Optical and Electrical Enhancement of Flux Creep in $YBa_2Cu_3O_{7-\delta}$ Epitaxial Films

E. Zeldov,[a] N. M. Amer, G. Koren,[b] A. Gupta, R. J. Gambino, and M. W. McElfresh
IBM Thomas J. Watson Research Center, Yorktown Heights, New York 10598-0218
(Received 17 February 1989; revised manuscript received 3 May 1989)

We report two novel flux-creep-related phenomena in $YBa_2Cu_3O_{7-\delta}$ films at elevated currents in the presence of magnetic fields: a sharp onset of nonequilibrium optical response and a current-dependent thermally activated electrical resistivity. In this regime the activation energy of the resistivity scales uniquely with current density as $\ln(J_0/J)$, with $J_0 \approx 3\times10^6$ A/cm^2. This nonlinear current dependence is significantly different from the predictions of the standard flux-creep model. At currents $\lesssim 7\times10^3$ A/cm^2 the resistivity is current independent and the optical response is purely bolometric.

PACS numbers: 74.60.Ge, 74.30.Gn, 74.70.Vy, 74.75.+t

Palstra *et al.*[1] have recently shown that flux motion in high-T_C single crystals is thermally activated, thus implying the existence of finite resistance at all temperatures at fields larger than H_{c1}. We report here the results of new experiments designed to investigate the effects of optical excitation and elevated electrical currents on the flux-creep mechanism: The photoresponse (PR) shows a sharp transition from bolometric to nonequilibrium behavior under the same conditions where the resistivity shows a transition from a current-independent to a unique current-dependent regime. In the latter high-current-density regime, the resistivity of the $YBa_2Cu_3O_{7-\delta}$ epitaxial film shows a thermally activated behavior with a novel logarithmic scaling of the activation energy with current density. These new findings have important theoretical and experimental implications, and in particular may help resolve existing discrepancies between transport and magnetic-relaxation results in high-T_C superconductors.[2]

High-quality epitaxial films were deposited on (100) $SrTiO_3$ substrates using 355-nm Nd-doped yttrium-aluminum-garnet laser ablation.[3] An excimer-laser–microscope system was used to pattern a 0.3-μm-thick film to form a microbridge 22 μm wide and 200 μm long. PR measurements were carried out with a 1.5-mW HeNe laser beam (633 nm) focused to $\simeq$110 μm on the microbridge and chopped in the range of 40 Hz to 18 kHz. The four-probe technique was used to measure simultaneously the resistivity and the PR signal as a function of temperature at various bias currents and in the presence of magnetic fields (**H**$\|$**c** axis, 5 to 60 kOe).

We describe first the PR of the $YBa_2Cu_3O_{7-\delta}$ film. The temperature dependence of PR shows a sharp maximum in the transition region which is qualitatively similar to our earlier results in zero magnetic field.[4] Application of the field broadens the peak and shifts it to lower temperatures. The measured signal, however, is the sum of the bolometric and nonequilibrium contributions, where the former dominates at all temperatures except at the lower edge of the resistive transition. This bolometric contribution is proportional to the temperature derivative of the resistivity, $d\rho/dT$, which is calculated numerically from $\rho(T)$ data like those shown in Fig. 1(a). A sensitive method for distinguishing between the two contributions is to normalize the PR by $d\rho/dT$ as measured under identical experimental conditions. Hence, in the temperature range where the response is purely bolometric this procedure will result in a constant value, ΔT, which is a measure of the temperature increase of the sample due to optical heating.[4] In the range where the nonequilibrium response coexists with the inevitable bolometric signal, the ratio will rise above ΔT, reflecting the relative amplitude of the nonequilibrium signal. Figure 1(b) shows this result for various magnetic fields at 10-mA bias current (1.5×10^5 A/cm^2). At temperatures above T_C, a flat bolometric response is observed which is independent of magnetic field and bias

