Evaluation of field-angle anisotropy of critical current in multifiramentaly Bi-2223 tapes prepared by CT-OP process

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Abstract

The critical current property of Bi-2223 silver sheathed tape has been significantly improved by application of ConTrolled Over Pressure (CT-OP) process with adjusting temperature and oxygen partial pressure at the final heat treatment. In this paper, the field-angle dependence of the critical current density was measured at 77.3 K and the crystalline misorientation angle was estimated for four specimens with different critical current densities. It is found that in a parallel magnetic field, the critical current density of the latest Bi-2223 tape of 190 A class is remarkably higher than the other specimens over a wide region of magnetic field. On the other hand, although the critical current density of the latest tape in a normal magnetic field is higher than the other specimens, the difference is relatively small especially at high magnetic fields. Thus, the field-angle anisotropy of the latest tape is higher than the other specimen. The observed results can be explained by the improved condensation energy density and the better c-axis alignment in the latest tape.

Key words: Bi-2223 tape, over pressure sintering, DI-BSCCO, critical current density, flux creep-flow model
PACS: 74.72.Hs, 74.25.Sv, 74.25.Qt

Preprint submitted to WTP–32/ ISS2007 *November 6, 2007*

1 Introduction

The critical current property of Bi-2223 silver sheathed tape has been significantly improved by application of ConTrolled Over Pressure (CT-OP) process with adjusting temperature and oxygen partial pressure at the final heat treatment [1]. Not only the critical current density but also the critical current, the n-value and the irreversibility field have been increased by the development of the CT-OP process. In addition, it was reported that the critical temperature of Bi-2223 tape was appreciably enhanced [2]. This indicates that Bi-2223 tape has a sufficient room for further improvement, if the optimization of the process condition is achieved. Just after introduction of the CT-OP process, these improvements were mainly attributed to the improved connectivity of superconducting grains due to the better c-axis alignment resulted from elimination of voids [3]. After that the critical current was further improved to the level of 150 A. This improvement was attributed to the enhancement of the flux pinning strength, which was considered to result from development of the condition of the CT-OP process [4].

The critical current of the latest Bi-2223 tape reached the level of 200 A in the self field. However, the critical current density at high fields, the irreversibility field and the n-value of the latest Bi-2223 tape of 190 A class were similar to the previous Bi-2223 tape of 150 A class. These results seemed to be caused by weakly pinning regions indicating a widened statistical distribution of the flux pinning strength. If such a pinning distribution is improved, a

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significant improvement of the critical current property is expected [5].

In this paper, the field-angle dependence of the critical current density was measured and the crystalline misorientation angle was obtained. The field-angle anisotropy of the critical current density is compared with those in previous Bi-2223 tapes. The obtained property is analyzed using the flux creep-flow model [6]. The correlation between the field-angle anisotropy of the critical current density and the crystalline misorientation angle of Bi-2223 tapes will be discussed.

2 Experimental

Four Bi-2223 tapes with different critical current densities were measured. The critical current of the specimens is 104 A(#1), 126 A(#2), 147 A(#3) and 197 A(#4) at 77.3 K in the self field. Specimen #1 was manufactured by the ambient pressure process, and specimens #2 $\sim$ #4 were manufactured by CT-OP process. The specification of the present(#4) and previous(#1$\sim$#3) Bi-2223 tapes is listed in Table 1. The field-angular dependence of the transport critical current density was measured at 77.3 K. The direction of magnetic field is kept normal to the direction of the current and the field-angle is measured from the tape surface. The field angle-anisotropy was defined by $J_c(0°)/J_c(90°)$. The electric field criterion to determine the critical current density was 1.0×10^{-4} V/m. The irreversibility field was determined as the magnetic field at which the obtained critical current density decreased to 1.0×10^7 A/m^2.

3 Results and Discussion

Fig. 1(a) and (b) show the magnetic field dependence of the critical current density in normal and parallel magnetic fields at 77.3 K, respectively. For comparison the results of previous specimens #1 $\sim$ #3 are also shown in the figures. It is found that the critical current density of specimen #4 is higher than those of previous specimens #1 $\sim$ #3 in both directions of the magnetic field. Thus, it can be said that the critical current density of specimen #4 is totally improved.

