Pressure Dependence of Flux Dynamics in $Bi_2Sr_2CaCu_2O_{8+\delta}$

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An important problem in high temperature superconductivity is that of understanding, and ultimately controlling, fluxoid motion. Results are presented in this paper which were obtained using a new technique for measuring the pressure dependence of the transition to superconductivity in a diamond-anvil cell. By monitoring the third harmonic of the *ac*- susceptibility, we observe the onset of irreversible flux motion. This, in turn, enables us to study the effects of pressure on flux motion. Pressure changes the atomic interplanar spacing, and hence the interplanar coupling, without significantly altering the intraplanar superconductivity. Therefore we are able to separate the effects of coupling from other properties that also might affect the flux motion, such as superconducting condensate density, anisotropy, and pinning. Our results directly show the relationship between lattice spacing and the irreversibility line in $Bi_2Sr_2CaCu_2O_{8+\delta}$. [superconductivity; flux dynamics; diamond-anvil cell; *ac* susceptibility; $Bi_2Sr_2CaCu_2O_{8+\delta}$]

1. Introduction

Pressure has played an important role in the development and understanding of superconductivity. More than a decade before the discovery of the high transition temperature (T_c) copper-oxides by the Nobel Prize winners Bednorz and Müller[1], pressure was involved in other reports of high temperature superconductivity. In 1976, pressures of 7 to 9 GPa were used to synthesize, for the first time, the superconductor Nb3Ge. [2] It was the unusually large effect of pressure ($dT_c/dP \cong 10$ K/GPa) in $La_{1.8}Ba_{0.2}CuO_4$, reported by Chu *et al.*[3], that led Wu *et al.* to the idea of substituting smaller ions for La in the in the hope of generating a permanent "internal pressure." This, in turn, led to the first discovery of superconductivity above 90 K in $YBa_2Cu_3O_{7-\delta}$.[4] The effect of pressure on the Hg-cuprate superconductors is even more striking: At atmospheric pressure, T_c in $HgBa_2Ca_2Cu_3O_{8+\delta}$ is 135 K, at 30 GPa T_c increases to 164 K — currently the highest T_c on record.[5]

There also are materials which are superconducting only under high pressure. Silicon and iodine, for example, undergo insulator-to-metal transitions at elevated pressures and have been shown to superconduct in the metallic phase.[6; 7; 8; 9] More recently, Takeshita *et al.* have shown that SnI_4 superconducts only above 30 GPa.[10] Even sulfur, a wide bandgap insulator at normal pressure, was shown to become metallic at about 90 GPa by Luo *et al.*[11] and Struzhkin *et al.* demonstrated that it superconducts below 10 K and, when the pressure is elevated to 160 GPa, it undergoes a structural phase transition and T_c increases to 17 K — the highest known T_c for all the elements.[12; 13; 14]

The important role played by pressure in the study reported in this paper is that it allows the separation of physical properties which can affect flux motion. Understanding the dynamics of flux motion presents a major challenge to the application of high T_c superconductors for uses in high magnetic fields and therefore with high currents.[15] The superconductor $Bi_2Sr_2CaCu_2O_{8+\delta}$ is two dimensional in many of its properties and therefore an excellent candidate system for the study of flux dynamics.

Theorists have recognized that the large anisotropy parameter and the temperature dependence of the Josephson coupling between the planes should cause a crossover from vortex lines to pancakes, *i.e.*, the topology of the vortices should change from 3-dimensional tubes to 2-dimensional disks.[16; 17; 18] These unusual flux dynamics have been shown to lead to an anomolously low irreversibility field, H_{irr}, compared to H_{c2}. [19] The value of H_{irr} forms an irreversibility line in the *H*-*T* plane, which varies depending on the experimental technique. Theorists have endeavored to connect this feature to the physical properties of HTS. Recent experiments by Fuchs and coworkers [20; 21] have clarified this by demonstrating that in $Bi_2Sr_2CaCu_2O_{8+\delta}$, H_{irr} is determined by surface barriers. We make use of this to identify the role of the interplanar spacing on the formation of flux lines.

