Full-penetration temperature and magnetic relaxation in a single crystal of $Bi_2Sr_2CaCu_2O_x$

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We have developed the concept of a characteristic temperature T^* at which the flux first fully penetrates the sample. Based on this concept, we have interpreted the effects of the temperature on the magnetic relaxation that have been measured in a single crystal of $Bi_2Sr_2CaCu_2O_x$ in a broad range of temperature (5–35 K) and applied magnetic field (0.1–4 kG). The magnetic relaxation exhibits a clear peak in the $dM/d\ln t$-versus-temperature plot, and the peak position is highly affected by the applied field. We have also interpreted the peak shift of $dM/d\ln t$ with different fields in terms of the flux-creep and the critical-state models.

INTRODUCTION

It has been experimentally observed that high-T_c superconductors exhibit strong magnetic relaxation which decreases logarithmically with time. This pehnomenon has been explained by the giant flux-creep model.[1–5] Such behavior indicates that high-T_c superconductors may not be able to support supercurrents persistently in certain temperature and field regions.

The activation energies of high-T_c superconductors have also been estimated to be much lower than those of conventional superconductors. More important, a so-called irreversibility line has been discovered in both Y-Ba-Cu-O and Bi-Sr-Ca-Cu-O systems. The existence of this irreversibility line indicates that the flux-motion behavior in high-T_c superconductors may be fundamentally different from that in conventional superconductors. Palstra *et al.*[6–8] measured the resitive-transition broadening in the applied field and observed a thermally assisted dissipation in both $YBa_2Cu_3O_y$ and $Bi_2Sr_2CaCu_2O_x$. Their results showed that this dissipation can cause significant electrical resistance even well below T_c. To interpret these observations in both inductive and transport experiments, various models have been proposed, including the energy distribution model,[9] the collective pinning model,[10] and the vortex-glass model.[11,12]

In the present paper we report measurements of the magnetic relaxation in a single crystal of $Bi_2Sr_2CaCu_2O_x$. We have extended the investigation of the relationships between the relaxation rates and temperature at various applied fields. Specifically, we have introduced the full-penetration-temperature concept based on the critical-state model, and we have interpreted the magnetic relaxation data with a previously developed theoretical expression in terms of the Anderson-Kim flux-creep model.[1,4,5,13]

EXPERIMENT

The single crystal used in this study was grown with the flux method given earlier.[4] The quality of the crystal was examined by x-ray-diffraction, resistivity, and magnetization measurements. The x-ray-diffraction results showed a single $Bi_2Sr_2CaCu_2O_x$ phase. A superconducting transition with a width $\Delta T \sim 6.5$ K at 87 K was observed in the magnetization experiments at an applied field of 0.5 G. The magnetization data were taken with a commercial superconducting quantum interference device magnetometer over a wide range of temperature (5–35 K) and applied field (0.1–4 kG). The sample was first cooled in zero magnetic field (ZFC) to a desired temperature T below the transition temperature T_c. A magnetic field H was then applied, and the magnetization M of the sample was measured as a function of time t. The initial data point of the magnetization was taken at $t_i = 180$ sec after the field was set. The direction of the applied field was normal to the a-b plane of the single crystal.

RESULTS

Figure 1 shows magnetization-versus-time data at different temperatures and at the field of 1 kG. Plots of the magnetization versus $\ln(t)$ roughly give straight lines, indicating the logarithmic behavior of the time decay. As can be seen in the figure, the magnetization exhibits small relaxation rates at low temperatures (5–8 K). The relaxation rate gradually increases with increasing temperature, reaching a maximum at 10 K, and then decreases at higher temperatures. At 20 K the system nears an equilibrium state, and only a very small change in the magnetization is observed.

