Thickness dependence of irreversibility field in Bi-2212 thin films

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Abstract

The irreversibility field along the *c*-axis was measured for four Bi-2212 thin films and two Bi-2212 single crystals with different thicknesses. The irreversibility field at the same reduced temperature decreased according as the thickness decreased. This result suggests that flux lines are fairly strongly coupled along their length over the distance longer than the film thickness investigated here even in two-dimensional superconductor. The thickness dependence is theoretically explained by the flux creep-flow model. From a difference of critical current property between thin films and single crystals, a critical thickness was found for the dimensional crossover of flux lines.

Keywords: Bi-2212 thin film, Irreversibility field, flux creep-flow model
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1 Introduction

It is known that irreversibility field depends on the flux pinning strength and the dimensionality of superconductor. But, it was shown that the irreversibility field of a thin film is lower than that of a thick tape even for fairly two-dimensional Bi-2223 superconductor [1]. This result suggests that flux lines are fairly strongly coupled over the length longer than the film thickness even in two-dimensional superconductors. This is explained by the flux creep theory [1] from the viewpoint of difference of the longitudinal flux bundle size.

It was found that the longitudinal elastic correlation length of flux lines is much longer than the distance between the CuO_2 layers even in the most two-dimensional Bi-2212 [2][3]. This correlation length is determined only by the magnetic field and the critical current density but is directly independent of the dimensionality of superconductor. This indicates that flux lines are fairly strongly coupled along their length in any superconductors and is consistent with the thickness dependence of the irreversibility field.

In this study, the irreversibility field is measured for four Bi-2212 thin films and two Bi-2212 single crystals with different thicknesses and its thickness dependence is investigated using the flux creep-flow model.

2 Experimental

The specimens were four Bi-2212 thin films and two Bi-2212 single crystals. The films were deposited on MgO substrates by a laser ablation method. The thickness of each thin film was about 0.1, 0.2, 0.5 and 1.0 μm. The critical temperature of these films was 60, 72, 82 and 79 K, respectively. The single crystals were prepared by a flux method. The thickness of each single crystal was about 5.0 and 10 μm, and the critical temperature was 86 and 88 K, respectively. The c-axis was directed normal to the flat wide surface of the film. The DC magnetization in a magnetic field parallel to the c-axis was measured using a SQUID magnetometer. The critical current density was estimated from the magnetization hysteresis and the irreversibility field was determined by the field at which J_{c} was reduced to 1.0×10^6 A/m^2.

3 Results and Discussion

Figures. 1 and 2 show the critical current density of Samples 2 and 6 at various temperatures, for example. The critical current density of single crystal specimen in Fig. 2 decreases monotonically with increasing magnetic field at temperature higher than 30 K, although it increases drastically with decreasing temperature below 30 K and the peak effect appears. This significant change is caused by the dimensional crossover of flux lines. By contrast, in the case of films, such a significant change does not appear and the critical current density decreases monotonously with increasing temperature and magnetic field in the entire region. This will be argued later. Figure 3 shows the temperature dependence of the irreversibility field for all samples at $T/T_{\mathrm{c}} \geq 0.2$. The irreversibility field of all samples decreases monotonically with increasing temperature.

According to the collective flux creep theory, the pinning potential, U_0, is described in terms of the virtual critical current density in the creep-free case, J_{c0}. It is known that U_0 depends on the flux pinning strength and the volume of the flux bundle. The longitudinal flux bundle size, L, is

$$L \simeq \left(\frac{C_{44}}{\alpha_{\mathrm{L}}}\right)^{1/2} = \left(\frac{Ba_{\mathrm{f}}}{2\pi\mu_0 J_{\mathrm{c0}}}\right)^{1/2}, \tag{1}$$

where $C_{44} = B^2/\mu_0$ is the tilt modulus, α_{L} is the Labusch parameter and a_{f} is a flux line spacing. If the thickness of superconductor, d, is thinner than L, we have [1]

$$U_0 = \frac{4.23 g^2 k_{\mathrm{B}} J_{\mathrm{c0}} d}{2\pi B^{1/2}} \tag{2}$$

for the present experimental condition. In the above, g^2 is a number of flux lines in the flux bundle. On the other hand, if d is thicker than L, we have

$$U_0 = \frac{0.85 g^2 k_{\mathrm{B}} J_{\mathrm{c0}}^{1/2}}{(2\pi)^{3/2} B^{1/4}}. \tag{3}$$

