Bulk transport properties of $Bi_2Sr_2CaCu_2O_8$ crystals in the Corbino disk geometry

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Transport measurements have been made on $Bi_2Sr_2CaCu_2O_8$ single crystals in the Corbino disk geometry where vortices should not cross the sample edges in a fixed applied field. The results are compared directly with a strip geometry by cutting the disk into a strip and remeasuring the sample using the same contacts. Pronounced differences are observed in both the resistive transition and the current-voltage characteristics in these two geometries. The critical current density in the vortex solid phase is at least 20 times smaller than usual estimates for a strip geometry. We conclude that the transport properties of $Bi_2Sr_2CaCu_2O_8$ samples in the strip geometry are dominated by surface barriers in both solid and liquid vortex phases over a wide range of fields and temperatures. [S0163-1829(99)50326-3]

The $Bi_2Sr_2CaCu_2O_8$ (BSCCO) high-temperature superconductor has extreme anisotropy and very weak bulk pinning above about 30 K. An understanding of the contributions to the irreversible properties is essential for the elucidation of the transitions and crossovers in its H-T phase diagram.[1–3] Although it is well known that the magnetization of BSCCO crystals is dominated by geometrical and surface barriers above about 30 K,[4–7] it is only recently that transport measurements performed on single crystals have also been shown to be significantly affected by the presence of surface[8–10] and geometrical barriers.[12] These effects obscure the underlying bulk behavior over a wide range of fields and temperatures. The bulk behavior is of central importance for an understanding of the complex phase diagram and thermodynamic transitions in the vortex matter. Below, we use the term ''surface barrier'' (SB) to include both surface and geometrical barriers. Fuchs *et al.*[8] used a miniature Hall probe array to measure the self field of an applied transport current and evaluate the current distribution in a BSCCO single crystal. The current was shown to flow predominantly at the sample edges over a large field and temperature range, suggesting that a type of SB dominates the transport behavior, even above melting in the vortex liquid (VL) state. This SB results in the edges acting as low resistance shorts. Thus, in strips with current electrodes which are closer to the edges than to each other the measured resistance, R, considerably underestimates the bulk resistance, R_B. Accordingly, transport measurements performed on large BSCCO crystals with contacts positioned further from the edges than from each other have allowed a semiquantitative estimate of the effect of surface currents on the measured resistance. This study[10] shows an enhancement in R of the platelike sample by up to two orders of magnitude relative to that of a strip cut from it. Large plate samples also show reduced apparent activation energy in the VL and a smaller apparent critical current, I_c, in the vortex solid.[10] While Ref. 10 shows that the effects of surface currents on transport properties are considerable, the geometry and the associated current and vortex flow patterns are complicated. Here we have fabricated samples in the Corbino disk (CD) geometry.[11] In this case, although there is a radial gradient in the current density, J, for perpendicular applied fields, the Lorentz force is azimuthal and the vortices should flow in concentric circles without crossing the sample edges, thus avoiding the effects of the SB. This allows direct access to the bulk properties of the vortex solid. Profound differences are observed in the transport measurements performed on CD samples and strip-shaped samples cut from the disks. We conclude that sample quality strongly affects the magnitude of SB effects observed, thus resolving the recent controversy.[13]

High quality single crystals of BSCCO with $T_c \approx 89$ K were obtained from two different sources.[14,15] The crystals were cut with a miniature wire saw to typical dimensions of $1.50\ \mathrm{mm} \times 1.50\ \mathrm{mm} \times 0.06\ \mathrm{mm}$ and then carefully cleaved to obtain optically smooth single crystals with thicknesses of about 15 μm. A 300 nm Au film was immediately evaporated onto the fresh surface following cleaving. A focused ion beam (FIB) was then used to mill five concentric tracks ≈ 8 μm wide and 1–2 μm deep at 100 μm spacings. Measurements using a superconducting quantum inter-

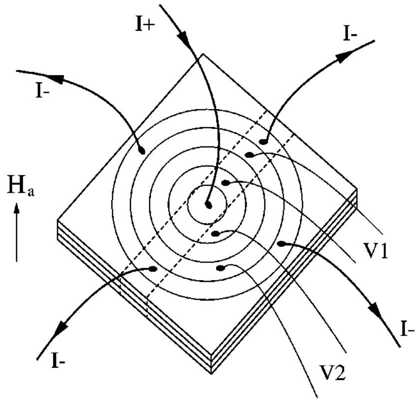

FIG. 1. Schematic of Corbino disk with annular electrodes for current, *I*, and voltages, V1 and V2. The sample is coated with Au and the concentric circles denote the FIB tracks through the Au layer. The dashed line indicates where the strip was cut from.

