

Pinning characteristics at high fields in superconducting
Bi-2223 single crystals

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Abstract

Pinning properties such as the critical current density and the irreversibility field of superconducting Bi-2223 single crystals with different O₂ annealing conditions were investigated before and after a heavy ion irradiation which nucleated columnar defects parallel to the *c*-axis. The critical current density was enhanced by a factor of 3 to 4 after the irradiation due to the strong pinning effect by the columnar defects. In addition, the irreversibility field was also improved, and the improvement becomes

larger at higher temperatures. The enhancement of the pinning properties was larger in O₂ annealed specimen, suggesting an improvement of the dimensionality of the superconductivity. The experimental results were theoretically analyzed using the flux creep-flow model. It was found that the theoretical prediction can explain the experimental results of the critical current density and the irreversibility field.

Keywords: Bi-2223 single crystal, columnar defects, critical current density, irreversibility field, dimensionality of superconductivity.

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1 Introduction

Bi-2223 superconductor has several advantages for application such as relatively high critical temperature, easy grain alignment by mechanical treatment to achieve long wires. In fact, long silver-sheathed wires of order of several km have been fabricated by the powder in tube method. Recently, the critical current density of wires has been improved by 30% by the controlled

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over pressure (CT-OP) sintering technique compared with the normal pressure sintering process [1]. The improvement of the critical current density by the CT-OP process is mainly ascribed to the densification and the better c -axis orientation in Bi-2223 superconducting phase, which is important for the connectivity of grains.

Further improvement of the critical current density is an essential problem for application of Bi-2223 wires, and for this purpose it is necessary to introduce strong pinning centers. Then, a question arises if Bi-2223 is a material with a potential for introduction of strong pinning centers. Since the flux pinning strength is directly related with the condensation energy density, the potential of Bi-2223 is expected to be clarified from estimating the condensation energy density. Recently, the condensation energy density of Bi-2223 [2] was estimated from the flux pinning strength of columnar defects nucleated in single crystals by heavy ion irradiation. It was found that the condensation energy density of an O₂ annealed Bi-2223 was higher than that of Y-123 at low temperatures [2]. This shows that Bi-2223 has a sufficient potential for application at low temperatures.

In this study, the strong flux pinning properties of columnar defects at high fields are investigated in detail and the results are compared with the theoretical analysis using the flux creep-flow model.

2 Experiments

(Bi,Pb)-2223 single crystal specimens were prepared by the KCl flux method, in which 15% of Bi site was substituted by Pb [3]. The size of the single crystals was typically $80 \mu\text{m} \times 80 \mu\text{m} \times 1 \mu\text{m}$, and the c -axis is normal to the wide surface. About one hundred of specimen pieces were placed on an aluminum plate of size of $4 \text{ mm} \times 4 \text{ mm}$. Specimen #1 was measured in as-received condition. Specimen #2 was prepared with an additional heat-treatment at 350°C for 24 hours in 1 atm oxygen atmosphere. Purpose of O_2 annealing is enhancement of superconductivity in block layers by O_2 doping. The critical temperature of specimens #1 and #2 is 107.6 K and 106.8 K, respectively. The columnar defects were nucleated parallel to the c -axis by irradiation of Au-ions with the energy of 200 MeV. The matching magnetic field of the dose, B_ϕ , was 1.0 T and the radius of the columnar was about 5.0 nm. The critical temperature decreased about 3 K after the irradiation.

The critical current density, J_c , was estimated from the DC magnetization method using a SQUID magnetometer. A magnetic field was applied parallel to the c -axis, i.e., parallel to the columnar defects. For a single piece specimen, the hysteresis of the magnetic moment, Δm , is given by

$$\Delta m = \frac{(3a - b) b^2 c}{6} J_c \quad (1)$$

in terms of J_c , where a , b and c are the length, the width and the thickness

of the specimen ($a > b$). In the present study, c and J_c are assumed to be constant in all single crystal pieces. Then, the total observed magnetic moment is approximated as

$$\Delta m = \left(\sum_{i=1}^n K_i \right) J_c, \quad (2)$$

where K_i is the constant given by

$$K_i = \frac{(3a_i - b_i) b_i^2 c}{6}, \quad (3)$$

and a_i, b_i are the length and width of each piece ($a_i > b_i$). The irreversibility field B_i is determined by the magnetic field at which J_c reduces to 1.0×10^8 A/m².

