Columnar-Defect-Induced Resistivity Minima and Bose Glass Scaling of Linear Dissipation in $Tl_2Ba_2CaCu_2O_8$ Epitaxial Films

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(Received 7 October 1993)

The angular dependence of the flux flow resistivity $\rho(\Theta,T,H)$ in $Tl_2Ba_2CaCu_2O_8$ is measured as the external field is brought into alignment with heavy-ion-irradiation-induced columnar defects. A flux lock-in state, manifested as a minimum in the $\rho(\Theta,T,H)$ data, evolves as the system is cooled deeper into the mixed state. This observation provides compelling evidence for nonzero line tension of vortices in this highly anisotropic superconductor. The temperature dependence of the flux flow resistivity at perfect alignment is consistent with Bose glass theory of vortex localization at columnar defects.

PACS numbers: 74.60.Ge, 74.72.Fq

The mapping of Abrikosov vortices onto a 2D random array of columnar defects leads to interesting phases and crossovers in the mixed state of high temperature superconductors [1-3]. In addition to a strong flux pinning at columnar defects, an issue of profound technological importance and subject of numerous recent publications [4], the Bose glass theory [1] for flux pinning by columnar defects predicts a minimum in the linear resistivity as the flux lines are aligned parallel to the defects. The evolution of this minimum as one goes deeper into the mixed state is governed by a *transverse Meissner effect* [1,5] in the Bose glass regime where barriers for vortex loop excitations grow with the decreasing current. The theory also predicts power law behaviors characterized by a set of exponents, for linear and nonlinear dissipations. In this respect, it is similar to the vortex glass theory of a second-order phase transition driven by weak point disorder [6]. The linear resistivity vanishes on approaching the Bose glass temperature (T_{BG}) from above as

$$\rho(T) \sim (T-T_{BG})v'(z'-2)\,. \qquad (1)$$

At T_{BG}, the electric field (E) vs current density (J) isotherms follow the following power law:

$$E \sim J^{(z'+1)/3}\,. \qquad (2)$$

The critical exponents v' and z' are as yet undetermined.

While most of these predictions remain to be tested, there is another issue that has been a cause of concern regarding the applicability of this theory to highly anisotropic systems such as $Tl_2Ba_2CaCu_2O_8$ (Tl-2212) and $Bi_2Sr_2CaCu_2O_8$ (Bi-2212) cuprates. For these layered compounds, it has often been speculated that the concept of a line vortex based on the Ginzberg-Landau mass tensor or interlayer Josephson currents may not apply at high temperatures where the vortices may be truly two-dimensional [7]. In such an extreme limit of decoupling, a minimum in the resistivity as the external field is made parallel to the defects is not expected.

In this paper we describe the applicability of the Bose glass theory to linear dissipation in Tl-2212 films containing radiation-induced columnar defects. For inductions $\mathbf{B} \lesssim \mathbf{B}_\phi$ $(=1.2\phi_0\phi)$, where ϕ_0 and ϕ are flux quantum and defect density, respectively, we observe a distinct minimum in the linear resistivity as the external field is brought into alignment with the columns. The onset of this flux lock-in transition occurs in a dynamic vortex state where dissipation is strong. The flux flow resistivity in the configuration for perfect alignment vanishes following Eq. (1). Interestingly, however, this dependence persists even when $\mathbf{B} > \mathbf{B}_\phi$, indicating the importance of collective pinning in the limit of dilute disorder. We consider these results novel as they show the following features: (a) evolution of a lock-in state on cooling through the flux liquid, (b) evidence for a nonzero line tension of vortices in this highly anisotropic system, and (c) Bose glass scaling of the linear resistivity.

