ELSEVIER

Physica C 341-348 (2000) 985-986

PHYSICA C

www.elsevier.nl/locate/physc

Current-enhanced anisotropy of $Bi_2Sr_2CaCu_2O_8$ in the mixed state

B. Khaykovich[a], Y. N. Myasoedov[a], K. Teitelbaum[a], E. Zeldov[a], D.T. Fuchs[b], T. Tamegai[c], S. Ooi[c], M. Konczykowski[d], S. F. W. R. Rycroft[e]

[a]Department of Condensed Matter Physics, The Weizmann Institute of Science, 76100 Rehovot, Israel
[b]Quantum Institute, University of California, Santa Barbara, CA 93106
[c]Department of Applied Physics, The University of Tokyo, Hongo, Bunkyo-ku, Tokyo 113-8656, Japan
[d]CNRS, UMR 7246, Laboratoire des Solides Irradies, Ecole Polytechnique, 91128 Palaiseau, France
[e]Research Center in Superconductivity, University of Cambridge, Cambridge CB3 0HE, UK

Transport and local magnetization measurements carried out *simultaneously* in $Bi_2Sr_2CaCu_2O_8$ (BSCCO) crystals reveal *finite* resistivity well *below* the magnetic irreversibility line, where the vortices should be *pinned*. This resistivity is non-monotonic with temperature and extremely non-linear. We describe the new observation in terms of a shear-induced decoupling, in which the pancake vortices flow only in the top few layers and are decoupled from the pinned vortices in the rest of the crystal.

Investigation of transport properties in type II superconductors is one of the most common methods to study vortex dynamics. The measured resistivity describes the vortex motion as a function of temperature, magnetic field, and the applied current. In layered anisotropic superconductors like BSCCO the typical ratio of in-plane to out-of-plane resisitvities $\rho_{ab}/\rho_c \simeq 10^{-4}$, and furthemore, the resistances can be significantly non-linear [1]. As a result, the measured resistance R depends on sample geometry and contact configuration. Yet it is generally assumed that the local values of ρ_{ab} and ρ_c are determined by the corresponding current densities j_{ab} and j_z. In this paper we demonstrate that at elevated currents an additional important element, the c-axis gradient of the in-plane current dj_{ab}/dz, may have a dominant effect in highly anisotropic materials like BSCCO. This gradient induces a very large velocity gradient dv_{ab}/dz of the pancake vortices in the different CuO_2 planes, leading to Josephson decoupling of the planes and to significant increase of ρ_c and the anisotropy γ.

Four wires were attached to the top *ab* surfaces of BSCCO crystals. The bottom surface of the crystals was attached to an array of 19 2DEG Hall sensors, $30 \times 30\ \mu m^2$ each, allowing *simultaneous* resistance and local magnetization measurements in the presence of transport current. Some crystals contained columnar defects produced by 5.8 GeV Pb irradiation with very low matching fields $B_\phi = 5$ to 60 G. The results are qualitatively similar before and after irradiation. Typical results of simultaneous resistive and magnetization measurements *in presence* of elevated transport current I_a are shown in Fig. 1. The results seem to be paradoxical. Finite resistivity should be present only above the magnetically measured IL (above 1600 Oe in Fig. 1). Below the IL the resistivity should be immeasurable in standard transport measurements. This is indeed the case at low I_a. However, at elevated currents, substantial resistance is measured *con- currently* with the hysteretic magnetization well below the IL as seen in Fig. 1. From the width of the hysteretic magnetization loop we evaluate the critical current density $J_c = 1.8 \times 10^4\ A/cm^2$, which translates into total critical current of $I_c = 3.7$ A at T=30K and H_a=500 Oe. Obviously, a transport current of 25 mA, which is more than two orders of magnitude lower than I_c, cannot result in measurable resistance under regular circumstances.

