Transport Properties Governed by the Inductance of the Edges in Bi$_2$Sr$_2$CaCu$_2$O$_8$

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We study the distribution of transport current across superconducting Bi$_2$Sr$_2$CaCu$_2$O$_8$ crystals and the vortex flow through the sample edges. We show that the $T_x$ transition is of electrodynamic rather than thermodynamic nature, below which vortex dynamics is governed by the edge inductance instead of the resistance. This allows measurement of the resistance down to two orders of magnitude below the transport noise. By irradiating the current contacts the resistive step at vortex melting is shown to be due to loss of c-axis correlations rather than breakdown of quasi-long-range order within the a-b planes.

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Numerous phase transitions have been proposed to interpret the intricate $B - T$ phase diagram of vortex matter in the high temperature superconductor Bi$_2$Sr$_2$CaCu$_2$O$_8$ (BSCCO) \[1,2\]. The first-order melting at $T_m$, that separates a quasi-ordered vortex solid from a vortex liquid, is widely accepted to be a genuine thermodynamic phase transition \[3,4\]. Experiments indicate that the glass line, $T_g$, is another thermodynamic transition that apparently separates amorphous solid from liquid at high fields \[5,6,7,8\] and Bragg glass from depinned lattice at low fields \[9,10\]. On the other hand, the $T_x$ transition, which resides above $T_m$ and $T_g$, has remained highly controversial. A number of experiments \[9,10,11,12,13,14\], numerical simulations \[15,16\], and theoretical studies \[17,18\] argued that it is a transition into a phase with intermediate degree of order such as a disentangled liquid \[19\] or a decoupled- \[20,21\], soft- \[22\], or super-solid \[23,24\]. In this letter we show that $T_x$ does not represent a thermodynamic transformation of a bulk vortex property, but rather reflects an electrodynamic crossover in the dynamic response of the sample edges. The inductance of the sample edges, though immeasurably low, completely governs the vortex dynamics below $T_x$. We use this finding to investigate the resistance due to vortex motion down to two orders of magnitude below the sensitivity of transport measurements.

The resistance of several BSCCO single crystals of typical size 1500×350×20 μm$^3$ in a dc magnetic field, $H_{dc}||c$-axis, was measured using two complimentary techniques: directly via transport and indirectly by determining the ac current distribution with Biot-Savart law from the self-induced ac magnetic field profile using an array of 10×10 μm$^2$ GaAs Hall sensors. In addition, to eliminate the c-axis contribution to the measured resistance we irradiated the c-axis contribution to the measured resistance we irradiated the...
ated the current contacts at GANIL (Caen, France) with 1 GeV Pb ions to a matching dose of $B_{th} = 0.5$ T, while masking the rest of the sample, which remained pristine.

Figure 1(a) shows the temperature dependence of the current-induced ac field, $B^{(1)}(x)$. At high temperatures the current distributes uniformly because it is solely dictated by the flux flow resistance in the bulk, $R_b(T)$. Accordingly, $B^{(1)}(x)$ measured by the Hall sensors across the sample (Fig. 1(c), circles) fits perfectly to that calculated via Biot-Savart law (solid line) from a uniform current $j^{(1)}(x)$ (upper panel).

With cooling $B^{(1)}(x)$ gradually flattens out, becomes completely flat at $T_{sb}$, and eventually inverted at yet lower temperatures. The inverted $B^{(1)}(x)$ profile is associated with essentially pure edge currents (Fig. 1(f)). The Bean-Livingston surface barrier [25] and the platelet sample geometry [26] impose an energetic barrier that progressively impedes vortex passage through the edges. This defines an effective edge resistance, $R_e(T)$, that decreases rapidly with cooling and becomes smaller than the bulk resistance $R_b(T)$ below $T_{sb}$. As a result, most of the current shifts from the bulk, where little force is required to move vortices across, towards the edges, where it facilitates the hindered vortex entry and exit [27]. Bulk vortex pinning becomes dominant only at significantly lower temperature (not shown).

