Anisotropy of critical current densities in Ba$_{1-x}$K$_x$Fe$_2$As$_2$ and Ba(Fe$_{1-x}$Co$_x$)$_2$As$_2$ with splayed columnar defects

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Abstract. Effects of bimodal splayed columnar defects in Ba$_{1-x}$K$_x$Fe$_2$As$_2$ and Ba(Fe$_{1-x}$Co$_x$)$_2$As$_2$ single crystals through 2.6 GeV U irradiation and 220 MeV Au irradiation are investigated. Magnetic field profiles measured by magneto-optical imaging clarified the presence of in-plane anisotropy of the critical current density ($J_c$) in 2.6 GeV U irradiated crystals, where $J_c$ parallel to the splay plane is larger than that perpendicular to the splay plane. However, the in-plane anisotropy of $J_c$ is absent in 220MeV Au irradiated crystals. Possible origin of this discrepancy is discussed based on the structure of introduced defects.

1. Introduction

Columnar defects in type-II superconductors serve as artificial pinning centers, which lead to an enhancement of critical current density $J_c$ [1, 2, 3]. It has been proposed that a further enhancement of $J_c$ is possible by dispersing the direction of the columnar defects [4]. In such a system with splayed columnar defects, enhancement of $J_c$ has been confirmed in 1.08 GeV Au irradiated YBa$_2$Cu$_3$O$_{7-\delta}$ single crystals [5] and 2.6 GeV U irradiated Ba$_{1-x}$K$_x$Fe$_2$As$_2$ single crystals [6]. Due to the competing effects of suppression of vortex motion by unequal lengths of vortex segments between splayed columnar defects and detrimental effect of misalignment of vortices, the optimal splay angles were found to be $\approx \pm 5^\circ$ in both of the above systems.

However, since these results were obtained through magnetization measurements, the estimated $J_c$ is a weighted average of $J_c$’s along two directions in the $ab$ plane. Since directions parallel and perpendicular to the splay plane of columnar defects can be distinguished in a system with bimodal splayed columnar defects, $J_c$ parallel to the splay direction ($J_c||$) and $J_c$ perpendicular to the splay direction ($J_c\perp$) can be different. Such an in-plane anisotropy of $J_c$ in systems with splayed columnar defects has been confirmed through resistivity measurements in 1 GeV Au irradiated YBa$_2$Cu$_3$O$_{7-\delta}$ [7] and 3.9 GeV Au irradiated YBa$_2$Cu$_3$O$_{7-\delta}$ [8], where Ohmic dissipation was higher when the current is passed in the direction perpendicular to the
splay plane, suggesting $J_{c\parallel} > J_{c\perp}$. By contrast, magneto-optical (MO) images of 0.9 GeV Pb irradiated DyBa$_2$Cu$_3$O$_{7-\delta}$ with splayed columnar defects indicated $J_{c\parallel} > J_{c\perp}$ at high fields with anisotropy increasing at higher fields, while $J_{c\parallel} < J_{c\perp}$ at low fields [9]. For iron-based superconductors, MO images of 2.6 GeV U irradiated Ba$_{0.6}$K$_{0.4}$Fe$_2$As$_2$ with splayed columnar defects indicated $J_{c\parallel} > J_{c\perp}$ at high temperatures close to $T_c$ under the self-field [10]. However, for iron-based superconductors, no observation has been made on other materials or other ions.

Here, we report in-plane anisotropy of $J_c$ in Ba$_{0.6}$K$_{0.4}$Fe$_2$As$_2$ single crystals and Ba(Fe$_{0.93}$Co$_{0.07}$)$_2$As$_2$ single crystals with splayed columnar defects observed through MO imaging, and discuss the possible mechanism for the behavior.

