Effect of heavy ion irradiation on critical current property in DyBCO coated conductors

G. Isobe [a], M. Kiuchi [a], E.S. Otabe [a], T. Matsushita * [a],
S. Okayasu [b], W. Prusseit [c],

[a] *Faculty of Computer Science and Systems Engineering, Kyushu Institute of Technology, 680–4 Kawazu, Iizuka 820–8502, Japan*

[b] *Japan Atmic Energy Agency, 4–49 Mura-matu, Tokai-mura, Naka-gun 319–1184, Japan*

[c] *THEVA Düennschichttechnik GmbH, Rote-Kreuz-Str.8 ,85737 lsmaning, Germany*

Abstract

Effect of heavy ion irradiation was investigated for DyBCO coated conductor fabricated by ISD(inclined substrate deposition) process to study the flux pinning property by columnar defects. It was found that the critical current density in the specimen with large columnar defects increased sufficiently at high magnetic fields. On the other hand, the enhancement of the critical current density was not sufficient for the case of small columnar defects. The obtained results were analyzed using the flux creep-flow model and the most probable value of the virtual critical current density in the ideal creep free case was estimated for columnar defects. These results were compared with the value expected by the statistical summation theory and agreement was obtained. This theoretical result predicts that introduction of columnar defects with larger radius of higher density is effective for improvement of the critical current density.

Keywords: DyBaCuO, irradiation, columnar defect, artificial pinning, matching field, flux creep-flow model, statistical summation model
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[1] Corresponding author.
T. Matsushita
Postal address: Department of Computer Science and Electronics, Kyushu Institute of Technology, 680–4, Kawazu, Iizuka 820–8502 Japan
Phone: +81–948–29–7663; Fax: +81–948–29–7661
E-mail address: matusita@cse.kyutech.ac.jp

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1 Introduction

Long superconducting tapes with high critical current density at high magnetic fields are required for various applications. REBCO coated conductors are expected for such tapes because REBCO has higher critical current density than Bi-2223 tapes especially at high magnetic fields. The critical current density in YBCO coated conductors, which have been commonly fabricated, has been improved by development of fabrication technique of highly oriented substrates. However, the critical current density is not sufficient for various applications especially at 77 K. For the improvement of the critical current property, REBCO coated conductors with other rare earth elements than Y have been investigated because of the higher critical temperature [1]. On the other hand, introduction of artificial pinning centers has also been tried to improve the flux pinning property in particular at high magnetic fields [2]. The both trials are important to attain a high performance at 77 K.

In this study, the effect of heavy ion irradiation was examined to enhance the critical current density in DyBCO coated conductors. It is empirically known that columnar defects nucleated by heavy ion irradiation enhance significantly the critical current density due to the strong pinning of flux lines. Since the size and the number density of columnar defects are detectable, the observed flux pinning characteristics can be compared with the theoretical prediction [3]. Discussion will be given on the result and the possibility of further improvement of critical current density at high fields.

2 Experiments

Specimen was DyBCO coated conductor prepared with ISD(Inclined substrate deposition) method [4]. MgO-buffer layer of 3.7 μm was deposited by ISD method on a substrate of Hastelloy C276 and MgO cap layer of 0.3 μm was grown homo-epitaxially. Then, DyBCO layer of 1.5 μm thick was deposited by co-evaporation method. The width of the tape was 10 mm. The critical temperature was 89.7 K and the critical current in the self field at 77.3 K was 220 A before the ion irradiation.

The tape was cut in small pieces of 3.8×3.5 mm for DC magnetization measurement by SQUID magnetmetor. Specimens were irradiated with gold ion with energy of 320 MeV or nickel ion of 200 MeV. The matching field (B_ϕ) to the defects was 1.0 T for gold ion irradiation and was 0.5 T, 1.0 T, 3.0 T or 5.0 T for nickel ion irradiation. The critical temperature reduced to 88.3 K for gold ion irradiation and to 89.6 K, 89.6 K, 89.5 K, 89.2K for each dose of nickel ion irradiation. The radius of columnar defects is about 5 nm for the gold ion irradiation and about 2nm for the nickel ion irradiation.

DC magnetization was measured in a magnetic field perpendicular to the tape surface and the critical current density was estimated using the Bean model. The irreversibility field was determined by the magnetic field at which J_c reduced to 1.0×10^8 Am^{-2}.

