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Role of anisotropy in the dissipative behavior of high-temperature superconductors

T. T. M. Palstra, B. Batlogg, L. F. Schneemeyer, and J. V. Waszczak
AT&T Bell Laboratories, 600 Mountain Avenue, Murray Hill, New Jersey 07974
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In a comparative study of the dissipative behavior of various classes of high-T_c superconductors in large magnetic fields, we demonstrate that materials with a large electronic anisotropy, like the Bi and Tl compounds, have intrinsically smaller pinning energies than more isotropic materials. Consequently, the highly anisotropic materials exhibit thermally assisted dissipation down to temperatures far below T_c. In spite of small pinning energies, large critical current densities J_c can be observed in the critical-state regime at $T < T_{cr}$. In this regime irradiation damage produces large changes in J_c, but only modest changes in the magnitude of the pinning energies as evidenced in the thermally activated regime. We introduce a general criterion, which denotes the temperature and magnetic-field regime in which superconductors can be applied.

In the high-temperature superconductors vortex pinning energies are comparable to thermal energies in a large part of the magnetic-field–temperature (H-T) phase diagram. Consequently, the dissipation in this regime is dominated by thermally assisted flux motion,[1,2] which has been described successfully by various diffusion models.[3–6] It is generally believed that the small magnitude of the activation energies is mostly related to the small coherence length.[7] In this paper we demonstrate that the low pinning energies are in addition related to the large anisotropy of these materials, i.e., the coupling strength between the superconducting Cu-O layers. The activation energies for flux motion are found to decrease systematically with increasing anisotropy.

The second subject of this paper is to explore the relation between the value of the depinning critical currents J_c and the pinning energies $U(T)$ in these anisotropic media. It was observed experimentally that the critical current density J_c can vary by 2 orders of magnitude when comparing single crystals and thin films of the same material, yet the width of the resistive broadening in an applied magnetic field is very similar.[8,9] A similar observation is that the "irreversibility line" remains unaffected by irradiation damage, whereas J_c does change.[10] In this paper we will discuss an interpretation of this behavior, as well as the practical consequences: In which part of the H-T phase space can we exploit the superconducting properties of the high-T_c materials? We restrict ourselves to "well-connected" materials and exclude the influence of weak links, grain boundaries, etc.

First, the relationship between anisotropy and activation energies is discussed. Figure 1(a) shows the resistive transition of single crystals of representatives of various classes of the high-T_c compounds: $Ba_2YCu_3O_{7-\delta}$ for $\delta \approx 0$ and 0.3, $Bi_2Sr_2CaCu_2O_8$, and $Tl_2Ba_2CaCu_2O_8$. A magnetic field of 5 T is applied perpendicular to the Cu-O planes, and the scales are normalized to $\rho_n(T_c)$ and T_c. Clearly, there is a distinct difference in their behavior, e.g., $Ba_2YCu_3O_7$ has a vanishing resistance (on this scale) for $T/T_c \approx 0.9$, whereas for Tl 2:2:1:2 the resistance becomes immeasurably small only for $T/T_c \approx 0.3$.

Previously, we have shown that the "foot" of the field-broadened $\rho(T)$ curve can be associated with thermally activated flux motion:[1]

$$\rho(T)/\rho_0 = \exp(-U(T)/k_BT)\,, \tag{1}$$

with the prefactor ρ_0 related to the vortex diffusion constant in the absence of pinning, and $U(T)$ the temper-

