Transport properties governed by surface barriers in Bi$_2$Sr$_2$CaCu$_2$O$_8$

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One of the most common investigation techniques of type-II superconductors is the transport measurement, in which an electrical current is applied to a sample and the corresponding resistance is measured as a function of temperature and magnetic field. At temperatures well below the critical temperature, $T_c$, the resistance of a superconductor is usually immeasurably low. But at elevated temperatures and fields, in the so-called vortex liquid phase, a substantial linear resistance is observed. In this dissipative state, which in anisotropic high-temperature superconductors like Bi$_2$Sr$_2$CaCu$_2$O$_8$ may occupy most of the mixed-state phase diagram, the transport current is usually assumed to flow uniformly across the sample as in a normal metal. To test this assumption, we have devised a measurement approach which allows determination of the flow pattern of the transport current across the sample. The surprising result is that, in Bi$_2$Sr$_2$CaCu$_2$O$_8$ crystals, most of the current flows at the edges of the sample rather than in the bulk, even in the highly resistive state, due to the presence of strong surface barriers. This finding has significant implications for the interpretation of existing resistivity data and may be of importance for the development of high-temperature superconducting wires and tapes.

Figure 1 Experimental set-up. A schematic top view of Bi$_2$Sr$_2$CaCu$_2$O$_8$ crystal (1.5 x 1.5 x 0.01 mm) attached to an array of seven GaAs/AlGaAs two-dimensional electron-gas Hall sensors underneath the sample. The sensors have an active area of 10 x 10 $\mu$m$^2$ and are 10 $\mu$m apart. There is one sensor outside the sample; the other six span more than half of the sample width. Magnetic field $H_{BC}$ is applied perpendicular to the sample surface. An a.c. current $I_{applied}$ is applied through the crystal electrical contacts. The sensors are used to probe the perpendicular component of the self-induced a.c. field, $B_{applied}$, generated by the a.c. current.
The experiments were carried out on several Bi$_2$Sr$_2$CaCu$_2$O$_8$ (BSCCO) crystals ($T_c \approx 88$ K) with typical dimensions of $1.5 \times 0.15 \times 0.01$ mm. The crystals were attached directly to the surface of a linear Hall-sensor array consisting of seven $10 \times 10 \mu$m sensors as shown schematically in Fig. 1. A d.c. magnetic field, $H_{dc}$, was applied perpendicular to the surface (parallel to the c-axis of the crystal). A low-frequency (65–400 Hz) a.c. current, $I_{ac}$, in the range 0.4–10 mA (r.m.s.), was applied to the sample using gold contacts. The findings described below are independent of the frequency and the amplitude of $I_{ac}$, and so only data obtained for 4 and 10 mA at 72.8 Hz are presented. In this study, we have used a sensitive a.c. technique to measure the field profile $B_{ac}(x)$ across the sample, where $B_{ac}(x)$ is the self-induced field of the transport current $I_{ac}$. This method differs from the measurements of $B_{dc}(x)$ induced by $H_{dc}$ which provide valuable information about the local magnetization or susceptibility of the sample. The present study requires high resolution because $B_{ac}$ is of the order of 0.1 G as compared to the typical $B_{dc}$ of 1,000 G. The use of the a.c. mode provides the necessary separation between the field $B_{dc}$ due to transport current, and the field $B_{dc}$ due to the applied field. The transport-current distribution across the sample is then determined from the experimental $B_{ac}(x)$ profiles.

In a highly dissipative state, the current is expected to flow uniformly across the sample as in a normal conductor, as shown on the left in Fig. 2a. In this case, the resulting vertical component of the self-induced field is given by the solid curve on the right in Fig. 2a, as calculated using the Biot–Savart law. At low temperatures, on the other hand, material disorder pins the vortices and prevents their motion, resulting in a finite critical current. In this case the transport current is expected to flow in a way similar to the case of the Meissner state where $B_{ac}(x)$ is expelled from the sample as shown in Fig. 2c. As the superconductor is cooled down in the presence of $H_{dc}$, a monotonic increase of the critical current is expected and therefore a gradual transition from $B_{ac}$ of Fig. 2a to Fig. 2c should occur.

