YBa_2Cu_3O_{7-\delta}$ epitaxial thin films

Cao Xiaowen
High Magnetic Field Laboratory, Institute of Plasma Physics, Chinese Academy of Sciences, Hefei 230031, China

Wang Zhihe*
National Laboratory of Solid State Microstructures and Department of Physics, Nanjing University, Nanjing 210093, China

Xu Xiaojun
Structure Research Laboratory, University of Science and Technology of China, Hefei 230026, China
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We measure the magnetoresistance of $YBa_2Cu_3O_{7-\delta}$ epitaxial thin films as a function of angle θ between applied magnetic field H and the ab planes at a fixed temperature of 90 K below T_c, and a temperature T for $H \| c$ axis, respectively. The magnetoresistance curves for various angles θ show a three-dimensional anisotropic scaling behavior. The magnetoresistance curves reveal three distinguishable regions: a low-field nonlinear region, a high-field nonlinear one, and a linear one between them. The transition from a low-field nonlinear magnetoresistance to linear magnetoresistance shows a crossover from thermally activated to diffusive vortex motions as distinct from reported early. The H-T phase diagram of a vortex system is discussed.

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I. INTRODUCTION

The nature of flux motion and the energy dissipation of high-temperature superconductors in a mixed state are of considerable fundamental and technological importance, and continue to be subjects of considerable interest and controversy.[1–10] The reason for this interest is the existence of several vortex phases in H-T phase diagrams of these materials. These phases are separated by different kinds of thermodynamic transitions. It is known that in clean $YBa_2Cu_3O_{7-\delta}$ (YBCO) single crystals a vortex solid transforms into a liquid through a first-order phase transition. When correlated disorder is present in the materials, the transition from a vortex solid to a liquid is a second-order phase transition. In a range of temperatures and magnetic fields, the resistivity shows an activated behavior with a field-dependent activation energy $U(H)$ (Ref. 1) and a temperature-dependent one $U(T)$.[11] In higher ranges of temperature and field, the resistivity in a mixed state exhibits flux flow, a diffusive flux motion behavior.[8,9,12,13] For temperatures above T_c, the resistivity as a function of an applied field shows a normal-state magnetoresistance.[14] However, the nature and behavior of vortex liquid are still unknown.

In this paper, we investigate the angle and temperature dependencies of the magnetoresistance, and a crossover from activated to diffusive dissipation. We also discuss a H-T phase diagram of a vortex system for an YBCO epitaxial film in a mixed state below T_c.

Experiment

The high-quality c-axis-orientated YBCO epitaxial thin film used in this study was deposited onto the (00l) surface of a single crystal $SrTiO_3$ by dc sputtering. An x-ray-diffraction pattern showed only the (00l) peaks, and the full width at half-maximum of the rocking curve for the (005) diffraction peak was less than 0.3°. A film with the thickness of 300 nm was patterned into a narrow bridge 20 μm wide and 100 μm long. The current and voltage leads were attached by indium solder on silver terminals deposited onto the surface of the film. The ac susceptibility as a function of temperature showed a superconducting T_c of 91.6 K, and the transition width ΔT_c, defined by a temperature interval from 90% χ'_{ac} to 10% χ'_{ac}, is smaller than 0.3 K. This is consistent with the result of electrical measurements, as reported in Ref. 15. The critical current density J_c, defined as the current density at which a voltage of 1 μV appeared, was 3.8×10^6 A/cm^2 at 77 K and zero applied magnetic field.

The magnetoresistance of the film was measured in a variable temperature insert by a four-probe technique. The current density in the electrical measurement is 167 A/cm^2. The sample was held on a rotatable holder to vary the angle between the film surface and the magnetic field with a 0.1° resolution. The temperature was measured by a calibrated Rh-Fe resistance thermometer, corrected for the effect of magnetic field and controlled by a DRC-93CA temperature controller with an accuracy of 10 mK. A magnetic field of up to 10 T was supplied by a water-cooled solenoid magnet system.

