

Faculty of Engineering
Faculty of Engineering - Papers

University of Wollongong

Year 2003

Magnetic hysteresis and relaxation in
Bi2212 single crystals doped with Fe and
Pb

K. K. Uprety* J. Horvat† X. L. Wang‡
G. D. Gu** M. Ionescu†† H. K. Liu‡‡
S. X. Dou§ E. H. Brandt¶

*University of Wollongong

†University of Wollongong, jhorvat@uow.edu.au

‡University of Wollongong, xiaolin@uow.edu.au

**Brookhaven National Laboratory, New York, USA

††University of Wollongong, mionescu@uow.edu.au

‡‡University of Wollongong, hua@uow.edu.au

§University of Wollongong, shi@uow.edu.au

¶Max-Planck Institut fur Metallforschung, Germany

This article was originally published as: Uprety, KK, Horvat, J, Wang, XL et al, Magnetic hysteresis and relaxation in Bi2212 single crystals doped with Fe and Pb, IEEE Transactions on Applied Superconductivity, June 2003, 13(2)3, 3770-3773. Copyright IEEE 2003.

This paper is posted at Research Online.

<http://ro.uow.edu.au/engpapers/33>

Magnetic Hysteresis and Relaxation in Bi2212 Single Crystals Doped With Fe and Pb

K. K. Uprety, J. Horvat, X. L. Wang, G. D. Gu, M. Ionescu, H. K. Liu, S. X. Dou, and E. H. Brandt

Abstract—Magnetic hysteresis and magnetic relaxation measurements have been performed to study vortex pinning behaviors for pure, Fe doped and heavily Pb doped Bi2212 single crystals. Unlike pure and Fe doped Bi2212 crystals, heavily Pb doped crystal showed strong vortex pinning behavior. We interpret the strong pinning in heavily Pb doped Bi2212 single crystals as arising from the improved Josephson coupling in Bi2212 single crystal after heavy Pb doping. In heavily Pb doped single Bi2212 crystals, $H_{\text{dis}}(T)$ was observed to decrease with increasing T . Here, $H_{\text{dis}}(T)$ is an order-disorder field that separates a weakly elastically disordered vortex lattice from a plastically disordered vortex solid. However, in pure and Fe doped Bi2212 single crystals, $H_{\text{dis}}(T)$ was observed to be temperature independent. We also report a significant shift of T_{CR} , a crossover temperature separating two pinning regimes, toward higher temperatures with heavy Pb doping of Bi2212 single crystals. On the other hand T_{CR} did not shift with Fe doping of Bi2212 single crystals. It is argued that the temperature dependence of $H_{\text{dis}}(T)$ and the shift of T_{CR} in heavily Pb doped Bi2212 crystals was related to the enhanced c -axis conductivity caused by the Pb situated between the CuO_2 layers and imposing a 3D characteristic on the vortex lattice.

Index Terms—Bi2212 single crystal, crossover temperature, iron, lead, order-disorder field.

I. INTRODUCTION

IN layered superconductors, the vortices for an applied field parallel to the c -axis are described by pancake vortices. For less anisotropic materials, such as $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ (Y123), the pancake vortices are coupled through Josephson currents forming 3D vortex lines. However, for the large anisotropic materials, such as $\text{Bi}_2\text{Si}_2\text{CaCu}_2\text{O}_{8+\delta}$ (Bi2212), the pancake vortices are decoupled due to thermal energy. The decoupled pancake vortices move via Lorentz forces, producing dissipation. The dissipation is one of the serious problems in bringing these materials into technical applications. However, the dissipation can be reduced by improving the vortex pinning and this can be done by introducing pinning centres or improving the Josephson coupling of the pancake vortices.

In this paper, we study the vortex pinning behavior in Bi2212 single crystals doped with Pb and Fe. In heavily Pb doped Bi2212 crystals, it is known that Pb is between CuO_2 planes and thus reduces the anisotropy parameter [1], [2]. Our

magnetic hysteresis and magnetic relaxation results showed a strong vortex pinning in heavily Pb doped Bi2212 single crystals. The improved pinning in Bi2212 single crystals with heavy Pb doping opens up a potential technological application of these materials in the industry. Based on our observed experimental results, we have proposed that strong pinning behavior in heavily Pb doped Bi2212 single crystals came from the improved Josephson coupling of 2D pancake vortices. We will also show that the vortex pinning in Bi2212 single crystals is not improved by Fe doping. In Fe doped Bi2212 single crystals, Fe substitutes into CuO_2 planes and does not change its anisotropy parameter [3].

