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Reduction of the magnetization decay rate in high-T_c superconductors

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Small decrements in the temperature ΔT of superconducting samples in the critical state are shown to cause substantial reduction in the rate of magnetic relaxation. Quantitative agreement is obtained between experimental data and a model, which assumes the decay of the supercurrent subsequent to the change in temperature can be described in terms of the critical state. Experiments were performed in an applied field of 5.07 kG, on thick film (1.6 μm) samples which generate a substantial self-field ($\sim$5 kG). The effect of temperature reduction is shown to be calculable from a knowledge of the decay-rate exponent n and $J_c(T)$ in the relevant temperature range. These results indicate that cooling in the critical state can be used to study magnetization decay at current densities reduced from the critical current.

Large magnetic relaxation effects have been observed and extensively studied in $YBa_2Cu_3O_{7-\delta}$,[1-5] even at low temperatures and in thin films with high critical currents. This has been suggested as a fundamental limitation to the use of high-temperature superconductors in technological applications. Recently,[6] we discussed how these effects could be substantially reduced, and effectively eliminated, by raising the critical current density in the material relative to the actual current density, where the critical current is defined with respect to a given voltage criterion. Here, we extend these measurements to higher fields, and also demonstrate quantitative agreement between measured magnetization decay after the sample temperature is lowered and a simple model for this decay.

Large reductions in the magnetic decay rate can be accomplished by relatively small changes in the temperature of a sample in which a persistent current circulates.[7] This effect is illustrated in Fig. 1, which shows magnetization decay versus time for a thin-film $YBa_2Cu_3O_{7-\delta}$ superconductor at 30.7 K in an applied field of 5.07 kG. A reduction ΔT in the temperature by 1 K reduces the decay rate by a factor of 3, while reducing the temperature by 4.5 K reduced the decay rate by a factor of approximately 100. We have observed similar reductions in the rate of decay in applied fields up to 17.5 kG. Temperature changes can have a dramatic impact on the time required to reach a given level of current stability in an application requiring a persistent current. Since for isothermal decay, the rate of current decay scales as approximately $1/t$ (where t is time),[7] a 100-fold reduction in the decay rate also represents a 100-fold reduction in the time required to stabilize persistent current to a given level of decay. Reduction of the sample current by this method has been suggested as a means of studying magnetization decay at current densities much lower than the critical current.[8] In the case of collective pinning, strong changes in the flux-bundle activation energy $U(J,T)$ measured from flux creep are expected.

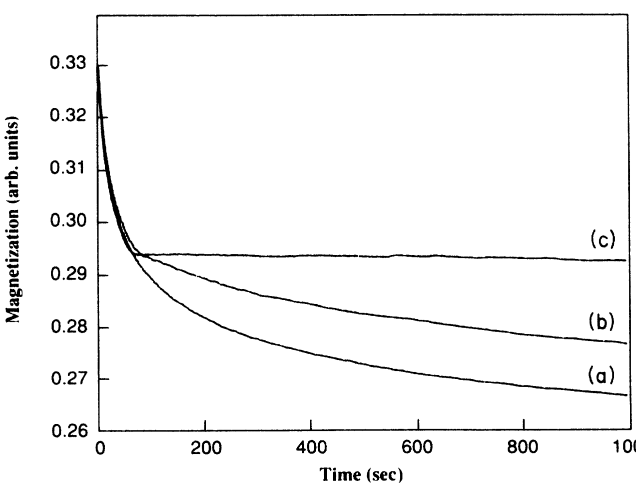

FIG. 1. Magnetization vs time at 5.07 kG for three cases: (a) isothermal decay at 30.7 K; (b) decay at 30.7 K, followed by decay at 29.7 K; (c) decay at 30.7 K, followed by decay at 26.2 K.

Epitactic $YBa_2Cu_3O_{7-\delta}$ films were grown to 8200 Å on polished single-crystal MgO substrates from a stoichiometric target using an off-axis geometry.[9] Films were cooled in 300 Torr of O_2 after growth, and had zero resistance at 85 K with a resistive transition width of less than 1 K. X-ray diffraction showed the films to be highly textured with the c axis perpendicular to the substrate surface. A small amount of randomly oriented $YBa_2Cu_3O_{7-\delta}$ was observed, with a peak intensity of approximately 0.1% of the intensity from the oriented peaks.

