Physica C 153–155 (1988) 1469–1470
North-Holland, Amsterdam

LOW-FIELD MEISSNER FRACTION OF YBaCuO IN A FLUX PINNING MODEL

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We report a large increase in Meissner fraction (flux expulsion) at low fields in dense ceramic and crystal YBaCuO. The effect can be interpreted in terms of the irreversibility line $1 - t \propto H^{2/3}$ observed in these materials, and is at least qualitatively consistent with a flux pinning picture.

In a recent paper (1) we reported a strong field-dependence of the Meissner flux expulsion fraction ($-4\pi M/H$ where M is magnetization and H applied field in cgs units) in an YBaCuO crystal, particularly in the low field ($H < 10$ Oe) regime. By contrast we found much weaker dependence in low density ceramics of LaSrCuO and YBaCuO. We suggested a possible interpretation of the effect in terms of a superconducting glass model. Now we have found a strong effect in high density ceramic as well as a crystal prepared by different technique. We discuss how the effect can be understood in the context of flux pinning.

Experimental procedures are as described earlier (1). Cooling in zero field and turning on the field gave the low-temperature zero-field-cooled (ZFC) flux exclusion or shielding measurement. Cooling through T_c in the field gave the low-temperature field-cooled (FC) flux expulsion or "Meissner" measurement. Turning off the field at low temperature after field-cooling gave a low-temperature remanent moment which was in all cases accurately the difference of the flux expulsion and exclusion at the nominal field with no demagnetizing corrections, as expected from a simple flux-pinning model.

Results for a $450 \times 530 \times 241 \mu m^3$ crystal of YBaCuO are shown in Fig. 1. The crystal has a T_c of 90.5 K. It was prepared by a somewhat different technique (2) but shows behavior similar to that of the earlier crystal (1). (We note that in this earlier work, due to a temperature calibration error, T_c was reported incorrectly and should have been 89 K.) The demagnetization-corrected shielding is now close to 100%, better than the earlier crystal, but the Meissner fraction climbs steeply with lowered field as before.

These remarkable increases in Meissner fraction are easily explained, at least qualitatively, in a superconductive glass model (1). But many other observations are explained by conventional flux pinning, and recently even the irreversibility line $1 - t \propto H^{2/3}$, once apparently the strongest argument for the glass model, has also been explained in terms of thermally activated flux creep (3). Here we propose a flux pinning mechanism for the Meissner fraction increase.

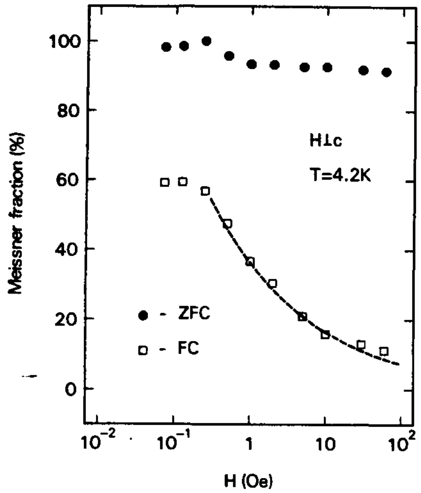

FIGURE 1
Meissner fraction (squares) and diamagnetic shielding (dots) for a single crystal YBaCuO with T_c of 90.5K. H is perpendicular to c-axis. Dashed curve represents the fit to the Eq.1.

Fig. 2 shows a schematic field-temperature plane with solid lines representing $H_{c2}(T)$ and $H_{c1}(T)$ from earlier crystal studies (4), and the approximate irreversibility line $H_{irr}(T)$ from our data. Obviously, along $H_{c2}(T)$, $M=0$ and the Meissner fraction $-4\pi M/H$ is 0%. Similarly along $H_{c1}(T)$, $M = -H/4\pi$, so that the Meissner fraction is 100%. Between these two limits, the classic theory (5) of Type II superconductors predicts a highly non-linear dependence of the equilibrium M on H. For example near H_{c2}, the appropriate relation is

$$\frac{4\pi M}{H} = -\frac{1}{(2\kappa^2 - 1)\beta_A}\left[\frac{\phi_0(1-t)}{1.09\pi\xi_0^2 H} - 1\right] . \quad (1)$$

