Film thickness dependence of critical current characteristics of YBCO-coated conductors

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Abstract

The dependence of superconducting layer thickness on the critical current characteristics was investigated in the range of 0.5 to 1.5 μm for YBCO coated conductors made by the PLD process. Since the dimension of the pinning is considered to be three as indicated by the pinning correlation length, it is concluded that the observed thickness dependence of the critical current density at low fields come simply from a degradation in the superconducting layer structure with increasing thickness. The irreversibility field and the n-value increase with the thickness. These dependencies are well described by the theoretical model of the flux creep and flow.

Keywords: critical current density, YBCO coated conductor, superconducting layer thickness, n-value, irreversibility field, flux creep-flow model
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1 Introduction

It has been clarified that the critical current density J_c at low magnetic fields decreases with increasing superconducting layer thickness d for YBCO coated tapes fabricated by the PLD process. This is similar to the results on thin films deposited on single crystal substrates [1]. This behavior seems to be explained by the two-dimensional collective pinning mechanism for random point pins [2] which predicts as

$$J_c \propto d^{-1/2}. \tag{1}$$

The two-dimensional pinning occurs for superconducting thin films of thickness below the pinning correlation length l_{44} approximately given by

$$l_{44} \simeq \left(\frac{B a_f}{2\pi \mu_0 J_c} \right)^{1/2}, \tag{2}$$

where a_f is the flux line spacing.

On the other hand, it has recently been found that the structure of superconducting layer is deteriorated with appearance of voids and a-axis aligned grains for thick coated tapes fabricated by the PLD process [3], indicating that these defects are the reason for the decrease in the critical current density. In addition, J_c dose not depend on d appreciably for YBCO coated tapes fabricated by TFA-MOD method [4]. This suggests that the three-dimensional pinning mechanism works and seems to be consistent with the above speculation.

At hight fields, the critical current density shows the opposite thickness dependence: it is higher for a thicker superconducting tape [5]. This decrease of J_c in thin specimens at high temperatures and/or high magnetic fields is caused by the flux creep. That is, the pinning potential U_0 is small for a thin tape, since the flux bundle volume is limited by the thickness d. This indicates that the dimensionality of flux pinning becomes two-dimensional at high temperatures and/or at high magnetic fields. Such a change occurs because l_{44} becomes large due to decreasing J_c at this region of temperature and magnetic field.

For these reasons the thickness dependence of the critical current density of YBCO coated tapes is complicated and the optimum thickness of the superconducting layer will be different for different conditions of temperature, magnetic field and electric field depending on the kind of application. Hence, it is necessary to clarify all the mechanisms which influence the critical current properties and to find out the method of estimation of J_c for the optimum design of superconducting layer thickness for each application.

In this paper, the thickness dependence of YBCO tapes fabricated by the PLD method is investigated in the range of 0.5 to 1.5 μm. In order to clarify the dimensionality of pinning, the thickness dependence is measured over a wide temperature range to change l_{44} which determines the dimensionality. The reason for the decrease of J_c with increasing thickness in PLD processed tapes is discussed. The irreversibility field at high temperatures and the n-value are compared with the theoretical prediction of the flux creep-flow model.

2 Experiments

The specimens were PLD-processed YBCO-coated conductors deposited on IBAD substrates with GZO inner layer and CeO_2 cap layer. The thicknesses of YBCO layer was 0.5, 1.0 and 1.5 μm. The critical temperature of these specimens are listed in Table 1.

The DC magnetization and its relaxation were measured by a SQUID magnetometer in a magnetic field parallel to the c-axis of the specimens. Measurements were done up to 7 T over the temperature range of 5 to 85 K. E-J characteristics were estimated from the relaxation measurements and J_c was determined using the electric field criterion of $E_c = 1.0 \times 10^{-8}$ V/m. The irreversibility field was defined by the magnetic field at which J_c reduces to 1.0×10^8 A/m^2. The n value was defined in the electric field range of $E = 10^{-9}$–10^{-8} V/m.

3 Results and Discussion

Figure 1 shows the J_c-B curves of the specimens measured at 5 and 77.3 K. It is clearly seen that J_c decreases with increasing d at 5 K and this dependence does not change with the magnetic field. At 77.3 K, however, the thickness dependence is much weaker and J_c of the thinnest specimen decreases most rapidly with increasing magnetic field. This decrement of J_c of thin specimens at high temperatures and magnetic fields is caused by the flux creep.

Figure 2 shows the thickness dependence of J_c at 0.1 T at various temperatures. It is found that J_c obeys Eq. (1) as shown by the straight lines over a wide temperature range. Hence, the two-dimensional collective flux pinning seems to be realized. However, a simple estimation using Eq. (2) with the J_c-values of specimen #3 reveals that l_{44} is about 0.085 μm at 5 K and is thinner than d over a wide range of temperature as show in Fig. 3. This shows that the pinning is three-dimensional for which J_c should be independence of the thickness. The observed thickness dependence is considered to come from a degradation in the superconducting layer structure with increasing thickness.