Thin films of Tl-2212 were prepared on (100) $LaAlO_3$ substrates by a two-step process that involved rf sputtering of a BaCaCuO target followed by annealing in Tl_2O vapors. X-ray rocking curve analysis of the films showed epitaxial growth with the c axis normal to the plane of the substrate. Details of film preparation and x-ray based characterization are described elsewhere [8]. Two films of thickness $\sim$550 nm were photolithographically patterned into a six probe geometry for simultaneous measurements of longitudinal and Hall resistivities. A standard ac lock-in technique operated at a 270 A/cm^2 excitation current density was used for this purpose. The samples were mounted on a worm-gear based goniometer assembly that allowed angular resolution $\sim$0.225°. The measurements were carried out in a superconducting solenoid.

Columnar defects of diameter 50-70 nm were created by irradiating the samples with 276 MeV silver ions [9] at an angle 2° off the c axis in order to avoid possible channeling. The energy loss rate ($\sim$28 keV/nm) and thermalization distance ($\sim$14 μm) of these ions in Tl-2212 are well above the threshold required for the production of continuous tracks across the thickness of the film.

In the inset of Fig. 1 we show the geometry of our ex-

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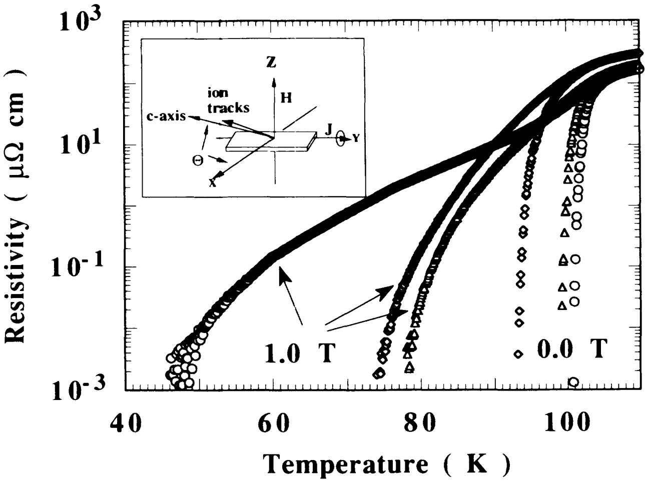

FIG. 1. Temperature dependence of resistivity at 0 and 1 T before (circles) and after irradiation at ϕ_1 (triangles) and ϕ_2 (diamonds). Measurements were made with H∥c ($\Theta=90°$). Inset shows the geometry of measurements.

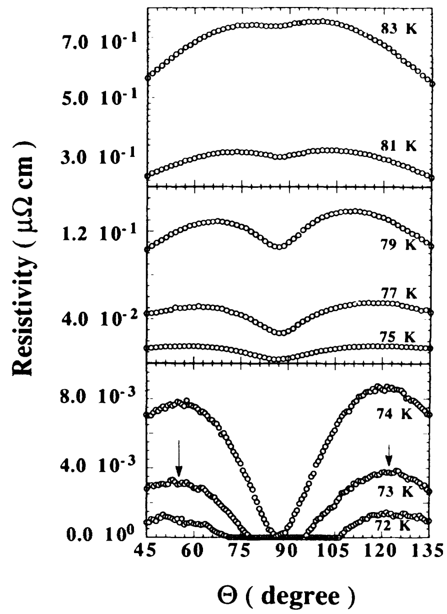

FIG. 2. Angular dependence of resistivity at 1 T after irradiating the sample at fluence ϕ_2. Arrows define Θ_a (see text). Note the three separate Y scales.

periment and the relevant vectors involved in the problem. The transport current **J** and applied field **H** were always orthogonal to each other for maximum Lorentz force on the vortices. The angle Θ was varied from 45° to 135°; $\Theta=88°$ and 90° correspond to $\mathbf{H}_{\parallel}$ columns and **H**∥**c**, respectively. The main body of Fig. 1 shows the longitudinal resistivity of a film measured at 0 and 1 T field before and after irradiation. The fluence $\phi_1=3\times10^{10}$ ions/cm^2 and ϕ_2 (cumulative)$=1.3\times10^{11}$ ions/cm^2 used here correspond to matching fields ($\mathbf{B}_\phi$) of 0.7 and 3.1 T, respectively.