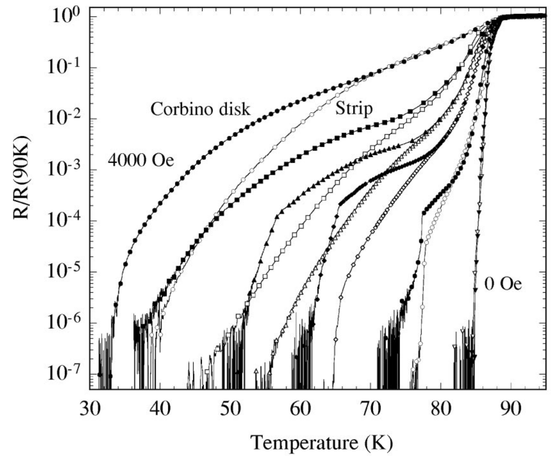

FIG. 2. Reduced resistance as a function of temperature in CD1 (solid data points) and corresponding strip CS1 (open data points) at applied fields of 0 (▽), 100 (○), 300 (◇), 500 (△), 1000 (□), and 4000 Oe (○). The values for the resistivity in the normal state (at 100 K) of the Corbino disk and strip are 540 and 570 $\mu\Omega$ cm, respectively. The currents in the CD and strip were 10 mA and 3 mA, respectively, for comparable current densities.

ference device (SQUID) magnetometer showed that neither T_c nor the melting line is shifted showing that there is no unwanted damage by implantation of ions. The CD thus consists of four annular Au contact rings and a central contact pad, as shown by the schematic in Fig. 1. The central and outermost pads were used as current contacts and the inner rings act as voltage contacts. 10 μm Au wires were attached to the pads with silver epoxy using a micro-manipulator. Two to four contacts were placed onto each current ring to ensure each was equipotential and current flow radial (see below). After annealing at 420 °C for five minutes in O_2 contact resistances were 2–3 Ω. Once CD's had been fully characterized, each was cut into strip-shaped samples of width 200–400 μm, taking care to ensure that the current and voltage contacts remained intact. These strips were then measured for comparison with the parent CD's. The resistive transition was measured as a function of temperature at various fields applied parallel to the c axis. The voltages at two positions on the CD, V1 and V2 (see Fig. 1), were measured simultaneously using lock-in amplifiers and low noise transformers at 72 Hz. dc current-voltage (IV) measurements were made and the magnetic moment was measured as a function of field using a SQUID magnetometer for samples of the same material and similar size and shape as the strip samples. Four CD samples and associated cut strips were measured in total. All samples showed the same qualitative behavior. The results presented are from two samples with the most pronounced effect.

Figure 2 shows the $R(T)$ curves of Corbino disk CD1 compared to the strip CS1 cut directly from it. Above T_c the difference between the two resistances is consistent with the change in cross-sectional area, confirming that current flows uniformly between the voltage electrodes. Hence, the normal-state resistance of the CD is *smaller* than that of the strip as expected. Below T_c the resistance of CD1, which is indicative of the bulk resistance, R_B, is dramatically *enhanced* relative to CS1, which is dominated by the surface resistance, R_S. The enhancement is clear both in the solid and liquid phases below and above the first-order transition (FOT) (Refs. 16,17) which is indicated by the sharp change in the slope of $R(T)$ for the 100, 300, and 500 Oe curves. The effect is most evident at fields of $\approx$500 Oe, consistent with Ref. 10. In the solid phase CD1 displays a (nonlinear) resistive ''tail'' which persists to a temperature below that at which the strip resistance falls below the level of sensitivity. This is consistent with the abrupt enhancement of a SB determined critical current (I_c) upon freezing.[10,18,19] Figure 2 presents data at 3 mA and 10 mA applied to the strip and the CD, respectively, to ensure comparable J. The effect is only slightly reduced when comparing the data at the same current of 10 mA. The melting lines for both geometries are concurrent at all fields, demonstrating good sample homogeneity and that the cutting has not induced significant damage. In the CD geometry the resistance of the outer electrode ring is not negligible and in fact comparable to the contact resistance, so that care must be taken to ensure a uniform radial current. In order to confirm that it is indeed uniform, Fig. 3 shows data taken from the two different voltage pairs in sample CD1. Close agreement between the pairs demonstrates that the current is almost radially uniform. Small differences between V1 and V2 may arise because of some

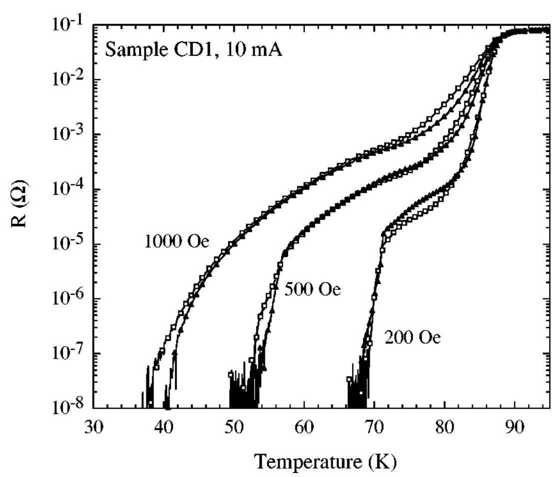

FIG. 3. Resistive transitions for CD1 at three applied fields showing agreement between the voltage pairs V1 (□) and V2 (▲) indicating uniform radial current flow.