Fig. 2 shows the relationship between J_c and the magnetic field component normal to the tape for specimen #4, where θ is the angle of magnetic field measured from tape surface. This result shows that the critical current density is uniquely expressed as a function of the normal field component in the large angle region. On the other hand, the critical current density tends to be saturated with decreasing field-angle. The value of field angle at which the curve deviates from the master curve in the large angle region gives approximately the out-of-plane misorientation angle of grains [7,8]. The value of the misorientation angle of specimen #4 is smaller than the other specimens as shown in Fig. 3. This result is consistent with a value of FWHM of a rocking curve for a similar specimen [9]. Fig. 4 shows the field-angle anisotropy of critical current density, $J_c(0°)/J_c(90°)$, of the Bi-2223 tapes at 77.3 K. The field-angle anisotropy of specimen #4 is higher than other specimens #1 $\sim$ #3.

Fig. 5 (a) and (b) show the irreversibility field in a normal and parallel magnetic field, respectively. In a normal magnetic field, the value of irreversibility field of specimen #4 is higher than that of specimen #3, whereas it becomes slightly lower at temperatures below 60 K. On the other hand, in a magnetic field parallel to the tape surface, the irreversibility field of #4 is considerably higher than those of the other specimens over the whole temperature region.

The observed results of the J_c-B characteristics are compared with the theoretical prediction of the flux creep-flow model. The pinning parameters, m, γ, g^2, A_{m} and σ^2, are determined so that a good fit is obtained between the experimental and theoretical results. The obtained theoretical results on the critical current density and irreversibility field are compared with the experimental results for the four specimens in Fig. 1 and Fig. 5, respectively. It is seen that agreement is satisfactory. The parameters used in normal and parallel magnetic fields are shown in Table 2(a) and 2(b), respectively.

The obtained parameters show that the value of A_{m} of specimen #4 in both directions of magnetic field is the highest among the four specimens. This is considered to be attributed to improvement of the condensation energy density of specimen #4. The higher critical temperature of specimen #4 than the other specimens supports this speculation. In addition, the anisotropy of A_{m} of specimen #4 shown in Table 3 is the highest among four specimens. This is consistent with the largest anisotropy of J_c. This is considered to be attributed to the better c-axis alignment in specimen #4. The value of σ^2 is the lowest in specimen #4 for both directions of the magnetic field. It is considered that the decrease in σ^2 is also caused by the better c-axis alignment and the decrement of the weak link of grain boundaries.

The remarkable improvement of the critical current density of #4 in a magnetic field parallel to the tape comes from the these reasons. The increase in the irreversibility field in this field direction comes also from the same reasons.

On the other hand, the critical current density in a magnetic field normal to the tape is partly improved by the improved superconducting property, but is partly deteriorated by the enhanced anisotropy due to the better crystal alignment, i.e., the decrease in the upper critical field. In fact, the maximum upper critical field at 0 K in specimens #3 and #4 with the misorientation angle of 9° and 6° is estimated as 240 T and 160 T, respectively, with assumption of $B_{c2}(90°)$=50 T and the anisotropy parameter of 30. The behavior of the irreversibility field can also be explained by the same mechanism.

4 Summary

In a parallel magnetic field, the critical current density of the latest Bi-2223 tape of 190 A class (#4) is remarkably higher than the other specimens (#1∼#3) over a wide region of magnetic field at 77.3 K. On the other hand, although the critical current density of #4 in a normal magnetic field is higher than the other specimens, the difference between specimens #4 and #3 is relatively small especially at high magnetic fields. Thus, the field-angle anisotropy of specimen #4 is higher than the other specimen. The irreversibility field of specimen #4 in a parallel direction was highest among the specimens over the whole temperature region. The value of irreversibility field of specimen #4 in a normal direction was higher than that of specimen #3 at high temperatures, but it becomes slightly lower at temperature below 60 K.

It is considered that the remarkable improvement of the critical current density and the irreversibility field of specimen #4 in a magnetic field parallel to the tape comes from the better c-axis alignment and the improvement of the condensation energy density. On the other hand, the critical current density and the irreversibility field in a magnetic field normal to the tape is partly improved by the improvement of the superconducting property, but is partly deteriorated by the enhanced anisotropy due to the better crystal alignment.

Appendix

According to the flux creep-flow model [6], the critical current properties can be calculated as a function of the virtual critical current density, J_{c0}, in a creep-free case. The virtual critical current density is usually expressed by

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

where m, γ and δ are pinning parameters and δ=2 is used.

In usual oxide superconductors, J_{c0} is known to be widely distributed. Here only the parameter A in Eq. (1) is assumed to be statistically distributed as

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

where A_m is the most probable value of A, σ^2 is a parameter representing the distribution width of A, and K is a normalizing constant. The pinning potential U_0 which determines the flux creep property is described in terms of J_{c0}. In the three-dimensional pinning regime where the superconducting filament thickness is larger than the pinning correlation length, U_0 is given as

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

where g^2 is the number of flux lines in the flux bundle. This number is determined so that the critical current density under the flux creep is maximized and is theoretically derived in Ref.[10]. However, g^2 is used here as a fitting parameter for simplicity with the assumption that g^2 depends only on the temperature. This seems to be allowed, since the treated range of magnetic field is much narrower in comparison with the value of the upper critical field.

