Pressure Dependence of Flux Dynamics in High Temperature Superconductors[1]

M. P. Raphael*, M. E. Reeves†,‡, E. F. Skelton‡, C. Kendziora‡

*Catholic University of America
Washington, DC 20032
†The George Washington University
Washington, DC 20052
‡Naval Research Laboratory
Washington, DC 20375

Abstract.
One of the important problems of high-temperature superconductivity is to understand and ultimately to control fluxoid motion. We will describe a new technique for measuring the pressure dependence of T_c in a diamond anvil cell by the third harmonic of the ac susceptibility. It requires no background subtraction and allows the use of gasket materials made from hardened steels. More significantly, the third harmonic indicates the onset of irreversible (with respect to changes in applied magnetic field) flux motion. Thus we are able to simultaneously apply high (up to 10 GPa) pressures and high (up to 10 T) magnetic fields to study the effect of changes in interplanar coupling on the motion of flux. In other reported studies, the interplanar coupling has been adjusted by chemical doping which introduces defects (or pinning sites). By contrast, we can directly change the interplanar spacing without introducing defects. Thus, the effects of coupling can be separated from those of pinning. We will present results which show significant pressure induced shifts in the irreversibility line in $YBa_2Cu_3O_{7-\delta}$ and $Bi_2Sr_2CaCu_2O_8$

INTRODUCTION

Since the discovery of high temperature superconductivity, the dynamics of flux motion has posed a major challenge to the application of these materials for use in high magnetic fields. [1] Early on, Nelson realized the important role played by reduced dimensionality in the crystal structure. [2] Further theoretical work by Fisher has revealed the possibility of a rich structure of phases in the H-T plane, encompassing the phenomena of flux lattice melting from a lattice or glass to a gas or liquid. [3] These developments have shifted the focus of research to

1) This work is sponsored by the Office of Naval Research and DARPA. We acknowledge helpful discussions with T. P. Devereaux, J. H. Claassen, M. S. Osofsky, and R. J. Soulen, Jr.

the physics of the properties of the fluxoids as a model system for a 2-d gas of bosons. [4–6] In this view, the weaker the coupling of fluxoids between planes, the more 2-d and Bose-gas-like will be the observed properties. Thus, of all the HTS materials studied, the most interesting is $Bi_2Sr_2CaCu_2O_{8+\delta}$ with its extraordinarily high anisotropy. [7] Recent experimental work on $Bi_2Sr_2CaCu_2O_8$ has revealed the distinction between surface and bulk effects, indicating the ranges of field and temperature over which 2-d rather than 3-d dynamics dominates. [8] This has been essential for illuminating the complex nature of the mixed-state phase diagram in this material. The importance of anisotropy underscores the need to quantify the effect of changes in the crystal structure (e.g. c -axis lattice spacing) with the observed properties of the flux motion. Several studies have shown shifts of the irreversibility and melting lines in $Bi_2Sr_2CaCu_2O_{8+\delta}$ by oxygen-reduction-induced changes in the c -axis lattice spacing. [9,10] In these and similar experiments, it has been shown that increasing the interplanar spacing strongly affects the flux motion by reducing the dimensionality of the system of fluxoids from 3-d to 2-d. However, in all experiments where atoms are added to or removed from the crystal structure, the defect density and hence the number of pinning sites must necessarily change. This effect cannot be discounted when analyzing the results of these experiments. Also, doping experiments change the anisotropy ratio by modifying properties of the superconducting condensate. A more direct means of determining the effect of lattice spacing on the anisotropy is desired, which, at the same time, maintains the underlying pinning structure in the superconductor. This would allow the separation of the effects of pinning on defect sites from those of anisotropy, and hence provide needed input to theoretical models for predicting the melting temperature of the flux matter. [11]

The experiment which we will describe addresses this question by the application of quasi-hydrostatic pressure to change the lattice spacing. We simultaneously monitor the flux motion by measurements of the third harmonic of the ac susceptibility. In the case of $YBa_2Cu_3O_{7-\delta}$ and even more so in $Bi_2Sr_2CaCu_2O_8$, the c -axis shows the largest compression. The results show that the irreversibility line in both materials shifts to higher temperatures as the lattice is compressed. In the case of $Bi_2Sr_2CaCu_2O_8$, this corresponds to an elevation in the temperature at which the interplanar coupling between the fluxoids ceases to be significant. Thus, the thermal energy required to effect flux motion is shown to depend very sensitively on the interplanar spacing.

