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Critical current density and vortex dynamics in uranium irradiated Co-doped $BaFe_2As_2$

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ABSTRACT

We report the effect of defects introduced by heavy-ion irradiation with 2.6 GeV uranium ions at several matching fields in single crystalline $Ba(Fe_{0.925}Co_{0.075})_2As_2$. The suppression rate of T_c at lower matching fields is larger than that at higher matching fields. The critical current density calculated from magnetic hysteresis loop is enhanced up to 4.1×10^6 A/cm^2 at 2 K. Clear dips in magnetic hysteresis loops near zero field are observed at high matching fields. Field dependence of normalized relaxation rate is suppressed, and the relationship between the dip and the relaxation rate is discussed.

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1. Introduction

In 2008, new iron-pnictide superconductor, $LaFeAsO_{1-x}F_x$ with $T_c \sim 26$ K [1], was discovered. After that several systems of iron-based superconductors, such as 122 system [2], 11 system [3], 22426 system [4], have followed. In these materials the highest superconducting transition temperature is increased up to 56 K by rare-earth substitution [5]. Extensive research works have been performed to understand the mechanism of superconductivity and to investigate the potential for applications. For practical use, the iron-based superconductors are required to have high current densities at high magnetic fields and temperatures.

We have reported that Co-doped $BaFe_2As_2$ has superconducting critical current density, $J_c \sim 10^6$ A/cm^2 at low temperatures, which is slightly larger than that in polycrystalline MgB_2 [6,7]. Moreover this J_c is approximately the same order of magnitude as the typical J_c value in $YBa_2Cu_3O_7$ single crystals [8]. It is within the acceptable range for practical applications. To enhance J_c a very effective way is to introduce defects which act as pinning centers. Irradiation with swift heavy ions is the most common way to introduce columnar defects, which are more effective for pinning than point defects [9]. This is because columnar defects are correlated disorder. This method has been used for high-temperature cuprate superconductors and contributed to dramatic enhancement of J_c [9,10]. Furthermore, we have reported that the critical current density is enhanced around six times after introduction of columnar defects in Co-doped $BaFe_2As_2$ single crystals by Au ion irradiation [11].

In this paper, we report the rate of suppression of transition temperature, critical current density, and normalized relaxation rate in Co-doped $BaFe_2As_2$ irradiated by 2.6 GeV U ions at several different matching fields. Clear dips in magnetic hysteresis loops are observed.

2. Experimental

Single crystals of optimally Co-doped $BaFe_2As_2$ were grown by FeAs/CoAs self-flux method [6]. The Co concentration was determined by EDX measurements. 2.6 GeV U ions were irradiated along the c-axis of the single crystals by using RIKEN cyclotron. The matching field is defined by

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

where n is the area density and Φ_0 is a quantum of flux. In our experiment matching fields of 0.2, 0.5, 1, 2, 4, 8, and 16 T were used. Magnetization was measured by a commercial SQUID magnetometer (MPMS-XL5, Quantum Design). The dynamics of vortices were evaluated by monitoring the time dependence of magnetization for 1 h.

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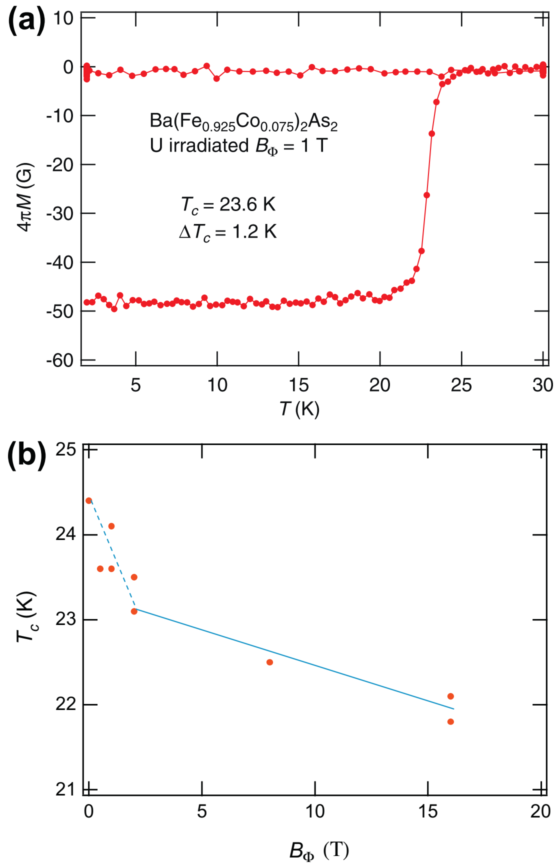

Fig. 1. (a) Temperature dependence of the zero-field-cooled (ZFC) and field-cooled (FC) magnetizations along *c*-axis at 10 Oe in uranium irradiated $Ba(Fe_{0.925}Co_{0.075})_2As_2$. (b) A relationship between T_c and matching field in uranium irradiated $Ba(Fe_{0.925}Co_{0.075})_2As_2$. The solid and broken lines are guides to the eye.

