Resistive evidence for vortex-lattice sublimation in $Bi_2Sr_2CaCu_2O_8$

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Multiterminal measurements have been made on $Bi_2Sr_2CaCu_2O_8$ crystals to investigate the vortex dimensionality at the fields and temperatures where the first-order transition takes place in the vortex lattice. A sharp hysteretic transition is seen in transport properties with current injected either parallel or perpendicular to the ab planes. The data indicate that both resistivity components disappear concurrently, and the melting and c-axis decoupling transitions occur simultaneously at a sublimation transition of the vortex lattice. [S0163-1829(97)05110-2]

The first-order transition (FOT) in the vortex lattice of high-T_c superconductors continues to attract considerable experimental and theoretical interest. Early evidence for a possible first-order transition came from resistive measurements on clean $YBa_2Cu_3O_7$ (YBCO) crystals.[1–3] More compelling evidence was subsequently found in thermodynamic measurements of the local and global magnetization and transmittivity of $Bi_2Sr_2CaCu_2O_8$ (BSCCO) (Refs. 4–9) and YBCO (Refs. 10 and 11) crystals. Resistive measurements on BSCCO have now also shown that the thermodynamic step in magnetization at the transition is accompanied by a shoulder in the transport properties at very small voltages.[12–16] Many of the concerns about possible nonequilibrium origins of the observed transition[17,18] have most recently been removed, at least in YBCO, by calorimetric measurement of the latent heat at the magnetically determined transition, showing clearly that it is both thermodynamic and first order.[19] However the detailed underlying mechanism of this transition remains unresolved. In particular, the magnitude and temperature dependence of the observed entropy change are very different from the predictions for a simple vortex-lattice melting.[20,21] One possible way in which the properties of this transition may be modified is if the melting is accompanied by simultaneous decoupling of the vortices along the direction perpendicular to the CuO planes.

Several experimental studies have indicated that decoupling may be involved in the FOT, both in BSCCO (Refs. 4,9,22,23) and in YBCO crystals.[24] In contrast, detailed theoretical investigations have described the melting and decoupling as two well separated transitions.[25,26] More recent analysis, however, suggests that in highly anisotropic materials like BSCCO the two transitions may occur concurrently.[27] In this paper we report multiterminal transport measurements which were carried out in order to elucidate the underlying mechanism of the first-order transition in BSCCO crystals. The importance of such transport measurements is that they are able to probe the out-of-plane behavior, information which is not readily available from magnetization and other experimental techniques. The presented data strongly support a simultaneous melting and decoupling transition, in which a solid lattice of vortex lines undergoes a sublimation into a weakly coupled gas of vortex pancakes.

The BSCCO crystals, with $T_c \simeq 86$ K, were grown by the traveling solvent floating-zone method.[28] Crystals with typical dimensions of 2 mm$\times$300 μm$\times$10 μm were cut and cleaved from the starting boule. Four gold wires were attached to each surface with silver epoxy. The crystals were annealed in air at 600 °C for 5 min yielding contact resistances of a few ohms per pair. The schematic experimental

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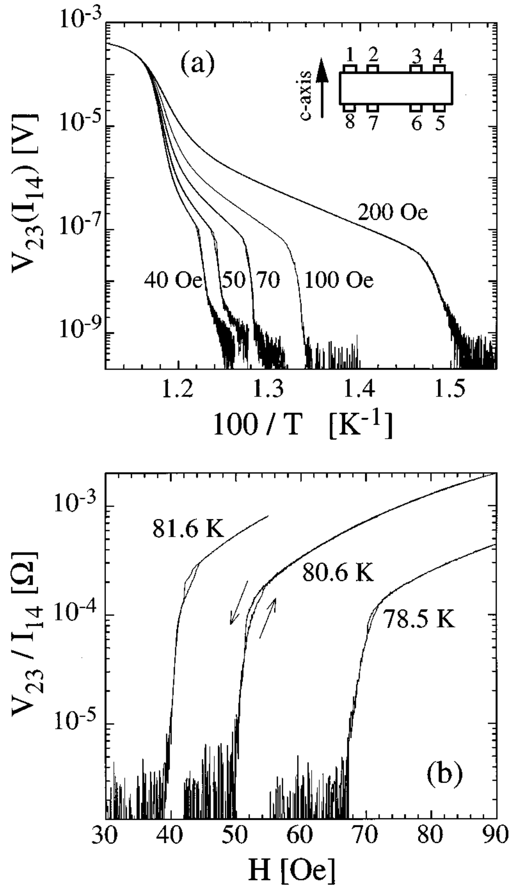