This speculation is consistent with the fact that the thickness dependence does not change with temperature over a wide range below 70 K.

Figure 4 shows the temperature dependence of the irreversibility field. It is found that the irreversibility field is the highest for the thickest specimen #3, and this trend is clearer at higher temperature. Figure 5 shows the thickness dependence of the irreversibility field at 77.3 K. This clearly demonstrates the advantage of thicker tapes for applications at high magnetic fields.

The critical current properties were analyzed using the flux creep-flow model [6]. The important quantity which determines the pinning property is the pinning potential U_0, and is given by

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

where g^2 is the number of flux lines in the flux bundle and J_{c0} is the virtual critical current density in a creep-free case, and L is the longitudinal flux bundle size given by the pinning correlation length in the creep-free. Thus, under the influence of the flux creep, L increases to l_{44}. The scaling law of J_{c0} is assumed as

$$J_{\mathrm{c0}} = A \left(1 - \frac{T}{T_{\mathrm{c}}}\right)^m B^{\gamma-1} \left(1 - \frac{B}{B_{\mathrm{c2}}}\right)^2, \tag{4}$$

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

$$f(A) = K \exp\left[-\frac{(\log A - \log A_{\mathrm{m}})^2}{2\sigma^2}\right], \tag{5}$$

where A_{m} is the most probable value of A and σ^2 is a parameter representing a distribution width and K is a normalization constant.

The parameter g^2 is determined so as to maximize the critical current density under the flux creep [7], and is given by

$$g^2 \; = \; g_{\rm e}^2 \left[\frac{5k_{\rm B}T}{2U_{\rm e}} \log\left(\frac{Ba_{\rm f}\nu_0}{E_{\rm c}} \right) \right]^{4/3} , \tag{6}$$

where $g_{\rm e}^2$ is the value of g^2 for three dimensional perfect triangular flux line lattice, $U_{\rm e}$ is the pinning potential when $g = g_{\rm e}$, $E_{\rm c}$ is the criterion of electric field to determine $J_{\rm c}$, and ν_0 is the attempt frequency of the flux bundle. Since $U_{\rm e}$ depends on the thickness, g^2 depends on the thickness. Recently, it was found that g^2 takes a larger value in a Bi-2212 superconducting film thinner than the pinning correlation length [8]. This means that the transverse flux bundle size tends to become large so as to reduce the significant effect of flux creep in thin films, although $J_{\rm c0}$ decreases. The pinning parameters $A_{\rm m}$, σ, m, γ and g^2 are adjusted so that the calculated E-J curves agree with the experiments. The obtained parameters are listed in Table 2. g^2 of the thinnest specimen #1 takes a slightly larger value than other two. This behavior is similar to the case of Bi-2212[8], although the value of g^2 is much smaller. This seems to be caused by the larger value of $U_{\rm e}$ in Eq. (6) for Y-123.

In Fig. 6 the observed and calculated E-J curves are compared for specimen #2 at low and high temperatures. It is found that the agreement is good between experimental and theoretical results. The experimental and theoretical results of the n value are compared in Fig. 7. Although the n value is high and does not appreciably depend on the thickness at 5 K, it becomes smaller and the thickness dependence becomes stronger at high temperatures. Such a behavior is exactly explained by the theoretical model of the flux creep and flow. In Fig. 5 the theoretically estimated irreversibility field is compared with the experimental results. Although the thickness dependence is appreciable, it is fairly weaker than the simple theoretical result in which the variation in

g^2 is not considered.

Thus, thicker tapes have better performance at high magnetic fields and/or at high temperatures and are suitable for applications to superconducting coils such as NMR magnets operated in a persistent current mode in high magnetic fields.

4 Summary

The dependencies of the critical current density, irreversibility field and n-value on the thickness of superconducting layer were investigated for YBCO coated tapes fabricated by the PLD method. It was found that the estimated pinning correlation length was much thinner than the thickness over a wide range of temperature. Hence, it can be concluded that the observed pinning is the three-dimensional one. Hence, the observed thickness dependence of the critical current density at low fields is attributed to a degradation in the superconducting layer structure in PLD-processed tapes with increasing thickness. This is consistent with the fact that the observed thickness dependence does not change over a wide range of temperature below 70 K. At high temperatures, the irreversibility field and the n-value increased with increasing thickness. These behaviors can be explained by the flux creep-flow model. Thus, for the better performance at high temperatures and/or at high magnetic fields the thicker tapes are more suitable.

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Figure captions

Fig. 1 Critical current density of the three specimens at 5 K and 77.3 K.

Fig. 2 Thickness dependence of critical current density at 0.1 T at various temperatures. Straight lines show the dependence given by Eq.(1).

