Anisotropic Critical Current Densities in \( \text{Ba}_0.6\text{K}_{0.4}\text{Fe}_2\text{As}_2 \) with Splayed Columnar Defects

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Abstract. Enhancement and non-monotonic field dependence of critical current density \((J_c)\), called anomalous peak effect, were observed in \( \text{Ba}_1-x\text{K}_x\text{Fe}_2\text{As}_2 \) with splayed columnar defects. In principle, anisotropy of in-plane \(J_c\) should be present in this superconductor since the introduced splayed columnar defects introduce anisotropy in the plane. This study reports in-plane anisotropy of \(J_c\) observed in 2.6 GeV U irradiated \( \text{Ba}_{0.6}\text{K}_{0.4}\text{Fe}_2\text{As}_2 \) with splay angles of \(\pm 15^\circ\) and \(\pm 20^\circ\). Results show that \(J_c\) component parallel to the splay plane is larger than the perpendicular component, and the parallel component contribute to the anomalous peak effect at around \(B_{\Phi}/3\) more.

1. Introduction

Columnar defects (CDs) were proved to enhance the critical current density \((J_c)\) in cuprate superconductors [1], and further enhancement is reported by splaying the direction of CDs [2]. In iron-based superconductors (IBSs), similar enhancements of critical current density by the introduction of CDs have been reported [3, 4]. In the case of \( \text{Ba}_{1-x}\text{K}_x\text{Fe}_2\text{As}_2 \), in addition to the enhancement of \(J_c\), a non-monotonic field dependence of \(J_c\), called the anomalous peak effect, has been reported [5, 6]. In the present study, \( \text{Ba}_{0.6}\text{K}_{0.4}\text{Fe}_2\text{As}_2 \) crystals were irradiated by 2.6 GeV U ions from two directions, each with a dose-equivalent magnetic field of \(B_{\Phi} = 4\) T. We controlled splay angles \((\theta_{\text{CD}})\), which are angles between the incident direction and the \(c\)-axis, by tilting the \(ab\)-plane of samples during the irradiation. By introducing splayed CDs, which break in-plane symmetry, \(J_c\) is expected to have an in-plane anisotropy [7]. So, the two components \(J_{c\parallel}\) and \(J_{c\perp}\) that are parallel and perpendicular to the splay plane, respectively, need to be figured out to determine which component contributes more to the anomalous peak effect. The magneto-optical (MO) imaging can be implemented to determine the in-plane anisotropy of \(J_c\). However, it requires observations under high fields, which is difficult using a garnet film with a low saturation field. Thus, the MO imaging was only used for the inspection of the homogeneity of the sample. The in-plane anisotropy of \(J_c\) is evaluated based on the magnetization data obtained for two separate samples with different in-plane aspect ratio with respect to the splay plane. Generally, the Bean model is used to calculate the average \(J_c\) of rectangular superconductors...
under an assumption of constant in-plane $J_c$. After cutting out two rectangular pieces with different aspect ratios from the original sample, $J_c$ in the two directions were evaluated to reveal the splayed CDs-induced anisotropy in the in-plane $J_c$.

2. Experimental Methods

Ba$_{0.6}$K$_{0.4}$Fe$_2$As$_2$ crystals used in this study were synthesized with FeAs self-flux method [8]. First, we prepared FeAs. Fe powder (99.9% up, Kojundo Chemical Lab. Co., Ltd.) and As grains (7N, Furukawa Denshi Co., Ltd.) were mixed at a molar ratio of 1 : 1, and vacuum-sealed the mixture into a quartz tube. FeAs was obtained by heating at 700 °C for 40 h after an intermediate heating at 500 °C for 10 h. Second, Ba pieces (99.9%, Furuiuchi Chemistry), K lumps (99.5%, Kojundo Chemical Lab. Co., Ltd.) and FeAs powder were mixed at a molar ratio of 0.6 : 0.44 : 4 inside a glove box filled with Argon. The mixture was put in a alumina crucible tube and the tube was sealed in a stainless steel tube with a stainless steel lid. Finally, Ba$_{0.6}$K$_{0.4}$Fe$_2$As$_2$ crystals were synthesized by heating this at 600 °C for 5 h, then raising the temperature to 1100 °C, holding this temperature for 10 h, and cooling it to 800 °C at a rate of 5 °C/h. To introduce CDs, the 2.6 GeV U irradiation was performed using the RIKEN Ring Cyclotron, and the total dose for each sample was $B_\Phi = 8$ T. After selecting areas without defects, smaller pieces with $\theta_{\text{CD}} = \pm 15^\circ$ were cut by a razor blade while pieces with $\theta_{\text{CD}} = \pm 20^\circ$ were cut by focused ion beam (FIB).