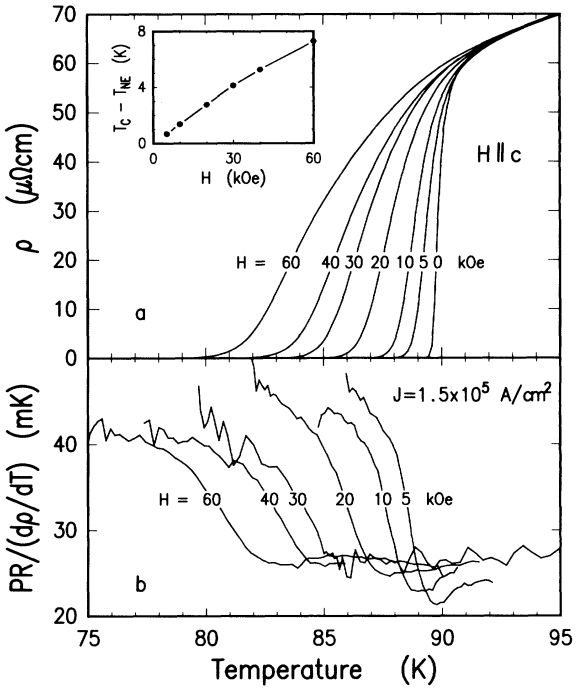

FIG. 1. (a) The resistive transition and (b) the normalized photoresponse of the $YBa_2Cu_3O_{7-\delta}$ epitaxial film at various magnetic fields. Inset: The nonequilibrium PR onset temperature, T_{NE}, as a function of H.

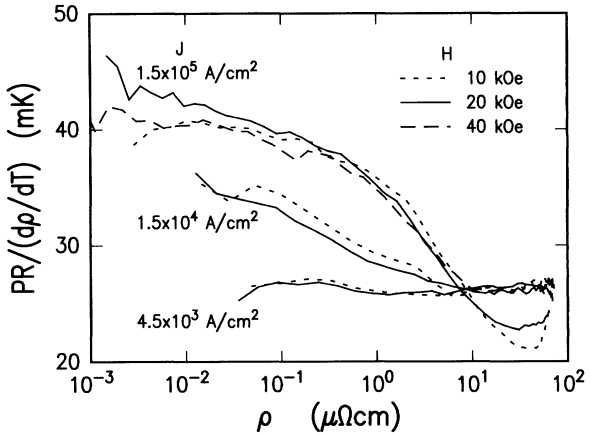

FIG. 2. The normalized PR as a function of resistivity at various magnetic fields and current densities.

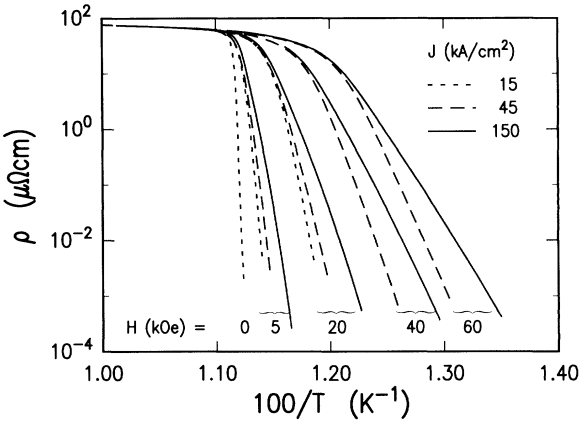

FIG. 3. Arrhenius plot of the resistivity at several representative values of magnetic field and current density.

current (the "undershoot" at low magnetic fields is due to self-heating effects at high resistivities and large $d\rho/dT$). This response extends through a large portion of the transition region, whereas at low resistances a sharp onset of the nonequilibrium response is observed. The magnetic field dependence of this onset temperature, T_{NE}, is shown in the inset of Fig. 1(a). In Fig. 2 the normalized PR is replotted as a function of ρ. This representation manifests the strong correlation between the nonequilibrium PR and the "dark" resistivity of the sample, indicating a common basic mechanism which we discuss below. The nonequilibrium response sets in at a specific resistivity, $\rho \cong 9\ \mu\Omega$ cm ($\cong 15\%$ of ρ_n), which is magnetic field independent. In addition, at a given current, the shape of the normalized PR as a function of resistivity is magnetic field independent as well. Finally, PR has a current threshold of about 7×10^3 A/cm^2 below which the response is purely bolometric in the entire measureable resistivity range.

We now turn to the resistive transition results. In Fig. 3 the resistivity of the film is plotted versus $1/T$ for representative values of H and J. We divide the data, which cover over 5 orders of magnitude, into two regions. In the high-resistivity range ($\simeq 0.2\rho_n$ to ρ_n) the transition is broadened by the magnetic field, resistivity is current independent, and the V-I characteristics are linear. In the low-resistivity range, at low currents the behavior is current independent and is described by an Arrhenius law as reported recently by Palstra *et al.* in $YBa_2Cu_3O_{7-\delta}$ and $Bi_{2.2}Sr_2Ca_{0.8}Cu_2O_{8+\delta}$ single crystals.[1] We find, however, that at high-current densities the observed activation energy, U, is strongly current dependent. In this regime the V-I characteristics are superlinear with the power-law behavior of $\rho(J)$. Figure 3 shows some degree of "bending" in the low-resistivity curves, implying a temperature dependence of the activation energy. Our data show a good fit with the proposed $(1-t)^{3/2}$ type of behavior[1,5,6] ($t = T/T_C$). In Fig. 4 we present the activation energy $U(0,H,J)$ as deduced from the low-resistivity data by a fit with Tinkham's temperature dependence $U(t,H,J) = U(0,H,J)g(t) = U(0,H,J) \times (1-t^2)(1-t^4)^{1/2}$. The striking feature of Fig. 4 is the unique $\ln(J)$ dependence of the activation energy at current densities above 7×10^3 A/cm^2. In this regime $U(0,H,J)$ decreases with current and the magnetic field as