FIG. 1. (a) Arrhenius plot of the primary voltage, $V_{23}(I_{14})$, for crystal A, for $I=8$ mA at fields applied parallel to the c axis of 40, 50, 70, 100, and 200 Oe. The data are presented for both increasing and decreasing temperature (except at 100 Oe). The inset shows the contact configuration. (b) Plot of the primary resistance, V_{23}/I_{14}, for crystal B at three temperatures as a function of increasing and decreasing applied field (I = 2 mA for 81.6 and 78.5 K curves, and 1.2 mA for the 80.6 K curve). Hysteretic behavior as a function of temperature (a) and field (b) is observed at the onset of the resistive transition.

configuration is shown in the inset of Fig. 1(a). The transport properties were measured with subnanovolt resolution using an ac current at 72.8 Hz with low noise transformers and lock-in amplifier techniques. The magnetic field, applied in either persistent or swept mode by a superconducting magnet, was always parallel to the crystalline c axis. Data for two of the measured crystals, labeled A and B, are presented.

In this paper we focus on the low-field and high-temperature regime where the FOT is observed.[5] Figure 1(a) presents the temperature dependence, on an Arrhenius plot, of the primary voltage, $V_p = V_{23}(I_{14})$ for crystal A measured with an applied current of 8 mA (rms) at several magnetic fields. The figure contains curves for both warming and cooling cycles. The voltage displays an initial decrease below the mean field T_c, then shows broad Arrhenius-like behavior, and finally drops dramatically by approximately two orders of magnitude at the FOT to below our resolution of about 500 pV. Figure 1(b) presents the primary resistance as a function of field at three temperatures for crystal B. This shows that the sharp resistive transition is also present as a function of applied field. In addition, we were able to resolve a small hysteresis at the onset of the resistive transition as a

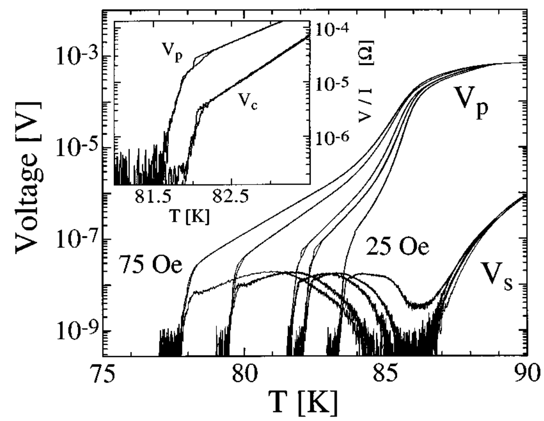

FIG. 2. Primary $V_{23}(I_{14})$ and secondary $V_{23}(I_{85})$ voltages as a function of temperature for crystal B, for fields of 25, 35, 40, 60, and 75 Oe, and $I=2$ mA. The inset shows expanded V_p data at 40 Oe and also presents the c-axis voltage $V_c = V_{45}(I_{18})$ at $I=6$ mA.

function of both the temperature and the applied field as indicated in Fig. 1. The position of the sharp resistive drop has been shown to correspond closely to the magnetization step observed by simultaneous local,[13] as well as by global magnetization measurements.[12] The resistive transition showed no variation over repeated thermal cycling. The similarity between these resistive data in BSCCO on a logarithmic scale, and those for YBCO on a linear scale[2] is apparent. The transition in BSCCO occurs at resistivities of about 10^{-4} of ρ_n, the normal-state resistivity, compared to about 10^{-1} in YBCO. The smaller resistivity values in BSCCO compared to those in YBCO are consistent with simple Bardeen-Stephen-type considerations.[12]

Figure 2 shows both primary V_p and secondary V_s voltages for crystal B as a function of temperature at 2 mA and several applied fields. There are two main features in these data. The first is the remarkable reentrant behavior of V_s. This behavior is sensitively determined by the temperature dependence of the resistive anisotropy as well as the sample dimensions. The large resistive anisotropy ($\sim 10^5$) above T_c means that currents injected at the top surface penetrate to a characteristic depth of only about 1 μm. As a result V_s is about three orders of magnitude smaller than V_p in our geometry in the normal state.[29] As temperature is decreased the in-plane resistivity ρ_{ab} decreases. On the other hand, ρ_c continues to increase displaying semiconducting-like behavior as shown below (Fig. 4). As a result, V_s decreases dramatically and reaches a minimum in the vicinity of $T_c \simeq 86$ K. At lower temperatures ρ_c drops faster than ρ_{ab}, and the effective penetration depth for the current grows causing the reentrant increase of V_s. This nonmonotonic behavior of V_s is thus an effect of current redistribution and does not correspond directly to any specific changes in the vortex dynamics.[16]

The second main feature in Fig. 2, the abrupt simultaneous drop of V_p and V_s and the coincidence of the two voltages at the transition, is of central importance. The close correspondence of V_p and V_s suggests a dramatic change in ρ_c at the FOT since the coincidence of the voltages implies a vanishing voltage along the c axis. A shoulder in the behavior of ρ_c was indeed previously observed.[14] We have thus also measured the behavior along the c axis. The inset in Fig. 2 shows the c-axis voltage $V_c = V_{45}(I_{18})$ at 40 Oe, along with

