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Experimental observation of quantum creep in high-T_c superconducting YBCO-PrBCO superlattices

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Abstract

Measurements of the dynamical relaxation rate of the magnetic moment of YBCO/PrBCO multilayers with decoupled YBCO layers of 1.2, 2.4, 3.6, 4.8 and 9.6 nm thickness have been carried out with a high sensitivity capacitance torque magnetometer. The relaxation at low temperature increases with decreasing YBCO layer thickness and reaches ~ 7% at 2 T in the thinnest sample. Deviations from thermally activated flux motion, due to thermally assisted vortex tunneling are observed at temperatures up to 8 K.

1. Introduction

In the classical model [1,2] of Thermally Activated Flux Motion (TAFM) magnetic relaxation in type-II superconductors vanishes at zero temperature. This is a general behavior of any TAFM model. The disappearance of the relaxation at T = 0 does not depend on the special form of U(j), where U(j) is the activation energy barrier for thermally activated vortex motion as a function of the current density j in the sample. In the simple case of the Anderson-Kim model one expects the relaxation rate $S \equiv (-1/M(0))\, dM/d\ln t$ to be proportional to the temperature T at sufficiently low temperatures, where the explicit temperature dependence of U can safely be neglected.

Recently several authors have reported a non-zero extrapolation of S to T = 0 [3-7] and proposed that this phenomenon is due to quantum tunneling of vortices.
The probability of tunneling through the barrier between two adjacent configurations in the limit of strong ohmic damping can be estimated by means of the following expression derived by Caldeira and Legget [8]

$$P \propto \exp\left[-A\eta\,(\Delta q)^2/\hbar\right] \qquad (1)$$

where P is the tunneling probability, A is a numerical factor of order unity and Δq is the under barrier distance. The viscosity parameter η which describes the dissipative coupling of the tunneling vortex line to its environment can be estimated from the Bardeen-Stephen model [9]. In the limit of large current densities $j \approx j_c$ the distance under the barrier is to first order proportional to $(1 - j/j_c)^{1/2}$ [7] where j_c is the critical current corresponding to a vanishing activation energy. According to Larkin and Ovchinnikov the parameter A is equal to $A = 2\pi/9$ [10]. This leads finally to the following expression for the tunneling probability

$$P \propto \exp\left[-\frac{2\phi_0^2\, L\, x_{hop}^2}{\pi^2\xi_{ab}^2\rho_n\hbar}\,(1 - j/j_c)\right] \qquad (2)$$

where ξ_{ab} is the coherence length in the ab-plane, ρ_n is the normal state resistivity, ϕ_0 is the flux quantum, $2x_{hop}$ the distance between two adjacent pinning centres and L is the length of the tunneling vortex segment measured parallel to the applied magnetic field.

Equation (2) has the same functional dependence on j as in the Anderson-Kim model [1,2]. This observation allows us to write down directly the following expression for the relaxation in the tunneling regime [11]

$$S = \frac{\pi^2\xi_{ab}^2\rho_n\hbar}{2\phi_0^2\, L\, x_{hop}^2} \qquad (3)$$

where S is the normalized relaxation rate. This expression suggests that in sufficiently thin samples (i.e. in samples where L > d where d is the thickness of the sample) the relaxation rate should be especially high. To check this expectation we measured magnetic relaxation in YBCO/PrBCO superlattices.

2. Experimental technique

The experiments were performed on c-axis oriented $YBa_2Cu_3O_7/PrBa_2Cu_3O_7$ superlattices, with various

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thicknesses of the YBCO-layers. These superlattices were sputtered on $SrTiO_3$ substrates with size 7 × 7 mm^2 [12,13]. Each sample consisted of 8 YBCO layers separated by PrBCO layers of thickness 9.6 nm (8 unit cells). The PrBCO layers are sufficiently thick to ensure complete decoupling of the YBCO layers. The critical temperature T_c defined as the onset of the resistive transition is 83 K, 66 K and 40 K for superlattices with YBCO layer thickness of 4.8 nm, 2.4 nm and 1.2 nm, respectively. The normal state resistivity was in all samples approximately $\rho_n \approx 300\ \mu\ \Omega$ cm just above T_c.

The critical currents j_c measured at T = 4.2 K and B = 0.6 T are 3.5×10^9 Am^{-2}, 9×10^8 Am^{-2} and 3×10^8 Am^{-2} for YBCO layers of 4.8 nm, 2.4 nm and 1.2 nm, respectively.

Magnetic hysteresis measurements were performed with a torque magnetometer which consists of two capacitor plates connected with crossed BeCu springs [14]. The sample is glued to the mobile capacitor plate. The magnetic moment **m** of the sample leads to a torque $\tau = \mathbf{m} \times \mathbf{B}$ which induces a change in capacitance. This change is measured with a lock-in technique.

The torque vanishes when the magnetic field is exactly parallel to the c-axis because the currents in the sample are confined to the ab-plane and consequently the magnetic moment is parallel to the c-axis. For this reason all the experiments are carried out with an arbitrarily chosen angle of 18° between the c-axis and the magnetic field. For the interpretation of the data this off-axis configuration is equivalent to H//c-axis.