Previous studies of the role of anisotropy have shown shifts of the irreversibility and melting lines in oxygen reduced $Bi_2Sr_2CaCu_2O_{8+\delta}$. [22; 23; 24; 25] However, the problem with this earlier work is that oxygen annealing simultaneously produces four physical changes in the sample: (1) the interplanar spacing along the *c*-axis; (2) T_c; (3) the in-plane penetration depth, λ_{ab}; and (4) the density of pinning sites. And at low temperatures, the situation is further complicated by the influence of bulk pinning. For these reasons, in a doping study, the effects of interplanar separation, penetration depth, and pinning site density on flux dynamics are intermingled. In order to better understand the irreversible flux motion, it is necessary to deconvolute these phenomena. In this work, we investigate the effects of varying the interplanar spacing on the irreversibility line directly. We note that our work is complemented by and consistent with the results of a recent similar effort by Tamegai *et al.* who measured the effects of hydrostatic pressure and oxygen doping on the vortex phase diagram of $Bi_2Sr_2CaCu_2O_{8+\delta}$. [26]

2. Experiment

We previously reported on some of the advantages of measuring the third, rather than the first, harmonic of the *ac*-susceptibility in a diamond-anvil cell (DAC), *viz.*, no background signal needs to be subtracted; there is a significant improvement in signal sensitivity and a concomitant insensitivity to ferrous metals. The first two advantages allow the use of smaller samples (and indirectly the ability to achieve higher pressures); the latter feature allows the use of hardened steel gaskets and therefore also the ability to achieve higher pressures.[27; 28] A fourth, and perhaps the most important advantage of measuring the third harmonic, is that it is responsive to the irreversible flux motion.

Single crystals of $Bi_2Sr_2CaCu_2O_{8+\delta}$ were used in this study. These were grown by a self-flux technique starting with a stoichiometric ratio of cations (Bi:Sr:Ca:Cu::2:2:1:2). Additional details of the crystal growth are reported elsewhere.[29; 30] The crystal used for the measurements was in the shape of a rectangular platelet with dimensions 200 x 200 x 50 μm^3 and a T_c of 86.3 K at ambient pressure.

High pressure was generated in a diamond-anvil cell (DAC) fabricated of Be-Cu; the DAC was coupled to a He^4 insertion cryostat. The sample and a small ruby chip were contained in the cavity of a Be-Cu gasket. The remaining volume of the cavity was filled with a 4:1::methanol:ethanol mixture, which served as the pressure transmitting medium. The pressure was applied and measured at room temperature and a calibration was used to determine the pressure at low temperatures to within an uncertainty of ±0.3 GPa. A schematic drawing of the key elements of the diamond-anvil cell is given in Fig. 1.

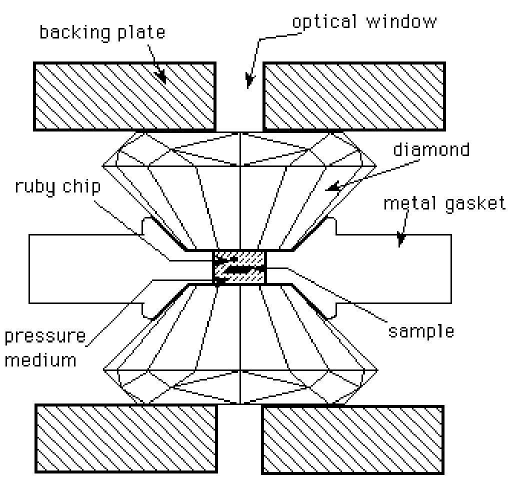

Fig. 1. Key elements of the diamond-anvil cell and the *ac*-susceptibility coils.

Primary and secondary coils wound on the diamond facets with 400 and 350 turns, respectively, were used for the *ac*-susceptibility measurement with both *ac*- and *dc*-magnetic fields applied parallel to the *c*-axis of the sample, which is also approximately parallel to the cylinder axis of the pressure cell. The pressure and *dc*-field ranges are from 0 to 10 GPa and from 0 to 10 T, respectively; the *ac*-field amplitude was 0.5 mT and the excitation frequency was 3.7 kHz. T_c was determined from the 3rd-harmonic of the *ac* susceptibility. As discussed above, the 3rd-harmonic signals the onset of irreversible flux motion, with respect to changes in *H*. Additional details of the apparatus are given in Ref. [31], and of the 3rd-harmonic technique in Ref. [32]. (Measurements made with this apparatus on single crystals of $YBa_2Cu_3O_{7-\delta}$ and $Tl_2Ba_2CuO_{6+\delta}$ are also reported in Ref. 32.)

3. Results and Discussion

The effect of the superconducting transition on the third harmonic in the $Bi_2Sr_2CaCu_2O_{8+\delta}$ crystal is shown in Fig. 2. The nonlinear-response peak is a result of irreversible flux motion in the superconductor. The irreversibility line is defined by the locus of points determined by *H* and the onset temperature, T_1. See Figs. 2 and 3.