3 Theory

According to the flux creep-flow theory, the current-voltage curve of a superconductor under a flux creep is determined by the pinning potential, U_0 , which can be described in terms of the virtual critical current density, J_{c0} , in a creep-free case as:

$$U_0 = \frac{0.835 k_B g^2 J_{c0}^{1/2}}{\zeta^{3/2} B^{1/4}}, \quad (4)$$

where k_B is the Boltzmann constant and g^2 is a number of flux lines in the flux bundle. ζ is a constant depended on the kind of pinning center, and $\zeta = 4$

is known for strong pinning centers. The scaling law of J_{c0} is assumed as

$$J_{c0} = A \left(1 - \frac{T}{T_c}\right)^m B^{\gamma-1} \left(1 - \frac{B}{B_{c2}}\right)^2, \quad (5)$$

where A , m , γ are the pinning parameters. The pinning parameter A which represents the pinning strength is assumed to be statistically distributed as

$$f(A) = K \exp \left[-\frac{(\log A - \log A_m)^2}{2\sigma^2} \right], \quad (6)$$

where A_m is a most probable value of A , σ^2 is a parameter representing a distribution width and K is a normalization constant. The local electric field, E' , is determined from the mechanism of flux creep and flow. Thus, the average E - J curve is calculated from

$$E(J) = \int_0^{\infty} E' f(A) dA. \quad (7)$$

The theoretical J_c -value is determined from the calculated E - J curve with the electric field criterion of 2.0×10^{-8} V/m of the same condition as in the experiment. The details of the analysis are described in Ref. [4]. The parameters A_m , m and γ are determined so as to obtain a good agreement between theoretical and experimental results of J_c . These parameters are listed in Table 1. $\sigma^2 = 0.001$ and $g^2 = 1$ are assumed in the theoretical calculation.

4 Results and Discussion

Figure 1 (a) and (b) show the magnetic field dependence of the critical current density of specimen #1 before and after the irradiation, respectively. The solid lines represent the theoretical predictions. For the case of before the irradiation, the results in an entire region of magnetic field are compared with the theory, since point-like defects are considered to be dominant pinning centers and can be expressed by Eq. (5) over a wide range of magnetic field. The theoretical results agree well with the experimental results. On the other hand, for the case of columnar defects after the irradiation, the pinning properties are quite different between the field regions below and above the matching field of 1 T. In this paper, we focus on the pinning properties in the high field region and hence, the comparison with the flux creep-flow model is done in the magnetic field region above 1 T. The agreement is satisfactory as can be seen in Fig. 1 (b). The critical current density decreases rapidly with increasing magnetic field in this field region. This is caused by a rapid decrease in the trapping rate of flux lines by the columnar defects. As a result the pinning parameter, γ , takes a negative value. Figure 2 (a) and (b) show the case of specimen #2. It is also found that the agreement is fairly good.

In both specimens J_c increases by a factor of 3 to 4 due to the columnar defects after irradiation. Comparing Figs. 1 (b) and 2 (b), it is found that the J_c

of specimen #2 is generally larger than that of specimen #1. It is considered that the dimensionality of specimen #2 is improved by the O₂ annealing, resulting in a better performance of the pinning property by columnar defects.

Figure 3 (a) and (b) show the normalized temperature dependence of the irreversibility field of specimens #1 and #2, respectively. It is found that B_i is remarkably enhanced by the irradiation in both specimens. The solid and dotted lines represent the theoretical predictions. A good agreement is obtained between the theoretical and experimental results. It is observed that the enhancement of B_i due to the irradiation becomes large with increasing temperature. This is due to the strong pinning effect by the columnar defects against the flux creep at high temperatures. This tendency is larger in specimen #2. This also seems to be ascribed to the improved dimensionality of the superconductor by O₂ annealing.

5 Summary

In this study, the pinning properties of superconducting Bi-2223 single crystals with different O₂ annealing conditions are investigated before and after the heavy ion irradiation. Following results are obtained:

- The critical current density increases by a factor of 3 to 4 and the irreversibility field is remarkably enhanced due to the columnar defects after

the irradiation.

- The enhancement of these quantities is larger in the O₂ annealed specimen.

