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Thermally activated flux motion and quantum creep in $YBa_2Cu_3O_7$ and $Y_2Ba_4Cu_8O_{16}$ films

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Abstract

The dynamical relaxation rate $Q \equiv \mathrm{dln}\, j_s/\mathrm{dln}(dB/dt)$ where j_s is the current induced in a superconductor when the external field is swept at a rate dB/dt, has been measured in $YBa_2Cu_3O_7$ and $Y_2Ba_4Cu_8O_{16}$ films of 100 nm and 180 nm thickness as a function of magnetic field at temperatures between 2 K and T_c. The data show i) a non zero relaxation at low T due to quantum creep, ii) a plateau between 15 and ~ 50 K and iii) a divergence when T approaches the irreversibility line. The data are analyzed within the collective pinning model. At low temperatures it is shown that *both* j_s and Q are influenced by quantum creep.

1. Introduction

Since the first report of large magnetic relaxation effects in high-T_c superconductors numerous investigations of giant creep have been carried out in these materials. Although the temperature dependence of the relaxation rate $S \equiv (1/M(0))dM/d\ln t$ (where M(t) is the magnetic moment at time t) varies from sample to sample it is quite remarkable that the majority of results falls in a band $S = 0.04 \pm 0.02$. The diversity in temperature dependences reported for S is partly due to specific defect properties of the samples and partly to experimental difficulties [1]. For example, in bulk samples with large critical currents it is difficult, if not impossible, to have a full penetration of the magnetic field. This complication can be avoided by using thin films with the field perpendicular to the a-b plane. Because of the large demagnetization factor of the sample this geometry is, however, very sensitive to variations of the external field. Large errors are induced in the determination of S if the sample is moved in and out of a pick-up coil system (as used in certain SQUID magnetometers) or if there is an overshoot of the magnetic field when the sweep is stopped at the beginning of the relaxation measurements. Overshoot effects on S are discussed by Griessen et al. [2] and Schnack et al. [3]. An elegant method which avoids these difficulties is the dynamical relaxation technique [4-6]. In this method the macroscopic transport current density j_s flowing in a sample is measured as a function of the sweep rate dB/dt. As shown by Schnack et al. [3] and Jirsa et al. [6] j_s varies often as ln(dB/dt) and the dynamical relaxation rate Q defined as

$$Q \equiv \frac{d\ln j_s}{d\ln(dB/dt)} \tag{1}$$

is essentially equal to S. The great advantage of this method is that dB/dt can be varied over a wide range without problems. The purpose of this work is to present dynamical relaxation data for two e-gun co-evaporated epitaxial films of $YBa_2Cu_3O_{7-\delta}$ and $YBa_2Cu_4O_8$ as a function of temperature ($2\ K \le T < T_c$) and magnetic fields up to 7 T. The reason for investigating two different YBCO compounds was to see whether or not twin boundary or oxygen non-stoichiometry ($\delta \neq 0$) play an important role in relaxation effects.

2. Sample preparation and experimental techniques

Two films have been used in this experiment. One film has the $YBa_2Cu_3O_7$ structure while the other one has predominantly the $YBa_2Cu_4O_8$ structure. Henceforth we denote them as Y123 and Y124, respectively. Both films were obtained by UHV co-deposition of pure Y (99.99%), Cu (99.9999%) from E-gun evaporators, and BaF_2 from a K-cell. After the deposition a wet post-annealing was performed in order to remove fluorine from the film [7]. X-ray diffraction patterns show only (00*l*) peaks. The FWHH of the (005) peak of Y123 is 0.28°, which means that the film has a very good crystallinity. The thicknesses of the films is about 180 nm (Y123) and 100 nm (Y124), respectively. The Y124 film contains predominantly the $YBa_2Cu_4O_8$ phase although subpeaks of the 123 structure are found around each (00*l*) peak. The ratio of intensities between the (124) peaks and the corresponding (123) peaks is, however, rather large (up to 70). The FWHH for the typical (0012) peak of Y124 is 0.44°. From electrical resistivity measurements for Y123, we determined $T_c = 90.8$ K and a transition width of 0.5 K. The ratio R(300 K)/R(100 K) is 3.0. The resistive transition for the Y124 sample shows that the T_c (zero resistivity) and transition width are 79 K and 0.5 K, respectively. The upward curvature of the resistivity in the temperature range from 300 K to 90 K and the low normal state resistivity (28 μΩ cm at 100 K) are typical characteristics of a 124-film. The Y123 film is patterned into a ring with an inner diameter of 7 mm and an outer diameter of 8 mm. The Y124 sample is rectangular with an area of 3 × 4 mm^2.