II. EXPERIMENTAL PROCEDURES

The heavily Pb doped $\text{Bi}_{2-x}\text{Pb}_x\text{Sr}_2\text{CaCu}_2\text{O}_8$ crystal was grown by the self-flux method with the nominal Pb content $x = 0.34$ [4]. The size of the Pb doped single crystal was $0.71 \times 1.11 \times 0.038 \text{ mm}^3$, and the critical temperature T_c was 69 K. The critical temperature T_c of the crystal was obtained from the magnetic ac susceptibility measurement, with the frequency and amplitude of the excitation field of 117 Hz and 0.1 Oe, respectively. The Fe doped single crystals were prepared by using the floating zone method and the nominal Fe content in the $\text{Bi}_{2.1}\text{Sr}_{1.9}\text{Ca}_{1.0}(\text{Cu}_{1-y}\text{Fe}_y)\text{O}_8$ single crystals was $y = 0$ and 0.005 [5]. The sizes of the $y = 0$ and 0.005 single crystals were $1.95 \times 2.10 \times 0.116 \text{ mm}^3$ and $1.3 \times 2.5 \times 0.15 \text{ mm}^3$, respectively. The $y = 0$, and 0.005 crystals had $T_c = 88.5$ and 82.25 K, respectively. Here, $y = 0$ is a pure Bi2212 single crystal. Magnetic hysteresis loops and magnetic relaxation measurements were performed using Oxford Instruments Vibrating-Sample Magnetometer (VSM). In all measurements, the field H was applied parallel to the c -axis of the crystals.

In the hysteresis loop measurements recorded at different temperatures, the magnetic field was changed at a rate of 20 Oe/s, and the data were recorded at different temperatures.

During the magnetic relaxation measurements, the crystals were first zero-field-cooled from well above T_c and then stabilized at a fixed temperature T . A magnetic field H larger than the field used in the relaxation measurements by several times the field of full penetration was applied. The field was then lowered to the measuring field and the magnetic moment as a function of time was measured. The relaxation data were recorded at different fields and temperatures. In the experimental results, the experimental points of the first 100 seconds are not included because of uncertainty in the time that passed between the establishment of the field and the measurement of the first experimental point. The following relation has been used to obtain the normalized relaxation rate $S \equiv d \ln |M_{\text{in}}| / d \ln t$.

Manuscript received August 8, 2002. This work was supported by Australian Research Council, Australia.

K. K. Uprety, J. Horvat, X. L. Wang, M. Ionescu, H. K. Liu, and S. X. Dou are with Institute for Superconducting and Electronic Materials, University of Wollongong, Wollongong, NSW 2522, Australia (e-mail: kku01@uow.edu).

G. D. Gu is with Brookhaven National Laboratory, Upton, NY 11973 USA.

E. H. Brandt is with Max-Planck-Institut für Metallforschung, D-70506 Stuttgart, Germany.

Digital Object Identifier 10.1109/TASC.2003.812544

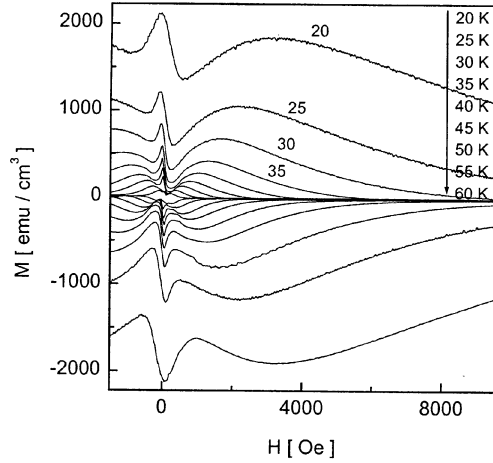


Fig. 1. The magnetic hysteresis loops for a heavily lead doped Bi2212 single crystal at temperatures $T = 20, 25, 30, 35, 40, 45, 50, 55,$ and 60 K.

