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Field-driven transition in $Ba_{1-x}K_xFe_2As_2$ with splayed columnar defects

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Abstract. Columnar defects in type-II superconductors serve as artificial pinning centers, which lead to enhancement of critical current density. However, little is known about the details of vortex motion in iron-based superconductors with columnar defects. In this study, we performed magnetization measurements in $Ba_{0.6}K_{0.4}Fe_2As_2$ single crystals with splayed columnar defects for several directions of magnetic field in order to investigate an anomalous peak effect in the system. We report results of detailed magnetization measurements, and discuss possible origins of the field-driven transition.

1. Introduction

Columnar defects in type-II superconductors serve as artificial pinning centers, which lead to 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 $YBa_2Cu_3O_{7-\delta}$ [5] and $Ba_{1-x}K_xFe_2As_2$ [6] single crystals. 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 $\approx \pm 5°$ in both of the above systems. However, little is known about the detail of vortex motion in superconductors with columnar defects. Actually, we found an anomalous peak effect when the splay angle of columnar defects is increased further [6]. On the other hand, it has been reported that a field-driven transition occurs in $Bi_2Sr_2CaCu_2O_{8+y}$ [7, 8, 9, 10] and $YBa_2Cu_3O_{7-\delta}$ [11] when columnar defects are introduced. Theoretically, a Monte Carlo simulation for $Bi_2Sr_2CaCu_2O_{8+y}$ with columnar defects suggests a field-driven transition with enhancement of vortex trapping rate by columnar defects at 1/3 of matching field B_Φ [12]. The relationship between the anomalous peak effect in $Ba_{1-x}K_xFe_2As_2$ with splayed columnar defects, and the field-induced transition in cuprates is not clear.

Here, we report results of detailed magnetization measurements in $Ba_{0.6}K_{0.4}Fe_2As_2$ single crystals with splayed columnar defects, and discuss possible origins of the field-driven transition.

2. Experimental Methods

$Ba_{0.6}K_{0.4}Fe_2As_2$ single crystals ($T_c \sim 38$ K) were synthesized by FeAs flux method [13, 14, 15], and were shaped into rectangular parallelepiped of length and width of approximately 500 μm and of thickness of 30 μm or less. Columnar defects were installed into the crystals by 2.6 GeV ^{238}U irradiation at the RIKEN Ring Cyclotron with a total dose of $B_\Phi = 8$ T. The incident directions of U ions were splayed by tilting the crystals about their *ab*-plane using a well-controlled servo-motor, and the splay angle ($\theta_{\rm CD}$) is denoted by the angle between their *c*-axis and the ion beam.

Magnetization measurements were performed with a superconducting quantum interference device (SQUID) magnetometer. For several directions of magnetic field, the component of magnetization parallel to the field was measured. For these measurements, an acrylic sample holder with a rotating sample slot was employed. Here we define ϕ_H as the angle between the splay-plane and the field-plane and θ_H as the angle between *c*-axis and the field. Magnetization measurements were performed for fields parallel to the *c*-axis ($\theta_H = 0°$), fields tilted in the splay-plane ($\phi_H = 0°, \theta_H \neq 0°$), and fields tilted in a plane perpendicular to the splay-plane ($\phi_H = 90°, \theta_H \neq 0°$). The critical current density, $J_{\rm c}$, was calculated from the results of the

