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Condensation energy density properties of Ba-122 pnictide superconductor with columnar defects introduced by heavy-ion irradiation

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Abstract

It is important to investigate condensation energy density of superconducting material, since it determines its pinning property. According to the heavy-ion irradiation, the columnar defects are introduced to the superconductor which act as the strong pinning centers, and the critical current density is enhanced by the new pinning centers. Since the number density and the size of the columnar defects can be observed, the condensation energy density is estimated by using the pinning summation theory. In the present study, we prepared $Ba(Fe_{0.93}Co_{0.07})_2As_2$ (Ba-122) pnictide superconductors by self-flux method. 200 MeV Au ions were irradiated into the specimens along *c*-axis and the matching field was 2 T. After the irradiation, the critical current density was 6 times larger than that before the irradiation. The estimated condensation energy density is in the order of 10^4 J/m^3 and is slightly smaller than those of cuprate superconductors. The temperature dependence is similar to that of $YBa_2Cu_3O_x$ oxide superconductors, since the anisotropy parameter is small in Ba-122. Therefore, it is expected to use Ba-122 at high temperatures near the critical temperature.

Keywords: Keywords: condensation energy density, Ba-122 single crystal, heavy-ion irradiation, flux pinning

1. Introduction

Newly discovered series of Fe pnictide superconductors have been studied from many interests of physics and engineering, since the superconducting mechanism is different from those of cuprate superconductors and conventional metal superconductors, and the critical temperature is quickly raised to 55 K after the first discovery in LaFeAsO (1111-type) [1]. Many efforts have been done for preparing wires for future applications. The first SmFeAsO wire prepared by the powder-in-tube method with critical temperature of 52 K was reported on the same year of discovery of 1111-type [2]. It is well known that there are two types of critical current densities inside the wire which are corresponding to local and global critical

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currents. Although the local critical current density value of 2.0×10^9 A/m^2 was observed by magnetization method, the global critical current density was 3.9×10^7 A/m^2 and 100 times smaller than the local value. It is desired to enhance the connectivity between the grains to improve the characteristics of critical current density. In the case of cuprate superconductors, the same problem was well known and was overcome by introducing new techniques, such as coated conductor in $REBa_2Cu_3O_x$(Rare Earth-123) superconductor [3] and controlled over pressure processing in $Bi_2Sr_2Ca_2Cu_3O_x$ (Bi-2223) [4]. It is expected that the problem of grain boundaries in Fe pnictide superconductors will be solved by introducing a suitable technique in near future. In fact, critical current over 60 A in (Ba, K)Fe_2As_2 in Ag sheath wire has recently been reported [5]. Therefore, it would be of great interest to estimate the potential of the critical current density in Fe pnictide superconductor.

The condensation energy density of a superconductor, $F_c = B_c^2/2\mu_0$ is a physical quantity which represents the strength of the superconductivity, i.e., the energy density difference between the normal and superconducting states, where B_c is the thermodynamic critical field. In practical cases, the pinning mechanism which determines the critical current density is the condensation energy interaction of normal cores of flux lines and pinning centers. That is, the critical current density is determined by the products of the condensation energy density, volume, number density and efficiency of pinning center. For example, the value of F_c of Nb-Ti is 2.2×10^5 J/m^3 at 0 K and is 5 times smaller than that of Nb_3Sn. Therefore, it is essential to improve the pinning efficiency to obtain high critical current density by introducing complicated form of α-Ti as the pinning centers for practical Nb-Ti wire.

Thus, it is necessary to estimate F_c of a Fe pnictide superconductor to understand the future potential of critical current density. In our previous works, the temperature dependences of F_c of cuprate superconductors such as RE-123 and Bi-2223 were estimated using the pinning center introduced by heavy-ion irradiation [6]–[10]. The density and size of the pinning center were estimated from the observation of an electron microscopy. Therefore F_c was estimated from the results of the critical current density. In this study, the condensation energy density of Ba(Fe, Co)$_2$As$_2$ (Ba-122) Fe pnictide superconductor is estimated from the characteristics of the critical current density with columnar defects introduced by heavy-ion irradiation. The potential of Ba-122 is discussed.