It is assumed that the dependencies of J_{c0} on temperature and magnetic field are expressed as

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

where A, m and γ are pinning parameters. It is known that the value of critical current density is widely distributed in high-temperature superconductors. For simplicity it is assumed that A in Eq. (4) obeys the distribution:

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

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

When these parameters are given, the current-voltage characteristic can be calculated using the flux creep-flow model [1] and the critical current density is obtained using the same criterion with experiments. The fitting parameters, A_{m}, σ^2, m and γ, are adjusted so as to get a good agreement with the experimental results on the critical current density. g^2 is estimated so that the critical current density under the flux creep takes on a maximum value [4]. For example, we have g^2=0.21 at $B = 0.1$ T and T=30 K. Since the obtained g^2 value is smaller than 1 in the corresponding range of magnetic field and temperature, the theoretical minimum value $g^2 = 1$ is used. The parameters used for the numerical calculation of the E-J characteristic are listed in Table 1.

The obtained critical current density is represented by the solid lines in Figs. 1 and 2. In case of the film, it is found that the agreement is fairly good in the high field region. However, the observed critical current density is much lower than the theoretical prediction in the low field region. This disagreement comes from the deviation from the prediction of the critical state model [5] for such a film thinner than the correlation length. This is, the distribution of the shielding current is not like one for which the regions with the current density $\pm J_{\mathrm{c}}$ exist distinctly, but the current density gradually changes in space from positive to negative. Hence, the current density is almost zero in the central region of the film and the resultant magnetic moment takes on a small value.

Since the pinning parameters of each sample are different as given in Table 1, the theoretically predicted thickness dependence is also different. For this reason, we try to normalize the irreversibility field and the thickness by the bulk irreversibility field and L, respectively. The result is depicted in Fig. 4. The irreversibility field generally increases with increasing d and is saturated for d thicker than L. It was found that the irreversibility field in thicker single crystal is almost in the saturated regime.

This behavior can be easily explained by the mechanism of flux creep. If the distribution of J_{c0} is disregarded for simplicity, the flux creep theory [6] predicts that the irreversibility field is derived from the condition;

$$E_{\mathrm{c}} = B a_{\mathrm{f}} \nu_0 \exp\left(-\frac{U_0}{k_{\mathrm{B}} T}\right), \tag{6}$$

where E_{c} is the electric field criterion for the determination of the critical current density and ν_0 is the attempt frequency.

Substituting Eqs. (2) - (4) into Eq. (6), the irreversibility field is easily obtained:

$$B_{\mathrm{i}}^{(3-2\gamma)/2} = \frac{K_1}{T}\left[1 - \left(\frac{T}{T_{\mathrm{c}}}\right)^2\right]^m d; \qquad d < L, \tag{7a}$$

$$= \left(\frac{K_2}{T}\right)^2 \left[1 - \left(\frac{T}{T_{\mathrm{c}}}\right)^2\right]^m; \qquad d > L, \tag{7b}$$

with

$$K_1 = \frac{4.23 g^2 A}{2\pi \log\left(B a_{\mathrm{f}} \nu_0 / E_{\mathrm{c}}\right)}, \tag{8}$$

$$K_2 = \frac{0.835 g^2 A^{1/2}}{(2\pi)^{3/2} \log\left(B a_{\mathrm{f}} \nu_0 / E_{\mathrm{c}}\right)}. \tag{9}$$

