Physica C 235–240 (1994) 2959–2960
North-Holland

PHYSICA C

Observation of Quantum Creep in oxygen deficient $YBa_2Cu_3O_{7-\delta}$ at fields up to 7 T

A. J. J. van Dalen[a], R. Griessen[a], S. Libbrecht[b] E. Osquiguil[c] and Y. Bruynseraede[b]

[a] Faculty of Physics and Astronomy, Free University, 1081 HV Amsterdam, The Netherlands

[b]Laboratorium voor Vaste-Stoffysika en Magnetisme, K.U. Leuven, 3001 Leuven, Belgium

[c]Centro Atómico, 8400 San Carlos de Bariloche, R. N. Argentina

Superconducting current densities j_s and dynamic relaxation rates $Q \equiv d\ln j_s/d\ln(dB_e/dt)$ in an oxygen deficient $YBa_2Cu_3O_{7-\delta}$ epitaxial film were measured as a function of temperature ($1.5K < T < T_{irr}$) in magnetic fields up to 7 T by means of high sensitivity capacitance torquemeters. Below 5 K, the relaxation rate remains high and does not extrapolate to $Q = 0$ at $T = 0K$. This is associated to the quantum tunneling of vortices through the energy barrier separating two adjacent vortex configurations. In the case of ohmic dissipation the quantum creep rate is proportional to the normal state resistivity $\rho_n(0)$ at $T = 0$ K. In order to check this theoretical prediction we measured Q as a function of the oxygen content of the sample. The quantum creep rate increases systematically with increasing $\rho_n(0)$. However, Q remains finite even when $\rho_n = 0$.

High-T_c superconductors are characterized by a large relaxation of the induced current density j_s as a result of the low energy barriers separating adjacent vortex configurations. These low energy barriers strongly favour the occurence of quantum creep of vortices which becomes the dominant relaxation mechanism at low temperatures. The quantum creep rate is influenced by the interaction between the tunneling particle and its environment. In high-T_c superconductors this interaction is due to the viscosity arising from the dissipation in the core of the vortex. As shown by Griessen *et al.* [1] for the case of ohmic dissipation, the quantum creep relaxation rate Q_0 at $T = 0$ K is simply evaluated from Larkin and Ovchinnikov's [2] expression for the tunneling rate in presence of dissipation and the Bardeen-Stephen [3] expression for the viscosity $\eta = \Phi_0 B_{c2} L_c^c/\rho_n(0)$ for a vortex segment of length L_c^c. One obtains then

$$Q_0 = \left.\frac{d\ln j_s}{d\ln(dB_e/dt)}\right|_{T\to 0} = \frac{e^2\rho_n(0)}{2\hbar L_c^c} \qquad (1)$$

in the case where the effective range of the pinning potential is equal to ξ and $\rho_n(0)$ is the normal state resistivity at $T = 0$ K. A more detailed derivation of eq. 1 is given in the quantum collective creep theory of Blatter *et al.* [4]. The c-axis correlation length of the vortex is given by

$$L_c^c \approx \frac{\xi}{\gamma}\sqrt{\frac{j_0}{j_c}} \qquad (2)$$

where ξ is the coherence length in the ab-plane, $\gamma = \lambda_c/\lambda_{ab} = \xi_{ab}/\xi_c$ is the anisotropy and $j_0 \approx H_c/\lambda$ and j_c are the depairing and critical current densities, respectively.

In this paper we present torque measurements on an epitaxial $YBa_2Cu_3O_{7-\delta}$ film of dimensions 11 mm × 6 mm × 450 nm. The nominal oxygen deficiency δ of this film is adjusted by post annealing in an oxygen atmosphere, following the constant oxygen content lines in the partial oxygen pressure-temperature ($P_{O_2} - T$) phase diagram. The reversibility and reproducibility of this procedure has been controlled by performing resitivity measurements on the fully oxydized film before and after the experiments. More details about the preparation and oxygen loading process have been published elsewhere [5]. The relaxation rate is obtained from measurements of j_s as a function of the sweeprate dB_e/dt of the external field B_e. This is done by making minor hysteresis loops

0921-4534/94/$07.00
SSDI 0921-4534(94)02045-0

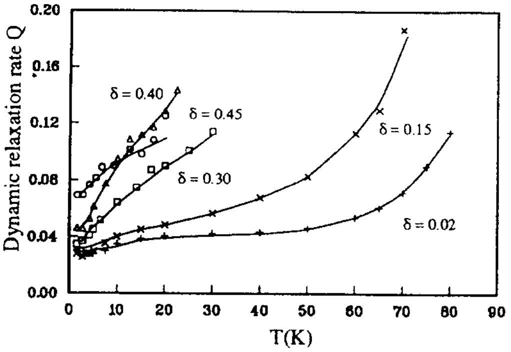

Figure 1. *Dynamic relaxation rate Q as a function of temperature at $B_e = 2.0T$. The values of the oxygen deficiency δ are 0.02, 0.15, 0.30, 0.4 and 0.45.*

