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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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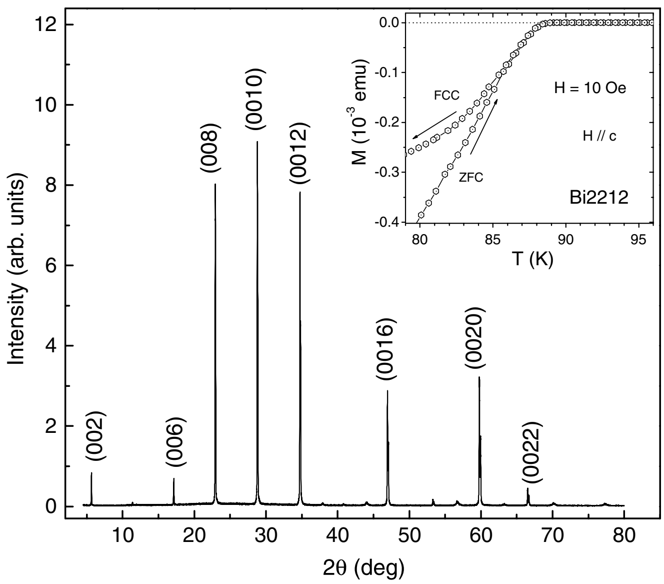

Fig. 1. X-ray diffraction pattern for sample Bi2212-a, showing only $(0,0,l)$ peaks for θ angles relative to the crystal plane. The inset shows the beginning of a magnetic transition, with $T_c \approx 88$ K ($H = 10$ Oe).

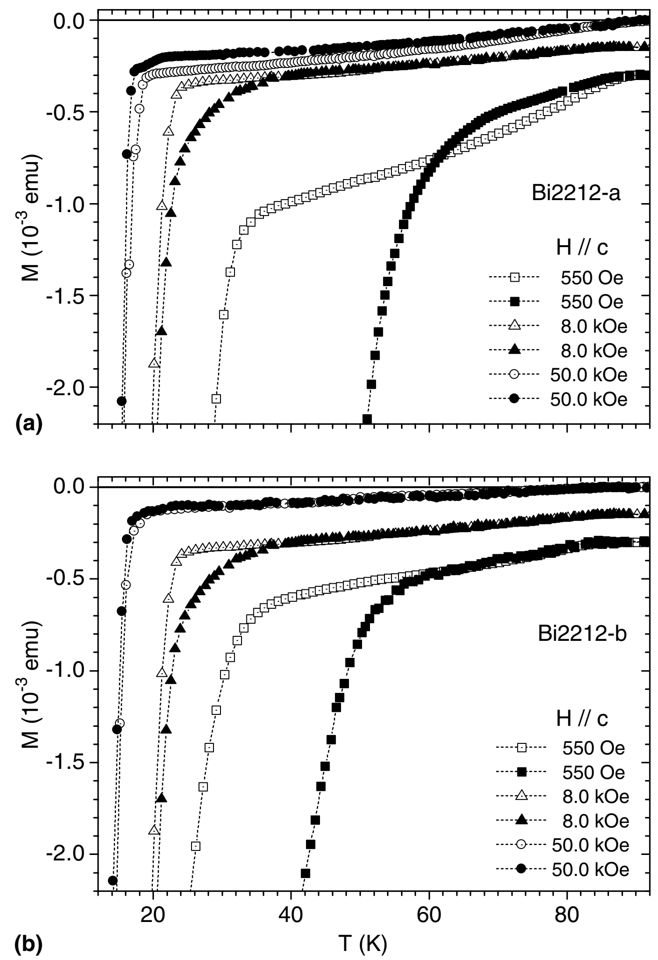

Fig. 2. ZFC magnetic moment as a function of temperature for samples (a) Bi2212-a and (b) Bi2212-b, before (open symbols) and after (filled symbols) irradiation with 200 MeV Ag ions. The curves for $H = 8.0$ kOe and 550 Oe are shifted downward by steps of -1.5×10^{-4} emu, for clarity.

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.

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