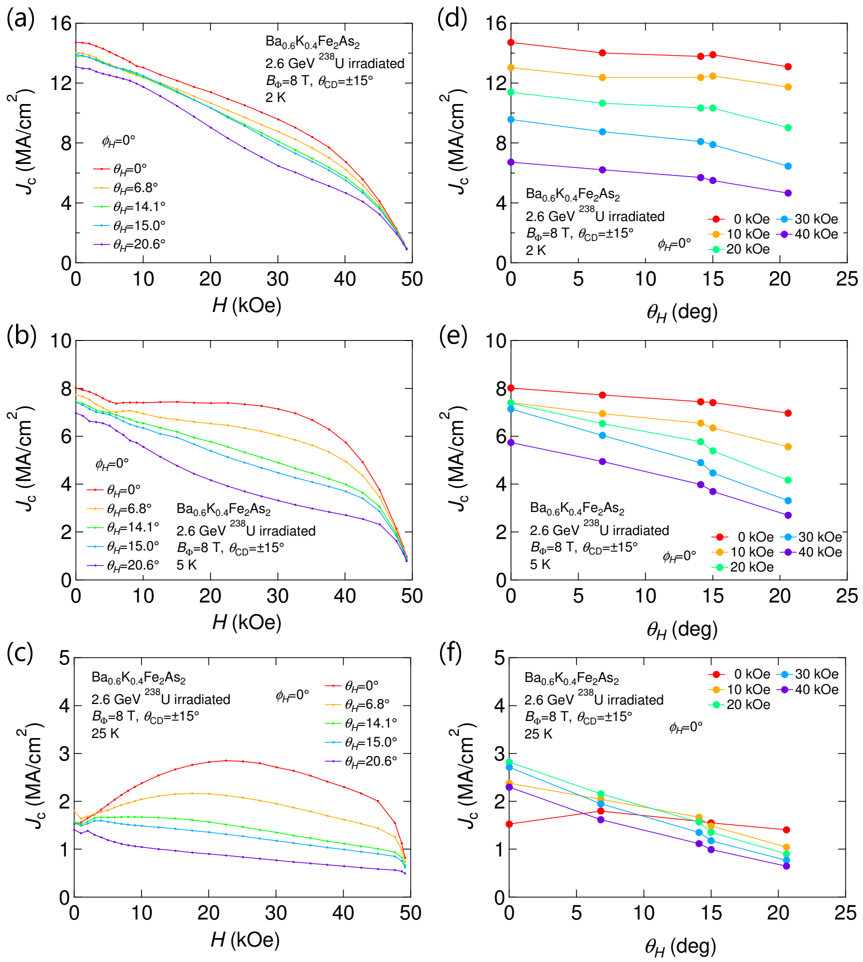

Figure 1. θ_H and magnetic field dependence of $J_{\rm c}$ for fields in the splay-plane ($\phi_H = 0°$) in $Ba_{0.6}K_{0.4}Fe_2As_2$ single crystals with splayed columnar defects of $\theta_{\rm CD} = \pm 15°$. Magnetic field dependence of $J_{\rm c}$ at several θ_H at 2 K, 5 K, and 25 K are shown in (a), (b), and (c), respectively. $J_{\rm c}$ as functions of θ_H at several fields at 2 K, 5 K, and 25 K are shown in (d), (e), and (f), respectively.

