Direct Observation of Dissipative Flux Motion and Pinning by Twin Boundaries in $YBa_2Cu_3O_{7-\delta}$ Single Crystals

W. K. Kwok, U. Welp, G. W. Crabtree, K. G. Vandervoort,[a] R. Hulscher, and J. Z. Liu[b]

Materials Science Division, Argonne National Laboratory, Argonne, Illinois 60439

(Received 28 November 1989)

We present the first direct observation of Lorentz-force-induced dissipative flux motion and the effect of twin boundaries as pinning centers in a single crystal of $YBa_2Cu_3O_{7-\delta}$ with twin planes oriented in a single direction.

PACS numbers: 74.70.Ya, 74.60.Ec

The broad resistive transition of high-T_c copper-oxide superconductors in a magnetic field has been a topic of great interest. Early measurements showed a large featureless broadening which was qualitatively fitted by Tinkham[1] using a flux-flow model based on a network of Josephson junctions. In later measurements the resistive broadening has been described by thermally activated flux-creep or flux-flow behavior.[2] However, the expected angular dependence of these phenomena on the relative orientation of transport current and magnetic field has not been detected so far, leaving this interpretation controversial.[3] In this Letter we present careful measurements of the resistive transition of $YBa_2Cu_3O_{7-\delta}$ single crystals in magnetic fields applied in the *a-b* plane. We observe for the first time, a resistive contribution which shows the expected angular dependence, thus giving strong evidence for the presence of flux-motion effects. However, the flux-motion contribution is only a fraction of the total resistivity below T_c.

A major question in all flux-motion models is the nature of the pinning center. Various defects have been suggested including oxygen-vacancy clusters, growth flux inclusions, second phases, and twin boundaries. Here we present clear evidence that the twin-boundary planes act as strong pinning centers in the flux-flow regime when they are aligned parallel with the magnetic field.

The sample was prepared by a self-flux method described elsewhere[4] which yielded platelet single crystals. A crystal with dimensions $0.8\times0.6\times0.04$ mm^3 containing twinning planes oriented in only one direction as determined with a polarized light microscope was selected from this batch. ac resistivity was measured by a four-probe technique with gold wires attached to the sample with silver paint and with typical measuring current densities of $J < 16$ A/cm^2 at a frequency of 17 Hz.

In the present experiment, the transport current was applied parallel to the crystallographic *a* (*b*) direction. The magnetic field was applied in the *a-b* plane and the crystal was rotated about its *c* axis from the maximum Lorentz-force configuration ($H \perp I$) to the nominally zero-Lorentz-force configuration ($H \parallel I$). The high upper-critical-field slope in the *a-b* plane of -10 T/K (Ref. 5) restricts measurements of the field dependence of the superconduting properties along these directions to a narrow temperature range. However, this geometry is favorable for the study of Lorentz-force-induced flux motion since within the *a-b* plane the superconducting properties of $YBa_2Cu_3O_{7-\delta}$ are almost isotropic.[6] Therefore, the orientation of the magnetic field with respect to the transport current can be varied without encountering anisotropy of the superconducting properties. The angular resolution is ±1° about the *c* axis with a misorientation of the magnetic field of less than 0.5° off the *a-b* plane.

Figure 1 shows the resistive transition curves in a magnetic field of 1.5 T with the current-field orientation $H \parallel I$ and $H \perp I$ and a measurement current density of 0.3 A/cm^2. For comparison, a zero-field transition curve is also included. In zero field, the resistive transition is extremely sharp with a midpoint $T_c = 92.49$ K and a width of $\Delta T_c(10\%\text{–}90\%) < 200$ mK. The application of a magnetic field leads to broad resistive transitions even in the nominal force-free configuration ($H \parallel I$), as has been