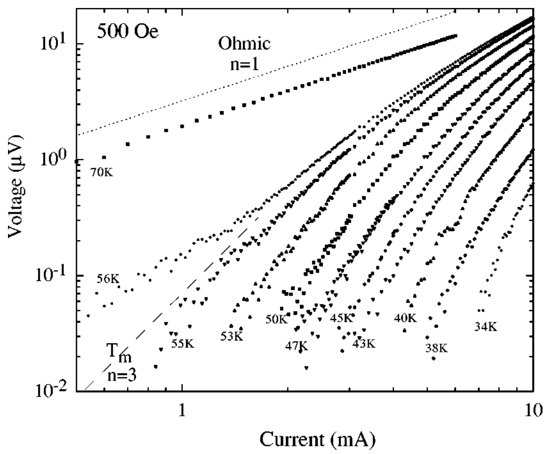

FIG. 4. *IV* characteristics of CD2 at 500 Oe and temperatures between 34 and 70 K.

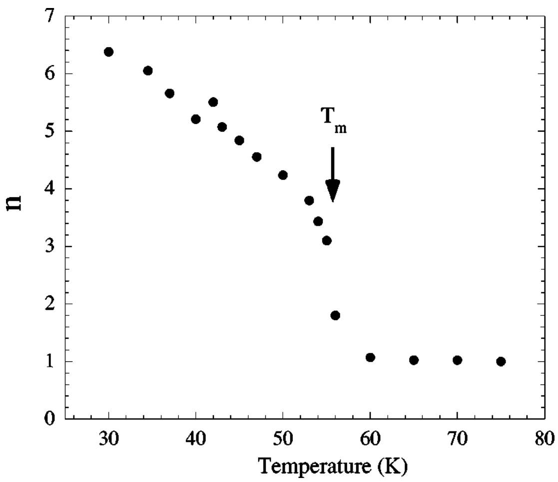

FIG. 5. Temperature dependence of the slope, *n*, of the *IV* curves of sample CD2 shown in Fig. 4. The curves show a linear behavior for $T>T_m$.

current flow along the Au electrodes (the sample is not a perfect short while it still has finite R, hence some current sharing occurs) resulting in a finite voltage drop along the ring. Figure 2 shows that these variations are, however, very small compared to the magnitude of the SB effect.

Since R for the CD is enhanced relative to the strip sample, and since T_m is the same, we expect that the apparent activation energies in the liquid phase, U/k_B, evaluated from Arrhenius plots, will also reflect a difference. At 10 mA and 100 Oe, we find values of 4000 and 2000 K for CS1 and CD1, respectively, with a stronger dependence on field for the strip than for the CD. Fuchs *et al.*[10] find values of 4600 and 3000 K for a strip and plate, respectively, while Mazilu *et al.*[13] find values of 2000–3000 K for both strip and CD geometries. We emphasize, on the other hand, that the behavior is not clearly Arrhenius-like in any wide range so that these values are sensitive to the temperature window which is selected to fit to the data.

Next we move to the behavior in the solid phase below the melting transition. I_c is much smaller in the CD's than in the strips and it is thus possible to measure the *IV* characteristics over a large temperature range below T_m without inducing significant ohmic heating. Figure 4 shows *IV* curves at 500 Oe and selected temperatures between 34 and 70 K for CD2. The arrowhead or second peak field in these samples is at about 600 Oe. At 70 K, in the VL phase, the characteristics of CD2 are linear and ohmic, unlike observed elsewhere in strip samples where nonlinearity was ascribed to viscosity.[20] Figure 5 shows how the slope of the *IV* curves, *n*, varies with temperature, where $I \propto V^n$. For the nonlinear current regime below T_m the exponent is evaluated by forcing a linear fit to the data in the decade above where the signal vanishes below our sensitivity. The data suggests that the nonlinearity in the VL phase measured in strip samples is associated with surface currents and is not a bulk effect. The exponent of the *IV* curves jumps to 3 in a narrow window about melting at 55 K, reminiscent of a Kosterlitz-Thouless transition.[21,22] This may reflect a sharp reduction in interplanar coupling between vortex pancakes at T_m. Below T_m, negative curvature develops in the *IV* curves, consistent with a diverging activation energy for vortex motion, together with the onset of pinning and a finite I_c.