While the zero field T_c of the pristine material is 104.5 K (midpoint), in a 1 T field directed parallel to the c axis ($\Theta=90°$) the dissipation becomes detectable at ~48 K. This enormous broadening of the resistive transition is a characteristic feature of these highly anisotropic cuprates [10]. At the first level of fluence ϕ_1, however, the onset of dissipation shifts to higher temperatures by ~30 K. This is a clear manifestation of flux localization at the columnar defects. After the fluence ϕ_2, the onset of flux flow resistivity shifts to lower temperatures. Since the defects outnumber flux lines by a factor of 3 at this fluence, there are two possible causes for this reentrant behavior. The first is a global suppression of the superconducting order parameter in the material as a result of radiation damage. This is manifested as a reduction of the zero field critical temperature $T_{c\phi2}$ (midpoint) by ~2.5 K and a factor of 2 increase in the normal state resistivity of the material. An equally nontrivial consequence of the higher defect density is a wider variation in the depth (U_0) of the cylindrical wells which model columnar pins. This results from a finite spread in the size of the ion-induced tracks [9]. When the dispersion γ in the well depths becomes of the order of U_0, it promotes variable range hopping (VRH) of vortices to distant unoccupied defects. At low current densities the VRH leads to linear resistivity [1,5,11]. This situation is similar to Mott variable range hopping in the Anderson localized states of a doped semiconductor [12].

We now look for alignment effects in dissipation when the sample is rotated with respect to the direction of the external field. Figure 2 shows the angular scans taken at several temperatures in a 1 T field. The resistivity contours at temperatures >83 K were symmetric around $\Theta=90°$. At 83 K, however, the resistivity shows a dip around $\Theta=90°$ which develops into a well-defined minimum as we go to lower and lower temperatures. Before we proceed to discuss the angular dependence of resistivity, it is important to state that extended defects such as grain boundaries, screw dislocations, etc., that have a perpendicular orientation to the substrate, may contribute to the observed minimum. However, ρ vs Θ measurements on the unirradiated material did not show such pinning effects to the lowest levels of dissipation. There are three distinct features associated with the flux lock-in transition seen in Fig. 2: (a) The minima have a distinct asymmetry around the $\Theta=88°$ axis due to the fact that the columnar defects were made 2° off the c axis; (b) the minima are seen up to fairly high levels of dissipation ($\rho<1$ $\mu\Omega$ cm); and (c) at sufficiently low temperatures, the linear resistivity is unmeasurable ($\rho<10^{-3}$ $\mu\Omega$ cm) over a range of angles around the axis of the columns. In the angular scans taken at 3 T (Fig. 3), however, the resistivity at 88° remains higher than its values at $\Theta=45°$ and 135°. If we define an accommodation angle Θ_a as half of the angular width between resistivity maxima (as marked by arrows in Figs. 2 and 3), we

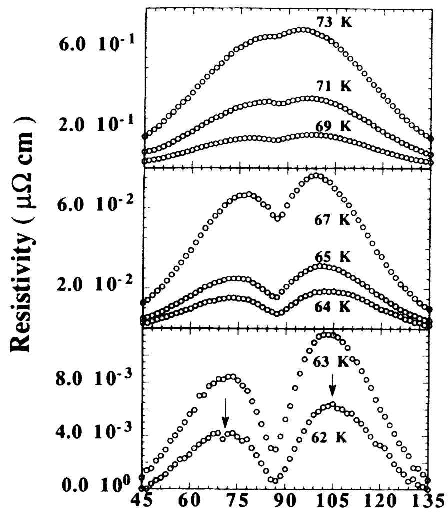

FIG. 3. Angular dependence of resistivity measured at an applied field of 3 T after irradiating the sample at fluence ϕ_2. Note the three separate Y scales.