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3. Results and discussion

A high sensitivity capacitance torque-magnetometer similar to that described by Griessen et al [8,9]. is used to measure the torque $\tau = M \times B$, where M is the magnetic moment of the film which is related to the macroscopic current density j_s through

$$M = \frac{\pi a^3 j_s D}{3} \qquad (2)$$

for a disc of radius a and thickness D, and through

$$M = \frac{\pi}{3}(a_0^3 - a_i^3) D j_s \qquad (3)$$

for a ring with outer diameter a_0 and inner diameter a_i. The magnetic moment of the film is parallel to the c-axis since the currents are confined to the a-b plane. By sweeping the magnetic field up and down at a certain rate dB/dt we can therefore determine j_s in a disc at a given field B from the difference in up-sweep and down-sweep torques $\Delta\tau$ by means of

$$j_s = \frac{3\,\Delta\tau}{2\pi a^3 D B \sin\theta} \qquad (4)$$

where θ is the angle between the external field and the c-axis. A similar relation holds for a ring. The magnetic field is provided by an Oxford Instrument 7 T superconducting coil. The sweeping rates used in this work range from 2×10^{-5} T/s to 4×10^{-2} T/s. The temperature is stabilized to ± 0.1 K even at the fastest sweep rates. The temperature dependence of j_s at various magnetic fields is shown in Fig. 1 for Y123. The current density decreases rapidly with increasing temperature except at temperatures below ~ 10 K where a flattening is clearly observed. The relatively weak dj_s/dT below 10 K is a direct consequence of the *thermally assisted* tunneling of vortices.

The temperature dependence of the dynamical relaxation rate Q evaluated at the fastest sweep ($dB/dt = 4 \times 10^{-2}$ T/s) is shown in Fig. 2 for Y123 and Y124 at B = 0.5 T. Both sets of data exhibit the same characteristic features:

i) at low temperatures Q does not extrapolate to Q = 0 at T = 0.

ii) in the intermediate temperature range (typically 30 K to 65 K for Y123 or 20 to 50 K for Y124) Q is almost constant in qualitative agreement with the observation of Malozemoff and Fisher [8]. For Y124 the relaxation in the plateau ($Q \cong 0.04$) is significantly smaller than for Y123 ($Q \cong 0.07$). At higher fields these plateaus are gradually disappearing and at 7 T they are not observed at all. This casts some doubts about the "universality" of the plateaus claimed in ref. [8]

iii) for temperatures approaching the irreversibilty line there is a marked upturn in the Q versus T curves.

The general behaviour of the data in Fig. 2 is similar to that reported by Civale et al. [9] for an unirradiated and proton irradiated YBCO single crystal and by Lensink et al. [10] for a neutron irradiated YBCO single crystal.

The three regimes described above are best put in evidence in a (T/Q) versus T plot. As shown in Fig. 3 such a plot is linear except at the low and high temperature ends. The linearity of these plots is easily understood in terms of the interpolation formula proposed in the collective pinning theory for the activation energy

$$U(j) = \frac{U_c}{\mu}\left[\left(\frac{j_c}{j}\right)^{\mu} - 1\right] \qquad (5)$$

and the analytical expression [3]

$$U(j_s, T) = kT \ln\left(\frac{2 v_0 B}{a\, dB/dt}\right) \qquad (6)$$

which relates implicitly the current density j_s to the sweep rate dB/dt at fixed T and B. Since the attempt velocity v_0 is

