Physica C 518 (2015) 47–50

Contents lists available at ScienceDirect

Physica C

journal homepage: www.elsevier.com/locate/physc

Effects of heavy-ion irradiations in K-doped $BaFe_2As_2$

F. Ohtake [a], T. Taen [a], S. Pyon [a], T. Tamegai [a,*], S. Okayasu [b], T. Kambara [c], H. Kitamura [d]

[a] Department of Applied Physics, The University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-8656, Japan
[b] Advanced Science Research Center, Japan Atomic Energy Agency, Tokai, Ibaraki 319-1195, Japan
[c] Nishina Center, RIKEN, 2-1 Hirosawa, Wako, Saitama 351-0198, Japan
[d] Radiation Measurement Research Section, National Institute of Radiological Sciences, 4-9-1 Anagawa, Inage-ku, Chiba 263-8555, Japan

ARTICLE INFO

Article history:
Received 30 January 2015
Received in revised form 15 June 2015
Accepted 17 June 2015
Available online 25 June 2015

Keywords:
$(Ba_{0.6}K_{0.4})Fe_2As_2$
Heavy-ion irradiation
Critical current density
Columnar defect

ABSTRACT

We report the effects of heavy-ion irradiation in $(Ba_{0.6}K_{0.4})Fe_2As_2$ single crystals including its dose dependence. We found that the suppression of T_c is weak up to a certain dose of irradiation. Critical current density (J_c) under self-field is strongly enhanced up to 15 MA cm^{-2} at 2 K by the introduction of defects through irradiations with different energies and ion species. This upper limit is in agreement with the previous report for that in cuprate superconductors. The dose dependence of J_c follows $B_\Phi{}^{1/2}$, which can be explained by the simple scenario on the interaction between a driven vortex and discontinuous columnar defects.

1. Introduction

After the discovery of iron-based superconductors (IBSs) in 2008 [1], numerous research works have been performed to understand the mechanism of this novel superconductivity. At the same time, because of their large critical current densities (J_c) at high magnetic fields and temperatures, they have been investigated as promising materials for practical applications. It is known that J_c in superconductors can be further enhanced by introducing defects using swift particle irradiations [2]. In our previous studies, remarkable effects have been demonstrated in IBS using heavy-ions [3–8] and protons [9] into Co-doped Ba-122 single crystals. In these reports, we irradiated heavy-ions such as 200 MeV Au, 800 MeV Xe, and 2.6 GeV U to create columnar defects, which have excellent geometrical matching with vortices, and are expected to be ideal pinning centers. Actually, 200 MeV Au at a dose-equivalent matching field (B_Φ) of 2 T enhanced J_c by a factor of six even at low temperatures [3]. Recently, another promising IBS $(Ba_{1-x}K_x)Fe_2As_2$ was found and has started to attract interest due to its high transition temperature (T_c) and J_c in the pristine sample. It has been reported that J_c was enhanced up to 5×10^6 A/cm^2 by irradiating 1.4 GeV Pb at $B_\Phi = 21$ T [10]. We have also reported proton [11] and several heavy-ion irradiations [12,13] into the same system and achieved J_c as high as 1×10^7 A/cm^2 [12]. In this paper, we investigated the effect of several heavy-ion irradiations into optimally K-doped Ba-122 single crystal, $(Ba_{0.6}K_{0.4})Fe_2As_2$, with $T_c \sim 38.8$ K. Changes in T_c and J_c are systematically studied as a function of the irradiation dose.

2. Experiments

Single crystals of optimally K-doped $BaFe_2As_2$ used in the present irradiation experiments were synthesized by FeAs self-flux method. The K composition was determined by EDX measurements. 200 MeV and 320 MeV Au irradiations were performed using the tandem accelerator in JAEA. 2.6 GeV U irradiation was performed using a ring cyclotron at RIKEN. 800 MeV Xe irradiation was performed at NIRS-HIMAC. In all cases, particles were irradiated along *c*-axis of the crystals that were prepared to be thin enough so that irradiated ions can penetrate through them. The irradiation dose is counted by the dose-equivalent magnetic field called “matching field”, where each defect is occupied by single vortex

$$B_\Phi = n\Phi_0, \tag{1}$$

where *n* is the nominal areal density of the defects and Φ_0 is a flux quantum. Magnetization of the crystal was measured by a commercial SQUID magnetometer (MPMS-XL5, Quantum Design).