2. Experiments

Specimens were single crystalline $Ba(Fe_{1-x}Co_x)_2As_2$ grown by FeAs/CoAs self-flux method. The concentration of Co was determined by EDX measurements as $Ba(Fe_{0.93}Co_{0.07})_2As_2$. The critical temperature was $T_c = 24$ K measured by the temperature dependence of magnetization in field-cooled and zero-field-cooled by a SQUID magnetometer. The heavy-ion irradiations of 200 MeV Au was performed along c-axis using the TANDEM accelerator in JAEA. 800 MeV Xe ions were irradiated at NIRS-HIMAC along c-axis. In addition 2.6 GeV U ions were irradiated at RIKEN. The heavy iron irradiations created columnar defects in the specimens. The matching magnetic field, B_ϕ is 2 T in all irradiations. Furthermore, $B_\phi = 16$ T was performed for U ions irradiation. The critical temperature does not change appreciably after the heavy-ion irradiations except of U ions irradiation. The critical current density is estimated from the magnetic field dependence of the magnetization measured by a SQUID magnetometer. Further informations are reported in references [11]–[13].

3. Theory

The pinning mechanism of columnar defects created by heavy-ion irradiation is considered to be the condensation energy interaction, since the defect is amorphous and is in a normal state. Hence, the elementary pinning force is given by

$$f_p = \frac{\pi B_c^2 r_0 t}{4\mu_0} \tag{1}$$

when the coherence length in the a-b plane, ξ_{ab}, is longer than the radius of the defect, r_0, where t is the length of the defect and is considered to be equal to the thickness of the specimen in the present case. On the other hand, the elementary pinning force is given by

$$f_p = \frac{\pi B_c^2 \xi_{ab} t}{4\mu_0} \tag{2}$$

for $r_0 > \xi_{ab}$. The coherence length $\xi_{ab}(0) = 3.4$ nm is used for the current estimation which is close to the reported value of 2.44 nm [14]. Therefore, the condition between ξ_{ab} and r_0 depends on the temperature dependence of $\xi_{ab}(T) = \xi_{ab}(0)(1 - T/T_c)^{-1/2}$.

The number density of defect is given by $N_p = B_\phi/\phi_0 t$ and the probability for flux lines to be trapped by the defects is given by $B\pi(r_0 + \xi_{ab})^2/\phi_0$. Here, the effective number density of defect N'_p is given by the product of N_p and the probability as

$$N'_p = \frac{\pi(r_0 + \xi_{ab})^2 B B_\phi}{t\phi_0^2}. \tag{3}$$

Finally, the critical current density is theoretically predicted as

$$J_{c0} = \frac{\eta N'_p f_p}{B} = \frac{\pi\eta(r_0 + \xi_{ab})^2 B_\phi f_p}{t\phi^2}, \tag{4}$$

where η is the pinning efficiency given by

$$\eta = \frac{\sqrt{c^2 + 6c + 1} - c - 1}{2}; \quad c = \frac{\phi}{\pi^2 r_0^2 B_\phi}. \tag{5}$$

The value of J_{c0} is estimated from the measurement result of the critical current density using flux creep-flow theory. The detail of estimation of J_{c0} is reported elsewhere [15]. Therefore, the condensation energy density, F_c can be estimated.

4. Results and Discussion

The value of critical current density after the heavy-ion irradiation of Au increases 6–7 times as large as that of before irradiation from 2–20 K at low magnetic fields. Hence, the columnar defects are successfully introduced in the specimen and work as strong pinning centers. Figure 1 shows the magnetic field

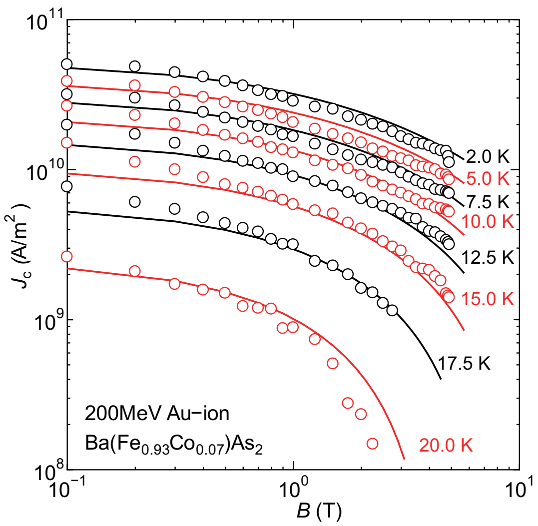

Fig. 1. Magnetic field dependence of critical current density in irradiated Ba-122 at various temperatures. Solid lines represent the theoretical value by the flux creep-flow model.