The dynamic properties of the surface barriers have two types of asymmetries. The first arises from the two edges of the sample generally having somewhat different microscopic imperfections. It leads to different edge resistances and therefore asymmetric current distribution between the right and left edges. The $T_x$ line, situated below $T_{sb}$ (Fig. 2), marks the temperature below which this right-left asymmetry sharply disappears and the amplitudes of the two edge currents become equal (Fig. 1(f)). Hence, an antisymmetric current component $\delta j^{(1)}$ (Fig. 1(d)), that was present above $T_x$, and its induced small symmetric contribution $\delta B^{(1)}(x) = B^{(1)}(x, T_x + \delta T) - B^{(1)}(x, T_x - \delta T)$ to the otherwise antisymmetric $B^{(1)}(x)$, vanish below $T_x$.

The second type of asymmetry arises from the inherent asymmetry between hard vortex entry and easy exit through the surface barriers [28]. Since the vortex entry and exit sides swap during the ac cycle, this asymmetry gives rise to a unique chiral second harmonic edge current, $\delta j^{(2)}$, and to the corresponding second harmonic signal $\delta B^{(2)}(x)$ (Fig. 1(e)). It builds up gradually upon cooling (Fig. 1(b)) until it pinches off sharply at $T_x$ (hereinafter determined at half of the $B^{(2)}(x)$ roll-off). Accordingly, $T_x$ marks the temperature below which the vortex flow turns insensitive to both the entry-exit and the right-left asymmetries of the surface barriers.

The $T_x$ transition was previously ascribed to the advent of a new vortex phase with a higher degree of order [4, 13, 16, 17, 18]. We show that $T_x$ has rather electrodynamic nature, arising from the sample edges inductance. Following Ref. [29] we model the vortex dynamics by equivalent electric circuit with three parallel channels - the bulk and two edges. Our measurements show no dependence on the current magnitude (Fig. 1(b), dark vs. pale lines). Therefore, we follow the Ohmic model of Ref. [29] that assigns each channel geometrical self and mutual inductances in series to their resistances.

The sample inductance is usually disregarded since it is inmeasurably small in direct transport measurements. Nevertheless, it affects the current distribution in the sample. The effective edge inductance, as opposed to the edge resistance, is temperature independent and dictated solely by the geometry of the edges $L_e = (\mu_0/4\pi)[\ln((2w/d) + 1/4)]$, where $l, w,$ and $d$ are the sample’s length, width, and thickness, respectively [29]. $T_x$ is the temperature below which the edge impedance turns from being predominantly resistive to inductive, $R_e(T_x) = 2\pi f L_e$. Consequently, $T_x$ is frequency dependent and allows sensitive determination of $R_e(T)$ similar to the extraction of resistance from ac susceptibility [30, 31]. At 350 Oe and $f = 73$ Hz we measure $T_x \simeq 59$ K. Using $L_e = 304$ pH, calculated from sample geometry, we obtain $R_e(59 K) = 1.4 \times 10^{-7}$ Ω (Fig. 3 white cross). Note, that this value is 2-3 orders of magnitude lower than the current dependent resistance measured simultaneously in transport (open circles), which below $T_{sb}$ should reflect the edge resistance $R_e$.

The transport resistance measured in the geometry of Fig. 3(a), however, has a large contribution from the e-
axis resistivity, $\rho_c$. Due to the extreme anisotropy of BSCCO $\rho_c$ is orders of magnitude larger than $\rho_{ab}$, giving rise to nonlinearities and shear effects [32, 33]. The dissipation due to $\rho_c$ that arises from current tunneling between the CuO$_2$ planes, however, is not accounted in the electrodynamic considerations of the edge inductance [29]. The non-uniformity of current flow along the c-axis can be remedied by introducing columnar defects solely under the current contacts (see Fig. 3(b)). Below the Bose-glass transition, $T_{BoG}$ (Fig. 2 diamonds), the vortices become strongly pinned to the columnar defects increasing the c-axis correlations and greatly reducing the sample anisotropy [34, 35, 36]. This is remarkably demonstrated in a multi-contact measurement of a sample irradiated in such a manner (Fig. 3(c)). Above $T_{BoG}$ the high anisotropy results in poor c-axis current penetration. Therefore, the primary resistance, $R_p$, measured on the current injecting surface, is much higher than the secondary resistance, $R_x$, measured on the opposite surface. At $T_{BoG}$, signaled by the plunging c-axis resistance $R_c$, the secondary resistance recovers and equals the primary edge resistance measured by voltage contacts in the central pristine region of the sample (Fig. 3 open squares), decreases by two orders of magnitude, and turns Ohmic. Moreover, the resistive behavior now becomes fully consistent with the inductive edge model. As shown below, all the data sets can be fitted by a single parameter - an effective edge inductance of $L_e = 490$ pH (black cross in Fig. 3). The similarity of this value to the calculated 304 pH is remarkable, considering the crude modeling of the edges (round wires of diameter $d$ [29]) and the uncertainties in various parameters.

