Pressure Dependence of the Irreversibility Line in $Bi_2Sr_2CaCu_2O_{8+\delta}$

M. P. Raphael, M. E. Reeves, E. F. Skelton, C. Kendziora

Abstract— **One of the important problems of high-temperature superconductivity is to understand and ultimately to control fluxoid motion. We present the results of a new technique for measuring the pressure dependence of the transition to superconductivity in a diamond anvil cell. By measuring the third harmonic of the ac susceptibility, we determine the onset of irreversible flux motion. This enables us to study the effects of pressure on flux motion. The application of pressure changes interplanar spacing, and hence the interplanar coupling, without significantly disturbing the intraplanar superconductivity. Thus we are able to separate the effects of coupling from other properties that might affect the flux motion. Our results directly show the relationship between lattice spacing, effective-mass anisotropy, and the irreversibility line in $Bi_2Sr_2CaCu_2O_{8+\delta}$. Our results also demonstrate that an application of 2.5 GPa pressure causes a four-fold decrease in the effective-mass anisotropy.**

Keywords— **pressure effects, flux dynamics, irreversibility line, High-T_c superconductor.**

I. Introduction

CRYSTALLINE anisotropy in the high-T_c superconductors is known to have profound effects on vortex topology and dynamics. Early theoretical studies predicted a crossover in the H-T plane from 3-D vortex lines to 2-D pancakes for highly anisotropic superconductors such as $Bi_2Sr_2CaCu_2O_{8+\delta}$. [1]. Such predictions have been verified experimentally by magnetization [2] and muon-spin rotation [3] studies, and, most recently, by pressure-induced changes in the irreversibility line, H_{irr} [4].

In addition to the unusually large anisotropy of $Bi_2Sr_2CaCu_2O_{8+\delta}$, numerous studies have now confirmed that critical currents in this system are a result of surface barriers rather than pinning centers in the bulk of the material [5]. Surface barriers result from the superposition of two forces: (1) the vortex's attraction to its image outside the sample and (2) the Lorentz force on the vortex from shielding currents which act to push the vortex into the bulk. The result is an asymmetric potential well for vortex entry with respect to vortex exit, which gives rise to a signature peak in the second harmonic of the *ac* susceptibility. A dimensional crossover from 3-D vortex line to 2-D pancake will occur when intraplanar repulsive forces between vortices dominate the interplanar Josephson coupling. Thus, 2-D behaviour is expected at high fields, where the density of vortices is large, and low temperatures, where superconducting coherence lengths are small. The height of the surface barrier depends upon the vortex state in the bulk [6]. Highly mobile 2-D pancakes are easily displaced in the bulk, which results in low barriers of entry; a rigid vortex lattice will create a relatively large barrier. To understand flux dynamics in $Bi_2Sr_2CaCu_2O_{8+\delta}$, and to ultimately control it, the influence of crystalline anisotropy on surface barriers requires investigation.

The effects of anisotropy and surface pinning are quite relevant to the transport properties of Bi-2223 tapes. In several studies, these tapes have been shown to exhibit 3-D rather than the expected 2-D scaling of their I-V curves, even at low temperatures[7]. This is attributed to the dominant character of the transport current carried in the grain boundaries, around individual superconducting grains. This surprising result is obtained because of the strong effect of pinning by surface barriers[5]. Furthermore, these authors have shown that the efficiency of the surface barriers is enhanced as the effective anisotropy of the materials composing the tapes decreases. Thus, a temperature-dependent effective anisotropy is attributed to determine the field at which the ordered vortex lattice is destroyed (order-disorder transition) in Bi-2223 tapes. These measurements and others like them make a clear case that the relationship between crystalline anistropy and surface barriers merits further investigation. Furthermore, purposeful altering of the anisotropy is desireable for engineering superconducting materials more suitable for high-current-carrying applications.

