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Transport in the superconducting mixed state of $Bi_{2+x}Sr_{2-y}CuO_{6\pm\delta}$

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Flux-flow resistance and Hall effect were measured in a $Bi_{2+x}Sr_{2-y}CuO_{6\pm\delta}$ crystal in the superconducting mixed state. The Hall mobility saturates to a temperature-independent plateau at $\mu_H = 0.9$ mT^{-1} at high field ($H > 5$ T), while the resistance varies nearly as $\log(H)$. The absence of features to identify $H_{c2}(T)$ is contrasted with other type-II superconductors of similarly low $T_c = 7$ K.

The fluxon motion giving rise to resistivity and the Hall effect in the superconducting mixed state is generally influenced by pinning, i.e., by local variations in vortex potential. In cuprate superconductors, the division between the mixed and normal states is characteristically indistinct, and flux pinning is notably ineffectual for delineating an $H_{c2}(T)$ phase boundary, if one exists.[1] In addition to weak pinning, magnetic transitions in the highly anisotropic layered cuprates are also broadened because of thermally excited fluxons.[2] Thus it is of interest to study $Bi_{2+x}Sr_{2-y}CuO_{6\pm\delta}$,[3,4] the single Cu-O-layer phase in the family of high-T_c alkaline-bismuth cuprates. This material has relatively low T_c, ~5–10 K, and may be compared to better-understood conventional superconductors. In this work the magnetic field is applied along the c axis to probe vortex circulation and motion in the a-b plane, parallel to the layers. The findings are qualitatively similar to the high-T_c cuprates.[5,6] The flux-flow resistance varies nearly as $\log(H)$, suggesting a two-dimensional mechanism and precluding an identification of $H_{c2}(T)$. The Hall mobility saturates to a plateau, independent of magnetic field and temperature. The material seems to be a clean type-II superconductor, but it is markedly different from such superconductors as elemental niobium or the layered dichalcogenides, 2H-$NbSe_2$ and 2H-NbS_2, which have similar T_c's.

Crystals of superconducting $Bi_{2+x}Sr_{2-y}CuO_{6\pm\delta}$, with $x \lesssim 0.1$, and $y \lesssim 0.1$, $\delta \sim 0$, were grown by slowly cooling a molten mixture of the metal oxides, an excess of CuO, and NaCl in a 0.04-atm partial pressure of O_2.[7] Crystal growth, structure, transport anisotropy, penetration depth, and tunneling studies were reported in earlier work.[8] Within a solid solution region, superconducting crystals are relatively close in composition and structure to crystals which are not superconducting,[8–20] so that nonuniformities are likely to be present in most samples. Compositional inhomogeneity can affect pinning and broaden resistive transitions. The crystal selected for magnetotransport study was a thin plate, 1.2×1.9 mm^2 in the a-b plane and 4.5 μm along the c axis, which was annealed at 600 °C in 0.1-atm O_2 for several h and slowly cooled. Four electrical contacts for van der Pauw measurements were placed in a rectangular pattern at the crystal edges with silver cement cured at 200 °C.

The magnetotransport measurements employed a 15-T magnet wound with multifilamentary Nb-Ti and Nb-Sn superconducting wire, where the remanent field at the sample is typically less than 0.01 T. Resistance data for crossed current and voltage contact pairs were recorded at fixed temperature by slowly sweeping the magnetic field for both polarities. The resistance component even in H, multiplied by a calibration factor determined by a van der Pauw analysis, was used to obtain the magnetoresistivity shown as ρ_e in Fig. 1. This procedure reduces sensitivity to the changes in current path that occurs if current and voltage contacts were permuted. The curves in Fig. 1 were normalized to the residual resistivity $\rho(0) = 90$ $\mu\Omega$ cm, which was obtained by extrapolating the temperature dependence shown in the inset and approximates the normal-state resistivity for $T < T_c$. The transition temperature is 7 K. The Hall coefficient was obtained from the component odd in H, and was combined with ρ_e to compute the Hall mobility μ_H shown in Fig. 2. The curves correspond to a regime where the flux-flow voltages scale linearly with current, an indication of stochastic thermal motion, rather than flux trapping, in pinning potentials. Flux creep associated with pinning is more apparent at low temperatures and magnetic fields, where the