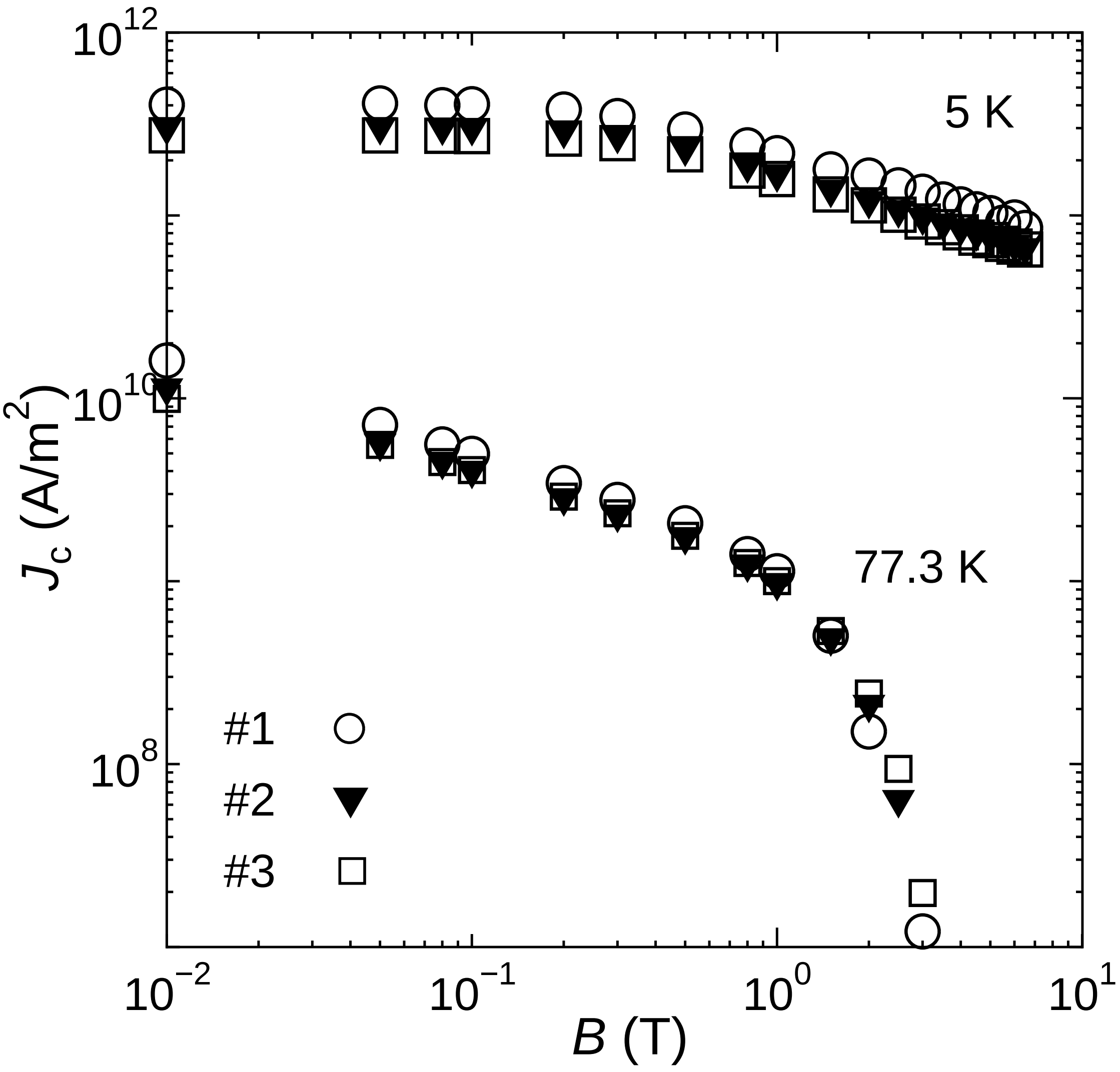
Fig. 3 Temperature dependence of l_{44} estimated at 0.1 T with J_{c}-values of specimen 3.

Fig. 4 Temperature dependence of irreversibility field.

Fig. 5 Thickness dependence of irreversibility field at 77.3 K. Solid and open symbols represent the experiment and theoretical results, respectively.

Fig. 6 E-J curves of specimen #2 at low temperatures and high temperatures. Solid lines are theoretical results.

Fig. 7 Thickness dependence of n value. Solid and open symbols represent the experiment and theoretical results, respectively.