All reliable evaluations of $J_c$ via magnetic measurements reply on the homogeneity of the sample. For detecting macroscopic defects, MO imaging was performed on both pieces with $\theta_{\text{CD}} = \pm 15^\circ$ and $\pm 20^\circ$. Single crystals were attached to a copper sample holder with Apiezon N grease and then covered with a mirror-coated ferrimagnetic garnet indicator film. The sample was cooled by using He-flow cryostat (Microstat-Hires, Oxford Instruments) placed under the microscope with halogen lamp as a light source. By setting the polarizer and analyzer away from the crossed Nicols configuration, the light intensity detected by the CCD camera can be a unique function of the local magnetic induction including its polarity, which can be determined by the calibration just above $T_c$.

Magnetization of each sample was measured by the superconducting quantum interference device (SQUID) magnetometer (MPMS-XL5, Quantum Design). We used an extended Bean model with anisotropic $J_c$ to evaluate anisotropic components of in-plane $J_c$, which will be explained in the next section.

3. Bean Model with In-plane Anisotropy

Generally, in the case of $J_c$ calculation using the Bean model, in-plane isotropy is assumed, and the following formula is obtained:

$$J_c = \frac{20\Delta M}{a (1 - \frac{a}{b})^3},$$

where $\Delta M$ is the difference between magnetization in the magnetizing process and magnetization in the demagnetizing process, while $a$ and $b$ are the width and the length of the sample, respectively [9, 10]. However, after breaking the isotropy of pinning by the introduction of splayed CDs, $J_c$ components in the two directions, parallel and perpendicular to the splay plane, have different values. In this case, depending on the anisotropy and the aspect ratio, the relationship between $\Delta M$ and $J_c$ changes into

$$\Delta M = \frac{J_c^a b}{20} \left(1 - \frac{b}{3a} \frac{J_c^a}{J_c^b}\right) \frac{J_c^b}{J_c^a} > \frac{b}{a},$$

$$\Delta M = \frac{J_c^a b}{20} \left(1 - \frac{a}{3b} \frac{J_c^b}{J_c^a}\right) \frac{J_c^b}{J_c^a} < \frac{b}{a},$$

where $J_c^a$ and $J_c^b$ are $J_c$ components along the directions of width and length, respectively [11].
Figure 1. MO images of irradiated Ba$_{0.6}$K$_{0.4}$Fe$_2$As$_2$ crystals with (a) $\theta_{CD} = \pm 15^\circ$ and (b) $\theta_{CD} = \pm 20^\circ$ in the remanent state. Red rectangles mark the smaller pieces cut from them and white arrows indicate splay directions. (c) Scanning ion microscope image of the crystal with $\theta_{CD} = \pm 20^\circ$ after FIB cutting. Red circles mark two pieces chosen for magnetization measurements. Note that (b) and (c) correspond to two different faces of the same crystal.

According to this relationship, $J_{c||}$ and $J_{c\perp}$ of a crystal can be calculated by cutting two smaller pieces with a different aspect ratio from it.

4. Results and Discussion

MO images of samples with $\theta_{CD} = \pm 15^\circ$ and $\pm 20^\circ$ after the introduction of splayed CDs are shown in Figs. 1(a) and (b), respectively. Two smaller pieces with different aspect ratios need to be picked up from each sample. Dark contrasts in MO images in the rectangular sample correspond to area with defects. To guarantee reliability, those areas need to be avoided when cutting two smaller pieces with different aspect ratio. For the $\theta_{CD} = \pm 15^\circ$ piece, dimensions of the parallel and perpendicular smaller pieces cut from it are $212 \times 128 \ \mu m^2$ and $181 \times 311 \ \mu m^2$.

