Effects of 2.6 GeV uranium irradiation on FeSe[†]

Y. Sun,[*1] A. Park,[*1] S. Pyon,[*1] T. Tamegai,[*1] A. Ichinose,[*2] A. Yoshida,[*3] and T. Kambara[*3]

The introduction of nonmagnetic disorders has been proven to be an effective method to identify the gap structures of novel superconductors.[1)] For point defects introduced by light-particle irradiations, such as electrons and protons, a clear suppression of T_c was observed in both cuprates and iron pnictides, which was attributed to the sign change of the order parameter in d-wave and $s_\pm$ (or competition between $s_\pm$ and s_{++} via inter- and intra-band scatterings), respectively. In the case of correlated disorders created by heavy-ion irradiation, such as columnar defects, an obvious suppression of T_c together with the increase in the normal-state resistivity has been reported in cuprates. However, the T_c shows only a small or nondetectable change in iron pnictides. The penetration depth in Co- or K-substituted $BaFe_2As_2$ was found to change after heavy-ion irradiation, which is consistent with the $s_\pm$ scenario. On the other hand, the columnar defects created by heavy-ion irradiation are also strong pinning centers due to the geometrical similarity with vortices, which have already been proven to be effective for the enhancement of critical current density J_c. Their controllability is also advantageous in the study of vortex physics. Thus, studies of the effects of heavy-ion irradiation on FeSe are crucial to the understanding of its pairing mechanism and vortex physics, which is important for the application of this material.

In this report, the effects of heavy-ion irradiation on FeSe single crystals are studied in detail by irradiating 2.6-GeV uranium up to a dose-equivalent matching field of $B_\phi = 16$ T. FeSe single crystals were grown by the vapor transport method. The obtained crystals were of high quality with a sharp superconducting transition width $\Delta T_c < 0.5$ K from susceptibility measurements and a large residual resistivity ratio of $\sim$33 as reported in our previous publications.[2–4)] Before the irradiation, single crystals were cleaved to thin plates with thickness $\sim$20 μm along the c-axis, which is much less than the projected range of 2.6-GeV uranium for FeSe of $\sim$60 μm, calculated by "Stopping and Range of Ions in Matter-2008 (SRIM-2008)". The 2.6 GeV uranium beam was irradiated parallel to the c-axis of the crystal at room temperature. The uranium irradiation was performed at the RI Beam Factory operated by RIKEN Nishina Center and CNS, the University of Tokyo.

The columnar defects were confirmed by high-resolution transmission electron microscopy observation, and they are almost continuous along the c-axis with a diameter of $\sim$10 nm, which is much greater than that of 2-5 nm observed in iron pnictides. As shown in Fig. 1, the value of T_c is found to be gradually suppressed by introducing columnar defects at a rate of $dT_c/dB_\phi \sim$ -0.29 KT^{-1}, which is greater than that observed in iron pnitides.[5)] The quick suppression of T_c suggests a unique pairing mechanism of FeSe.

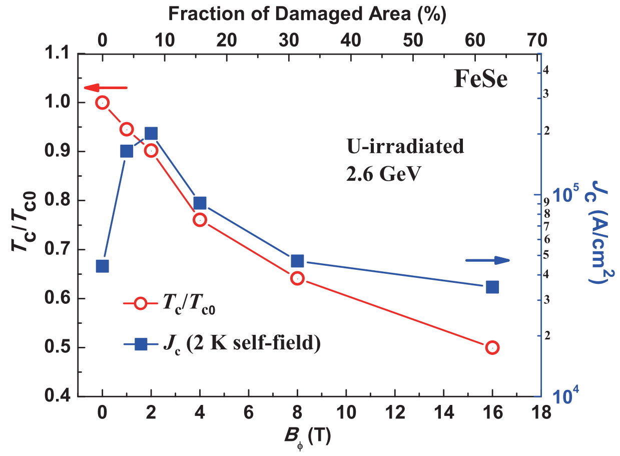

Fig. 1. Normalized T_c (T_c/T_{c0}, where T_{c0} is the value of T_c for the pristine sample) and the self-field J_c at 2 K as a function of the matching field B_ϕ (bottom axis) and damaged area (top axis) for the 2.6-GeV uranium-irradiated FeSe.

The critical current density is first dramatically enhanced with irradiation reaching a value over $\sim 2\times10^5$ A/cm^2 at 2 K (self-field) for $B_\phi = 2$ T, and then gradually suppressed with further increase in B_ϕ. The evolution of T_c and J_c with irradiation dose is explained by the large diameter of columnar defects. The nature of the quick enhancement of J_c by a small dose of heavy-ion irradiation in FeSe is also advantageous for real application. In addition, vortex dynamics study shows that the δl-pinning associated with charge-carrier mean-free-path fluctuations and the δT_c-pinning associated with spatial fluctuations of the transition temperature are found to coexist in pristine FeSe, while the irradiation increases the δl-pinning and makes it dominant above $B_\phi = 4$ T.

References
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*1 Department of Applied Physics, The University of Tokyo
*2 Central Research Institute of Electric Power Industry, Electric Power Engineering Research Laboratory
*3 RIKEN Nishina Center