In Fig. 2 we plot the relaxation rate $(dM/d\ln t)$ as a function of temperature for applied fields of 0.1, 0.5, 1, and 4 kG, which are taken between $\ln(t) = 7.0$ and 9.4 by a computer fitting program, since the relaxation rate becomes nearly constant at a given temperature in this time interval. The relaxation rate initially increases with increasing temperature at low-temperature regions for all fields except 4 kG. For instance, at 1 kG $dM/d\ln t$ peaks near 10 K, as shown in Fig. 2(c). Figure 2 also shows a clear shift in the peak of $dM/d\ln t$ versus T with different applied fields. The estimated peak temperatures are 20, 12, and 10 K for applied fields of 0.1, 0.5, and 1 kG, respectively. However, it was observed that $dM/d\ln t$ de-

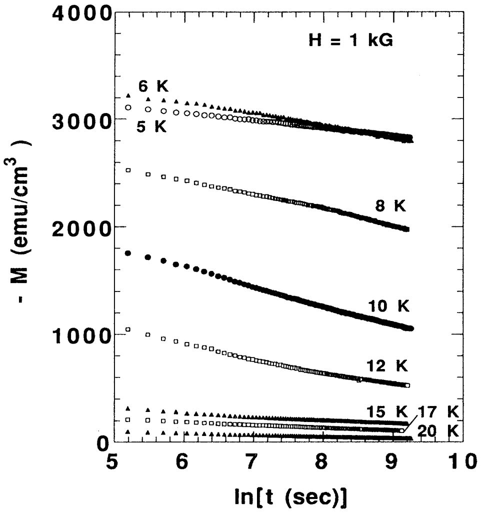

FIG. 1. Magnetization vs time at a given field $H=1$ kG for a single crystal of $Bi_2Sr_2CaCu_2O_x$ at temperatures indicated. The field, parallel to c, is applied after cooling the sample in zero field.

creases monotonically with temperature down to 5 K for an applied field of 4 kG.

DISCUSSION

Logarithmic time decay of the magnetization has been well described by the flux-creep model for conventional superconductors.[13] According to this model, thermal activation causes the flux lines in the critical state to hop over a potential well U_0. Yeshurun *et al.*[1–3] have interpreted the magnetic relaxation behavior in high-T_c superconductors by combining an extended Bean's critical-state model and the flux-creep model.

With a different approach, we developed an expression to describe the magnetic relaxation behavior over a much wider field regime.[4] As proposed previously, a local critical current density can be written as

$$J_c(T,H_i)=J_c(T)(1-H_i/H_0)\ , \tag{1}$$

where H_i is the local magnetic field, $J_c(T)$ is a microstructure-related parameter with the dimension of current density, and H_0 is a material parameter with the dimension of field. Obviously, $J_c(T)$ is the critical current density at zero field. The parameter H_0 is probably the characteristic field related to H_{c1}, H_c, and H_{c2}.[4]

Recently, a generalized critical relation was proposed, which unifies all previous forms of the critical-state model.[14] Equation (1) can be easily obtained from this generalized critical-state relation with the condition $H_i/H_0 \ll 1$. A previous study indicates that the linear critical relation Eq. (1) is a good approximation at least at low temperature and field.[4] It should also be noted that the linear critical-state relation [Eq. (1)] is the simplest function among the various field-dependent critical current densities. But it makes a completely different feature from the Bean model in the magnetic relaxation behavior, especially in the full-penetration case.[4]

In a critical state, $-dH_i/dx=4\pi J_c(T,H_i)/c$, where c is the speed of light, and $J_c(T,H_i)$ is the critical current density at the temperature T and local field H_i [Eq. (1)]. If we assume that the lower critical field H_{c1} is negligible and that D is the dimension of the sample perpendicular to the applied field, the magnetization is given by[4]

$$4\pi M=-H-H_0\frac{2x_0}{D}\ln\left[1-\frac{H}{H_0}\right]-\frac{2x_0}{D}H\ ,\quad H\le H^*\ , \tag{2a}$$