3 Results and Discussion

Fig. 1 shows the critical current density of DyBCO coated conductor before and after the gold ion irradiation [5]. The critical current density at low magnetic fields is slightly degraded by the irradiation. This is considered to be caused by weak links of grain boundaries damaged by the irradiation. On the other hand, the critical current density is enhanced at magnetic fields above 1 T especially at high temperatures. The irreversibility field is also improved significantly. These improvements are attributed to the strong flux pinning by columnar defects. Fig. 2(a)–(d) shows the critical current density of DyBCO coated conductors before and after the nickel ion irradiation with different B_ϕ. In the case of 0.5 T and 1.0 T for B_ϕ, the critical current density is only slightly increased by the irradiation at high temperatures. The improvement is more appreciable for the case of $B_\phi = 1.0$ T. For higher B_ϕ the improvement is appreciable even at low temperatures, although the factor of improvement is low. Fig. 3 shows the variation in irreversibility field of DyBCO coated conductor by the irradiation. The irreversibility field is significantly improved for the case of the gold ion irradiation.

The critical current properties were analyzed using the flux creep-flow model [6]. According to flux creep-flow model, the pinning potential energy U_0 is important quantity to determine the flux creep characteristics. U_0 depends on the superconducting film thickness d as

$$\begin{aligned} U_0 &= \frac{0.835 g^2 k_\mathrm{B} J_\mathrm{c0}^{1/2}}{\zeta^{3/2} B^{1/4}}; \quad d > L, \\ &= \frac{4.23 g^2 k_\mathrm{B} J_\mathrm{c0} d}{\zeta B^{1/2}}; \quad d < L, \end{aligned} \tag{1}$$

where J_c0 is the virtual critical current density in the ideal flux-creep free case and ζ is a constant depending on the kind of pinning center. Here, $\zeta = 4$ is used for strong pinning center [7] for gold ion irradiation, and $\zeta = 2\pi$ is used for specimens irradiated by nickel ions since dominant existing pinning centers are weak. The pinning correlation length L is given by

$$L = \left(\frac{Ba_{\mathrm{f}}}{2\pi\mu_0 J_{\mathrm{c0}}}\right)^{1/2}. \tag{2}$$

In the above a_{f} is the flux line spacing and g^2 is the number of flux lines in the flux bundle, which is assumed to be determined so that the critical current density under the flux creep is maximized [8]. The temperature and magnetic field dependence of the virtual critical current density is empirically known to be expressed as

$$J_{\mathrm{c0}} = A\left(1-\frac{T}{T_{\mathrm{c}}}\right)^{m} B^{\gamma-1}\left(1-\frac{B}{B_{\mathrm{c2}}}\right)^{2}, \tag{3}$$

where A is a constant representing the magnitude of J_{c0}, m and γ are pinning parameters. It is empirically known that the pinning strength is distributed widely in oxide superconductors. Here it is simply assumed that only the parameter A is distributed as

$$f(A) = K\exp\left[-\frac{(\log A - \log A_{\mathrm{m}})^2}{2\sigma^2}\right], \tag{4}$$

where A_{m} is the most probable value of A, σ is a parameter representing a distribution width and K is normalization constant.

When the parameters A_{m}, σ, γ and m are given, the theoretical E-J curve can be calculated. The theoretical value of the critical current density is determined using the electric field criterion of $E_{\mathrm{c}} = 1.0 \times 10^{-8}$ V/m corresponding to the DC magnetization measurement. These pinning parameters are determined so that the calculated J_{c}-B curves agree with the experiment. σ is assumed to be similar to the value in YBCO coated conductor [9]. It is found in Figs. 4 and 5 that the theoretical results explain the observed results well. The obtained parameters in the low and high temperature regions are listed in Table 1 (a) and (b), respectively. A_{m} is remarkably improved by introduction of strong pinning centers by gold ion irradiation. However, the distribution of A is fairly wide in spite of the sharp distribution of the elementary pinning force of columnar defects. Such wide distribution of A is considered to be caused by non-uniform spatial distribution of defects in the superconductor. For specimens irradiated by nickel ions A_{m} and σ^2 increased with B_ϕ. However, the increase in A_{m} is much weaker than in the case of gold ion irradiation. The wider distribution of A seems to be caused by addition of the strong columnar defects to existing natural pinning centers.