The local electric field, E', is determined from the mechanism of flux creep and flow. Thus the total electric field is given by

$$E(J) = \int_0^\infty E' f(A) \mathrm{d}A. \tag{4}$$

Hence, the average E-J curve is calculated from Eq. (4). The details of the analysis are described in Ref. [6].

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Table 1 : Specifications of specimens.

	Condition at final heat treatment	I_c[A](77.3 K, s.f.)	Year of manufacture
#1	Ambient pressure	104	2004
#2	Over pressure	126	2004
#3	Over pressure	147	2005
#4	Over pressure	197	2006

Table 2 : Parameters used for numerical calculation in a magnetic field (a)normal and (b)parallel to the tape surface at 77.3 K, respectively.

(a)	A_m	σ^2	γ	m	g^2
#1	3.32×10^9	0.043	0.49	3.48	1.28
#2	3.45×10^9	0.025	0.50	3.51	1.13
#3	3.59×10^9	0.021	0.51	3.49	1.09
#4	3.85×10^9	0.019	0.46	3.53	1.06

(b)	A_m	σ^2	γ	m	g^2
#1	5.79×10^9	0.033	0.49	3.48	1.78
#2	6.37×10^9	0.017	0.50	3.51	1.77
#3	7.02×10^9	0.013	0.51	3.49	1.69
#4	8.79×10^9	0.011	0.46	3.53	1.71

Table 3 :The anisotropy of A_m.

#1	#2	#3	#4
1.74	1.84	1.95	2.28

Figure 1 Magnetic field dependence of critical current density at 77.3 K in a magnetic field (a) normal to the tape surface and (b) parallel to the tape surface. Symbols show experimental results and lines show the theoretical results based on the flux creep-flow model.

Figure 2 Critical current density of specimen #4 at 77.3 K versus a magnetic field component normal to the tape surface.

Figure 3 Crystalline misorientation angle.

Figure 4 Field angle anisotropy of critical current density at 77.3 K.

Figure 5 Temperature dependence of irreversibility field in a magnetic field (a) normal to the tape surface and (b) parallel to the tape surface. Symbols show experimental results and lines show the theoretical results based on the flux creep-flow model.

