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The vortex decoupling transition in Bi2212 crystals with columnar defects

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Abstract

Two $Bi_2Sr_2CaCu_2O_{8+\delta}$ single crystals were characterized, before and after irradiation with 200 MeV Ag ions under fluence of 5×10^{10} ions/cm^2. Columnar defects were produced along the *c*-axis direction in one crystal, and in a direction tilted by an angle of 30° with respect to the *c*-axis for the other crystal. The 3D–2D vortex decoupling lines were significantly shifted to higher temperatures, after irradiation of the crystals, for magnetic fields smaller than the matching value $B_\Phi \approx 1$ T. For $B > 3$ T the decoupling lines for the irradiated crystals tend smoothly to the same behavior observed in the original crystals, up to the maximum probed field of 5 T. Interestingly the vortex pinning by columnar defects was found to be almost independent of the applied magnetic field direction, as revealed by the width of magnetization loops.

Keywords: Vortex decoupling; Decoupling transition; Columnar defects; Bi2212 crystals

1. Introduction

It is well established [1,2] that large improvements of the critical current and considerable enlargement of the irreversibility region in the $H \times T$ plane, are obtained by introducing columnar defects (CDs) in samples of the high T_c superconductors. This is important not only from a technological viewpoint, but also because these results are related to rich novel properties of the vortex system [3]. One example [4] is the occurrence of the *lock-in* effect in an irradiated $ErBa_2Cu_3O_{7-\delta}$ crystal, when the direction of the applied magnetic field makes a small angle with the CDs lines.

A theory that predicts a Bose-Glass phase [5], well supported by experiments [6,7], has provided basic fundamental ideas to deal with the interaction of vortices localized near CDs. The fluctuations of Josephson-coupled pancake vortices, in layered superconductors containing CDs, has been investigated in a detailed theoretical study [8] that found an increased interlayer coupling, due to the suppression of thermal fluctuations of pinned pancakes. This leaded to the prediction of an upward shift of the decoupling line [9], relative to what is usually observed in pure systems. More recently a very interesting melting of *porous* vortex matter, consisting of ordered vortex crystallites embedded in the *pores* of a rigid matrix of vortices pinned on CDs, has been reported [10]. In the same system it was also revealed [11] a new delocalization line that separates a homogeneous vortex liquid from a heterogeneous *nanoliquid* phase, consisting of nanodroplets of vortex liquid caged in the *pores*.

In this paper we report new results on the decoupling line for $Bi_2Sr_2CaCu_2O_{8+\delta}$ (Bi2212) single crystals, before and after irradiation with swift Ag ions. In special we present a quantitative verification for the predicted upward shift of the decoupling line.

2. Materials and methods

Several Bi2212 single crystals were obtained using the conventional self-flux method, starting from a powder

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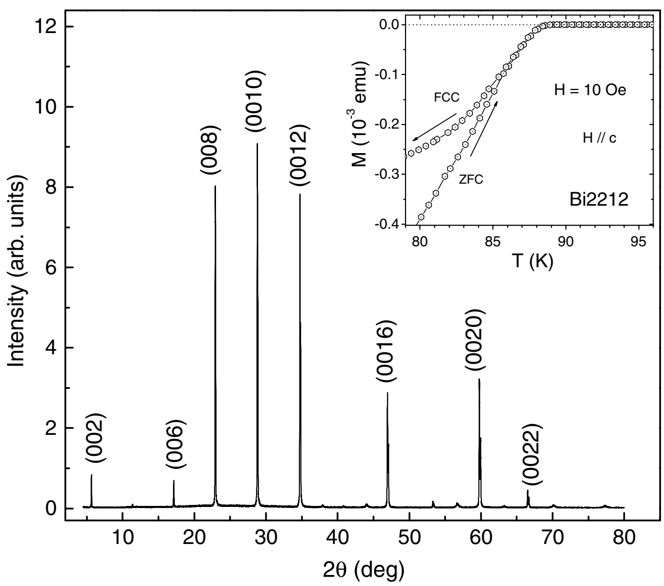

Fig. 1. X-ray diffraction pattern for sample Bi2212-a, showing only $(0,0,l)$ peaks for θ angles relative to the crystal plane. The inset shows the beginning of a magnetic transition, with $T_c \approx 88$ K ($H = 10$ Oe).