Here the obtained A_{m} is compared with the theoretical result of statistical summation of the pinning forces of columnar defects. According to the statistical summation theory, when the radius of columnar defects r_0 smaller than coherence length in the a-b plane ξ_{ab}(12.6 nm at 77 K), the virtual critical current density is given by

$$J_{\mathrm{c0}} = \eta \frac{\pi^2 B_{\mathrm{c}}^2 (r_0 + \xi_{ab})^2 r_0 B_\phi}{4\mu_0 \phi_0^2}, \tag{5}$$

where ϕ_0 is the flux quantum, B_{c} is the thermodynamic critical field and η is the pinning efficiency given by

$$\eta = \frac{1}{2}(\sqrt{c^2 + 6c + 1} - c - 1). \tag{6}$$

In the above, $c = \phi_0 / \pi^2 r_0^2 B_\phi$. We used $B_{\mathrm{c}}(77\ \mathrm{K}) = 0.192$ T, which is the same value as that of YBCO.

The value of the virtual critical current density at low fields given by Eq. (5) was compared with A_{m}, i.e., the J_{c0} value at $T = 0$ K and $B = 1$ T, expected from the flux creep-flow model, and agreement was observed for gold ion irradiation [10]. It can be said that these theories explained well the experimental results in this case.

In this paper, we focus on the experimental result for nickel ion irradiation. The critical current density after the nickel ion irradiation was not enhanced significantly. Thus, columnar defects nucleated by nickel ion irradiation are not strong enough and the contribution from the existing pinning centers can not be neglected. Based on the collective pinning theory [11] it is proposed that J_{c0} is given by

$$J_{\mathrm{c0}} = (J_{\mathrm{c0n}}^2 + J_{\mathrm{c0s}}^2)^{1/2}, \tag{7}$$

where J_{c0s} is the component caused by columnar defects and J_{c0n} is that by existing natural pinning centers. The estimated most probable value of J_{c0}, A_{m}, is compared with the theoretical result of summation theory. The most probable value of J_{c0n} at $B = 1$ T, $T = 77$ K, $J_{\mathrm{c0m}}(1$ T, 77 K$)$, was evaluated for the specimen before the irradiation using the flux creep-flow model:

$$J_{\mathrm{c0m}}(1\ \mathrm{T}, 77\ \mathrm{K}) = A_{\mathrm{m}} \left(1 - \frac{77}{90}\right)^{2.1} = 1.0 \times 10^{10}\ [\mathrm{A/m^2}]. \tag{8}$$

Symbols in Fig. 6 are the most probable value of virtual critical current density evaluated from experimental results using the flux creep-flow model, while the solid line is the prediction of the statistical summation theory. These are close to each other at low B_ϕ. However, the experimental values are lower than the theoretical prediction at high B_ϕ. This indicates that the flux pinning is not strengthened as expected by the nickel ion irradiation. This might be caused by small radius of columnar defects nucleated by nickel ion irradiation. In Fig 6, the dotted line shows the most probable value of J_{c0} evaluated with $r_0 = 1$ nm. Since this line is much close to the experimental results, the real radius of the columnar defects may be as small as 1 nm. This speculation seems to be supported by the fact that the degradation of T_{c} in specimen irradiated by Ni ions with B_ϕ=5.0 T (0.5 K) is much lower than that in specimen irradiated by Au ions with B_ϕ=1.0 T (1.4 K). Although some aspects are still unknown the present theoretical results seem to explain the flux pinning property by columnar defects.

The theoretical result of Eq. (5) predicts that J_{c0} will be increased by increasing r_0 and B_ϕ. This seems to be expected to hold also for the flux pinning for nano-rods which can be introduced artificially to superconductors. Enhancement of the critical current density by introduction of pinning centers larger than the coherence length with high number density is expected.

4 Summary

The effect of heavy ion irradiation on the critical current density was investigated for DyBCO coated conductor deposited on ISD-MgO substrate. The gold ion irradiation was successful to enhance significantly the critical current density at high fields and the irreversibility field. However, such significantly increase was not achieved by the nickel ion irradiation. This difference is considered to be attributed to the difference in the radius of columnar defects. These results were explained well by the theoretical models of statistical summation and flux creep-flow model. From this agreement it can be concluded that introduction of defects larger than the coherence length with high number density is effective for enhancement of the critical current density at high fields. This seems to be effective also for the introduction of artificial nano-rods.

