

Evaluation of anisotropy of J_c in silver-sheathed Bi-2223 tape

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Abstract

The magnetic field angle dependence of J_c was measured by four probe method and DC magnetization method. The latter measurement was used for the specimen before and after bending to break the intergrain current in order to investigate only the intragrain current. It was found that the intragrain critical current density could be increased by a factor 2.7 in a parallel magnetic field when the c -axis misorientation could be improved. From the field angle dependence of the intragrain critical current density, the anisotropy parameter was estimated as 20.4.

Key words: Bi-2223 tape, intragrain critical current density, anisotropy parameter, misorientation angle

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1 Introduction

Silver-sheathed Bi-2223 tape is a promising candidate of HTS wire which is expected for practical applications and long length wires over 1 km with relatively high critical current density have been fabricated. However, the critical current density of PIT Bi-2223 tapes has not been significantly improved. This originates from the fact that these tapes are of polycrystalline structure and a crystal misorientation of grains is a major factor which deteriorates the critical current property as well as a sausaging of superconducting filaments and weak links of grain boundaries. The relatively low n values in Bi-2223 tapes are attributed to these factors. In previous measurement [1], it was found that the influence of the sausaging of superconducting filaments was not significant in the present PIT tapes, since the effect of other factors is much stronger than that of the sausaging. Hence, it is necessary to quantitatively clarify the influence of other factors on the critical current density, and the effect of crystal misorientation of grains is investigated in this study. For this purpose, it is necessary to distinguish the effects of in-plane misalignment and out-of-plane misalignment of grains.

The current flowing the tape consists of two components, i.e., the intergrain current which flows across grain boundaries and the intragrain current which flows inside grains. The intergrain current corresponds to the transport current. On the other hand, the magnetic moment has contributions from the two currents. Only magnetization intragrain current can be picked up by breaking the intergrain current. In order to clarify the effect of the out-of-plane misalignment, the anisotropy only of the intragrain current must be clarified.

In this study, the magnetic field angle dependence of J_c was measured

by the four probe method and the DC magnetization method. In order to evaluate the intragrain current, the intergrain currents was broken by bending the specimen and the DC magnetization method was used for measuring the intragrain current. The real anisotropy in the intragrain J_c was evaluated by the combination of the apparent anisotropic intragrain J_c obtained from the magnetic measurement and the distribution of the c -axis orientation angle by a theoretical analysis with the anisotropy of the irreversibility field.

2 Experimental

The measured specimen was a multifilamentary Bi-2223 silver-sheathed tape with 61 filaments prepared by the powder-in-tube method. The width and thickness of the tape were 4.2 mm and 0.22 mm, respectively. The average width and thickness of superconducting filaments were about 390 μm and 13 μm , respectively. The critical temperature, T_c , was 109 K and the critical current at 77.3 K in self field was about 80 A.

In order to evaluate the intragrain current, it is necessary to break the connectivity between grains by bending the specimen. For this purpose, the bending strain of about 8.8 % was applied in two directions and it was confirmed that the transport critical current density was reduced to zero after the bending. Fig. 1 shows a cleaved cross-section of a superconducting filament by bending observed by SEM. It is seen that the filament is cleaved also in the direction of the thickness and the typical thickness of each chip is about 1.5 μm .

The critical current density of the tape was measured by the four probe method and the DC magnetization method. The usual electric field criterion

of $E_c = 1.0 \times 10^{-4}$ V/m was used for the four probe method and the typical electric field at the DC magnetization measurement was of the order of 10^{-8} V/m. The field angle θ from the surface was changed from 0° to 90° keeping the field direction normal to the length of the tape at 77.3 K. The magnetic field was applied up to 0.12 T in the both measurements.