Yet there is another important mechanism, the Bean–Livingston surface barrier, which is usually not taken into account in transport studies. Here we use the term surface barrier to refer to both the Bean–Livingston and a similar geometrical barrier mechanism. Because the presented data are mainly for $H_{dc} > H_c(T)$ (the lower critical field), the contribution of the geometrical barrier is negligible in this case. In order to enter or leave a superconductor, a vortex has to overcome a potential barrier at the surface. This barrier is the result of competition between two forces acting on the vortex near a parallel surface: an inward force due to the presence of the shielding currents, and an outward force due to the attraction between the vortex and its fictitious mirror image outside the sample. In the presence of significant surface barrier, the transport current flows at the edges of the sample, where the vortices enter and leave the superconductor, in order to drive the vortices over the barrier. $B_{ac}(x)$, calculated assuming that the entire current flows at the edges, is shown by the solid curve in Fig. 2b. This field profile is quite different from that of the uniform flow in Fig. 2a. In particular, the signs of $B_{ac}(x)$ within the sample are opposite.

It has been shown that surface barriers have an important contribution to the hysteretic magnetization of clean high-$T_c$ superconductors. These barriers govern the magnetization below the so-called irreversibility line. Owing to practical sensitivity limitations, transport measurements are usually carried out above this irreversibility line where the magnetization is reversible and...
hence surface effects are expected to be of no importance. The effect of surface barriers on transport measurements has been considered theoretically\(^\mbox{13}\), and some studies have suggested that surface barriers may be of significance\(^\mbox{3}\), in particular as a source of voltage noise\(^\mbox{24,25}\). The flow patterns of the transport current have been tested in several investigations of thin films and tapes\(^\mbox{26–29}\) but these studies have focused on the critical state behaviour and sample inhomogeneities rather than on surface barriers.

Figure 3 shows the self-field \(B_x\) as measured by the sensors on cooling the BSCCO crystal in \(H_{dc} = 0.1\) T and \(I_{ac} = 4\) mA. The curves are labelled by the sensor number as indicated in the left-hand side of Fig. 2. At elevated temperatures, \(B_x(x)\) decreases monotonically across the sample (sensors 2–7) owing to a uniform transport current. The measured field profile at 83 K is shown in Fig. 2a (right) by the open symbols, along with the calculated field profile for 4 mA uniform current shown by the solid curve. The fit clearly indicates that at high temperatures the transport current flows uniformly across the width of the crystal. At low temperatures, \(T < 36\) K in Fig. 3, \(B_x(x)\) is finite only outside the bulk of the sample (sensor 1, and sensor 2 which is close to the edge) and is zero inside the sample. This behaviour indicates strong bulk pinning and a finite critical current. Figure 2c (right) shows the measured field profile at 25 K and the corresponding calculated curve for this case. At intermediate temperatures, if the surface barrier is neglected, one expects a gradual crossover from a uniform current flow to bulk pinning as indicated by the dashed line for sensor 2 in Fig. 3. However, the measured \(B_x\) is drastically different and displays a negative signal which cannot be explained by any model based on bulk vortex properties. This inversion of the polarity of \(B_x\) at \(T = 70\) K for all sensors within the sample is the result of current flow at the edges of the sample due to the presence of surface barriers. The measured field profile at \(T = 55\) K is shown in Fig. 2b (right). The solid curve is calculated for the 4 mA current flowing entirely at the edges of the sample. The clear agreement with the data indicates that the surface barrier completely dominates the vortex dynamics, and as a result, practically the entire current, within experimental resolution of few per cent, flows at the edges of the sample. Figure 3 shows that at high temperatures the current flows uniformly, then crosses over to a complete surface flow over a wide range of temperatures, and finally changes to bulk-pinning-like flow only at low temperatures.

The above results have important implications for the interpretation of transport measurements. Figure 4 shows the resistance transition in the same BSCCO crystal at various applied fields. Such measurements are usually interpreted in terms of bulk resistivity caused by, for example, viscous vortex flow or pinning. Apparently, only the very top region of our data, where the current flows uniformly in the bulk (dark lines in Fig. 4), reflects bulk vortex properties. Most of the data shown by the grey lines, however, do not reflect bulk vortex properties but rather the properties of the surface barrier. The situation can be roughly represented by the two equivalent circuits at the top of Fig. 4. At elevated temperatures, the sample can be regarded as a uniform resistor. But at lower temperatures (grey lines) the surface barriers act as low resistance shunts, and hence practically all the current flows at the edges. As a result, the total measured resistance is that of the surface barrier rather than that of the bulk.

