First-Order Decoupling Transition in the Vortex Lattice of $Bi_2Sr_2CaCu_2O_8$ from Local Mutual Inductance Measurements

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We have used a miniature mutual inductance technique to measure the ac transmittivity of $Bi_2Sr_2CaCu_2O_8$ crystals in small applied dc fields. A sharp change in the inductive voltage in the vicinity of the irreversibility line at fields below 60 mT and temperatures above about 40 K is observed. The effects of ac frequency, dc field, and the orientation of the applied dc field with respect to the c axis are investigated. This sharp feature appears to be similar to the melting transition recently observed in local magnetic measurements. We find it is associated with changes in the c-axis resistivity and is consistent with a first-order decoupling transition.

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The large anisotropy and unusual parameter values in very anisotropic high temperature superconductors result in a complex vortex phase diagram [1]. A clear understanding of the behavior has been hindered by the different time scales and criteria used in different experiments for identifying various crossovers and transitions [2–6] well below B_{c2}, which is also still controversial [7]. The question of the existence of the first-order thermodynamic melting or decoupling transition that has been predicted to occur is still by no means resolved. Sharp hysteretic features in the resistivity have been observed in $YBa_2Cu_3O_{7-\delta}$ (YBCO) [8,9] and suggest a first-order melting transition may occur. However, these features may also be attributed to nonequilibrium current-induced effects in the vortex lattice [10]. Liang *et al.* [11] have recently reported magnetic evidence for such a transition in YBCO. In $Bi_2Sr_2CaCu_2O_8$ (BSCCO), on the other hand, several reports have ascribed sharp drops or changes in magnetization or susceptibility to possible melting or decoupling [2–4]. Indirect evidence from transport measurements has now been presented by Pastoriza and Kes [12]. They ascribe features in the resistivity of inhomogeneously heavy-ion irradiated BSCCO crystals to a shear-driven melting transition.

In general, resolution of the question of whether these features are due to melting or decoupling has been frustrated by the pronounced geometrical effects that occur in thin platelike samples in the perpendicular geometry in clean systems and small applied fields of the order of the lower critical field [13,14]. This geometrical barrier results in irreversible magnetization with a corresponding peak in the loss component of the susceptibility [15] and is also expected to affect the transport behavior [16] even in the absence of any significant bulk pinning, which is precisely the case for BSCCO above 40 K. The central implication, at least for this paper, of this geometrical barrier is the highly nonuniform internal field that results from vortices forming a "droplet" [13] in the sample center, contrary to expectations from usual critical state models. This means that any critical behavior (e.g., melting of the lattice) for which clear theoretical predictions occur cannot be experimentally verified by global measurements, since the effects are smeared in temperature by the field distribution.

However, the advantages of the use of microscopic hall probes or miniature pickup coils for investigation of dc magnetization, ac susceptibility, or harmonic transmittivity of the typical platelike crystals of BSCCO has resulted in much progress recently. Zeldov *et al.* [3,16,17] have used miniature hall probes and elucidated the geometrical barrier and nonuniform internal field. In addition, they have shown a discontinuous field and temperature dependent decrease in the dc magnetic induction (flux density), which they have attributed to a first-order melting transition of the vortex lattice. Since this occurs in the reversible region of the magnetization curve, it is by far the most convincing evidence for a phase transition yet published. The "melting" line is, moreover, separate from the irreversibility line which, in this regime, is determined by geometrical or Bean-Livingston barriers and not by depinning. The melting line crosses the irreversibility line at about 45 K before ending abruptly at a critical point. The temperature dependence of the melting feature is noted [3] to be equally consistent with a decoupling transition (which may also be a first-order thermodynamic transition [18]) as it is with melting of a vortex lattice. Ando *et al.* [4] have used a miniature mutual inductance technique and observe a small, frequency independent feature in the susceptibility of BSCCO crystals above the irreversibility line. They attribute this to a thermally induced decoupling line. This hypothesis is rather strongly supported by the good fits to the temperature dependence of the decoupling field [4], which they observe for three crystals in different doping states with rather different anisotropies.

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We have used a method similar to Ando *et al.* [4] but with miniature pickup and drive coils on either side of the crystal. The small size of our pickup coils allows us to measure a reasonably uniform internal field distribution so that we are able to detect a transition that is very narrow in both temperature and field. Because of the pancake-type geometry of the coils we have sizable in- and out-of-plane components of the ac field, and we are thus sensitive to both in- and out-of-plane screening currents as shown by Arribere *et al.* [19]. With this local mutual inductance probe we are able to separate the development of the two diffusive loss peaks, which we associate with the in- and out-of-plane resistivities, from that of the sharp first-order transition. In addition, we have measured the angular dependence of this transition as well as measuring the c-axis resistivity. The data indicated that the sharp feature we measure is the same as that reported by both Ando *et al.* [4] and Zeldov *et al.* [3].