2. Experimental Methods

Ba$_{0.6}$K$_{0.4}$Fe$_2$As$_2$ single crystals ($T_c \sim 38$ K) were synthesized by FeAs flux method [11, 12, 13], and Ba(Fe$_{0.93}$Co$_{0.07}$)$_2$As$_2$ single crystals ($T_c \sim 24$ K) were synthesized by FeAs/CoAs flux method [14]. The crystals were shaped into rectangular parallepipeds with length and width of approximately 500 $\mu$m and with thickness below half of the projected range of ions. Bimodal splayed columnar defects were installed into the crystals through 2.6 GeV U irradiation or 220 MeV Au irradiation. 2.6 GeV U irradiation was performed using the RIKEN Ring Cyclotron, and 220 MeV Au irradiation was performed using the tandem accelerator in JAEA. The bimodal splay angle ($\theta_{cd}$) is denoted by the angle between their $c$-axis and the ion beam. For 2.6 GeV U irradiation, all the samples were irradiated at a total dose of $B_0 = 8$ T. For 220 MeV Au irradiation, all the samples were irradiated at a total dose of $B_0 = 8$ T $\times \cos\theta_{cd}$.\(^{-1}\)

In order to estimate $J_c$, magnetization measurements were performed with a superconducting quantum interference device (SQUID) magnetometer. The single crystal was placed in a quartz sample holder and fixed with Apiezon N grease. $J_c$ was calculated from the results of the magnetization measurements using extended Bean model.

In order to observe the in-plane anisotropy of $J_c$, MO imaging was performed. The single crystal was mounted on a copper sample holder and held together with Apiezon N grease to fix and to increase thermal conductivity to the sample holder. On top of the sample holder, a ferrimagnetic garnet indicator film with a reflective mirror was placed in direct contact with the crystal. The whole assembly was placed on a cold finger and shrouded by a radiation shield, then cooled by a He-flow cryostat. The light intensity versus flux density reference was obtained after locating the sample above the $T_c$ between -500 Oe and 500 Oe using a copper solenoid. The reference were fitted with a second order polynomial, in which the coefficients were used to calculate the flux density. Remanent state images were obtained after applying a field of 1 kOe for 1 second.

In the usual MO imaging method using a ferrimagnetic garnet indicator, an in-plane field is applied to diminish the effect of in-plane magnetic domain formed in the indicator. However, an in-plane field can induce an in-plane anisotropy of $J_c$. In order to observe the pure in-plane anisotropy of the samples, MO imaging was performed without applying in-plane field, which leads to MO images with noises due to in-plane magnetic domains.

3. Results and Discussion

For detailed discussions, it is crucial to be aware of the structure of introduced defects through irradiation. Figures 1(a)-(c) show scanning transmission microscope (STEM) images of 2.6 GeV U irradiated Ba$_{0.6}$K$_{0.4}$Fe$_2$As$_2$ single crystal, 220 MeV Au irradiated Ba$_{0.6}$K$_{0.4}$Fe$_2$As$_2$ single crystal, and 2.6 GeV U irradiated Ba(Fe$_{0.93}$Co$_{0.07}$)$_2$As$_2$ single crystal, respectively. The white arrows indicate the $c$-axis. It should be noted that individual defect structures are expected to be independent of splay angle as long as they are created by heavy ions injected from not too far from the $c$-axis. As shown in figure 1(b), in Ba$_{0.6}$K$_{0.4}$Fe$_2$As$_2$ single crystal, 220 MeV Au irradiation introduces discontinuous columnar defects with the length of $\sim$10 nm. As shown in figure
Figure 1. STEM images of cross-sections of (a) 2.6 GeV U irradiated Ba$_{0.6}$K$_{0.4}$Fe$_2$As$_2$ single crystal with splayed columnar defects of $\theta_{\text{CD}} = \pm 20^\circ$, (b) 220 MeV Au irradiated Ba$_{0.6}$K$_{0.4}$Fe$_2$As$_2$ single crystal with columnar defects of CD|$c$, and (c) 2.6 GeV U irradiated Ba(Fe$_{0.93}$Co$_{0.07}$)$_2$As$_2$ single crystal with splayed columnar defects with $\theta_{\text{CD}} = \pm 30^\circ$. The white arrows indicate the $c$-axis.