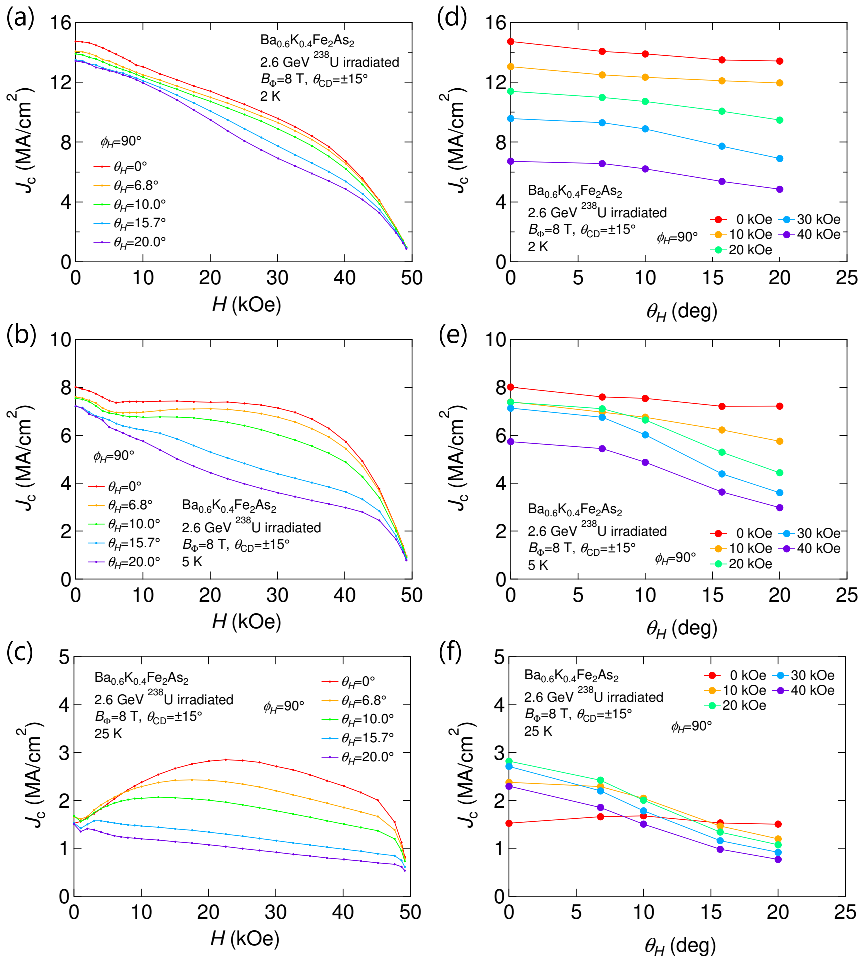

Figure 2. θ_H and magnetic field dependence of J_c for fields in a plane perpendicular to the splay-plane ($\phi_H = 90°$) in $Ba_{0.6}K_{0.4}Fe_2As_2$ single crystals with splayed columnar defects of $\theta_{CD} = \pm 15°$. Magnetic field dependence of J_c at several θ_H at 2 K, 5 K, and 25 K are shown in (a), (b), and (c), respectively. J_c as functions of θ_H at several fields at 2 K, 5 K, and 25 K are shown in (d), (e), and (f), respectively.

magnetization measurements using extended Bean model.

3. Results and Discussion

Figures 1(a)-(c) show magnetic field dependence of J_c at several θ_H for fields in the splay-plane ($\phi_H = 0°$) in $Ba_{0.6}K_{0.4}Fe_2As_2$ single crystals with splayed columnar defects of $\theta_{CD} = \pm 15°$. J_c as functions of θ_H at several fields are extracted from figures 1(a)-(c) and shown in figures 1(d)-(f). At 2 K, $J_c - H$ is weakly dependent on θ_H (figure 1(a)), and J_c is almost independent of θ_H as shown in figure 1(d). When the temperature is increased to 5 K, an anomalous peak effect starts to show up at around 30 kOe (figure 1(b)). This anomalous peak effect is suppressed as θ_H is increased. At higher temperature of 25 K, the anomalous peak effect shows up more clearly at around 25 kOe for $\theta_H = 0$, and it is suppressed quickly as θ_H is increased.

Figures 2(a)-(c) show magnetic field dependence of J_c at several θ_H for fields in a plane perpendicular to the splay-plane ($\phi_H = 90°$) in $Ba_{0.6}K_{0.4}Fe_2As_2$ single crystals with splayed

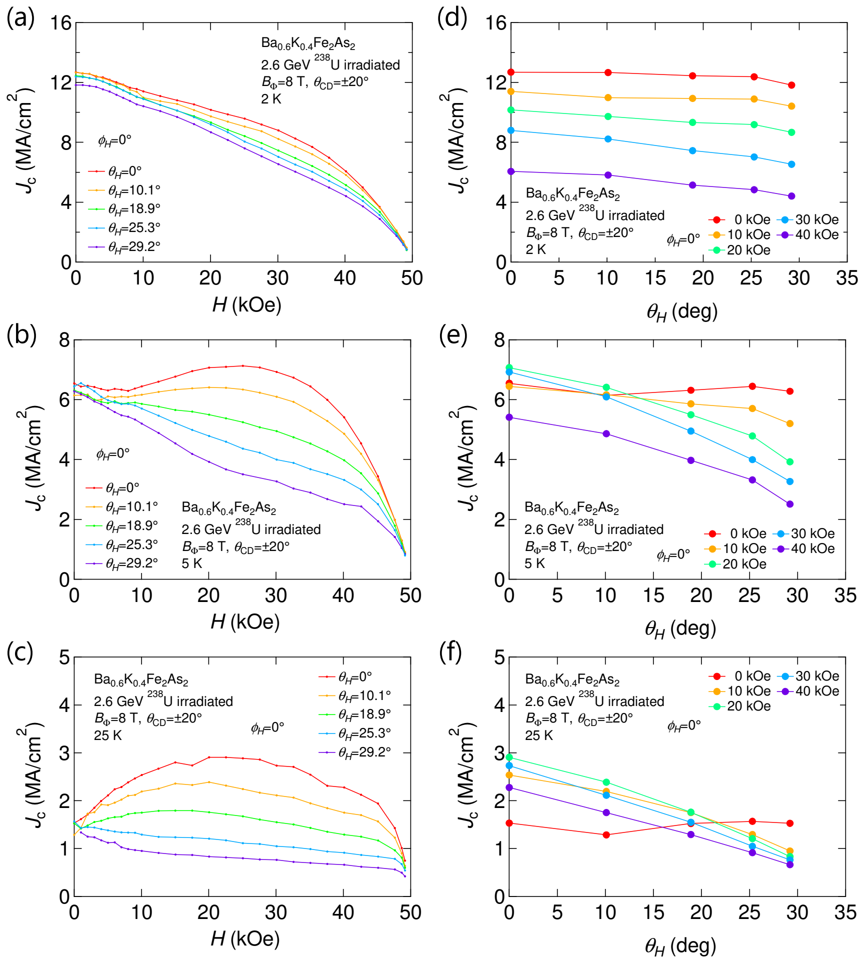

Figure 3. θ_H and magnetic field dependence of J_c for fields in the splay-plane ($\phi_H = 0°$) in $Ba_{0.6}K_{0.4}Fe_2As_2$ single crystals with splayed columnar defects of $\theta_{CD} = \pm 20°$. Magnetic field dependence of J_c at several θ_H at 2 K, 5 K, and 25 K are shown in (a), (b), and (c), respectively. J_c as functions of θ_H at several fields at 2 K, 5 K, and 25 K are shown in (d), (e), and (f), respectively.

