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Josephson coupling, in-plane pinning, and vortex dimensionality in $Bi_2Sr_2CaCu_2O_{8+\delta}$

R. A. Doyle, J. D. Johnson, N. E. Hussey, and A. M. Campbell
IRC in Superconductivity, University of Cambridge, West Cambridge Site, Cambridge CB3 0HE, England

G. Balakrishnan and D. McK Paul
Department of Physics, University of Warwick, Warwick CV4 7AL, England

L. F. Cohen
Department of Physics, Imperial College, London SW7 2BZ, England

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The c-axis I-V characteristics of an oxygen overdoped $Bi_2Sr_2CaCu_2O_{8+\delta}$ single crystal have been measured to determine the current density $J_c^c(T)$ across the CuO_2 planes. In zero field, close to T_c, they show large capacitance resistively shunted junction behavior, a signature of phase locking of the Josephson junctions. In the quasi-force-free configuration with an applied field of $2T$, the zero-field-cooled $J_c^c(T)$ has a nonmonotonic behavior, its decrease at intermediate temperatures coinciding with a change in the form of the I-V curve. History effects are also observed. These features can be explained in terms of both disorder in the in-plane pinning of flux pancakes and a change in the Josephson coupling as the temperature is lowered.

High-temperature superconductors are layered structures and therefore anisotropic.[1] Superconductivity resides primarily in the highly conductive CuO_2 planes which are separated by layers of other atoms. In very anisotropic type-II superconductors like $Bi_2Sr_2CaCu_2O_{8+\delta}$ (Bi-2212) the vortex structure strongly depends on the direction of the applied field.[4] For $B\|ab$ the field penetrates preferentially between the layers and interlayer vortices experience intrinsic pinning. For $B\|c$, the vortices are composed of Abrikosov "pancake" vortices in the layers. Depending on the strength of the interlayer coupling, these pancakes may be joined by Josephson strings. Further, in Bi-2212, the c-axis coherence length is much smaller than the CuO_2 layer spacing over the entire range of superconducting temperatures[2] and the out-of-plane or c-axis behavior normal to the layers below T_c is determined primarily by Josephson weak-link coupling. The bulk phenomenology must then be described using a Lawrence-Doniach treatment.[3]

The bulk behavior of Bi-2212 crystals in applied fields has been investigated by two rather separate schools. The first[5-11] has focused on the mixed-state behavior and describes their results in terms of the dimensionality (longitudinal correlation length) and (related) pinning of the (pancake) vortices and interaction of transport and shielding currents. Daemen *et al.*[12] have treated this situation theoretically both in terms of thermally activated decomposition and pinning-induced disorder of the three-dimensional (3D) vortex lattice. The second type of approach[13-17] focuses on the Josephson effects observed along the c axis. We show here that a complete description of the behavior of these crystals can only be made by considering both pinning and Josephson effects.

The mixed-state approach has, using different experiments, identified various features in the low-field, low-temperature regime ($B < 3$ T, $T < 30$ K) below the dc irreversibility line. These imply a rather complex H-T phase diagram with several crossover regimes where the effective dimensionality of the vortex dynamics is suggested to be different. A schematic phase diagram is shown in Fig. 1 where the region of the experiments in this work is indicated. Experiments which have determined this diagram include anomalous peaks in the global (bulk) magnetization,[9,11] μSR (Ref. 6) and neutron diffraction,[7] ac susceptibility,[5] and transport measurements.[8] In short, these map out (i) a temperature-independent characteristic field, $B^* = B_{2D} = \Phi_0/(\gamma s)^2$, (between about 15 and 30 K) at which a 3D-2D or an order-disorder transition is proposed to occur moving from region 1 to region 2 in Fig. 1 with increasing field[7] and (ii) a weakly field-dependent temperature T^*, at which a similar transition occurs with increasing temperature[8] above fields of about 50–100 mT.[11] To our knowledge no analytical theoretical description for this latter crossover exists as yet.

