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PHYSICA A

Angular dependence of the magnetization curves and interlayer Josephson coupling in $Bi_2Sr_2CaCu_2O_8$

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Magnetization curves were measured for $Bi_2Sr_2CaCu_2O_8$ crystals which were irradiated with 5.8 GeV Pb ions along the *c* direction or at 45° with respect to it. Each ion produces continuous columnar defect that crosses the sample and yields a unidirectional pinning center. The density of the defects in the various samples ranges from 10^{10} to 2.5×10^{11} ions/cm^2. In all the irradiated samples the width of the magnetization curves is found to be the largest for fields along the defects indicating that when the field is at other directions the vortices are tilted away from the defects. This manifests the important role of the Josephson coupling between the CuO_2 planes. We also report on accelerated flux escape around zero magnetization and around zero field, particularly in samples with a high dose of irradiation.

Experiments on $Bi_2Sr_2CaCu_2O_8$ (BSCCO) show that this layered high-temperature superconductor is highly anisotropic. Therefore, it was suggested that the interlayer Josephson coupling (IJC) between the superconducting CuO_2 planes may be neglected [1] implying that the component of the field parallel to the layers penetrates freely and the vortices are in the form of two dimensional (2D) "pancakes" coupled only via magnetic interactions [2]. Pancakes which reside in different planes order (at low temperatures) in stacks along the *c* direction [3] but since the pancakes are produced by the component of the field which is perpendicular to the layers, these stacks are not tilted when the external field is tilted [2]. Only in the presence of IJC the screening of the field parallel to the layers does not vanish and the vortices may be tilted by the external field [2]. Experimentally, it is usually difficult to distinguish between the behavior of a layered superconductor with weak IJC and that of a layered superconductor with no coupling at all [1]. Since the possibility to tilt vortices by an external field is a feature that distinguishes qualitatively between the two cases, a manifestation of this feature is an unambiguous evidence for the presence of IJC.

In order to test the possibility to tilt the vortices by an external field, we irradiated BSCCO crystals with 5.8 GeV Pb ions. In such irradiation, each ion produces a continuous amorphous track, with a diameter of 5–7 nm, that crosses the crystal [4] and the induced columnar defects serve as unidirectional pinning centers for the vortices, namely, pinning is most efficient when the vortices are along the defects. Recently, we have reported [5] on measurements on BSCCO crystals which were irradiated with a total fluence of 10^{11} ions/cm^2. We have found that the width of the magnetization curves, which reflects the pinning strength, is largest when the field is along the defects. This indicates that when the field is at other directions the vortices are tilted away from the defects.

Here we describe magnetization curves for samples which were irradiated with various doses and we find unidirectional pinning in all samples. We focus on temperatures $T \leq 50$ K and show that although unidirectional pinning may seem suppressed in this range of temperatures [5,6], it is clearly observed (a) near the irreversibility field where the critical current is small, (b) in magnetization curves with the applied field at high angles relative to the c direction; and (c) in samples with large doses of irradiation. These data assess the presence of the IJC also in the low temperature regime. The IJC is expected to vanish at high enough fields [7]. However, our observation of unidirectional pinning is naturally limited to the irreversible regime. Therefore, the fields at which unidirectional pinning is observed are only a lower bound for the much higher expected decoupling field.

The measurements were performed on 3 samples irradiated along the c direction: a $1.5 \times 1.1 \times 0.044\,\mathrm{mm}^3$ crystal (IR1) with a total fluence of 10^{10} ions/cm^2 ($B_\phi = 0.2$ T), a $1.6 \times 0.95 \times 0.046\,\mathrm{mm}^3$ crystal (IR2) with a total fluence of 10^{11} ions/cm^2 ($B_\phi = 2$ T), and a $1 \times 0.95 \times 0.042\,\mathrm{mm}^3$ crystal (IR3) with a total fluence of 2.5×10^{11} ions/cm^2 ($B_\phi = 5$ T). B_ϕ is the matching field, namely, the field at which there is one vortex per columnar defect. We also measured a $1.6 \times 0.9 \times 0.046\,\mathrm{mm}^3$ crystal (IR4) irradiated at 45° relative to the c direction with a total fluence of 10^{11} ions/cm^2 ($B_\phi = 2$ T). The magnetization curves were measured with the applied field at different angles ϕ with respect to the c direction. All the measurements were performed on an "Oxford Instruments" vibrating sample magnetometer (VSM) which allows a rotation of the sample relative to the magnetic field. Sample preparation is described in ref. [8]. The transition temperature $T_c = 85$ K of the unirradiated samples is reduced by less than 0.5 K after irradiation.