Previous studies of the role of anisotropy have shown shifts of the irreversibility and melting lines in oxygen-reduced $Bi_2Sr_2CaCu_2O_{8+\delta}$ [8], [9]. Oxygen annealing simultaneously produces these four physical changes in the sample: (1) the c -axis lattice spacing, (2) T_c, (3) the in-plane penetration depth, λ_{ab}, and (4) the density of pinning sites. A typical annealing study achieves a reduction in the c -axis lattice parameter of roughly 8 pm, a 0.3% change, at the cost of altering T_c by 20% or more [9], [10]. Not unrelated, is the fact that λ_{ab} at zero Kelvin has been shown to vary with oxygen doping, from 210 nm to 305 nm [10]. At low temperatures, the situation is further complicated by the influence of bulk pinning. Thus, in a doping study, the effects of interplanar separation, penetration depth, and pinning site density on the flux dynamics are all intermingled. This problem is partially addressed in a study by Tamegai *et al.*[11], which reports shifts in the melting line with the application of pressure. To better understand the irreversible flux motion, it is necessary to deconvolve these

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phenomena.

In this paper, we present the results of a study in which we directly investigate the effect of varying the interplanar spacing on the irreversibility line. This is shown to increase the interlayer coupling, while only negligibly changing the intraplanar superconductivity. In our study, the application of pressures up to 2.5 GPa decreases the c -axis by 50 pm (a factor of 3 greater than the change in either the a or b -axis). H_{irr} is increased by a factor of 10 at high temperatures; T_c is only changed by 4%; and λ_{ab}(T) is only marginally altered. As a result, we are able to show clear evidence of a 3-D to 2-D crossover in the flux dynamics and demonstrate a significant pressure-induced change in the anisotropy parameter.

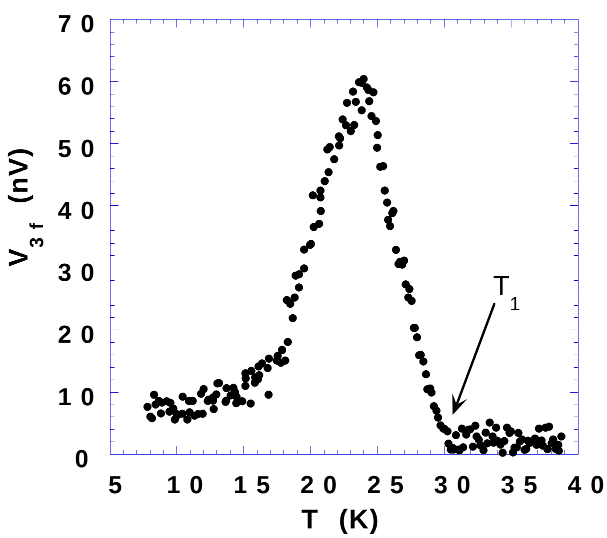

Fig. 1. The third harmonic peak in $Bi_2Sr_2CaCu_2O_8$ when there is no applied pressure and the applied field is 3.0 T.

II. Experimental Details

The $Bi_2Sr_2CaCu_2O_{8+\delta}$ single crystal used in this study was grown by a self-flux technique using a stoichiometric ratio (Bi:Sr:Ca:Cu=2:2:1:2) of cations [12]. The crystal shape is that of a platelet, with dimensions 200 × 200 × 50 μm^3 and a T_c of 86.3 K. Quasi-hydrostatic pressure is applied to the sample using a diamond anvil cell with a 4:1 methyl-ethyl alcohol solution as the pressure-transmitting medium. The pressure is applied and measured at room temperature and a calibration is used to determine the pressure at low temperatures to within an uncertainty of ±0.3 GPa. In this way, we obtain a linear increase in T_c from 86 K at 0 GPa to 90 K at 2.5 GPa [4].

The irreversible flux motion is detected by measuring the second and third harmonics of the *ac* susceptibility with primary and secondary coils wound around the diamond facets. Both the *ac*- and *dc*-magnetic fields are applied parallel to the c -axis, which is also parallel to the cylinder axis of the pressure cell. The *ac*-field amplitude is 0.5 mT, and the excitation frequencies used are 360 Hz and 3.7 kHz. Details of this technique and of the diamond anvil cell are given in [13] and [14].

