Observation of Free Flux Flow at High Dissipation Levels in $YBa_2Cu_3O_{7-\delta}$ Epitaxial Films

Milind N. Kunchur and David K. Christen
Solid State Division, Oak Ridge National Laboratory, P.O. Box 2008, Oak Ridge, Tennessee 37831-6057

Julia M. Phillips
AT&T Bell Laboratories, 600 Mountain Avenue, Murray Hill, New Jersey 07974
(Received 25 September 1992)

The *total* resistivity ($\rho = E/J$, not dE/dJ) was measured in epitaxial $YBa_2Cu_3O_{7-\delta}$ films up to high dissipation levels using a pulsed current source. In the reversible region, $\rho(J)$ has an S shape; it is Ohmic at low J (thermally activated free flux motion), goes through a nonlinear transition region (depinning), and becomes Ohmic again at the highest J (*free flux flow*, i.e., purely viscous motion). The free-flux-flow resistivity ρ_{fff} obeys $\rho_{\text{fff}}/\rho_n \simeq H/H_{c2}(T)$, with $dH_{c2}/dT \approx 2$ T/K.

PACS numbers: 74.60.Ge, 74.40.+k, 74.60.Ec, 74.72.Bk

The motion of an isolated vortex line in an ideal type-II superconductor in the mixed state is governed by simple viscous damping. In the steady state the drag force per unit length of the vortex, F_{drag}, equals the force driving the motion [such as the Lorentz force exerted by a current $\mathbf{F}_{\text{Lorentz}} = (\mathbf{J} \times \mathbf{\Phi}_0)/c$] and is proportional to the drift velocity v, so that $F_{\text{drag}} = \eta v$, where η is the coefficient of viscosity. We will refer to this dissipative condition of a superconductor as the *free-flux-flow* state since the term *flux flow* is used rather loosely in the literature to mean just about any situation where the fluxons are not completely pinned in place against driving and thermal forces. Various models [1–4] calculate η from fundamental considerations and, under certain conditions, yield a surprisingly simple relationship between the resistivity in the free-flux-flow state ρ_{fff}, and the magnetic flux density B within the superconductor:

$$\rho_{\text{fff}}/\rho_n \approx B/H_{c2}(T)\,. \tag{1}$$

Here ρ_n is the resistivity in the normal state and H_{c2} is the upper critical field at the temperature T. The right-hand side (RHS) of Eq. (1) is roughly equal to the volume fraction of normal material, and is expected to be correct within a prefactor of the order of unity only when the vortices translate rigidly without a backflow current passing through the vortex core [3,4]. In the case of a gapless superconductor, the prefactor can be field dependent and can cover a range 0.33–5.2 [4]. Because of the highly demagnetizing geometry in our measurements and because $H \gg H_{c1}$, $B \approx H$ and distinction between the applied field H and B can be neglected.

In the original theories of free flux flow it is presumed that ρ_{fff} is the *total* resistivity (i.e., E/J), not the differential resistivity (dE/dJ), of a linear region that may be observed after an offset caused by pinning. In general the two are related in a complicated way and become equal only in the limit $J \gg J_{c0}$ [5]; here J_{c0} is the depinning critical current density in the absence of thermally activated processes. Most earlier work, such as that of Kim, Hempstead, and Strnad [6], took the flux-flow resistivity to be dE/dJ. In other cases it was observed [7] that $E \propto J$ in the limit of $J \rightarrow 0$, and this low-J resistivity was assumed to arise from flux flow. It is now established [8] that the Ohmic behavior observed at low dissipation is due to thermally activated flux motion (TAFF) [9] and not free flux flow. Thus in a real superconductor at finite temperatures the behavior is complicated by pinning forces, intervortex correlations, and thermal agitation. To our knowledge the simple behavior predicted by Eq. (1) has not been observed for the total resistivity with the use of the appropriate temperature-dependent $H_{c2}(T)$, over an extended field range ($B \ll H_{c2}$ to $B \approx H_{c2}$).

High-T_c superconductors have notoriously poor pinning and weak intervortex correlations at high temperatures and fields (especially for $H \parallel c$, the orientation used here). In fact it has been proposed that the vortex solid is molten [10] above the irreversibility line, although this interpretation is controversial [8]. This makes the $H \parallel c$ reversible region an ideal candidate for the observation of free flux flow. In addition we measure the response (E and ρ) up to much higher current densities (power dissipation densities as much as 3×10^8 W/cm^3) than have been explored in the past. The motivation is that at a sufficiently large driving force pinning and intervortex correlation forces should become negligible compared with the driving and viscous forces. We found that the total resistivity $\rho(J)$ is a monotonically increasing function of J but has J-independent plateaus (i.e., Ohmic behavior) in the limit of very low J (TAFF) and very high J (free flux flow). The high-J plateau values of the resistivity for different fields and temperatures were found to follow Eq. (1) over three decades [$B/H_{c2}(T) \sim 0.001$ to 1]. The upper critical fields found from Eq. (1) are consistent with values found in the literature. Thus this method presents a new approach to measuring this important fundamental parameter, and elucidates the conventional nature of the vortex state in high-T_c materials.