The DC magnetization method using a SQUID magnetometer (MPMS-7) was done before and after breaking of the intergrain currents by bending the specimen. The critical current density, J_c , was determined from the hysteresis of magnetic moment Δm with an assumption of Bean's model. Each filament was approximated by a rectangle and there are two patterns of shielding current inside the filament depending on θ . In the case of $0 \leq \theta < \theta_{\text{th}} = \tan^{-1}(w/d)$ with d and w denoting the thickness and width of filaments, respectively, the shielding current flows as shown in Fig. 2(a) and (b), J_c is evaluated from

$$J_c = \frac{6\Delta m \cos^2 \theta}{n_f d^2 \left[(w - d \tan \theta) \left(3l - \frac{d}{\cos \theta} \right) \cos \theta + 2d \left(l \cos \theta - \frac{d}{4} \right) \tan \theta \right]}, \quad (1)$$

where n_f is the number of filaments and l is the length of filaments, for the case of unbroken filaments. In the above the side along the length is assumed to be parallel to the y -axis for simplicity. In the case of $\theta_{\text{th}} \leq \theta < 90^\circ$, the current flows as in Fig. 2(c) and J_c is evaluated from

$$J_c = \frac{6\Delta m \sin^2 \theta}{n_f w^2 \left[\left(d - \frac{w}{\tan \theta} \right) \left(3l - \frac{w}{\sin \theta} \right) \sin \theta + 2w \left(l \sin \theta - \frac{w}{4} \right) \frac{1}{\tan \theta} \right]}. \quad (2)$$

The corresponding values are $n_f = 61$, $d = 13 \mu\text{m}$, $w = 390 \mu\text{m}$ and $l = 3.82 \text{ mm}$.

After the bending, cleaved chips are approximated again by rectangles and the same formula can be used for the estimation of J_c , where n_f , d , w and l mean the number and corresponding sizes of the chips, respectively. In this case the typical thickness of each chip, d , is found to be about $1.5 \mu\text{m}$ by SEM observation. The values of w and l are hard to be found from the view of side surface, and these values are speculated so that J_c -value at $\theta = 90^\circ$ after the bending is the same as that before the bending. Thus, we have $w = l = 10\mu\text{m}$ and $n_f = 6.6 \times 10^6$. These values of w and l are of the same order of magnitude as assumed by Kawano *et al.* [2].

The value of θ_{th} before and after the bending is about 88 and 81 degree, respectively, and Eq. (2) was used only $\theta = 90^\circ$ in this measurement. In the case of $\theta = 90^\circ$, Eq. (2) is equivalent to Eq. (1) with exchanging d and w .

3 Results and Discussion

The magnetic field angle dependence of the transport J_c at $T = 77.3 \text{ K}$ is shown in Fig. 3. This result shows that the critical current density is uniquely expressed as a function of a magnetic field component normal to the tape surface, $B \sin \theta$, in the large angle region. This originates from a large anisotropy of electron mass. However, the angle dependence at each magnetic field deviates from this function at small angles. The value at which the deviation starts is about 12 degree and is approximately the same in the range of magnetic field of the measurement. This value is reasonable when comparing with the result reported by Kaneko *et al.* [3]. The reason for the plateau region in which J_c is independent of the normal field component is the out-of-plane misorientation of grains [4,5]. Therefore, the standard deviation of the c -axis orientation angle is estimated as about 12 degree.

Figs. 4 and 5 show the angular dependence of DC magnetization J_c before and after breaking the intergrain current, respectively. Comparing these results, it is found that the anisotropy of J_c increases by breaking the connectivity. The magnetization J_c at 90° before the bending is about one order of magnitude smaller than the transport J_c at $B = 0.12$ T. This originates from the difference of the electric field criterion between the two measurements as above-mentioned. That is, the difference of the electric field of four orders of magnitude can explain the difference of J_c of one order of magnitude for the low n -value at a high magnetic field [6]. In comparison to this the difference of J_c at $\theta = 0^\circ$ is much smaller than that at $\theta = 90^\circ$. This is due to the contribution of large intragrain currents from grains which are exactly parallel to the magnetic field.

The intrinsic anisotropy of the critical current density originates from the anisotropy of irreversibility field. That is, the larger anisotropy at a higher field shown in Fig. 5 comes from the deterioration of J_c at $\theta = 90^\circ$ at which the irreversibility field is lowest. It is assumed that the angular dependence of irreversibility field can be expressed as the anisotropic effective mass model [7]:

$$B_i(\theta) = \frac{B_i(0)}{\sqrt{\cos^2 \theta + \gamma^2 \sin^2 \theta}}, \quad (3)$$

where $B_i(0)$ is a value in magnetic field in the a - b plane and γ is the anisotropy parameter. Thus, the angular dependence of the critical current density is expressed as [8]

$$J_c(\theta) \propto B^{\gamma_p - 1} \left(1 - \frac{B}{B_i(\theta)} \right)^\delta, \quad (4)$$

where γ_p and δ are the pinning parameters.