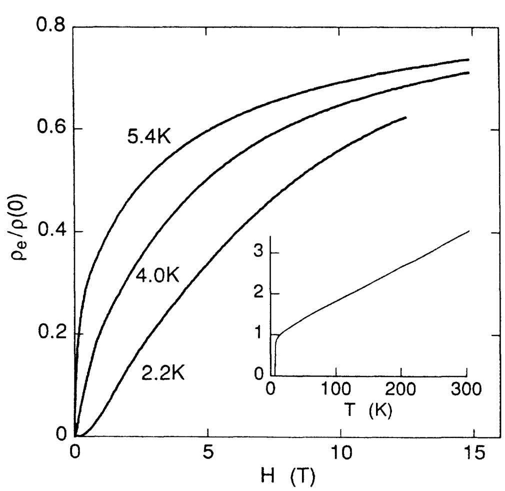

FIG. 1. Magnetoresistance curves for a $Bi_{2+x}Sr_{2-y}CuO_{6\pm\delta}$ crystal below the 7-K transition temperature. Inset: temperature dependence at $H = 0$. Curves are normalized to $\rho(0) = 90$ $\mu\Omega$ cm, and transport is in the a-b basal plane of the crystal.

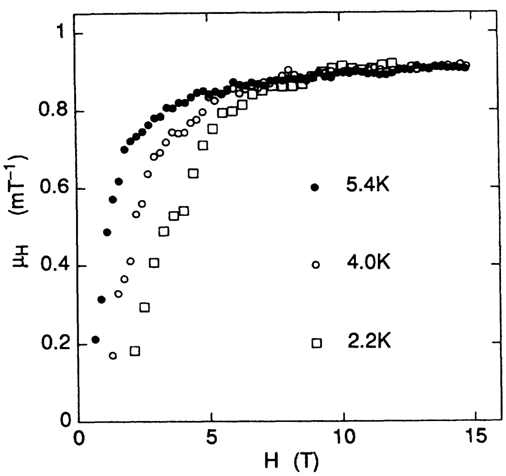

FIG. 2. Magnetic-field dependence of the Hall mobility in the mixed state at the temperatures indicated.

magnetoresistance curves show an onset of resistance at a magnetic-field threshold, determined by instrumental sensitivity, increasing from ~0.1 T at 2.2 K to ~4 T at 0.5 K.

Strongly two-dimensional transport was suggested by the nonmetallic, factor of 10^5 larger resistivity along the c axis found in earlier work.[8] From the finite $\rho(0)$ and a two-dimensional model, one calculates a disorder parameter of $(k_F l)_{ab} = 35$, where k_F is the Fermi wave vector and l the elastic mean free path in the a-b plane. The measured Hall coefficient is hole type, $R_H = 5.7\times10^{-10}$ m^3C^{-1}, independent of temperature to within experimental accuracy. A free-carrier model of one hole per Cu predicts a somewhat larger R_H of 2.2×10^{-9} m^3C^{-1}. Thus $k_F < 0.5$ Å^{-1} and $l > 75$ Å are conservatively inferred. Since $H_{c2}(0)$ is above 15 T (transition midpoint at 0.5 K, which underestimates H_{c2}), the coherence distance is $\xi(0) < 50$ Å in the a-b plane and a clean type-II superconductivity description seems adequate.