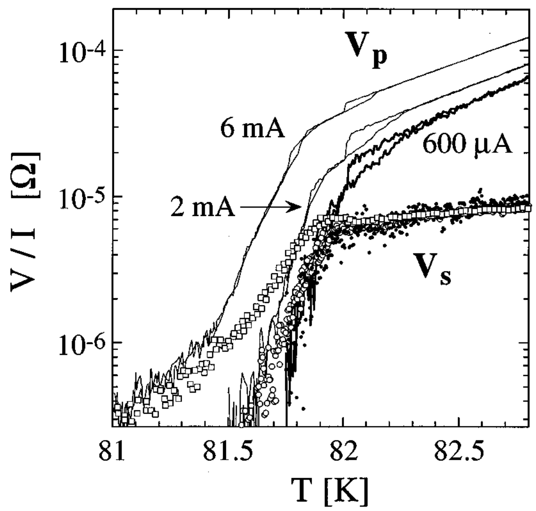

FIG. 3. Apparent primary and secondary resistances, V_p/I and V_s/I, at 40 Oe for crystal B at different currents of 600 μA, 2 mA, and 6 mA. V_p data are shown by solid curves (thick line indicates 600 μA), and V_s by symbols (□ is 6 mA, ○ is 2 mA, ● is 600 μA).

V_p in the vicinity of the transition. The FOT is clearly seen in both V_p and V_c as a sharp hysteretic drop at the transition. Although $V_{45}(I_{18})$ may slightly underestimate ρ_c due to the current redistributing back toward the current electrodes as the resistive anisotropy decreases below T_c, these effects can mainly shift the measured behavior along the vertical axis and cannot affect the temperature at which any strong features are observed. Importantly, if ρ_{ab} drops suddenly while ρ_c does not change, the ab planes become more equipotential and the current along the c axis spreads more evenly throughout the sample, thus increasing V_{45}. Hence the data indicate that both ρ_{ab} and ρ_c drop dramatically at the FOT. We therefore conclude that the melting transition is accompanied by a decoupling transition. Similar results were recently obtained on untwinned YBCO crystals.[24] However, there is a major difference. In the YBCO crystals of similar dimensions V_p and V_s are precisely equal just above the FOT, and their values separate continuously as temperature is increased.[24] This behavior suggests that at the FOT, the correlation length along the c axis in the liquid phase in YBCO is larger than the sample thickness, and it decreases monotonically away from the FOT. In BSCCO, on the other hand, the behavior is markedly different. As seen in Fig. 2, and in Fig. 3 below, V_p and V_s differ typically by a factor of 3 to 5 *immediately* above the FOT indicating that the phase correlation length along the c axis drops discontinuously to very small values as we cross the melting transition. The difference in V_p and V_s immediately above the transition is observed in samples[16] as thin as 1 μm. This implies that the phase above the FOT in BSCCO is best described as a decoupled gas of very short vortex segments or single-layer pancakes, that sublimate from a solid vortex-lattice through a first-order transition. It seems that in YBCO in contrast, a more appropriate description is that of a gradual crossover from extended line vortices (stretching from one side of the sample to the other) immediately above melting, to shorter and shorter vortices approaching the limit of completely decoupled gas high above the transition.

The suggested sublimation transition is consistent with small-angle neutron-scattering (SANS) data[30] on BSCCO, which show clear diffraction peaks in the vortex solid phase, and a complete loss of diffraction intensity above the transition as expected for a pancake gas. A vortex line liquid, on the other hand, should result in a diffraction ring pattern which was not found in SANS experiments.[30] It is also interesting to note that an alternative mechanism for the apparent FOT was proposed recently,[31] based on the observation of equal V_p and V_s above the transition in YBCO.[24] In this scenario the apparent transition is a result of a sharp crossover that occurs when the c-axis phase coherence in the vortex liquid becomes comparable to the sample thickness. Our finding of significantly different values for V_p and V_s at the transition in BSCCO is thus of major importance for any future theoretical developments.

