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Effect of surface barriers on transport properties of $Bi_2Sr_2CaCu_2O_8$ single crystals using the Corbino disc configuration

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Abstract. Transport measurements have been made on $Bi_2Sr_2CaCu_2O_8$ single crystals in both Corbino disc and strip geometries. Pronounced differences are observed in both the resistive transition and the current–voltage characteristics in these two geometries. Surface barriers affect the behaviour of the strip and reduce the measured resistance of the vortex liquid by over two orders of magnitude with respect to the Corbino geometry. The critical current density of the Corbino disc, which reflects the true bulk critical current, is a factor of at least 20 times smaller. We conclude that the transport properties of $Bi_2Sr_2CaCu_2O_8$ samples in the strip geometry are dominated by SB in both the solid and liquid vortex phases over a wide range of fields and temperatures.

1. Introduction

In high temperature superconductors an understanding of the contributions to the irreversible properties is essential for the elucidation of the complex phase diagram and thermodynamic transitions in the vortex matter [1–3]. Although it is well known that the magnetization of $Bi_2Sr_2CaCu_2O_8$ (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 [11]. These effects obscure the underlying bulk behaviour over a wide range of fields and temperatures. 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 behaviour, even 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 considerably underestimates the bulk resistance. Accordingly, transport measurements performed on large BSCCO crystals with contacts positioned further from the edges than from each other have allowed a semi-quantitative estimate of the effect of surface currents on the measured resistance. This study [10] shows an enhancement in the resistance of the platelike sample by up to two orders of magnitude relative to that of a strip cut from it. While [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 disc (CD) configuration. In this case the effects of the SB are avoided by enforcing a radial current distribution so that the Lorentz force is always azimuthal and vortices flow in concentric circles without crossing the sample edges.

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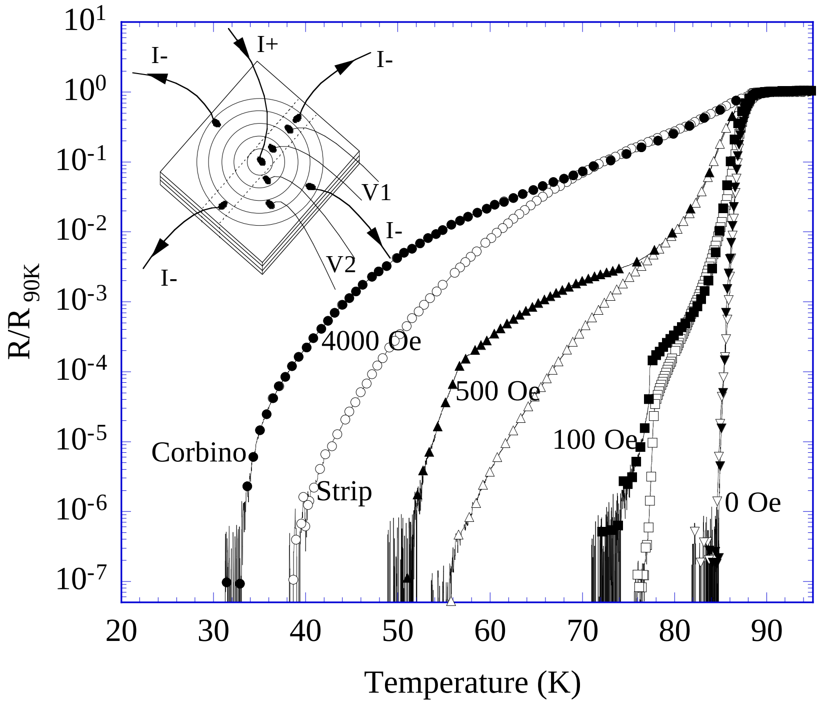

Figure 1. Reduced resistance as a function of temperature in CD1 (solid data points) and corresponding strip CS1 (open data points) at various representative fields. Currents in the CD and strip were 10 and 3 mA respectively for comparable current densities. The inset shows a schematic diagram of the Corbino disc and the dashed line indicates how the strip was cut out.

This allows direct access to the bulk properties of the vortex solid (VS).