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Table 1: Pinning parameters used in the theoretical calculation

(a) The parameters at 20 K and 50 K

B_ϕ(T)(ion)	A_m	σ^2	γ	m	g^2
0.0(–)	5.0×10^{11}	0.040	0.60	1.6	1.0
1.0(Au)	1.0×10^{12}	0.050	0.48	1.5	1.0
0.5(Ni)	5.3×10^{11}	0.041	0.63	1.6	1.0
1.0(Ni)	5.8×10^{11}	0.045	0.63	1.6	1.0
3.0(Ni)	6.0×10^{11}	0.045	0.65	1.6	1.0
5.0(Ni)	6.1×10^{11}	0.047	0.66	1.6	1.0

(b) The parameters at 70 K, 77 K and 80 K

B_ϕ(T)(ion)	temperature	A_m	σ^2	γ	m	g^2
0.0(–)	70 K, 77 K, 80 K	6.0×10^{11}	0.031	0.48	2.1	2.4
1.0(Au)	70 K	1.3×10^{12}	0.037	0.37	2.0	1.7
	77 K					2.0
	80 K					2.5
0.5(Ni)	70 K	6.4×10^{11}	0.031	0.49	2.1	2.2
	77 K, 80 K					2.5
1.0(Ni)	70 K, 77 K, 80 K	7.1×10^{11}	0.032	0.50	2.1	2.3
3.0(Ni)	70 K	7.8×10^{11}	0.034	0.51	2.1	2.2
	77 K, 80 K					2.5
5.0(Ni)	70 K, 77 K, 80 K	8.7×10^{11}	0.039	0.52	2.1	2.4

Figure captions

Fig. 1 Critical current density of DyBCO coated conductor before and after gold ion irradiation.

Fig. 2 Critical current density of DyBCO coated conductor after nickel ion irradiation with (a) $B_\phi = 0.5$ T, (b) $B_\phi = 1.0$ T, (c) $B_\phi = 3.0$ T and (d) $B_\phi = 5.0$ T.

Fig. 3 Temperature dependence of irreversibility field before and after irradiation.

Fig. 4 Critical current density of DyBCO coated conductor (a) before and (b) after gold ion irradiation. Symbols and solid lines represent the experiment and theoretical results, respectively.

Fig. 5 Critical current density of DyBCO coated conductor after nickel ion irradiation. Symbols and solid lines represent the experiment and theoretical results, respectively.

Fig. 6 Virtual critical current density of DyBCO coated conductor with nickel ion irradiation. Solid symbols are values of $J_{\mathrm{c}0}$ expected from experiments using the flux creep flow model. Solid and dotted lines are predictions of statistical theory for $r_0 = 2.0$ nm and 1.0 nm respectively.