Here κ is the standard Ginzburg-Landau ratio of penetration-to-coherence lengths, $\beta_A = 1.16$ is a geometrical factor of the vortex lattice, $\phi_0 = 2 \times 10^{-7}$ Gcm^2 is the flux quantum, ξ_0 is the zero-temperature penetration depth (as-

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0921–4534/88/$03.50 © Elsevier Science Publishers B.V.
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suming the clean-limit relation $\xi = 0.74\xi_0/(1-t)^{1/2})$ and $t = T/T_c$ is the reduced temperature. Eq. 1 implies that the Meissner fraction $4\pi M/H$ is determined by the ratio of $(1\text{-}t)/H$, which forms a line in the H-T plane intersecting T_c. A set of such lines is drawn dashed in Fig. 2 and labeled by the corresponding Meissner fraction; again actual YBaCuO parameters are used (4).

A field-cooling experiment corresponds to moving horizontally left in Fig. 2, as shown schematically by the dotted line. In practice demagnetization corrections cause the line to slope up below H_{c2}, but this is a small effect as long as M remains small near H_{c2} . As the dotted line crosses the different dashed contours, $-4\pi M/H$ increases, corresponding to increasing flux expulsion from the superconductor.

Once the irreversibility line is reached, however, the flux can be assumed pinned in position to all lower temperatures. Since $\phi_0 = BA$ and A is now fixed, B and hence M must be fixed (in the zero-demagnetization limit), even though the temperature decreases and the microscopic structure of the vortices changes. Therefore the Meissner fraction determined along the irreversibility line remains the Meissner fraction at low temperature. Thus at fixed field we can substitute for 1-t in Eq. 1 the form of the irreversibility line, e.g. $1 - t = aH^{2/3}$, to obtain a prediction of the Meissner fraction as a function of field. The formula now contains an inverse $H^{1/3}$ term.

The fit to Eq.1 is shown as a dashed line in Fig. 1 and follows the data remarkably well. The fitting parameter a, the amplitude of the irreversibility line, gives $6\text{x}10^{-4}$K/Oe $^{2/3}$. The size of the reversible region is so small at low fields (1) that it is difficult to obtain reliable data for comparison. The experimental irreversible line at higher fields (3) yields $a=4.8\text{x}10^{-4}$, in reasonable agreement with the above fit.

Actually the simple theory of Eq. 1 does not adequately treat the low field region for a number of reasons. First, as the Meissner fraction increases, strong non-linearities develop in the classic M(H) theory (5). Second, at low fields one must be concerned about inhomogeneity in T_c, which would smear out effects dependent on the tiny temperature differences predicted by the simple irreversibility relation $1 - t = aH^{2/3}$. Furthermore the 2/3 law is known not to hold in all cases, and it requires more careful study in our crystals. It is remarkable, therefore, and probably coincidental, that the theory works so well in Eq. 1 in the region below about 1 Oe. Nevertheless, the agreement at higher fields gives new support to the flux creep model for crystals of YBaCuO.

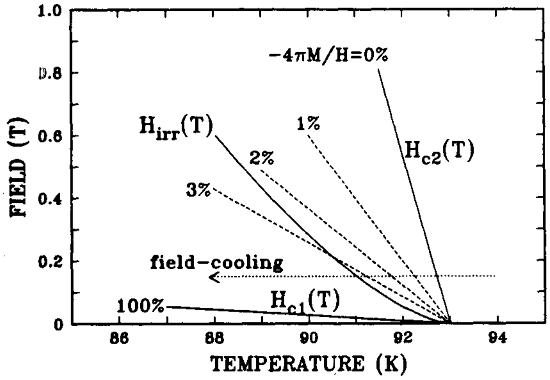

FIGURE 2

Upper and lower critical fields and approximate irreversibility line in a YBaCuO single crystal (3). Magnetization fractions are shown with dashed lines. Field cooling corresponds to dotted line.

ACKNOWLEDGEMENTS

The authors thank E. Engler for the ceramic sample, T. Worthington, W. J. Gallagher and R. L. Greene for discussions about the material parameters, and P. Kes for a helpful remark about inhomogeneity in T_c.

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