The current density j_s in the ab-plane is deduced from the width of the magnetic moment hysteresis loops by means of

$$m^+ - m^- = \frac{8}{3} j_s D a^3 \tag{4}$$

where m^+ is the magnetic moment during sweeping up of the field, m^- the magnetic moment during sweeping down, D is the total thickness of the YBCO layers (i.e. D = 8d in our multilayers), 2a is the length of one side of the square sample. We assume that the induced current flows through the YBCO layers only.

According to Schnack et al. [11] the spatial current distribution in the sample is almost homogeneous in accordance with the Bean model. However, the current density j_s induced by changing the external magnetic field is *in general not equal* to the critical current density j_c. This difference is caused by the relaxation of the flux line distribution during a field sweep. For a thin film perpendicular to the magnetic field, the current density is implicitly given by [11,15]

$$U(j_s, T) = kT \ln\left[\frac{4x_{hop}\omega_0 B}{a\ dB/dt}\right] \tag{5}$$

where ω_0 is the microscopic attempt frequency for thermally activated flux motion and $B = \mu H$, where H is the external magnetic field. From this formula it is clear that the induced current density (and also the width of the magnetic hysteresis loop) depends on the sweep rate dB/dt of the external magnetic field. The normalized derivative [15]

$$Q = \frac{1}{j_s} \frac{dj_s}{d\ln(dB/dt)} \tag{6}$$

is essentially equal to the normalized relaxation rate

$$S = \frac{-1}{M(0)} \frac{dM(t)}{d\ln t} \tag{7}$$

obtained from relaxation measurements in a static magnetic field. The quantity Q being determined from measurements where the field is continuously swept is called below the dynamical relaxation rate.

In our experiments we have extracted the dynamical relaxation rate Q from minor torque hysteresis loops measured for a broad range of sweeping rates dB/dt. For each hysteresis loop the field is swept from $B_0 - \Delta B$ to $B_0 + \Delta B$ and back to the starting value $B_0 - \Delta B$. The width ΔB of the field loop is always larger than the penetration field $B_p = \mu_0 j_c d \approx 3 \cdot 10^{-5}$ T to ensure full penetration of the field into the sample (and thus the validity of our analysis). The explicit field dependence of j_s can safely be neglected because the width ΔB is much smaller than the average applied field B_0.

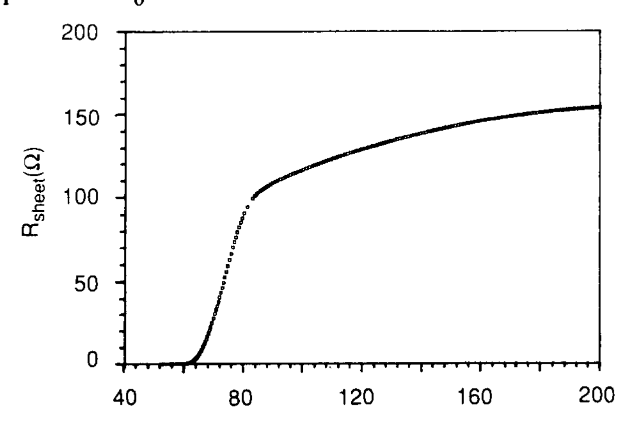

Figure 1. Temperature dependence of the sheet resistance of a YBCO/PrBCO (4.8 nm/9.6 nm) superlattice consisting of 8 layers of each compound.

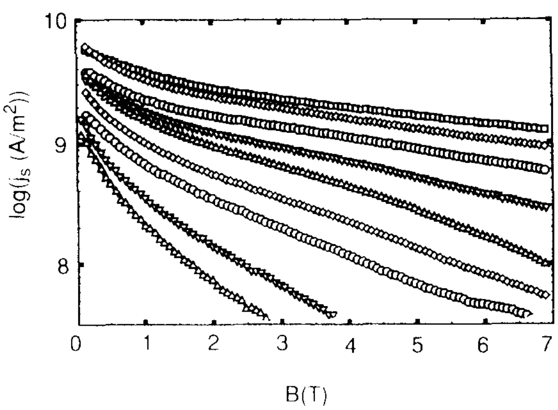

Figure 2. Magnetic field dependence of the induced current density j_s in a YBCO/PrBCO (4.8 nm/9.6 nm) superlattice consisting of 8 layers. The current density is determined from magnetic torque measurements by means of eq. (4). From top to bottom the curves represent measurements at 2.3, 5.4, 8.7, 10.9, 14.6, 20.5, 24.5, 28.0 and 31.5 K, respectively. The sweep rate is dB/dt $= 4 \times 10^{-2}$ T/s.