$$U(0,H,J) \propto H^{-\beta}\ln(J_0/J)\,. \tag{1}$$

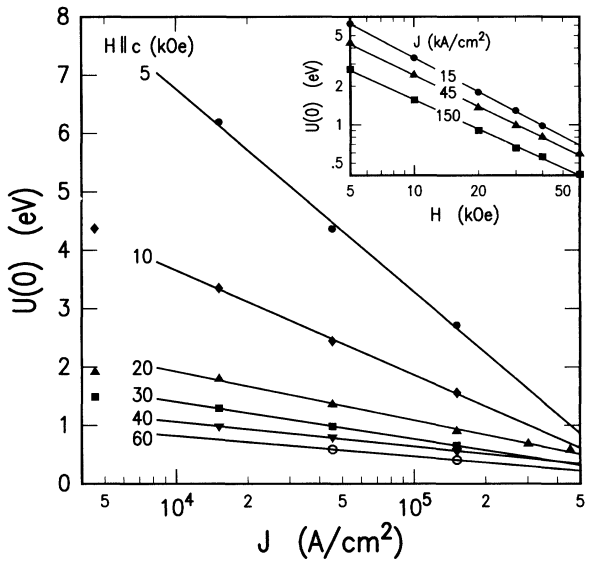

FIG. 4. The activation energy, $U(0,H,J)$, as a function of current density and magnetic field as obtained from the fit of the experimental data with $U(t,H,J) = U(0,H,J)(1-t^2) \times (1-t^4)^{1/2}$. The lines emphasize the logarithmic dependence of U on J, and the power-law dependence on H. The slopes of the lines in the inset are 0.88, 0.81, and 0.76 for current densities of 15, 45, and 150 kA/cm^2, respectively.

The nonlinear J dependence of the activation energy is our main result here and its theoretical and experimental implications are discussed below. The power-law factor, β, of the magnetic field dependence is sensitive to the choice of the temperature function, $g(t)$, due to the fact that the magnetic field significantly shifts the temperature range of the experiment. Thus, for example, using Tinkham's $g(t)$, the inset of Fig. 4 gives a β value of 0.88 at 15 kA/cm^2, and a similar fit by the $(1-t)^{3/2}$ function of Yeshurun and Malozemoff[2] results in $\beta=0.95$. These two values are very close to the predicted $1/H$ dependence[2,5] and thus are self-consistent with the choice of $g(t)$. For comparison a fit to the data with a temperature-independent U results in $\beta=0.55$. We emphasize, however, that the observed logarithmic current dependence of U is essentially independent of $g(t)$ since at a given magnetic field the shift of the temperature range with bias current is not significant. This logarithmic decrease was obtained with all of our trial $g(t)$ functions, including the case of temperature-independent U, with extrapolated J_0 values in the range of 10^6 to 4×10^6 A/cm^2. The J_0 in Eq. (1) is the "critical" current at which U will drop to zero.

Additional evidence for the logarithmic current dependence of U, which excludes any possible temperature-dependent effects, is the observation of the power-law V-I characteristics at high currents. Using our empirical activation-energy behavior, the resistivity obtains the unique form

$$\rho=\rho_0\exp(-U/kT)=\rho_0(J/J_0)^{Ag(t)H^{-\beta}/kT},$$

where A is some proportionality constant. Thus, at a given temperature and magnetic field, the resistivity is predicted to be a power-law function of J as is indeed observed experimentally.