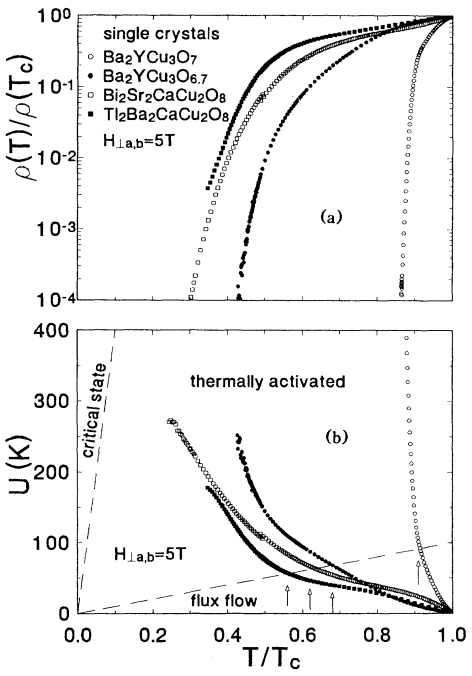

FIG. 1. (a) The temperature dependence of the resistive transition in a magnetic field of 5 T perpendicular to the Cu-O planes, normalized for ρ_n and T_c, for representatives of various classes of high-temperature superconductors: $Ba_2YCu_3O_7$ (open circles), $Ba_2YCu_3O_{6.7}$ (solid circles), $Bi_2Sr_2CaCu_2O_8$ (open squares), and $Tl_2Ba_2CaCu_2O_8$ (solid squares). (b) The temperature dependence of the activation energies for flux motion for these four compounds derived from the resistivity data (see text). Indicated are the different regimes for flux motion: flux flow for $U(T) < k_BT$, thermally activated regime for $1 < U(T)/k_BT < 40$, and the critical state for $U(T) > 40k_BT$. The arrows indicate the crossover temperature T_x from flux flow to thermally activated dissipation at $U(T) \approx k_BT$.

ature-dependent pinning energies. This means that for a given field, $U(T)$ can be obtained by replotting the data of Fig. 1(a) as

$$U(T) = k_B T \ln(\rho_0/\rho(T)) . \quad (2)$$

The value of $U(T)$ is only weakly dependent on ρ_0, and ρ_0 can be estimated from reasonable assumptions. Previously, ρ_0 was taken within the Bardeen-Stephen[11] dissipation model: $\rho_0 = \rho_n H/H_{c2}$, or it was deduced from a graphical extrapolation of $\rho(T)$ vs T^{-1} in the limit $T^{-1} \rightarrow 0$.[12] For simplicity, we take $\rho_0 = \rho(T_c)$. While introducing a small systematic error in our estimate of the pinning energy $U(T)$, this does not affect the comparison between the various compounds. Thus, we construct the temperature dependence of $U(T)$ as shown in Fig. 1(b) for these high-T_c materials.

From Fig. 1(b) we can see that there is a temperature where the activation energy becomes comparable to thermal energies.[13] This is, in our interpretation, the transition from the thermally activated dissipation regime with $U \gtrsim k_B T$ to the flux flow regime, $U < k_B T$, where flux motion is no longer impeded by energy barriers but only by a viscous drag force. We denote this crossover temperature by T_x and see that, for $H_\perp = 5$ T, $T_x \sim 80$ K for $Ba_2YCu_3O_7$, but $T_x \sim 50$ K for $Bi_2Sr_2CaCu_2O_8$. Obviously, T_x is magnetic-field dependent in that T_x increases in lower fields. The temperature dependence of $U(T)$ shown in Fig. 1(b) indicates that the zero-temperature activation energy is largest for $Ba_2YCu_3O_7$ and lowest for Tl 2:2:1:2.

Now we will relate the value of T_x to the anisotropy. The anisotropy of the various high-T_c materials is a consequence of their layered crystal structure with stacks of "conducting" (high conduction electron density) Cu-O sheets, alternating with sheets of "poorly conducting" (low conduction electron density) material like Bi-O or Tl-O. This electronic anisotropy has been probed in various ways, such as the electrical resistivity anisotropy ρ_c/ρ_{ab}.[14] For the present discussion the anisotropy of the superconducting properties is particularly significant, and magnetic torque measurements in the reversible regime below T_c seem to be an appropriate method to measure them.[15–17] These results were analyzed in terms of an effective mass anisotropy. (Again, the present conclusions do not depend on how the anisotropy is measured in detail.) Defining $\gamma = (m_c/m_{ab})^{1/2}$ it was found that γ varies from ≈ 5 for $Ba_2YCu_3O_7$ to values as large as ≈ 50 for Bi 2:2:1:2 and $\gamma \approx 100$ for Tl 2:2:1:2. In Fig. 2 the value of T_x/T_c is plotted for various materials versus the value of γ from magnetic torque measurements. From this plot it is clear that increasing anisotropy results in a systematic decrease of T_x. Replacing γ by $(\rho_c/\rho_{a,b})$ gives a similar plot.

