Flux creep characteristics in high-temperature superconductors

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We describe the voltage-current characteristics of $YBa_2Cu_3O_{7-\delta}$ epitaxial films within the flux creep model in a manner consistent with the resistive transition behavior. The magnitude of the activation energy, and its temperature and magnetic field dependences, are readily derived from the experimentally observed power law characteristics and show a $(1 - T/T_c)^{3/2}$ type of behavior near T_c. The activation energy is a nonlinear function of the current density and it enables the determination of the shape of the flux line potential well.

Recent work[1–5] attributes the resistive transition in high-temperature superconductors, in the presence of magnetic fields, to flux creep.[6] In particular, the exponentially decreasing resistivity on the low-temperature side of the transition[1,3,4] is consistent with the thermally assisted hopping of the flux lines, which are otherwise pinned due to some structural defects. Although this thermally activated behavior is generally understood, the voltage-current (V-I) characteristics, and especially the power law behavior at elevated current densities, are still controversial. Attempts have been made[7] to explain these characteristics based on the Kosterlitz–Thouless (KT) type of transition.[8] Also, a transition into superconducting "vortex-glass" phase has been proposed recently.[9] We carried out a systematic study of the resistive transition and the V-I characteristics in the presence of high magnetic fields where one would not expect KT effects. We find that both the thermally activated resistivity and the power law characteristics are consistent with the flux creep model,[6] *without* the need to invoke any additional dissipation mechanisms. The key feature that resolves the controversial results is the nonlinear current dependence of the activation energy, U. Such a dependence is due to the particular shape of the flux line potential well which we derive from the experimental data. In addition, since the power law constants of the V-I characteristics are shown to be directly related to the activation energy, we are able to obtain the temperature dependence of U from our data.

High quality $YBa_2Cu_3O_{7-\delta}$ epitaxial films were laser ablated onto (100) $SrTiO_3$ substrates and patterned by an excimer-laser-microscope system[10] to form a microbridge 0.4 μm thick, 24 μm wide, and 200 μm long. The four-probe dc technique was used and in addition, an ac measurement was made to rule out heating effects.

Figure 1(a) shows the resistive transition at a field of 6 T and various current densities. At low temperatures, the resistivity is thermally activated and U is strongly current dependent. It is tempting to interpret[1] the rather straight lines of this Arrhenius plot as an indication of a temperature-independent U with resistivity $\rho = \rho_0 e^{-U/kT}$. However, the slope of the curves, $U_{eff} = -kd(\log\rho)/d(1/T)$, is equal to $U - TdU/dT$ rather than simply being U. The correction term, due to the temperature derivative of U, may be very significant[5] and may cancel out the temperature dependence of U. This effect is shown in Fig. 1(b) where we plot the experimental U_{eff} derived from Fig. 1(a) along with theoretical U and U_{eff} based on Tinkham's model[2]: $U(t) = U(0)(1-t^2)(1-t^4)^{1/2}$, where $t = T/T_c$. At lower temperatures, the theoretical U_{eff} is only weakly T dependent in contrast to U, and fits the data well in the flux creep regime. The initial rise in the experimental curves at high temperatures corresponds to the gradual decrease of ρ with decreasing T in the flux flow regime,[5] while the thermally activated behavior of the flux creep is observed at lower T. We emphasize that it is not possible to derive, unambiguously, the value of U and its temperature dependence from the resistive transition data due to the correction factor in U_{eff}. U can be uniquely determined, however, from the V-I characteristics, as we show below, and the agreement of the data

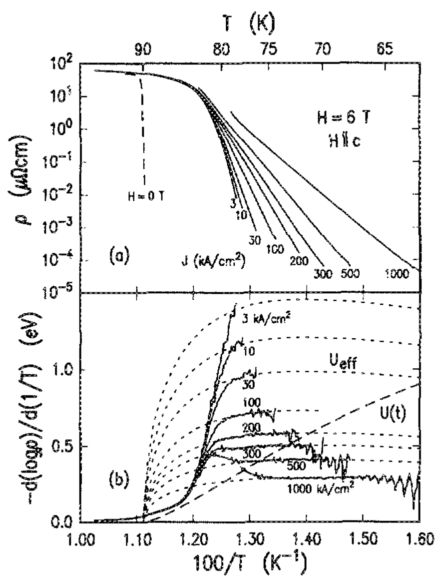

FIG. 1. (a) Arrhenius plot of the resitivity of $YBa_2Cu_3O_{7-\delta}$ epitaxial film at $H = 6$ T and various current densities. (b) The logarithmic derivative of the resistivity (solid lines), the theoretical activation energy $U(t) = U(0)(1-t^2)(1-t^4)^{1/2}$ (dashed), and the fit of the theoretical $U_{eff} = U(t) - tdU(t)/dt$ (dotted) to the experimental data. The "upward tailing" at the high-temperature end of the experimental curves at high currents is due to self-heating effects in the film.