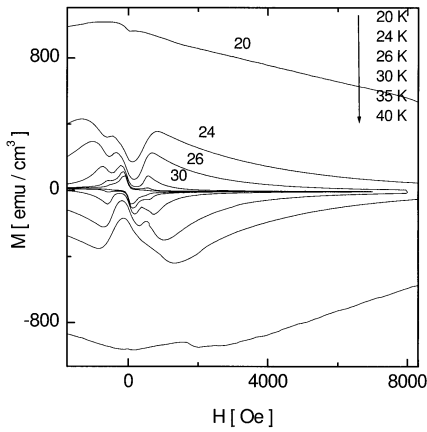


Fig. 2. The magnetic hysteresis curves for pure Bi2212 single crystals at temperatures $T = 20, 20, 24, 26, 28, 33, 40$ K.

III. EXPERIMENTAL RESULTS

Fig. 1 shows the second magnetization peak for heavily Pb doped Bi2212 single crystal. The peak is seen at all temperatures close to T_c . However, in pure ($y = 0$) and iron doped ($y = 0.005$) Bi2212 single crystals, the peak has appeared only between 20 and 40 K (see Figs. 2 and 3).

Fig. 4 shows dM/dH as a function of the applied field H for pure ($y = 0$) Bi2212 single crystals. The peak in dM/dH has occurred at an inflection point of the second peak in the hysteresis loop at a field $H = H_{\text{infl}}(T)$. We have interpreted $H_{\text{infl}}(T)$ as the order-disorder transition field H_{dis} . The temperature independence of $H_{\text{infl}}(T)$ was observed for pure and iron doped Bi2212 single crystals, whereas in heavily Pb doped single crystals, $H_{\text{infl}}(T)$ was observed to decrease with temperature (see Fig. 5).

The inset to Fig. 4 shows a sharp minimum in $S(H)$ at $H_{\text{infl}}(T)$, indicating two different flux creep processes before and after $H_{\text{infl}}(T)$. The relaxation data and hysteresis loop are also presented along with S .

Fig. 6 shows the normalized relaxation rate S as a function of temperature T for pure, Fe doped and heavily Pb doped Bi2212 single crystals. The peak in $S(T)$ has been proposed as T_{CR} , a

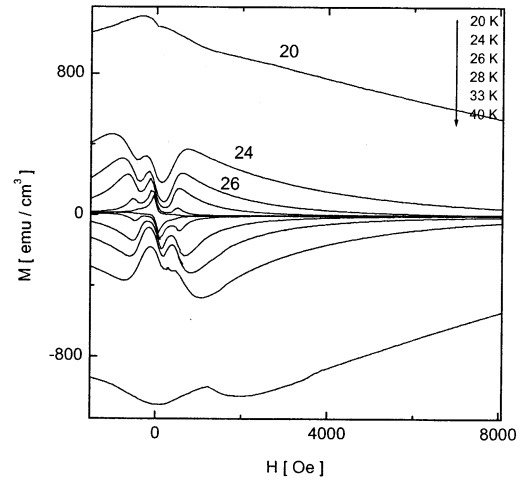


Fig. 3. The magnetic hysteresis curves for $\text{Bi}_{2.1}\text{Sr}_{1.9}\text{Ca}_{1.0}(\text{Cu}_{1-y}\text{Fe}_y)_2\text{O}_8$ single crystal with Fe concentration $y = 0.005$ at temperatures $T = 20, 20, 24, 26, 28, 33, 40$ K.