EXPERIMENT

In our technique, quasi-hydrostatic pressure is applied to the sample using a diamond anvil cell. Primary and secondary coils, wound around the diamond facets, are used for the ac-susceptibility measurement with both the ac- and dc-magnetic fields applied parallel to the c -axis. Typical ac-field amplitudes of 0.5-1.0 mT are used at a frequency between 3 and 5 kHz. 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. Details of this technique and of the diamond anvil cell are given in references [12] and [13]. The $Bi_2Sr_2CaCu_2O_8$ 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. [14] The $YBa_2Cu_3O_{7-\delta}$ sample was grown using the a self-decanting flux method as described in reference [15]. The $YBa_2Cu_3O_{7-\delta}$ sample has a T_c of 92.0 K and the $Bi_2Sr_2CaCu_2O_8$ sample has a T_c of 86.3 K. Figure 1 shows a V_{3f} vs T scan for a $YBa_2Cu_3O_{7-\delta}$ sample of a typical size, $200 \times 200 \times 50\ \mu\ m^3$. Despite the small sample size, the signal to noise ratio is excellent and there is no background subtraction necessary. [12] Upon cooling, irreversible flux motion gives rise to a nonlinear response in the superconductor at an onset temperature, T_1 (see Figure 1). The irreversibility line is defined to be the locus of points determined by H and T_1. As the temperature is lowered further, the energies associated with pinning and the formation of a flux lattice begin to dominate the dynamics and the nonlinear response diminishes. In $Bi_2Sr_2CaCu_2O_8$, it has been shown that over a large portion of the phase diagram the vortex dynamics is dominated by surface barriers. The surface barrier energy increases abrubtly as the sample is cooled and the 2-d vortices begin to couple between the planes. This gives rise to the sharp onset of the V_{3f} signal that we observe. In addition, surface barriers also give rise to a peak in the second harmonic of the ac susceptibilty, which we observe for dc fields less the 500 mT. [8]

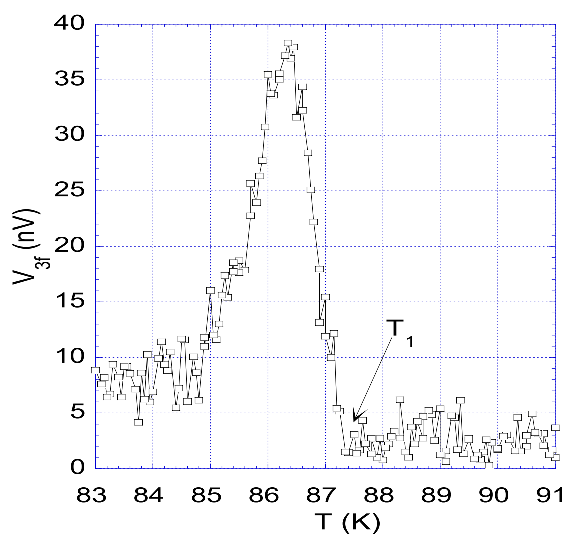

FIGURE 1. Third harmonic peak of a $YBa_2Cu_3O_{7-\delta}$ sample at 4 GPa and with an applied field of 2.5 Tesla.

