Flux pinning property and peak effect in Y-123 bulk superconductor with changed oxygen content

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Abstract

It is known the peak effect in melt-processed Y-123 bulk superconductors is caused by the disorder transition of flux lines pinned by oxygen deficient regions with lower T_c. In order to study the effect of dimensionality of superconductor on the peak effect, a change in the pinning characteristics by heat treatment at 550 °C was measured. J_c decreased and the peak effect became less pronounced. At the same time, the peak field and the dip field reduced. This shows that the disorder transition of flux lines took place much easier than before the heat treatment. It is speculated that the pinning energy and the transverse flux bundle size reduced due to a change of specimens to more two-dimensional underdoped state.

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1 Introduction

In melt-processed Y-123 bulk superconductors the critical current density J_c has a broad peak at medium fields in the medium range of temperature. It has been revealed that oxygen deficient regions with lower T_c are relevant to the peak effect [1][2], while 211 phase particles are not.

In a previous measurement [3][4] it was found that J_c decreased in a medium field region and the peak effect disappeared by addition of 211 phase particles to Y-123 bulk superconductor in spite of an increase of J_c at low and high fields. This shows that the pinning mechanism of the lower T_c regions, which causes the peak effect, is not an attractive pinning based on the condensation energy interaction, but a repulsive one based on the kinetic energy interaction under the presence of the proximity effect [5].

However, the elementary pinning force of the kinetic energy interactions decreases monotonically with increasing magnetic field and the peak effect does not directly originate from the elementary pinning mechanism. On the other hand, the peak effect is considered to be caused by some transitional change in the property of flux lines as assumed in the disorder transition [6]. That is, the pinning efficiency is considered to enhance by a softening of elasticity of flux lines at the peak effect.

The experimental results of Küpfer *et al.* [7] on Y-123 superconductor suggests that the disorder transition is induced by the flux pinning interaction itself. That is, for a more strongly pinned superconductor, the flux line lattice is more heavily deformed and hence, its softening probably starts at a lower field. Hence, the disorder transition field seems to be mainly determined by the elastic energy and the pinning energy.

Both of the pinning strength of oxygen deficient regions and the elastic properties, especially the shear modulus, of flux lines depend on the dimensionality of superconductor. Thus, it is expected that the change of the dimensionality of superconductor affects the disorder transition.

To investigate this phenomenon, in this study, four specimens which had been measured were heat treated again at relatively high temperature such that these specimens be in more two-dimensional state. The results on the critical current density and the irreversibility field were compared with the theoretical predictions of the flux creep-flow model [8].

2 Experimental

Specimens were Y-123 superconductors prepared by the melt-process with different conditions of addition of 211 phase particles and platinum to vary the pinning strength. These conditions are listed in Table 1. These specimens were heat treated at 500 °C for 20 h in a flowing oxygen atmosphere of 1 atm, slowly cooled down to 450 °C within 10 h, and then cooled down to room temperature [4]. The specimens were cut so that the c-axis was directed along the long axis of the specimen. The size of four specimens was about $3.14 \times 2.09 \times 0.82$ mm^3. Then, these specimens were heat treated again at 550 °C for 100 h in the same atmosphere condition. It is speculated that the specimens become more oxygen deficient by this heat treatment [9]. The critical temperature T_c of specimen 00, 01 and 11 were in the range of 88.8 K$\sim$90.2 K and decreased by the heat treatment. However, T_c of specimen 10 increased to 90.8 K by 1.4 K. The size and volume fraction of the 211 phase particles, which are considered to be unchanged by this heat treatment, are listed in Table 1.

The magnetization in a magnetic field along the c-axis was measured using a SQUID magnetometer and the critical current density, J_c, was estimated from the measured magnetization hysteresis using the extended Bean model. The electric field during the magnetization measurements was typically of the order of 1.0×10^{-9} V/m. The irreversibility field was determined by the field at which J_c was reduced to 1.0×10^5 A/m^2.

3 Results and Discussion

Figure 1 shows the magnetic field dependence of J_c of specimen 00 at 50.0 K and 77.3 K. The temperature range of the peak effect of this specimen is 20-65 K, while that was 40-87 K before the heat treatment. At the same time the critical current density decreased and the peak effect became less pronounced. In addition, the irreversibility field decreased drastically by the heat treatment. These results seem to be explained by the speculation that the specimens became underdoped by the heat treatment. That is, the order parameter, $|\Psi|$, in the block layer was reduced by a reduction of a carrier density, resulting in a decrease of the condensation energy density. Similar results were obtained also for specimens 01 and 11. By contrast, J_c in the low field region and the irreversibility field did not decrease much in specimen 10 in comparison with other specimens. In addition, T_c of this specimen increased by the heat treatment. Hence, specimen 10 seems to be in an overdoped state in the beginning. It is speculated that this specimen is not in a highly underdoped state even after the heat treatment.

Figure 2 shows the relationship between J_c and the effective surface area of

211 phase particles in a unit volume, f/d, at 30.0 K and at 0.1 T and 4.0 T. It is found that the correlation is very strong even after the heat treatment, if the result on specimen 10, which is more three-dimensional, is disregarded. Hence, it can be concluded that 211 phase particles are dominant pinning centers in the low and high field regions, although the specimens become underdoped. Since the structure of 211 phase did not change by the heat treatment at 550 °C, the reduction of J_c originates from the change in the condensation energy density.