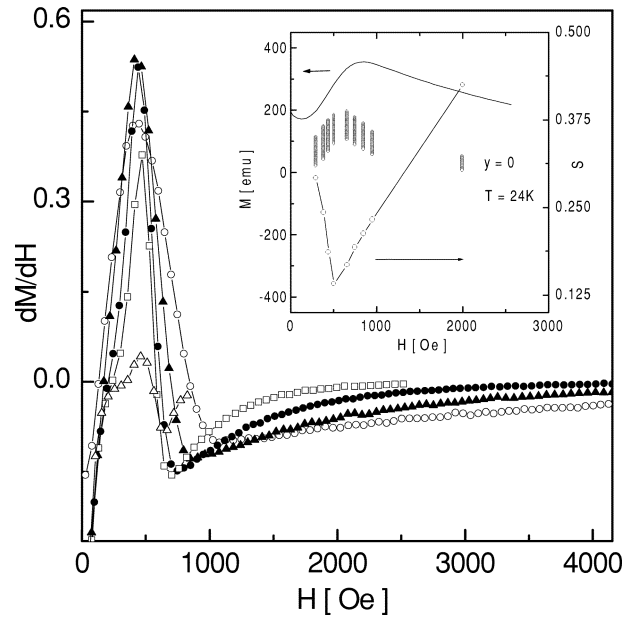


Fig. 4. dM/dH as a function of applied magnetic field H for pure Bi2212 single crystals. The inset shows the magnetization M as a function of applied field H measured at $T = 24$ K for pure Bi2212 single crystal. The small circles show the decay of the magnetization M with time t (relaxation between 100 and 3600 sec) at $T = 24$ K for this crystal. The normalized relaxation rate S is indicated by large open circles.

crossover temperature separating two pinning regimes [6], [7]. Fig. 6 shows the peak in $S(T)$ appears at $T = 19$ K for pure and Fe doped crystals. However, the peak in $S(T)$ for heavily Pb doped crystal was observed at $T = 35$ K (see inset of Fig. 6).

IV. DISCUSSION

The strong second magnetization peak, persisting close to T_c reflects improved vortex pinning in the heavily Pb doped Bi2212 crystal, see Fig. 1. A similar strong second peak has been reported in Y123 single crystals close to T_c [8]. Pure Bi2212 single crystal has a resistivity anisotropy parameter, $\gamma^2 = \rho_c/\rho_{ab} \approx 10^4 - 10^5$ at 100 K [1], [9]. Oxygen under-doped Bi2212 single crystal has $\gamma^2 \approx 10^5$, whereas

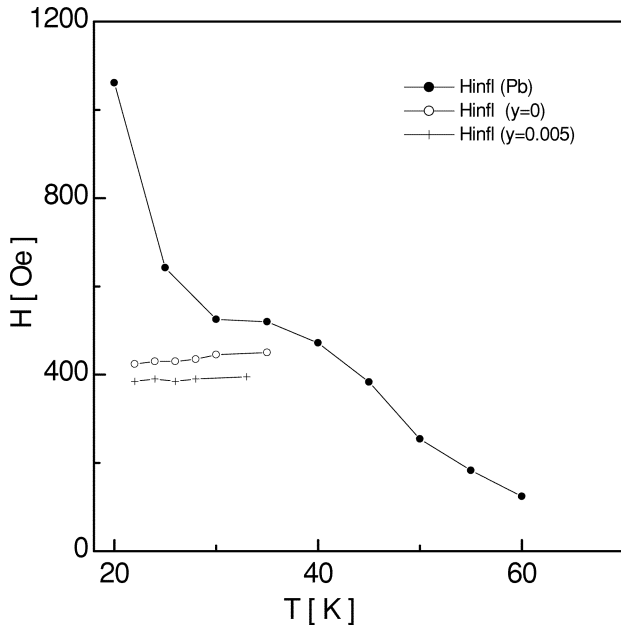


Fig. 5. The order-disorder transition field, $H_{\text{dis}}(T)$ as a function of temperatures for pure, Fe doped and heavily Pb doped Bi2212 single crystals.

