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Observation of two-dimensional vortices in $Bi_2Sr_2CaCu_2O_x$

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We report transport measurements in the mixed state of single crystals of $Bi_2Sr_2CaCu_2O_x$ using a modified version of the dc flux transformer geometry pioneered by Giaever in low-T_c materials. We find that over a wide range of the phase diagram the vortices are effectively two dimensional in character. Our results suggest that vortex cutting is an efficient process and that it is unlikely that the vortices are strongly entangled in this region of the phase diagram.

The magnetic phase diagram of the mixed state of the oxide superconductors has proven to be a rich system with many physical phenomena playing a role. It has been found that thermal fluctuations,[1-3] pinning disorder,[4] and dimensionality[5,6] are all important in the statics and dynamics of magnetic vortices. The observations of novel dynamics have been variously described in terms of melting,[1,3] vortex glass behavior,[6] giant flux creep,[7] and flux entanglement.[2] At the moment there is strong evidence[8] to support the vortex glass model as a good description of the low-temperature ordered phase in these materials in the disordered limit with the transition becoming first order in the clean limit. However, the role that vortex entanglement[9] plays in the high-temperature dynamics is still very much an open question.

The key issue with regard to entanglement is the extent to which the vortices can be considered as elastic rods piercing the entire thickness of the sample. It is clear, if the vortices can easily break and reconnect, that the importance of entanglement will be minimal. Likewise, if the vortices are really two-dimensional pancakes[5] existing as separate entities in the individual superconducting layers, then the importance of entanglement will also be minimized. In this limit of extreme anisotropy, with pancake vortices, one would also expect that the importance of point pins would be very different. This extreme anisotropy would also affect the relevant dimensionality within the vortex glass[6] and melting[1-3] pictures. In this work we will present data using a modified dc flux transformer effect to show that over a wide range of the phase diagram the vortices are effectively two dimensional, suggesting that it is unlikely that the vortices are strongly entangled.

In the $Bi_2Sr_2CaCu_2O_x$ system, for currents flowing in the *a-b* plane and the magnetic field parallel to the *c* axis, it is well known that the resistive transition broadens with increasing field without noticeable changes in the onset temperature.[10] This behavior has been interpreted as the dissipation arising as three-dimensional vortices hop between nearby pinning sites.[11] However, this contradicts the evidence for a low-temperature phase transition in the vortex structure.[9,12] Analysis of the *I-V* curves provides support for the existence of a three-dimensional vortex glass transition. However, the role that the layered structure plays as well as the importance of thermal fluctuations at high temperatures in overwhelming the interlayer coupling is unclear. In this regime the vortices may very well be pancakes lying in the Cu-O planes. It is these ideas that we wish to explore with the data presented here.

Our experiments consist of an *a-b* plane electrical transport in the mixed state of $Bi_2Sr_2CaCu_2O_x$ single crystals using flux transformer contact geometry. Using this geometry it is possible to simultaneously study the magnetic-field-induced dissipation in both faces of our single-crystal sample subject to a nonuniform current distribution. Our results show that the in-plane dissipation is not correlated over the thickness of the sample along the *c* direction over a wide portion of the phase diagram. This suggests that the vortices are two dimensional in character.

The original flux transformer experiments[13] in low-T_c materials showed that dissipation in a type-II superconductor arises from the motion of vortices. In his pioneering work, Giaever used two superconducting tin films which were separated by a thin, insulating SiO_2 layer. In that experiment, a dc electrical current was passed through one of the films (the primary) so as to induce flux flow, and the voltage drop was measured across both films. He found that a voltage drop occurs across both the primary *and* the secondary films and that the magnitudes of the drops were the same in both films. Because a voltage appeared in the secondary in the absence of a driving current, this was proof that the dissipation in the flux flow regime is produced by the movement of vortices. Subsequently, pinning[14] and thermal fluctuations[15] have been included in the analysis, allowing a complete understanding of the coupling as a function of current and temperature. We have performed an analogous experiment in single-crystal $Bi_2Sr_2CaCu_2O_x$ where the strong anisotropy in this system has allowed us to dispense with the insulating layer. It was our hope that this experiment would provide an insight in the study of the vortex line dimensionality in high-T_c materials.