The crystals we have used were produced using the traveling floating zone technique [20]. Samples were cut from the boule and recleaved and cut into dimensions of about 1 mm × 1 mm × 0.01 mm. Small pancake-type coils were wound using 20 μm insulated copper wire. The coils were usually between 100 and 400 μm in diameter and 1 to 5 layers thick. Close to identical coils were placed on each side of the crystal: One was used as a drive coil and the other as a pickup coil. This is indicated schematically in the inset to Fig. 1. The coil shape changes the precise form of the data but does not change the physics we observe except that the sharp decoupling features described below become increasingly sharp and well defined as we use smaller coil areas. An ac field of less than 0.3 mT was used. Careful checks showed that the inductive voltages we measure are always in the linear regime for these amplitudes. This makes it less likely, although we cannot preclude this possibility, that our data are affected by current-induced rearrangement of the vortex lattice, which can produce sharp jumps in transport properties. We use lock-in amplifiers and low noise transformer techniques for nominal 30 pV sensitivity in a frequency range of 77 Hz to 100 kHz. We measure the complex signal with a dual phase lock-in amplifier so that we determine the in-phase or real (shielding) voltage as well as the out-of-phase or imaginary (loss) voltage. It should be noted that this experiment does not directly measure the susceptibility of the sample, but rather the transmittivity, which is related to the susceptibility. A uniform dc field was generated by either a small copper solenoid or an iron core magnet, which could be rotated around the cryostat (and sample) axis. In addition, we have measured the linear quasi-dc (76 Hz) c-axis resistivity of the crystals using a four point method. Details of the contact preparation and measurement technique have been described elsewhere [21].

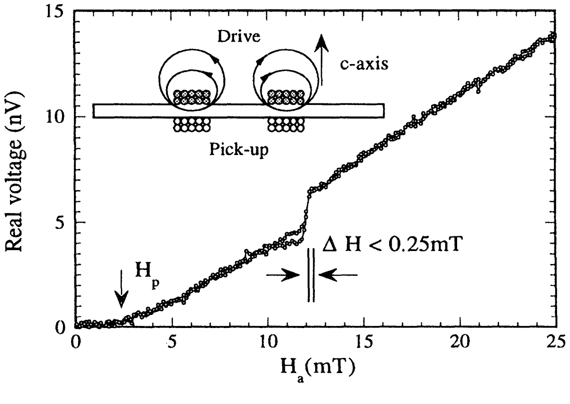

FIG. 1. Field dependence of the transmitted real (in-phase) voltage measured at 10 kHz and 77.3 K. Both increasing and decreasing fields are shown. The field regime where vortices first enter the sample and which is dealt with in Ref. [15] is indicated by H_p. The inset shows a schematic of the measurement configuration.

Figure 1 presents the dc magnetic field dependence of the measured real voltage at 10 kHz and 77.3 K for increasing and decreasing the field when the dc field is oriented parallel to the c axis. The arrow of 2 mT indicates where the geometrical barrier results in a loss peak [15]. At these low fields, in the vicinity of the penetration field, the behavior is hysteretic [15], although this hysteresis is below our resolution. However, we concentrate on higher fields where the behavior is reversible as also seen in Ref. [15]. At around 13 mT at this temperature there is a sharp increase in the measured voltage. This occurs at the same value of field in increasing and decreasing field. The width of this change is less than 0.25 mT, and some small hysteresis is apparent and reproducible in the tail of the sharp feature. Careful checks of the angular dependence show that the position of the sharp feature is determined only by the component of the field parallel to the c axis.

Changes in the local permeability have been reported by Ando *et al.* [4] as a function of temperature. We show similar results to theirs in Figs. 2(a) and 2(b) for a dc field of 10 mT and for three different frequencies. It is clear from both components of the voltage that the temperature at which the sharp feature occurs is frequency independent over more than 3 orders. Moreover, the feature we measure is less than 0.5 K wide and considerably more pronounced than that measured by Ando *et al.* [4]. This is easily understood by the small size of our measurement coil. For this crystal it has a diameter of 100 μm and an area of 7500 μm^2. This is larger than that of Zeldov *et al.* [3] by 2 orders, but smaller than Ando *et al.* [4] by $1\frac{1}{2}$ orders. It also explains why Pastoriza *et al.* [2] see that the frequency dependence of their global susceptibility vanishes below about 40 mT while they see no sharp features.