We discuss now the above optical and electrical results. The nonequilibrium PR occurs only in a relatively well defined region, namely $\rho<0.15\rho_n$ and $J>7\times10^3$ A/cm^2 for all the applied magnetic fields. Remarkably, this is the same region where ρ becomes strongly current dependent and the activation energy exhibits the Eq. (1) behavior. We argue that these phenomena are flux-creep related. We define the resistive transition "base line" $\rho_B(T,H)$ as the low-current limit of $\rho(T,H,J)$. For a given H, the resistivity follows this base line for currents below some threshold value and shows a dramatic increase at higher currents. This base line is precisely the "resistive transition" described recently by Tinkham[5] and investigated experimentally by several groups.[1,6,7] Tinkham argues that the thermally activated flux-line motion is highly damped and involves phase slippage analogous to the case of the heavily damped current-driven Josephson junction.[8] The application of this approach to our high-resistivity data yields a reasonable qualitative fit. However, the exact shape of the curves is somewhat different. In addition, the broadening of the transition is close to Tinkham's $H^{2/3}$ dependence only at high fields, whereas below 20 kOe the broadening scales almost linearly with field as can be seen in the inset of Fig. 1(a).

In this study we concentrate on the high-current regime. To discuss it we consider the basic equation for flux-creep-induced resistivity:[9]

$$\rho_f=\frac{2\nu_0BL}{J}\exp\left(-\frac{U_0}{kT}\right)\sinh\left(\frac{JBV_CL}{kT}\right), \tag{2}$$

where ν_0 is the attempt frequency and U_0 is the nominal activation energy for a flux-line bundle of volume V_C to hop a distance L. Indeed, Eq. (2) predicts a transition from a current-independent thermally activated base line resistivity at low driving forces to a current-dependent resistivity at high driving forces. This transition occurs when the argument of the sinh function is on the order of unity. Using our threshold current of 7×10^3 A/cm^2 and a magnetic field of, e.g., 20 kG we obtain an average value of 538 Å for characteristic length scales of the volume and the hopping distance of a flux bundle. This is a physically reasonable value, especially if we compare it to the calculated flux-line spacing, a_0, of 345 Å at the above field. Thus, the existence of the transition and the observed threshold current are consistent with Eq. (2); however, the predicted behavior at high driving forces is different from the experimental results.[10] According to Eq. (2), in this regime, the effective activation energy should decrease linearly with J while we find a strong logarithmic dependence, and the resistivity should increase approximately exponentially with the current whereas experimentally the increase follows a power law.[11] We qualitatively ascribe this behavior to the following: At low driving forces such that the argument of the sinh function is small, the bias current does not alter either the mechanism or the rate of the flux-bundle hopping, but rather induces a small imbalance between the two directions perpendicular to the current which results in a nonzero net creep. Hence, the flux-line bundles still hop randomly at the rate determined by the thermal equilibrium conditions, and their net drift due to the Lorentz force is small compared to their thermal motion. On the other hand, if the driving force is substantially increased, the flux creep, or the forced unidirectional hopping rate of bundles, will be enhanced significantly and may become orders of magnitude larger than the random thermal equilibrium motion. Thus, in this regime we expect a transition to a much different dynamics of a strongly correlated collective motion in which the involved pinning energies and the hopping volumes and distances may differ significantly from those at low driving forces. An additional possible source of a nonlinear $U(J)$ is the current dependence of the pinning potential range L_P. As pointed out by Beasley, Labusch, and Webb,[12] at high-current densities L_P may become current dependent due to the distortion of the potential

well by the Lorentz force, thus resulting in a nonlinear driving force term in Eq. (2).

The nonequilibrium PR exists in the regime of high-current densities where the apparent motion of the fluxons is significantly different from their motion at thermal equilibrium. The photoinduced increase of the resistivity arises from the enhancement of such flux motion due to optical excitation. The detailed mechanism responsible for such enhancement is yet to be investigated. However, we believe that the enhanced flux creep is due to the presence of a nonequilibrium energy distribution of phonons rather than a nonequilibrium density of quasiparticles[13] which is very low at the optical illumination level we used. The more energetic excess phonons presumably enhance the thermal activation of the flux bundles in the presence of large driving forces, and thus increase the flux-creep resistivity.

Our final remark is related to the relevance of the results to magnetic relaxation in $YBa_2Cu_3O_{7-\delta}$ crystals. In these experiments,[2] the magnetization is observed to decay logarithmically with time and the extracted activation energies are more than an order of magnitude lower than ours. In the flux-creep framework, based on Eq. (2), the logarithmic decay is obtained in the case of strong driving forces where the argument of the sinh function is large. Our results show, however, that in this regime the actual behavior of the flux creep is different from the predictions of Eq. (2), and thus the calculated estimates of the activation energies may need to be revised. In particular, the observed logarithmic creep rate is proportional to dU/dJ (or $dU/d\nabla B$). If U decreases linearly with J, as is usually assumed,[12] $-dU/dJ$ equals U_0/J_C, where U_0 is the true pinning energy. However, since our results show a nonlinear current dependence, U_0 thus evaluated may be significantly underestimated. Using the observed logarithmic current dependence, with $J_0 \simeq 3\times10^6$ A/cm^2, the value of $J\,dU/dJ$ is lower by a factor of 6 than the actual pinning energy U_0 (which is U at 7×10^3 A/cm^2). This result and the above arguments may help to resolve the large discrepancies in the activation energies obtained from these different experiments.

