Effects of swift Xe irradiation in Ba(Fe$_{1-x}$Co$_x$)$_2$As$_2$ single crystals

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Abstract. We have systematically investigated the effects of 300 MeV Xe irradiation along c-axis in optimally Co-doped BaFe$_2$As$_2$. Reflecting the cascade defects morphology induced by the irradiation, $T_c$ in this system is reduced while the value of $\Delta T/T_c$ is small. Here we report the details of suppression rates of $T_c$ experimentally without an ambiguity of piece dependencies. We found that the reduction is systematic if we assume sample thickness dependence in creating defects. We also discuss the observed saturation behavior of $J_c$ in terms of defect density.

1. Introduction
Superconductors with higher superconducting transition temperature ($T_c$) and higher critical current density ($J_c$) are desired in application. One of the ways to achieve higher $J_c$ is an introduction of pinning centers for vortices and particle irradiation is commonly used for such a purpose. Generally speaking, particle irradiation is better to evaluate the efficiency of pinning than chemical substitution since this method does not seriously change electronic structure of the sample nor deteriorate its quality. However, point defects, usually introduced by light particle irradiation, could work as pair breakers and reduce $T_c$, which is a disadvantage for applications. These facts indicate that some parameter of particle irradiation has an important information in optimizing $J_c$ characteristics. In that sense, it is important to study the effect of particle irradiation and we have already reported two important cases in optimally Co-doped BaFe$_2$As$_2$: columnar defects introduced by Au irradiation [1] and point defects by proton irradiation [2].

As expected, 200 MeV Au irradiation at a dose of $B_\phi = 20$ kG successfully enhances $J_c$ five times as large as that of a pristine sample at 2 K under zero field without changing $T_c$ [1]. Similar results were obtained in 1.4 GeV Pb irradiation by Prozorov et al. [3]. By contrast, we can clearly observe a reduction of $T_c$ in 3 MeV proton irradiation at a dose of $1.2 \times 10^{16}$ cm$^{-2}$, $\Delta T_c/T_c \sim 17\%$ with 2.5 times enhancement of $J_c$ at 2 K under zero field [2, 4].

As mentioned above, we now know the general behavior of $T_c$ and $J_c$ in two important defects morphology. The next step is to study another possible morphology of defects to be introduced either intentionally or accidentally in application. Here we report the effects of 300 MeV Xe
irradiation in Ba(Fe$_{0.93}$Co$_{0.07}$)$_2$As$_2$. In the case of 800 MeV Xe irradiation in the same system, TEM observations show cascade defects with increasing doses [5]. Since we can naturally deduce that 300 MeV Xe irradiation makes a similar cascade defects morphology, we clarify the effects of cascade defects to $T_c$ and $J_c$ in this experiment.

2. Experiments

Single-crystalline samples of optimally-doped Ba(Fe$_{0.93}$Co$_{0.07}$)$_2$As$_2$ were synthesized by FeAs/CoAs self-flux method and their fundamental properties are reported in Ref.[6]. The average Co concentration in the batch was determined by energy-dispersive x-ray spectroscopy measurements. 300 MeV Xe irradiation along $c$-axis was performed at a dose of $B_\phi = 10, 20, 40, 80, \text{ and } 160 \text{ kG}$ in Japan Atomic Energy Agency. In this paper, we denote defects density with $B_\phi$, which corresponds to surface defects density $n_\phi$ via an equation $B_\phi = n_\phi \phi_0$, $\phi_0 = 2.07 \times 10^{-7}$ G-cm$^2$ is flux quantum. The samples were cleaved before the irradiation with thickness less than the projected range of $\sim 18 \mu$m calculated by the Stopping and Range of Ions in Matter-2008 [7]. Magnetization was measured by a commercial SQUID magnetometer (MPMS-XL5, Quantum Design) before and after the irradiation in each sample with field along $c$-axis. Magneto-optical images were taken after irradiation to estimate $J_c$ by local measurements.

3. Results and Discussion

Figure 1 shows temperature dependence of magnetization before and after the irradiation with $B_\phi = 20$ kG. We can clearly observe a reduction of $T_c$. We emphasize that this reduction is absolutely related to the irradiation because magnetization measurements are performed in the same sample. In other words, piece dependencies of Co concentration and so on are excluded, giving credit to our discussion.

![Figure 1](image.png)

Figure 1. Temperature dependence of magnetization before and after 300 MeV Xe irradiation at a dose of $B_\phi = 20$ kG in Ba(Fe$_{0.93}$Co$_{0.07}$)$_2$As$_2$.