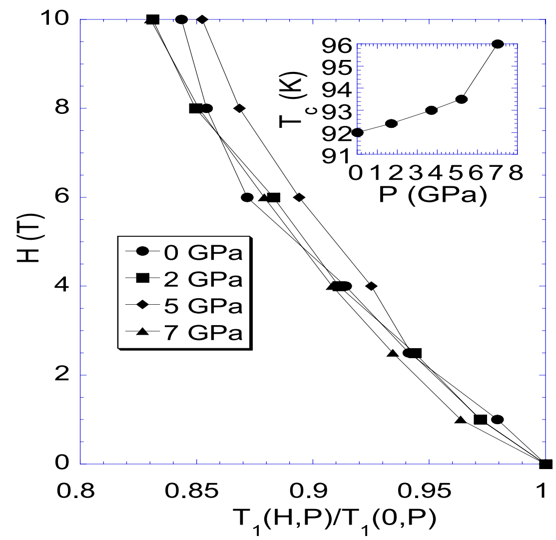

FIGURE 2. $YBa_2Cu_3O_{7-\delta}$ irreversibility lines at various pressures scaled by T_c(P).

RESULTS AND DISCUSSION

Figure 2 shows the scaled irreversibility lines of the $YBa_2Cu_3O_{7-\delta}$ sample at various pressures. Each line is scaled by T_c(P) (see inset) so that the relative changes are more easily identified. The largest change in the irreversibility line occurs at 5 GPa where it moves up significantly in field. At 7 GPa it moves back down, even below the 0 GPa data for most fields. Surface barriers in $YBa_2Cu_3O_{7-\delta}$ appear to be strongly influenced by twinning and oxygen content. [16,17] However, the observation of these effects is at fields well below 1 Tesla, so that pinning is expected to be the dominant cause of the nonlinear response for the field ranges shown in Figure 2.

The situation is quite different in $Bi_2Sr_2CaCu_2O_8$, for which Burlachkov *et al.* have considered the case in which the irreversibility line is governed by surface barriers. [18] For fields much greater than the penetration field, H_p, they derive an exponential form for the irreversibility field,

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

$$T_o = \frac{\phi_o^2 d}{(4\pi\lambda)^2 ln(t/t_o)} \tag{2}$$

where η is on the order of one, ϕ_o is the fluxon, λ is the penetration depth, d is the interlayer spacing, and t and t_o are time scales related to the rate of flux creep through the surface barrier. [19] In the high field regime ($H > 1T$)

we are able to determine T_o by fitting our data to equation (1) using reasonable values for H_{c2} ($50T < H_{c2} < 250T$) or equally well by the approximation $H_{irr} \approx H_{c2}(T_o/2T)exp(-2T/T_o)$, valid for $T > T_o$. Fits using the latter equation are shown in Figure 3. 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 (± 2 K). The 0 GPa and the 1.5 GPa data merge while H_{irr} at 2.5 GPa is shifted to slightly higher fields.

At about 1 Tesla there is a crossover to a low field regime where the irreversibility line becomes strongly pressure dependent. While this crossover has been previously observed [20], these measurements are the first to show that the two regimes have very different dependencies on the interlayer coupling. We note that our low field data resemble the T_x line measured in reference [8] which separates more ordered vortex phases from that of the pancake gas. The correspondence between the two lines indicates that the increased coupling caused by pressure serves to aid in the transition to a 3-d phase. We note that our results at low fields are consistent with the observed shift in the irreversibility and melting lines caused by changes in oxygen content. [9,10,21] However, the changes in the c -axis parameter that we achieve with pressure are much greater than those caused by oxygen doping. In addition, oxygen doping significantly alters the superconducting condensate, changing T_c from 60K to 90K. On the other hand, by applying a pressure of 2.5 GPa to $Bi_2Sr_2CaCu_2O_8$, the c -axis parameter is changed by 0.05 nm (versus 0.01 nm in a typical doping experiment) with only a 4 K increase in T_c. [10,22,23]