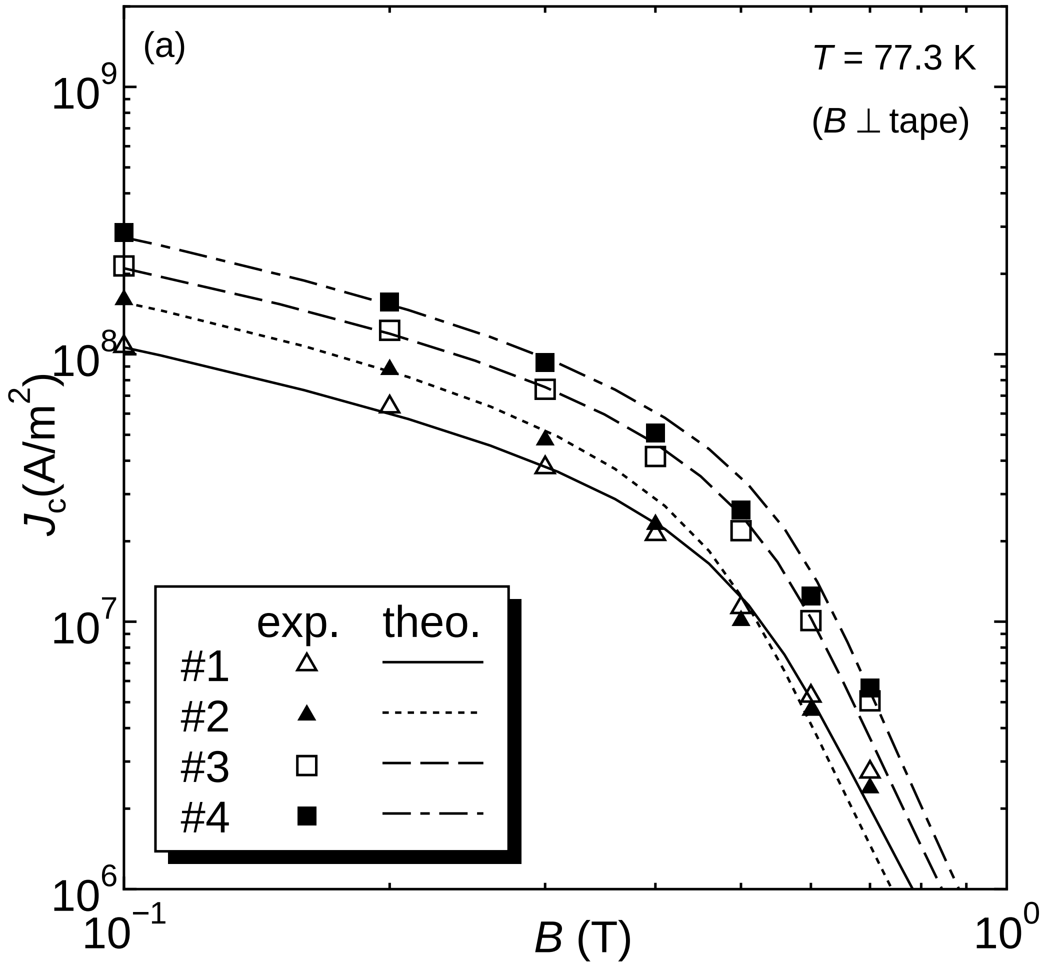


Fig. 1(a): S. Takayama *et al.* WTP–32/ISS2007