mixture of high purity (>99.99%) Bi_2O_3, $CaCO_3$, $SrCO_3$ and CuO. The metallic elements followed a near stoichiometric proportion, with Bi in excess. Crystal growth was favored by a well-controlled temperature gradient in the alumina crucible. The crystals chosen for the present study, labeled as Bi2212-a ($1.94 \times 1.52 \times 0.05$ mm^3, $T_c \approx 88$ K) and Bi2212-b ($1.93 \times 0.73 \times 0.05$ mm^3, $T_c \approx 87$ K), were submitted to an oxygen annealing at $T = 450$ °C for a period of one week. In Fig. 1 the X-ray pattern measured for sample Bi2212-a, using Cu-Kα radiation, shows only $(0,0,l)$ peaks for θ angles relative to the crystal plane. The inset of Fig. 1 shows the beginning of a magnetic transition, with a critical temperature $T_c \approx 88$ K, for an applied magnetic field $H = 10$ Oe.

After characterization of the initial crystals they were irradiated with a beam of 200 MeV Ag ions, under fluence of 5×10^{10} ions/cm^2, using the 15 UD Pelletron accelerator at IUAC, New Delhi. Columnar defects with a nominal matching field $B_\Phi = 1$ T were then produced along the crystal c-axis direction for sample Bi2212-a, and in a direction tilted 30° with respect to the c-axis for sample Bi2212-b.

The magnetization curves presented in this work were measured with a Quantum Design SQUID magnetometer, model MPMS-5.

3. Results and discussion

Fig. 2 shows some plots of the magnetic moment as a function of temperature for both crystals, before (open symbols) and after (filled symbols) irradiation, with magnetic fields applied along the c-axis. We show here only ZFC (zero field cooling) data, although FCC (field cooling on cooling) measurements were also made. Typically the ZFC curves display two distinct transitions [12,13], one around the bulk T_c where they depart from the normal-state baseline, and the other forming a knee at a relatively lower temperature, identified as the Josephson decoupling transition. This latter transition is shifted to lower temperatures and becomes increasingly sharper when H is increased. However, it seems to saturate near the ideal field independent quasi-two-dimensional decoupling temperature T_{2D} [3,9], which is a characteristic of the pancake vortex system.

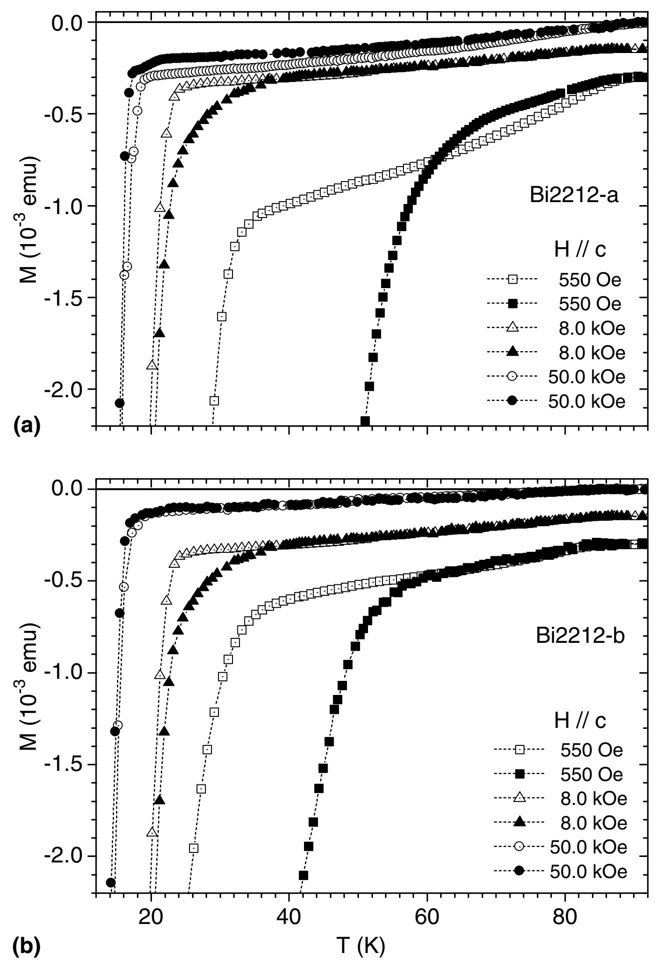

Fig. 2. ZFC magnetic moment as a function of temperature for samples (a) Bi2212-a and (b) Bi2212-b, before (open symbols) and after (filled symbols) irradiation with 200 MeV Ag ions. The curves for $H = 8.0$ kOe and 550 Oe are shifted downward by steps of -1.5×10^{-4} emu, for clarity.