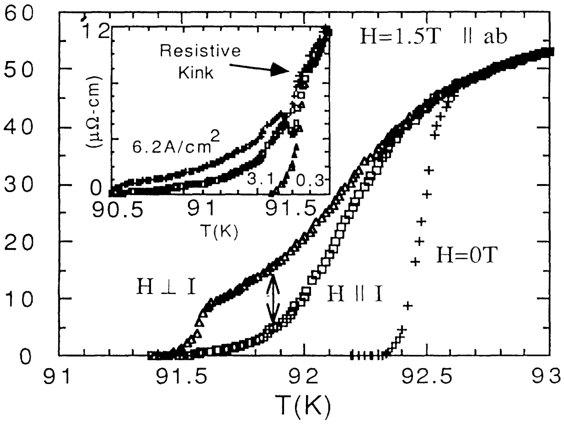

FIG. 1. Resistive transition in zero field and 1.5 T for the $H \parallel I$ and $H \perp I$ current-field orientation along the *a-b* plane of the crystal. The excess resistivity indicated by the arrow is attributed to Lorentz-force-driven flux motion. Inset: Current dependence of the resistive transition in the region of the kink for $H = 1.5$ T perpendicular to I.

reported earlier.[3] The origin of this loss mechanism has not yet been determined; flux cutting, curved flux lines[7] and flux entanglement,[8] fluctuations,[9] and Josephson networks[1] have been proposed as possible origins. In the $H \perp I$ configuration we observe a considerably higher resistance. This *excess resistivity* between the $H \perp I$ and $H \parallel I$ configuration (indicated by the arrow in Fig. 1) can be attributed to Lorentz-force-driven flux motion, as we show in detail below. The *excess resistivity* begins at ~92.4 K close to the magnetically determined transition temperature in this field[5] and gradually increases with lower temperatures down to 91.6 K where a kink appears in the $H \perp I$ resistivity curve. Below this kink, the *excess resistivity* rapidly decreases to zero, reaching zero resistivity at the same temperature as the $H \parallel I$ curve.

The origins of the broadening in the $H \parallel I$ configuration and the kink are not yet understood, although one can rule out pinning due to twinning planes since both the kink and the broadening are also observed in untwinned single crystals.[10] The temperature at which the kink occurs separates the resistive behavior into two regions as shown in the inset of Fig. 1. A strong current dependence of the resistivity appears below the kink, introducing a long resistive tail at high currents which tends to conceal the presence of the kink. Above the kink, a nearly Ohmic behavior is observed.

In a simple flux-motion model, the rate of energy dissipation per unit length of vortex may be written as

$$P = \mathbf{F}_L \cdot \mathbf{v}_L ,$$

where $\mathbf{F}_L$ is the Lorentz force and $\mathbf{v}_L$ is the velocity of a flux line. Since $\mathbf{v}_L$ originates from a Lorentz force, its magnitude is directly proportional to $\sin(\theta)$, where θ is the angle between the magnetic field and the transport measuring current. Hence an angular dependence of the form $\sin^2(\theta)$ is expected for a resistive component due to Lorentz-force-driven flux motion.

Three angular scans at the temperatures indicated by the vertical lines in Fig. 3 have been performed. The results shown in Fig. 2 (where a measuring current density of ~15 A/cm^2 was used to obtain higher resolution) can be nicely fitted to a $\sin^2(\theta)$ dependence. This strongly supports an interpretation of the excess resistivity in terms of Lorentz-force-driven flux motion. The smooth $\sin^2(\theta)$ dependence we report in Fig. 2 is not seen in similar experiments on thin films of $YBa_2Cu_3O_{7-\delta}$ with twin boundaries oriented in both the $\langle 110 \rangle$ and $\langle 1\bar{1}0 \rangle$ directions.[11] A difference in the resistivity for $H \parallel I$ and $H \perp I$ has been observed previously in single-crystal samples of $YBa_2Cu_3O_{7-\delta}$ (Refs. 12-14) but without confirmation of the Lorentz-force mechanism by the $\sin^2(\theta)$ dependence at intermediate angles. Apparently, the Lorentz-force component of the resistivity can be seen only in high-quality single crystals.[12]

With decreasing temperature the angular-independent background resistivity strongly decreases (see Fig. 1), so that at the lowest temperature an almost pure flux-flow contribution is left. At the same time a sharp drop in resistivity almost going to zero appears at 45° from the $H \perp I$ direction and repeats itself every 180°, i.e., whenever the applied magnetic field is parallel to the twin planes. The width of the drop is very narrow; ±2° which is for the present setup probably determined by the instrumental resolution.