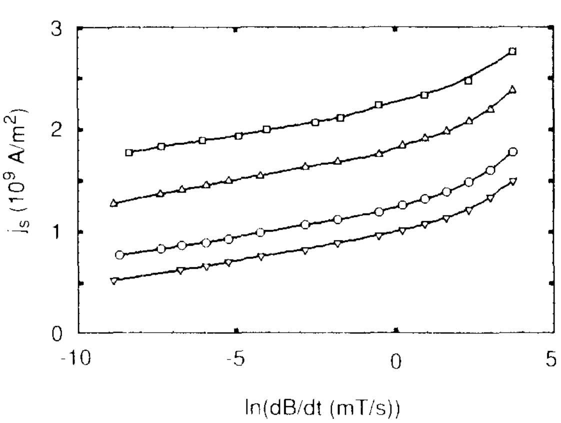

Figure 3. Influence of the sweep rate on the current density j_s of the same sample as in Fig. 2 at 2.3 K (□), 5.4 K (Δ), 8.7 K (O) and 10.9 K (∇). For all curves B = 2 T.

3. Results and discussion

Although we have investigated quantum creep in various superlattices we report here only measurements on a YBCO/PrBCO (4.8 nm/9.6 nm) multilayer consisting of 8 layers of each material. Results for other multilayers will be published elsewhere. Figure 1 shows the sheet resistance of this sample as a function of temperature. The onset T_c is ~ 82 K and the resistivity near T_c is approximately 300 μ Ω cm.

Figure 2 shows the induced current j_s determined by means of eq. (4) from the torque loops measured on the YBCO/PrBCO (4.8 nm/9.6 nm) superlattice. The magnetic field is swept from B = 0 T to B = 7.0 T and back to B = 0 T. For each curve the temperature is stabilized within 0.1 K. The curves are measured at a sweep rate dB/dt = 40 mT/s. The induced current decreases rapidly with increasing temperature and increasing field. This is a direct consequence of eq. (5), which states that the pinning energy $U(j_s)$ increases with increasing temperature and field. This means that the ratio j_s/j_c decreases with increasing temperature and field because both in the Kim-Anderson model and the collective pinning model U(j) is a decreasing function of j/j_c. Since j_c is always a decreasing function of T this leads to a rapid decrease of j_s.

Figure 3 shows the induced current density j_s as a function of the sweep rate dB/dt at selected temperatures. Linear behavior of j_s as function of ln(dB/dt) is clearly observed at all temperatures in agreement with the prediction of eq. (3).

The temperature dependence of the dynamical relaxation rate Q in Fig. 4 shows a plateau at $Q \cong 0.03$ for temperatures below 5 K. This indicates that deviations from TAFM due to thermally assisted quantum creep [16] occur at temperatures as high as 8 K in a 4.8 nm thick YBCO layer. In multilayers with thinner YBCO layers (d = 1.2, 2.4 or 3.6 nm) this effect is even more pronounced. The dynamical relaxation is also much larger at T = 0 K, e.g. $Q \cong 0.07$ for d = 1.2 nm. Such large values for Q are due to the fact that in thin samples the length L in eq. (3) is limited by the thickness of one YBCO layer. For example for

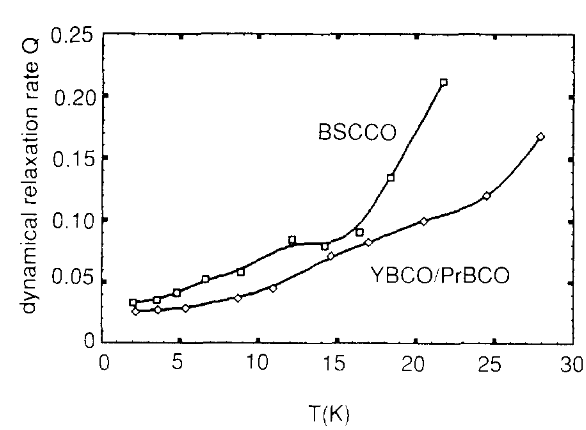

Figure 4. Comparison of the temperature dependence of the dynamical relaxation rate of the YBCO/PrBCO (4.8 nm/9.6 nm) superlattice (lower curve) and of a $Bi_2Sr_2CaCu_2O_8$ single crystal (upper curve) at B = 2 T.

L = d = 1.2 nm and ρ_n = 300 μ Ω cm we estimate from eq. (3) that $Q \cong 0.07$ if $x_{hop} = 2\xi_{ab}$. A tunneling distance of the order of the coherence length in the ab-plane is in agreement with the assumptions made in the theory of quantum creep [16,17]. For the d = 4.8 nm multilayer Q at low temperatures is expected to be 0.02 in agreement with the data in Fig. 4. The temperature dependence of Q for a YBCO/PrBCO multilayer is expected to be similar to that of $Bi_2Sr_2CaCu_2O_8$ single crystals because of their rather large anisotropy. This is clearly shown in Fig. 4.

4. Conclusions

The expectation that quantum creep is especially large in samples with a thickness smaller than the correlation length L measured parallel to the magnetic field is confirmed by measurements of the dynamical relaxation rate of YBCO/PrBCO multilayers with decoupled YBCO layers of 1.2, 2.4, 3.6, 4.8 and 9.6 nm and of a $Bi_2Sr_2CaCu_2O_8$ single crystal. In contrast to magnetization relaxation data [5,7] for a $YBa_2Cu_3O_7$ single crystal which exhibits a quantum creep plateau below 1 K we find that *thermally assisted* quantum tunneling of vortices [10,17] is already detectable below 8 K in a magnetic field of 2 T.

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