Several authors (Ref. [6] and references therein) have demonstrated, for fields parallel to the c axis, that the loss

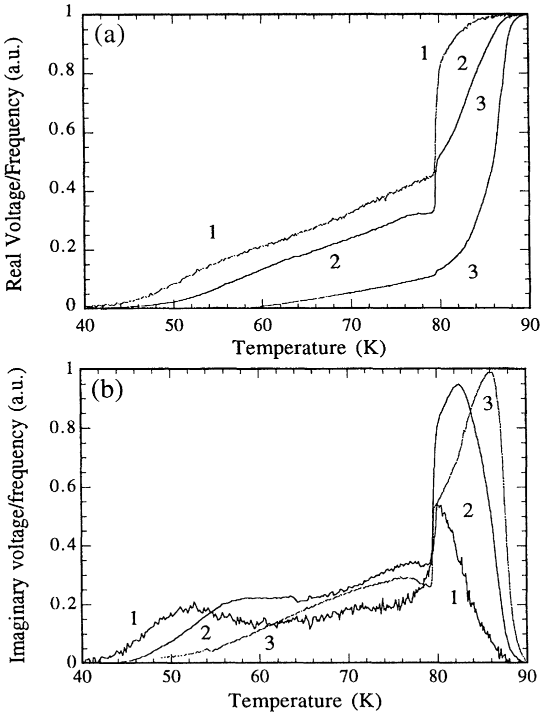

FIG. 2. (a) The temperature dependence of the real (in-phase) transmitted voltage with a dc field of 10 mT parallel to the c axis and for three frequencies, 77 Hz (curve 1), 10 kHz (curve 2), and 100 kHz (curve 3). (b) as for (a), but showing the imaginary (out-of-phase) or loss component.

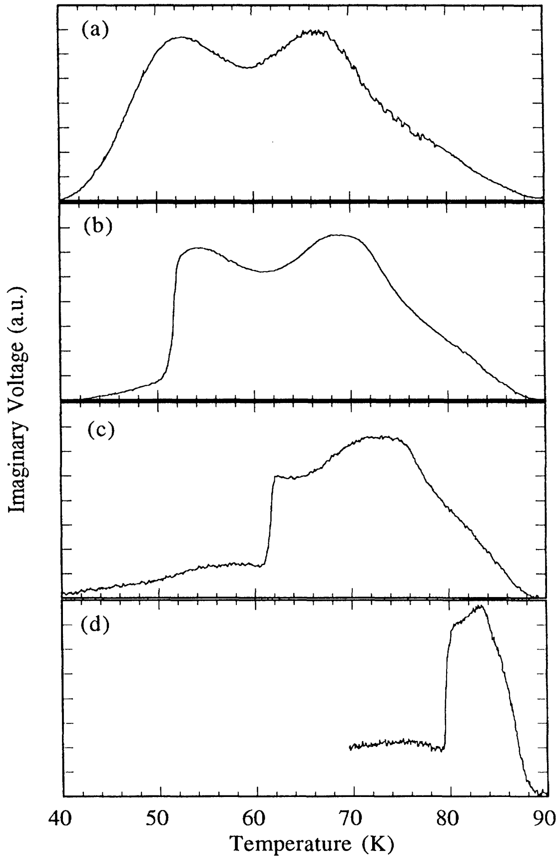

FIG. 3. The imaginary transmitted voltage measured at 10 kHz with dc fields of (a) 70 mT, (b) 60 mT, (c) 40 mT, and (d) 10 mT applied parallel to the *c* axis of the crystal. The peak at higher temperatures is associated with in-plane resistivity and that at lower temperatures with out-of-plane currents.

peak in χ'' occurs when the skin depth obtained from dc in-plane resistivity matches the sample dimensions. We see two clear loss peaks and the high temperature peak corresponds to the in-plane resistivity [6]. The origin of the peak at lower temperatures is more complicated since simple electromagnetic theory would predict that, in cylindrical symmetry in a normal metal, we would not induce any *c*-axis currents. However, for a weakly coupled layered superconductor in the mixed state the tilting of flux lines induced by the ac field must be transmitted to the bottom face of the crystal by Josephson strings, which involve *c*-axis currents between the planes. This second loss peak then reflects a maximum loss due to flux cutting as the *c*-axis coherence is broken with increasing field or temperature. Although we measure the transmittivity, the temperature dependence of the imaginary voltage in Fig. 3(a) is very similar to reported susceptibility data measured with the ac field parallel to the *ab* planes of a BSCCO crystal. At the highest field of 70 mT, in Fig. 3(a), there is no evidence of any sharp transition. As the field is reduced, a sharp transition appears in the tail of the lower temperature peak, which we associate with the *c*-axis resistivity. When the field is further lowered this transition moves to higher temperatures through the *c*-axis peak. Since at these fields the *ab*-plane resistivity has no effect on the measurements, it follows that this transition must be associated with a sudden change in the *local c*-axis resistivity, i.e., a decoupling transition. It is worth pointing out that this is consistent [22] with measurements of activation energies from the *ab*- and *c*-axis resistivities in BSCCO crystals, which are the same to within about 20%. In view of the large anisotropy of BSCCO this is strong evidence that the transport properties of flux pancakes are also largely determined by the *c*-axis coupling.