Figure 1 plots the magnetoresistance as a function of magnetic field up to 8 T for various angles, $\theta=0°–90°$, where θ is the angle between the magnetic field and the ab planes, as defined in the inset of Fig. 1, at a fixed temperature of 90 K. We can distinguish three regions: a nonlinear region at low field, one at high field, and a linear one between them. They expand in a wider field range with decreasing angle θ, respectively, also showing a strongly anisotropic dissipation behavior. In the field dependence of the resistivity for $H \| c$ axis at several fixed temperatures, as shown in Fig. 2, three

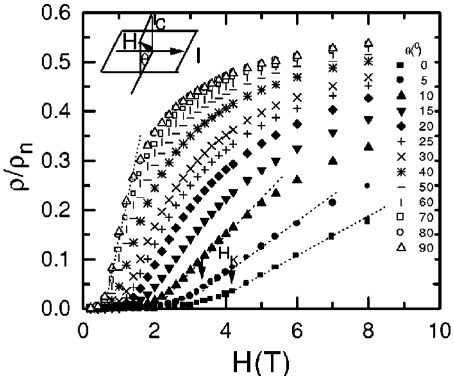

FIG. 1. Field dependence of the resistivity for various angles θ at a fixed temperature of 90 K, H_K separates the regions of low-field nonlinear dependence ($H<H_K$) and linear field dependence ($H>H_K$), showing that a crossover from activated to diffusive dissipation behavior occurs at H_K. The inset shows the definition of angle θ.

similar regions can also be distinguished. However, they appear in a higher field range and expand on a wider field range with reducing temperature, respectively.

II. ANALYSIS AND DISCUSSIONS

A. 3D scaling behavior of angle-dependent magnetoresistance curves

YBCO is known to be an intermediately anisotropic superconductor with an anisotropy factor $\gamma=\sqrt{m_c/m_{ab}}=5$–9,[16] and exhibits, in general, three-dimensional (3D) anisotropic properties. According to Blatter *et al.*,[17] the dependence of a physical parameter as a function of angle and magnetic field should scale as the product $\varepsilon(\theta)H$, where the factor $\varepsilon(\theta)$ has a form

$$\varepsilon(\theta)=\sqrt{\sin^2\theta+\cos^2\theta/\gamma^2}. \tag{1}$$

If we properly normalize the magnetoresistance as a function of the magnetic field H and angle θ by an effective field $\varepsilon(\theta)H$ with $\gamma=7$, all the curves in Fig. 1 could converge

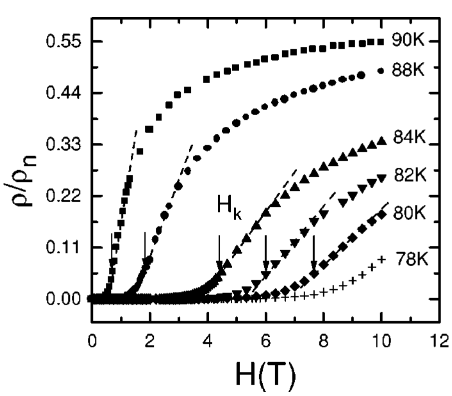

FIG. 2. Field dependence of the resistivity at several fixed temperatures. H_K separates the low-field nonlinear ($H<H_K$) dependence shift and the linear ($H>H_K$) field dependence shift toward low field with reducing temperature.

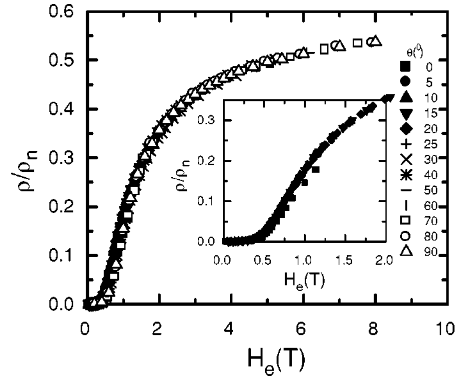

FIG. 3. Normalized magnetoresistance by $\varepsilon(\theta)H$ as a function of magnetic field for various angles θ. All the curves in Fig. 1 converge onto one curve, showing a 3D anisotropic scaling behavior. The inset shows that the scaling behavior at low field is not as good as that at high field, due to activation.

onto one curve, as shown in Fig. 3, showing an anisotropic 3D scaling behavior. However, it should be noted that the scaling law is more valid at high field (fluctuation regime) than at low field (activated regime), as shown in the inset of Fig. 3.

On the other hand, the scaling behavior of the magnetoresistance as described by Blatter *et al.*'s approach[17] is still controversial. As an example, in Ref. 18 the scaling of ρ_{xx} by Blatter *et al.*'s approach is shown to fall in the field region where ρ_{xx} is negative.[18]

B. Activated-diffusive crossover and *H*-*T* phase diagram

As mentioned above, in the magnetoresistance curves shown in Fig. 1, three regions—a nonlinear region with a positive curvature at low field, one with negative curvature at high field, and a linear one between them—can be distinguished. The low-field nonlinear region may be attributed to the dissipation caused by flux creep, and was discussed in detail by Chien *et al.*[11] in terms of $\rho=\rho_0\exp(-U/H)$. Here we discuss it no further.