It is considered that the dimensionality of the superconductivity of Bi-2223 is improved by O₂ annealing.

- The theoretical prediction by the flux creep-flow model can well explain the experimental results of the critical current density and the irreversibility field.

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Figure captions

Fig. 1 Magnetic field dependence of J_c (a) before and (b) after Au-ion irradiation for as-grown specimen #1.

Fig. 2 Magnetic field dependence of J_c (a) before and (b) after Au-ion irradiation for annealed specimen #2.

Fig. 3 Normalized temperature dependence of irreversibility field of specimens (a) #1 and (b) #2, respectively.

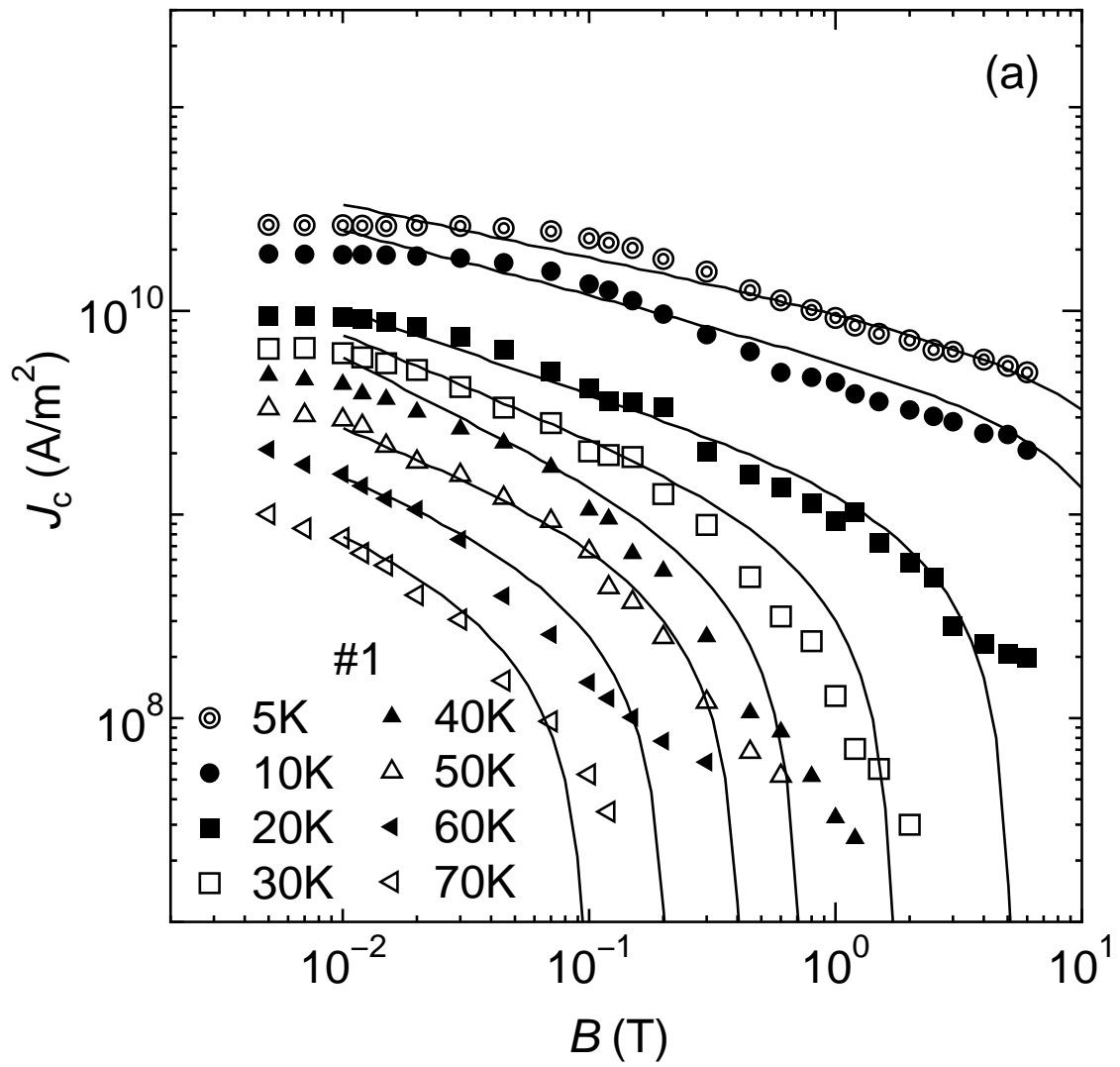


Fig. 1(a): I. Kohno *et al.* PCP-60/ISS2005

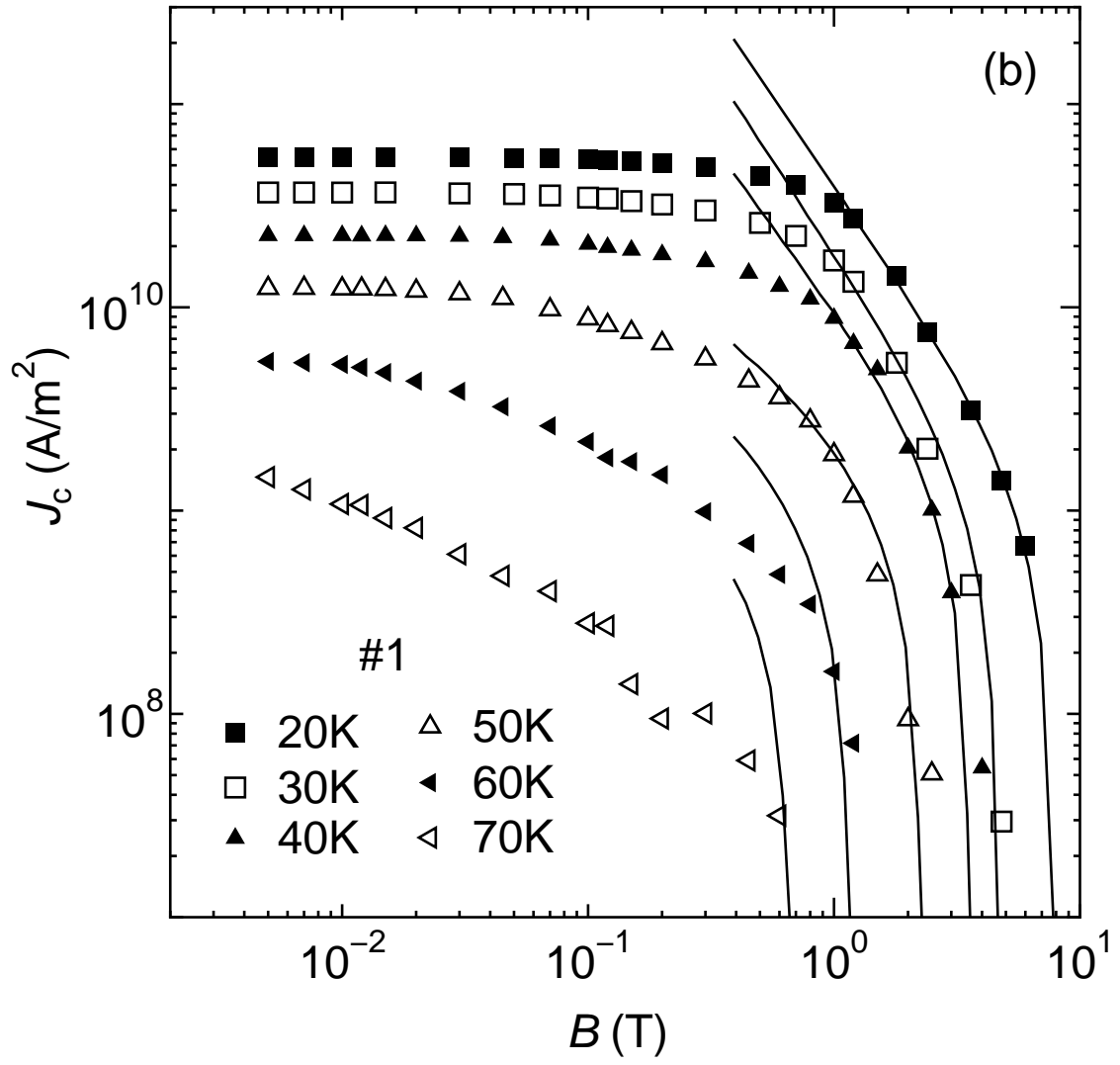


Fig. 1(b): I. Kohno *et al.* PCP-60/ISS2005

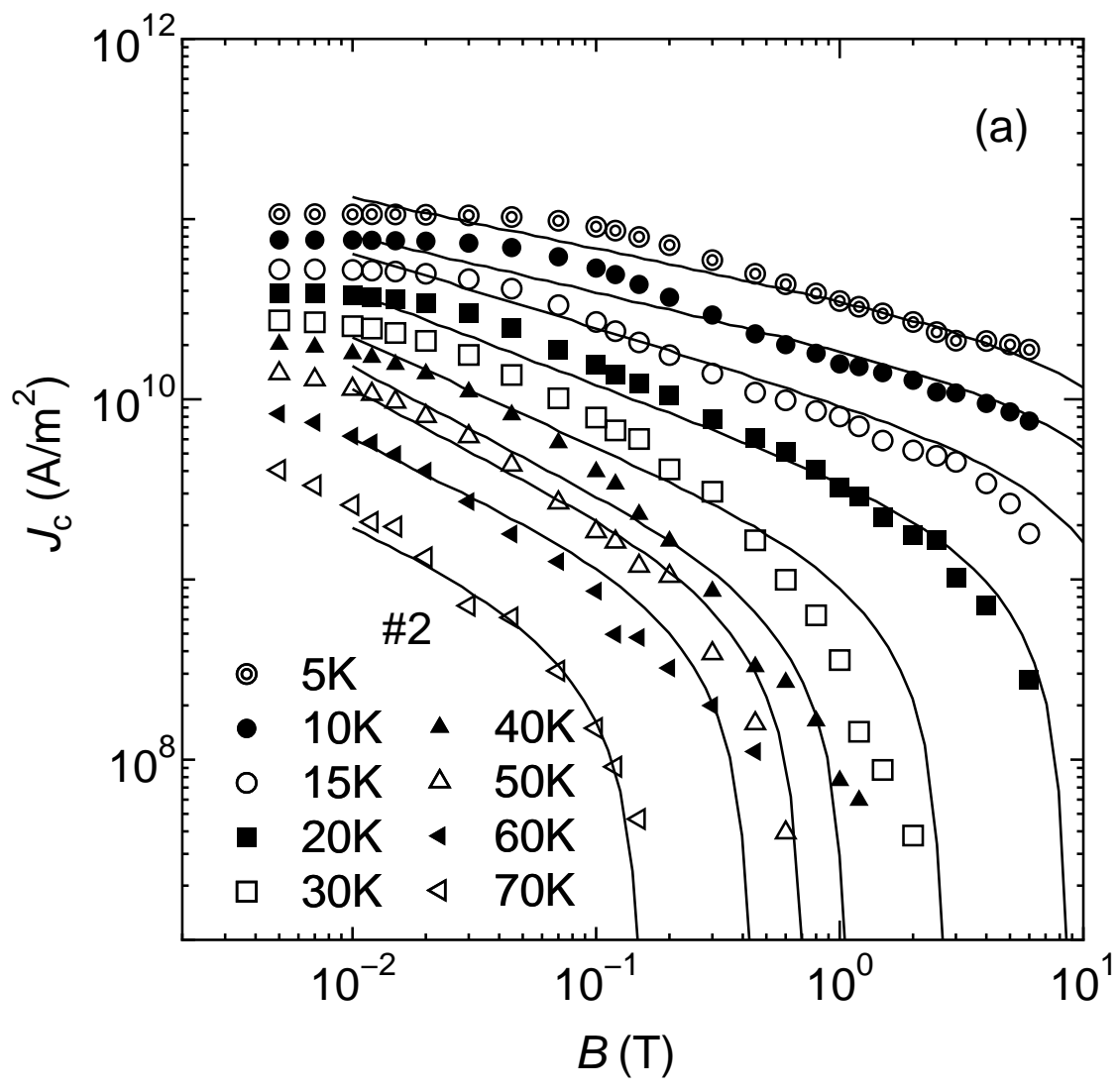