To further establish the role of the edge inductance in the $T_x$ transition we extract $R_e(T, H)$ by repeatedly monitoring the current distribution with frequencies ranging from 0.3 Hz to 1 kHz. At all frequencies $B(t)$ rises gradually with cooling (Fig. 4(a)), as more current is shunted to the edges, until it vanishes at a frequency-dependent temperature, $T_x(f)$. The extracted edge resistance, $2\pi f L_e$ versus $T_x(f, H)$ (Fig. 4(b), circles), matches accurately the resistance measured in transport (thin lines), and extrapolates it well below the transport noise floor. A fit to an Arrhenius behavior (dotted line) yields an edge energy barrier $U_c^e \sim 18T_x$.

The excellent agreement of the edge resistance extracted from $T_x(f)$ to that measured in transport confirms that the edge inductance drives the electrodynamic $T_x$ transition. In terms of vortex dynamics, the resistive component of the edge impedance arises from vortex dissipation thermally activated over the surface barriers. Dissipation due to bulk vortex motion is negligible, since bulk pinning is very weak, hence $R_0 \gg R_c$. Nevertheless, bulk redistribution of vortices reflects the inductive component of the edge impedance. With changing current polarity during the ac cycle the vortices, complying with the $B^{(1)}(x)$ profile of Fig. 1(f), shift from one side of the sample to the opposite in association with an inductive $dB/dt$. At high temperatures the number of vortices redistributing from right to left during half a cycle due to $dB^{(1)}(x)/dt$ is still much smaller than those that dissipatively cross the edges and move across the sample. With cooling, however, the number of vortices that cross the edges decreases exponentially. Below $T_x$ it becomes negligible compared to the number of redistributing vortices. The second harmonic vanishes because vortex redistribution in a ‘closed box’ is necessarily antisymmetric. Our main finding is that although the edge inductance is immeasurably small in transport measurements, it completely governs vortex dynamics below $T_x$.

We now focus on the behavior of the edge resistance at melting. In the pristine sample a sharp resistive drop [39] is observed at $T_m$ (Fig. 5 solid dots), whereas after contact irradiation the behavior is continuous (solid squares). Moreover, the two curves merge at the lowest measurable resistance (circled), indicating that in the presence of a uniform c-axis current the edge resistance shows no sharp features. Hence, the common resistive melting drop in BSCCO arises from a sharp drop in $\rho_c$. Another intriguing feature at melting (Fig. 3(c), as-
tract the temperature dependent edge resistance (\(\pi\)) due to enhanced c-axis correlations that lies below the melting point (Pa). Consequently, the exponential temperature dependence of the edge resistance becomes steeper on approaching the melting as the contour lines bunch together. This is attributed to the enhanced stiffness of the pancake vortex stacks. Nevertheless, we do not find a singular behavior at melting which would have manifested itself in overlapping contour lines. On the contrary, once the c-axis contribution is eliminated the edge resistance in solid joins smoothly that of the liquid.

In summary, the spatial distribution of transport current and its frequency dependence show that the \(T_x\) line, tentatively ascribed to a phase transition of vortex matter in BSCCO, is rather an electrodynamic transition. Consequently, in the wide field and temperature range that lies below the \(T_x\) line the inductance of the sample edges, usually dismissed in transport experiments, dominates the current flow and causes ac displacement of vortices across the bulk without crossing the sample edges. At \(T_x\), the inductive part of the edge impedance equals the resistive part, which allows measurement of resistance down to two orders of magnitude below the transport noise. In the vicinity of the melting transition, we find that once the c-axis contribution is eliminated via ion irradiation of the current contacts, the edge resistance shows no sharp features at melting.

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