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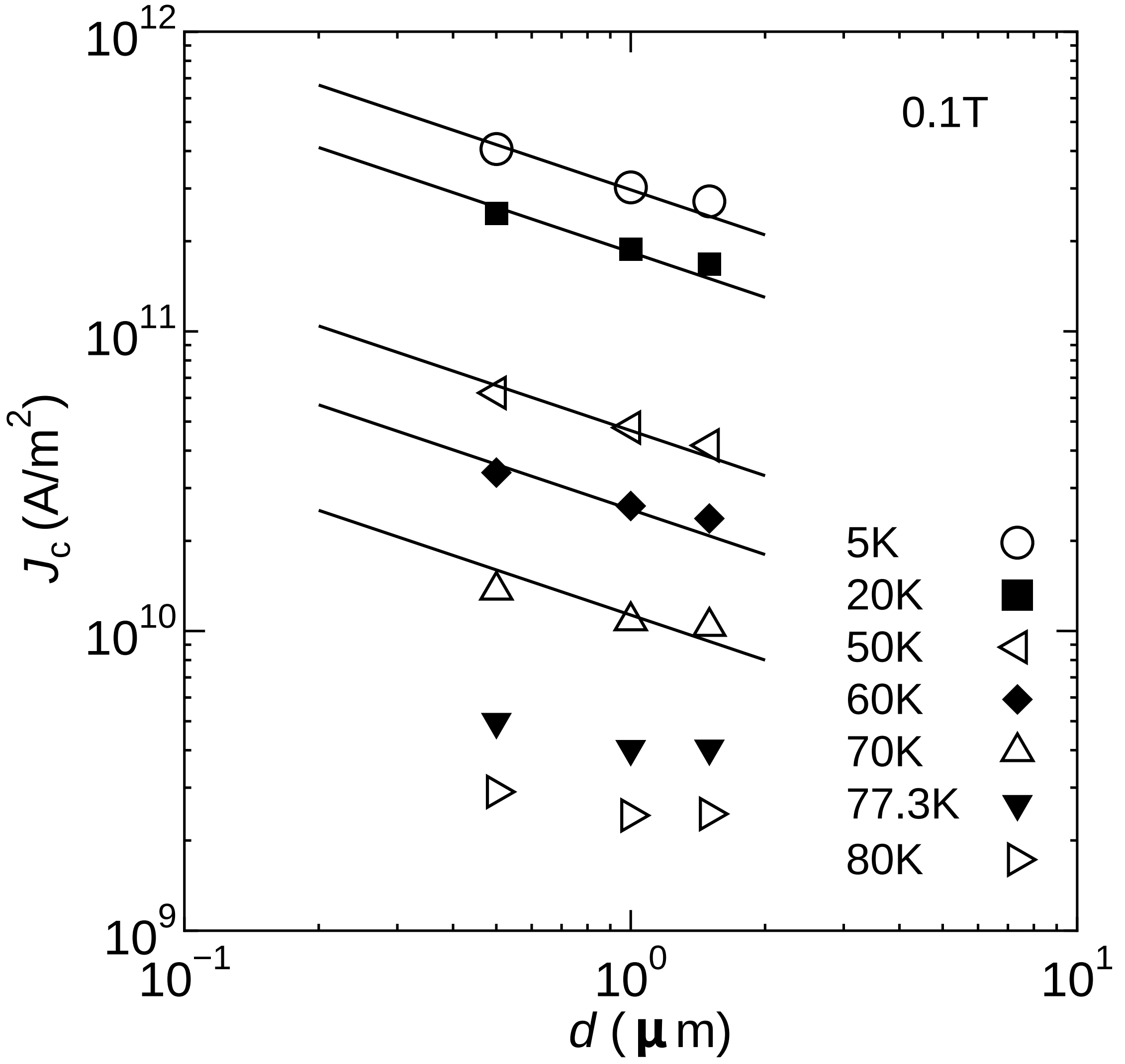