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in Fig. 1(b) with the $(1-t)^{3/2}$ type of function is self-consistent with our V-I results.

From Fig. 1(b) we obtain the current dependence of U, as shown in Fig. 2. The logarithmic behavior[4] is remarkably accurate over almost three decades in current density. We thus write U in the general form of

$$U(t,H,J) = U_J(t,H)\ln(J_0/J), \qquad (1)$$

where J_0, the "critical current" at which U approaches zero, is of the order of 4×10^6 A/cm^2 and is generally magnetic field and temperature dependent.

Using the standard flux creep model,[6] the resistivity is given by

$$\rho = (2\nu_0 BL/J)\exp(-U_0/kT)\sinh(JBV_C L_p/kT), \qquad (2)$$

where U_0 is the nominal activation energy, L_p is the pinning potential range, and ν_0 is the attempt frequency of a flux bundle of volume V_C to hop a distance L. Equation (2) predicts a current independent ρ at low driving forces and an exponential current dependence at high driving forces. The latter, however, is based on the assumption of a linear current dependence of U. This approximation is generally not valid due to the distortion of the flux line potential well by the Lorentz force, resulting in a current-dependent L_p. Instead, we use the experimental $U(J)$ of Eq. (1) to obtain the ρ-J characteristics at high currents:

$$\rho = \frac{\nu_0 BL}{J}\exp\left(-\frac{U}{kT}\right) = \frac{\nu_0 BL}{J_0}\left(\frac{J}{J_0}\right)^{(U_J/kT)-1}. \qquad (3)$$

One then expects a transition from current-independent ρ at low currents to a power law behavior, rather than an exponential, at high J, consistent with the experimental results in Fig. 3. At high temperatures, the resistivity is current independent and the initial decrease of ρ with T is due to fluctuation effects followed by the flux flow. When ρ drops below $\simeq 10\%$ of ρ_n, the flux creep regime is reached where ρ is constant at low currents and shows a gradual transition into a power law regime at elevated J. Finally, at even lower temperatures, only the power law regime is accessible experimentally. Thus, we have a fundamental understanding of the ρ-J characteristics within the flux creep model which is consistent with the resistive transition behavior.

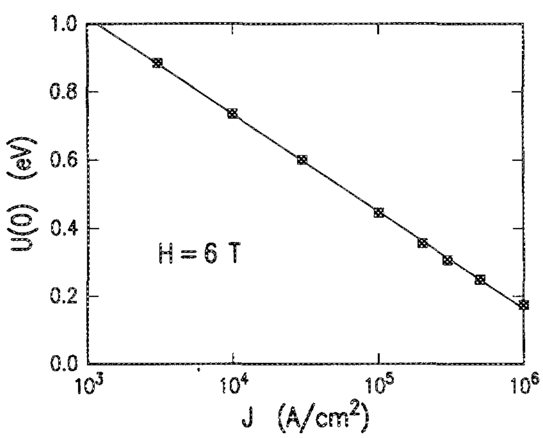

FIG. 2. Logarithmic current dependence of the activation energy as derived from Fig. 1.

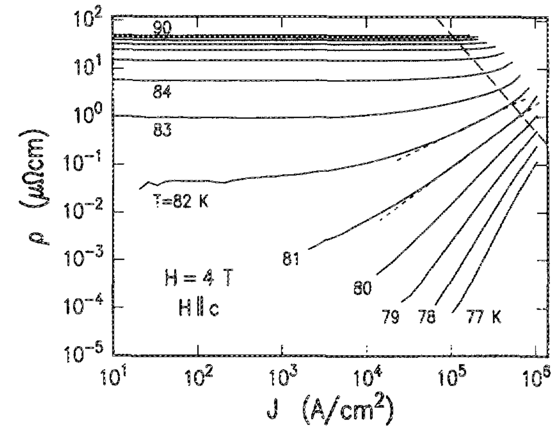

FIG. 3. Experimental ρ-J characteristics at various temperatures at $H=4$ T. The dotted lines emphasize the power law behavior at high current densities at the intermediate temperatures. The dashed curve in the upper right corner is the limit of 1 mW power dissipation in the film, above which the self-heating effects are observed.

The unique feature of Eq. (3) is that the power law factor depends solely on U_J. Hence, at a given temperature and magnetic field, the logarithmic slope of ρ-J curve at high currents gives the U_J value directly. Measuring the slope at various temperatures and magnetic fields allows us to find experimentally the T and H dependence of the activation energy (Fig. 4), an important and controversial issue.[5] Remarkably, at various magnetic fields, the temperature dependence of U_J is very close to the $(1-t)^{3/2}$ type of behavior predicted theoretically.[2,11] In addition, the magnetic field dependence of U_J is found to follow $H^{-1.28}$, again similar to the theoretical $1/H$ predictions.[2,3,11] Since J_0 enters logarithmically in Eq. (1), some possible variations in J_0 with T and H will not have a significant effect, and thus U exhibits temperature and field dependences very similar to that of U_J shown in Fig. 4. The uniqueness of Fig. 4 is that the results shown are a straightforward presentation of the power law