2. Experiment

Single crystals of BSCCO with $T_c \approx 89$ K were obtained from two different sources [12, 13]. The crystals were cut to typical dimensions of 1.50 mm $\times$ 1.50 mm $\times$ 0.06 mm and then cleaved to obtain optically smooth crystals with thicknesses of about 15 μm. A 300 nm Au film was evaporated onto the fresh surface following cleaving and a focused ion beam (FIB) was then used to mill five concentric tracks $\approx 8\mu$m wide and 1–2 μm deep at 100 μm spacings. Measurements using a SQUID magnetometer showed that neither T_c nor the melting line are 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 diagram in the inset to figure 1. The central and outermost pads were used as current contacts and the inner rings as voltage contacts. 10 μm Au wires were attached to the pads with silver epoxy using a micro-manipulator. After annealing at 420 °C for 5 minutes in O_2, contact resistances were 2–3 Ω.

Once characterized, each CD 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 CDs. 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, were measured simultaneously using lock-in amplifiers and low noise transformers at 72 Hz. Close agreement between voltage pairs demonstrates that the current flow is radially uniform [14]. Dc current–voltage (I–V) measurements were performed at various fields and temperatures. 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 and all showed the same qualitative behaviour.

3. Results and discussion

Figure 1 shows $R(T)$ curves of Corbino disc CD1 compared to the strip CS1 cut directly from it. Above T_c the resistance of the CD is *smaller* than that of the strip, consistent with their difference in cross-sectional area, confirming that current flows uniformly between the voltage electrodes. At a field dependent temperature below T_c the resistance of CD1 becomes dramatically *enhanced* relative to that of CS1. This difference is clear both in the solid and liquid phases, below and above the first order transition (FOT) [15, 16] which is indicated by the sharp change in the slope of $R(T)$ for the 100 and 500 Oe curves. 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 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 in the strip [10, 17, 18]. 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,

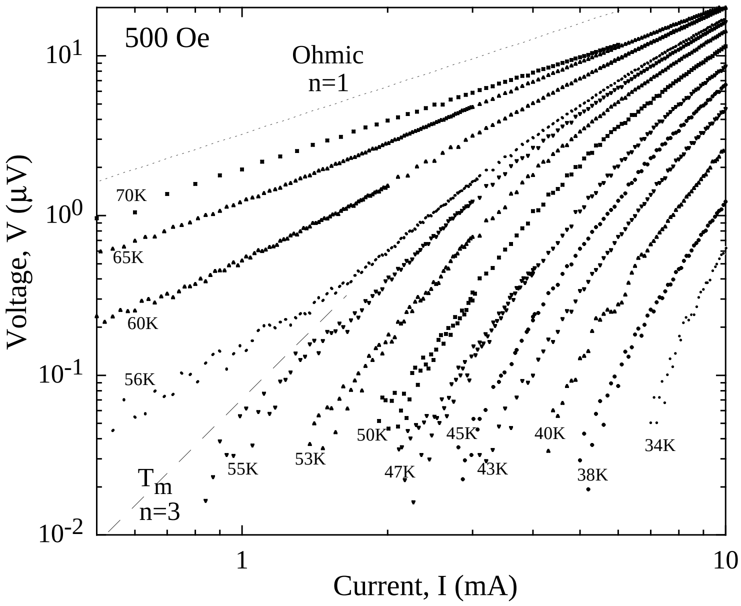

Figure 2. I–V characteristics of CD2 at 500 Oe and temperatures between 34 K and 70 K.

evaluated from Arrhenius plots will also reflect a difference. At 10 mA and 100 Oe, we find values of 4000 K 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 similar values of 4600 K and 3000 K for a strip and plate respectively. We emphasize, on the other hand, that the behaviour 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.