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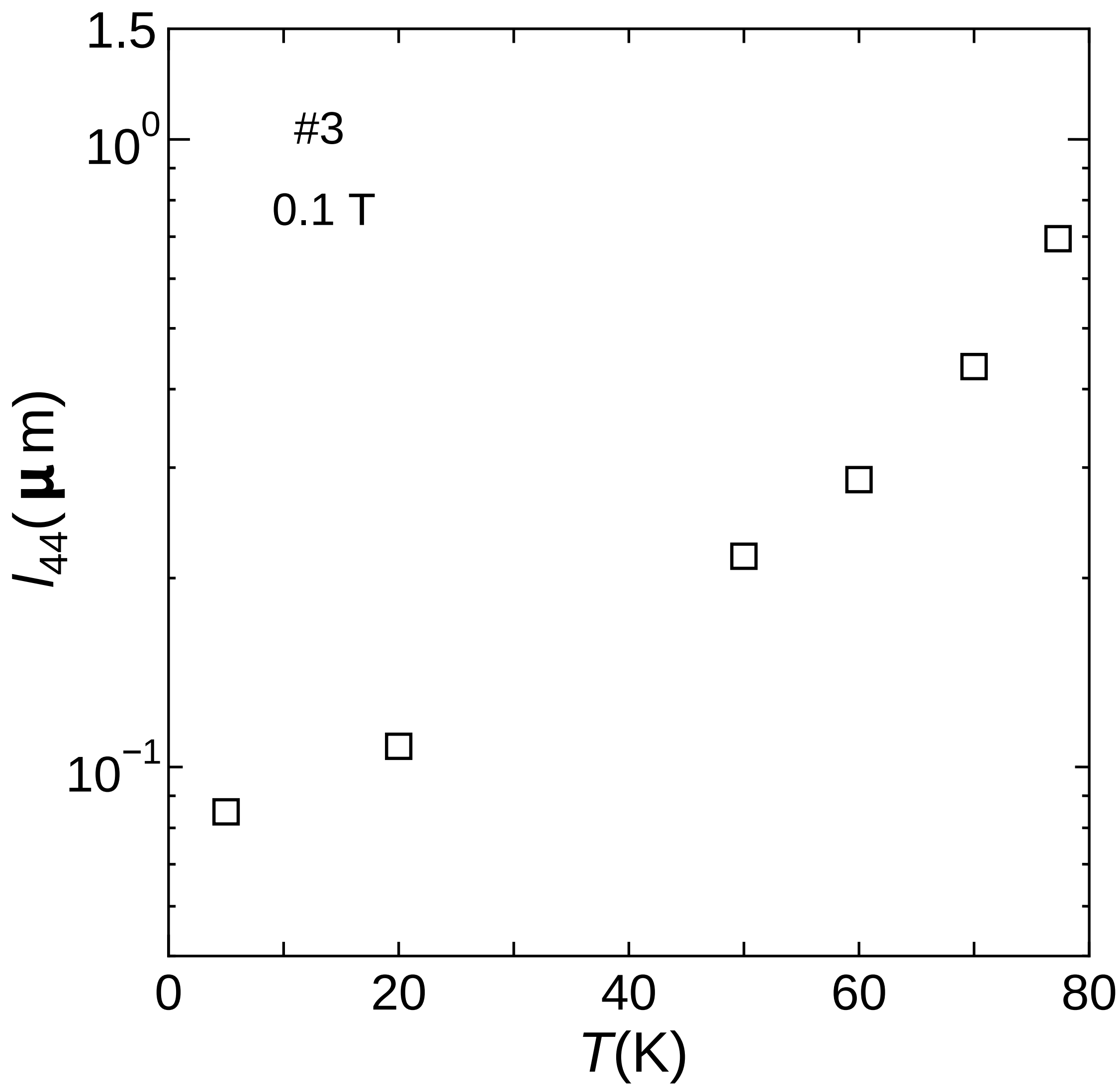

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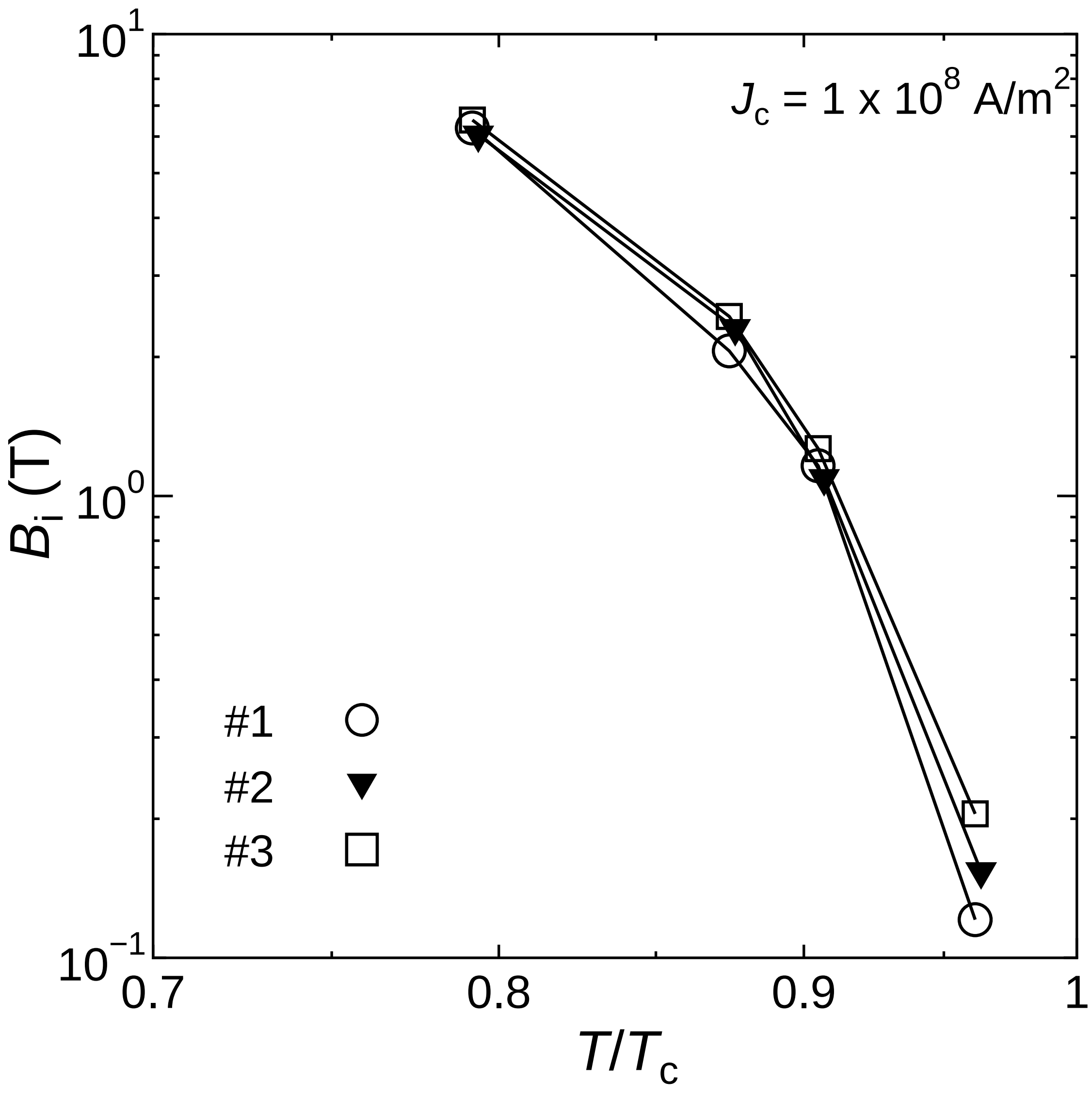