The $B \times T$ decoupling lines (assuming $B \approx H$), shown in Fig. 3 (Bi2212-a) and Fig. 4 (Bi2212-b), were obtained from the many $M \times T$ transition curves for 10 Oe $\leqslant H \leqslant$ 50 kOe. The inset of Fig. 3 shows examples of the auxiliary straight lines used to extrapolate the curves near the transition region, in order to extract the Josephson decoupling temperatures. This criterion produces errors of about ± 1 K for $H > 10$ kOe and about ± 5 K for $H < 1$ kOe, due to the transition broadening at lower fields.

The decoupling transition is clearly shifted to higher temperatures for both samples after irradiation, due to pancake vortex pinning by the columnar defects. Figs. 2–4

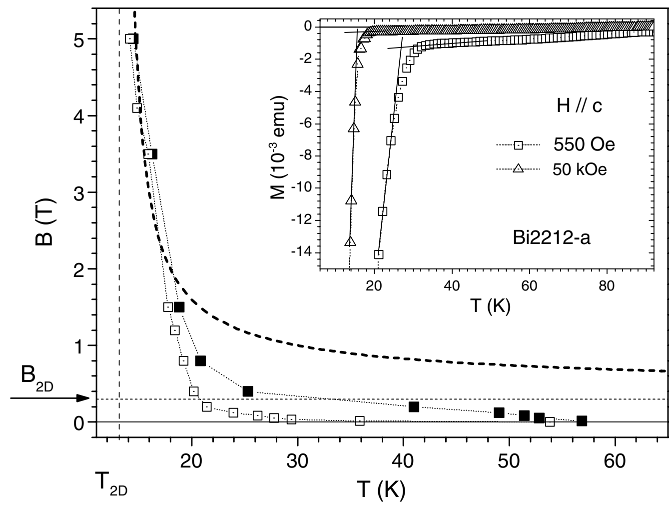

Fig. 3. $B \times T$ decoupling phase diagram for crystal Bi2212-a, before (open symbols) and after (filled symbols) irradiation. The thick dotted curve represents a fit of Eq. (1). The inset shows details of the criterion used to extract the decoupling temperatures.

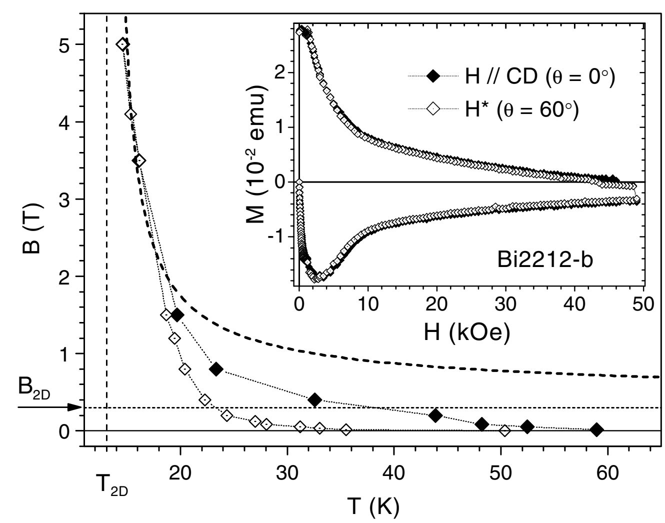

Fig. 4. $B \times T$ decoupling phase diagram for crystal Bi2212-b, before (open symbols) and after (filled symbols) irradiation. The thick dotted curve represents a fit of Eq. (1). The inset shows $M \times H$ curves for H parallel (filled symbols) and making an angle of 60° (open symbols) with the columnar defects.

show that this effect is very similar in both samples, for H parallel to the crystals c-axis. It is worth noticing that this temperature shift is larger than 20 K for $H < 2$ kOe, but almost disappears for $H > 30$ kOe. This result agrees with a more effective suppression of the pancakes thermal motion, predicted to occur at higher temperatures [8]. However, even for the higher fields, one sees much rounded transition knees for the samples after irradiation (Fig. 2). We attribute this effect to a possible non-uniformity of the CDs system. This could produce some distribution of the pancakes pinning strength, thus causing a transition broadening.