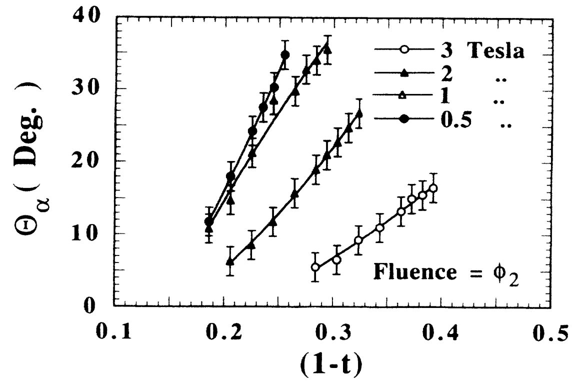

FIG. 4. The accommodation angle Θ_a plotted as a function of $(1-t)$ for a fluence ϕ_2 and applied fields of 0.5, 1, 2, and 3 T.

find that Θ_a is much larger at fields where vortices are outnumbered by the defects. The variation of Θ_a as a function of $(1-t)$, where $t=T/T_{c\phi 2}$, is shown in Fig. 4 for measurements taken at 0.5, 1, 2, and 3 T after the cumulative fluence ϕ_2. A smooth extrapolation of these curves to $\Theta_a=0$ suggests that the onset of pinning occurs at $t\sim 0.85$.

The onset of dissipation as the magnetic field is tilted away from the axis of the columns has been discussed in the framework of the Bose glass theory. This problem is somewhat similar to the persistence of a lock-in state over finite angles as the external field is tilted away from the **H**‖**ab** plane configuration [13]. An analogous situation is encompassed in the pinning of flux lines by twin planes in $YBa_2Cu_3O_7$ [14]. In the case of columnar defects, tilting of the flux lines away from alignment would lead to formation of superkinks which cost elastic energy. Thus, there is a critical value for the perpendicular component of the field (**H**sinΘ), below which the flux lines remain locked in. At higher temperatures or in the Bose glass phase but with higher tilts, the field penetrates transverse to the columns via formation of superkinks. This process is governed by variable range hopping to a distant column with compatible energy. The energetics of the tilt for a single vortex shows that beyond a certain accommodation angle Θ_a defined as $\Theta_a\sim(U_0/\tilde{\varepsilon}_1)^{1/2}$, where the tilt energy $\tilde{\varepsilon}_1$ is expressed in Ginzberg-Landau parameters as $\tilde{\varepsilon}_1 \sim(M_\perp/M_z)(\phi_0/4\pi\lambda_{ab})^2\ln(\lambda_{ab}/\xi_{ab})$, the transverse field penetrates indiscriminately. A strong anisotropy $(M_\perp/M_z\ll 1)$ in the case of Tl-2212 would reduce the line tension significantly. If the vortices in this system are viewed as 2D Josephson coupled, we still expect a finite line tension due to the interplanar strings [3,13]. The tilt modulus is effectively zero in the case of a decoupled system leading to $\Theta_a\sim\infty$. In this case, the columnar defects would lead to an overall gain in pinning without any angular selectivity. While the general features of the data shown in Figs. 2 and 3 are consistent with the above arguments, a quantitative comparison of our results with theory would require renormalization of the single vortex Θ_a for many-body effects in the system.

A question of significant interest is how far in the inequality $\mathbf{B}>\mathbf{B}_\phi$ the alignment effect prevails. Angular scans taken at 3 T after irradiation at ϕ_1 showed no signs of a minimum to the lowest levels of dissipation. Similar measurements at 4 T and ϕ_2 had only a small depression centered at $\Theta=88°$ [15]. This null result, however, does not imply the absence of any pinning in the system. A finite pinning at these flux densities is seen in the shift of the ρ vs T scans to higher temperatures. We address this issue below.