1(c), in Ba(Fe$_{0.93}$Co$_{0.07}$)$_2$As$_2$ single crystal, 2.6 GeV U irradiation also introduces discontinuous columnar defects with the length of $\sim$100 nm. As shown in figure 1(a), in Ba$_{0.6}$K$_{0.4}$Fe$_2$As$_2$ single crystal, 2.6 GeV U irradiation introduces more continuous columnar defects. Structures perpendicular to the $c$-axis observed in 2.6 GeV U irradiated Ba(Fe$_{0.93}$Co$_{0.07}$)$_2$As$_2$ single crystal (figure 1(c)) are considered to be stacking faults.

Figures 2(a)-(b) show magnetic field dependence of $J_c$ in the pristine and irradiated Ba$_{0.6}$K$_{0.4}$Fe$_2$As$_2$ single crystals. As shown in figure 2(a), the self-field $J_c$ at 2 K in the pristine Ba$_{0.6}$K$_{0.4}$Fe$_2$As$_2$ single crystal exhibits a value of 3.6 MA/cm$^2$. As shown in figure 2(b), splayed columnar defects introduced through 220 MeV Au irradiation enhance the self-field $J_c$ at 2 K over 20 MA/cm$^2$.

Figures 2(c)-(e) show magnetic field dependence of $J_c$ in the pristine and irradiated Ba(Fe$_{0.93}$Co$_{0.07}$)$_2$As$_2$ single crystals. As shown in figure 2(c), the self-field $J_c$ at 2 K in the pristine Ba(Fe$_{0.93}$Co$_{0.07}$)$_2$As$_2$ single crystal exhibits a value of 1.2 MA/cm$^2$. As shown in figures 2(d)-(e), splayed columnar defects introduced through 2.6 GeV U irradiation and 220 MeV Au irradiation enhance the self-field $J_c$ at 2 K over 2.5 MA/cm$^2$.

Figure 3(a) shows the remanent state MO image of 2.6 GeV U irradiated Ba(Fe$_{0.93}$Co$_{0.07}$)$_2$As$_2$ single crystal with splayed columnar defects with $\theta_{\text{CD}} = \pm 5^\circ$ after sweeping the field from 1 kOe back to zero field at 21 K. A critical state with a double Y-shaped current discontinuity line is formed. Unlike the isotropic case with a discontinuity line of an angle of 45$^\circ$ with respect to the sample edge, in-plane anisotropy of $J_c$ appears as a skewed double Y-shaped discontinuity line. It is confirmed $J_{c\parallel} > J_{c\perp}$ for 2.6 GeV U irradiated Ba(Fe$_{0.93}$Co$_{0.07}$)$_2$As$_2$ single crystal with splayed columnar defects, which is consistent with the result for 2.6 GeV U irradiated Ba$_{0.6}$K$_{0.4}$Fe$_2$As$_2$ [10].

For quantitative analysis of the in-plane anisotropy of $J_c$, line profiles (figure 3(b), (c)) were taken along two lines parallel (white) and perpendicular (red) to the splay direction in figure 3(a). The distances of the flux density peak from the sample edge are not equal. Here, the in-plane anisotropy of $J_c$ can be estimated from the ratio of the two distances. For 2.6 GeV U irradiated Ba(Fe$_{0.93}$Co$_{0.07}$)$_2$As$_2$ single crystal with splayed columnar defects with $\theta_{\text{CD}} = \pm 5^\circ$, the in-plane anisotropy is estimated as $J_{c\parallel}/J_{c\perp} \sim 1.23$ at 21 K.
**Figure 2.** Magnetic field dependence of $J_c$ in (a) pristine Ba$_{0.6}$K$_{0.4}$Fe$_2$As$_2$ single crystal, (b) 220 MeV Au irradiated Ba$_{0.6}$K$_{0.4}$Fe$_2$As$_2$ single crystal with splayed columnar defects with $\theta_{CD} = \pm 5^\circ$, (c) pristine Ba(Fe$_{0.93}$Co$_{0.07}$)$_2$As$_2$ single crystal, (d) 2.6 GeV U irradiated Ba(Fe$_{0.93}$Co$_{0.07}$)$_2$As$_2$ single crystal with splayed columnar defects with $\theta_{CD} = \pm 5^\circ$ and (e) 220 MeV Au irradiated Ba(Fe$_{0.93}$Co$_{0.07}$)$_2$As$_2$ single crystal with splayed columnar defects with $\theta_{CD} = \pm 20^\circ$.