Our experimental arrangement is sketched in the inset in Fig. 1. As shown, we have made six electrical contacts on each of our samples. On the top of the sample we have made two contacts for the current and two for the voltage in the standard geometry. On the bottom we have made two additional voltage contacts. The voltage leads on the top and bottom of the sample are aligned with each other.

Because our current contacts are only in contact with the top of our sample, the current distribution in our crystal will be very inhomogeneous due to the strongly anisotropic resistivity[16] in this system. In the mixed state of a type-II superconductor the vortices will move in the presence of a current due to the Lorentz force. In our experimental arrangement, the Lorentz force on any given vortex will be much stronger at the top of the sample than the bottom due to this inhomogeneous current distribution. If the vortices in this system were rigid rods, moving parallel to the applied field, then the velocity of any two points on a given flux line should be the same, regardless of the fact that there will be a different Lorentz force at those two points. Even for elastic rods, this will be true in the steady state. Therefore, in the high-temperature regime where pinning should be unimportant, these moving vortices would be expected to produce the same dissipation on both faces of the crystal. As we will show below, our results indicate that there is a much smaller dissipation on the bottom of our sample than the top. In fact, our data indicate that the dissipation in each face is given solely by the value of the current on this face, without a contribution from the vortex motion correlated in the c direction. This indicates that the flux lines readily cut and reconnect during transport.

We have used high-quality $Bi_2Sr_2CaCu_2O_x$ single crystals grown by directional solidification.[17] The crystals are thin platelets with typical dimensions of $2\times2\times0.030$ mm^3. As is typical for these crystals, the smallest dimension is along the c direction in our crystals and the a-b planes are parallel to the flat faces of the sample. Electrical contacts were made by evaporating silver pads onto the surface soon after cleaving the crystal to expose a fresh face. After annealing at 400 °C in flowing oxygen, gold wires were attached to the silver pads using silver epoxy. The typical contact resistance was 10 mΩ. Special care was taken during the silver evaporation to avoid short circuiting the faces of the sample. The voltage contacts were typically 0.7 mm apart and the current leads were typically 1.5 mm apart. The magnetic field was applied parallel to the c axis of the crystal.

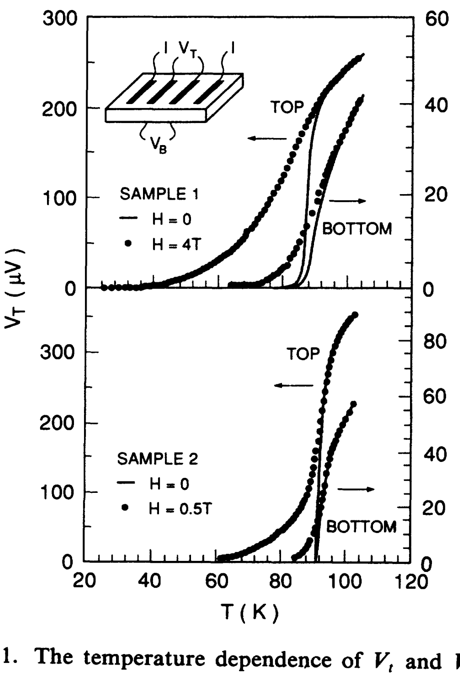

FIG. 1. The temperature dependence of V_t and V_b for the two samples investigated at different fields is shown. The contact geometry is shown in the inset.

At room temperature, it was found that the voltage at the top of the sample V_t was about three times the voltage seen at the bottom of the sample V_b. The ratio V_t/V_b increases with decreasing temperature reaching a value of 8 at $T=100$ K. This result agrees with independent measurements of the a-b- and c-axis resistivities and the simple model outlined below.

In Fig. 1 we show the temperature dependence below the superconducting transition of both V_t and V_b as a function of temperature at various applied fields for two different samples. The voltages were measured simultaneously using an ac lock-in technique with a driving current of 1 mA at a frequency of 90 Hz. For $H=0$, both V_t and V_b became zero at the same temperature (83 K for sample 1 and 93 K for sample 2). The transition width as measured using a 10–90 % criteria was found to be 5 K for sample 1 and 3 K for sample 2.

