Simultaneous resistivity onset and first-order vortex-lattice phase transition in $Bi_2Sr_2CaCu_2O_8$

D. T. Fuchs, E. Zeldov, and D. Majer
Department of Condensed Matter Physics, The Weizmann Institute of Science, Rehovot 76100, Israel

R. A. Doyle
Department of Condensed Matter Physics, The Weizmann Institute of Science, Rehovot 76100, Israel and Interdisciplinary Research Center in Superconductivity, University of Cambridge, Cambridge CB3 OHE, England

T. Tamegai and S. Ooi
Department of Applied Physics, The University of Tokyo, Hongo, Bunkyo-ku, Tokyo, 113, Japan

M. Konczykowski
Laboratoire des Solides Irradiés, CNRS URA-1380, École Polytéchnique, 91128 Palaiseau, France
(Received 13 February 1996; revised manuscript received 8 April 1996)

Simultaneous measurements of resistivity and local magnetization using microscopic Hall sensors were carried out on $Bi_2Sr_2CaCu_2O_8$ crystals as a function of applied field and temperature. The resistivity onset is found to occur concurrently with the first-order vortex-lattice phase transition, determined by the equilibrium magnetization step. This behavior strongly suggests that the vortex lattice melts at the phase transition. The apparently reversible magnetization below the transition is ascribed to substantial flux creep. [S0163-1829(96)50826-X]

Recent theoretical predictions of a possible first-order vortex-lattice phase transition in type-II superconductors in the presence of thermal fluctuations,[1–3] as opposed to traditional second-order mean-field expectations, have stimulated a broad experimental effort in search of this fundamental phase transition. A wide range of experimental techniques has been exploited in this pursuit in high-T_c superconductors,[4–21] as well as in low-T_c materials.[22,23] The first significant experimental evidence that this new type of transition may exist was the observation of a sharp resistive transition in clean $YBa_2Cu_3O_7$ (YBCO) crystals.[5–8] In spite of extensive experimental efforts,[4] this resistive transition has so far only been observed in YBCO crystals even though a similar transition is anticipated to occur in all high-T_c superconductors. In this paper we show that a clear resistive transition exists in $Bi_2Sr_2CaCu_2O_8$ (BSCCO) crystals as well. This behavior is strongly indicative of a first-order vortex-lattice melting transition. Resistivity however is not a thermodynamic property and a true first-order phase transition should also have clear thermodynamic fingerprints. Recently, a first-order-phase transition in BSCCO crystals was thermodynamically established by equilibrium magnetization measurements.[14–17] In order to unambiguously link the two phenomena we have, in addition, carried out simultaneous measurements of magnetization and resistivity. Our central result is that the thermodynamic magnetization step and the resistive onset occur *concurrently* at the first-order vortex-lattice phase transition in BSCCO.

The BSCCO crystals studied in this work were prepared by the traveling solvent floating zone technique[24] in two different laboratories. Crystal A (T_c=83.5 K) was cut to dimensions of $2300\times400\times50\ \mu m^3$, crystal B ($T_c$=86 K) to $680\times175\times15\ \mu m^3$, and crystal C ($T_c$=90 K) to $2000\times450\times25\ \mu m^3$. Four electrical contacts for transport measurements were attached to the top surface of crystals A and B using Ag epoxy annealed at 550 °C. The bottom *ab* crystalline surface was placed in direct contact with an array of nine two-dimensional-electron-gas GaAs/AlGaAs Hall sensors each of area $10\times10\ \mu m^2$.[14,25] The experimental setup (see inset of Fig. 1) allowed simultaneous measurement of the local magnetic field B in the central region of the crystal and the four-probe resistance R. The magnetic field H_a was applied parallel to the c axis of the crystal, and the measurements were carried out as a function of temperature and applied field. The resulting data for crystal B are very similar to the data for crystal A described further below.

In order to exclude possible artefactal effects associated with the nonuniform current distribution in this geometry, and the resulting mixture of ρ_{ab} and ρ_c resistivities[26,27] measured by the planar contacts on crystals A and B, we also prepared a purely in-plane configuration on crystal C. In addition to the four contacts on the top surface two contacts were made to the edges of the sample in order to ensure a uniform current distribution. The two central top contacts were used as voltage contacts whereas the transport current was injected either through the contacts on the top or the edges. The behavior at the resistive onset, which is described in detail below, was not significantly affected by the different current distributions in the two configurations. However, the finite thickness of the epoxy contacts at the edge of the crystal C prevented the simultaneous use of Hall sensors for local magnetization measurements of this crystal. Since the resistive data for all three crystals show the same basic features, we concentrate in what follows on the simultaneous measurements of both resistivity and magnetization in crystal A.