The primary interest of previous work[15,16] on the Josephson c-axis behavior is determination (i) of the Josephson parameters of the individual junctions and (ii) of the regimes where phase coherence is displayed by the series array formed by the interplanar junctions. Kleiner *et al.*[16] have recently presented a thorough theoretical description and experimental model (using conventional

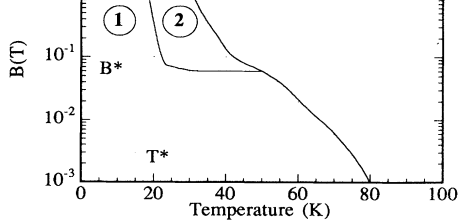

FIG. 1. Schematic H-T phase diagram for BSCCO 2212 derived from Refs. 5–9 for H applied parallel to the c axis. H^* and T^* are characteristic crossover fields. The line deliniating high fields and temperatures is the irreversibility line. The arrow indicates the regime of the results presented here.

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multilayer junctions) of phase locking in finite fields in very anisotropic layered systems.[15,16] These studies have concentrated on field and temperature regimes close to but not explicitly overlapping the regions in which several features have been related to 2D-3D transitions in the vortex dimensionality of 2212.

Here, we have measured the mixed-state behavior of a crystal showing pronounced Josephson coupling. Since the magnetic interaction between the layers in Bi-2212 is known to be about 50 times smaller than the Josephson coupling,[13] any 2D to 3D transition is likely to be dominated by the latter. The c-axis J_c has been measured below the irreversibility line for $B \| c$ where it may be of extreme importance for, inter alia, the use of silver clad Bi-2212 wires. We show that existing explanations of the behavior in this regime are inadequate and suggest that the history effects here are a nontrivial function both of the Josephson properties of the c axis, the interaction between in-plane disorder and c-axis long-range coherence as well as the flux cutting in the force-free configuration.[19] Any complete analytical description must include all of these factors. The effects we have measured here may be responsible for some of the unusual features measured and reported elsewhere.

Samples of $Bi_{2.2}Sr_{1.64}Ca_{1.16}Cu_2O_7$ were grown using the traveling floating-zone technique in a double ellipsoidal infrared furnace. The details of the growth technique are given in Ref. 20. Optically smooth rectangular crystals were cleaved from the as-produced mosaics. These were annealed in flowing oxygen for 24 h at 750 °C to "metallize" the c axis. The sample described here was a crystal with dimensions of 1.2 mm × 0.32 mm × 12 μm. Four 25 μm gold wires were attached to the bottom and to the top faces of the crystal, respectively, in a multiterminal dc flux transformer geometry. The wires were attached using Du Pont 6838 silver epoxy which was baked on in flowing air for 5 min at 400 °C. This resulted in subohmic contact resistances. The contact geometry is as for Ref. 18. The crystal has a measured T_c [determined at $\rho(T)/\rho(100\ \mathrm{K})=10^{-5}$] of 88.5 K and ΔT_c (10–90 %) = 1.3 K. The I-V characteristics were measured using a dc measurement system with a Keithley K192 nanovoltmeter. The resistance at room temperature corresponds to 3.52 Ω cm which is typical.[21] When measuring the c-axis resistivity, good agreement is found between voltage pairs at different distances from the current electrodes, from above T_c to where the resistance vanishes. We thus assume the top and bottom faces are equipotential where the resistance is linear and that the current flow along the c axis is therefore reasonably uniform. Certainly this is expected to be the case at I_c and we assume no large errors are incurred in the analysis here with this sample geometry.

Figure 2 presents the zero-field c-axis I-V curve at 87.2 K. It indicates pronounced hysteretic resistively shunted junction (RSJ)-like behavior as observed elsewhere.[13–17] The characteristics of such I-V curves have been clearly shown to derive from a series array of the same number of junctions as the copper-oxide bilayers.[16] The characteristic voltage (at the sharp increase in voltage almost to R_N), extrapolated back to zero K using the BCS temperature dependence suggests about 95% gap suppression in agreement with Ref. 13 which finds $\Delta(0)=3\%$ of the BCS value of 15 mV for oxygen overdoped crystals. This is also in agreement with Ref. 17.