We have also investigated the current dependence of the flux transformer behavior. Figure 2 suggests that although the primary and secondary voltages approach each other in the transition region, they do not coincide exactly. Figure 3 shows V_p and V_s at 40 Oe for three different currents. The behavior of the data as we use lower currents strongly suggests that the primary and secondary voltages show very good correspondence at low driving forces demonstrating a full c-axis phase coherence in the vortex-solid phase. At higher currents some nonlinear behavior occurs in the vicinity of the transition including possible current-induced vortex-line cutting.[32] In the liquid phase, on the other hand, V_p and V_s are always well separated above the FOT, emphasizing the abrupt decoupling at the transition. Figure 3 also demonstrates that the resistive behavior is strongly nonlinear in the vortex solid phase below the FOT as recently observed in multiterminal measurements in YBCO (Ref. 24) and briefly discussed for BSCCO in Ref. 13. Above the transition, V_p shows only weakly nonlinear behavior that may originate from a small but finite correlation between pancakes in the gaseous phase. It is interesting to note that V_s shows completely linear current dependence in this regime. This implies that the velocity of vortices on the top surface of the crystal barely affect that at the bottom surface, and confirms our conclusion that the liquid is decoupled or in other words that the vortex matter above the FOT is a gas. This also implies that the current redistribution through the thickness of the crystal is not trivial in this nonlinear regime and requires further investigation. We note in addition, that we do not observe any systematic change of the FOT temperature with varying the applied current[16] as judged, for example, by the position of the sharp hysteretic step in V_p on decreasing temperature (see Fig. 3). This robust behavior of the thermodynamic phase transition against the different flux velocities at various driving forces has been confirmed by our simultaneous transport and magnetization measurements[13] and is consistent with recent measurements on YBCO.[11]

Figure 4 presents the ratio of the primary and secondary voltages, V_s/V_p, together with the c-axis voltages V_c at several fields, over a wide range of temperatures. Both quantities are a measure of the c-axis correlation. The aim of this construction is to check whether there are any other features in the behavior which are possible candidates for a separate decoupling transition.[16,25] Firstly it is apparent from Fig. 4 that the V_s/V_p ratio jumps abruptly from values of about 0.2

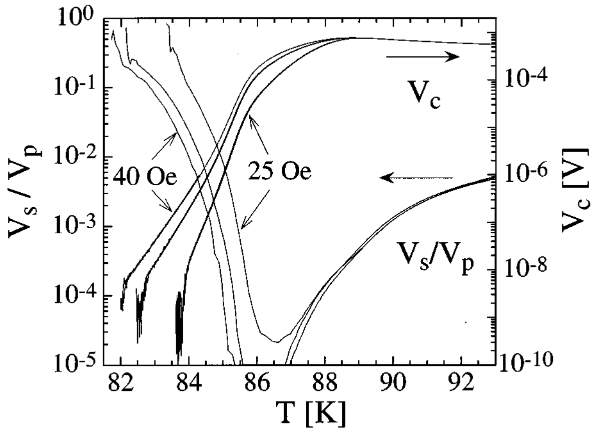

FIG. 4. The ratio $V_s/V_p(T)$ for 25, 35, and 40 Oe for crystal B plotted together with $V_c = V_{45}(I_{18})$ for the same fields. V_c data are shown for both increasing and decreasing temperature ($I=2$ mA).

towards unity at the FOT implying that the vortices decompose from correlated lines to short decoupled segments at the transition as discussed above. Further, as indicated in the figure, and for all samples we have measured, both V_c and the ratio of V_s/V_p are smooth functions of temperature showing no evidence for additional transitions above the FOT. This is further support for our conclusion that the melting and decoupling transitions are simultaneous, contrary to what has been suggested elsewhere.[16]

We now discuss briefly the resistive hysteresis that we observe at the FOT. It is now well established that the FOT in clean YBCO crystals is accompanied by a resistive hysteresis.[1,3,17,33] Figures 1–3 show that a sharp hysteresis also exists[16] in BSCCO both as a function of temperature and field. The hysteresis appears mostly at the onset of the resistive transition, it is asymmetric and often displays several subfeatures, similar to those observed[17,33] in YBCO. The resistivity shows sharp drops on decreasing temperature or field, and a more gradual behavior on the ascending branch. A more detailed account of the results will be provided elsewhere.[34] We note, however, that we find no evidence for subloops as also reported previously for YBCO.[17] The absence of subloops was suggested[17] to imply that the observed resistive transition may not be related to a thermodynamic FOT in YBCO. However calorimetric measurements have now precluded this possibility.[19] Thus the detailed physical mechanism underlying the hysteresis at the FOT in both YBCO and BSCCO remains to be resolved.

In conclusion, the resistive transitions for current applied both parallel and perpendicular to the ab planes in BSCCO crystals show discontinuous, hysteretic changes at the magnetically determined FOT. These results strongly suggest that melting and decoupling transitions occur simultaneously in BSCCO and therefore that the vortex solid sublimates directly into a vortex gas. We see no evidence for a disentangled line liquid or for any decoupling transition existing separately from the FOT. The additional entropy associated with loss of c-axis coherence may be important in reconciling the large discrepancy in the measured and estimated latent heat. The resistively determined FOT in both BSCCO and YBCO are qualitatively similar including the hysteretic behavior, however the c-axis phase coherence above the FOT in BSCCO is reduced to much shorter length scales immediately upon melting.

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