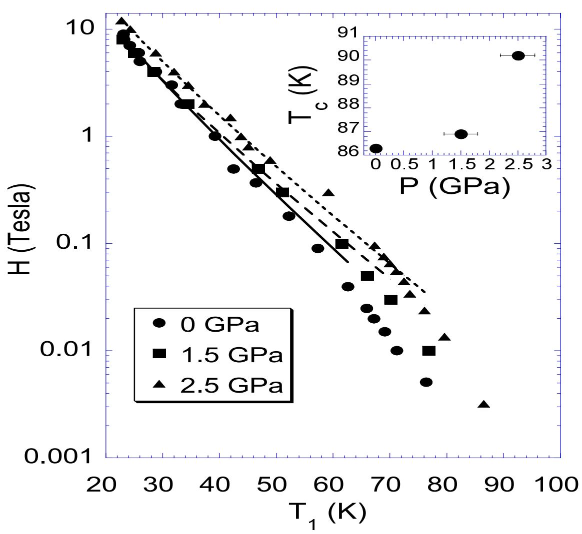

FIGURE 3. $Bi_2Sr_2CaCu_2O_8$ irreversibility lines at various pressures. The data are fit by an exponential function at high fields. The inset shows T_c as a function of pressure.

CONCLUSIONS

By measuring the third harmonic of the ac susceptibility, we have shown that pressure affects the irreversibility line significantly. The results for $YBa_2Cu_3O_{7-\delta}$ demonstrate that an increase in the interplanar coupling causes a shift in the depinning line to higher temperatures. In $Bi_2Sr_2CaCu_2O_8$, the results at high fields are consistent with surface barriers dominating the vortex dynamics. In this material too, the effect of decreasing the interplanar spacing is to shift the irreversibility line to higher temperatures.

REFERENCES

1. Y. Yeshurun and A.P. Malozemoff, *Phys. Rev. Lett.* **60**, 2202 (1988).
2. David R. Nelson, *Phys. Rev. Lett.* **60**, 1973 (1988).
3. M.P.A. Fisher, *Phys. Rev. Lett.* **62**, 1415 (1989).
4. D.R. Nelson and H.S. Seung, *Phys. Rev. B* **39**, 9153 (1989).
5. M.P.A. Fisher, *et al.*, *Phys. Rev. B* **40**, 546 (1989).
6. G. Blatter, *et al.*, *Rev. Mod. Phys.* **66**, 1125 (1994).
7. D.A. Farrell *et al.*, *Phys. Rev. Lett.* **63**, 782 (1989).
8. D.T. Fuchs, *Phys. Rev. Lett.* **80**, 4971 (1998).
9. B. Khaykovich, *Phys. Rev. Lett.* **76**, 2555 (1996).
10. K. Kishio, *et al.*, *Proceedings of the 7th International Workshop on Critical Currents in Superconductors* edited by H.W. Weber (World Scientific, Singapore, 1994), p.339.
11. Zhi-Xiong Cai, *et al.*, *Physica C* **299**, 91 (1998).
12. M.P. Raphael, M.E. Reeves, E.F. Skelton, *Rev. Sci. Inst.* **80**, 4971 (1998).
13. C.C. Kim, *et al.*, *Rev. Sci. Inst.* **65**, 992 (1994).
14. C. Kendziora, *et al. Phys. Rev. B* **45**, 13025 (1992).
15. T. A. Vanderah, *et al.*, *Journal of Crystal Growth* **118**, 385 (1992).
16. R. Liang, *et al.*, *Phys. Rev. B* **50**, 4212 (1994).
17. M. Konczykowski, *et al.*, *Phys. Rev. B* **43**, 13707 (1991).
18. L. Burlachkov *et al.*, *et al.*, *Phys. Rev. B* **50**, 16770 (1994).
19. V. N. Kopylov, *et al.*, *Physica C* **170**, 291 (1990).
20. A. Schilling, *et al.*, *Phys. Rev. Lett.* **71**, 1899 (1993).
21. C. Bernhard, *et al.*, *Phys. Rev. B* **52**, R7050 (1995).
22. J. S. Olsen, *et al.*, *Physica Scripta* **44**, 211 (1991).
23. C. Kendziora, *et al.*, *Physica C* **257**, 74 (1996).