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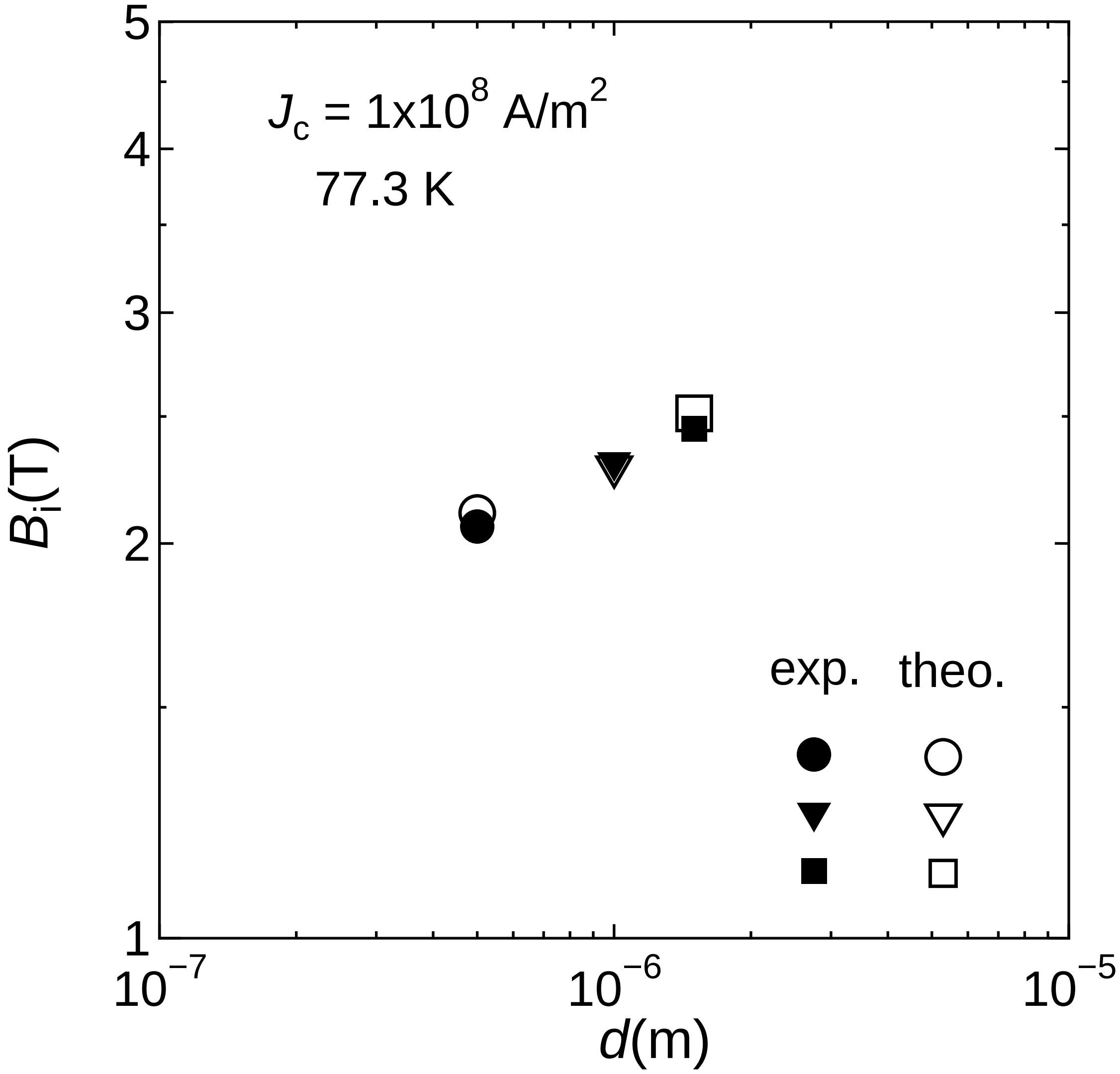