In this study we investigated two c-axis-oriented epitaxial films of $YBa_2Cu_3O_{7-\delta}$. The films were deposited and postannealed on (100) surfaces of $LaAlO_3$ substrates by means of the BaF_2 process, described elsewhere [11]. The precise stoichiometry and postannealing conditions were chosen to provide films with few microstructural defects. The single-crystal-like quality of the films is supported by the following observations: (i) Ion channeling along the c axis gives minimum yields $\chi_{min} < 3\%$, similar to the low values observed in single crystals; (ii) a large zero field $J_{c0} \simeq 10^6$ A/cm^2; (iii) relative insensitivity of J_{c0} to magnetic fields applied parallel to the a-b planes, but a rapid decay for $H \parallel c$; (iv) a weak irreversibility line (e.g., $B_{irr} \simeq 2$ T at 77 K); and finally (v) enhancement of the irreversibility line and $J_{c0}(H)$ when defects are introduced by ion irradiation [12]. The bridge that was measured was photolithographically patterned on the film, and had the following dimensions ($t \times l \times w$): 100 nm$\times$3 mm$\times$100 μm.

The I-V characteristic was determined by sending pulses of current through the sample and measuring the time responses of the voltage $V(t)$ across the sample and the voltage $I(t)R$ across a noninductive standard resistor placed in series—the same four-probe configuration as used in continuous dc measurements. The pulse width ranged from 5 μs to 2 ms. The duty cycle was varied from 0.001% to 5% to rule out cumulative heating. The voltages were first preamplified by instrumentation amplifiers and then displayed and measured on a digital storage oscilloscope. Pulses with adjustable rise/fall times (to control ringing and inductive coupling) were created by a pulse generator and sent to a high-speed voltage-to-current converter, which had a compliance voltage of 400 V and rise time < 1 μs. The design details of the converter and other electronics built for this experiment will be discussed elsewhere [13]. The apparatus was checked for consistency and accuracy by measuring various standard resistors and by comparing with continuous dc measurements on the same sample. The agreement was within 2%.

Figure 1 shows three voltage pulses $V_1(t)$, $V_2(t)$, and $V_3(t)$, and the current pulse $I_3(t)$ corresponding to $V_3(t)$. The current pulse always has a flattop independent of load and for all pulse widths. The "current" for each I-V point is taken to be the plateau value of $I(t)$. V_1, V_2, and V_3 are traces at different plateau currents. The top of the voltage pulse becomes progressively more sloped as a function of the power dissipation. From the measured dV/dt, it was found that heating was not adiabatic and that thermal conduction processes played a role even on these short time scales. The last point on each I-V curve was taken at a dissipation level such that $(dV/dt)/V_{t=0}$ was about 8%/μs. V (at $t=0$) was obtained by extrapolating the linear portion back to the leading edge of the pulse where the sample temperature equals the nominal temperature. The uncertainty in the time origin leads to an uncertainty in V (and hence ρ) of about $\pm 5\%$ at the highest current on each I-V curve.

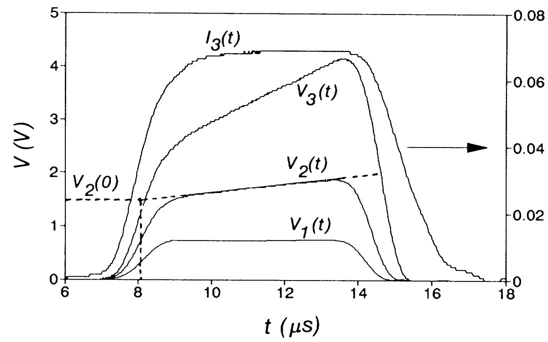

FIG. 1. The time profiles of voltage and current through specimen II at $H=0.015$ T and $T=88.2$ K. The plateau currents for the three voltage pulses are $I_1=46$ mA, $I_2=58$ mA, and $I_3=69$ mA. Also shown is the extrapolation procedure described in the text for obtaining $V_2(t=0)$.