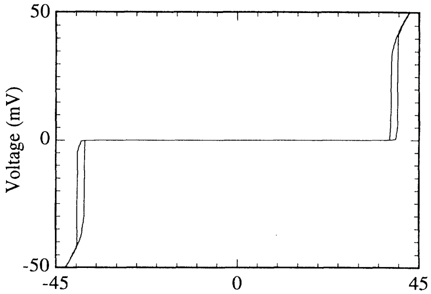

FIG. 2. c-axis I-V curve for the crystal at 87.2 K in zero applied field. Clear RSJ behavior is exhibited.

The sharpness of the transition suggests either that the junctions are very well matched or that they are phase locked. Low-field magnetization data with $B \| ab$ (Ref. 22) Bi-2212 show a rounded peak at the field of first flux penetration B_{pen}. If this process is governed by Josephson decoupling, as is the case for $Nd_{2-x}Ce_xCuO_4$ (NCCO) (Ref. 23) and Tl-2201,[24] where sharp drops in magnetization are observed at B_{pen}, the diffuse nature of observed initial flux penetration (which corresponds to interplanar decoupling) in Bi-2212 implies that the junctions have a distribution of coupling strengths and so phase locking seems more probable.

In order to examine the proposed 3D to 2D temperature-dependent crossover below the irreversibility line in moderate fields ($\gg 50$ mT), the c-axis I-V curves of the crystal were measured with 2 T applied parallel to the c axis. The J_c^c should be sensitive to such a crossover since loss of c-axis correlation along the length of a vortex parallel to the c axis means that the spatial variation of the phase in each of the layers becomes different. This results in a local phase difference between adjacent points in different layers, reducing J_c^c. Figures 3(a) and 3(b) present selected c-axis I-V curves on linear and log axes, respectively, after cooling the sample in zero field (ZFC) and then applying a 2 T field. Figure 3(b), in particular, shows that the form of the I-V curve changes *very rapidly* in a temperature interval of less than 1 K at 12.2 K. Figure 4 presents the J_c values extracted using a criterion of 3 μV and also indicates the field cooled (FC) values measured at 12.5 K and then immediately remeasured. Ignoring the data below 12.2 K in Figs. 3(a) and 4, all the other data are remarkably similar in all respects to that in Ref. 8 for 3 T. There are *two observations here.* The first is that the nonmonotonic J_c^c is intimately related to the change in the form of the I-V curve and is also therefore strongly criterion dependent. The second observation is that J_c^c starts to increase again at low temperatures.

At the lowest temperatures the I-V curve is flux-flow-like. As the temperature is increased, the curve begins to look RSJ-like. J_c^c therefore increases with increasing temperature. Eventually the irreversibility line is reached and a thermally activated tail appears in the I-V curve and results in a decrease in J_c. We suggest that the

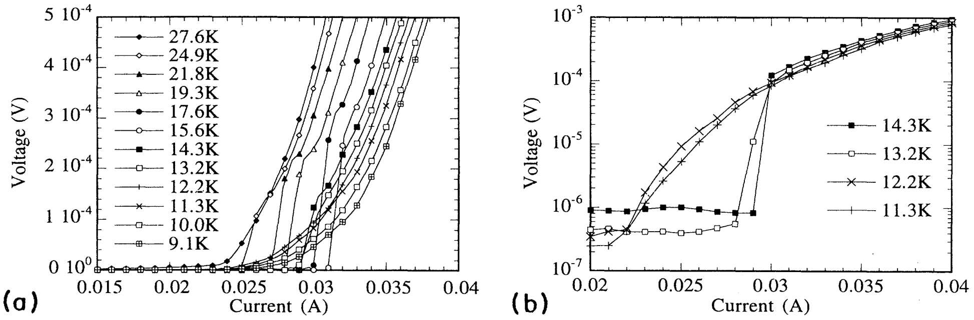

FIG. 3. (a) Zero-field cooled I-V curves with 2 T applied parallel to the c axis for several temperatures as marked in the figures. The lines are a guide for the eye. (b) Selected data from (a) indicating the very rapid change in the form of the I-V curve at about 13 K. The lines are guides. The data below 1 μV are due to thermal emf's.