In conventional superconductors this change in behavior from stronger pinning for $Ba_2YCu_3O_7$ to weaker pinning Tl 2:2:1:2 would be attributed to the particular defect structure of each material and the interaction between the defects and the vortices. However, in the high-T_c superconductors the different activation energies can be explained in a natural way by correlating tilt modulus of the vortices with the anisotropy of the material:[18,19] The tilt modulus of the vortices is reduced by the poorly

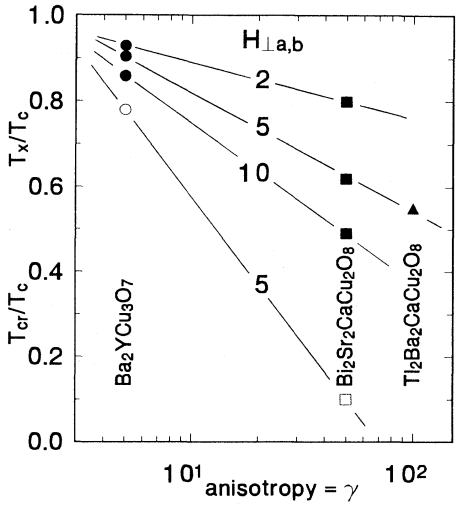

FIG. 2. Dependence of the crossover temperatures T_{cr} (open symbols) and T_x (solid symbols) normalized for T_c on the electronic effective mass anisotropy in various magnetic fields $H_{\perp a,b}$ for $Ba_2YCu_3O_7$ (circles), $Bi_2Sr_2CaCu_2O_8$ (squares), and $Tl_2Ba_2CaCu_2O_8$ (triangle).

conducting sheets of Bi-O or Tl-O, where the supercurrent density is much lower than in the "conducting" Cu-O sheets. If the Cu-O sheets were completely electronically decoupled, the vortices in adjacent layers would only have a magnetic interaction. This means that the length scale L_c along the vortex over which a vortex can move independent of the rest of the vortex structure will be much smaller for large anisotropy. Consequently, the activation energies for flux motion also will be small for high-anisotropy compounds, as the pinning energy scales with the correlation volume of the vortices. For the very anisotropic Bi and Tl compounds, the correlation lengths L_c are apparently so small that the pinning energies are as small as a few $k_B T$ in a large part of the H-T phase diagram. Therefore, we think that the anisotropy is an important concept to explain the small activation energies. A comparison with NbN [isotropic, low T_c, small coherence length, no resistive broadening, and thus large $U(T)$][20] and the transition-metal dichalcogenides [anisotropic, low T_c, significant resistive broadening, and thus small $U(T)$][21] further underlines this reasoning.

Having identified the small pinning energies with the large anisotropy, we now turn to the consequences of low activation energies for the critical current J_c. Formally J_c is related[4] to $U(T)$ via $U = J_c B V_c r_p$, with V_c the volume of correlated vortices moving independently of the rest of the vortex structure, and r_p the range of the pinning potential. V_c is set by two length scales: $V_c = R_c^2 L_c$, with R_c and L_c the correlation lengths of the vortices perpendicular and parallel to the vortices, respectively. As we argued above L_c is smaller for the very anisotropic Bi and Tl compounds than for Y 1:2:3. Therefore, J_c of the very anisotropic materials can be as large as in more isotropic materials, because the smaller value of $U(T)$ can be offset by the reduction of V_c. A more intuitive picture is that in the very anisotropic materials the vortices can fully exploit the

pinning sites in each CuO layer, without being opposed by the vortex stiffness. Thus, the small activation energies observed in the thermally activated regime are not in contradiction with the large values of J_c in the critical state.

The unfortunate consequence of the two-dimensional (2D) nature of these materials, however, is that the regime in H-T phase space in which the resistivity is negligible, i.e., the critical state, is enormously reduced. One may separate the critical state from the thermally activated regime by the "practical" criterion that the supercurrents decay slower than $1:10^4$/h. Assuming thermally activated dynamics $[\tau=\tau_0\exp(-U/k_BT)]$ with an attempt frequency $\tau_0=10^9$ Hz, this yields a criterion used to design superconducting magnets:[22]

$$\rho/\rho_0=\exp(-U(T)/k_BT)\sim 10^{-16}. \quad (3)$$

This occurs at a temperature T_{cr} at which $U(T)\sim 40k_BT$, as indicated in Fig. 1(b). Extrapolating the linear temperature dependence of $U(T)$, we have plotted the magnetic-field dependence of this crossover temperature T_{cr} in Fig. 3. Thus we separate the dissipation into three regimes: flux flow for $U(T)\lesssim k_BT$ at $T>T_x$, thermally activated dissipation for $k_BT\lesssim U(T)\lesssim 40k_BT$, and the critical-state regime for $U(T)\gtrsim 40k_BT$ at $T<T_{cr}$.