The linear resistance as a function of magnetic field always ranges from $\rho/\rho_n=0.045$ to 0.18, although it expands in a wider field range with decreasing angle θ, as seen in Fig. 1. The constant value of the linear resistance at various angles θ might be related to a constant macroscopic Lorentz force and a fixed measurement temperature.

It was well known that the dissipation process in the diffusive regime is characterized by a linear resistivity versus magnetic field behavior typical of the flux flow regime[19,20]

$$\rho=\rho_n H/H_{c2}. \tag{2}$$

Obviously, the above-mentioned linear relation of ρ/ρ_n vs H in Figs. 1 and 2 is in agreement with Eq. (2), showing a flux flow behavior: a diffusive flux motion. This shows that a crossover from thermally activated to diffusive flux motions occurs between the low-field nonlinear and linear magnetoresistances. The linear field dependence of the magnetoresistance was previously observed in YBCO.[10] With increasing magnetic field, the magnetoresistance deviates from linearity, as seen in Figs. 1 and 2. The deviation was accounted for by the fluctuation of the superconducting order parameter.[11] However, it is notable that a crossover from activated to diffusive flux motion was defined as a transition from linear to high-field nonlinear magnetoresistance, i.e., the crossover field H_K separated the regions of strong ($H<H_K$) and weak ($H>H_k$) field dependences, in Ref. 11. In addition, the fluctuation is enhanced with increasing anisotropy; as a result, the fluctuation region expands toward a low field and the linear region may disappear, as observed in $YBa_2Cu_3O_7/PrBa_2Cu_3O_7$ multilayers[21,22] and $Bi_2Sr_2CaCu_2O_y$ samples.[23,24] Under this condition, the magnetoresistance curves can be scaled by 2D Larkin theory,[25] and the crossover field H_K could be defined as a field at which the curvature of magnetoresistances transits from positive at low field to negative at high field.

It is known that the activation energy for flux creep in YBCO is smaller by 1–2 orders of magnitude than that in low-temperature superconductors, and decreases with increasing temperature and magnetic field.[7,26] From such a small magnitude of the activation energy, and its decrease with temperature or field, one may predict a temperature T_K or a field H_K at which the activation energy is equal to thermal energy, $U=kT$. Below T_K or H_K, the activation energy is larger than the thermal energy; thus the flux motion occurs by thermally activated flux motion. Conversely, above T_K or H_K, the thermal energy is larger than the activation energy, and the flux motions become diffusive,[27] i.e., are characterized by the flux flow. This implies that a crossover from thermally activated to diffusive flux motion occurs at T_K or H_K. It could be surmised, from the above argument, that the thermally activated flux creep resistivity should be equal to the flux flow resistivity,[28] $\rho_{creep}=\rho_{flow}$, at T_K or H_K. This means that a crossover from a pinned to an unpinned regime takes place at T_K or H_K. According to Vinokur *et al.*[7] at T_K or H_K the characteristic time of the plastic deformation of a vortex, t_{pl}, is equal to the characteristic time of pinning, t_{pin}.

The above discussion shows that there exists a phase boundary which is labeled as the H_K line above the irreversibility line H_{irr}. The temperature dependence of H_K, taken from Eq. (2), is plotted in Fig. 4 and follows $H_K \propto (1-t)^n$ with $n=1.27$. The H_K line divides the vortex liquid into two regimes: an activated regime and a diffusive regime.

It is known from Eq. (2) that the slope of linear magnetoresistance in Fig. 2 is equal to $1/H_{c2}$, and increases with increasing temperature. Therefore, the upper critical field at various temperatures can be deduced. The temperature dependence of the mean field H_{c2} deduced from the slope of linear magnetoresistance in Fig. 2 is plotted in Fig. 4. It can be seen that $H_{c2}(T)$ exhibits a good linearity with a slope 1.46 T/K in the temperature range studied. According to GLAG theory,[29] $H_{c2}(0)=0.69T_c(-dH_{c2}/dT)_{T\simeq T_c}$; therefore, the upper critical field at 0 K, $H_{c2}(0)$, can be estimated to be about 92 T. For comparison, an irreversibility line (zero resistance criteria) determined on an identical sample in this study is also plotted in Fig. 4.