In the normal state $V_t \neq V_b$ due to the anisotropy of the resistivity. In the superconducting state we find that $V_t \neq V_b$ throughout the temperature and field range studied (0.1–7 T). This observation is a direct indication that the vortex lines do not act as rigid lines in this region of the magnetic phase diagram. Throughout the entire temperature and field range studied, both V_t and V_b were found to be linear in current and independent of frequency between 5 and 800 Hz.

In Fig. 2 we show the ratio V_t/V_b as a function of temperature for various applied fields. Also shown in Fig. 2 is the result for $H=0.5$ T for sample 2. Other fields have been omitted for clarity, since we found that the results are sample independent. One would expect that for rigid vortices, the ratio V_t/V_b should approach 1 at low temperatures at all fields. The main point of this paper is that instead, as is shown in Fig. 2, we find that this ratio increases sharply as the temperature is reduced and that it is field dependent. Pinning cannot play a significant role as this region is characterized by a reversible magnetization.[18]

We can quantitatively understand the data shown in Fig. 2 in the following way. Shown in the inset in Fig. 3 is a simple circuit diagram for our sample. We propose that the voltages we measure, V_t and V_b, arise from the in-plane resistance R_{ab} times the current flowing on each face. We postulate that R_{ab} is the same for both faces of the sample. In our model R_c is the effective resistance connecting the top and bottom faces of our sample. Solv-

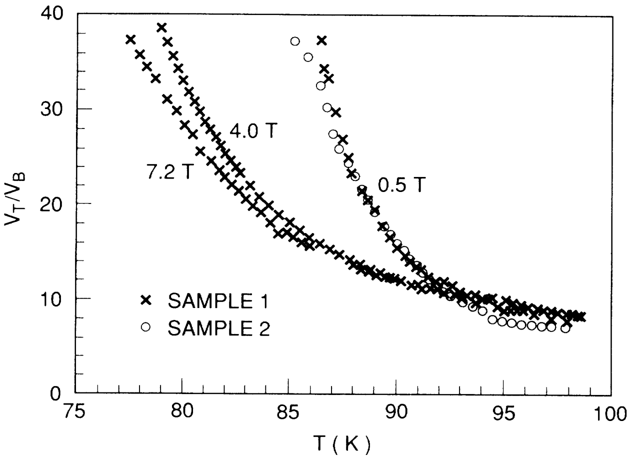

FIG. 2. The temperature dependence is shown for the ratio V_t/V_b for the two samples investigated at the different fields labeled.

ing this circuit leads to the relation

$$V_t/V_b = 1 + 2R_c/R_{ab} \ . \tag{1}$$

Our model is certainly valid in the normal state. In this region R_{ab} and R_c will be determined by the in- and out-of-plane resistivities and the geometrical factors. When we compared V_t/V_b with ρ_c/ρ_{ab} in the normal state we implicitly assumed this relationship. In the superconducting state, a test of this model is more nontrivial. If we find relation (1) to be valid in the superconducting state, then there is no contribution to the dissipation on the lower face of the sample from vortex motion induced at the top.

To test the above relation, we can follow Briceno *et al.*[16] and pick a temperature where R_c is field independent. At such a temperature the field dependence of V_t/V_b should be given by Eq. (1) above and the measured field dependence of R_{ab}. Such an analysis is shown in Fig. 3.

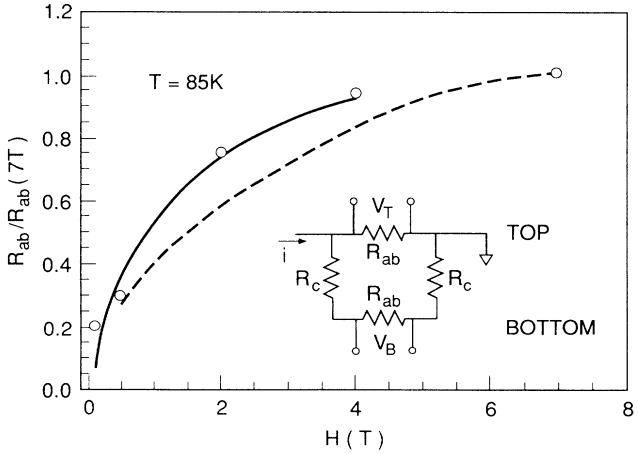

FIG. 3. The open circles are the derived field dependence for the in-plane resistance R_{ab} (sample 1) at 85 K normalized to its value at 7 T. R_{ab} was derived from measurements of V_t/V_b using Eq. (1) for the equivalent resistance circuit as shown in the inset. The dashed line is the measured value of R_{ab} as measured in the crystal from Ref. 12 and the solid line is extracted from the thin film data of Ref. 17.