The two criteria T_x and T_{cr} can be compared with other frequently used characteristic temperatures of high-temperature superconductors, notably the irreversibility line and the vortex-glass transition temperature.[23] The irreversibility line T_{irr} is defined as the temperature where the vortex relaxation time equals the measurement frequency, and is thus frequency dependent. It concurs with our criterion T_{cr} for a measurement time $\tau=10^4$ h and it equals T_x when τ is the vortex attempt frequency. The vortex glass transition T_{gl} is defined as the temperature at which the linear resistivity becomes zero, and was inferred from nonlinear resistivity measurements. As our measurements are in the low-current (linear response) regime, T_{gl} is smaller than the range in which the resistivity is measurable. Irrespective of the nature of vortex dynamics at these temperatures (vortex glass[23] versus collective flux creep[5]), we can always define the criterion T_{cr} at $U=40k_BT$ for practical applications. The nature of the dynamics will, of course, influence the extrapolation of our data ($U<10k_BT$) to define T_{cr}, but this effect is small and does not affect the comparison between the various compounds.

For practical application one has to operate the superconductors in the critical state, which is for Y 1:2:3 for $T/T_c<0.8$ at $H_{\perp a,b}=5$ T, but for Bi 2:2:1:2 and Tl 2:2:1:2 this means that $T/T_c<0.1$ at the same magnetic field. Obviously this criterion can be relaxed for smaller magnetic fields, or for other orientations of the magnetic fields (see Fig. 3) with respect to the basal planes or the electrical current direction. In zero applied field only the self-field has to be considered, which relaxes the criterion to $T/T_c\lesssim 1$.

Finally, we want to discuss the consequences of "artificial" pinning sites, e.g., irradiation damage, precipitates, on the pinning energy $U(0)$ and the critical current J_c. High-energy ion beam irradiation damage is able to produce localized damage on length scales of the order of the coherence length, creating strong pinning centers.[24] However, as a result of the strong pins the vortex lattice will be disordered, reducing the correlation length R_c. This means that an enhancement of the pinning force, $J_c\phi_0$, is accompanied by a reduction of the correlation volume V_c. Therefore, $U(0)$ can remain relatively unchanged upon ion beam irradiation, even as the critical current can be enhanced significantly.

This is the model we propose to understand the result of controlled damage, as shown in Fig. 4. Here, the resistive transition of single crystal Bi 2:2:1:2 is plotted in a magnetic field of $H_{\perp a,b}=1$ T with 2 MeV He ion beam irradi-

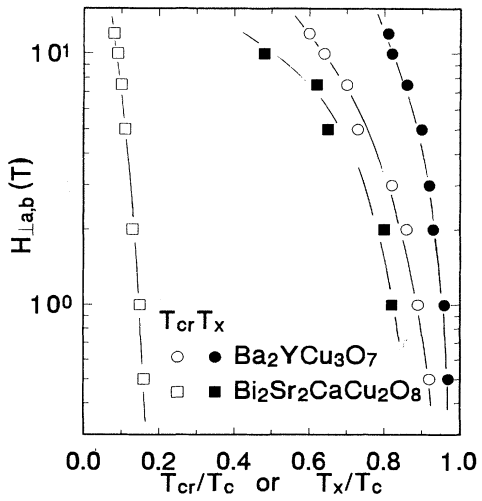

FIG. 3. Dependence of the crossover temperatures T_{cr} (open symbols) and T_x (solid symbols) normalized for T_c on the magnetic field $H_{\perp a,b}$ for $Ba_2YCu_3O_7$ and $Bi_2Sr_2CaCu_2O_8$.