In the measured tape, the direction of c -axes of grains are distributed around the direction perpendicular to the tape surface. The effect of the misalignment of grains is considered. It is assumed that the distribution of the c -axis orientation angle can be expressed by a Gaussian distribution:

$$f(\theta') = \frac{1}{\sigma\sqrt{2\pi}} \exp\left(-\frac{\theta'^2}{2\sigma^2}\right), \quad (5)$$

where θ' is the angle between the c -axis of the grain and the direction perpendicular to the tape surface, and σ is the standard deviation of the c -axis orientation angle and we have $\sigma = 12^\circ$ from the results in Fig. 3. The angular dependence of the experimental J_c is considered to be expressed as

$$J_c(\theta) = \int f(\theta') J'_c(\theta + \theta') d\theta', \quad (6)$$

where $J'_c(\theta)$ is the critical current density without the c -axis misorientation.

In the theoretical analysis of the field angle dependence of J_c using this model, $B_i(0)$ was determined by extrapolating the magnetization $J_c(B)$ in the parallel field to zero. The parameters, δ , γ_p and γ are determined so that a good fit is obtained between the experimental and theoretical results for the field angle dependence of the magnetization J_c and the irreversibility field after breaking the connectivity. The used parameters are shown in Table 1. The dot-dash line and solid symbols in Fig. 6 show the theoretical and experimental results on the normalized magnetization J_c at $B = 0.08$ T calculated from Eq.(6), respectively. In the above the assumed intrinsic angular dependence of the intragrain critical current density without c -axis misorientation, $J'_c(\theta)$, is shown by the dash line in Fig. 6. The irreversibility field is shown in Fig. 7. Fairly good agreements are obtained.

On the other hand, the value of the anisotropy parameter, $\gamma = 20.4$, seems to be fairly smaller than the experimental estimation ranged from 30 to 50 [9]. This disagreement seems to be attributed to the assumption of direct application of the anisotropic effective mass model to the irreversibility field, which is considered to be strongly affected by the flux creep. For a more correct estimation of the anisotropy parameter, the analysis in which the effect of the flux creep is taken into account is necessary.

In Fig. 6, it is expected that the intragrain critical current density at $\theta = 0$ can be improved by a factor 2.7 by elimination of the c -axis misorientation of grains. This value corresponds to the case where the magnetic field is exactly applied parallel to each grain.

For the improvement of the transport critical current density of Bi-2223 tape, the in-plane alignment of grains is also necessary. The effect of in-plane alignment on the intergrain critical current density should be clarified for the first step.

4 Summary

The magnetic field angle dependence of magnetic J_c was measured for the Bi-2223 tape specimen before and after the bending, and the intrinsic anisotropy of intragrain critical current density was investigated when the orientation of the c -axis is aligned. It is found that the intragrain critical current density is improved by a factor of 2.7 in a parallel magnetic field.

The effect of the in-plane alignment of grains on the intergrain critical current density is necessary for the improvement of the transport critical current density.

The anisotropy parameter evaluated from the anisotropy of the intragrain critical current was 20.4. This value is smaller than the values reported in literatures. This seems to be caused by the assumption of direct application of the anisotropic effective mass model to the irreversibility field.

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Table 1
Parameters used for numerical calculation

pinning parameters:	$\delta = 3.0, \gamma_p = 0.75$
anisotropy parameter:	$\gamma = 20.4$
irreversibility field parallel to tape surface:	$B_i(0) = 2.04 \text{ T}$
standard deviation of c -axis alignment:	$\sigma = 12$

Figure 1 Microstructures of cleaved cross-section of bent superconducting filament.

Figure 2 Schematic illustration of current in a superconducting filament or chip which flows in a plane and normal to applied magnetic field: is applied (a) and (b) for $0 \leq \theta < \theta_{\text{th}}$ and (c) for $\theta_{\text{th}} < \theta \leq 90^\circ$.

Figure 3 Transport J_c for Bi-2223 tape at 77.3 K vs magnetic field component normal to the tape.

Figure 4 Field angle dependence of DC magnetization J_c at 77.3 K before breaking.