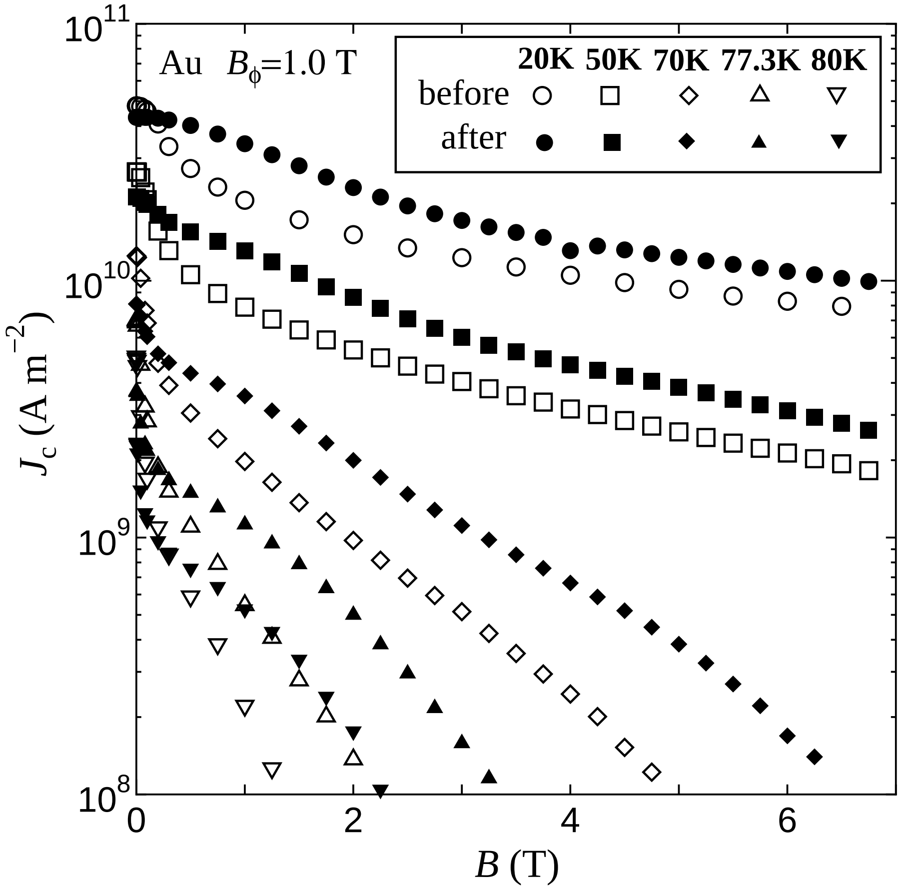
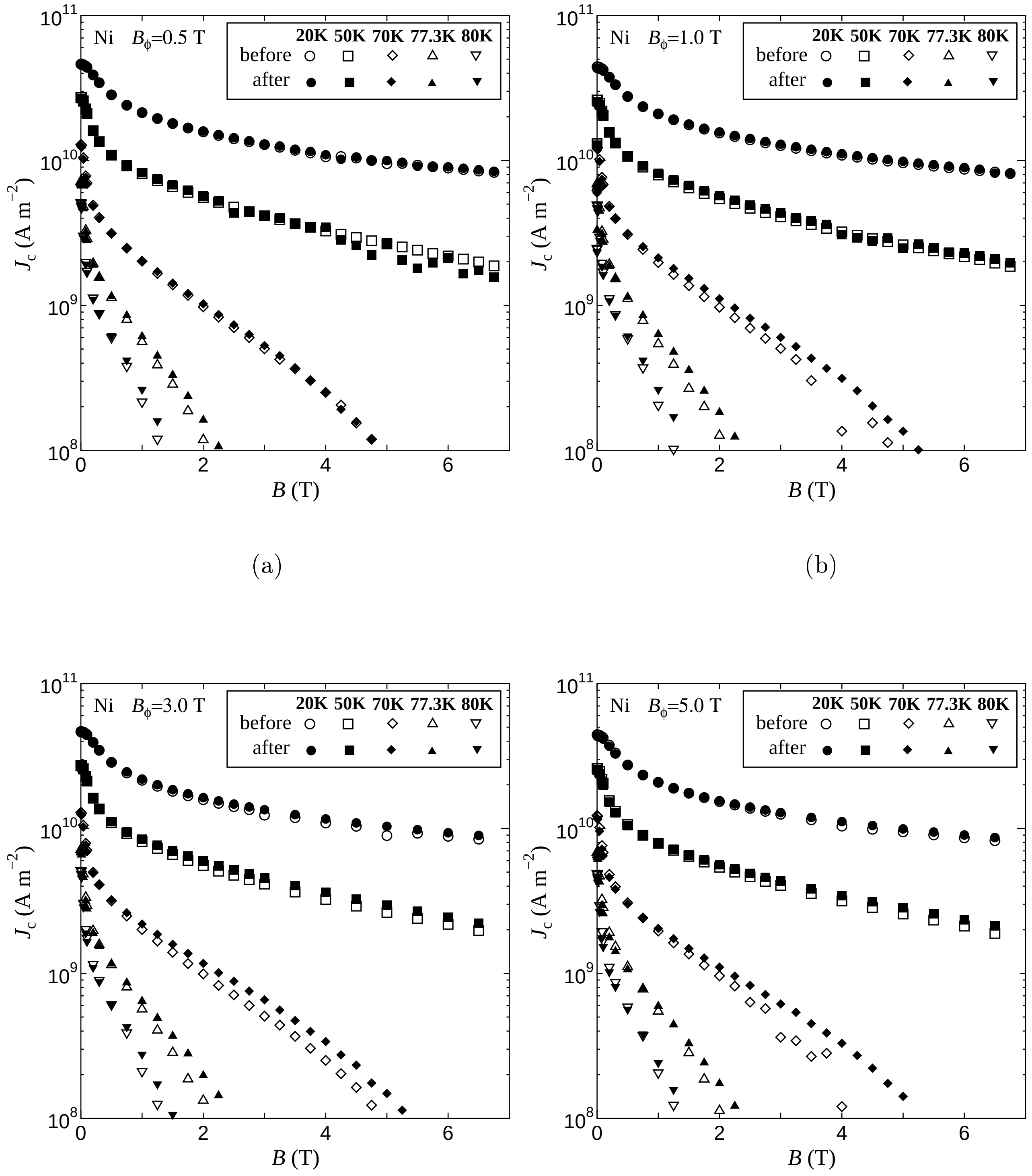