unusual nonmonotonic behavior of J_c^c reported here and originally observed by de la Cruz *et al.*[8] is related to the change in the form of the c-axis I-V curve. A model is presented in Ref. 8 to explain both the increasing J_c^c with temperature and the larger values (for the same temperature) measured for J_c^c in the field-cooled case. It proposes that J_c^c is determined by the in-plane pinning order; in the FC case, the pancakes lie approximately on top of each other resulting in a higher J_c value than the ZFC case, where the pancake vortices start off highly disordered because of finite pinning of the vortices as they enter the sample as the field is applied. Increasing the temperature (and the effect of thermal fluctuations) in the ZFC case allows redistribution of the pancake vortices toward the equilibrium state (the hexagonal phase with pancakes above each other). In this model the c-axis correlation length and J_c^c must decrease continuously or at least saturate moving toward lower temperatures. The re-entrant J_c^c which is observed below 12.2 K in Figs. 3 and 4 is clearly incompatible with previous explanations. We propose two other possible explanations, both of which directly include the Josephson coupling along the c axis.

The first explanation involves the characteristic length scales in the experiment. In the small junction limit ($\lambda_c < w$) the current distribution is homogeneous because self-field effects are unimportant. Here w is the crystal width (0.32 μm). Thus the I-V might be expected to be quite sharp, whereas in the large junction limit an inhomogeneous current distribution might blur the I-V curve out. As T is increased, λ_c, given[16] by $\lambda_c=[\Phi_0/(2\pi\mu_0(t+d)J_c^c]^{1/2}$ increases and one moves toward the small junction extreme. Therefore such a crossover seems plausible provided λ_c is close to w at low temperatures. Here d is the interlayer spacing and t is the electrode thickness. We use values for $d=1.2$ nm, $t=0.3$ nm, and extrapolate J_c back to 0 K using the Ambegaokar-Baratoff expression and find a value of 10 400 A/cm^2. This yields a value for $2\lambda_c$ at 15 K of 100 μm. This value is sufficiently close (given the uncertainty in our extrapolation back from $t=T/T_c=0.9$) to w that the possibility of such a temperature-dependent crossover cannot be ruled out.

The second explanation is related to the very small electrode (cooper-oxide bilayer) thickness between the junctions and involves phase locking of the junctions as suggested by Kleiner *et al.*[16] We propose that below the irreversibility line at temperatures greater than about 13 K (for our sample), thermal fluctuations effectively smear out the differences between the junctions and resonances in the junctions act to phase lock large numbers of these.[16] This results in a sharp I-V characteristic with a critical current intermediate between the weakest and strongest junctions. As the temperature is lowered, in a magnetic field, the effect of fluctuations decreases. Further, the intrinsic properties of the individual junctions, as well as the in-plane critical current density (which also determines the coupling) increase rapidly with upward curvature. This has the effect of increasing the *absolute difference* between the individual junction properties. This causes unlocking of the junctions as observed in Fig. 3(a) below 12.2 K where the I-V curve collapses to a rounded form representing the intrinsic spread of the junction properties. Once all the junctions lose phase coherence, the J_c behavior of each starts to increase again as expected, thereby explaining the lowest temperature data in Fig. 3. Luo and Gough[13] have also observed that at sufficiently low temperatures, differences in critical currents across layers start to induce early transitions in the c-axis I-V curves. These observations support the notion that there is an approximately field-independent temperature (between regions 1 and 2 in Fig. 1) at which a crossover occurs in 2212. However, Fig. 3 suggests that long-range (i.e., larger than the crystal thickness) c-axis correlation is apparent at higher temperatures (where the I-V curves are sharp) rather than at the lowest temperatures. The material effectively becomes more 2D or *less ordered at lower temperatures* in contradiction to existing thought. This crossover may at least partly account for the unusual μSR and neutron-diffraction data[6,7] in this field regime as well as the anomalous magnetization data.[11]