In conclusion, we have found that the dissipation of $YBa_2Cu_3O_{7-\delta}$ epitaxial films can be significantly enhanced by increased current densities as well as by optical excitation. In both cases the observed transition from quasithermal equilibrium behavior to the enhanced dissipation regime occurs under the same low-resistivity and high-current conditions. In the latter regime, the dissipation is thermally activated with a unique nonlinear dependence of the activation energy on current density, a result that is essentially different from the predictions of the simple flux-creep model. Further investigation of this new regime is vital to the understanding of the dissipation mechanisms in the high-T_C superconductors as well as to their useful applications.

We thank Y. Yeshurun and A. P. Malozemoff for helpful discussions. E.Z. is grateful to the U.S.-Israel Educational Foundation for support.

---

[a]On leave from the Department of Electrical Engineering and Solid State Institute, Technion-Israel Institute of Technology, Haifa 32000, Israel.

[b]Permanent address: Physics Department, Technion-Israel Institute of Technology, Haifa 32000, Israel.

[1](a) T. T. M. Palstra, B. Batlogg, L. F. Schneemeyer, and J. V. Waszczak, Phys. Rev. Lett. **61**, 1662 (1988); (b) T. T. M. Palstra, B. Batlogg, R. B. van Dover, L. F. Schneemeyer, and J. V. Waszczak, Appl. Phys. Lett. (to be published).

[2]Y. Yeshurun and A. P. Malozemoff, Phys. Rev. Lett. **60**, 2202 (1988); Y. Yeshurun, A. P. Malozemoff, F. Holtzberg, and T. R. Dinger, Phys. Rev. B **38**, 11828 (1988), and references therein.

[3]G. Koren, A. Gupta, E. A. Giess, A. Segmuller, and R. B. Laibowitz, Appl. Phys. Lett. **54**, 1054 (1989); G. Koren, A. Gupta, and R. J. Baseman, Appl. Phys. Lett. (to be published).

[4]E. Zeldov, N. M. Amer, G. Koren, and A. Gupta, Phys. Rev. B **39**, 9712 (1989).

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

[6]J. D. Hettinger, A. G. Swanson, W. J. Skocpol, J. S. Brooks, J. M. Graybeal, P. M. Mankiewich, R. E. Howard, B. L. Straughn, and E. G. Burkhardt, Phys. Rev. Lett. **62**, 2044 (1989).

[7]Y. Iye, T. Tamegai, T. Sakakibara, T. Goto, N. Miura, H. Takeya, and H. Takei, Physica (Amsterdam) **153-155C**, 26 (1988); B. Oh, K. Char, A. D. Kent, M. Naito, M. R. Beasley, T. H. Geballe, R. H. Hammond, and A. Kapitulnik, Phys. Rev. B **37**, 7861 (1988); J. Y. Juang, J. A. Cutro, D. A. Rudman, R. B. van Dover, L. F. Schneemeyer, and J. V. Waszczak, Phys. Rev. B **38**, 7045 (1988).

[8]V. Ambegaokar and B. I. Halperin, Phys. Rev. Lett. **22**, 1364 (1969); Yu. M. Ivanchenko and L. A. Zil'berman, Pis'ma Zh. Eksp. Teor. Fiz. **8**, 189 (1968) [JETP Lett. **8**, 113 (1968)].

[9]P. W. Anderson, Phys. Rev. Lett. **9**, 309 (1962); M. Tinkham, *Introduction to Superconductivity* (McGraw-Hill, New York, 1975).

[10]We emphasize that even at the high-current densities we observe flux-creep, *not* flux-flow behavior. See recent discussion in Ref. 1(b).

[11]Tinkham's approach (Ref. 5) can be extended to high-current densities by use of the Josephson-junction results in Ref. 8; however, the resulting current dependence of the activation energy is still significantly different from the experimental data.

[12]M. R. Beasley, R. Labusch, and W. W. Webb, Phys. Rev. **181**, 682 (1969).

[13]J. Talvacchio, M. G. Forrester, and A. I. Braginski, in *Science and Technology of Thin-Film Superconductors,* edited by R. McConnell and S. A. Wolf (Plenum, New York, 1989), and references therein.