Figure 1 shows the result of simultaneous measurement of the resistance and the local magnetization $B-B_{out}$ as a func-

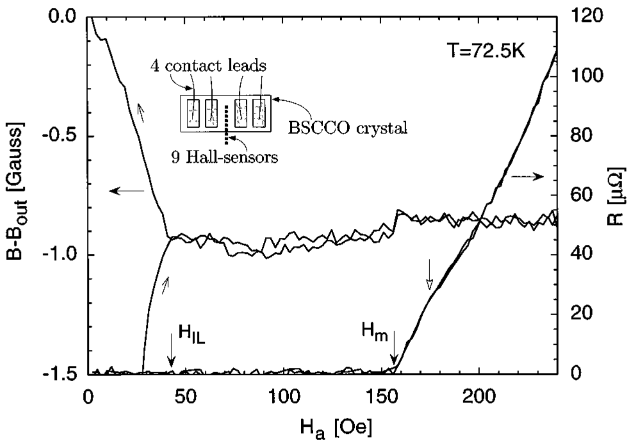

FIG. 1. Simultaneous resistance and local magnetization measurements of BSCCO crystal A as a function of increasing and decreasing applied field H_a. The first-order thermodynamic magnetization step coincides with the resistive onset at the phase transition H_m. The inset shows the experimental configuration. The two outer contacts on top of the crystal are used to inject the transport current while the inner pair is used to measure the resistive voltage drop. An array of microscopic Hall sensors at the bottom side of the crystal is used to measure the local perpendicular magnetic field B between the voltage contacts. Six sensors measure the field at the surface of the crystal and the other three measure the field just outside the crystal. The local magnetization $B-B_{\mathrm{out}}$ is obtained by subtracting the field measured outside the crystal from the field in the center of the crystal.

tion of the applied field at $T=72.5$ K with an applied transport current of 20 mA. A sharp step in local magnetization is apparent at H_m, the first-order vortex-lattice phase transition.[14] The striking result in Fig. 1 is that the resistivity vanishes precisely at the vortex-lattice phase transition. Previous resistive measurements in clean BSCCO crystals were unable to resolve this remarkable correspondence.[18,19] At fields lower than H_m, the resistivity is zero within our experimental resolution and appears to grow rather linearly with field for $H_a > H_m$. Figures 2 and 3 show several representative curves of the resistive transition as a function of field and temperature, respectively. The position of the van-

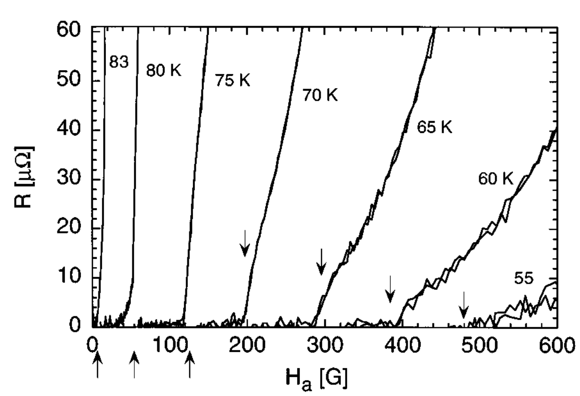

FIG. 2. Resistance as a function of increasing and decreasing applied field H_a at various representative temperatures as indicated. The applied transport current is 20 mA. The position of the corresponding magnetization step is indicated by the arrows.