3. Results and discussion

Fig. 1a shows the temperature dependence of zero-field-cooled (ZFC) and field-cooled (FC) magnetizations along *c*-axis at 10 Oe. The T_c of an irradiated sample with $B_\Phi = 1$ T is 23.6 K. This is slightly lower than the T_c of the unirradiated sample ~ 24.4 K. This is due to extended disorder caused by heavy-ion irradiation. It is believed that if perfect columnar defects are introduced, the T_c is not suppressed. In our case, defects introduced by U irradiation may not be continuous, though they are likely to be correlated. Fig. 1b shows a relationship between T_c and matching fields. As the matching field increases, the T_c decreases. In addition, the sharpness of transition is lost at higher matching fields. However the slope of T_c suppression is not the same across the entire range of matching fields. At low matching fields the slope is −0.6 K/T as shown by a broken line, which is steeper than that at high matching fields ~ −0.086 K/T, which is shown by the solid line. It is suspected that the defects introduced by irradiation overlap at higher matching fields. It should be noted that the suppression of T_c is almost the same as the case of Pb irradiation [12]. The fluctuation of T_c among samples with the same matching field is within 0.5 K.

Fig. 2 shows the temperature dependence of magnetization at several matching fields, 1, 2, 8, and 16 T. The fish-tail anomaly is not observed in the irradiated samples. The peak near zero field becomes broad in samples with 1 and 2 T matching fields. Besides, the clear dip near zero field is observed in samples with 8 and 16 T matching fields. Similar dip structures with reduced magnetization have been reported also in Pb irradiated sample [13]. It is known that various anomalies show up near $H = B_\Phi/3$ in irradiated high temperature superconductors [14,15]. The peak effect near $H = B_\Phi/3$ in $Bi_2Sr_2CaCu_2O_{8+\delta}$ irradiated with 5.8 GeV Pb ion is one of them [16]. In our case, peaks of magnetic hysteresis loops in samples with 8 and 16 T matching fields occur at similar field values smaller than $B_\Phi/3$. Anomalies at $\sim B_\Phi/3$ have not been observed in iron-based superconductors. From the magnetization hysteresis loop, critical current density J_c [A/cm^2] is calculated by using Bean model

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

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. 3 shows critical current densities evaluated by Eq. (2). J_c is increased up to 4.1×10^6 A/cm^2 for $B_\Phi = 16$ T at 2 K and 6 kOe, and due to clear dip near zero field J_c at 2 K and 0 Oe is 3.3×10^6 A/cm^2 for $B_\Phi = 16$ T. This value is larger than that obtained by Xe irradiation, so the pinning force of uranium irradiation is stronger than Xe [17]. However, the J_c enhancement with uranium irradiation is smaller than that obtained with 200 MeV Au ion irradiation reported earlier [11]. For the uranium irradiated sample with $B_\Phi = 2$ T, the J_c at 10 K is 1.3×10^6 A/cm^2, which is twice as large as the 1.4 GeV Pb irradiated sample [13]. In other words 2.6 GeV uranium irradiation is more effective than 1.4 GeV lead irradiation. Though stopping power and velocity of incident ions may be different, pinning force of defects varies in the following order 200 MeV Au > 2.6 GeV U > 800 MeV Xe ~ 1.4 GeV Pb.

Fig. 4 shows normalized relaxation rate $S = |d\ln M/d\ln t|$ at 5 K in the remanent state for the sample with $B_\Phi = 8$ T. We find that S is suppressed similar to Au and Xe irradiation. This result also supports that defects introduced by U ion irradiation definitely work as pinning centers. It seems that in the unirradiated sample a large suppression of S near zero field causes a sharp peak of magnetic hysteresis loop at zero field. It is known that in cuprate superconductors a large normalized relaxation rate makes peaks and dips in magnetic hysteresis loops [18]. Therefore we measured S every 500 Oe at low fields to investigate the relationship between clear dips in magnetic hysteresis loop and normalized relaxation rate. However, we could not observe the peak in S around zero field. Shorter time scale measurement may be required to resolve this problem.

4. Summary

In summary, we have studied the effect of defects introduced by heavy-ion irradiation with 2.6 GeV U ions of $Ba(Fe_{0.925}Co_{0.075})_2As_2$ crystals with several matching fields. We found that the slope of T_c suppression at low matching field is −0.6 K/T and it is suppressed at higher matching fields. Due to the defects working as pinning centers maximum J_c is enhanced up to 4.1×10^6 A/cm^2 for the sample with $B_\Phi = 16$ T at 2 K. Present results suggest that 2.6 GeV U ion irradiation is more effective for enhancement of J_c than 800 MeV Xe and 1.4 GeV Pb ion irradiation, but less effective than 200 MeV Au ion irradiation. Clear dips in magnetic hysteresis loops are observed at higher matching fields and the anomaly of the normalized relaxation rate at low fields is found to be suppressed.

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