Fig. 1 shows magnetization curves of IR4 for $\phi = \pm 45°$ at various temperatures and fig. 2 shows magnetization curves of IR1, IR2 and IR3 for $\phi = 0$, 45° at $T = 50$ K. In all the figures the magnetization $\boldsymbol{M} = \boldsymbol{m}/\cos\phi$, where $\boldsymbol{m}$ is the measured magnetization and ϕ is the angle between the field and the c

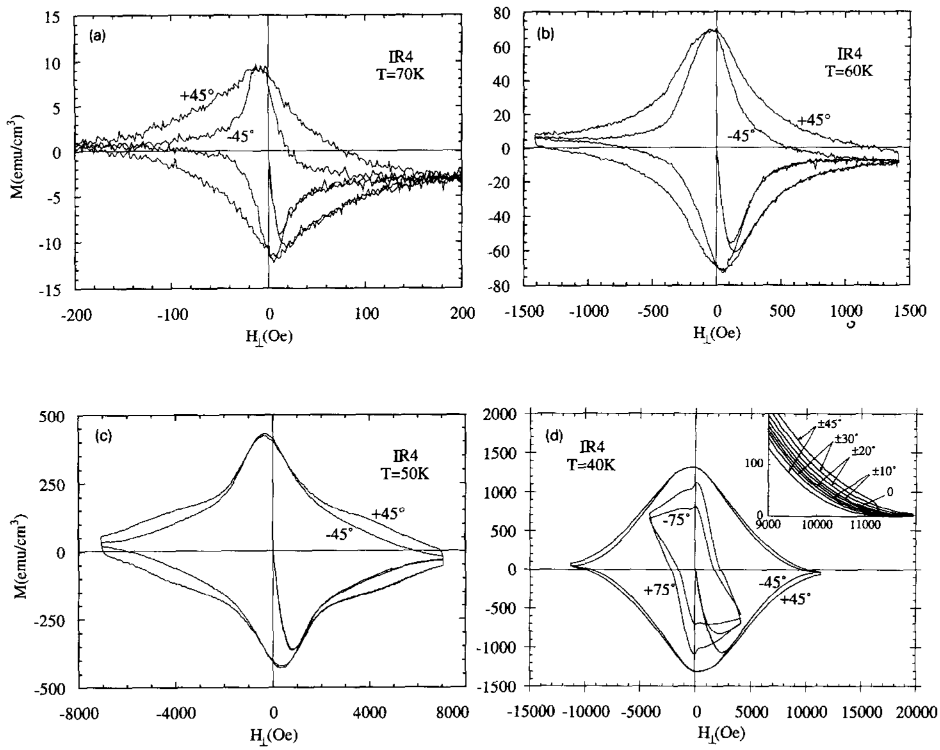

Fig. 1. Magnetization curves for IR4 with the applied field at different angles relative to the c direction at (a) $T = 70$ K, (b) $T = 60$ K, (c) $T = 50$ K, (d) $T = 40$ K. Inset to (d): the width of the magnetization curves in the high field limit. ϕ is the angle of the field relative to the c axis, $M = m/\cos\phi$, where m is the measured magnetization and $H_\perp = H\cos\phi$.

direction. This is done in order to correct for the fact that the VSM measures the component of the magnetization along the field , whereas the magnetization vector points in the c direction [9]. In order to compare magnetization curves with the applied field at different angles relative to the c direction we take into account that the main response of the sample magnetization is due to the component of the field perpendicular to the layers, $H_\perp$ [10]. For vanishing IJC the magnetization should indeed depend only on $H_\perp$. Therefore, the break of this scaling implies that IJC is present. Anyway, note that this scaling does not affect the comparison between magnetization curves taken with the field at symmetric angles relative to c (e.g. ±45°) for which the $\cos\phi$ terms have identical values.