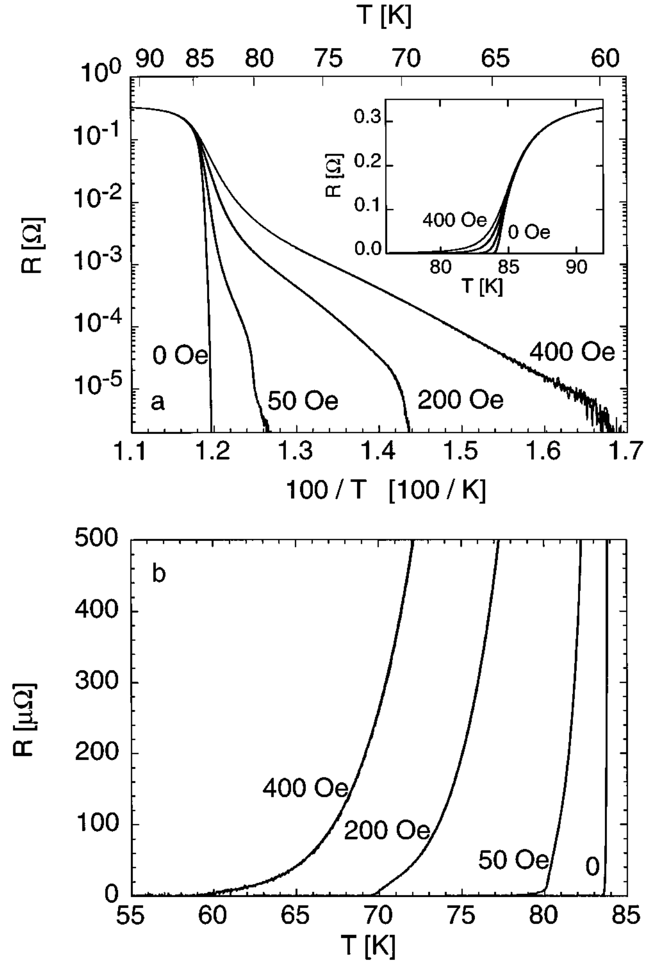

FIG. 3. Resistance versus increasing and decreasing temperature for $I=20$ mA at four values of applied field. The data are presented on a linear scale (inset), Arrhenius plot (a), and expanded linear scale for the low resistance range (b). The first-order vortex-lattice phase transition is manifested by sharp resistive onset, clearly resolved in the 200 Oe data in the Arrhenius plot. At 50 Oe a small resistive foot at $R<10^{-5}$ Ω is observed in the vortex-solid phase at high transport currents.

ishing resistivity coincides with the position of the phase transition obtained from the local magnetization step in a wide range of fields and temperatures. Careful checks showed that the transport current used for the resistivity measurement did not affect the local magnetization measurements.

The data in Fig. 2 show a well defined resistivity onset as a function of H_a, in the temperature range of 60 to 80 K. At lower temperatures, the resistivity in the vortex-liquid phase above $H_m(T)$ is too low for an accurate determination of the onset point within our experimental resolution. At high temperatures $T>80$ K ($T_c=83.5$ K) we observe a small resistive foot extending into the vortex-solid phase below H_m. This foot is also observed in $R(T)$ scans at low fields [see the 50 Oe curve in Figs. 3(a) and 3(b)]. The foot disappears at lower transport currents. We have also checked the V-I characteristics. In the foot region the characteristics are strongly nonlinear and we can resolve a finite voltage drop only at the highest applied currents close to 20 mA. The limited current

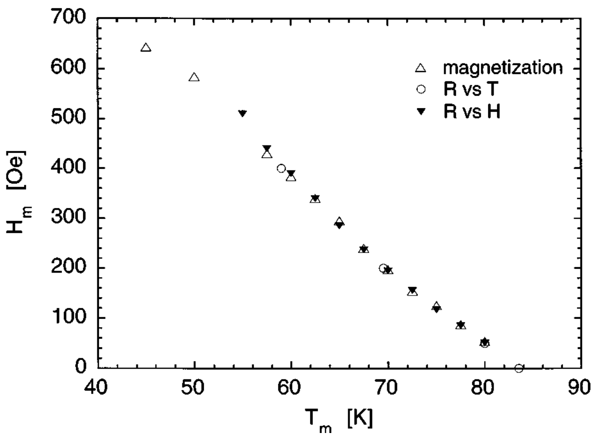

FIG. 4. The first-order phase transition line of BSCCO crystal at elevated temperatures. The transition line is composed of data from three different measurements: (△) local magnetization vs H_a (see Fig. 1), (▽) resistance vs H_a (see Fig. 2), and (○) resistance vs T (see Fig. 3). The coinciding data show that the resistive transition is determined by the vortex-lattice phase transition.

range where the signal is measurable is insufficient for us to reliably determine the functional dependence of V-I. At lower temperatures, $T<80$ K, in the vortex-solid phase at $H_a<H_m(T)$, we do not detect any voltage drop up to the highest current of 20 mA. Thus the resistive measurements indicate an effective critical current in excess of 100 A/cm^2 (assuming a uniform current flow) in the vortex-solid phase, except close to T_c where the effective critical current must drop to zero. In the vortex-liquid phase at $H_a>H_m(T)$ we obtain linear V-I characteristics in a wide range of temperatures and fields and the resistivity is thermally activated [see Fig. 3(a)]. At temperatures below about 60 K a weakly nonlinear power law V-I behavior starts to develop.