Fig. 1 shows the B_Φ dependence of T_c of $(Ba_{0.6}K_{0.4})Fe_2As_2$ irradiated with various ions with different energies measured by zero-field cooled (ZFC) and field-cooled (FC) magnetizations measurements along *c*-axis. The T_c of the pristine sample is 38.8 K, and those of irradiated samples with $B_\Phi < 8$ T were just slightly

---

[*] Corresponding author. Tel.: +81 3 5841 6846; fax: +81 3 5841 8886.
E-mail address: tamegai@ap.t.u-tokyo.ac.jp (T. Tamegai).

http://dx.doi.org/10.1016/j.physc.2015.06.009
0921-4534/

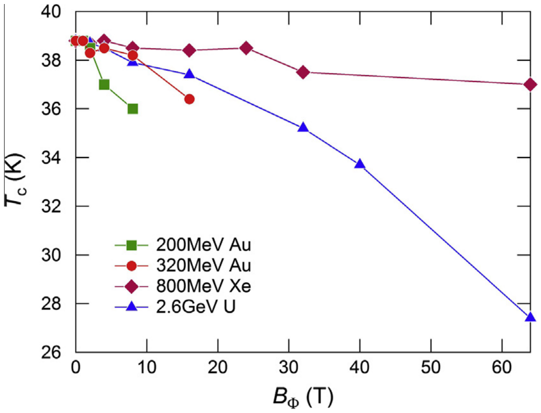

Fig. 1. The B_Φ dependence of T_c in $(Ba_{0.6}K_{0.4})Fe_2As_2$ single crystals irradiated with various ions with different energies.

lower than that of the pristine one. Theoretically, perfectly introduced correlated columnar defects do not suppress T_c, and it accounts for the weak suppression on T_c of the sample with small B_Φ. This weak suppression is believed to be caused by secondary electrons, which are created in the process of interaction between the energetic ions and atoms of sample and create small point defects that suppress T_c [14]. From this point of view, it can be seen that 800 MeV Xe ions makes less secondary electrons since almost no suppression of T_c was observed in samples with $B_\Phi < 24$ T, while other irradiations suppressed T_c more clearly even in the sample with $B_\Phi < 8$ T. However, T_c of the samples with higher B_Φ is remarkably suppressed. It is suggested that severe overlaps of defects introduced by irradiation occurs, which reduces the volume fraction of good superconducting regions sustaining higher T_c.

From the magnetization hysteresis loop, critical current density J_c [A/cm^2] can be calculated by using the Bean model

$$J_c = \frac{20\Delta M}{a(1 - a/3b)}, \qquad (2)$$

where ΔM [emu/cc] is $M_{down} - M_{up}$, M_{up} and M_{down} are the magnetization when sweeping fields up and down, respectively, and a [cm] and b [cm] are the sample widths with $a < b$.

Fig. 2 shows the B_Φ dependence of J_c in irradiated $(Ba_{0.6}K_{0.4})Fe_2As_2$ at 2 K under zero field. The strong J_c enhancement up to 15 MA cm^{-2} is observed in all cases, while J_c in irradiated $Ba(Fe_{0.93}Co_{0.07})_2As_2$ single crystal with heavy ions is enhanced only up to 6 MA cm^{-2} at the maximum [5]. The J_c of irradiated samples was enhanced with increasing B_Φ at different rate depending on irradiation ions and energies, which is explained by the difference of the degree of geometrical matching between introduced columnar defects and vortices. The diameter and length of the introduced defects are determined by various conditions, including the irradiated ion species and their energy. Based on the results of the present studies, we can say that 200 MeV and 320 MeV Au irradiation introduce most effective defects to enhance the value of J_c in $(Ba_{0.6}K_{0.4})Fe_2As_2$ single crystals.