Figure 5 Field angle dependence of DC magnetization J_c at 77.3 K after breaking.

Figure 6 Field angle dependence of intragrain critical current density at $B = 0.08 \text{ T}$ at 77.3 K. Symbols show experimental results in Fig. 4. The broken line shows the assumed field angle dependence for the ideal case of c -axis aligned tape and the chained line shows the calculated dependence.

Figure 7 Field angle dependence of irreversibility field at 77.3 K. Error bars show the irreversibility field obtained by extrapolating of J_c - B characteristics and the dash line shows the prediction of Eq. (3) with $B_i(0) = 2.04 \text{ T}$ and $\gamma = 20.4$.

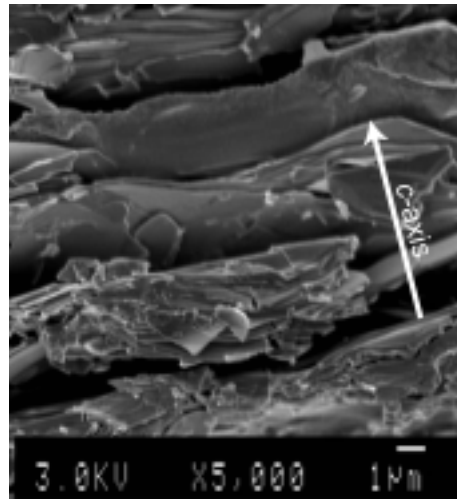


Fig. 1: Y. Himeda *et al.* WSP-39/ISS2004