**Figure 3.** (a) The MO image of 2.6 GeV U irradiated Ba(Fe$_{0.93}$Co$_{0.07}$)$_2$As$_2$ single crystal with splayed columnar defects with $\theta_{CD} = \pm 5^\circ$ at $T = 21$ K. The white arrow indicates the splay direction. (b) Line profiles along the white line in (a). (c) Line profiles along the red line in (a).

Figure 4(a) shows the remanent state MO image of 220 MeV Au irradiated Ba$_{0.6}$K$_{0.4}$Fe$_2$As$_2$ single crystal with splayed columnar defects with $\theta_{CD} = \pm 5^\circ$ after sweeping the field from 1 kOe back to zero field at 37 K. Since the crystal has a macroscopic defect in the left half, the in-plane anisotropy should be discussed focusing on the right half of the sample. Unlike 2.6 GeV U irradiated Ba$_{0.6}$K$_{0.4}$Fe$_2$As$_2$ and Ba(Fe$_{0.93}$Co$_{0.07}$)$_2$As$_2$, the angle between the discontinuity line and the sample edge is nearly 45°, which indicates isotropic $J_c$. Figures 4(b)-(c) show line profiles taken along two axes as shown by the white (parallel to the splay direction) and red (perpendicular to the splay direction) lines in figure 4(a). For 220 MeV Au irradiated
Figure 4. (a) The MO image of 220 MeV Au irradiated Ba$_{0.6}$K$_{0.4}$Fe$_2$As$_2$ single crystal with splayed columnar defects with $\theta_{CD} = \pm 5^\circ$ in the remanent state after applying a field of 1 kOe along the $c$-axis at $T = 37$ K. The white arrow indicates the splay direction. (b) Line profiles along the white line in (a). (c) Line profiles along the red line in (a).

Figure 5. (a) The MO image of 220 MeV Au irradiated Ba(Fe$_{0.93}$Co$_{0.07})_2$As$_2$ single crystal with splayed columnar defects with $\theta_{CD} = \pm 20^\circ$ in the remanent state after applying a field of 1 kOe along the $c$-axis at $T = 21$ K. The white arrow indicates the splay direction. (b) Line profiles along the white line in (a). (c) Line profiles along the red line in (a).

Ba$_{0.6}$K$_{0.4}$Fe$_2$As$_2$ single crystal with splayed columnar defects with $\theta_{CD} = \pm 5^\circ$, the in-plane anisotropy is estimated as $J_{c\parallel}/J_{c\perp} \sim 1.08 \sim 1$ at 37 K.

Figure 5(a) shows the remanent state MO image of 220 MeV Au irradiated Ba(Fe$_{0.93}$Co$_{0.07})_2$As$_2$ single crystal with splayed columnar defects with $\theta_{CD} = \pm 20^\circ$ after sweeping the field from 1 kOe back to zero field at 21 K. Unlike 2.6 GeV U irradiated Ba$_{0.6}$K$_{0.4}$Fe$_2$As$_2$ and Ba(Fe$_{0.93}$Co$_{0.07})_2$As$_2$, the angle between the discontinuity line and the sample edge is nearly 45$^\circ$, which indicates isotropic $J_c$. Figure 5(b)-(c) show line profiles taken along two axes as shown by the white (parallel to the splay direction) and red (perpendicular to the splay direction) lines in figures 5(a). For 220 MeV Au irradiated Ba(Fe$_{0.93}$Co$_{0.07})_2$As$_2$ single crystal with splayed columnar defects with $\theta_{CD} = \pm 20^\circ$, the in-plane anisotropy is estimated as $J_{c\parallel}/J_{c\perp} \sim 0.96 \sim 1$ at 21 K.