Figure 2. Magnetic hysteresis loops of (a) parallel piece with $\theta_{CD} = \pm 15^\circ$, (b) perpendicular piece with $\theta_{CD} = \pm 15^\circ$, (c) parallel piece with $\theta_{CD} = \pm 20^\circ$, and (d) perpendicular piece with $\theta_{CD} = \pm 20^\circ$. 
Figure 3. \( J_{\parallel}, J_{\perp}, \) and \( J_{\parallel}/J_{\perp} \) as functions of magnetic field for samples with \( \theta_{\text{CD}} = \pm 15^\circ \) (upper panel) and \( \pm 20^\circ \) (lower panel).

respectively, while for the \( \theta_{\text{CD}} = \pm 20^\circ \) piece, dimensions of the parallel and perpendicular smaller pieces cut from it are 103 \( \times \) 56 \( \mu \text{m}^2 \) and 53 \( \times \) 106 \( \mu \text{m}^2 \), respectively. Fig. 1(c) shows the ion beam image of the crystal with \( \theta_{\text{CD}} = \pm 20^\circ \) after FIB cutting. Pieces with red circles refer to two pieces selected for magnetization measurements.

Magnetic hysteresis loops, namely \( M-H \) dependence, for parallel and perpendicular pieces with \( \theta_{\text{CD}} = \pm 15^\circ \) and \( \pm 20^\circ \) are shown in Fig. 2. Based on these measurements, \( J_{\parallel}, J_{\perp}, \) and \( J_{\parallel}/J_{\perp} \) values for each \( \theta_{\text{CD}} \) can be calculated out by equations described in section 3, and results are shown in Fig. 3. Data points near 50 kOe are outside the validity of Eq. (2) since the critical state with uniform circulation of current is not realized. According to the results, we can conclude that both components contribute to the anomalous peak at around \( B_{\Phi}/3 \) (27 kOe), and \( J_{\parallel} \) contributes 20\% more to it in both cases. Moreover, the variation of \( J_c \) components at different external fields with broad peaks at around \( B_{\Phi}/3 \) is more significant at lower temperatures. There are two mechanisms for the enhancement of \( J_c \) by the introduction of splayed CDs. The motion of vortices within the splay plane can be suppressed by variable distance between neighboring splayed CDs, since making the length of kinks connecting trapped vortices longer is energetically unfavorable [5, 12]. On the other hand, vortex motion across the splay plane can also be suppressed, since forced entanglement of vortices involving vortex cutting is not preferable [5, 13]. Our finding that \( J_{\parallel} \) is larger than \( J_{\perp} \) indicates that the latter process contribute more to the occurrence of anomalous peak effect.

5. Summary
We introduced splayed CDs into \( \text{Ba}_{0.6}\text{K}_{0.4}\text{Fe}_2\text{As}_2 \) crystals with \( \theta_{\text{CD}} = \pm 15^\circ \) and \( \pm 20^\circ \) by 2.6 GeV U irradiation. After the irradiation, crystals with different aspect ratios with \( \theta_{\text{CD}} = \pm 15^\circ \) were cut by a razor blade and those with \( \theta_{\text{CD}} = \pm 20^\circ \) were cut by FIB. From the magnetization measurements by the SQUID magnetometer, we calculated the in-plane \( J_c \) anisotropy of each sample with its two components \( J_{\parallel} \) and \( J_{\perp} \). Results show that both components contribute to the anomalous peak effect, while \( J_{\parallel} \) is about 20\% larger than \( J_{\perp} \) at around \( B_{\Phi}/3 \) in both cases. This \( J_c \) anisotropy originates from the difference in the pinning force in two directions, which is caused by splayed-CDs-induced pinning center configuration. Forced entanglement of vortices by a small splay angle will make it harder for vortex to move across the splay plane.
than within the plane.

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