Magnetization measurements were performed on a Princeton Applied Research 155 vibrating sample magnetometer. Critical currents were determined using the Bean formula.[10] Critical currents determined from the Bean formula were $J_c = 3.5\times10^7$ A/cm^2 at 4.2 K and 1×10^6 A/cm^2 at 77.4 K, in zero applied field. Figure 2 shows the calculated critical current in an applied field of 5.07 kG as a function of temperature. No corrections for the self-field of the sample have been made. The critical current is found to decrease approximately exponentially with temperature at lower temperatures (<50 K) as has previously been reported for critical currents determined from magnetization measurements.[11,12] The solid line is a fit to the data between 20 and 50 K of the form

$$J_c = J_0 e^{-T/T_0}, \tag{1}$$

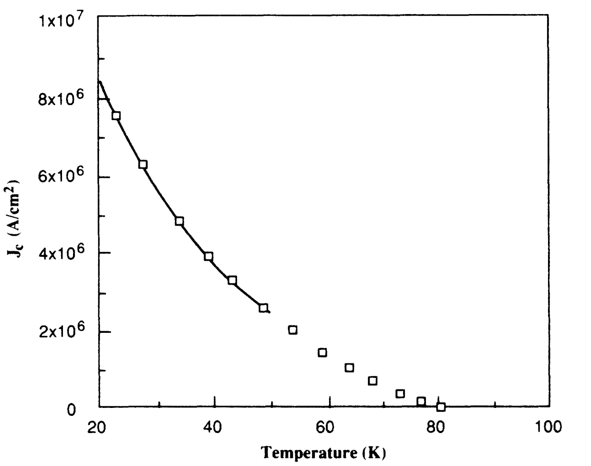

FIG. 2. Critical current vs temperature in an applied field of 5 kG, for an 8200-Å film deposited on MgO. The solid line is a fit with the form of Eq. (1).

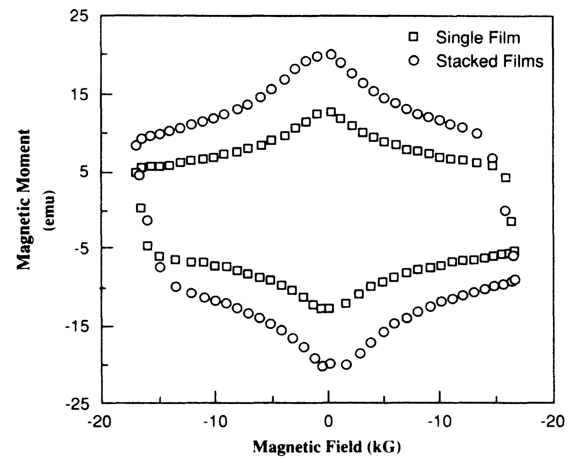

FIG. 3. Magnetization hysteresis loops for 8200-Å films.

with $T_0=24$ K, $J_0=2\times10^7$ A/cm^2. This expression is used to interpolate critical currents at 5 kG between 25 and 30 K, as discussed below.

Magnetization decay measurements were made by ramping the field slowly to a targeted value to saturate the observed moment, and recording the subsequent magnetic moment as a function of time. Studies of cooling in the critical state places stringent requirements on the performance of the magnetometer system and on the total moment of the superconducting samples. Drifts in the applied field especially affect the observed magnetization decay rate because of the demagnetization factor for thin films; this drift becomes significant after the temperature change ΔT, since the decay rate is strongly reduced. It is also of interest to measure the effect of temperature changes on samples which generate a substantial magnetic induction, since cooling is expected to be useful in systems which generate large magnetic fields. To increase the self-field, two of the samples described above were stacked face-to-face, separated by a thin layer of Teflon. This yielded a sample with an effective thickness of 1.64 μm. Figure 3 shows two magnetization loops measured at 4.2 K; the inside loop is for a single film of thickness 8200 Å, and the outside loop for the combined set of films. The self-field of the stacked sample at zero applied field is approximately 5 kG.[13] This effectively eliminated sensitivity to drifts in the applied field ($<0.02\%$ per min) for all of the measurements reported below.

Detailed magnetization decay measurements were performed on this stacked pair of films. Magnetization decay was measured at 5.07 kG and $T_1=30.7$ K. After a time $t_1\approx55$ sec, the temperature was lowered to a new temperature, T_2. The time required for the temperature to stabilize at T_2 depended on the magnitude of the temperature difference T_1-T_2, but was always less than 70 sec. Magnetization decay values were normalized at 30 sec to account for small variations (1%) in the saturation moment, which are attributed to overshoots in the applied field and variations (0.05 K) in the starting temperature T_1.