Note that $B_{\mathrm{i}}^{(3-2\gamma)/2}$ is proportional to A, i.e., to the flux pinning strength in the both cases. If we represent the bulk irreversibility field at a given temperature given by Eq. (7b) by B_{imax}, Eq. (7) is reduced to

$$\left(\frac{B_{\mathrm{i}}}{B_{\mathrm{imax}}}\right)^{\frac{3-2\gamma}{2}} = \frac{d}{L}; \qquad d < L, \tag{10a}$$

$$= 1; \qquad d > L, \tag{10b}$$

Where B_{imax} is the bulk irreversibility field. This explains the result shown in Fig. 4.

The above experimental and theoretical results show that the flux lines are fairly strongly coupled along their length even in the most two-dimensional

Bi-2212 superconductors. This is supported by experimental results of the longitudinal correlation-length measurement of the order of 10 μm [2][3].

As shown above, the peak effect caused by the dimensional crossover of flux lines was found only in thick single crystals. This fact shows that some critical thickness exists for the occurrence of such a transitional change. This critical thickness is given by the magnetic correlation length of Eq. (1) for three-dimensional superconductors like RE-123. In two-dimensional Bi-2212, this critical thickness seems to be much shorter than the magnetic correlation length, since it is of the order of a few μm. From the present measurement it is speculated that the critical thickness is of the order of submicrometer. This seems to be consistent with some correlation length estimated from the enhancement of J_c at the peak field [7]. That is, L was of the order of several μm in the three-dimensional state below the peak field. By contrast, J_c increased by a factor of 4 at the peak field. This correlation length, probably of the normal core of flux lines, was considered to decrease by a factor of 4^{-2}=1/16. This length is in the range of submicrometer. Thus, the so-called "two-dimensional" state of flux lines may be like that the magnetic flux outside the core is almost straight and the core itself is deformed along their length with a characteristic length of submicrometer.

On the other hand, the peak effect or the dimensional crossover of flux lines is not observed for tapes, even if its thickness is as thick as several μm. This might be caused by a disorder of flux lines due to weak-link grain boundaries and high density of defects.

4 Summary

The irreversibility field was measured for Bi-2212 thin films and single crystals with different thicknesses. The observed result was compared with the theoretical prediction of the flux creep-flow theory. The following results are obtained.

1. The irreversibility field of thicker specimen was generally higher. This agrees with the theoretical prediction of the flux creep-flow model and shows that the flux lines magnetically strongly coupled along their length.
2. The transitional change of critical current density associated with the dimensional crossover was observed in single crystals, but disappeared in thin films. This suggests that some critical thickness exists for the occurrence of the transitional change.

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Table 1
Parameters used for numerical calculation of E-J characteristic.

	$d[\mu m]$	A_{m}	m	γ	σ^2
Sample 1	0.1	3.0×10^9	0.5	0.98	0.005
Sample 2	0.2	6.2×10^9	2.0	0.60	0.02
Sample 3	0.5	5.2×10^9	3.9	0.99	0.05
Sample 4	1.0	3.2×10^9	3.2	0.99	0.05
Sample 5	5.0	2.7×10^8	4.3	0.28	0.08
Sample 6	10	2.2×10^8	5.6	0.10	0.10