In our experiment, pressure and *dc*-magnetic field are held constant while we measure the second and third harmonic of the *ac* susceptibility as a function of temperature. The generation of a peak in the third harmonic is a well-known response in type-II superconductors and is due to irreversible fluxoid motion [13]. We use the onset of this peak (see Fig. 1) to construct the irreversibility line, $H_{irr}(T)$.

III. Results

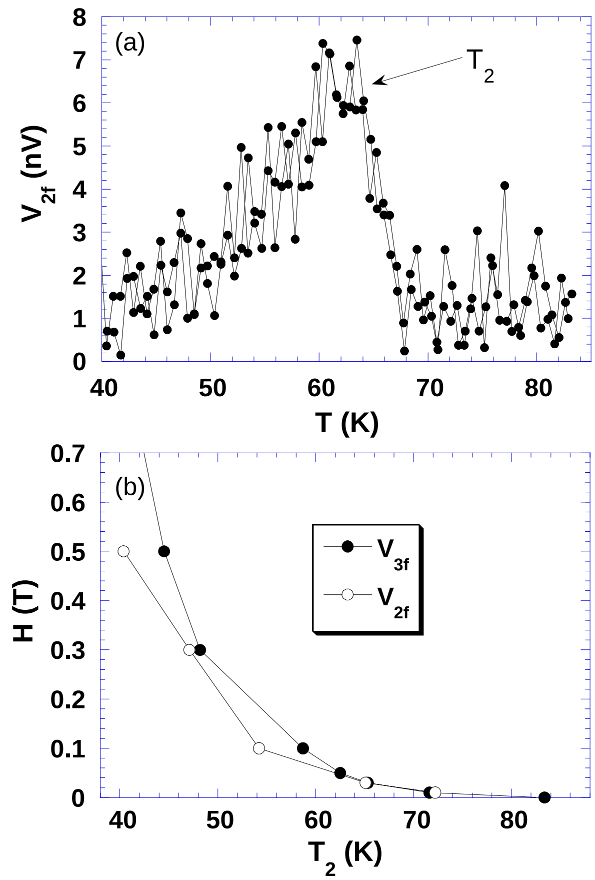

Fig. 2. The peak in the second harmonic of the *ac* susceptibility. (a) H=0.03 T, P=1.5 GPa and f=360 Hz (b) Field versus peak temperature, T_2, for the second and third harmonic peaks.

The nonlinear response due to irreversible flux motion in the superconductor is shown in Figs. 1, 2, and 3. In Fig. 1, the temperature-dependent peak in the third harmonic voltage signals the onset of a non-zero critical current, J_c. As described above, the simultaneous occurance of a peak in the second harmonic voltage is an indicator that surface barriers are contributing to the irreversible flux motion. We measure such a peak (see Fig. 2a) and show in Fig. 2b that its peak temperature, T_2, follows that of the peak temperature of the third harmonic voltage. We also note the height of the peak decreases monotonically with increasing field and falls below the sensitivity of our experiment at 0.5 T.