Magnetization decay in copper oxide superconductors has been interpreted in a variety of ways.[1-5] We make no attempt here to determine which of these interpretations is suitable for analyzing the observed decay, but instead adopt a phenomenological approach. The magnetization decay in thin film $YBa_2Cu_3O_{7-\delta}$ can be described phenomenologically by the relation

$$\frac{d\ln M}{d\ln t}=\frac{-1}{n-1}, \qquad (2)$$

where M is the magnetic moment of the sample and n is a constant, which we have found to be relatively independent of temperature over a wide temperature range. This form is approximately obtained at long times from a current-voltage characteristic

$$E=\alpha(T,B)J^n, \qquad (3)$$

where α is a proportionality constant, which varies with temperature and applied field. Equation (3) has a solution if the current decay rate is constant throughout the sample for cooling to temperature T_2:

$$M(t)=[M^{-(n-1)}(t_0)+\beta(t-t_0)]^{-1/n-1}, \qquad (4)$$

where $M(t_0)$ is the magnetization at the time the sample is cooled, and

$$\beta\approx\frac{2(n-1)\alpha(T_2,B)}{\pi^2 l}\left(\frac{3c}{a}\right)^n. \qquad (5)$$

a is the sample radius, and l is the sample thickness. β depends on temperature and field only through $\alpha(T,B)$. The solution (4) assumes that the decay of the persistent current can be described by specifying the initial magnetization, independent of how this value of magnetization was achieved. The long-time solution of Eq. (4) is just Eq. (2).

The reduction in the decay rate before and after the temperature change ΔT can be obtained from Eqs. (4) and (5). If ΔT occurs instantaneously at a given value of $M(t_0)$, the change in the decay rate is just

$$\frac{[dM(T_1,t)/dt]_{t_0}}{[dM(T_2,t)/dt]_{t_0}}=\frac{\alpha(T_1,B)}{\alpha(T_2,B)}. \qquad (6)$$

Values for β and n in Eq. (4) after the cooling can be obtained either by fitting isothermal magnetization decay data taken at temperature T_2 or calculations based on Eq. (3). n varies only slightly over the small range of temperatures to which the sample is cooled. In the present case, we extract values for n from isothermal magnetization decay at temperature T_1, and use β as a fitting parameter. This parameter is then compared with predicted values for β obtained from Eqs. (3) and (5) at different temperatures, using the interpolation formula for J_c given above. These predicted values are then compared with measured values to test in detail the validity of the model for the process.

Values for n and β for 5.07 kG and 30.7 K, the field and temperature for the decay before cooling by ΔT, were obtained from isothermal decay data at this temperature and field, as shown in Fig. 4. From this data, we extract values of $n=27$ and $\beta=(9.3\times10^4\ \mathrm{emu/cm^3})^{-26}/\mathrm{sec}$. As can be seen in the plot, the magnetization decay is quite well described by a power-law expression at this temperature and field. Departures from the form of Eq. (2), such as observed for magnetization decay at higher temperatures ($\sim$77 K), imply an E-J characteristic different from Eq. (3). This would require a solution different in detail from Eq. (4).

The above values were used in Eq. (4) to describe the effect of cooling on the observed magnetization decay. Figure 5 shows magnetization decay data in which the sample temperature was reduced at $t_1\approx55$ sec, in an applied field of 5.07 kG. The sample temperature was decreased from $T_1=30.7$ K to temperatures $T_2=30.5$ K, $T_2=29.7$ K, $T_2=28.3$ K, and $T_2=26.2$ K. The solid lines are fits of the form (4), with β used as a fitting parameter for each of the decay curves. As can be seen in Fig. 5, very reasonable fits to the decay are obtained over a wide range of decay rates. Thus Eq. (4) provides a very good description of the decay subsequent to the temperature reduction, with suitably chosen values for β.