Figure 2 shows $I_c(T)$ determined from the magnetization measurements together with the resistive data at various applied currents I_a. At low currents $R(T)$ is monotonic and only weakly

PII S0921-4534(00)00758-9

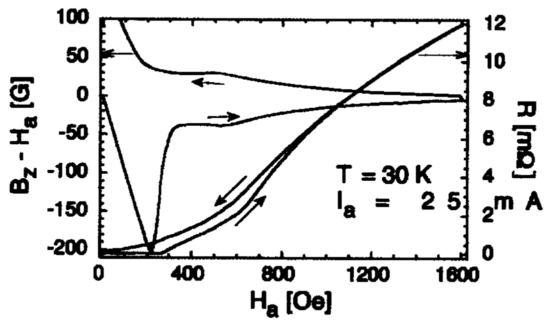

Fig.1 Resistance (right axis) and hysteretic magnetization loop in the sample center (left axis) vs. H_a at $T = 30$ K and $I_a = 25$ mA.

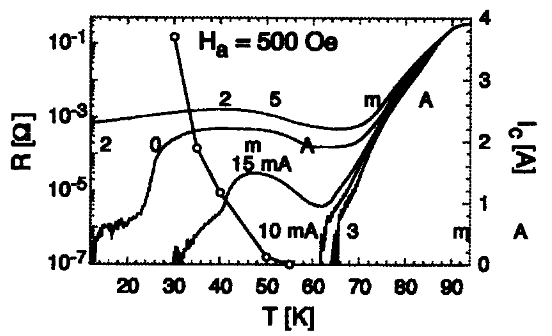

Fig.2 Resistance at various I_a (left axis) and magnetically measured critical current (right axis, circles) vs. T for irradiated sample of $B_\phi = 60$ G.

current dependent, and has a rather well-defined temperature $T_{R=0}$ at which $R(T)$ drops below experimental resolution. All these features change drastically at higher currents. The resistivity first drops to a minimum and then increases again by orders of magnitude, accompanied by a large shift of $T_{R=0}$ to lower temperatures. The reentrant resistance always occurs in the region where $I_a \ll I_c$. Heating effects can not explain the observed nonmonatonic $R(T)$ and the discrepancy between resistive and magnetization data, since these two measurements are affected to the same extent in our experimental configuration.

We describe the observed phenomena in terms of shear-induced decoupling and shear-enhanced anisotropy. At elevated temperatures in the vortex-liquid phase the in-plane current density $j_{ab}(z)$ decreases approximately exponentially from the top surface to the bottom [1]. As T is decreased the pinning becomes more effective. At some T the current density at the bottom becomes comparable or lower than J_c. As a result the vortices at the bottom stop moving or reduce their velocity substantially, whereas the vortices at the top maintain their high velocity since the current density there is significantly above J_c. As a result, the velocity gradient between the planes dv_{ab}/dz is increased. The enhanced dv_{ab}/dz results, in turn, in shear-induced phase slippage between the adjacent CuO_2 planes reducing the Josephson coupling and leading to decoupling of the planes [2,3]. As a result ρ_c and hence γ are increased significantly. The large ρ_c prevents the lower vortex pinned region from effectively shunting the current. This process is "self-enhanced", since larger γ causes the current to flow in a shallower layer, which results in even larger gradient dj_{ab}/dz, and larger ρ_c. The shear-induced decoupling explains the observed nonmonotonic $R(T)$, the highly non-linear $R(I)$, and the apparent discrepancy between the transport and the magnetization data. As T is decreased, this process causes an effective increase of γ, resulting in the observed nonmonotonic $R(T)$ in Fig. 2. In addition, the current gradient grows as I_a is increased, giving rise to the extremely non-linear $R(I)$ behavior in Fig. 2.

This work was supported by the German-Israeli Science Foundation GIF, by US-Israel Binational Science Foundation (BSF), by CREST, and by the Grant-in-Aid for Scientific Research from the Ministry of Education, Science, Sports, and Culture, Japan.

REFERENCES

1. R. Busch *et al.*, Phys. Rev. Lett. **69**, 522 (1992).
2. E. H. Brandt, Rep. Prog. Phys. **58**, 1465 (1995).
3. A. E. Koshelev, Phys. Rev. Lett. **76**, 1340 (1996).