The inset of Fig. 4 displays $M \times H$ curves in complete disagreement with results reported for $YBa_2Cu_3O_7$ crystals [1], with CDs making an angle of 30° with respect to the crystal c-axis. In Ref. [1] they observed a much larger width of the magnetization loop (related to larger vortex pinning), when H was applied in the same direction of the CDs, compared with a smaller loop width when H was making an angle of 60° with the CDs. In contrast, the same test performed in our sample Bi2212-b (inset of Fig. 4) shows almost the same hysteresis loop for the two field orientations, similarly to previous results found in Bi2212 crystals [14]. Since Bi2212 is much more anisotropic than $YBa_2Cu_3O_7$, a much significant 2D behavior is expected for the pancake vortices in the Bi2212 system. Therefore, it seems that when the interlayer coupling vanishes the pancake pinning by columnar defects becomes independent of the field direction, at least for angles up to 60° relative to the CDs direction. It is to be noted also that this test involves the symmetric tilting of the crystal c-axis, by an angle of ±30° relative to the field direction.

The high field region ($B > 2$ T) of the $B \times T$ decoupling line for both crystals, before and after irradiation, can be well described by a theory of 2D vortex melting that predicts, for B above the crossover field B_{2D} [3,9]

$$B_m(T) = B_{2D} \exp\left[b\left(\frac{T}{T_{2D}} - 1\right)^{-0.37}\right]. \quad (1)$$

The thick dotted curves in Figs. 3 and 4 represent fits of this equation to our data, with the parameters $B_{2D} = 0.3$ T, $T_{2D} = 13$ K and $b \approx 1.3$ (of order 1, as expected [9]), where

$$B_{2D} \approx \frac{\pi \Phi_0}{\gamma^2 d^2} \ln\left(\frac{\gamma d}{\xi_{ab}}\right), \quad (2)$$

$$k_B T_{2D} \approx \frac{d}{8\pi\sqrt{3}}\left(\frac{\Phi_0}{4\pi\lambda_{ab}}\right)^2, \quad (3)$$

k_B is the Boltzmann constant, $\Phi_0 = 2.07 \times 10^{-7}$ G cm^2 is the flux quantum, $\gamma = \lambda_c/\lambda_{ab}$ is the anisotropy parameter, $d = 15$ Å is the CuO_2 interplane distance and $\xi_{ab} \approx 20$ Å is the coherence length in the ab plane [3]. Using these data and the parameters obtained by the fit of Eq. (1), we were able to calculate $\lambda_{ab} \approx 2280$ Å (in-plane penetration depth) and $\gamma \approx 220$ (anisotropy), in close agreement with typical results for Bi2212 [3].

In the low field region ($B < B_{2D}$) the vortex pancakes are fully coupled, forming 3D flux lines, which are expected to present a melting line $B_m(T)$ for a pure system [9], before irradiation. After irradiation, a Bose-Glass melting line $B_{BG}(T)$ is expected, going above the $B_m(T)$ line, similarly to what has been observed in this study. However, we did not fit our data in the low field region because the transition points, detected by the global magnetization measurements, are not well defined. Therefore we restrict the present quantitative analysis to the high field region, for $B > B_{2D}$.

Our data allowed a quantitative verification that the decoupling lines, for a sample before and after irradiation, are expected [8] to merge smoothly for fields above B_{Φ}^2/B_{2D}. In fact, Figs. 3 and 4 show that for $B > 3$ T, both decoupling lines overlap quite well for both crystals. On the other hand, for $B \leqslant B_{\Phi}$, a large enhancement of the decoupling temperature for the irradiated crystals is observed, in agreement with the large suppression of pancakes thermal motion in this field region.

4. Conclusions

We studied two $Bi_2Sr_2CaCu_2O_{8+\delta}$ crystals, before and after irradiation with a beam of 200 MeV Ag ions, under fluence of 5×10^{10} ions/cm^2. Columnar defects with a matching field $B_{\Phi} = 1$ T were produced along the c-axis direction for one sample, and in a direction tilted 30° with respect to the c-axis for the other sample.