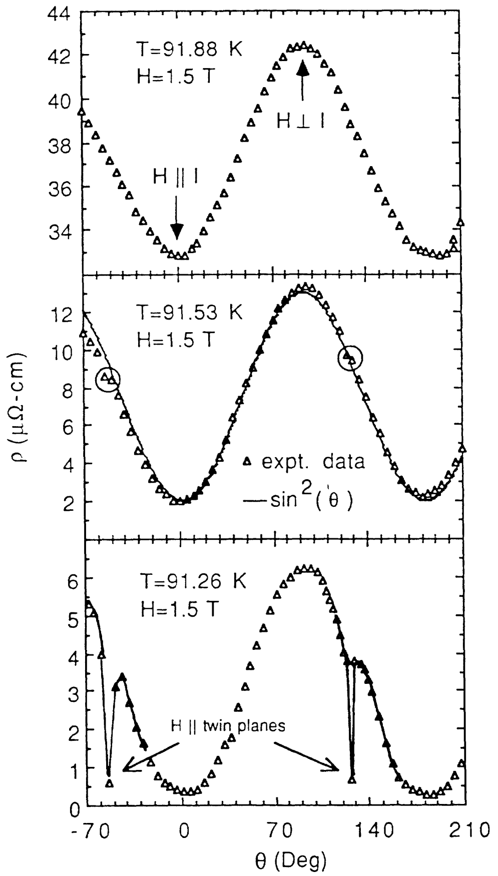

FIG. 2. Angular dependence of the resistivity at three temperatures: above (91.88 K), near (91.53 K), and below (91.26 K) the kink. The circles in the middle panel show the onset of pinning due to twin planes near the temperature of the resistive kink.

The sharp drop in resistivity may be due to pinning of the entire length of the vortex lines at the twin boundaries when the field is aligned along the twin planes in contrast to pinning at only local points along the vortices in the nonaligned case. These results are in contrast to models of pinning forces due to homogeneous twinning planes which predict no pinning force against motion in the twinning plane when the vortex line is parallel to the twinning plane.[15] However, the twinning plane is associated with a strain field 10-30 Å thick[16] which is a probable location of atomic defects such as oxygen disorder. These would contribute a pinning force against motion in the c direction which is highest when the flux lines are aligned with the twin planes. A similar mechanism was proposed[17] to explain a comparison of the magnetization hysteresis of a twinned and untwinned $YBa_2Cu_3O_{7-\delta}$ crystal.

The onset of high pinning when the magnetic field is aligned along the twin planes is evidenced in Fig. 2 for the angular scan in the temperature region just above the resistive kink at $T=91.53$ K. The resistivity deviates slightly (highlighted by circles in Fig. 2) from the expected $\sin^2(\theta)$ behavior at this angle, whereas no sign of any deviation is seen for the angular scan in the temperature region far above the kink at $T=91.88$ K. Hence it seems that the twin planes pin the vortices in this orientation only at temperatures below the resistive kink.

The spacing between vortices at 1.5 T is approximately 400 Å, assuming an equilibrium hexagonal flux-line-lattice (FLL) structure. The vortex spacing is only slightly smaller than the distance between twin planes, of order 10^3 Å. Thus the number of flux lines between the twinning planes is small and the system is close to the limit where each flux line could be pinned individually by a twinning plane. This is consistent with the observation that for H parallel to twin planes, the resistivity drops almost to zero. It also implies that a transition of the FLL (Ref. 18) to a liquid state would not affect the pinning or resistivity drastically at this temperature and field.

The peculiar temperature dependence of the pinning due to twinning planes is also seen in the resistive-transition curve for H parallel to twin planes shown in Fig. 3, with a measuring current density of ~ 6 A/cm^2. At high temperatures, the resistivity is similar to that observed for $H \perp I$. However, below 91.5 K the resistivity drops rapidly to zero. The behavior of the resistive transitions can be replotted in an Arrhenius plot (lower panel of Fig. 3) and fitted using a simple thermal activation model.[2] The onset of pinning due to twin planes is seen as a dramatic change in slope in the Arrhenius plot for H parallel to twin planes, below the kink at $T=91.5$ K, yielding an effective pinning potential (not corrected for temperature dependence of the condensation energy or coherence length) of $U_{\mathrm{eff}}/k = 1.38\times10^5$ K. This value of U_{eff}/k is approximately 5 times larger than the effective pinning potential $U_{\mathrm{eff}}/k = 2.11\times10^4$ K obtained for the $H \perp I$ curve in the same temperature region. Temperature corrections for the coherence length and condensation energy will not alter the factor-of-5 anisotropy in the pinning potential.