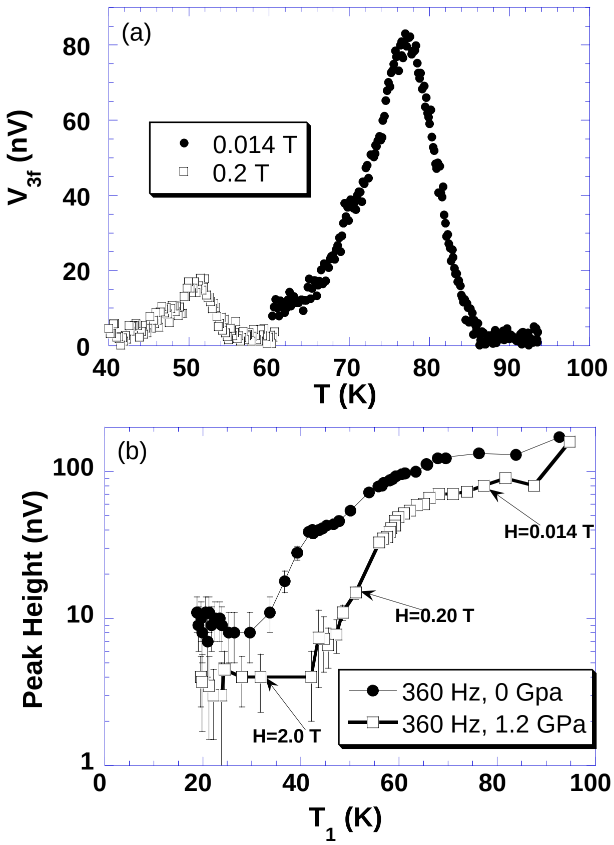

Fig. 3. The effect of applied field on peak height. (a) third harmonic peak for H=0.014 T and H=0.2 T (both peaks for P=1.5 GPa and f=360 Hz) (b) Peak height versus T_1 as the applied field is increased from 0 to 10 T. The applied field is increasing logarithmically from right to left as as can be seen from the labeling of the three datum points with their corresponding field.

Our experiment has higher sensitivity to third harmonic voltages [13] and we are able to easily measure peaks up to fields of 10 T, as shown in Fig. 3. As in the case of the V_{2f} measurement, the peak height decreases with increasing field or equivalently, decreasing irreversibility temperature. Fig. 3b illustrates the rapid reduction of the peak height, which levels off at low temperatures and high fields. This is discussed below as a consequence of the 3-D to 2-D vortex transition. The irreversibility line itself is defined by the locus of points determined by H and the onset temperature T_1 of the third harmonic peak (see Fig. 4). Fig. 4 shows an exponential decrease in the irreversibility field with temperature at high fields, and a crossover in the pressure and temperature dependence of H_{irr} near 50 mT.

IV. Discussion

There is considerable evidence that the irreversible flux motion in $Bi_2Sr_2CaCu_2O_{8+\delta}$ is determined by surface barriers [5]. The presence of the peak in the second harmonic voltage and the exponential temperature dependence of H_{irr} indicate that this is the case for our sample over a wide range of temperatures and fields. Thus we conclude that the irreversibility-line data are not indicative of a bulk transition in the sample.

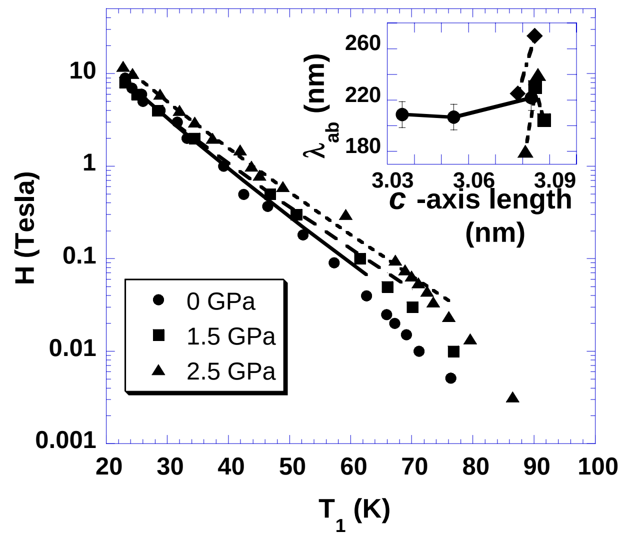

Fig. 4. H_{irr} at various pressures. At high fields the data show an exponential dependence which is expected for vortex pancakes penetrating the surface barrier. The inset shows a comparison of the change in λ_{ab} with c - axis for pressure-induced changes (circles) and oxygen-doping-induced changes: squares:[10], triangles:[19], diamonds:[20]. For our data, the c - axis is calculated from the pressure and the elastic moduli[17], and for the other data, from correlations between T_c, oxygen deficiency, and the c - axis spacing[21].