We have also therefore measured the linear *c*-axis resistivity directly using a four point method in the same regime of field and temperature to try to confirm this suggestion. The temperature dependence of the sharp feature, as well as the temperature where our resistance vanishes into the noise, is shown in Fig. 4. The proximity of the line to that measured by Zeldov *et al.* [3], as well as the qualitative similarity of Fig. 1 to the dc magnetization data in Ref. [3] (we see a sharp decrease in the shielding signal with increasing field where they see a sharp decrease in the magnetization), suggest that these signals are manifestations of the same phenomena. It is very difficult to believe that two transitions that are this sharp exist in such close proximity in the *H*-*T* plane and

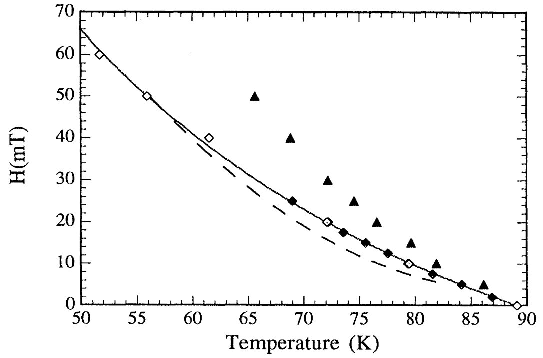

FIG. 4. The frequency independent decoupling transition for two crystals (open and closed diamonds). The solid line is a fit by the decouplng prediction (see text). The triangles indicate the resistively determined irreversibility line using a criterion of 10^{-4} Ω. The dashed line is an extrapolation from Arrhenius plots to 5×10^{-6} Ω.

that the measurements are sufficiently different that each is sensitive to only one of the transitions.

We have fitted the data using the decoupling expression from Ikeda [23], $B_d \approx B_0(1/T - 1/T_c)$ for decoupling. $B_0 = \Phi_0^3/4\pi^2\mu_0 k_B s \gamma^2 \lambda_{ab}(0)^2$ where $s = 1.5$ nm; the interlayer spacing and $\gamma = \lambda_c/\lambda_{ab}$ is the anisotropy parameter. We assume $\lambda_{ab}(0) = 180$ nm. This expression differs by a factor of order unity from the decoupling prediction [18] used in Ref. [3]. We find a very satisfactory fit over the entire range as seen in Fig. 4. The usual form for a melting transition $B_m = B_0(1 - T/T_c)^\alpha$ with $\alpha \leq 2$ is unable to fit the data close to T_c and requires a value for T_c which overestimates that determined magnetically or from the transport behavior. The value obtained for the anisotropy parameter γ from the decoupling fit is 169, which is quite reasonable, especially since the T_c value and form of $R_n(T)$ above T_c indicates that our crystals are slightly underdoped [4]. The value for T_c that we obtain is 89.3 K in clear agreement with the onset of diamagnetism.

Next we consider reconciliation of the resistive data with the inductive data. The resistivity disappears into the noise with our experimental sensitivity higher in the H-T plane than the measured decoupling transition. The temperature dependence of this behavior at different fields has a stronger curvature than the decoupling line, and is reminiscent of the geometrical barrier-controlled irreversibility line [17]. The dashed line in the figure indicates an extrapolation of Arrhenius plots to match the resistivity with the decoupling line. Our measurement sensitivity, which is typical, allows us to determine 5×10^{-5} Ω across typical crystal thicknesses of around 10–20 μm. Observation of an abrupt change in the resistivity clearly requires that any such effect should occur at least an order of magnitude of resistivity higher than that where the resistivity vanishes into the noise. In all of the above we have, however, ignored the effect of the distribution of the internal field due to the geometrical barrier, which may smear out sharp features even if sufficient voltage sensitivity could be attained. This is probably why signatures of this first-order transition have thus far not been seen in most transport measurements. Recently, Pastoriza and Kes [12] have seen sharp drops in in-plane resistivity in samples with strips of strong pinning (heavy ion irradiated) material, although no such features are observed in a homogeneous sample. It is likely that this is another manifestation of the fact that the effect only occurs on a local scale, and is smeared out in bulk samples. Their results are also consistent with a sharp decoupling transition.

In conclusion, we have presented data which suggest strongly that the sharp features observed in various magnetic and resistive measurements are associated with the same physical phenomenon. The frequency independence of this transition, the very good agreement with decoupling predictions, as well as the clear association of this feature with the out-of-plane diffusive mode, point strongly to a first-order decoupling or tilt-mediated transition rather than a melting or shear-mediated transition.

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