Figure 2(a)-(b) show field dependence of critical current densities at several temperatures in $B_\phi = 10$ kG and $B_\phi = 160$ kG sample, respectively. Critical current density is calculated by the Bean model formula [8, 9],

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

(1)
where $\Delta M$ is $M_{\text{down}} - M_{\text{up}}$, $M_{\text{up}}$ and $M_{\text{down}}$ are the magnetization when sweeping the field up and down, respectively, $a$ and $b$ are sample widths ($a < b$). In both samples the fish-tail effect, nonmonotonic field dependence of $J_c$ with a broad maximum, which existed before irradiation [10], disappears by irradiation. This behavior is similar to Au and proton irradiations [1, 2]. With increasing defect density, the reduction of $J_c$ at low field becomes smaller at all temperatures. This is in good agreement with introducing denser pinning centers.

![Figure 2](image2.png)

**Figure 2.** Magnetic field dependence of $J_c$ at 2, 5, 7.5, 10, 15, and 20 K after 300 MeV Xe irradiation at a dose of (a) $B_\phi = 10$ kG and (b) $B_\phi = 160$ kG in Ba(Fe$_{0.93}$Co$_{0.07}$)$_2$As$_2$.

![Figure 3](image3.png)

**Figure 3.** (a) Dose dependence of $T_c$ in 300 MeV Xe irradiated Ba(Fe$_{0.93}$Co$_{0.07}$)$_2$As$_2$. Solid and dotted lines are guides to the eye for $t \sim 6$ $\mu$m and $t \sim 9$ $\mu$m, respectively. $T_c$ is defined by the onset of magnetization. (b) Dose dependence of $J_c$ in 300 MeV Xe irradiated Ba(Fe$_{0.93}$Co$_{0.07}$)$_2$As$_2$.

Figure 3(a) shows dose dependence of $T_c$ in irradiated samples. We note that the reduction of $T_c$ is at most $\sim 4\%$. We might conclude that $B_\phi = 160$ kG is not enough to reduce $T_c$ or this system is robust to cascade defects. Even so, there should be some explanation of this ‘nonsystematic’ $B_\phi$ dependence in $T_c$ since error bar from piece dependence is excluded here. The most plausible scenario is that this reduction of $T_c$ comes from not only $B_\phi$ but also sample thickness $t$. In fact, if we consider a set of samples with similar thicknesses; $B_\phi = 10$ and 20 kG with $t \sim 6$ $\mu$m, or $B_\phi = 40, 80$, and 160 kG with $t \sim 9$ $\mu$m, $T_c$ is reduced systematically, as shown by solid and dotted lines in Fig. 3(a), respectively. If we assume that this $T_c$ reduction is
proportional to point defect density by secondary electrons in cascade defects, we should count point defects density per unit volume \( n_{pd} \) by

\[
    n_{pd} = \gamma(t)n_\phi,
\]

where \( \gamma(t) \) is a thickness \( t \) dependent efficiency of creating point defects [11]. In this 300 MeV Xe case, we can estimate \( \gamma(6 \mu m)/\gamma(9 \mu m) = 6 \) from Fig. 3(a). This trend requires \( n_{dp} \) distribution along beam direction. Note that there is no contradiction in the temperature dependence of magnetization without broadening at any dose since the magnetization for \( H//c \) is determined by the region with the highest \( T_c \) (lowest \( n_{pd} \)). This thickness dependence of \( T_c \) reduction is not fully understood, and further investigation of this curious problem is necessary.

\( B_\phi \) dependence of \( J_c \), on the other hand, has another trend. Since the \( T_c \) suppression at lower \( B_\phi \) is negligible, the linear dependence of \( J_c \) on \( B_\phi \) is quite natural. By contrast, there is a saturation behavior of \( J_c \) at large \( B_\phi \). Our preliminary results in 800 MeV Xe irradiation in the same system also show this saturation. This novel trend means that additional defects do not work as pinning centers when the density of defects exceeds a threshold of \( B_\phi \sim 20 \) kG. Of course, \( J_c \) should finally decline when a high enough density of defects are introduced.

Finally, we comment on the possibility of a larger \( J_c \). If we simply assume that upper layer of \( \sim 6 \mu m \) has pinning and the rest \( \sim 3 \mu m \) does not, this part has 1.5 times as large as the value of \( J_c \) averaged along \( c \)-axis (current estimation). If we apply this estimation, the highest value of \( J_c \) with cascade defects is comparable to that with discrete columnar defects. Namely, as increasing cascade defects, defects morphology becomes similar to discontinuous columnar defects, and we successfully reproduce the results of \( J_c \) in 200 MeV Au irradiated system.

4. Summary
We measured \( T_c \) and \( J_c \) of 300 MeV Xe irradiated \( \text{Ba(Fe}_{0.93}\text{Co}_{0.07})\text{As}_2 \) along \( c \)-axis with doses of \( B_\phi = 10, 20, 40, 80, \) and \( 160 \) kG. In the range of our measurement, the ratio of reduction of \( T_c \) is small and the enhancement of \( J_c \) is roughly twice. \( T_c \) reduction is not solely determined by \( B_\phi \), but depends on the thickness of the sample. Point defects created by secondary electrons could be the reason of this behavior. The enhancement of \( J_c \) is linear at small doses and is saturated at large doses.

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