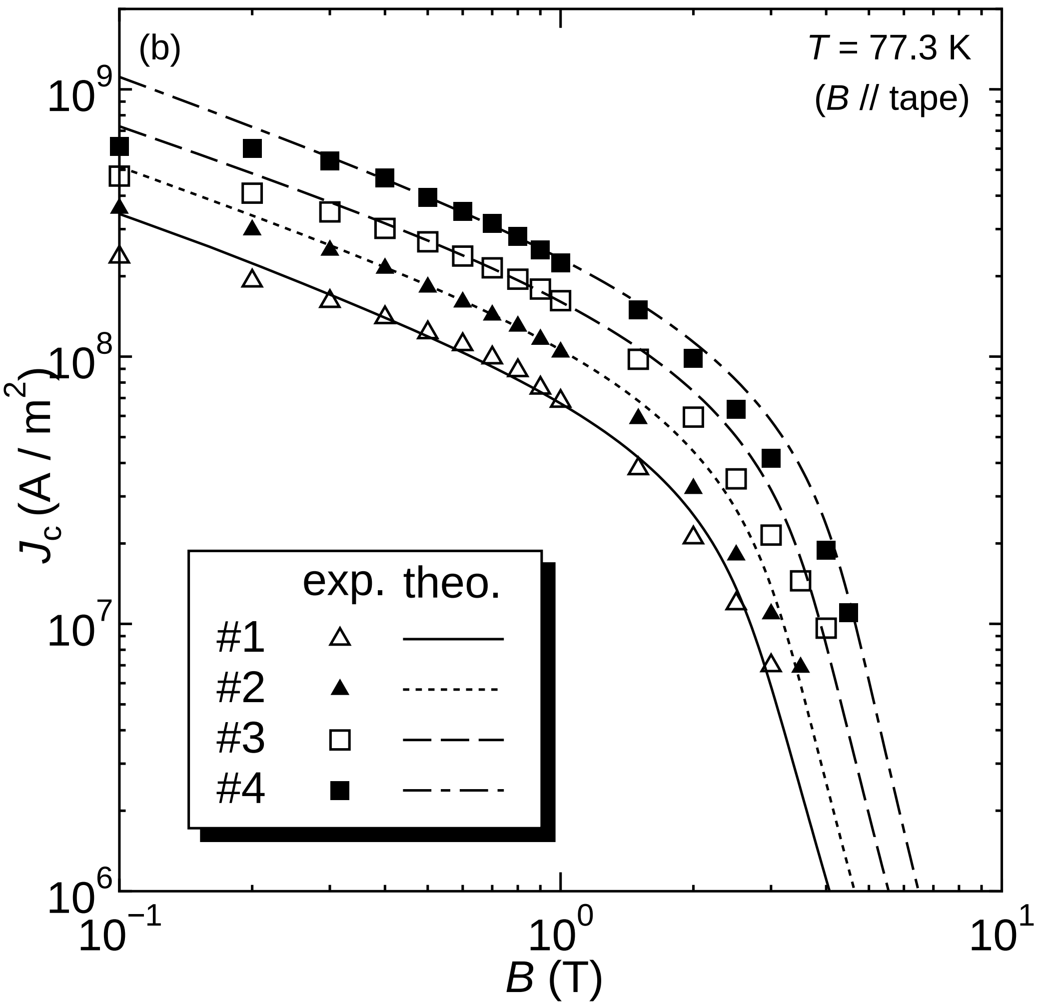
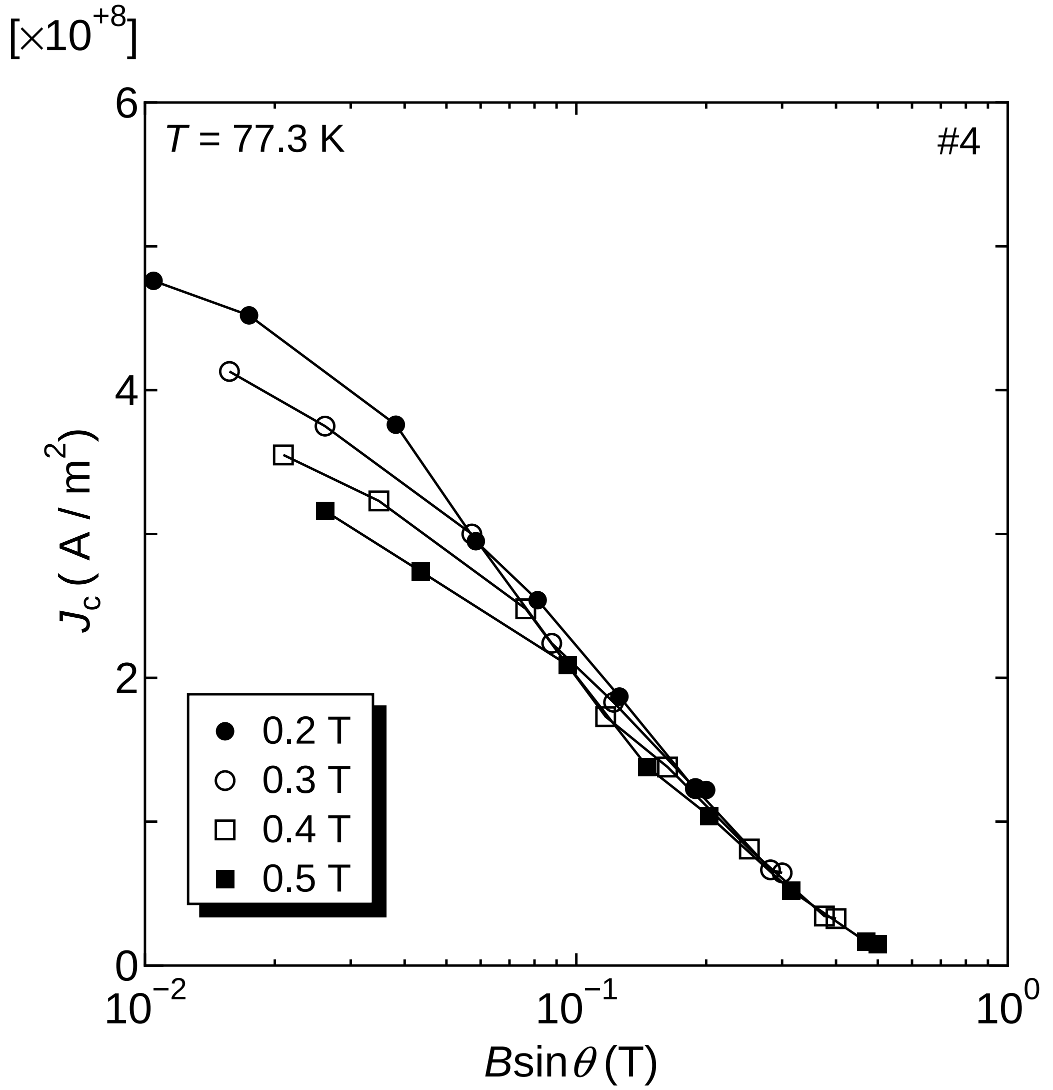