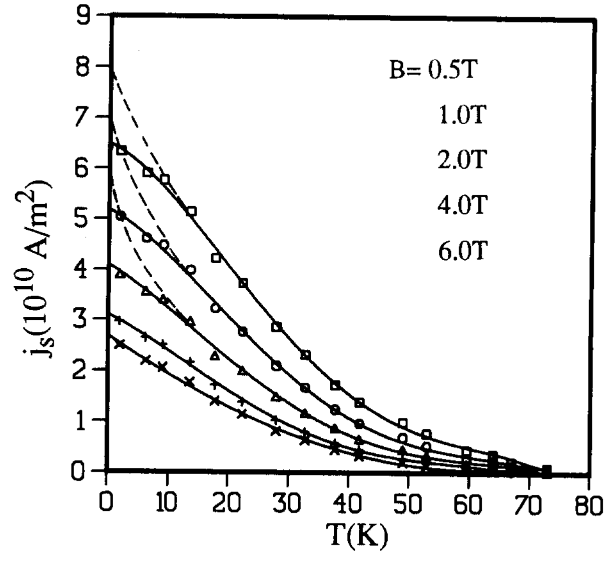

Fig. 1 Temperature dependence of the current density J_s measured at a sweep rate $dB_e/dt = 4 \times 10^{-2}$ T/s in a $YBa_2Cu_3O_{7-\delta}$ thin film of 180 nm thickness. The dashed lines represent j_s (T,B) in the absence of thermally assisted quantum-tunneling of vortices (see text).

not strongly T-dependent, the ln-term in eq. 6 can be treated as a constant C. From eqs. 5 and 6 follows that

$$\frac{T}{Q} = \frac{U_c}{k} + \mu C T \qquad (7)$$

where k is Boltzmann's constant degree Kelvin. Consequently U_c, the energy in k, is given by the intercept of the straight lines in Fig. 3 and μC by their slopes. The data show that up to 65 K in Y123 and 48 K in Y123 both U_c and μ are constant and equal to $U_c = 370$ K (Y123) and $U_c = 230$ K in (Y124). Since C can be determined from the following relation

$$C = Q^{-1}\frac{d\ln j_s}{d\ln T} \qquad (8)$$

at low temperatures (N.B. by "low temperatures" we mean low temperatures where quantum creep is negligible, e.g. T = 13 K in Y123) we can determine the exponent μ from the slopes of the straight lines in Fig. 3. We find that $\mu \approx 0.43$ (Y123) and $\mu \approx 0.8$ (Y124). The deviations from linearity at high temperatures is due to thermal depinning of vortices where according to collective pinning theories both U_c and j_c varie strongly with T [11]. This shall be discussed in a forthcoming publication [12]. Here we focus out attention on the low temperature deviations. As mentioned above lim $Q \neq 0$ when $T \to 0$. There is also a manifestation of quantum creep in the temperature dependence of j_s at low temperatures. This is clearly shown as follows. Since we have determined U_c, μ and C we can calculate the critical current j_c (defined as the current for which U vanishes) from the measured current j_s by means of

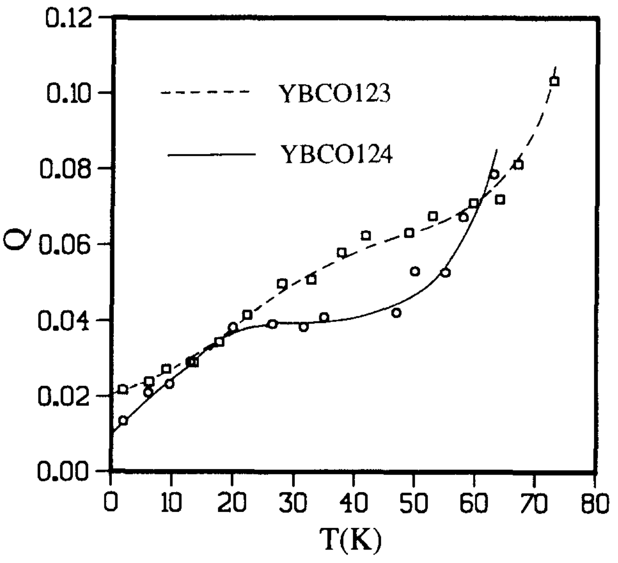

Fig. 2 Temperature dependence of the dynamic relaxation rate Q ≡ $d\ln j_s/d\ln(dB/dt)$ for Y123 and Y124 at 0.5 T.