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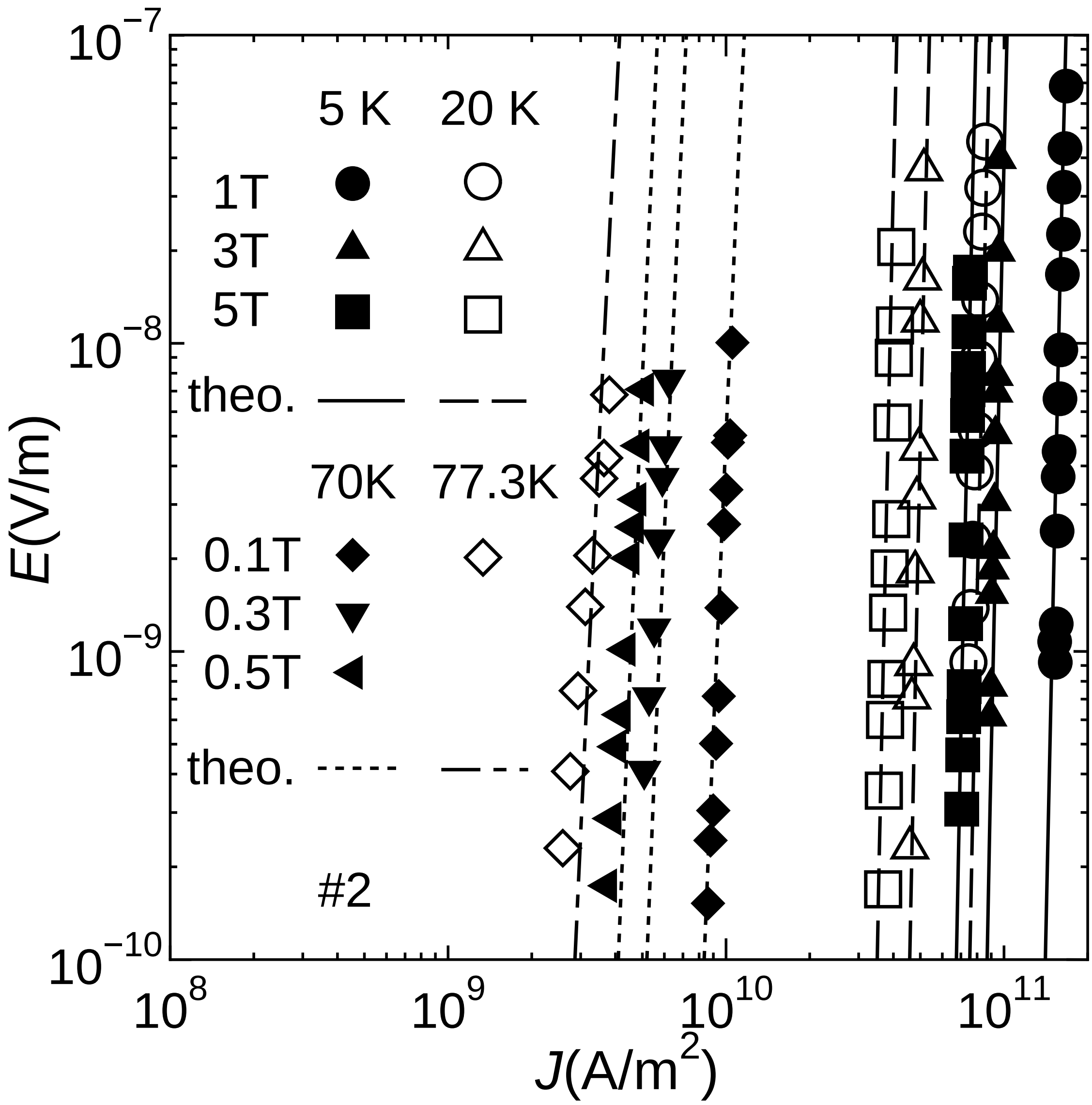