Fig. 1(b): S. Takayama *et al.* WTP–32/ISS2007



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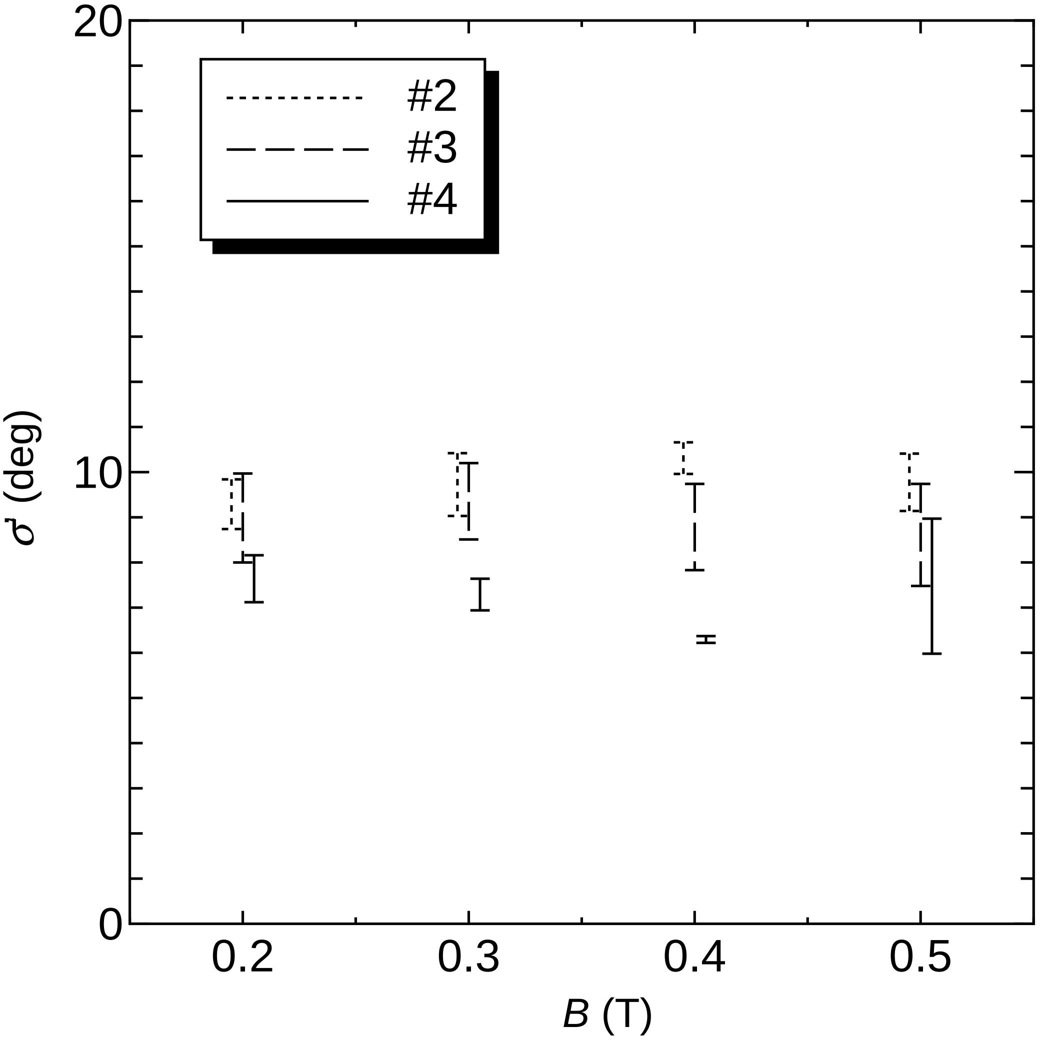