The behaviour below the melting transition demonstrates that I_c is much smaller in the CDs than the strips and it is thus possible to measure the I–V characteristics over a large temperature range in the VS phase. Figure 2 shows I–V curves at 500 Oe and selected temperatures between 34 K and 70 K for CD2. The arrowhead 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 those observed in the strip samples. Figure 3 shows how the slope of the I–V 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 our sensitivity limit. The data shows 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 Corbino I–V curves jumps to 3 in a narrow window about melting at 55 K, reminiscent of a Kosterlitz–Thouless transition [19, 20]. This may reflect a sharp reduction in interplanar coupling between vortex pancakes at T_m. Below T_m, negative curvature develops in the I–V curves, consistent 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 figure 4 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

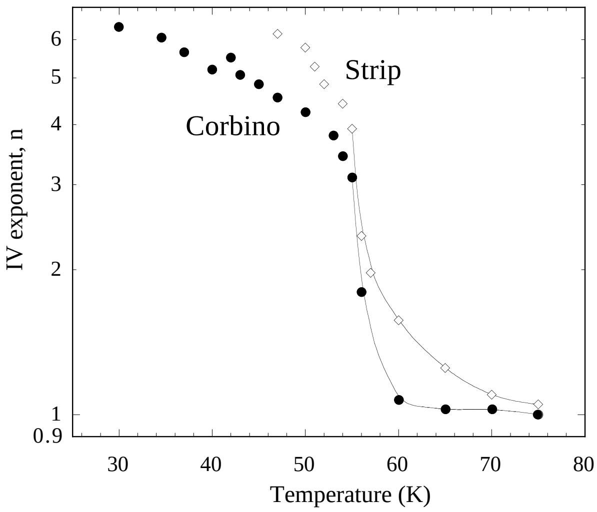

Figure 3. Temperature dependence of the slope, n, of the I–V curves. Note that in the Corbino sample n shows a linear behaviour for $T > T_m$. Solid lines are a guide for the eye.

[21]. 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. The left-hand axis of figure 4 shows the critical current density (J_c) for the Corbino and strip samples calculated as usual by assuming bulk current flow. Note that the J flowing at the edges of the strip is underestimated by this approach. In the case of the disc 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,

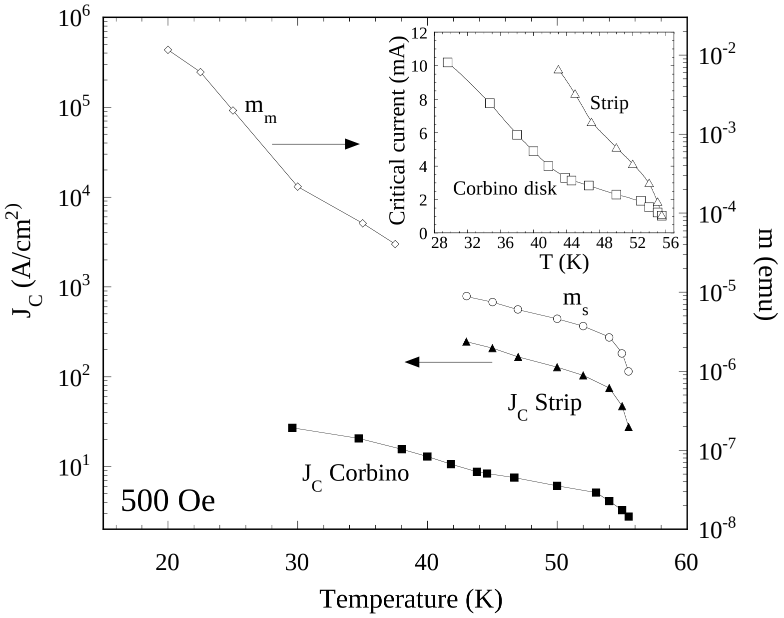

Figure 4. Temperature dependence of the effective J_c obtained from I–V measurements in CD2 and CS2 at 500 Oe. The inset shows the measured transport I_c extracted from the I–V curves with a voltage criterion of 100 nV.

m_s. The right-hand axis of figure 4 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 work 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 performed on standard striplike samples at temperatures above 30 K.

To summarize, the bulk transport properties in BSCCO crystals in the Corbino disc configuration are shown to be very different to those in the strip geometry, confirming that in the latter case they are dominated by surface barriers in both solid and liquid vortex phases and obscure the bulk properties. Using the Corbino disc configuration, 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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