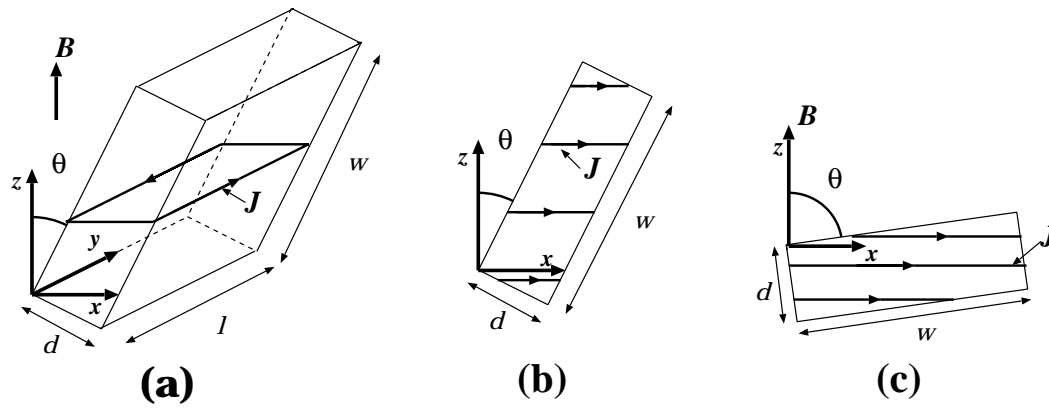


Fig. 2: Y. Himeda *et al.* WSP-39/ISS2004

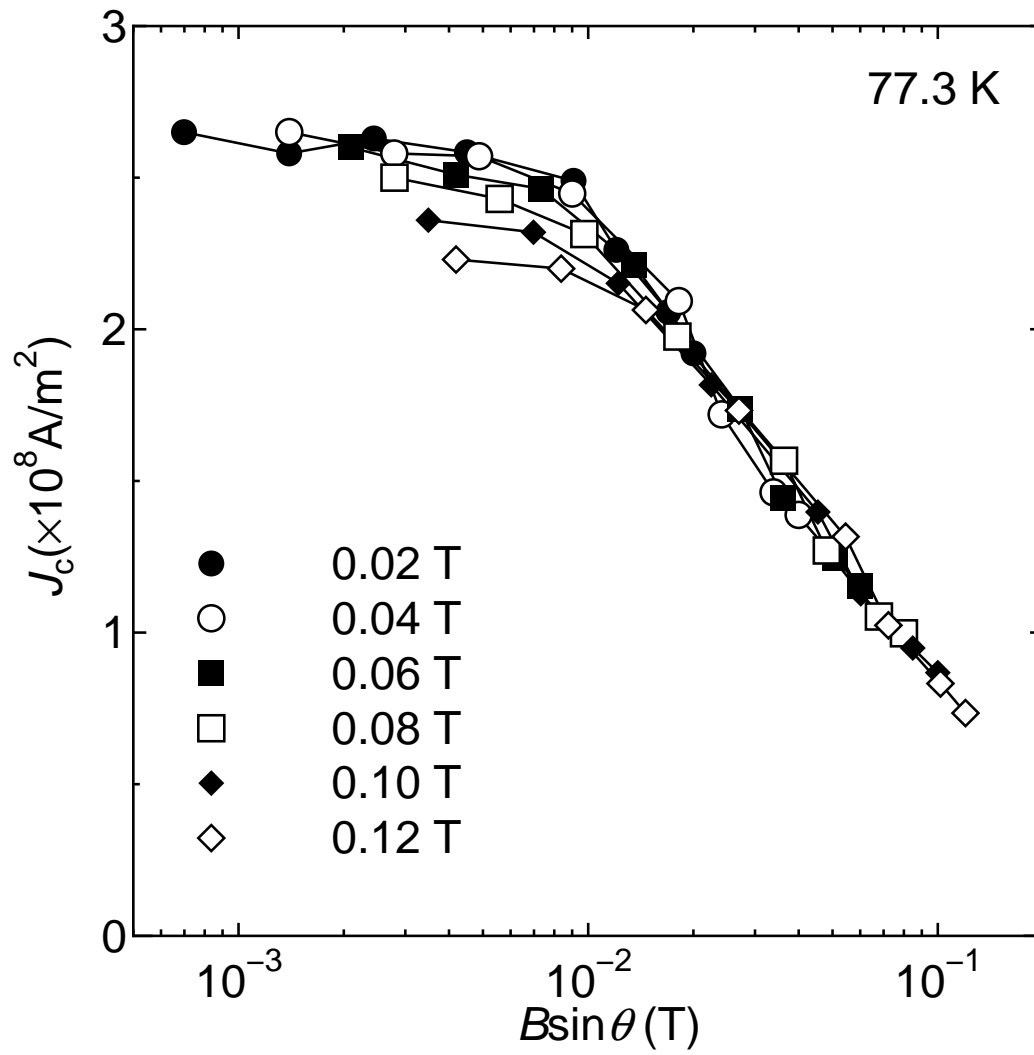


Fig. 3: Y. Himeda *et al.* WSP-39/ISS2004

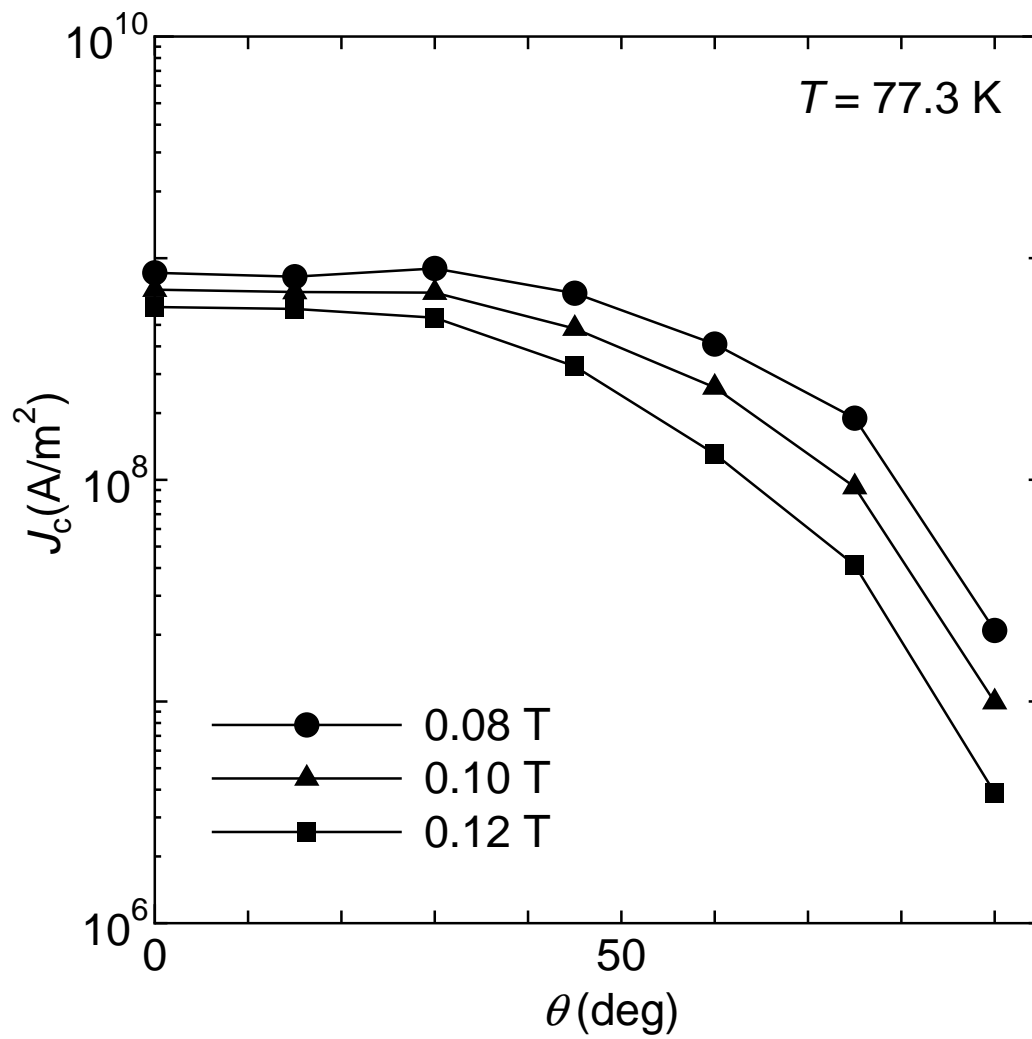


Fig. 4: Y. Himeda *et al.* WSP-39/ISS2004