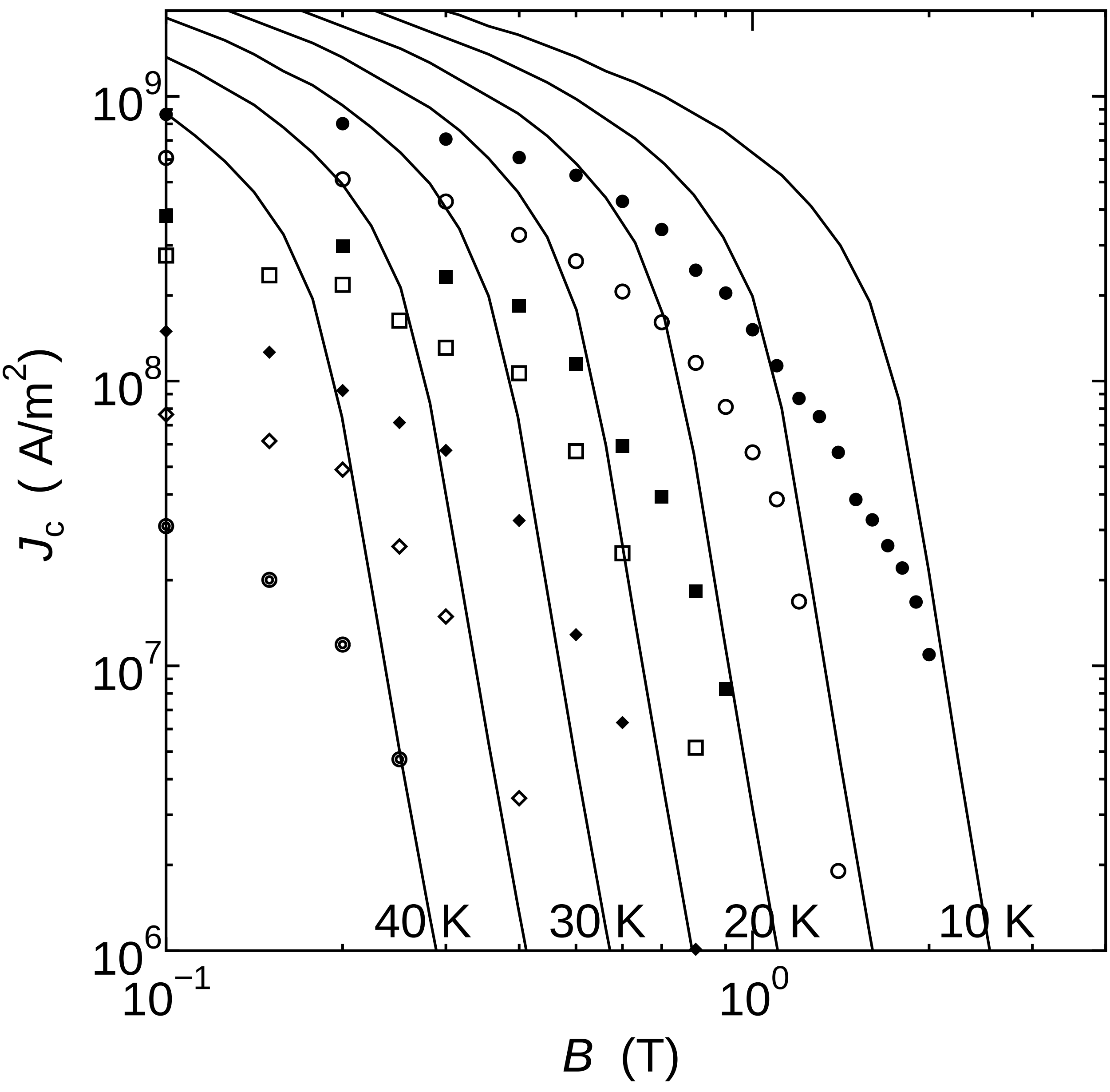


Fig. 1: H. Wada *et al.*/$VPP-30/ISS2001$

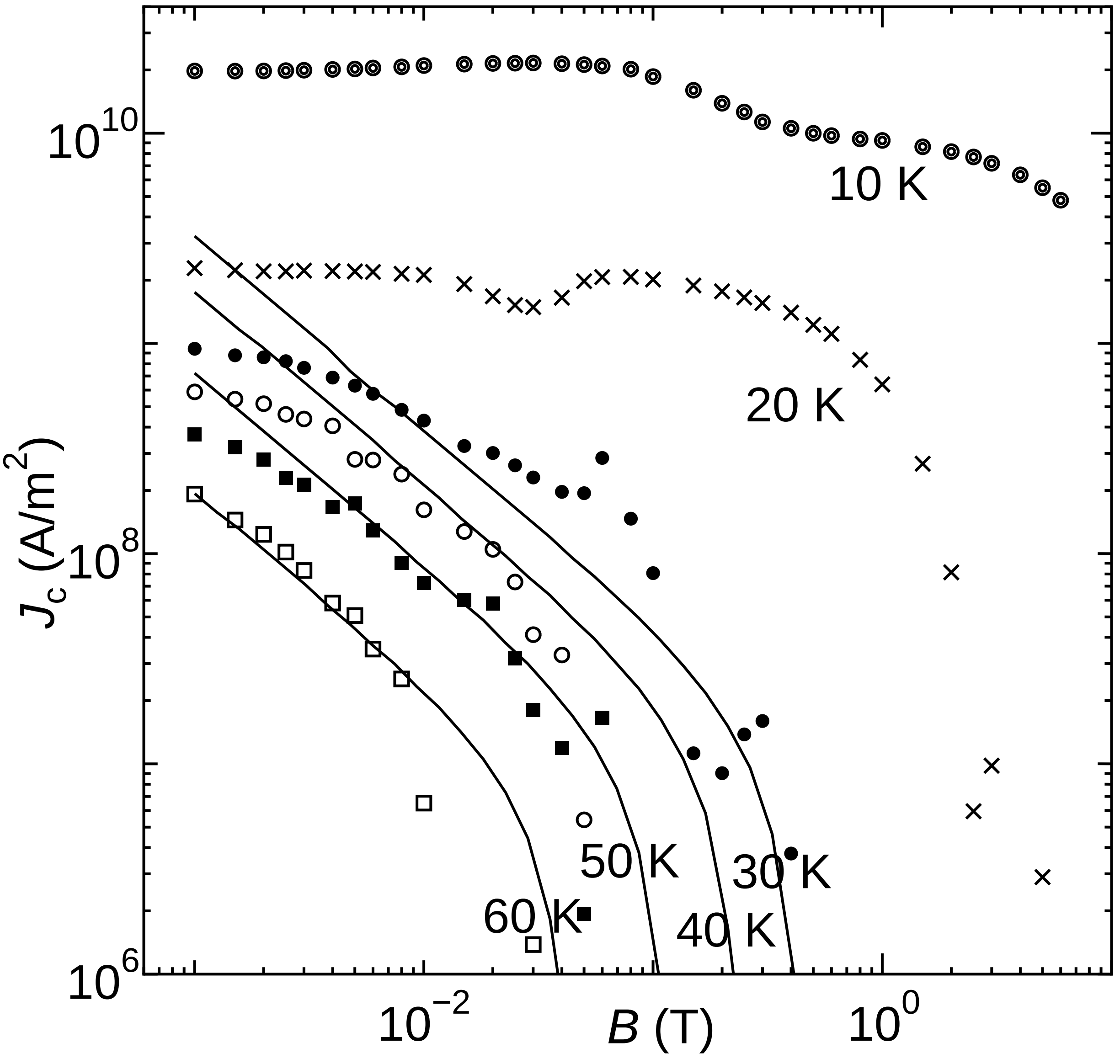