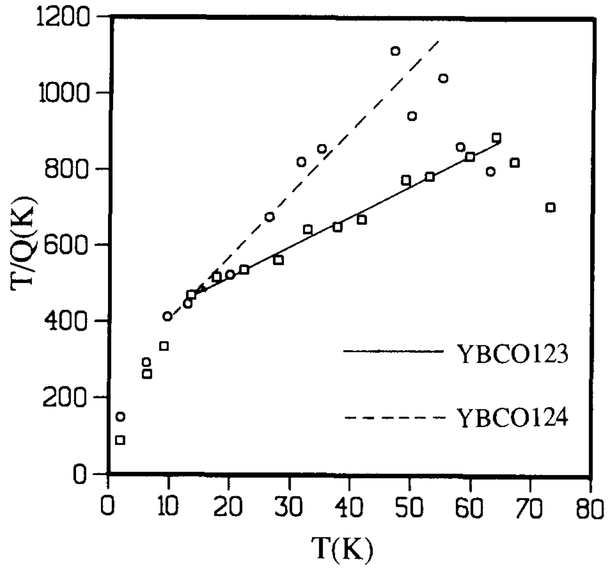

Fig. 3 Plots of T/Q versus T at 0.5 T for Y123 and Y124.

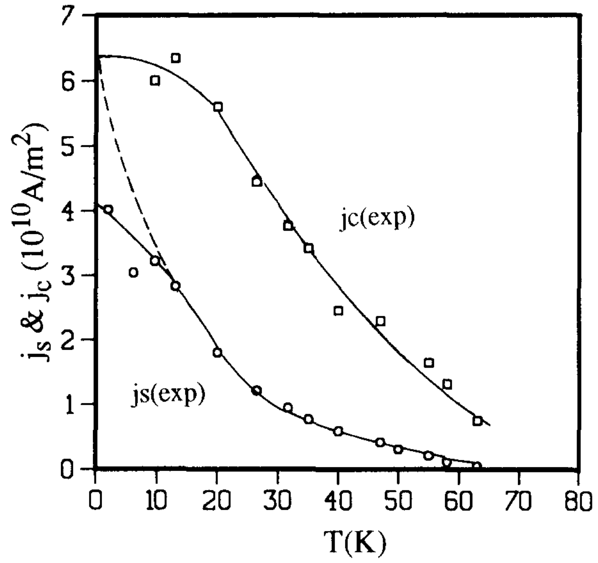

Fig. 4 Temperature dependence of the current density Js and the critical current density J_c determined from $j_s(T)$ and Q(T) data with in collective pinning model.

$$j_c(T) = j_s(T)\left[1+\mu\,\frac{kTC}{U_c}\right]^{1/\mu} \qquad (9)$$

The j_c versus T curve obtained in such a way is compared to $j_s(T)$ in Fig. 4. The interesting point is that $j_s(T=0) \neq j_c(T=0)$. This is due to *thermally assisted* vortex tunneling below ~ 10 K [15,16]. The dashed line indicates the temperature variation of j_s in absence of quantum creep. This implies that at *all* temperatures the measured current densities are always lower than the critical current.

4. Conclusion

Measurements of the current density j_s and of the dynamical relaxation rate Q as a function of temperature and magnetic fields show that $YBa_2Cu_3O_{7-\delta}$ and $Y_2Ba_4Cu_8O_{16}$ films behave very similarly. At relatively low fields (B = 0.5 T) the parameters U_c, μ and C which enters the activation energy for vortex motion in the collective pinning theory are temperature independent except below ~ 10 K and near the irreversibility line. Thermally assisted quantum creep leads both to a non vanishing relaxation at low T and a saturation of j_s below j_c when T approaches zero.

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