Burlachkov *et al.*[15] have developed a theoretical description for an irreversibility line determined by surface barriers. At low temperatures, the essential assumption is that the irreversible behavior is a result of vortex pancakes penetrating surface barriers. For high fields, much larger than the first penetration field ($H \gg H_P \approx 15$ mT) and $T > T_o$ (defined below), the irreversibility field assumes an exponential form,

$$H_{irr} \approx H_{c2}(T_o/2T)exp(-2T/T_o), \tag{1}$$

$$T_o = \frac{\phi_0^2 d}{(4\pi\lambda_{ab})^2 ln(t/t_o)}, \tag{2}$$

H_{c2} is the upper critical field, ϕ_0 is the fluxon, d is the interlayer spacing, and t and t_o are time scales related to the rate of flux creep over the surface barrier [16]. Here we equate the fractional change in the interlayer spacing with that of the c -axis obtained from compressibility data [17]. Then, we are able to determine T_o by fitting our data to Eq. (1) as shown in Fig. 4. For 0 GPa, 1.5 GPa, and 2.5 GPa, we obtain for T_o values of 20.6 K, 23.5 K, and 22.9 K, respectively ($\pm$ 2 K). A constant value of $H_{c2} \approx 180T$ is used here, though we obtain similar values of T_o over a range of reasonable, constant values for H_{c2} ($50T < H_{c2} < 250T$). The 0 GPa and the 1.5 GPa data are indistinguishable while the irreversibility line at 2.5 GPa is shifted to slightly higher temperatures. The most noteable

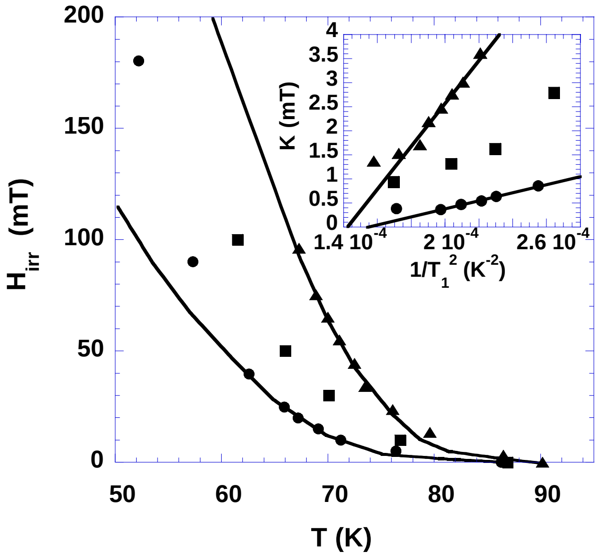

Fig. 5. Fit to the high-temperature data for pressures of 0 GPa (circles), 1.5 GPa (squares) and 2.5 GPa (triangles). The linear dependence seen in the inset is that expected for individual vortex lines penetrating the surface barrier, and the deviation from this fit at high temperatures is observed for applied fields close to H_{c1}.

feature is that the measured range of T_o values corresponds to a variation in λ_{ab}(T) of only 15 nm (see Fig. 4 inset). This indicates that the pressure has little effect on the penetration depth. (Here we have taken $ln(t/t_o)$ to be 30 as in [15].) This finding contrasts sharply with the results obtained in oxygen-doping experiments where the c-axis is changed very little, while λ_{ab} (as measured by magnetic susceptibility) is altered by 50 nm.