Values for β can also be obtained from critical-current measurements, using Eqs. (3) and (5) if the field criterion E_c is known. We use the measured value of β at 30.7 K to establish this criterion. Figure 6 compares the values of β obtained in this manner with the values extracted from fits to the magnetization decay. As can be seen in Fig. 6, the agreement is good, indicating that approximate values for the decay rate subsequent to a change in the sample temperature can be predicted from a knowledge of n and $J_c(T)$. If J_c is assumed to be of the form (1) over some temperature range, a simple expression for the reduction in decay rate upon cooling can be obtained:

$$\frac{[dM(T_1,t)/dt]_{t_0}}{[dM(T_2,t)/dt]_{t_0}}=\exp\left[-\frac{n(T_1-T_2)}{T_0}\right]. \qquad (7)$$

Thus the effect of cooling can be predicted if values for T_0

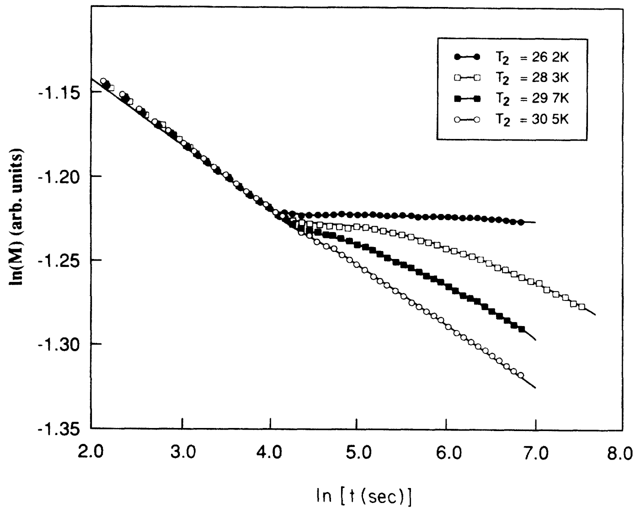

FIG. 5. Magnetization vs time (log-log) with cooling performed from 30.7 K to temperature T_2 at $\sim$55 sec. Solid lines are fits of the form Eq. (4). Final temperatures are T_2 = 30.5, 29.7, 28.3, and 26.2 K.

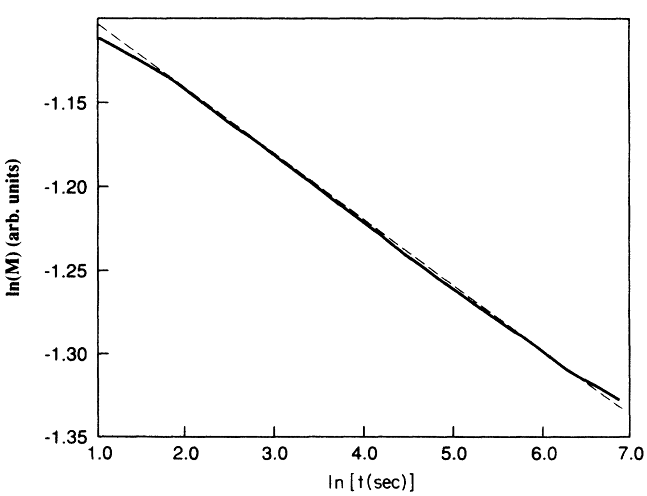

FIG. 4. Magnetization decay vs time (log-log) at 30.7 K and 5.07 kG. Solid line is a fit to a power law.

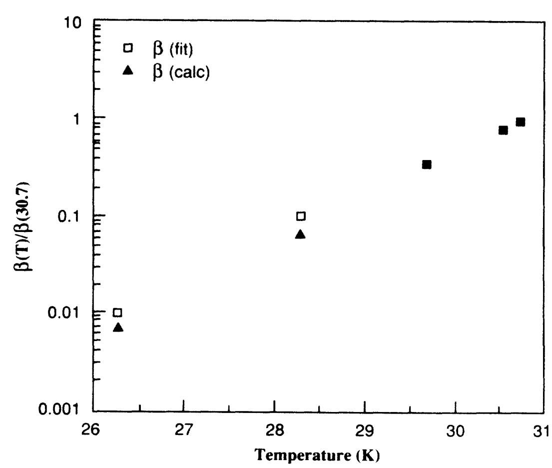

FIG. 6. Values of β normalized to 30.7 K calculated from the temperature dependence of J_c and extracted from fits shown in Fig. (4).

and n are known in the relevant temperature range. It should be noted that alternate representations for the time and temperature dependences could as well represent the data.

We have shown that the critical-state model is appropriate for the description of magnetization decay subsequent to a change in temperature. A model for the behavior of the magnetization and the decay rate subsequent to cooling yields results which are quantitatively in agreement with experiment. Thus decay experiments performed subsequent to cooling can be expected to yield quantitative results for pinning potentials at reduced current levels.[8] These results are shown to apply to samples which possess relatively large (0.5 T) self-fields, approaching values of technological interest. Cooling in the critical state can sharply reduce the dissipation level exhibited by superconductors. This reduction can be accomplished in short periods of time.

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