There are two remarkable features in Fig. 2; one is that in all irradiations J_c is enhanced in proportion to $B_\Phi{}^{1/2}$ systematically in the small B_Φ region, and another is that there seems to be an upper limit of J_c at ∼15 MA cm^{-2}. A similar upper limit was shown in the case of cuprate superconductors, whose J_c have not been enhanced more than 5–10% of its depairing current even when defects were perfectly introduced [2]. The depairing current of $(Ba_{0.6}K_{0.4})Fe_2As_2$ is roughly estimated as ∼200 MA cm^{-2}, the present maximum value of $J_c = 15$ MA cm^{-2} is equivalent to 7.5% of the depairing current, and this is the almost same as in the case of cuperates. Although the mechanism of this upper limit is still unknown, we can say that 200 MeV and 320 MeV Au and 2.6 GeV U ions irradiation are effective methods that enhance J_c of $(Ba_{0.6}K_{0.4})Fe_2As_2$ to the practically available maximum value.

The $B_\Phi{}^{1/2}$ dependence of J_c enhancement shown in Fig. 2 can be explained as follows [10]. Fig. 3 shows a schematic picture of a vortex and columnar defects. a_Φ is the mean distance between neighboring columnar defects, calculated as $a_\Phi = (\Phi_0/B_\Phi)^{1/2}$. We simulate the situation where nonideal discontinuous columnar defects are created through the sample by the irradiation. In the remanent state, the number of vortices is small enough to consider that there are no vortex–vortex interactions (single vortex regime). In such a case, we only take into account the vortex–defect interaction. When the Lorentz force $f_L = J_c\Phi_0/c$ acts on a vortex, a part of the vortex in the gap space is driven and makes a semi-loop ("vortex 1" in Fig. 3(a)), since vortex in that region gains no pinning energy by columnar defects. The semi-loop can be driven by the Lorentz force to the neighboring columnar defect ("vortex 2" in Fig. 3(a)). Once this happens, two segments of vortices between columnar defects can slide freely toward opposite directions ("vortex 3" in Fig. 3(a)). The sliding should stop when the segment of vortex reaches the gap as shown in Fig. 3(b), and the force balance in this situation determines the ultimate J_c. The Lorentz force on this segment $f_L a_\Phi$ is balanced by the restoring force of the segment, which is the pinning energy U_p in this case [10]. So, J_c is calculated as $J_c = cU_p/\Phi_0 a_\Phi$, which can explain the $B_\Phi{}^{1/2}$ dependence of J_c. Fang *et al.* proposed that the situation as shown in Fig. 3(b) occurs when B_Φ is larger than the typical threshold field (B_G) of the order

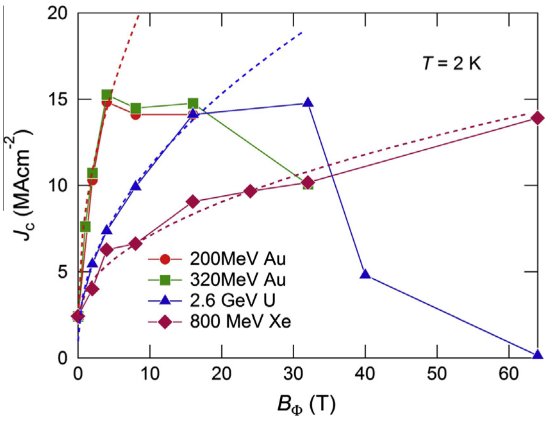

Fig. 2. The B_Φ dependence of J_c of irradiated $(Ba_{0.6}K_{0.4})Fe_2As_2$ at 2 K under zero field. Dashed lines show $B_\Phi{}^{1/2}$ dependence of enhanced J_c.

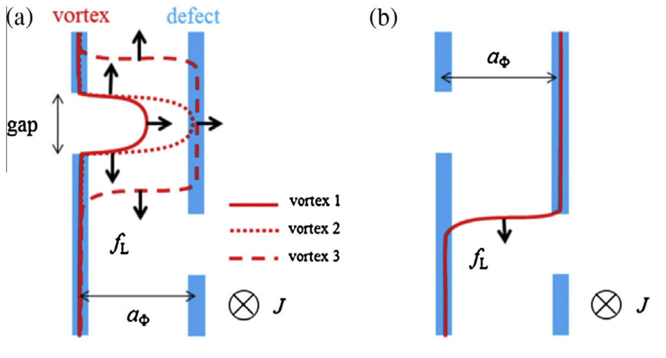

Fig. 3. The schematic picture of interaction between a vortex (red line) being driven by Lorentz force f_L and columnar defects (thick blue lines). $a_\Phi = (\Phi_0/B_\Phi)^{1/2}$ is the mean distance between neighboring columnar defects. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)