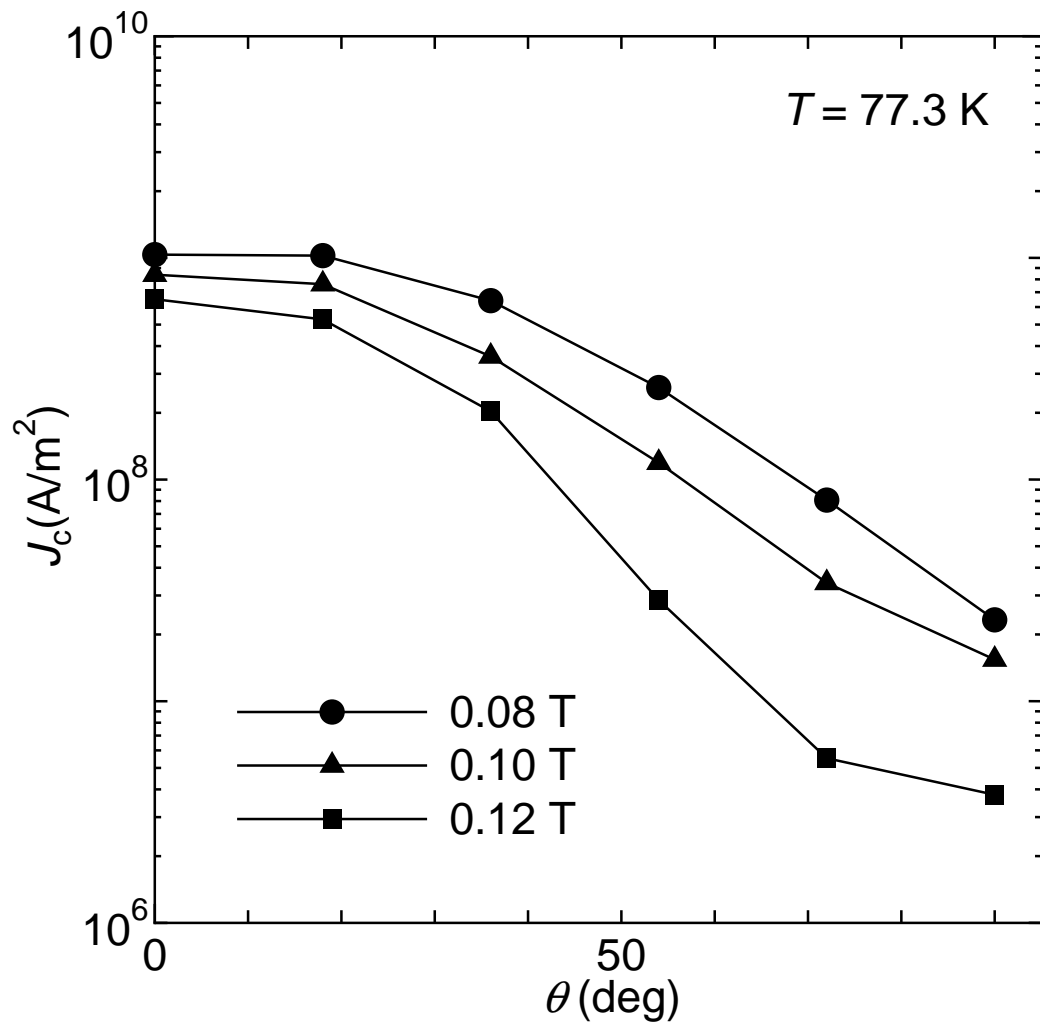


Fig. 5: Y. Himeda *et al.* WSP-39/ISS2004

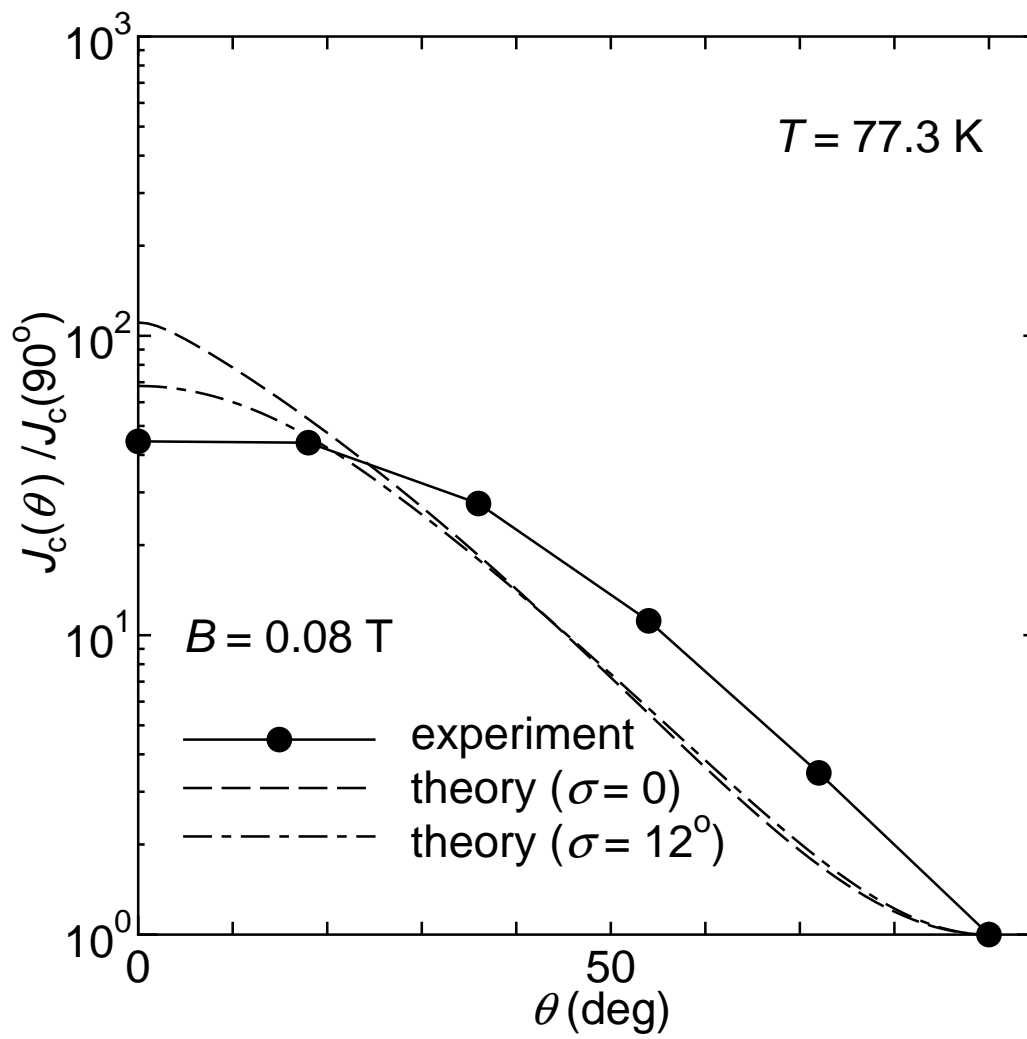


Fig. 6: Y. Himeda *et al.* WSP-39/ISS2004

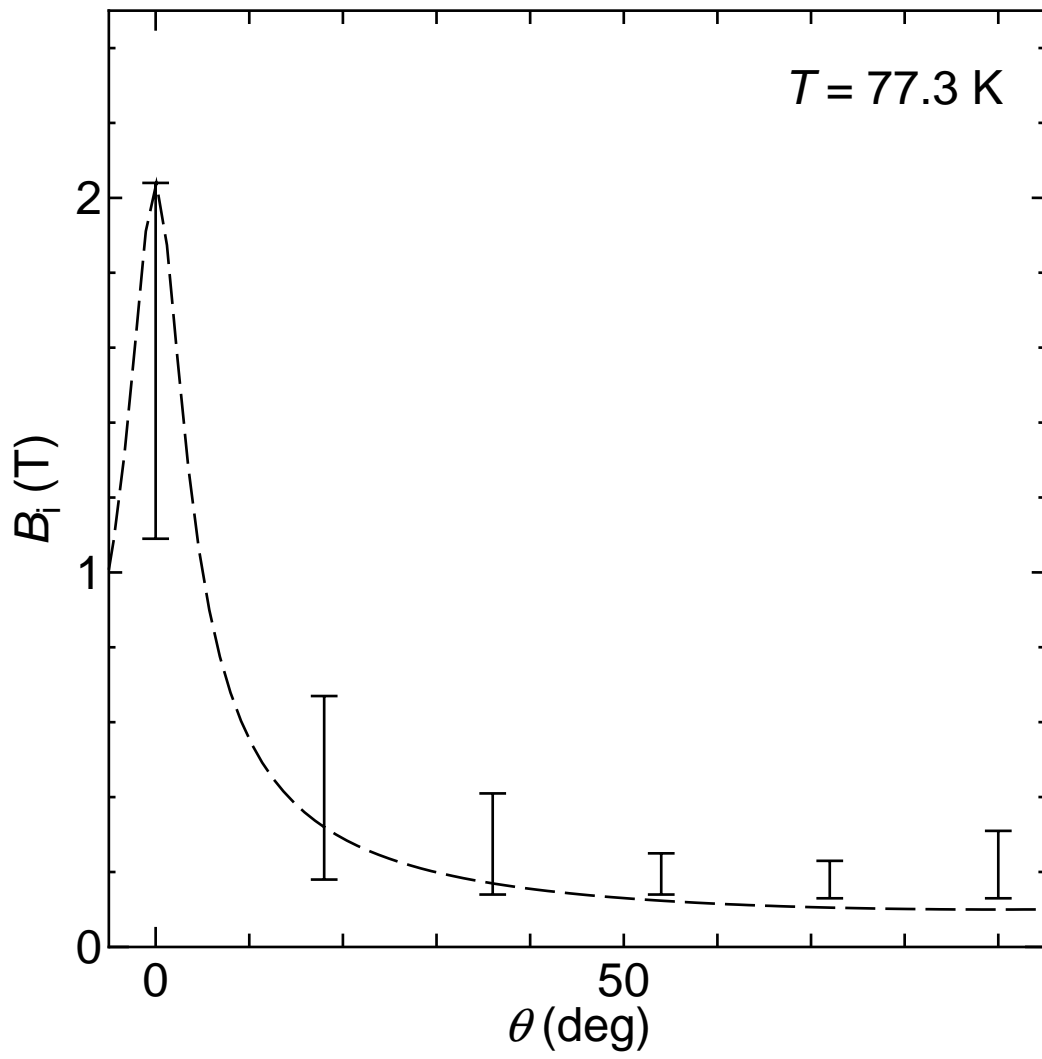


Fig. 7: Y. Himeda *et al.* WSP-39/ISS2004