The dependence of the width of the magnetization curves on ϕ, as observed in figs. 1 and 2, for various temperatures and doses of irradiation, demonstrates that pinning is most efficient when the field (and the vortices) are aligned along the defects. The fact that the width is smaller when the field is not along this

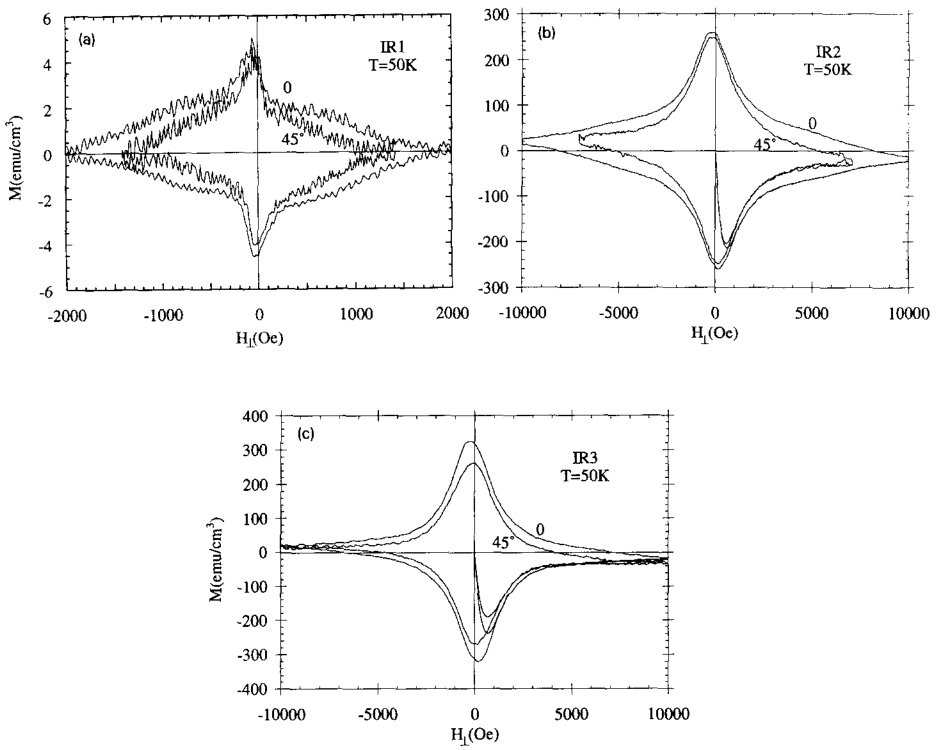

Fig. 2. Magnetization curves at $T = 50$ K for (a) IR1, (b) IR2, (c) IR3. Note that $\boldsymbol{M} = \boldsymbol{m}/\cos\phi$ where $\boldsymbol{m}$ is the measured magnetization and $H_{\perp} = H\cos\phi$.

direction indicates that in this case the pinning of the vortices is weaker and this implies that they are not fully trapped in the columnar defects. Instead, the vortices are tilted away from the defects by the applied field. As discussed above, this possibility to tilt the vortices by the external field excludes previous suggestions of practically vanishing IJC [1].

The relative unidirectional pinning decreases as the temperature is decreased and as pinning (and critical currents) increases (see fig. 1). Therefore, it might be difficult to observe unidirectional pinning at low temperatures, $T \leqslant 50$ K [5,6]. The origin of the unidirectional pinning is the difference between pinning of a vortex that is fully trapped by a columnar defect and the pinning of a vortex that is not aligned along the defect but still may cross the defect and thus some of its segments are trapped. The vortices depin from the defect by creating nucleus of size L_c out of the defect [11]. When the trapped segments are larger than L_c, the pinning is almost as that of a vortex which is fully aligned along the defect. Since L_c is inversely proportional to the critical current, it is possible that at low temperatures (and high critical currents) the trapping segment becomes comparable to L_c and this may suppress the unidirectional pinning. In fig. 1d we see that at angles up to ±45° it is difficult to observe unidirectional pinning at $T = 40$ K. However, focusing on the high field limit (and low critical current) it is clear that the width of the magnetization curves decreases as the angle between the applied field and the defect increases, probably due to the dependence of the size of the trapped segments on ϕ. At higher angles, $\phi = \pm 75°$, the unidirectional pinning is pronounced in the low field limit as well. These data assess the presence of IJC in the low temperature regime as well.