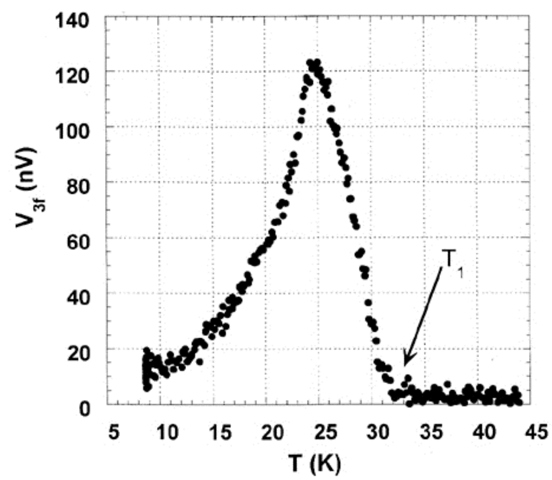

Fig. 2. The third harmonic of the *ac*-susceptibility in $Bi_2Sr_2CaCu_2O_{8+\delta}$ when there is no applied pressure and the applied *dc*-field is 1.5 T.

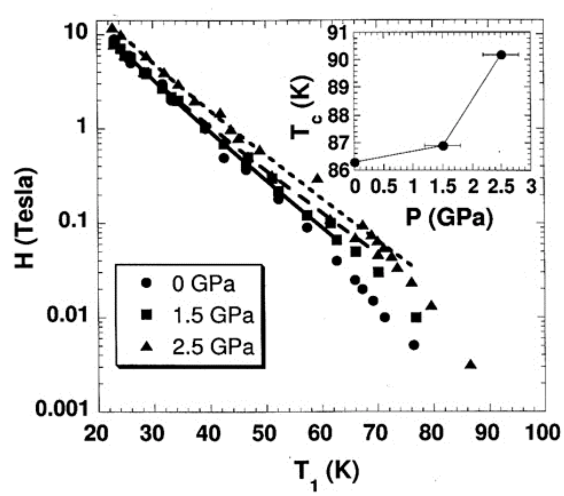

Fig. 3. H_{irr} at 0.0, 1.5, and 2.5 GPa. At high fields, the data show an exponential dependence which is expected for vortex pancakes penetrating the surface barrier. The inset shows the pressure dependence of T_c. For an explanation of this exponential temperature dependence, see Burlachkov *et al.* [33]

Significant progress has been made in recent years in understanding the physical origins of the irreversibility line. This line does not correspond to a phase boundary, but rather to the dividing point between reversible and irreversible flux motion, which may be limited by extrinsic factors, such as geometrical barriers, surface barriers, or pinning. In platelet-shaped samples, such as the one used in this study, the irreversibility line has been shown to lie both above and below the melting line, and to extend well into the high field regime.[20; 21; [34]] Moreover, the onset of irreversibility has been shown to be determined by the barrier energy for flux entry into the superconductor. The pressure and temperature dependence of this energy makes the irreversibility line well suited for studying a crossover from two dimensional to three dimensional vortex behavior. This crossover is illustrated in Fig. 3

These results are consistent with the muon-spin-resonance (μsr) data of Aegerter *et al*. [[35]] who reported that the crossover field is close to 50 mT. These authors further show that the crossover field is inversely proportional to the in-plane penetration depth, λ_{ab}, and independent of the anisotropy, as expected for bulk behavior.

Our result is that the crossover field is constant, but the crossover *temperature* increases as the interplanar coupling is enhanced, as expected for surface-barrier limited motion. At low temperatures, two-dimensional behavior occurs, and H_{irr} shows a weak pressure dependence. Above the crossover temperature of 70 K, the application of pressure significantly shifts the irreversibility line. This further underscores the importance of the coupling between the planes in the anisotropic three-dimensional regime of the flux dynamics.

4. Conclusions

The experiment reported in this paper illuminates the role of surface barriers to flux penetration in determining the position of the irreversibility line. The consistency of temperature and pressure dependencies of H_{irr} shows clear evidence that there are two regimes of flux motion. For temperatures below 60 K, the flux configuration is that of two-dimensional pancake vortices. This crosses over to one of highly anisotropic, three-dimensional flux tubes at higher temperatures. The irreversibility line is then determined by the energy needed to push pancake vortices into the sample at low temperatures or to push line vortices into the sample at temperatures closer to T_c. Additional and more theoretical analyses of the results of this work will be reported elsewhere.[[36]]

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