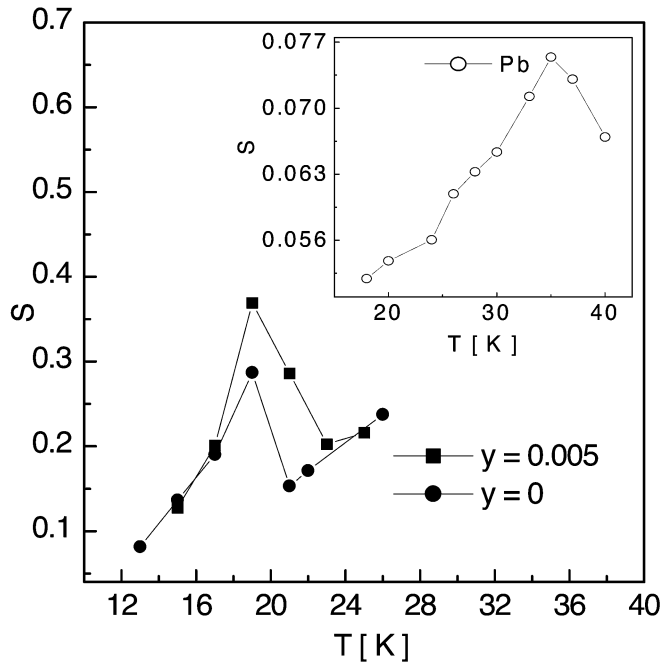


Fig. 6. Normalized relaxation rate vs temperatures for pure, Fe doped and heavily Pb doped Bi2212 single crystals. The relaxation are measured at $H = 620$ Oe for pure Bi2212 single crystal, at $H = 520$ Oe for iron doped crystal and at $H = 1200$ Oe for heavily Pb doped Bi2212 single crystal.

oxygen over-doped Bi2212 crystal has $\gamma^2 \approx 10^4$ at 100 K [9]. However, pure Y123 single crystal has $\gamma^2 \approx 7 - 30$ at 100 K [10]–[12]. This suggested that the strong pinning in Y123 can arise from the strong coupling of 2D pancake vortices. Furthermore, the H-T phase diagram of Y123 shows the presence of 3D vortex line in wide range of fields and temperatures [13]. In heavily Pb doped single crystal, Motohashi *et al.* have reported c -axis conductivity that was one order of magnitude larger than in pure Bi2212 single crystals, due to a significant

reduction of anisotropy in the resistivity $\rho_c/\rho_{ab} \approx 10^3$ at 100 K [1]. Winkler have reported an increased Josephson interlayer coupling energy by 3.5 times in heavily Pb doped Bi2212 single crystal, as compared to pure Bi2212 single crystal [14]. The increased coupling energy enhances the layer coupling in heavily Pb doped single crystal, which thus aligns the pancake vortices into strongly coupled stacks that behave as 3D vortex lines, similar to the vortex lines in Y123. We therefore believe that the strong pinning in the heavily Pb doped single crystals originates from the enhanced c -axis conductivity. Figs. 2 and 3 show that the pinning is not improved in Bi2212 single crystal with Fe doping. In the Fe doped single crystals, point defects are reported to reside in the CuO_2 planes, since iron replaces Cu in the plane [3]. The c -axis conductivity is not improved with Fe doping in this crystal, and thus pancake coupling does not improve either.

In our previous paper, we have established that H_{infl} , which corresponds to the steepest change of the magnetization (inflection point) on the low field side of the second peak, may be interpreted as the order-disorder transition field, H_{dis} , for pure, Fe doped and heavily Pb doped Bi2212 single crystals [15]. Here, H_{dis} separates the weakly disordered vortex lattice from the strongly disordered entangled vortex lattice. In pure Bi2212 single crystals, we observed $H_{\text{dis}} \approx 420$ Oe independent of temperature up to $T = 40$ K (see Figs. 4 and 5). A similar result has also been confirmed by Hall probe measurements [16]. The normalized relaxation rate also shows a minimum at H_{dis} indicating two different creep processes in two different solid regimes (see inset to Fig. 3). In Fe doped Bi2212 single crystals, we observed the temperature independence of H_{dis} . Unlike the pure and Fe doped Bi2212 single crystals, in heavily Pb doped Bi2212 single crystals, we have observed temperature dependence of H_{dis} , see Fig. 5. Y123 also has temperature dependence of H_{dis} [8], [17]. Thus, it is believed that the temperature dependence of H_{dis} comes from 3D vortex behavior.

We also observed a significant shift of T_{CR} , the crossover temperature that separates two pinning regimes in heavily Pb doped Bi2212 single crystal (see inset of Fig. 6). A similar shift of T_{CR} toward higher temperature has been reported for ion irradiation of Bi2212 single crystal [7]. However, for Fe doped crystal, T_{CR} did not shift toward higher temperature (see Fig. 6). The improved c -axis coupling in the ion irradiated Bi2212 crystals has been interpreted as cause of the shift of T_{CR} toward higher temperature [6], [7]. It is believed that the improved c axis conductivity is responsible for the shift of T_{CR} in heavily Pb doped Bi2212 single crystal.