Fig. 1: G. Isobe *et al.* WTP–113/ISS2007



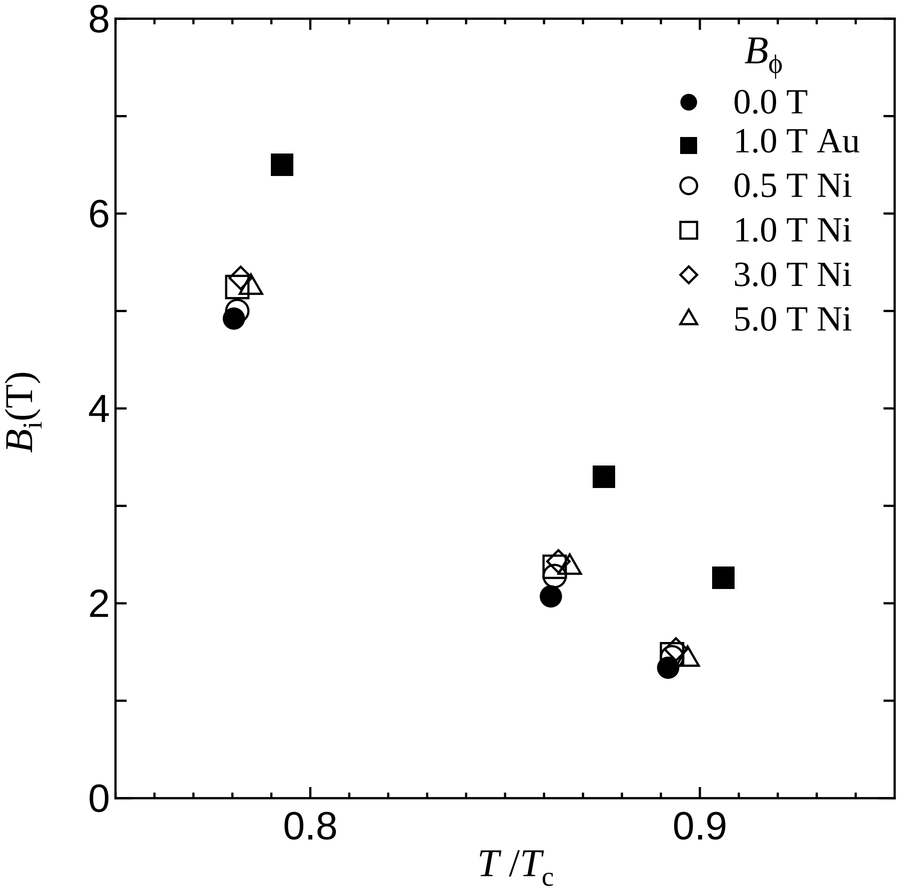
(a)

(b)

(c)

(d)