In summary, we have shown for the first time that the Lorentz-force-induced vortex motion leads to a dissipation in the form of an *excess resistivity* between the $H \parallel I$ and $H \perp I$ resistive measurements in $YBa_2Cu_3O_{7-\delta}$. This *excess resistivity* follows a $\sin^2(\theta)$ behavior as expected for Lorentz-force dissipation. In contrast, there is a large background resistivity which is independent of the angle between the magnetic field and measuring current whose origin is yet undetermined. There is an anomalous kink near the foot of the resistive transition in the $H \perp I$ configuration which appears to be the cutoff region below which the angular-independent resistive background is approximately zero and the resistivity is non-Ohmic.

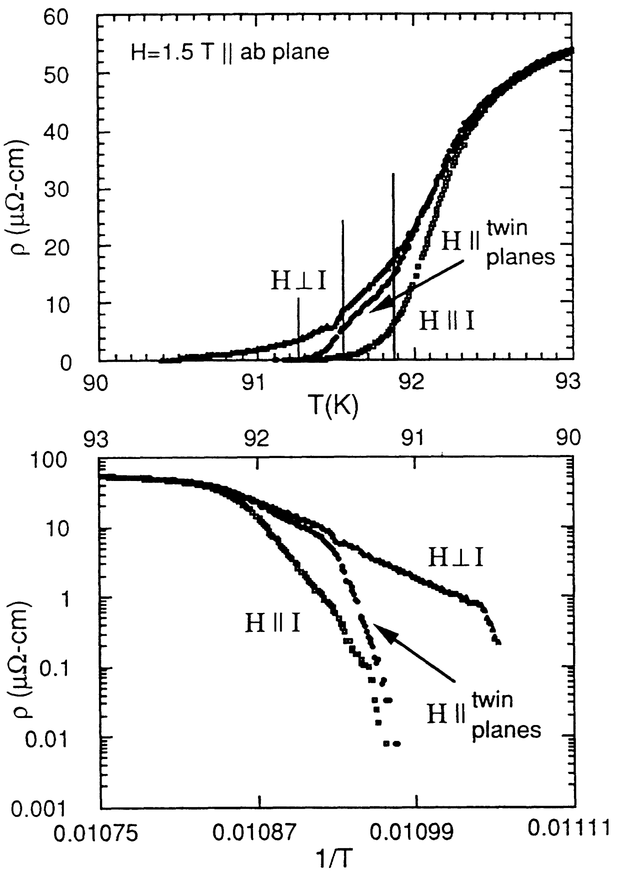

FIG. 3. Upper panel: Resistive transition in 1.5 T for the $H \parallel I$, $H \perp I$, and H parallel to twin planes configuration. The three vertical lines give the position of the angular scans shown in Fig. 2. Lower panel: An Arrhenius plot of the above data.

We directly observe pinning by twin boundaries at temperatures below the kink. The strength of the pinning is highly dependent on the orientation of the magnetic field with the twin planes. When the magnetic field is oriented along the twin planes, the pinning potential U_{eff}/k is approximately 5 times larger than for the nonaligned field orientations.

This work was supported by the U.S. Department of Energy, Basic Energy Sciences–Materials Science under Contract No. W-31-109-ENG-38 (G.W.C., W.K.K., and J.Z.L.) and the National Science Foundation–Office of Science and Technology Center under Contract No. STC8809854 (U.W. and K.G.V.), Science and Technology Center for Superconductivity–University of Illinois, Urbana-Champaign). K. G. V. and R. H. acknowledge partial support from the Division of Educational Programs, Argonne National Laboratory.

[a] Also at University of Illinois–Chicago, Chicago, IL 60680.

[b] Present address: University of California–Davis, Davis, CA 95616.