V. CONCLUSION

Magnetic hysteresis and magnetic relaxation measurements have been performed in pure, Fe doped and heavily Pb doped Bi2212 single crystals. In heavily Pb doped Bi2212 single crystal, strong second peak in the hysteresis loop up to the critical temperature T_c have been observed, whereas in pure and iron doped Bi2212 crystals the peak was observed between 20 and 40 K. We observed a decrease of the order-disorder transition field $H_{\text{dis}}(T)$ with increasing temperature in heavily Pb doped single crystals. The minimum observed in the field

dependent normalized relaxation rate $S(H)$ clearly shows two different flux creep processes above and below $H_{\text{dis}}(T)$, indicating two different regimes. In pure and Fe doped Bi2212 single crystals, $H_{\text{dis}}(T)$ was found to be field independent. In heavily Pb doped crystal, we observed a shift of T_{CR} toward higher temperatures. As for ion irradiated Bi2212 crystal, the enhanced c -axis coupling has been implicated in the shift of T_{CR} with heavy Pb doping of Bi2212 single crystals [7].

REFERENCES

- [1] T. Motohashi, Y. Nakayama, T. Fujita, K. Kitazawa, J. Shimoyama, and K. Kishio, *Phys. Rev. B*, vol. 59, p. 14 080, 1999.
- [2] Z. Hiroi, I. Chong, and M. Takano, *J. Solid State Chem*, vol. 138, p. 98, 1998.
- [3] B. vom Hedt, W. Lisseck, K. Westerholt, and H. Bach, *Phys. Rev. B*, vol. 49, p. 9898, 1994.
- [4] J. Horvat, X. L. Wang, and S. X. Dou, *Physica C*, vol. 324, p. 211, 1999.
- [5] G. D. Gu, G. J. Russell, and N. Koshizuka, *J. Crystal Growth*, vol. 137, p. 472, 1994.
- [6] K. K. Uprey, J. Horvat, X. L. Wang, M. Ionescu, H. K. Liu, and S. X. Dou, *Supercond Sci and Technol*, vol. 14, p. 479, 2001.
- [7] V. V. Metlushko, G. Guntherodt, I. N. Goncharov, A. Yu. Didyk, V. V. Moshchalkov, and Y. Bruynseraede, *Physica B*, vol. 194–196, p. 2219, 1994.
- [8] H. Küpfer, Th. Wolf, C. Lessing, A. A. Zhukov, X. Lançon, R. Meier-Hirmer, W. Schauer, and H. Wühl, *Phys. Rev. B*, vol. 58, p. 2886, 1998.
- [9] X. H. Chen, M. Yu, K. Q. Ruan, S. Y. Li, Z. Gui, G. C. Zhang, and L. Z. Cao, *Phys. Rev. B*, vol. 58, p. 14 219, 1998.
- [10] G. A. Shams, J. W. Cochrane, and G. J. Russel, *Physica C*, vol. 324, p. 243, 2001.
- [11] S. W. Tozer, A. W. Kleinsasser, T. Denney, D. Kaiser, and F. Holtberg, *Phys. Rev. Lett*, vol. 59, p. 1768, 1987.
- [12] T. A. Friedmann, M. W. Rabin, J. Giapintzakis, J. P. Rice, and D. M. Ginsberg, *Phys. Rev. B*, vol. 42, p. 6217, 1990.
- [13] G. Blatter, M. V. Feigel'man, V. B. Geshkenbein, A. I. Larkin, and V. M. Vinokur, *Rev. Mod. Phys*, vol. 66, p. 1125, 1994.
- [14] L. Winkeler, S. Sadewasser, B. Beschoten, H. Frank, F. Nouvertné, and G. Güntherodt, *Physica C*, vol. 265, p. 194, 1996.
- [15] K. K. Uprey, J. Horvat, X. L. Wang, M. Ionescu, H. K. Liu, S. X. Dou, and E. H. Brandt, *Phys. Rev. B*, vol. 65, p. 224 501, 2002.
- [16] B. Khaykovich, E. Zeldov, D. Majer, T. W. Li, P. H. Kes, and M. Konczykowski, *Phys. Rev. Lett*, vol. 76, p. 2555, 1996.
- [17] G. M. Mikitik and E. H. Brandt, *Phys. Rev. B*, vol. 64, p. 184 514, 2001.