Fig. 2(a): I. Kohno *et al.* PCP-60/ISS2005

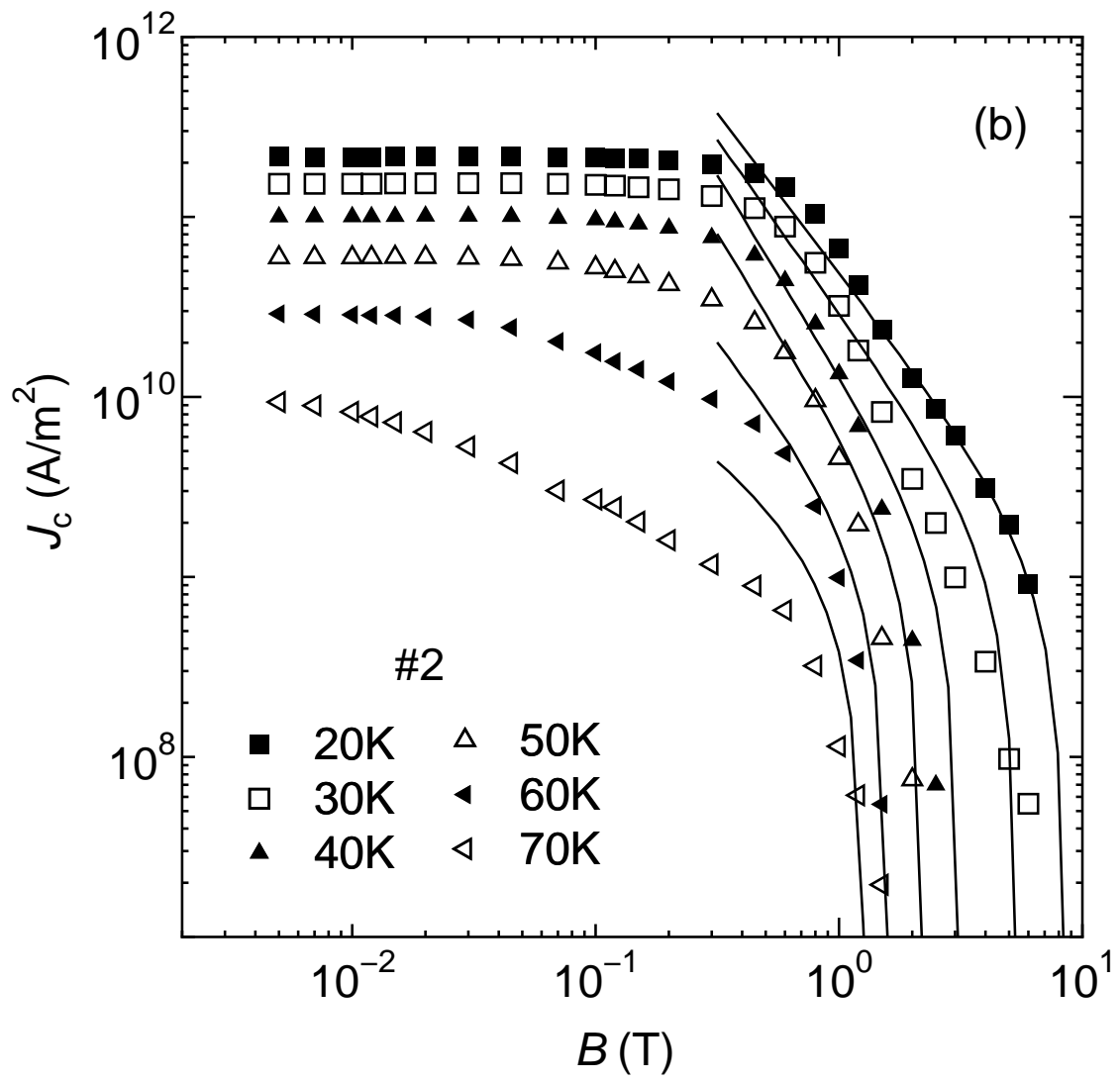


Fig. 2(b): I. Kohno *et al.* PCP-60/ISS2005

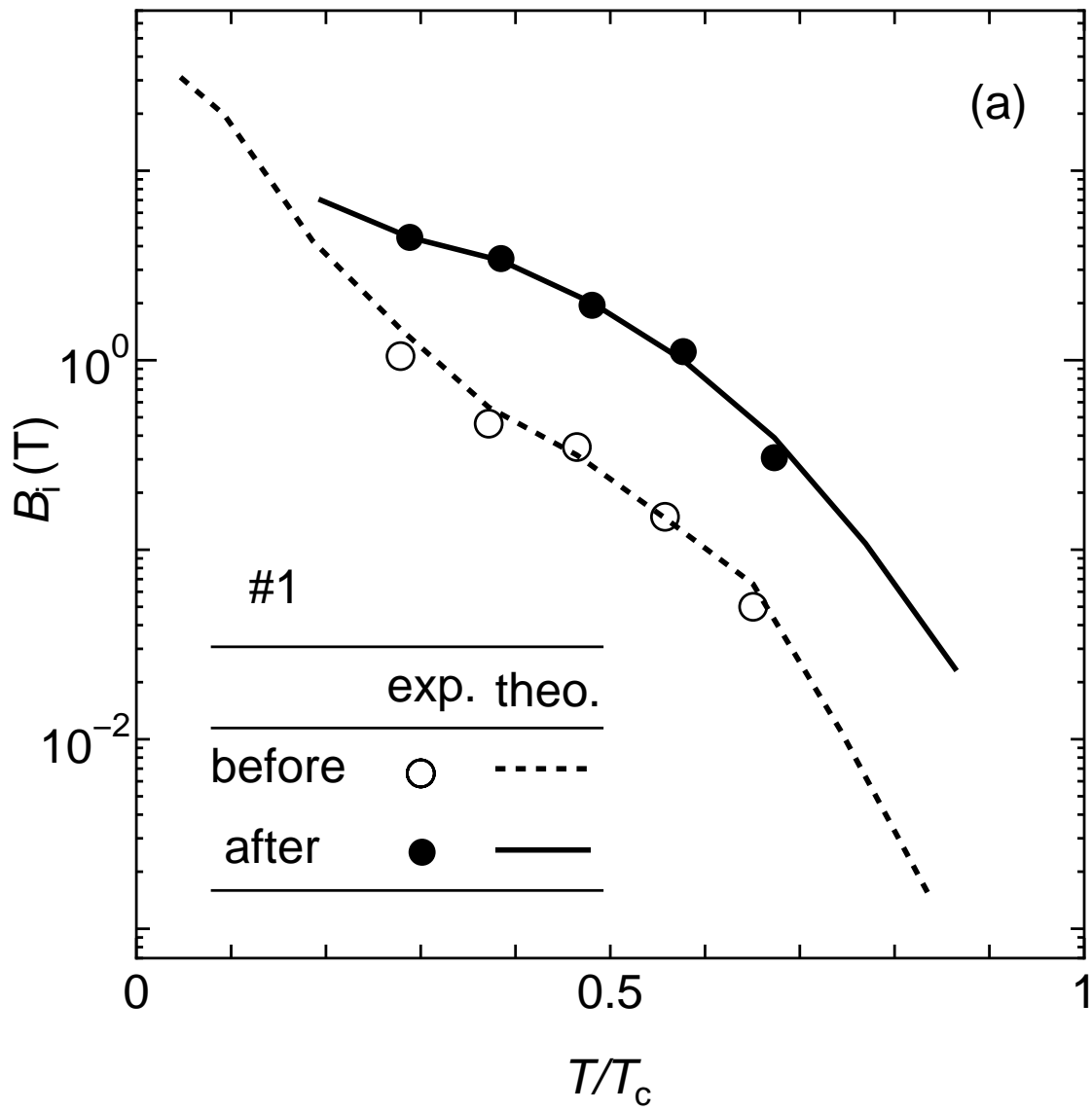


Fig. 3(a): I. Kohno *et al.* PCP-60/ISS2005

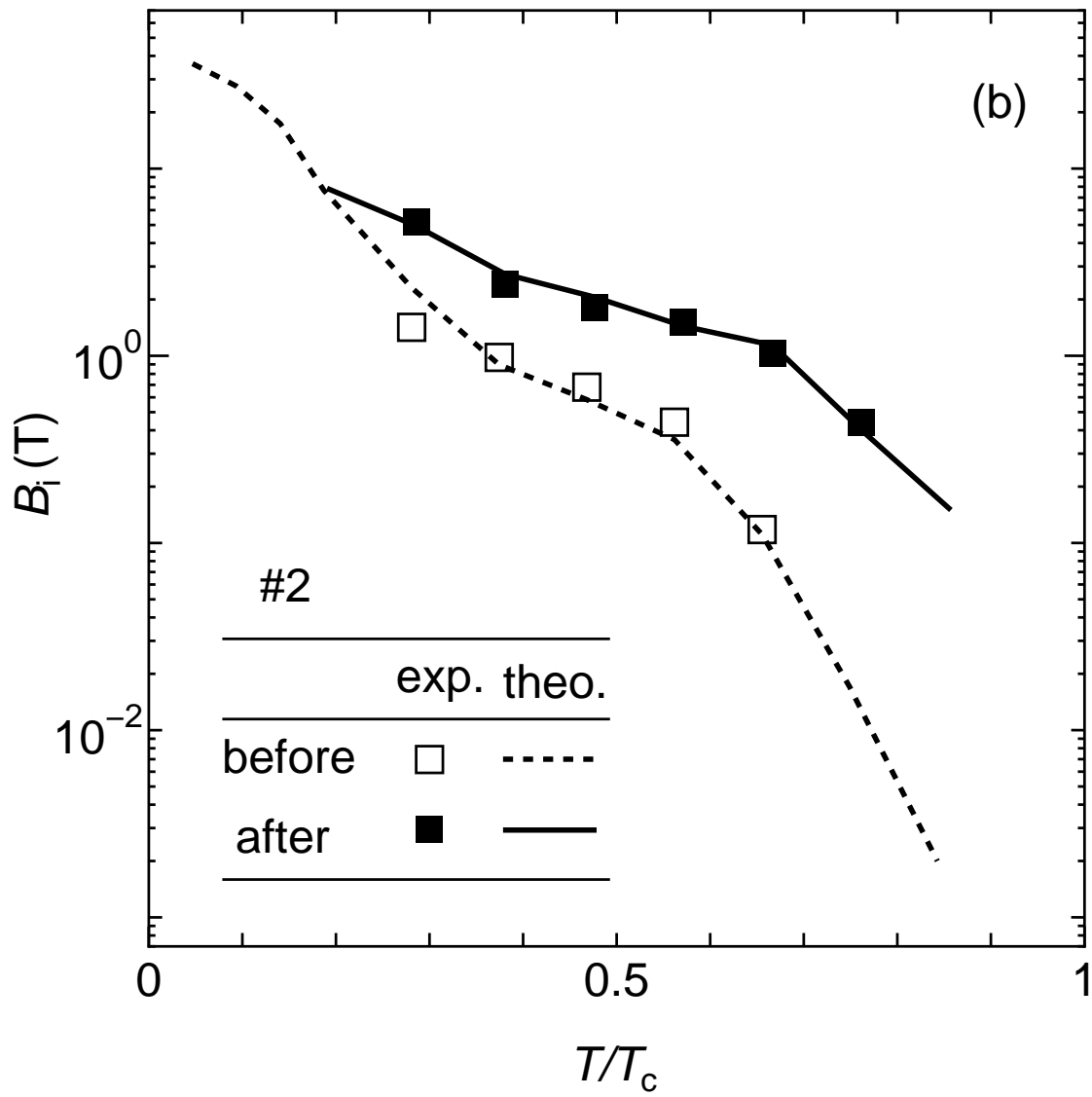


Fig. 3(b): I. Kohno *et al.* PCP-60/ISS2005

Table 1: Pinning parameters used in theoretical calculation.

Specimens #1 and #2 before irradiation			
T (K)	$A_m(\#1/\#2)$	m	$\gamma(\#1/\#2)$
5	$2.0 \times 10^{10}/7.3 \times 10^{10}$	6	0.75/0.73
20	$8.0 \times 10^9/2.0 \times 10^{10}$	6	0.60/0.50
40	$9.0 \times 10^9/1.5 \times 10^{10}$	6	0.50/0.35
70	$6.8 \times 10^{10}/9.0 \times 10^{10}$	6	0.40/0.35
Specimens #1 and #2 after irradiation			
T (K)	$A_m(\#1/\#2)$	m	$\gamma(\#1/\#2)$
20	$1.2 \times 10^{11}/1.5 \times 10^{11}$	3	-0.75/-0.75
40	$6.5 \times 10^{10}/9.0 \times 10^{10}$	3	-0.63/-1.2
70	$2.3 \times 10^{10}/6.0 \times 10^{10}$	3	0/0