[1] M. Tinkham, Phys. Rev. Lett. **61**, 1658 (1988).

[2] For a review, see A. P. Malozemoff, T. K. Worthington, E. Zeldov, N. C. Yeh, M. W. McElfresh, and F. Holtzberg, in *Strong Correlations and Superconductivity,* Springer Series in Solid State Sciences Vol. 89, edited by H. Fukuyama, S. Maekawa, and A. P. Malozemoff (Springer-Verlag, Heidelberg, 1989), p. 349.

[3] Y. Iye, S. Nakamura, and T. Tamegai, The Institute for Solid State Physics, The University of Tokyo report, 1989 (to be published); N. Kobayashi, H. Iwasaki, H. Kawabe, K. Watanabe, H. Yamane, H. Kurosawa, H. Masumoto, T. Hirai, and Y. Muto (to be published); H. Iwasaki, N. Kobayashi, M. Kikuchi, S. Nakajima, T. Kajitani, Y. Syono, and Y. Muto (to be published); K. C. Woo, K. E. Gray, R. T. Kampwirth, J. H. Kang, S. J. Stein, R. East, and D. M. McKay, Phys. Rev. Lett. **63**, 1877 (1989).

[4] D. L. Kaiser, F. Holtzberg, M. F. Chisholm, and T. K. Worthington, J. Cryst. Growth **85**, 593 (1987).

[5] U. Welp, W. K. Kwok, G. Crabtree, K. G. Vandervoort, and J. Z. Liu, Phys. Rev. Lett. **62**, 1908 (1989).

[6] U. Welp, M. Grimsditch, H. You, W. K. Kwok, M. M. Fang, G. W. Crabtree, and J. Z. Liu, Physica (Amsterdam) **161C**, 1 (1989); G. J. Dolan, F. Holtzberg, C. Feild, and T. R. Dinger, Phys. Rev. Lett. **62**, 2184 (1989); L. Ya. Vinnikov *et al.*, Pis'ma Zh. Eksp. Teor. Fiz. **49**, 83 (1989) [JETP Lett. **49**, 99 (1989)].

[7] A. M. Campbell and J. E. Evetts, Adv. Phys. **21**, 199 (1972); M. Tachiki and S. Takahashi, Solid State Commun. **70**, 291 (1989); E. H. Brandt, Phys. Rev. Lett. **63**, 1106 (1989).

[8] D. R. Nelson, Phys. Rev. Lett. **60**, 1973 (1988); M. P. A. Fisher, Phys. Rev. Lett. **62**, 1415 (1989).

[9] T. Tsuneto, J. Phys. Soc. Jpn. **57**, 3499 (1988).

[10] W. K. Kwok, U. Welp, G. W. Crabtree, K. G. Vandervoort, R. Hulscher, and J. Z. Liu (unpublished).

[11] Y. Iye, S. Nakamura, T. Tamegai, T. Terashima, and Y. Bando, in Proceedings of MRS '89 Fall Meeting, Boston, 27 November–1 December 1989 (Materials Research Society, Pittsburgh, to be published).

[12] B. Batlogg, T. T. M. Palstra, L. F. Schneemeyer, and J. V. Waszczak, in *Strong Correlations and Superconductivity* (Ref. 2), p. 368.

[13] J. N. Li, K. Kadowaki, M. J. V. Menken, A. A. Menovsky, and J. J. M. Franse, Physica (Amsterdam) **161C**, 313 (1989).

[14] W. K. Kwok, U. Welp, G. W. Crabtree, K. G. Vandervoort, and J. Z. Liu, Physica (Amsterdam) **162–164C**, 669 (1989).

[15] P. H. Kes and J. van den Berg, in "Studies of High Temperature Superconductors," edited by A. V. Narlikar (Nova Science, New York, to be published).

[16] Y. Zhu, M. Suenaga, Y. Xu, R. L. Sabatini, and A. R. Moodenbaugh, Appl. Phys. Lett. **54**, 374 (1989).

[17] U. Welp, W. K. Kwok, G. W. Crabtree, K. G. Vandervoort, and J. Z. Liu (to be published).

[18] M. P. A. Fisher, Phys. Rev. Lett. **62**, 1415 (1989).