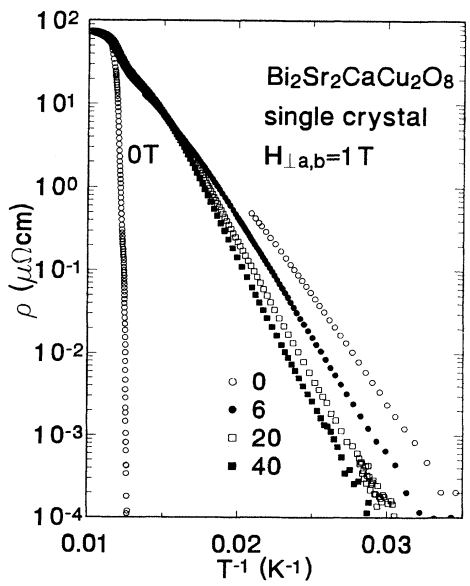

FIG. 4. Temperature dependence of the electrical resistivity of $Bi_2Sr_2CaCu_2O_8$ in $H_{\perp a,b}=1$ T upon irradiation damaging with a fluence of 0, 6, 20, and 40×10^{13} 2 MeV He/cm^2.

ation. We observe that the resistivity changes by as much as a factor of 30, however, the activation energies change only by 25%, and T_{cr}/T_c increases only from 0.12 to 0.16.[25] It should be realized that the difference in pinning energies between Bi 2:2:1:2 and Y 1:2:3, as estimated from Fig. 1(b), is as much as a factor of 100. On this scale our results are negligible. Still, the critical current J_c has been observed in single crystal Y 1:2:3 to increase by 2 orders of magnitude by irradiation damage.[9]

We conclude, therefore, that *strong* pinning sites will enhance J_c, but as the flux line lattice is disordered (smaller V_c) the pinning energies $U(0)$, and therefore the resistive broadening, will hardly change. It should be realized that the magnitude of $U(0)$ also determines the crossover temperature to the critical state, T_{cr}, and therefore the regime in H-T phase space in which these materials can be operated.[26] A better pin structure will be provided by *weak* pins, which will no disrupt the correlation in the flux-line lattice.

We think that the anisotropy of the materials is determined by the particular building blocks separating the parts with large conduction electron density, the Cu-O planes, and low conduction electron density, like the Bi-O and Tl-O double layers. Therefore, we expect that the anisotropy is similar for compounds with the same "insulating" building blocks like the Bi 2:2:1:2, the Bi 2:2:2:3, or Bi 2:2:0:1 series or the Tl 2:2:1:2, Tl 2:2:3:4, and other series. Thus within such a series we think that the critical and thermally activated regimes span about the same parts of the H-T phase diagram.

In conclusion, we have demonstrated that the pinning energy is mostly determined by the anisotropy of the high-temperature superconductors. We have defined a general criterion of $U=40k_BT$ for applications of superconductors, denoting the crossover temperature T_{cr} from the critical state to thermally assisted flux motion. We found a clear relation of the anisotropy with T_{cr} and with T_x which denotes the crossover from the thermally activated regime to the flux flow regime, $U/k_BT\sim 1$. In particular, the least anisotropic high-T_c material $Ba_2YCu_3O_7$, has the highest pinning energies. In the very anisotropic materials high values of J_c can still be obtained in the critical state. However, the most anisotropic materials have the smallest critical state regime extending only up to $\sim 0.15T_c$ for $H_{\perp a,b} > 0.5$ T.

Irradiation damage can increase the critical current by a few orders of magnitude in the critical state. In the thermally activated regime the resistivity can be changed a few orders of magnitude. However, the magnitude of the pinning energy can be hardly affected and therefore the size of the critical regime can only moderately be affected with irradiation damage. This makes the anisotropic materials, like the Bi and Tl compounds, impractical for use at 77 K in large magnetic fields. At 77 K only Y 1:2:3 remains in the critical-state regime in magnetic fields up to 3–4 T perpendicular to the basal planes.

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[25]For $H_{\perp a,b}=10$ T, $\rho(T)$ was found to increase for doses beyond $20\times 10^{13}/\text{cm}^2$ 2 MeV He.

[26]The "irreversibility line" also hardly changes with irradiation because its position is determined only by the magnitude of $U(T)$ and not by J_c.