columnar defects of $\theta_{CD} = \pm 15°$. J_c as functions of θ_H at several fields are extracted from figures 2(a)-(c) and shown in figures 2(d)-(f). At a glance, $J_c - H$ for $\phi_H = 90°$ is very similar to that for $\phi_H = 0°$ at the same θ_H. However, a close inspection makes it clear that the suppression of the anomalous peak effect with an increase in θ_H is weaker for $\phi_H = 90°$ as evidenced by the shallower initial slope of $J_c - \theta_H$ in figures 2(e) and (f).

Figures 3(a)-(c) show magnetic field dependence of J_c at several θ_H for fields in the splay-plane ($\phi_H = 0°$) in $Ba_{0.6}K_{0.4}Fe_2As_2$ single crystals with splayed columnar defects of $\theta_{CD} = \pm 20°$. J_c as functions of θ_H at several fields are extracted from figures 3(a)-(c) and shown in figures 3(d)-(f). Anomalous peak effects are also observed in these samples similar to those with $\theta_{CD} = \pm 15°$. However, there is a difference in that at 25 K $J_c - H$ in samples with $\theta_{CD} = \pm 20°$ still has an anomalous peak when the direction of field is closer to one families of columnar defects ($\theta_H \approx |\theta_{CD}|$) (figure 3(c)), while for $J_c - H$ in samples with $\theta_{CD} = \pm 15°$, the anomalous peak is already suppressed at $\theta_H \approx |\theta_{CD}|$ (figure 1(c)).

All the obtained results can be summarized as follows. In systems with splayed columnar defects, an additional component of J_c appears with a peak at $1/5-1/3$ of B_Φ, when the external field is applied along the average direction of the columnar defects. This additional component of J_c becomes larger as θ_{CD} is increased at least up to $\theta_{CD} = \pm 20°$. A clear peak effect of J_c has been observed at around 1/3 of B_Φ also in $YBa_2Cu_3O_{7-\delta}$ with columnar defects created by irradiating 580 MeV Sn ions when the field is applied along the direction of columnar defects [1]. However, in the case of 580 MeV Sn, the direction of columnar defects is naturally splayed due to the deflection of ion motion owing to its relatively low energy. Therefore, the actual situation is very similar to the present case of intentional splay of the direction of columnar defects. These results are interpreted as follows. In a system with regular array of columnar defects, vortex pinning becomes most effective at the matching field B_Φ. On the other hand, random distribution of columnar defects in heavy-ion irradiated system, the optimal vortex pinning is realized at some fraction of B_Φ because of the strong repulsive interactions between vortices trapped in columnar defects. Splay in the arrangement of columnar defects makes the pinning stronger due to the suppression of kink motion and entanglement of vortices when the magnetic field is applied along the average direction of columnar defects. When the magnetic field is tilted away from the average direction in a system with splayed columnar defects, one set of columnar defects are more preferentially occupied and the advantageous effect of splayed columnar defects mentioned above is weakened, and thus the anomalous peak effect is suppressed.

4. Summary

We performed detailed magnetization measurements in $Ba_{0.6}K_{0.4}Fe_2As_2$ single crystals with splayed columnar defects, and clarified external-field-direction dependence of J_c. The results suggest that in systems with splayed columnar defects there exists an additional component of J_c with a peak at $1/5-1/3$ of B_Φ, when the external field is applied along the average direction of the columnar defects. In contrast to a system with regular array of columnar defects, in a system with random distribution of columnar defects produced by heavy-ion irradiation, the optimal vortex pinning is realized at some fraction of B_Φ because of the strong repulsive interactions between vortices trapped in columnar defects. In a system with splayed columnar defects, pinning of vortices becomes stronger due to the suppression of kink motion and entanglement of vortices when the magnetic field is applied along the average direction of columnar defects. When the magnetic field is tilted away from the average direction in such a system, one set of columnar defects are more preferentially occupied and the advantageous effect of splayed columnar defects mentioned above is weakened, and thus the anomalous peak effect is suppressed.

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