Thus far, we have focussed only on surface-barrier penetration as the mechanism to explain the irreversibility line. There are other models that we have considered, which are rooted in bulk properties and which predict a power-law dependence for the irreversibility line:

$$H_{irr} = H_0(1-(T/T_c)^n)^\alpha. \tag{3}$$

The above result holds for an irreversibility line delimiting a flux-lattice-melting transition (n = 1, $\alpha \leq 2$) [8], a Bose-glass transition (n = 1, α = 2 or 4/3) [23], [24], or a bulk-interplanar-decoupling transition of the vortices (n = -1, α = 1) [8]. Our data can be represented by these models only for large values of the exponent (α = 7.4 for T < 60 K and α = 3.5 for T > 70 K) or for unphysically large values of the scaling fields H_0. This is similar to results obtained by Schilling and coworkers [2].

At high temperatures, we expect, as discussed above, to see the effect of interplanar coupling on the vortex dynamics. In contrast to the low-temperature result, these data exhibit a significant pressure effect. Thus, we are led to conclude that this stiffening of the irreversibility line observed above 60 K is due to the onset of 3-D coupling between the vortices. This warrants that the data be analyzed in terms of a model based on the penetration of the surface barrier by individual 3-D fluxoids.

For this case, the results of Burlachkov *et al.* indicate that the irreversibility line is described by the following expression [15]:

$$\frac{H_{irr}}{Z^2(T)ln^3(H_{c2}/H_{irr})} \approx \frac{\pi}{256\gamma}\frac{\phi_0 T_o^2}{d^2}\frac{1}{T^2} \tag{4}$$

where $\gamma = (m_c/m_{ab})^{1/2} = \lambda_c/\lambda_{ab}$ is the effective-mass-anisotropy parameter, and $H_{c2}(T)$ is linear with a slope of -2.7 T/K [22]. $Z(T) = \lambda_{ab}^2(0)/\lambda_{ab}^2(T)$ is the temperature dependence of the penetration depth, taken from the data of Waldmann *et al.* [20] In Fig. 5 we show the data and fits, and in the inset we linearize the data by plotting the left-hand side of Eq. 4 (K in the Fig.) *vs.* 1/T^2. At 0 GPa the data show a linear dependence for $10 < H < 40$ mT and $62.6 < T_1 < 71$ K. Not enough data were measured at 1.5 GPa to justify a fit, but the increase in slope is apparent. At 2.5 GPa the slope continues to increase, with the data showing a linear dependence for $24 < H < 96$ mT and $67 < T_1 < 76$ K. As demonstrated by the low-temperature data, the pressure does not significantly alter λ_{ab}. Thus, all physical quantities in (4) are constant with respect to pressure, except for the anisotropy parameter. Furthermore, the increase in slope is due to a pressure-induced decrease in the effective-mass anisotropy by a factor of four. We have now shown evidence for a 3-D to 2-D vortex transition based on theoretical fits to the irreversibility line data and from the rapid suppression of the peak in the third harmonic as seen in Fig. 3b.

V. Conclusions

In total, the results that we present show that even modest changes in the c -axis lead to dramatic effects on flux-line formation. We observe that the applied pressure seems to have little influence on the superconducting order parameter (as evidenced by the insensitivity of λ_{ab} and of T_c to pressure). By contrast, the application of pressure decreases the anisotropy and increases the energy needed to bend an individual vortex line. Thus, we demonstrate the importance of interplanar spacing on the formation of flux lines.

Our experiment probes the superconducting properties in a very different manner than is done in doping studies. In the pressure experiments (up to our maximum pressure of 2.5 GPa), the intraplanar superconductivity seems to be relatively unchanged, while the coupling between planes is strongly affected. This contrasts to doping experiments where the major effect seems to be to alter the superconducting order parameter, while causing only modest changes in interplanar spacing. Doping does effect the anisotropy, but mainly by changing the magnetic penetration depth.

We have shown that the application of pressure clearly exposes a dimensional crossover from 3-D vortex lines to 2-D pancakes in $Bi_2Sr_2CaCu_2O_{8+\delta}$. The crossover is also qualitatively evident from the decrease in the height of the third harmonic peak which reflects the diminishing surface-barrier energy as the applied field is increased. Finally, a peak in the second harmonic of the *ac* susceptibility provides additional verification that surface barriers are a significant source of irreversible flux motion.

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