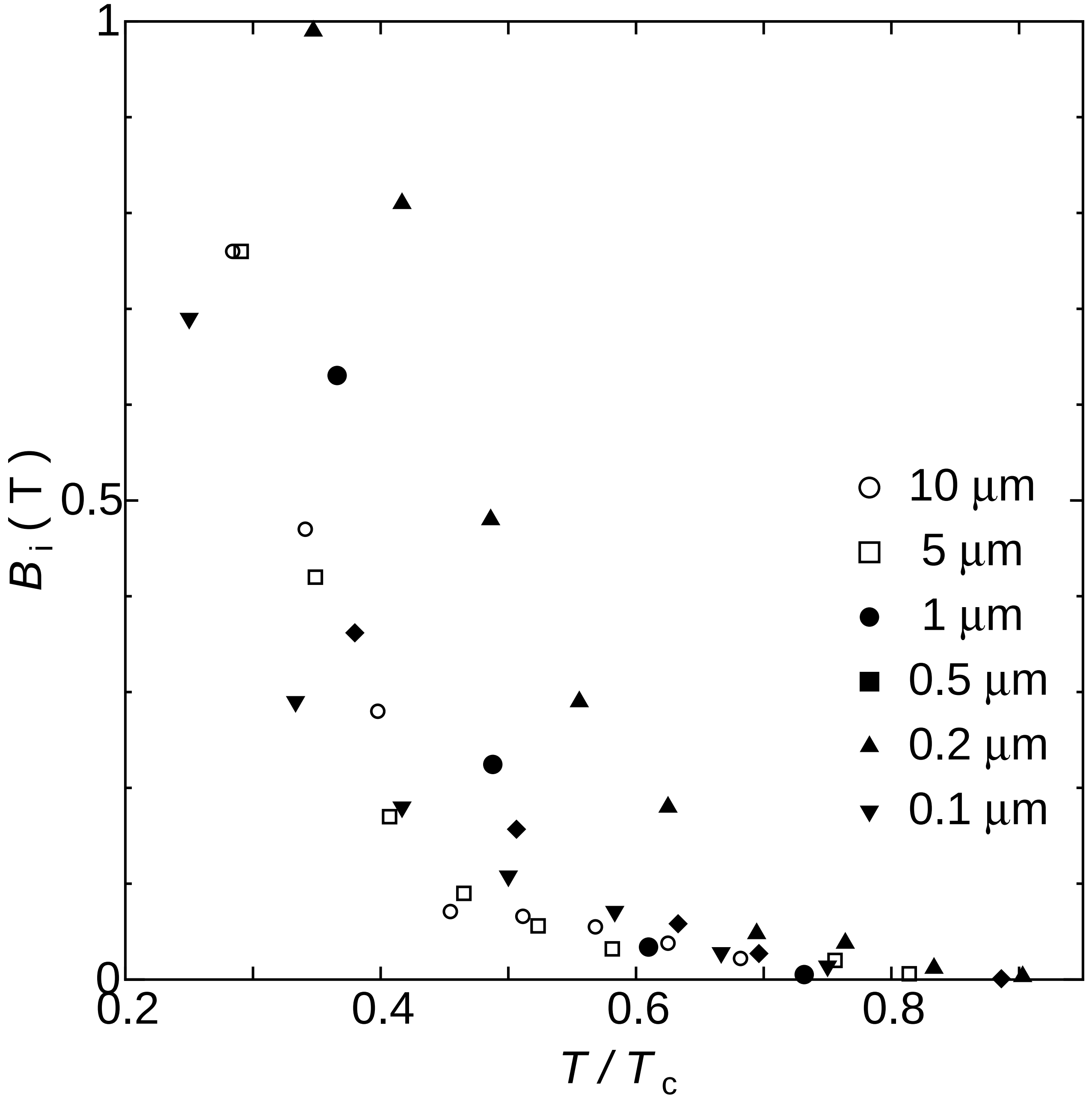