Figure 2 shows ρ versus J for various fields at a temperature of 85.4 K for specimen I. The J-ρ curves at other temperatures and for the second specimen are qualitatively similar. Also shown on the figure is J_d, the depairing current density, estimated for each field using [14]

$$J_d(T,B) = \frac{c}{3\pi\sqrt{6}} \frac{H_c(T)}{\lambda(T)} \left[1 - \frac{B}{H_{c2}(T)}\right] \simeq \left[\frac{H_c(0)}{\lambda(0)}\right] \left[1 - \frac{T}{T_c}\right]^{1/2} \left[1 - \frac{T}{T_c} - 0.71 \frac{B}{H_{c2}(0)}\right],$$

valid at high temperature, where values for the thermodynamic field $H_c(0)$, the penetration depth $\lambda(0)$, and the upper critical field $H_{c2}(0)$ are taken from the literature (1.2 T, 1400 Å, and 110 T, respectively). The dashed horizontal line near the top of the figure is the normal-state resistivity determined by extrapolating from the very linear high-temperature portion of the $\rho(T)$ trace (approximated well by $\rho_n = \rho_{rt} T/T_{rt}$). Except at the lowest fields, the curves all show an S shape, with three qualitative regimes of behavior. The behavior is initially Ohmic at low J (TAFF). In the second regime, dominated by current-driven depinning, $\rho(J)$ is a monotonically increasing function of J. Viewed over this restricted second regime, ρ (and E) appears to have a power-law dependence on J. At the highest J, there is reentrance into Ohmic behavior and ρ once again becomes constant. At the lowest fields, ρ does not saturate completely because the higher pinning and irreversibility require a larger current than can be safely applied. For this reason, the present measurements are in a temperature and field range that is largely above the irreversibility line.

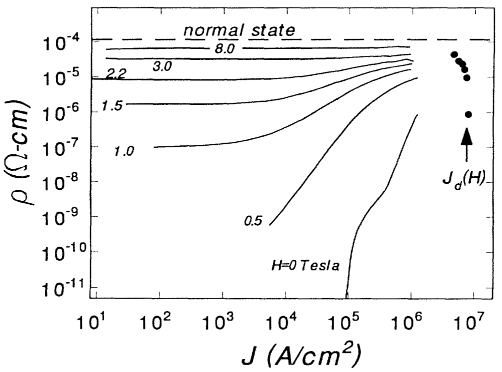

FIG. 2. Total resistivity $\rho = E/J$, for specimen I at 85.4 K, as a function of J at different fields. The dashed line shows the estimated resistivity of the normal state. The circles indicate the calculated field-dependent depairing current density. For clarity, the $J_d(H)$ are arbitrarily assigned to the measured curves at the extreme resistivity values.

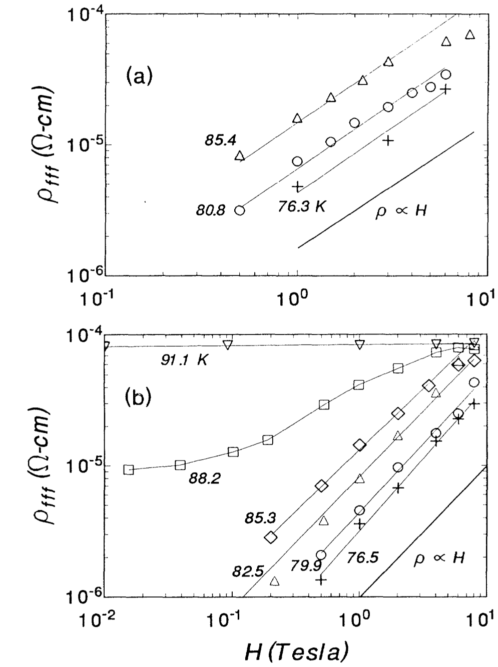

FIG. 3. Free-flux-flow resistivities vs the applied field for (a) specimen I and (b) specimen II. The lines are guides for the eye. Also shown for comparison are lines of unity slope (i.e., $\rho \propto H$).

The zero-field J-ρ curve in Fig. 2 shows three regimes: a rapid initial rise as J exceeds J_{c0}, a region of concave curvature that almost tends to saturate, and a final steep ascent with what appears to be a power-law behavior —possibly due to the flow of vortices associated with the continuously growing self-field of the current. Beyond this the resistivity might be expected to saturate once J reaches J_d.