The first-order phase transition line, determined by the position of the magnetization step, is shown in Fig. 4 along with that determined by the resistive transition. The coinciding data clearly show that the resistance behavior is determined by the vortex-lattice phase transition. It is generally expected that in the vortex-lattice (solid) phase the vortices are efficiently pinned by material defects, resulting in finite critical currents and a vanishing resistivity. In the vortex-liquid phase, on the other hand, pinning should be less important due to the vanishing shear modulus of the lattice; thus vortices can move easily creating dissipation and finite resistance.[1] The theoretically predicted decoupling transition should also be considered. In this latter scenario, vortex lines dissociate into uncorrelated vortex pancakes in the CuO planes. At low fields such a decoupling transition is expected to occur either above[28–30] or simultaneously with[31] the vortex-melting transition. If the thermodynamic transition evident in the magnetization data in Fig. 1 was related to decoupling of vortex-line-liquid into a vortex-pancake state, the resistivity would be expected to be finite and similar on both sides of the magnetization transition. Our observation that the resistivity vanishes below $H_m(T)$ but is finite above, is strong evidence that the thermodynamic transition is either vortex-lattice melting or simultaneous melting and decoupling.

Next we discuss some additional features of the phase transition. The field and the temperature dependencies of the resistivity (Figs. 1–3) appear to extrapolate rather continuously towards the melting transition at $H_m(T)$. This type of behavior resembles a second-order transition in the critical region,[1] but as we will show below is consistent with a first-order transition in BSCCO crystals. In the case of a first-order transition, a sharp resistive transition is expected to occur and was indeed observed in clean YBCO crystals.[5–8] In YBCO crystals, the step in the resistivity occurs at about 10^{-1} of the normal state resistivity and consequently is clearly observable, even on a linear scale. In BSCCO, on the other hand, the different parameter values conspire to shift the resistive melting transition to about 10^{-4} of ρ_n. This makes clear observation of this effect much more difficult and is probably one of the reasons why this effect has not been observed previously. However, careful examination of the data in Figs. 1 and 2 indicates a shoulder in $R(H)$, typically about 10 G above H_m, as indicated by the open arrow in Fig. 1. When the data is plotted on a logarithmic scale, the sharp resistive drop below the shoulder is clearly observed as shown in Fig. 3(a) (see, e.g., 200 Oe data). The finite width of the resistive drop is readily understood in terms of our previous studies on the internal field distribution in BSCCO crystals in the transverse field geometry. These show that the magnetic field B across the width of a platelet crystal is nonuniform in this field range and has a characteristic dome shape profile.[32,33] This effect causes the melting transition to occur first in the center of the crystal, and shift toward the edges only as the field is increased. Analysis of our local magnetization transition in the linear array of sensors spanning the crystal half-width shows that the region between H_m and the shoulder corresponds to the range of applied field over which the vortex-liquid phase spreads over the entire sample as the solid-liquid interface moves from the center to edge of the sample. As a result the sharp transition is smeared by the nonuniform field.

Figure 1 shows that the measured magnetization in the vortex solid phase, for the conditions employed in our experiments, is reversible in the field region $H_{IL}<H<H_m$. This indicates that the vortex solid is very weakly pinned as concluded previously.[33,34] These magnetic measurements do not exclude the existence of very low but finite critical current J_c which results in small magnetic hysteresis below our experimental resolution. The noise level of the magnetization data places an upper bound of $J_c<10$ A/cm^2 in this reversible region, assuming a Bean critical state model. The highest applied transport current density of about 100 A/cm^2 is an order of magnitude larger than this upper bound and one might therefore have expected to have observed a measurable resistivity below H_m. However, the apparent discrepancy is understood in respect of the large flux creep in BSCCO crystals.[35,36] The slow sweep rate of magnetic field in our experiment ($\sim$ 4 G/min) allows relaxation of the hysteretic magnetization, whereas the effective vortex viscosity is sufficiently high to result in unobservably low resistivity at the applied transport currents. This effect can also be formulated in terms of V-I or E-J characteristics. In magnetization measurements the effective electric field that is probed is orders of magnitude lower than in the resistive measurements. If the E-J characteristics are very steep, as is the case when a well defined J_c exists with no creep, then the resulting effective J values obtained from both measurements are comparable in spite of significant difference in effective electric field E. On the other hand, if the E-J characteristics are linear in the limit of low currents, the two experimental techniques will result in very different estimates of J_c.

In conclusion, we have conducted simultaneous resistance and local magnetization measurements of BSCCO crystals and have found that the first-order vortex-lattice phase transition is accompanied by a sharp resistive transition. This finding indicates that the observed thermodynamic phase transition is melting or simultaneous melting and decoupling of the vortex-lattice.

We are grateful to V. Geshkenbein and P. Kes for valuable discussions, to N. Motohira for providing one of the BSCCO crystals, and to H. Shtrikman for growing the GaAs heterostructures. This work was supported by the Israel Science Foundation administered by the Israel Academy of Sciences and Humanities, by the French-Israeli cooperation program (AFIRST), the U.S.-Israel Binational Foundation (BSF), and the Grant-in-Aid for Scientific Research from the Ministry of Education, Science and Culture, Japan.

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