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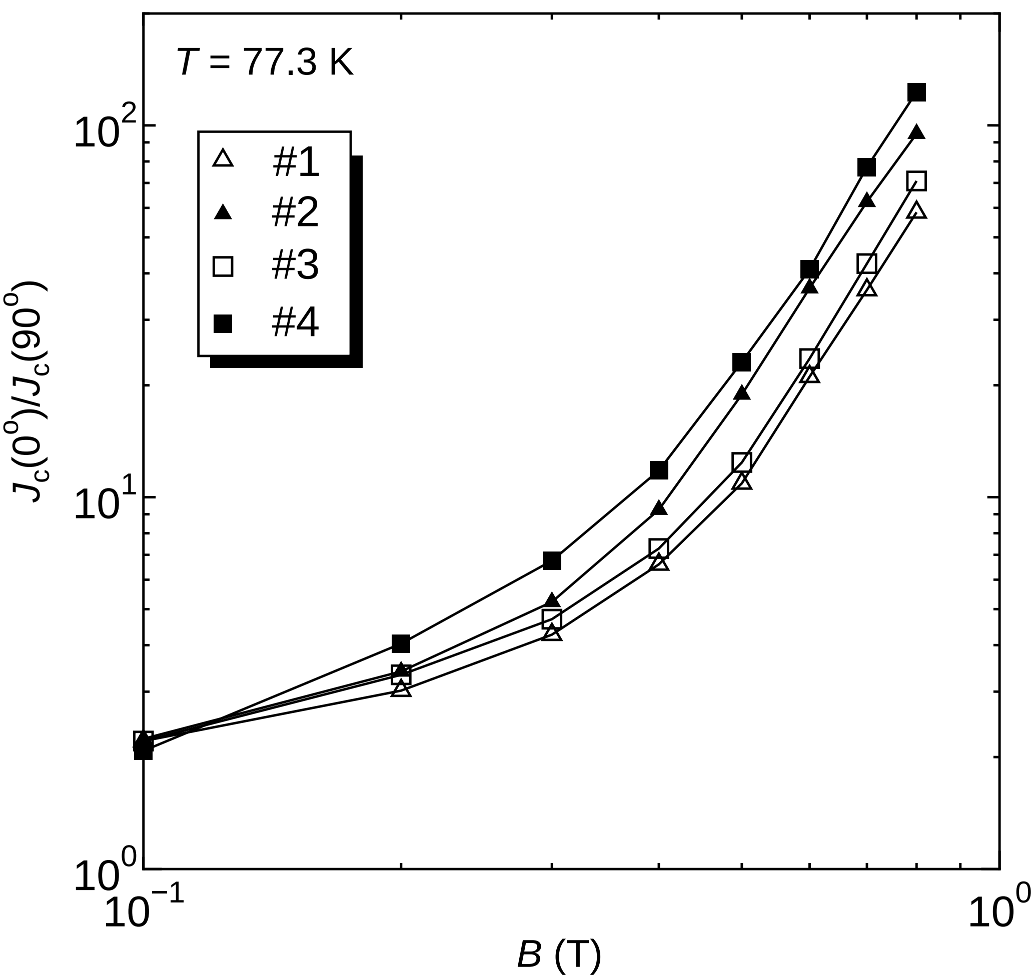
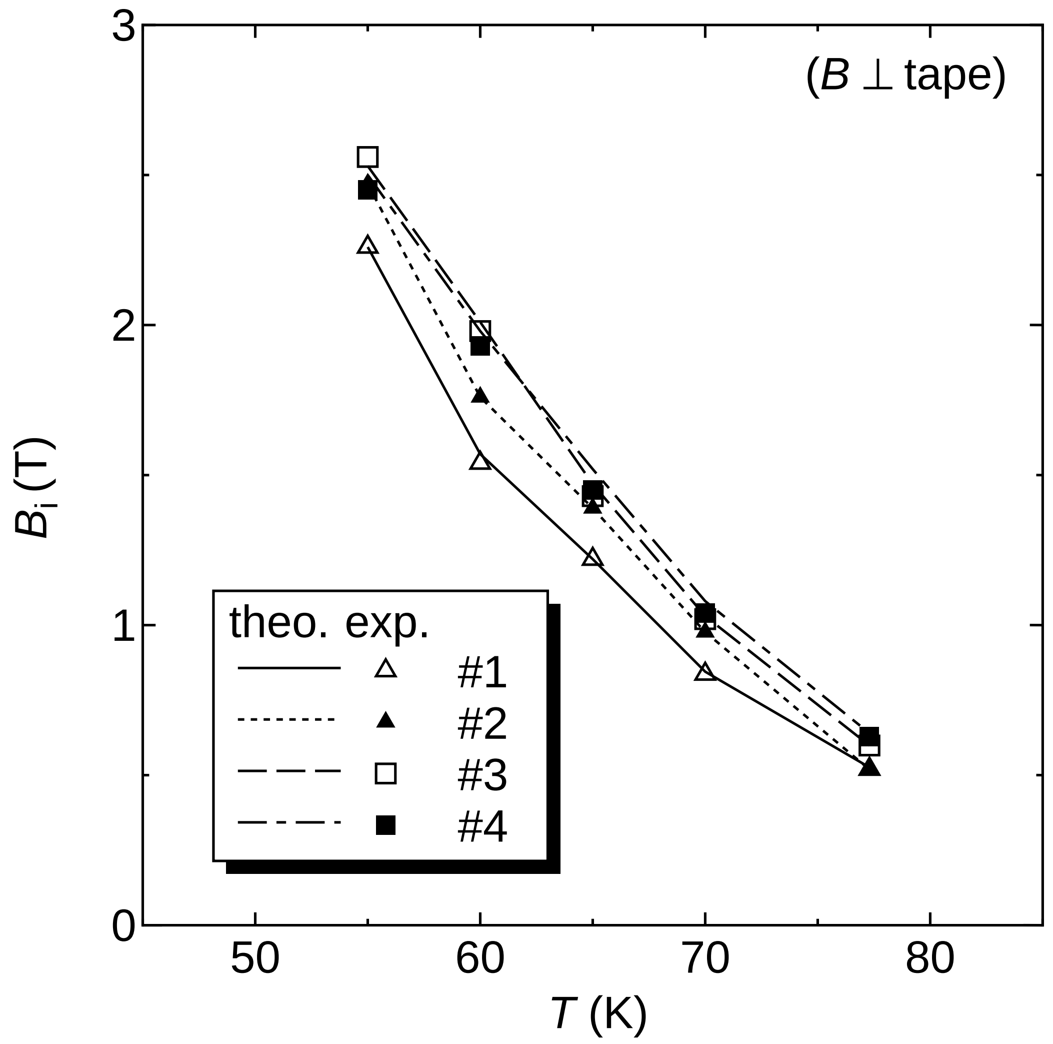