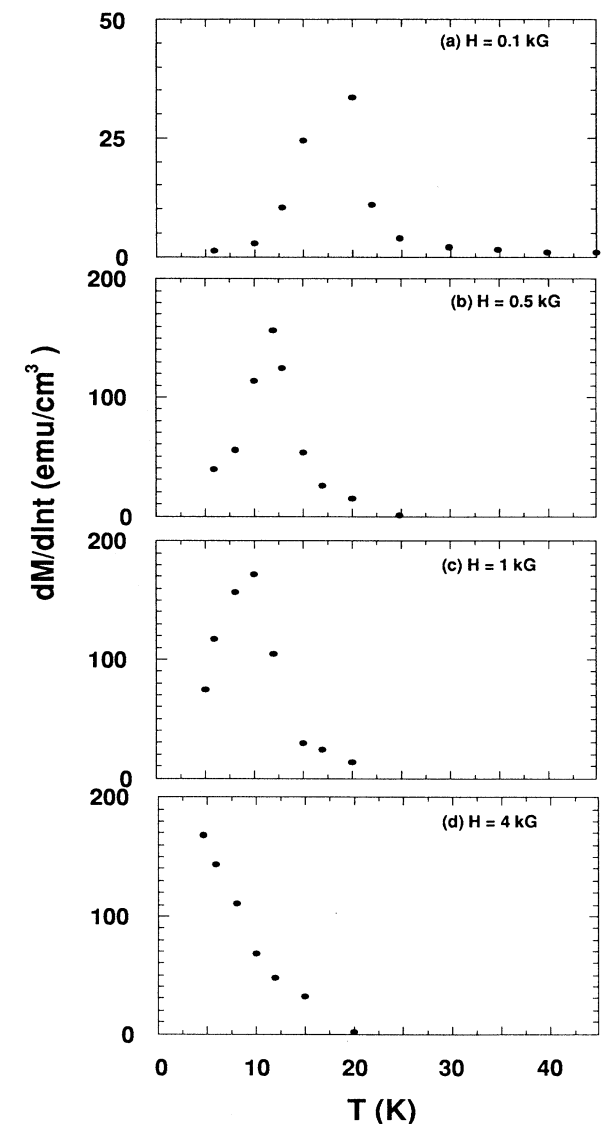

FIG. 2. Magnetic relaxation rate ($dM/d\ln t$) vs temperature at (a) $H=0.1$ kG, (b) $H=0.5$ kG, (c) $H=1.0$ kG, and (d) $H=4.0$ kG.

$$4\pi M = -H + H_0 + \frac{2x_0}{D}\left[\exp\left[\frac{D}{2x_0}\right] - 1\right](H - H_0)\ , \quad H \geq H^*\ , \qquad (2b)$$

where $H^* = H_0[1 - \exp(-D/2x_0)]$, which is the field required for the flux first to fully penetrate the slab, and $x_0 = cH_0/4\pi J_c(T)$. The time dependence of the magnetization is implicit in the quantity x_0 through $J_c(T)$.

Flux creep causes a reduction in critical current density at low temperature given by[15]

$$J_c = J_{c0}[1 - (kT/U_0)\ln(t/t_0)]\ , \qquad (3)$$

where J_{c0} is the critical current density without thermal activation, $1/t_0$ is a characteristic attempt frequency for the flux line to hop over pinning barriers (typically on the order of 10^9 Hz), and t is the measuring time. Combining Eqs. (2) and (3), we find the derivative of the magnetization with respect to time to the lowest order of kT/U_0:[4]

$$4\pi\frac{dM}{d\ln t} = \alpha\left[\frac{H^2}{H_0}\right]\left[\frac{kT}{U_0}\right]\ , \quad H \leq H^*\ , \qquad (4a)$$

$$4\pi\frac{dM}{d\ln t} = \beta(-H + H_0)\left[\frac{kT}{U_0}\right]\ , \quad H \geq H^*\ , \qquad (4b)$$

where $\alpha = x_0/D$, and $\beta = (2x_0/D)\{1 + [(D/2x_0) - 1]\exp(D/2x_0)\}$. It should be pointed out that the original form of Eq. (4a) is

$$4\pi\frac{dM}{d\ln t} = H_0\frac{2x_0}{D}\left[-\ln\left[1 - \frac{H}{H_0}\right] - \frac{H}{H_0}\right]\frac{kT}{U_0}\ , \quad H \leq H^*\ . \qquad (4a')$$