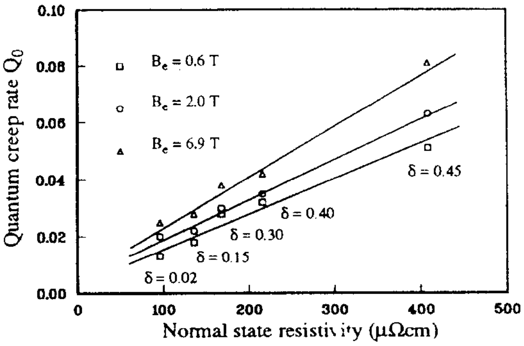

Figure 2. *Quantum creep rate Q_0 of $YBa_2Cu_3O_{7-\delta}$ as a function of the normal state resistivity $\rho_n(0)$ at B_e=0.6T, 2.0T and 6.9T.*

around B_e=0.6 T, 2.0 T and 6.9 T, respectively. The magnetic field sweep rate ranges from 0.3 to 40 mT/s. The angle Θ between the magnetic field direction and the c-axis of the film is 5°. In this case the currents are confined to the ab-plane and the magnetic moment is perpendicular to the plane of the film.

The measured dynamic relaxation rate is displayed in fig. 1 as a function of temperature for δ ranging from $\delta = 0.02$ to $\delta = 0.45$. The relaxation rate clearly increases with δ, indicating a decrease of the pinning energy. Furthermore we observe a non-zero extrapolation Q_0 of the relaxation rate to $T = 0$ K which is also increasing with increasing δ. Since eq. 1 suggests that Q_0 increases with $\rho_n(0)$ we have plotted Q_0 as a function of the normal state resistivity in fig. 2. As an estimate for $\rho_n(0)$ we have taken $0.8\rho_n(T_c)$. Q_0 increases linearly with $\rho_n(0)$ but there is an intercept for $\rho_n(0) = 0$ which implies that a finite relaxation remains even in a high normal conductivity material. This is not due to the oxygen concentration dependence of L_c^c since from published data for γ, λ and ξ [6,7] and the measured j_c we find from eq. 2 that L_c^c remains virtually constant. This implies that the normal state resistivity $\rho_n(0)$ in eq. 1 is not equal to the macroscopically measured ρ_{ab}. This is not surprising since the chains in $YBa_2Cu_3O_{7-\delta}$ are also contributing to the electric conductivity. With $L_c^c \approx$ 4nm determined from creep measurements in a series of $YBa_2Cu_3O_7/PrBa_2Cu_3O_7$ multilayers we estimate that $\rho_n(0) = 66$ $\mu\Omega$cm for the nearly stoichiometric $YBa_2Cu_3O_{6.98}$. It is interesting to note that this value is close to $\rho_n(T_c) = 76$ $\mu\Omega$cm measured in $Bi_2Sr_2CaCu_2O_{8+\delta}$, a compound without chains but insulating BiO layers. Finally we note that the data in fig. 2 show that Q_0 is weakly dependent on B_e in agreement with the single vortex quantum creep theory.

This work is part of the the research program of the Stichting voor Fundamenteel Onderzoek der Materie (FOM) which is financially supported by NWO.

REFERENCES

1. R. Griessen, J. G. Lensink and H. G. Schnack, *Physica C* **185-189** (1991) 337, eq. (11).
2. A. I. Larkin and Yu. Ovchinnikov, *JETP Lett.* **37** (1983) 382.
3. J. Bardeen and M. J. Stephen, *Phys. Rev.* **140** (1965) 1197.
4. G. Blatter, V. B. Geshkenbein and V. M. Vinokur, *Phys. Rev. Lett.* **66** (1991) 3297.
5. E. Osquiguil, M. Maenhoudt, B. Wuyts and Y. Bruynseraede, *Appl. Phys. Lett.* **60** (1992) 1627.
6. B. Janossy, D. Prost, S. Pekker and L. Fruchter, *Physica C* **181** (1991) 51.
7. K. E. Gray, D. H. Kim, B. W. Veal, G. T. Seidler, T. F. Rosenbaum and d. E. Farrell, *Phys. Rev. B* **45** (1992) 10071.