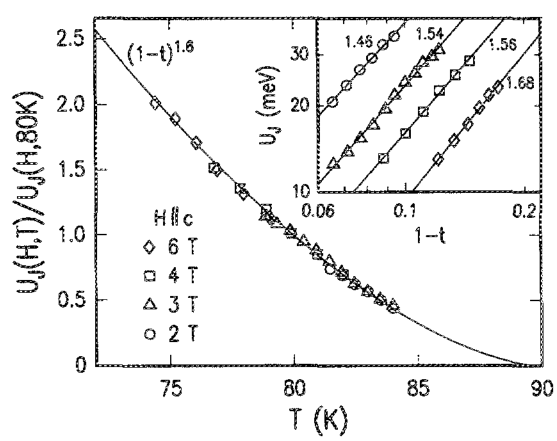

FIG. 4. Temperature dependence of U_J as obtained from the power law ρ-J characteristics. The data at fields of 2, 3, 4, and 6 T were normalized by 47.04, 27.27, 18.82, and 11.47 meV, respectively, to compensate for the H dependence of U_J and to emphasize the temperature dependence. Inset: U_J vs $1-t$ showing the $(1-t)^n$ type of behavior with $n\simeq 3/2$. The small gradual increase of n with H may indicate some field dependence of T_c; the n values shown were evaluated using a constant zero field $T_c = 89.9$ K.

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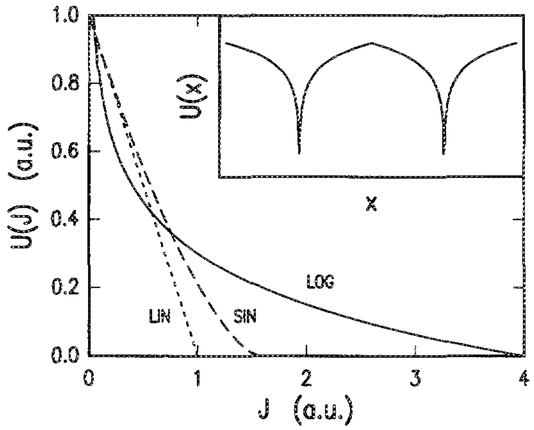

FIG. 5. Current dependence of U for the sawtooth (dotted) and harmonic (dashed) potential wells. Solid line: the observed logarithmic current dependence. Inset: the shape of the flux line potential well [Eq. (4)] giving rise to the logarithmic $U(J)$.

factors of the ρ-J characteristics and include no additional *a priori* assumptions. In contrast, one can derive U from the ρ vs T curves[1,3–5] only by assuming some temperature dependence of U, and the result will depend significantly on the particular choice.[4,5]

To obtain a deeper insight of the flux creep process described above, one has still to understand the nature of the logarithmic current dependence of U. To begin with, there is no physical reason for anticipating a linear $U(J)$, as commonly assumed. In the case of a sinusoidal potential well,[12] for example, $U(J)$ has the form shown by the dashed curve in Fig. 5. Experimentally, however, we observe a logarithmic current dependence as shown schematically by the solid line (at low currents U approaches some finite value of U_0).

We now seek a potential shape that gives rise to such $U(J)$. An exact analytical solution is given by the following function:

$$U(x) = \begin{cases} ax/x_0 & 0 \leqslant x \leqslant x_0 \\ a[\ln(x/x_0) + 1] & x > x_0 \end{cases}, \tag{4}$$

where a and x_0 are energy and position scaling factors, respectively. Using this function we construct a potential well which is shown schematically in Fig. 5. In this case, the flux line potential is localized in a narrow cone-like structure which exhibits a broad logarithmic decay. A physical mechanism that may result in such a potential well is a single defect that destroys or reduces the order parameter in a small volume within a radius of the order of the coherence length ξ. A single vortex will be in its lowest energy state at the defect location. Since in these high κ materials ($\kappa = \lambda/\xi$), the magnetic field of an isolated vortex decays logarithmically with distance in the range between ξ and the penetration depth λ, we expect the energy of the vortex to increase in some logarithmic way as its distance from the defect increases. Thus, the derived form of the potential well in Fig. 5 is rather plausible, with x_0 in Eq. (4) of the order of ξ and the separation between the adjacent wells equal to the Abrikosov lattice spacing a_0.

The logarithmic $U(J)$ has important implications and should be investigated in various high T_c systems in order to understand its origin. An illustrative example of the experimental significance of this result is the interpretation of the resistively measured critical current,[3,13] J_c, using some voltage criterion E_c. In the logarithmic case, we obtain the relation $J_c = J_0(E_c/2v_0BL)^{kT/U_J}$, which is different from the one derived from Eq. (2) for the linear case.[3] Furthermore, J_0 is determined by the maximum restoring force of the potential well, whereas J_{c0} in the linear case is related directly to U_0.

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