We will now look more closely at the resistivity on each high-J plateau of the J-ρ curves, calling that value $\rho_{\rm fff}$, in anticipation that it signifies free flux flow. Figure 3 shows plots of $\rho_{\rm fff}$ vs H for various temperatures for the two samples. First, for specimen II at $T=91.1$ K ($>T_c=88.5$ K) note the near absence of magnetoresistance. For another temperature $T=88.2$ K just below $T_c(=88.5$ K), the same specimen shows a positive magnetoresistance which does not adhere to a power law. Because of the proximity to T_c, sample inhomogeneity may lead to a field-dependent percolation pattern making the overall behavior complicated as observed. For all other temperatures and for both samples, ρ vs H gives approximatedy straight parallel lines of slope 1 indicating proportionality between ρ and H as expected for free flux flow. If Eq. (1) holds, the scaled data, ρ/ρ_n and $H/H_{c2}(T)$, should fall onto a universal straight line of slope 1 and zero intercept. ρ_n was determined as discussed earlier. At these temperatures H_{c2} has the temperature dependence $H_{c2}(T)=(dH_{c2}/dT)(T_c-T)$, so that dH_{c2}/dT is essentially the only fitting parameter. Additionally, the scaling can be slightly improved by a marginal adjustment in T_c. The T_c determined in this way for specimen I was 89.4 K which is midway between the zero-resistance value (88.5 K) and the resistive-transition-midpoint value (90.5 K). This T_c to which the flux flow $H_{c2}(T)$ extrapolates to zero is likely to more accurately represent the bulk of the specimen rather than the usual low-current zero-resistance value. The latter samples the first percolating path, whereas the high-J flux-flow measurement forces a more homogeneous flow of current through the entire volume. The T_c for the second specimen came out to be 88.5 K.

Figure 4 shows the scaled data for the two samples. The normalized data fall onto a single straight line of unity slope and zero intercept. The fitting parameter dH_{c2}/dT forces zero intercept and the parameter T_c slightly fine tunes the scaling of the data taken at different temperatures. Except for the intercept, the scaling of the data onto a single universal line of unity slope takes place *without any fitting parameters.* The values of dH_{c2}/dT that we find from this analysis are 1.85 ± 0.2 T/K for specimen I and 2.2 ± 0.3 T/K for the second specimen. (The indicated errors reflect only the uncertainty in the slope due to the scatter in the data.) These values are in agreement with H_{c2} obtained from equilibrium magnetization [15] and from fluctuation effects [16]. Earlier it was mentioned that there may be an additional prefactor in the RHS of Eq. (1), which in general may be field dependent. However, from the result obtained here, it appears that Eq. (1) holds for this system over the measured field range with a constant near-unity prefactor. This result suggests that in this region of J-ρ the vortex motion can be approximated by rigid translation without significant backflow currents passing through the core.

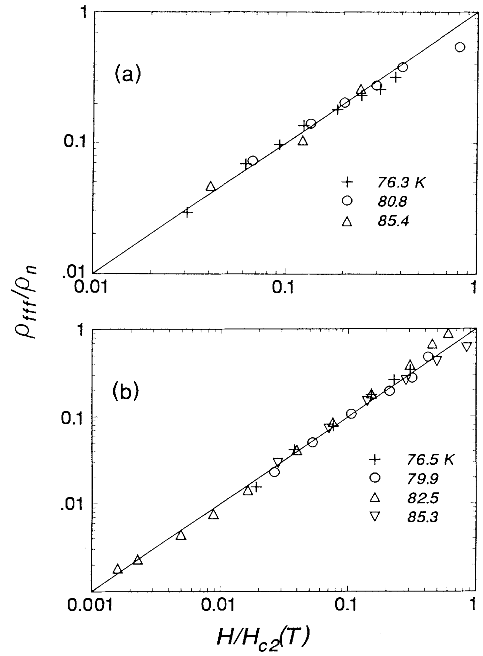

FIG. 4. Normalized free-flux-flow resistivity plotted against normalized field for (a) specimen I and (b) specimen II. The data for all fields and temperatures fall roughly on the line $\rho/\rho_n = H/H_{c2}(T)$.

In conclusion, this work demonstrates that, at high enough dissipation levels, the I-V characteristic reenters Ohmic behavior and the resistivity in that regime corresponds to free flux flow; the normalized magnetoresistance fits $\rho_{fff}/\rho_n \approx B/H_{c2}(T)$ with values of dH_{c2}/dT consistent with published ones. The present work also has implications for other flux-flow-dependent properties such as the Hall effect [17] and the Nernst effect [18]. Since such measurements are typically done at considerably lower dissipations, the flux flow associated with the measured property may be partially thermally activated rather than free.

Research was sponsored by the Division of Materials Sciences, U.S. Department of Energy, under Contract No. DE-AC05-84OR21400, with Martin-Marietta Energy Systems, Inc. The authors would like to thank C. E. Klabunde for help with the measurements, and M. P. Siegal and S. Y. Hou for sample preparation. The authors would like to acknowledge useful discussions with A. T. Dorsey, H. R. Kerchner, S. H. Liu, and J. R. Clem. M.N.K. would also like to acknowledge previous support from E. I. du Pont de Nemours and Company, Inc., for developmental work related to the present experiment.