In the framework of the Bose glass theory for the mixed state in high T_c cuprates, the linear resistivity and

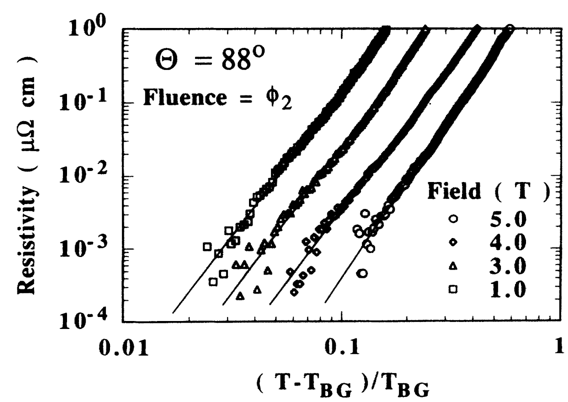

FIG. 5. Plots of $\rho(T,\Theta=88°)$ measured at 1, 3, 4, and 5 T after the fluence ϕ_2 vs $(T-T_{BG})/T_{BG}$. Solid lines are least-squares fits to Eq. (1).

TABLE I. The exponent $\nu'(z'-2)$ and T_{BG} obtained from $\rho(T,\Theta=88^\circ)$ data. The errors in the determination of the exponent and T_{BG} are ± 0.3 and ± 0.25 K, respectively.

Field (T)	$\nu'(z'-2)$	T_{BG} (K)	Field (T)	$\nu'(z'-2)$	T_{BG} (K)
0.5	4.5	73.25	2.5	4.2	65.25
1.0	3.9	72.25	3.0	4.1	59.75
1.5	3.8	72.0	4.0	4.0	48.0
2.0	3.6	70.25	5.0	4.3	39.0

the $E-J$ isotherms are expected to follow Eqs. (1) and (2). We have fitted the linear resistivity at $\Theta=88^\circ$ in the range $0 \leq \rho(T) \leq 1$ $\mu\Omega$ cm where a distinct minimum is observed in the angular scans to the Bose glass power law [Eq. (1)]. Figure 5 shows the plots of $\rho(T)$ vs $(T-T_{BG})/T_{BG}$, where T_{BG} has been taken as a free variable for the best least-squares linear fit to the data. Only a limited number of curves are shown for the sake of clarity. In Table I we list the values of $\nu'(z'-2)$ and T_{BG} deduced from the fits. Measurements [15] of $E-J$ characteristics at several temperatures spanning linear and nonlinear dissipation show that at the T_{BG} deduced from Fig. 5, the data follow Eq. (2) with $(1+z')/3 = 1.8 \pm 0.1$. Combining these two measurements we obtain $\nu' \sim 1.8 \pm 0.2$ and $z' \sim 4.4 \pm 0.3$.

In the regime of $\mathbf{B} > \mathbf{B}_\phi$ the vortices which go into the interstitial space between columnar defects would be bound to those trapped in the pinning sites. The observation of a power law behavior for $\rho(T)$ in this collective pinning regime appears to be governed by the same correlation lengths as in the Bose glass phase.

In conclusion, we have provided the first clear evidence of a nonzero line tension of vortices in a highly anisotropic superconductor. For $\mathbf{B} \lesssim \mathbf{B}_\phi$, this leads to a flux lock-in state when the vortices are aligned parallel to the columnar defects. This lock-in transition is characterized by a minimum in the angular dependence of the resistivity and is consistent with the Bose glass theory of dissipation in these materials. Our results also show that the temperature dependence of the linear resistivity is in agreement with the predictions of this theory.

We thank D. R. Nelson, V. M. Vinokur, T. Hwa, and D. O. Welch for helpful discussions. Our thanks are also due to K. G. Lynn for his input in initiating this collaboration and Y. Zhu and L. A. Parisi for help in TEM based dosimetry and film preparation, respectively. This research has been supported by the U.S. Department of Energy, Division of Materials Science, Office of Basic Energy Science under Contract No. DE-AC02-76CH00016.

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