Fig. 4: S. Takayama *et al.* WTP–32/ISS2007



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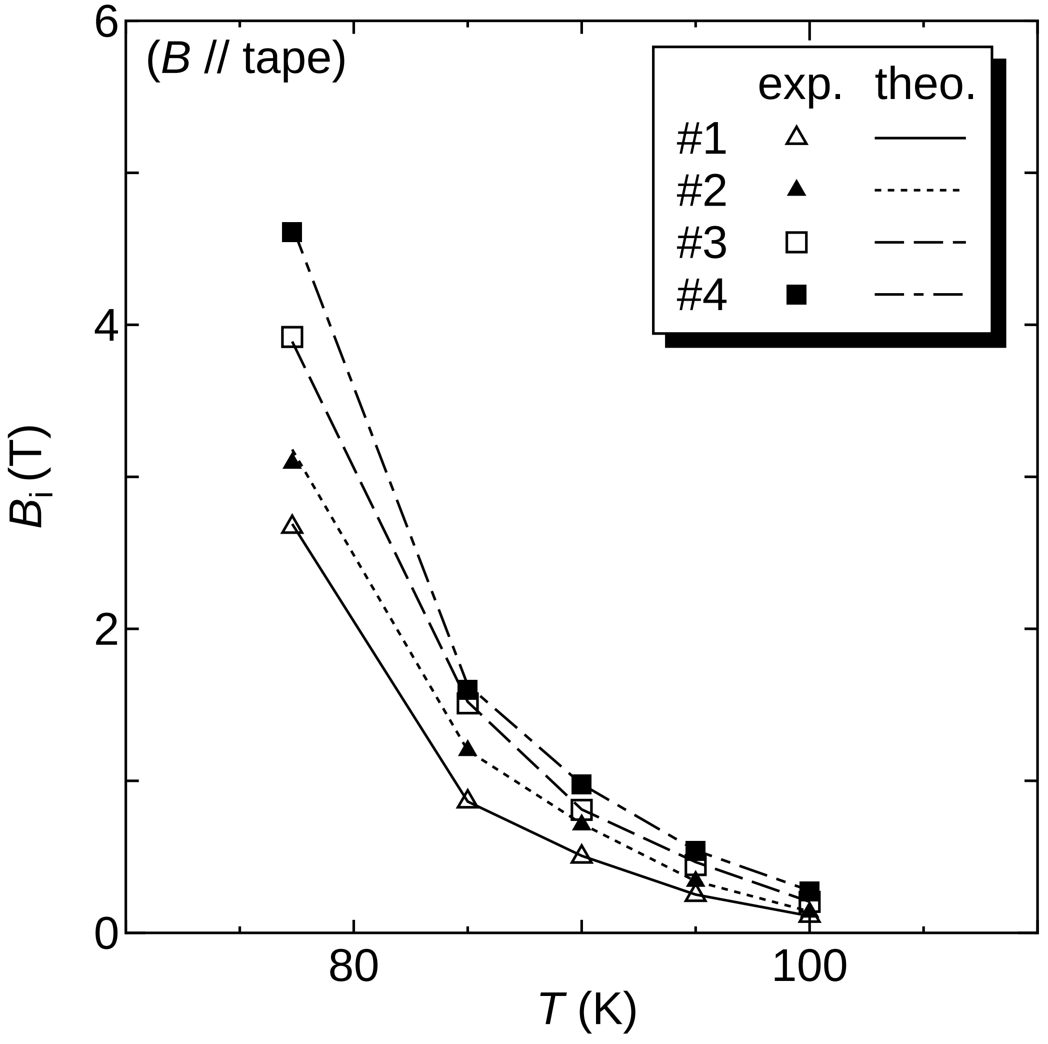

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