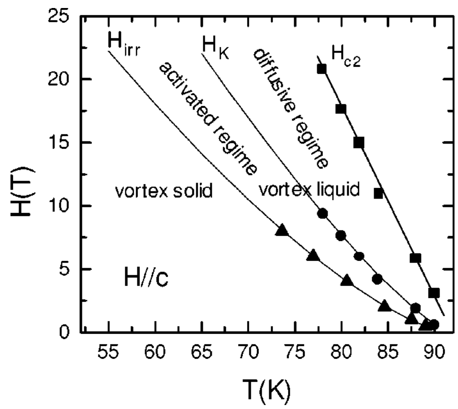

FIG. 4. HT phase diagram of the vortex system in a YBCO epitaxial thin film. The H_{c2} line exhibits a linear behavior. The solid line, $H_K \propto (1-t)^{1.27}$, is a fit to the data for $H_K(T)$. The irreversibility line H_{irr}, determined by the criterion of $\rho=0$, follows $H_{irr} \propto (1-t)^{3/2}$.

Our results suggest the following picture. When an applied magnetic field increases from zero at fixed temperature, the vortex solid undergoes a melting transition at the irreversibility field, H_{irr}. The melting transition is a first-order phase transition for clean single crystals,[30–32] and a second-order phase transition for correlated disordered materials.[33–36] Above and below H_{irr}, the critical current density J_c changes dramatically, and follows a distinct magnetic field and temperature dependences.[37] When the applied magnetic field increases further, the vortex liquid undergoes a crossover from activated to diffusive dissipations at a field H_K. Between H_{irr} and H_K, as shown in Fig. 4, the vortex possesses a pinning behavior,[38,39] showing a correlated vortex liquid state. When H_K is exceeded, the vortex liquid undergoes a transition from a correlated to an uncorrelated liquid state. The vortex motion is activated below H_K and is diffusive above H_K. Between H_K and H_{c2}, the vortex motion is characterized by free flow, showing a diffusive flux motion.

In the resistive transition as a function of temperature, according to Palstra *et al.*,[26] T_K was taken as a temperature at which the slope of the Arrhenius curve, $d\ln\rho/dT^{-1}$, versus T exhibits a sharp increase with decreasing temperature. Sometimes the resistance curve can manifest itself as a shoulder[6] or a kink for untwinned single crystals[7,31,40] at T_K. However, the kink has been believed to be associated with a melting of vortex lattice, a first-order phase transition.[12,31] The above arguments imply that the crossover line from thermally activated to diffusive flux motion is consistent with the melting line of a vortex lattice; thus the vortex liquid above a first-order phase transition line was certainly unpinned for clean material such as an untwinned single crystal. As a result, the flux motions above the first-order phase transition were characterized by a diffusive motion, and demonstrated by the linear voltage-current characteristic.[12] However, in oriented twinned crystals in an inclined magnetic field, the transport properties of a vortex liquid above the first-order phase transition at angles well beyond the so-called depinning angle θ_d showed that the vortex liquid remains correlated,[40,41] quite different from those observed in clean samples. On the other hand, for sufficiently good pinning material such as thin films and single crystals with defects, the vortex liquid above an irreversibility line (vortex glass line) can distinguish pinned and unpinned vortex liquids.[34] This means that there exists a phase boundary[39] above the irreversibility line, and that this phase boundary shows a crossover from thermally activated to diffusive vortex motions.[7,11,26]

III. CONCLUSION

We have measured the magnetoresistance as a function of magnetic field and angle θ and temperature below T_c for an epitaxial YBCO thin film. The magnetoresistance curves for various angles θ at 90 K show a 3D anisotropic scaling behavior; as a result, all the curves could be scaled onto one curve by a product $\varepsilon(\theta)H$, where $\varepsilon(\theta)=\sqrt{\sin^2\theta+\cos^2\theta/\gamma^2}$ and the anisotropy factor $\gamma=7$. The magnetoresistance curves can be divided into three regions: a low-field nonlinear region, a high-field nonlinear one, and a linear one between them. The low-field nonlinear magnetoresistance is caused by flux creep, an activated flux motion, while the linear magnetoresistance shows a flux flow behavior: diffusive flux motion. Therefore, the transition from a low-field nonlinear region to a linear one reveals a crossover from thermally activated to diffusive vortex motion. The high-field nonlinear behavior was believed to be due to the thermal fluctuation of superconducting order parameter. The H-T phase diagram, including $H_K(T)$ determined by an activated-diffusive crossover and $H_{c2}(T)$ deduced from linear magnetoresistances as a function of temperature, was discussed.

*Corresponding author. Email address: zhwang@netra.nju.edu.cn Fax: +86-25-3595535

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