In-plane pinning disorder must also play a role in this

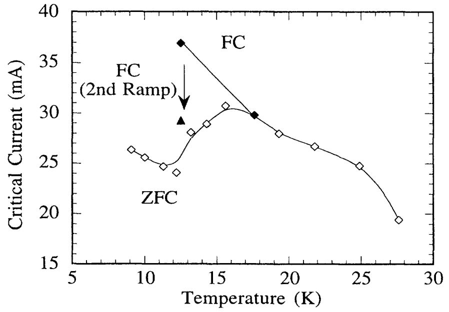

FIG. 4. J_c^c extracted from Fig. 3(a) (open diamonds) and also for the FC case: first cycle (closed diamond) and second cycle (closed triangles).

behavior though. This notion is supported by Fig. 4 (and Ref. 8) showing that the FC J_c^c value is larger than the ZFC case. With the reduction in J_c^c upon ZFC the sample can be easily understood in terms of interplane phase variations induced by misalignment of pancake vortices. To further illustrate this idea, we repeated the FC measurement after driving the sample into the flux-flow state ($I > 2I_c$). The measured J_c value then moves almost onto the ZFC branch as indicated in Fig. 4. The subsequent changes in the I-V curve are shown in Fig. 5 which indicates that the apparent decrease in J_c is accompanied by a rounding of the I-V curve. This suggests that, in agreement with de la Cruz *et al.*,[8] the c-axis long-range correlation is partly determined by in-plane disorder. Driving the c axis into the flux-flow state results in a rearrangement of the perfect pancake lattice in the planes (due to the finite angle of field with respect to the planes induced by interaction between the shielding and transport currents). This increases in-plane disorder and the random array of pancake vortices in the planes prevents phase locking and reduces the apparent array of pancake vortices in the planes prevents locking and reduces the apparent J_c^c. Gordeev *et al.*[10] have made similar measurements using a pulsed technique and show that the FC state is indeed the equilibrium configuration. This is qualitatively explained in terms of the interaction between the shielding and transport currents. Careful relaxation measurements[25] show that J_c creeps from the ZFC toward the FC value with time supporting this idea.

Finally, we discuss in broader terms the interpretation of sharp hysteretic features and the force-free configuration in general. It is now well documented that appropriate oxygen treatment of Bi-2212 results in RSJ behavior for the c axis. This is characterized by very sharp I-V curves which are hysteretic as shown in Refs. 14–17 and above. Because of experimental difficulties in anisotropic materials, measurements of the ab plane transport properties (multiterminal measurements in particular) may often measure a convolution of in- and out-of-plane properties and hence show sharp, hysteretic features. Geometrical corrections are unlikely to remove these very nonlinear signals and care should be taken when assigning such features to thermodynamic phase transitions.

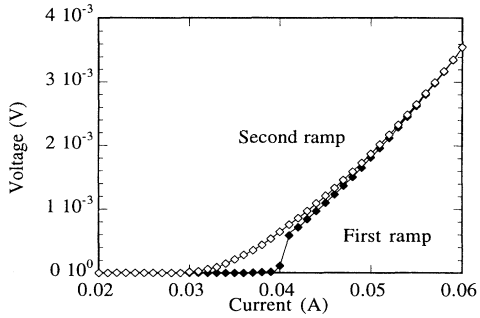

FIG. 5. History effect of the I-V curve for 2 T applied parallel to the c axis at 12.5 K. The curve was measured and then immediately remeasured.

A second point is equally important. It relates to the complexity of quasi-force-free configurations in general. These have been the subject of considerable interest in low-T_c materials in the past. Such configurations, where flux cutting and shear become dominant over depinning, may also manifest as very sharp and hysteretic I-V curves[26] *even in isotropic materials.*

In summary, the H-T phase diagram of Bi-2212 has been explored through I-V measurements of the c-axis critical current density with a field of 2 T applied parallel to the c axis. We find that the measured J_c in the c direction in the force-free configuration is a complex function of magnetic history, in-plane pinning disorder, and the phase-coherent state of the series junction array. We show that the nonmonotonic critical current previously observed starts to increase again at low temperatures and extend the existing explanations for this phenomenon to account for the Josephson-like nature of the c-axis coupling. The difficulties associated with interpretation of force-free data are well documented for low-T_c materials and should not be ignored.

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