We found that the decoupling transition became clearly shifted to higher temperatures, for both samples after irradiation, as a consequence of stronger vortex pinning by the columnar defects. This temperature shift was larger than 20 K for $H < 2$ kOe, but it was almost inexistent for $H > 30$ kOe. This result most possibly is explained by the larger suppression of pancakes thermal motion at higher temperatures.

In the high field region the decoupling lines for both crystals were fitted quite well by an expression from a theory of 2D vortex melting [9]. These fits allowed us to find the 3D–2D crossover field $B_{2D} \approx 0.3$ T, the quasi-two-dimensional decoupling temperature $T_{2D} = 13$ K, the in-plane field penetration depth $\lambda_{ab} \approx 2280$ Å, and the anisotropy parameter $\gamma = \lambda_c/\lambda_{ab} \approx 220$. All these parameters are in close agreement with typical results found for $Bi_2Sr_2CaCu_2O_{8+\delta}$ [3]. For applied magnetic fields such that $B > B_{\Phi}^2/B_{2D} \approx 3.0$ T we have verified a theoretical prediction that decoupling lines, taken in a sample before and after irradiation, must merge smoothly.

We found also that the vortex pinning by columnar defects was almost independent of the applied field direction, as revealed by the width of magnetization loops measured in the crystal with tilted columnar defects. The extreme two-dimensional character of the pancake vortices, in the highly anisotropic $Bi_2Sr_2CaCu_2O_{8+\delta}$ crystals, could explain this result. In other words, when the interlayer coupling vanishes the pancake pinning by columnar defects becomes independent of the field direction, at least for angles up to 60° relative to the columnar defects direction, as verified in this work.

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References

[1] L. Civale, A.D. Marwick, T.K. Worthington, M.A. Kirk, J.R. Thompson, L. Krusin-Elbaum, Y. Sun, J.R. Clem, F. Holtzberg, Phys. Rev. Lett. 67 (1991) 648.
[2] M. Konczykowski, F. Rullier-Albenque, E.R. Yacoby, A. Shaulov, Y. Yeshurun, P. Lejay, Phys. Rev. B 44 (1991) 7167.
[3] G. Blatter, M.V. Feigel'man, V.B. Geshkenbein, A.I. Larkin, V.M. Vinokur, Rev. Mod. Phys. 66 (1994) 1125.
[4] M.A. Avila, L. Civale, A.V. Silhanek, R.A. Ribeiro, O.F. de Lima, H. Lanza, Phys. Rev. B 64 (2001) 144502.
[5] D.R. Nelson, V.M. Vinokur, Phys. Rev. Lett. 68 (1992) 2398.
[6] L. Krusin-Elbaum, L. Civale, G. Blatter, A.D. Marwick, F. Holtzberg, C. Field, Phys. Rev. Lett. 72 (1994) 1914.
[7] C.J. van der Beek, M. Konczykowski, V.M. Vinokur, G.W. Crabtree, Phys. Rev. B 51 (1995) 15492.
[8] A.E. Koshelev, P. Le Doussal, V.M. Vinokur, Phys. Rev. B 53 (1996) 8855.
[9] L.I. Glazman, A.E. Koshelev, Phys. Rev. B 43 (1991) 2835.
[10] S.S. Banerjee, A. Soibel, Y. Myasoedov, M. Rappaport, E. Zeldov, M. Menghini, Y. Fasano, F. de la Cruz, C.J. van der Beek, M. Konczykowski, T. Tamegai, Phys. Rev. Lett. 90 (2003) 087004.
[11] S.S. Banerjee, S. Goldberg, A. Soibel, Y. Myasoedov, M. Rappaport, E. Zeldov, F. de la Cruz, C.J. van der Beek, M. Konczykowski, T. Tamegai, V.M. Vinokur, Phys. Rev. Lett. 93 (2004) 097002.
[12] O.F. de Lima, V.P.S. Awana, R.A. Ribeiro, M.A. Avila, Europhys. Lett. 51 (2000) 174.
[13] R.L. de Almeida, O.F. de Lima, Physica C 408–410 (2004) 512.
[14] J.R. Thompson, Y.R. Sun, H.R. Kerchner, D.K. Christen, B.C. Sales, B.C. Chakoumakos, A.D. Marwick, L. Civale, Appl. Phys. Lett. 60 (1992) 2306.