Fig. 3 shows magnetization curves for IR3 with the field at different angles ϕ at $T = 40$ K. This sample exhibits pronounced unidirectional pinning also at low temperatures, low fields and low angles. In addition, the figure exhibits two interesting features: (a) the magnetization curves have "knees", i.e. $M \approx 0$ for a field range $\delta H_\perp$ and (b) a sharp drop δM in the magnetization is observed

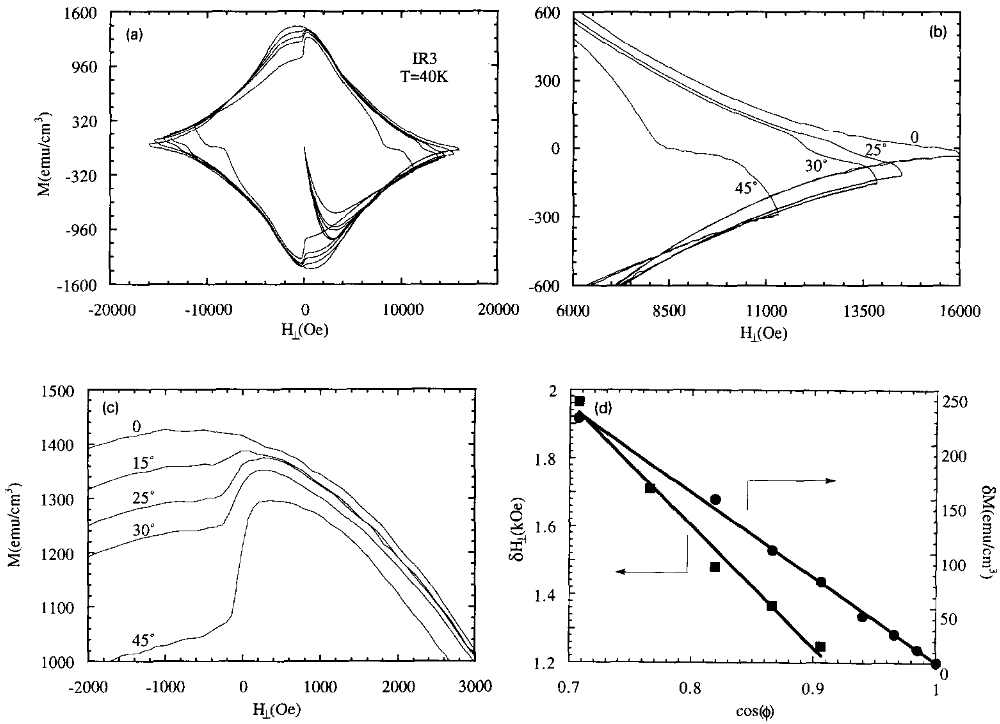

Fig. 3. (a) Magnetization curves of IR3 at $T = 40$ K with various angles ϕ with respect to the c direction (note that $M = m/\cos\phi$ where m is the measured magnetization and $H_\perp = H\cos\phi$), (b) blow-up of the "knees" around $M = 0$, (c) blow-up of the drop δM in the magnetization around $H = 0$, (d) the height of the drop δM in the magnetization and the width $\delta H_\perp$ of the knee vs $\cos\phi$ (the solid lines are only guides to the eye).

around $\boldsymbol{H} = 0$. Both $\delta H_\perp$ and δM decrease with $\cos\phi$, see fig. 3d. The knees and the drops reflect accelerated escape of vortices from the sample. The knees at $\boldsymbol{M} \approx 0$ resembles the magnetization curves due to surface barriers [12]. It is known that in samples were the irreversible magnetization is due to surface barriers, the descending branch of the magnetization curve is along $\boldsymbol{M} = 0$. However, if this is the correct interpretation of the knees it implies that the low field limit of the knee indicates the onset of bulk pinning. In this case we would expect that the onset of bulk pinning will be pushed to higher fields at lower temperatures. However, the assumed onset of bulk pinning is found to be pushed to lower fields at lower temperatures. In fig. 1d we see that also IR4 for $\phi = \pm 75°$ exhibit a drop in $\boldsymbol{M}$ and there is also a reminiscence of the knees, so it is clearly not a one sample effect. We should also note that the drops and the knees are not observed in any sample at $T \geqslant 50$ K. The origin of these interesting effects is not clear yet and they requires further study.

In conclusion, our data yield experimental observation of unidirectional pinning of vortices in BSCCO which implies the presence of IJC and excludes interpretation of vortex properties in BSCCO in terms of decoupled 2D pancakes. New features of knees and drops in the magnetization curves are also presented.

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