If the condition $H/H_0 \ll 1$ is satisfied, the term $\ln(1 - H/H_0)$ can be expanded to be $-H/H_0 - (H/H_0)^2/2$. Thus Eq. (4a') can be simplified and written as Eq. (4a).

As shown in Eq. (4), $dM/d\ln t$ increases with H^2 in the low-field region with $H < H^*$ and decreases linearly in the relatively higher-field region ($H > H^*$). This fact has been confirmed experimentally[4] by fitting the $dM/d\ln t$-verus-H curves with Eq. (4). As indicated earlier, the peak of $dM/d\ln t$ verus H should shift to lower fields with increasing temperature, and the peak position of $dM/d\ln t$ is roughly the full-penetration field H^*.

Next, we focus on the analysis of the $dM/d\ln t$-versus-T curves and consider the temperature effects on the critical state at a given applied field. We use the same formulas as mentioned above, but with a different physical interpretation and understanding of the temperature dependence of the critical-state model. The temperature T^* required for the flux to first fully penetrate the sample is denoted by

$$H = H_0(T^*)\{1 - \exp[-D/2x_0(T^*)]\}\ , \qquad (5)$$

as indicated earlier.[4,5] Figure 3 shows the local-magnetic-field distribution in a slab with thickness D at the different temperatures, but with a constant field. This figure describes the field profile for $T < T^*$ [Fig. 3(a)] and

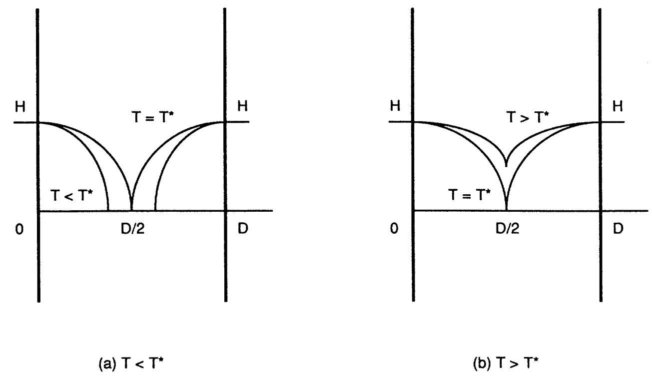

FIG. 3. Local-field distribution for a slab based on the critical-state model in the two cases: (a) $T < T^*$, and (b) $T > T^*$, respectively.

$T > T^*$ [Fig. 3(b)], respectively. As can be seen from the figure, the slab is partially penetrated by the local field for $T < T^*$, and it is fully penetrated only for $T > T^*$. Since the gradient of the local field is proportional to the critical current density, the gradient of the field decreases for lower current density. This is consistent with the physical meaning of critical current density as shown in Fig. 3, namely, that the gradient becomes flat with increasing temperature after full penetration.

Equation (5) is a complicated relation between the field H and the full-penetration temperature T^*. When the condition $D/2x_0 \ll 1$ is satisfied, this relation can be simplified as[16]

$$J_c(T^*) = cH/2\pi D\ . \qquad (6)$$

According to Eq. (6), $J_c(T^*)$ is proportional to H, and $J_c(T^*)$ decreases with T^* as long as a condition $dJ_c/dT|_{T^*} < 0$ holds.[17] This equation suggests a decreasing dependence of T^* with increasing field. This prediction is met by the experimental data shown in Fig. 2; i.e., the peak position ($\sim T^*$) of $dM/d\ln t$ shifts to lower temperatures as the applied field increases.