[1] M. Tinkham, Phys. Rev. Lett. **13**, 804 (1964); J. Bardeen and M. J. Stephen, Phys. Rev. **140**, A1197 (1965); J. R. Clem, Phys. Rev. Lett. **20**, 735 (1968).

[2] A. I. Larkin and Yu. N. Ovchinnikov, in *Nonequilibrium Superconductivity*, edited by D. N. Langenberg and A. I. Larkin (Elsevier, Amsterdam, 1986), Chap. 11. These authors rigorously derive the flux-flow-related dissipation for many different cases. In the limit of high electric field (i.e., high dissipation) and in the vicinity of T_c, they recover the form $\sigma/\sigma_N \approx H_{c2}/B$, i.e., our Eq. (1).

[3] Michael Tinkham, *Introduction to Superconductivity* (McGraw-Hill, New York, 1975).

[4] C. R. Hu and R. S. Thompson, Phys. Rev. B **6**, 110 (1972); R. S. Thompson and C. R. Hu, Phys. Rev. Lett. **27**, 1352 (1971).

[5] We consider the motion of a massless particle in a viscous medium, over a tilted washboard potential with V-shaped wells that exert a maximum pinning force $F_{\rm pin}$. It is straightforward to calculate the average driving force $F_{\rm avg} \equiv \eta v_{\rm avg}$ that results for a given applied force $F_{\rm drive}$. By making the analogies $J \leftrightarrow F_{\rm drive}$, $J_{c0} \leftrightarrow F_{\rm pin}$, $E \leftrightarrow F_{\rm avg}$, and $\rho \leftrightarrow F_{\rm avg}/F_{\rm drive}$, one obtains $\rho_{\rm total} = \rho_{\rm fff}\alpha(J^2 - J_{c0}^2)/[\alpha(J^2 - J_{c0}^2) + \beta J_{c0}^2]$. Here α and β are constants related to the well size and separation, and $\rho_{\rm fff}$ is the asymptotic limit. For finite J, $\rho_{\rm total} = E/J < \rho_{\rm fff}$ and $\rho_{\rm diff} = dE/dJ > \rho_{\rm fff}$.

[6] Y. B. Kim, C. F. Hempstead, and A. R. Strnad, Phys. Rev. **139**, A1163 (1965).

[7] R. B. van Dover, L. F. Schneemeyer, E. M. Gyorgy, and J. V. Waszczak, Phys. Rev. B **39**, 4800 (1989).

[8] E. H. Brandt, Int. J. Mod. Phys. B **5**, 751 (1991), and references therein.

[9] P. H. Kes, J. Aarts, J. van den Berg, C. J. van der Beek, and J. A. Mydosh, Supercond. Sci. Technol. **1**, 242 (1989).

[10] P. L. Gammel, L. F. Schneemeyer, J. V. Waszczak, and D. J. Bishop, Phys. Rev. Lett. **61**, 1666 (1988); also see discussion in [8].

[11] M. P. Siegal *et al.*, J. Appl. Phys. **68**, 6353 (1990); D. J. Carlson *et al.*, J. Mater. Res. **5**, 2797 (1990).

[12] M. P. Siegal *et al.*, Appl. Phys. Lett. **60**, 2932 (1992).

[13] M. N. Kunchur (to be published). Also, the interested reader may contact M.N.K.

[14] See Ref. [3] for the starting formulas used for deriving J_d's temperature and field dependences. The factor $1 - B/H_{c2}(T)$ accounts for the overall gap suppression by the average field.

[15] U. Welp *et al.*, Phys. Rev. Lett. **62**, 1908 (1989); Z. Hao *et al.*, Phys. Rev. B **43**, 2844 (1991); Z. Hao and J. R. Clem, Phys. Rev. Lett. **67**, 2371 (1991).

[16] U. Welp *et al.*, Phys. Rev. Lett. **67**, 3180 (1991).

[17] S. J. Hagen, C. J. Lobb, and R. L. Greene, Phys. Rev. B **43**, 6246 (1991), and references therein.

[18] M. Zeh, H.-C. Ri, F. Kober, R. P. Huebeber, A. V. Ustinov, J. Mannhart, R. Gross, and A. Gupta, Phys. Rev. Lett. **64**, 3195 (1990); S. J. Hagen, C. J. Lobb, and R. L. Greene, Phys. Rev. B **42**, 6777 (1990).