The sublinear magnetoresistance curves shown in Fig. 1 are nearly logarithmic functions of H. A gradual quenching of superconductivity by a magnetic field was also found for the $T_c = 85$ K superconductor $Bi_2Sr_2CaCu_2O_8$ (nominal composition),[6] a similarity which ought to render the magnitude of T_c itself as less relevant to the absence of sharp transitions at H_{c2} in cuprates. Arguments that midpoints of ρ-vs-H or ρ-vs-T transitions lie well below $H_{c2}(T)$ were discussed by Tinkham.[1] Figure 1 stands in stark contrast to the behavior of Nb, an archtypical clean type-II superconductor, in which the flux-flow resistance is much closer to being linear, taking pinning perturbations into account,[21] or to the layered niobium dichalcogenides, in which changes in slope at H_{c2} seem sufficiently distinct.[22,23] The tangent of the Hall angle at the highest field is $\omega_c\tau = 0.014$, where ω_c is the cyclotron frequency and τ the scattering time, implying negligible magnetoresistance in the normal state.

The Hall mobility shown in Fig. 2 is also distinctive, saturating at high field, in contrast to the resistance. In the high-T_c cuprates $YBa_2Cu_3O_7$ and $Bi_2Sr_2CaCu_2O_8$, the Hall coefficient is temperature dependent in the normal state, shows a peak near T_c, and in weak magnetic fields becomes negative below T_c.[24–26] There is also little indication of saturation in μ_H at high field, although the magnetic-field dependence is weaker in the more anisotropic $Bi_2Sr_2CaCu_2O_8$.[24] The present data show a systematic decrease at low H, but it has not been ascertained whether $\mu_H \rightarrow 0$ or the sign changes at low H. The Hall-effect anomaly in weak magnetic field has been discussed in terms of fluctuation theory.[24,27] Decreases in μ_H at low H could also be reflecting stronger pinning effects in type-II superconductors in weak magnetic fields. The longitudinal component of the vortex velocity, which determines the Hall potential, is much smaller than the transverse component, which determines the dissipative potential. Microscopic pinning forces modulating this small Hall component tend to depress its mean value.[21] Attributing these internal forces effectively to local magnetic fields, Fig. 2 gives an estimate of $\lesssim 5$ T.

The high-field plateaus are nearly independent of temperature at $\mu_H \approx 9\times10^{-4}$ T^{-1}, which is close to the Hall mobility of the normal state. This also suggests another fundamental difference with Nb, where the Hall angle is determined by the field in the vortex core, essentially H_{c2} and independent of H,[21] as predicted by some theories of fluxon motion in clean type-II superconductors.[28,29] A constant Hall tangent implies a temperature- and field-dependent Hall mobility, $\mu_H \propto H_{c2}(T)/H$. In the present case the Hall mobility is instead a constant. If vortex motion is indeed a correct description, then the magnetic field governing the Hall effect is the applied field H, rather than H_{c2}. A possible explanation is that vortex excitations in the vicinity of the applied-field vortices cause the local magnetic field in the cores to be nearly uniform and equal to H.[2,30]

In this study of $Bi_{2+x}Sr_{2-y}CuO_{6\pm\delta}$, as in the high-$T_c$ cuprates, the magnetoresistance conveys no indication of a demarcation between the mixed and normal states. The plateaus observed in the Hall mobility remain independent of temperature at high fields, where flux flow is observed without a pinning threshold. Thus there is no evidence for the role of $H_{c2}(T)$ as either a phase boundary or as the Hall magnetic field in the vortex core; results are judged to be essentially intrinsic because of the weak flux pinning in high magnetic fields. The resistivity of the crystal indicates sufficiently low disorder for clean type-II superconductivity, yet the results differ considerably from conventional low-T_c superconductors. Broad magnetic transitions are therefore observed in all layered-CuO superconductors with large electronic anisotropy, irrespective of the T_c. The drop in mobility in weak magnetic fields at low temperatures is attributed to extrinsic pinning potentials associated with inhomogeneity. Whether extrinsic disorder has any significant influence other than flux pinning remains undetermined in the present experiments.

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