Fig. 2: G. Isobe *et al.* WTP–113/ISS2007



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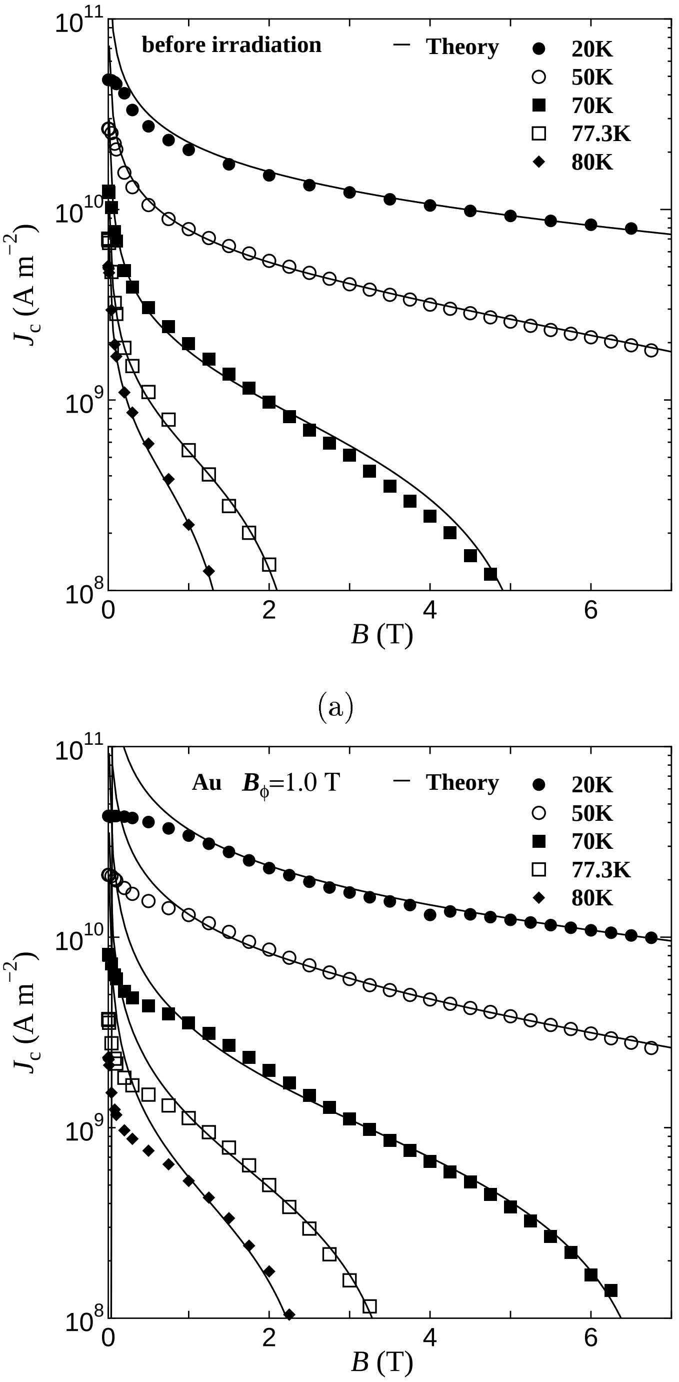

(a)

(b)