The measured I_c at various temperatures at 500 Oe, using a criterion of 100 nV, are shown in the inset of Fig. 6 for both CD2 and CS2. I_c for the strip is twice that for the CD even though the cross-sectional area is almost an order of magnitude smaller. Since the T_m is unaffected by cutting it is difficult to believe that any significant disorder is introduced.[23] We conclude that the only scenario consistent with both this observation and the enhanced resistance of the CD in the VL is that current flows almost entirely at the sample edges in the strip sample. In this case, calculation of a critical current density (J_c) by assumption of uniform current flow, either from transport or magnetization measurements (using the Bean model), is invalid and leads to a dramatic overestimation of the bulk J_c. The main part of Fig. 6 shows the J_c calculated as usual by incorrectly assuming bulk current flow. Although the approach is incorrect, it indicates the error incurred and shows that the bulk current,

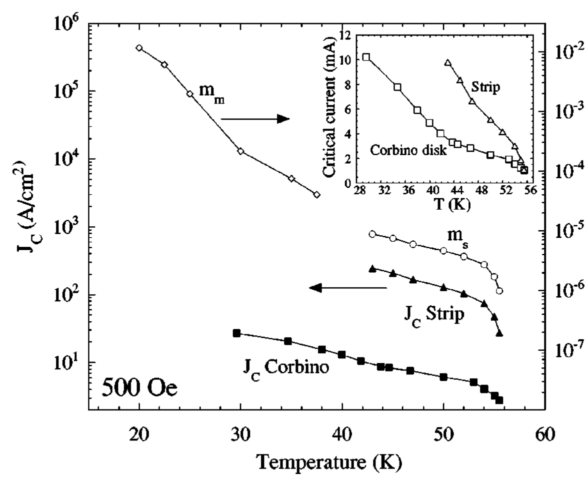

FIG. 6. Temperature dependence of the effective J_c obtained from *IV* measurements in CD2 (■) and CS2 (▲) at 500 Oe. The right-hand axis shows measured magnetic-moment (hysteresis) data of a strip sample, m_m (◇), compared with the magnetic moment expected from a current equal to the transport I_c flowing around a loop defined by the sample edges, m_s (○). The inset shows the measured transport I_c extracted from the *IV* curves with a voltage criterion of 100 nV.

accurately probed by the Corbino geometry, is 20 times smaller than estimates for the strip. Note that the J flowing at the sample edges is also underestimated by this approach. In the case of the disk geometry, because J has a radial dependence, we evaluate it at the inner voltage contact. This represents an upper bound for the calculated J_c in the CD. A further and more conclusive test for whether currents flow only at the edges can be made by comparing the *measured* magnetic moment in samples of similar size and shape as the strips, m_m, to the *calculated* magnetic moment expected if the measured transport critical current is assumed to flow entirely along the sample edges, m_s. The right-hand axis of Fig. 6 shows the temperature dependence of these values. Although the transport and magnetization data do not overlap, the two regions approach each other closely, supporting the conclusions here. Thus, the central result of this paper is that the bulk J_c obtained using the CD geometry is at least a factor of 20 smaller than values obtained from either transport measurements or magnetization loops at temperatures above 30 K. In both cases, surface currents arising from a SB dominate the measured response and obscure the bulk behavior.

Finally, we discuss the differences between the results here and those elsewhere.[13] First, the largest differences observed between the CD and strip samples occur in the vicinity of the FOT both in the solid and liquid phases, as is also seen in Ref. 10. Also, all of our data for the strip samples are weakly nonlinear above melting, as observed elsewhere.[9,10] Mazilu *et al.*[13] however, find no difference between CD and strip samples and find that their data are always in the linear regime. Given that the edges of the samples are prepared in a similar manner, the fact that the samples in Ref. 13 do not show clear signs of the FOT may indicate lower crystal quality, which may explain the discrepancy in the results. Furthermore, although one set of samples we have investigated is from the same source as Ref. 10, we also see the effect in samples from a different source. The variation in the magnitude of the effect from sample to sample confirms that the SB is extremely sensitive to sample quality and preparation. In the case of the lower quality samples used in Ref. 13, the effect of the SB may be significantly suppressed. Finally, and most importantly, the observed significant *reduction* in critical current density in the vortex solid phase in the Corbino disks, an area that was not explored in Ref. 13, provides clear evidence that the surfaces play a crucial role in the transport properties of high quality samples.

To summarize, the bulk transport properties in BSCCO crystals in the Corbino disk geometry are shown to be very different than in the strip geometry, confirming that in the latter case they are dominated by surface barriers in both solid and liquid vortex phases. This surface barrier obscures the bulk properties. Using the Corbino disk geometry, we avoid these barriers and have shown that the bulk critical current in BSCCO is more than an order of magnitude smaller than previous estimates.

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