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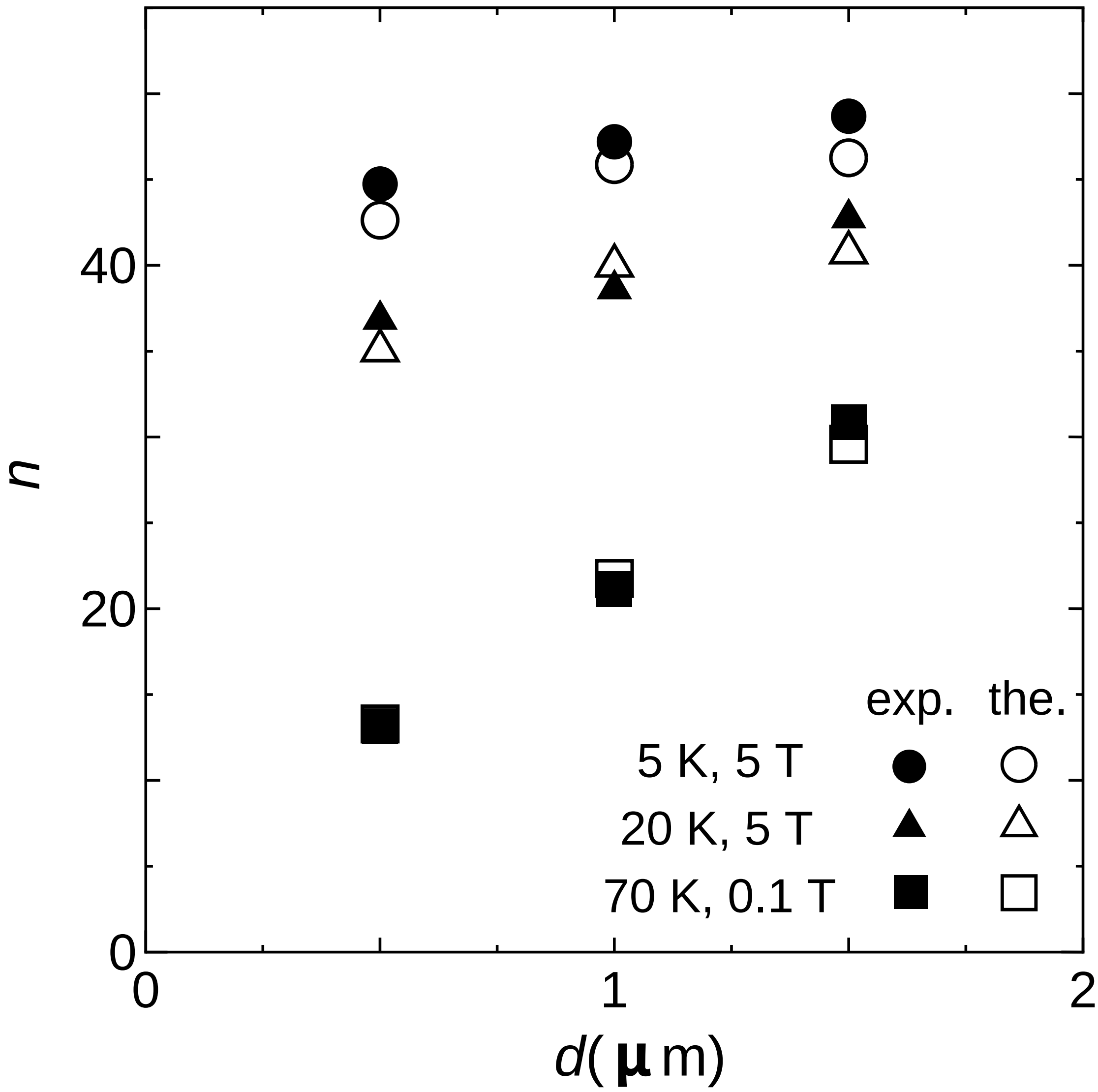

Fig. 7: K. Kimura *et al.* PCP–63/ISS2005

Table 1: Specification of specimens.

Specimen	Thickness d (μm)	T_{c} (K)
#1	0.5	88.4
#2	1.0	88.2
#3	1.5	88.4

Table 2: Pinning parameters of specimens in the low and high temperature regions.

low temperature regions

Specimen	A_{m}	m	σ^2(5 K/20 K)	γ	g^2
#1	6.0×10^{11}	2.5	0.0042/0.0048	0.63	3.0
#2	4.8×10^{11}	2.7	0.0046/0.0049	0.63	2.0
#3	4.3×10^{11}	2.7	0.0044/0.0045	0.63	2.0

high temperature regions

Specimen	A_{m}	m	σ^2(70 K/77.3 K)	γ	g^2
#1	6.6×10^{11}	1.4	0.047/0.060	0.53	3.4
#2	4.0×10^{11}	1.6	0.019/0.023	0.64	2.0
#3	2.9×10^{11}	1.7	0.013/0.015	0.60	2.0