Shown in Fig. 3 is our extracted values of R_{ab} normalized to the value at 7 T as a function of applied field at a temperature of 85 K. The values of R_{ab} were obtained using the measured values of V_t/V_b and Eq. (1). Also shown for comparison are direct measurements of this quantity measured on another single crystal[12] and in thin films.[19] Note the good agreement between our extracted values and the independently measured values.

This agreement implies that to within our experimental errors, we find no evidence for a contribution to the dissipation on the bottom of our sample from the movement of rigid vortices. This possibility has been previously discussed. Two-dimensional vortices,[12] nonrigid vortex lines,[2] and two-dimensional Maki-Thompson fluctuations[20] have all been proposed as being responsible for the dissipation as observed in this part of the phase diagram of $Bi_2Sr_2CaCu_2O_x$. However, the experimental results presented here represent the first experimental proof that the correlation length along the *c* axis, ξ_c, in this system is significantly shorter than the sample thickness. From Fig. 3 we can estimate bounds for ξ_c. If we assume that the 3% difference between our derived data and those obtained in thin films comes from correlated vortex motion and that correlated motion gives a contribution decaying with the following form e^{-L/ξ_c} (where L is the sample thickness), we find $\xi_c < 4$ μm. If we compared the derived R_{ab} data with our direct measurements in single crystals we find a lower bound, $\xi_c < 0.5$ μm. In the case of YBCO(123), a more isotropic material, neutron scattering[21] and transport in multilayers[22] have been used to extract $0.1 < \xi_c < 1$ μm. In principle, the dc transformer effect is a more direct measure of ξ_c, but there are as yet no measurements in YBCO for comparison.

In low-T_c materials, with inhomogeneous structures,[13,23] it was found that the dissipation was correlated in the direction perpendicular to the flow of the vortices due to the magnetic coupling between vortices. Our results show that in agreement with previous calculations[5] thermal fluctuations can destroy this coupling in this range of temperatures.

We note that the field dependence of R_{ab} is not linear as in the Bardeen-Stephen model.[24] However, the order of magnitude of the observed resistance on the top face still argues that it is due to the flow of vortices. In the Bardeen-Stephen model, $T_{\text{flux flow}} \sim R_{\text{normal}} * (B/H_{c2})$. The normal-state resistance at $T = 85$ K as extrapolated from above T_c is $1.2 * R_{ab}$ (7 T, 85 K). If we assume a value for the zero-temperature coherence length of 15 Å, then we estimate that, at 85 K, H_{c2} should be 7.6 T, close to the maximum applied field as shown in Fig. 3. Therefore, we conclude that if the vortices moved as rigid rods, they would give a contribution to R_{ab} on the bottom face which would be measurably large on the scale of the agreement shown in Fig. 3.

In previous work[12] using a SQUID picovoltmeter it was shown that at lower temperatures than probed here that three-dimensional correlations become important.

Unfortunately, our experimental resolution with the present apparatus does not allow us to probe that temperature region.

In conclusion, we have shown using the high-T_c modified version of the dc flux transformer effect, that over a large region of the phase diagram of the mixed state in $Bi_2Sr_2CaCu_2O_x$ the vortices are effectively two dimensional in character. This argues that entanglement is unlikely to be relevant to the dynamics in this regime. Our results agree with predictions which have suggested that at high temperatures the magnetic coupling between pancake vortices will be destroyed by thermal fluctuations leading to a regime in which the system acts like a stack of uncoupled two-dimensional vortex lattices.

Note added. Since the submission of this article, we have learned that a similar experiment has been performed by Busch *et al.* [Phys. Rev. Lett. **69**, 522 (1992)].

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