Fig. 2: H. Wada *et al.*/$VPP-30/ISS2001$



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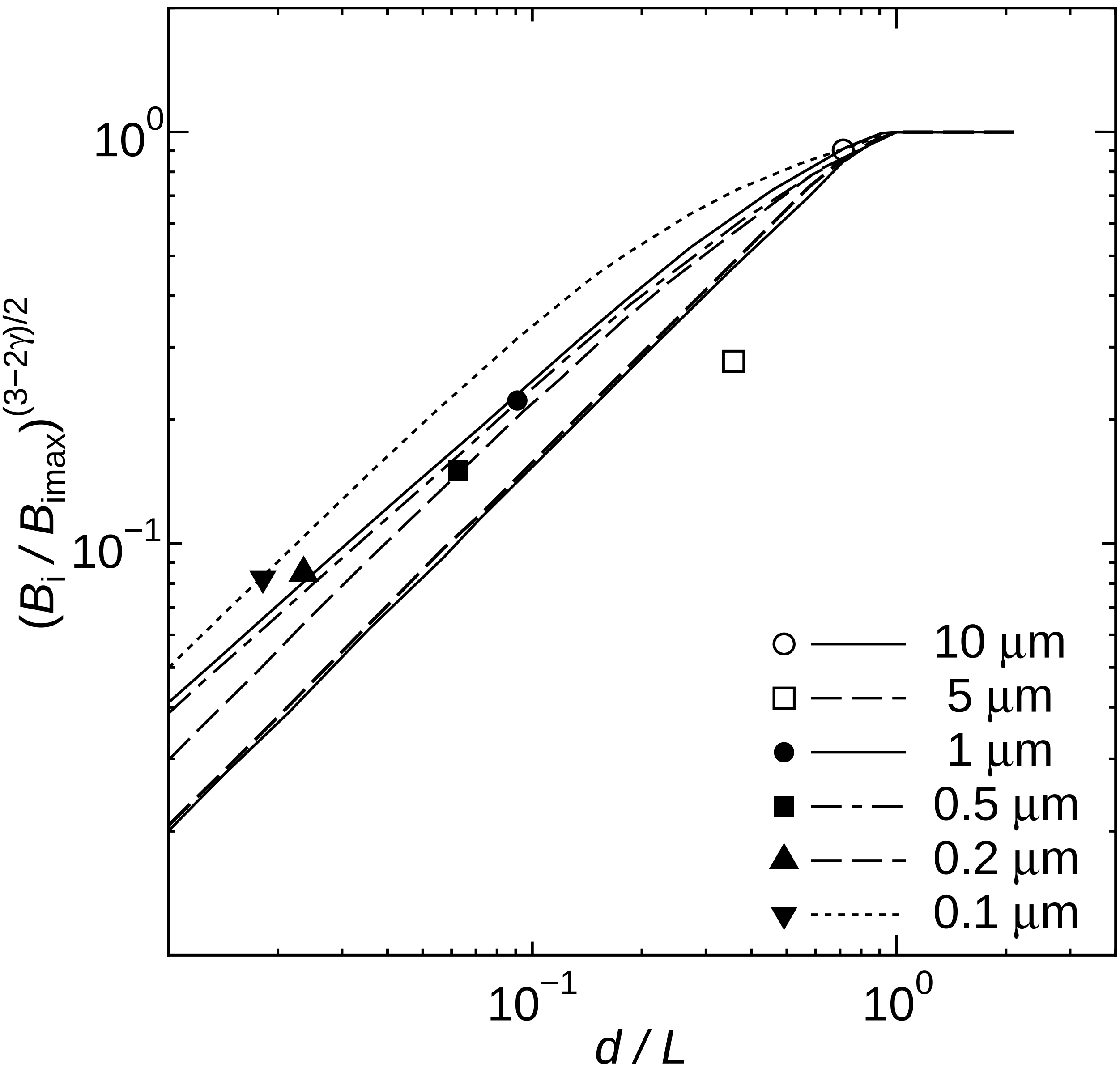

Fig. 4: H. Wada *et al.*/$VPP-30/ISS2001$

Figure caption

Fig. 1. Critical current density vs magnetic field in Sample 2. The solid lines are theoretical results of flux creep-flow model.

Fig. 2. Critical current density vs magnetic field in Sample 6. Theoretical results of flux creep-flow model shown by solid lines are compared with exreiments for $T \geq 30$K.

Fig. 3. The temperature dependence of the irreversibility field for all samples.

Fig. 4. Relationship between normalized irreversibility field at $T/T_{\mathrm{c}} = 0.42$ and normalized thickness. Lines show theoretical predictions for each sample.