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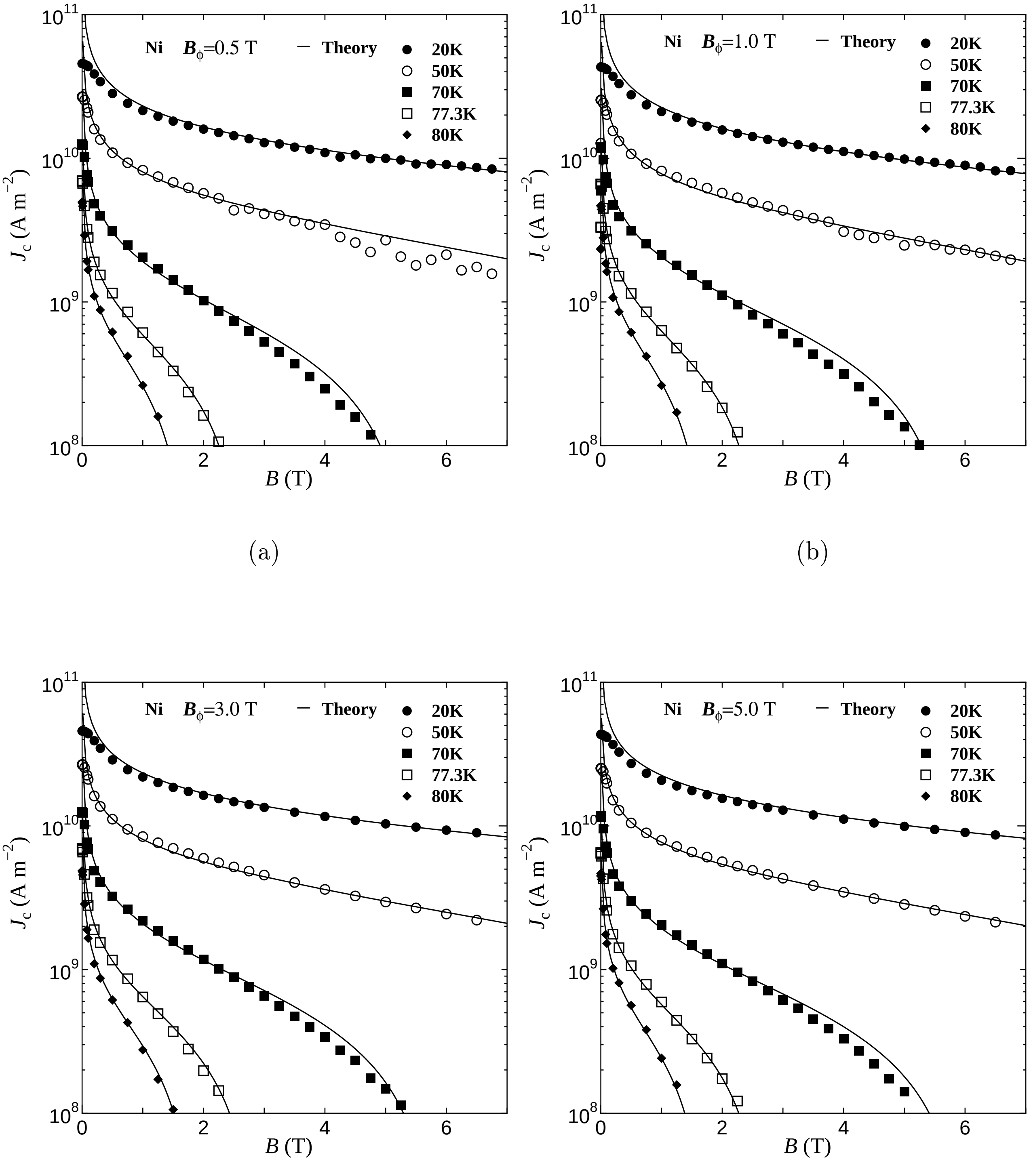

(a) (b)

(c) (d)

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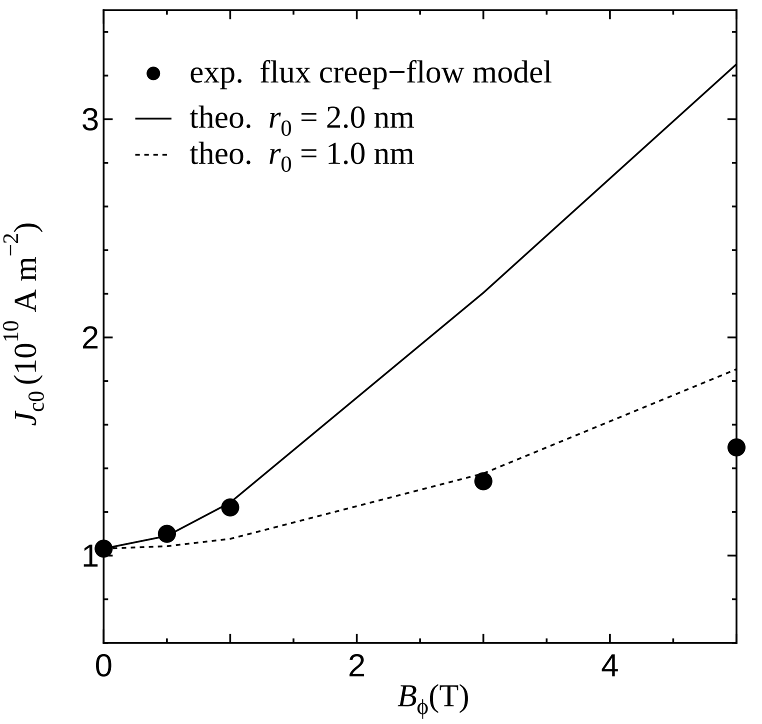

Fig. 6: G. Isobe *et al.* WTP–113/ISS2007