An alternative way of describing the process is by noting that the measured resistance always reflects the flow rate of the vortices across the sample. However, the flow rate, rather than being determined by bulk vortex pinning and viscous drag, is determined by the hopping rate over the surface barrier\(^\mbox{12}\). This activation is the rate-limiting process impeding vortex motion. Vortex flow rate over the barrier has to be equal to that in the bulk. As a result practically all of the current flows at the edges in order to provide the large force required to overcome the barrier, while only a very small fraction of the current flows in the bulk in order to overcome the small bulk viscous drag. The apparent measured resistance is thus orders of magnitude lower than the true bulk resistance. In other words, the vortices in the bulk are much more mobile, and the corresponding viscous drag coefficient and the pinning force are much smaller, than what is usually deduced from transport measurements\(^\mbox{20–23}\).

In addition, resistance of BSCCO crystals commonly displays thermally activated Arrhenius behaviour. In view of the work reported here, such Arrhenius behaviour is caused by the thermal activation over the surface barrier\(^\mbox{12}\) and does not reflect the bulk pinning, as is usually interpreted\(^\mbox{20,21}\). Another interesting observation is the recently reported sharp drop in resistance at the first-order vortex lattice melting transition in BSCCO\(^\mbox{35–37}\), which is seen, for example, in the 300 Oe data in Fig. 4 at about 65 K. Such a drop is usually ascribed to the sharp onset of bulk pinning on solidification of the lattice\(^\mbox{26,27}\). Analysis of the temperature dependence of the current distribution at 300 Oe indicates that even this feature mainly reflects a sharp change in the surface rather than bulk properties, as most of the current still flows at the edges of the crystal and the vortices are unpinched both above and below the melting transition. This does not mean that the bulk properties do not change, but rather that the transport measurements do not probe the true bulk vortex dynamics at the transition. Finally, several magneto-optical investigations have shown that, in BSCCO tapes and wires, the current distribution often peaks at the interface between the superconducting filaments and the Ag sheath rather than within the bulk of the filaments\(^\mbox{38}\). It is thus possible that the surface barriers are also of importance to the current-carrying capability of the commercial wires in a way similar to the behaviour of the single crystals.

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Icosahedral packing of B$_{12}$ icosahedra in boron suboxide (B$_2$O)

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Objects with icosahedral symmetry ($I_h$) bear a special fascination; natural examples are rare, but include radiolarians and virus particles (virions). The discovery of C$_{60}$, a molecule in the shape of a truncated icosahedron with $I_h$ symmetry, has aroused widespread interest. In 1962, Mackay described a radiating packing of spheres in $I_h$ symmetry, in which the centres of successive shells of spheres lie on the surfaces of icosahedra. There has been extensive investigation of the conditions under which such packing might be realized in assemblies of atoms or of molecules such as C$_{60}$ (ref. 5). Here we report the preparation, at high temperatures and pressures, of boron suboxide (B$_2$O) in which the preferred form of the material is as macroscopic, near-perfect, regular icosahedra, similar to the multiply-twinned particles observed in some cubic materials. A major difference is that B$_2$O has a rhombohedral structure that nearly exactly fits the geometrical requirements needed to obtain icosahedral particles. These icosahedral particles have a structure that can be described as a Mackay packing of icosahedral B$_2$O units, and thus has long-range order without translational symmetry.

The icosahedron (regular polyhedron with 20 triangular faces) is a forbidden morphology for single crystals: because of the absence of 5-fold axes in classical crystallography, the external forms of single crystals cannot exhibit such symmetry. However, some ‘crystalline’ objects without three-dimensional periodicity do not comply with this rule: in chrysotile and polygonal serpentine minerals, the fibre axis has 5-fold symmetry. Five-fold cyclic twins, usually imperfect, have long been known in minerals such as cassiterite (SnO$_2$), pentagonite or diamond. Small multiply-twinned particles (MTPs) are known with the form of pentagonal bipyramids (decahedra), and also, rarely, as icosahedra of elemental metals and of chemical-vapour-deposited (CVD) diamond. Many quasi-crystals have icosahedral space-group symmetry and, in some cases, crystallize in pentagonal dodecahedral and rhombic triacontahedral with icosahedral symmetry.