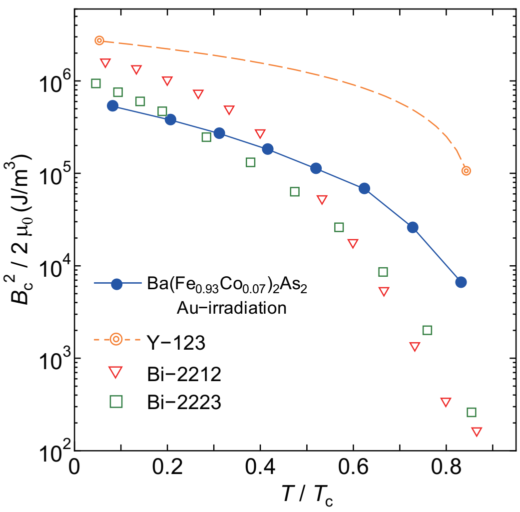

Fig. 2. Temperature dependence of the condensation energy density of various single crystalline superconductors, $YBa_2Cu_3O_x$ (Y-123)[16], $(Bi,Pb)_2Sr_2CaCu_2O_x$ (Bi-2212) and $(Bi,Pb)_2Sr_2Ca_2Cu_3O_x$ (Bi-2223)[7].

Table 1. Radius of columnar defects for several kinds of ion irradiation.

ion	Au	Xe	U (B_ϕ = 2 T)	U (B_ϕ = 16 T)
r_0 [nm]	2.5	1.0	1.9	1.1

dependence of the J_c and the theoretical value by the flux creep-flow model in various temperatures after irradiation. It is found that the experimental result of J_c is well explained by the flux creep-flow model.

Figure 2 shows the temperature dependence of the condensation energy density of various superconductors [7, 16]. The value at low temperatures is lower than those of cuprate superconductors, since the critical temperature and the upper critical field of Ba-122 are slightly smaller than those of the cuprate superconductors. However, the temperature dependence of the condensation energy density is close to that of Y-123. It is considered that the temperature dependence and the value of the condensation energy density are closely related to the anisotropy parameter, γ_a, which is the ratio of the coherence length along *a*-*b* plane and *c*-axis and reported as ∼ 2 [14], while it is known as $\gamma_a \sim 7$ for three dimensional Y-123. Hence, it is expected to use Ba-122 at high temperatures near T_c for future applications.

In the following, the sizes of the columnar defects by other ions irradiations are evaluated from the results of the condensation energy density. Since the condensation energy density is considered to be the same in the present study and the radii of the columnar defects, r_0 are unknown for Xe and U irradiations, it is expected to evaluate r_0 by the same manner. The results of r_0 are listed in Table 1. It is found that r_0 of Au is the largest and the others are smaller than that by Au. The reason for the small value of r_0 in U irradiation at B_ϕ = 16 T is considered by the overlap of the irradiation at high B_ϕ.

5. Conclusion

In this study, the condensation energy density of Ba-122 iron pnictide superconductors, which determines the pinning properties, is estimated from the summation theory and the flux creep-flow model. It is found that the value of the condensation energy density is slightly smaller than those of cuprate superconductors. However, the temperature dependence of the condensation energy density is close to that of three-dimensional Y-123, since the anisotropy parameter is small in Ba-122. Hence, it is expected that Ba-122 is used at higher temperature near T_c for future applications. The radii of the columnar defects by several kinds of heavy-ions are evaluated from the results of the condensation energy density and found that radii of the columnar by Xe and U are smaller than that by Au.

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