All the obtained results can be summarized as follows. 2.6 GeV U irradiated samples with splayed columnar defects show clear in-plane anisotropy with $J_{c\parallel} > J_{c\perp}$, while 220 MeV Au irradiated samples with splayed columnar defects have little in-plane anisotropy. These results are interpreted as follows. In systems with bimodal splayed columnar defects, the vortex motion is controlled by zig-zag type kinks for $J_{c\parallel}$, whereas the vortex motion is manifested by double kinks for $J_{c\perp}$, as suggested by López et al. [7], which leads to $J_{c\parallel} > J_{c\perp}$. One of the possible
origins of the difference between 2.6 GeV U irradiation and 220 MeV Au irradiation is continuity of the introduced columnar defects. Columnar defects in 220 MeV Au irradiated Ba$_{0.6}$K$_{0.4}$Fe$_2$As$_2$ are discontinuous, while those in 2.6 GeV U irradiated Ba$_{0.6}$K$_{0.4}$Fe$_2$As$_2$ are more continuous. Splayed continuous columnar defects such as those introduced in Ba$_{0.6}$K$_{0.4}$Fe$_2$As$_2$ through 2.6 GeV U irradiation can strongly suppress the vortex motion for $J_{c\parallel}$, which leads to $J_{c\parallel} > J_{c\perp}$, while splayed discontinuous columnar defects such as those introduced in Ba$_{0.6}$K$_{0.4}$Fe$_2$As$_2$ through 220 MeV Au irradiation serve as relatively isotropic pinning centers, which leads to little in-plane anisotropy of $J_c$. Though columnar defects introduced in Ba(Fe$_{0.93}$Co$_{0.07}$)$_2$As$_2$ through 2.6 GeV U irradiation are also discontinuous, each segment is much longer than those introduced in Ba$_{0.6}$K$_{0.4}$Fe$_2$As$_2$ through 220 MeV Au irradiation and can induce a larger in-plane anisotropy. Since 220 MeV Au irradiated Ba(Fe$_{0.93}$Co$_{0.07}$)$_2$As$_2$ single crystal has little in-plane anisotropy, columnar defects introduced in Ba(Fe$_{0.93}$Co$_{0.07}$)$_2$As$_2$ through 220 MeV Au irradiation are expected to be similarly discontinuous those introduced in Ba$_{0.6}$K$_{0.4}$Fe$_2$As$_2$ through 220 MeV Au irradiation.

4. Summary
We performed MO imaging to observe in-plane anisotropy of $J_c$ in 2.6 GeV U irradiated Ba(Fe$_{0.93}$Co$_{0.07}$)$_2$As$_2$, 220 MeV Au irradiated Ba$_{0.6}$K$_{0.4}$Fe$_2$As$_2$, and 220 MeV Au irradiated Ba(Fe$_{0.93}$Co$_{0.07}$)$_2$As$_2$ single crystals with bimodal splayed columnar defects. We found obvious in-plane anisotropy as $J_{c\parallel} > J_{c\perp}$ in 2.6 GeV U irradiated crystals and no obvious in-plane anisotropy in 220 MeV Au irradiated crystals. The difference between 2.6 GeV U irradiated crystals and 220 MeV Au irradiated crystals can be understood as the difference of pinning efficiency for $J_{c\parallel}$ due to the difference of continuity of introduced columnar defects.

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