Based on the critical-state model, the full-penetration temperature should be uniquely determined by Eq. (5) at a given applied field. On the other hand, the model requires that the same consideration should be valid for the full-penetration field at a given temperature. As we interpreted before, the position of the maximum in $dM/d\ln t$ versus H is near H^*. This implies that the peak H^* of $dM/d\ln t$ versus H at a given temperature T should be as same as the peak T^* of the $dM/d\ln t$-versus-T curve for a constant field H. As we reported previously,[4] $dM/d\ln t$ versus field peaks at 1.5 and 1 kG at temperatures of 8 and 12 K, respectively. It can be seen from Fig. 2 that the curve of $dM/d\ln t$ versus temperature has a peak near 10 K for an applied field of 1 kG. This confirms that (T^*, H) and (T, H^*) are actually the same. This point is also consistent with the full-penetration concept of the critical-state model.

We now develop an expression for the temperature dependence of $dM/d\ln t$. Based on the argument of full-penetration temperature in the critical-state model, Eq. (4) can be rewritten as

$$4\pi\frac{dM}{d\ln t}=\alpha(T)\left[\frac{H^2}{H_0(T)}\right]\left[\frac{kT}{U_0(T)}\right],\quad T\le T^* ,\qquad (7a)$$

$$4\pi\frac{dM}{d\ln t}=\beta(T)[-H+H_0(T)]\left[\frac{kT}{U_0(T)}\right],\quad T\ge T^* .\qquad (7b)$$

In principle, the magnetic relaxation behavior can be described by Eqs. (7). But the temperature dependence of the parameters J_c, U_0, and H_0 is not determined. Based on the previous magnetic relaxation measurement, we have estimated the values of parameters J_c and H_0 to be 1.2×10^4 A/cm^2 and 8 kG at 8 K for a single crystal of $Bi_2Sr_2CaCu_2O_x$.[4] The value of the parameter x_0 can be evaluated to be 5 mm at 8 K. The parameters involved should be well evaluated by the fitting magnetic hysteresis data to the critical-state model. Therefore, quantitative analysis of the experimental data for magnetic relaxation cannot be obtained until the temperature dependence of these parameters is well established.

Although the $dM/d\ln t$ seems to be a monotonically decreasing function of temperature down to 5 K for an applied field of 4 kG, we argue that a monotonically increasing part of $dM/d\ln t$ versus T should exist in the lower-temperature region (<5 K). The reason is that the flux-creep model predicts no thermal activation at zero temperature. Furthermore, based on the critical-state model, a monotonically decreasing behavior of $dM/d\ln t$ versus T should be expected since the applied field is already beyond the full-penetration field.

CONCLUSIONS

Based on the critical-state model and flux-creep picture, we proposed the concept of the full-penetration temperature T^* and extended an expression for the temperature dependence of $dM/d\ln t$. We measured the magnetic relaxation for a single crystal of $Bi_2Sr_2CaCu_2O_x$ at various temperatures and applied fields. We observed that the relaxation rate rises and falls with temperature at a given applied field and that the peak of $dM/d\ln t$ shifts with different fields. In particular, we showed that the peak position of $dM/d\ln t$ corresponds to the full-penetration temperature. We also explained the peak shift of $dM/d\ln t$ with an applied field as being due to decreasing T^* with increasing field.

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[16]Equation (5) can be simplified with a condition $D/2x_0\ll1$. When an expansion $\exp(-x)\approx1-x$ has been used, Eq. (5) becomes $H=H_0(T^*)[D/2x_0(T^*)]$. Using $x_0=cH_0/4\pi J_c(T)$, Eq. (5a) can be obtained. Moreover, Eq. (5a) is the same as that in the Bean model.

[17]The condition $dJ_c/dT<0$ means that J_c is a decreasing function of temperature. Since a magnetic hysteresis width is proportional to the critical current density in the Bean model, and the hysteresis width becomes large in the lower-temperature region, it implies that J_c decreases with increasing temperature; namely, the condition $dJ_c/dT<0$ is always satisfied in most systems.