Figure 3 shows the temperature dependences of the peak field (B_p), the dip field (B_d) at which the J_c takes on a minimum value and the irreversibility field (B_i) for specimen 00. The peak field and the dip field reduced by the heat treatment. This means that the disorder transition takes place more easily by making the superconductor more two-dimensional in spite of weaker pinning strength. This indicates that the elastic property of flux lines is dominant in determination of the disorder transition.

Here we shall analyze J_c and B_i for four specimens using the flux creep-flow model [8]. In the model, the pinning potential can be theoretically estimated in terms of the virtual critical current density in the creep-free case, J_{c0}, which is used as a parameter representing the pinning strength. The temperature and magnetic field dependencies of J_{c0} are assumed as

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

where A, m, γ and δ are pinning parameters. For simplicity it is assumed that only A in Eq. (1) is distributed in the form:

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

where A_{m} is the most probable value of A, σ^2 is a parameter representing the degree of distribution width and K is a constant. Another important parameter which determines the pinning potential is the number of flux lines in the flux bundle:

$$g^2 = \frac{C_{66}}{4J_{\mathrm{c0}}Ba_{\mathrm{f}}}, \tag{3}$$

where a_{f} is a flux line spacing and C_{66} is the shear modulus of flux line lattice which is associated with energy increase due to the deformation of $|\Psi|^2$ structure. According as the superconductor becomes two-dimensional, $|\Psi|^2$ in the blocking layer decreases and its layer thickness increases, resulting in smaller C_{66} or g^2. Thus, g^2 is directly related to the dimensionality of the superconductor. $\delta = 2$ is assumed for the present case of not too strong pinning [10]. Other parameters, A_{m}, m, γ, g^2 and σ^2 are adjusted so as to get a good agreement between the theory and experiment for J_{c}. The E-J characteristics are calculated using the flux creep-flow model with the parameters listed in Table 2 and the critical current density is estimated with the electric field criterion of $E_{\mathrm{c}} = 1.0 \times 10^{-9}$ V/m, corresponding to the magnetization measurement.

The values of m and γ are approximately equal to 3/2 and 1/2, respectively, as theoretically predicted for the pinning by nonsuperconducting 211 phase particles. In addition, the value of A_{m} becomes large when f/d becomes large, as shown in Tables 1 and 2. This fact also proves that the flux pinning by 211 phase particles is dominant except the peak field region. The value of A_{m} was reduced to about 0.7 of that before the heat treatment. This result means that the pinning energy is decreased by the heat treatment. This is caused by a decrease of the condensation energy due to a reduction of a carrier density, as argued above.

The value of g^2 changed from 3.9 ± 0.6 to 1.8 ± 0.2 by the heat treatment. This result also indicates that the specimens became two-dimensional superconductor by the reduction of carrier density. The reduction of g^2 means that the shear modulus of flux line lattice decreases much more than $J_{\mathrm{c}0}$ decreases, as indicated by Eq.(3). This is consistent that with the above argument the disorder transition takes place more easily by the change of the superconductor to more two-dimensional state. However, the reason why the softening of C_{66} is more remarkable than the reduction of pinning force is not clear.

The value of g^2 of specimen 10 is larger than g^2 of any other specimens. This is consistent with the above speculation that specimen 10 was more three-dimensional.

In Fig. 4, the theoretical results of J_{c} of specimen 10 at 60.0, 77.3 K and 83.0 K are shown by the solid lines and are compared with experimental results. It is found that the agreement is good in the high field region. At each temperature the theoretical result deviates from the experimental result in the medium field region. This is natural because only the pinning by 211 particles is considered with a disregard of the softening effect of flux lines. The irreversibility field, B_{i}, is also determined theoretically with the same definition as in experiment. The experimental and theoretical results are compared for specimens 10 and 11 in Fig. 5. It is found that the agreement is good. This also proves that the flux pinning by 211 phase particles is dominant in the high field region, similarly to the situation before the heat treatment.

4 Summary

To investigate the effect of the change of the dimensionality of superconductor on the peak effect, the pinning characteristics were investigated for melt-processed Y-123 specimens heat-treated at 550 °C. The following results are obtained.

1. The critical current density decreased and the peak effect became less pronounced. At the same time, the peak field and the dip field reduced. This shows that the disorder transition of flux lines took place much easier than before the heat treatment.
2. It is speculated that the pinning energy and the transverse flux bundle size reduced. These variations seem to be caused by a change of superconducting specimens to more two-dimensional underdoped state.
3. From the behaviors of much easier disorder transition and reduction of transverse flux bundle size, it can be concluded that the softening of C_{66} is more remarkable than the reduction of pinning force. The reason is not clear for now.

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Table 1
Specifications of specimens.

specimen	addition of		211 particle		T_c(K)	T_c(K)
	Pt	211	size d(μm)	volume fraction f	before	after
00	no	no	∼10	10 %	91.0	88.8
01	no	25 wt%	∼10	25 %	90.2	89.3
10	yes	no	∼1	2∼3 %	89.4	90.8
11	yes	25 wt%	∼1	25 %	91.8	90.2

Table 2
Pinning parameters used for calculation of E-J characteristics in all ranges of field and temperature.

specimen	A_m	m	γ	g^2	σ^2	δ
00	5.83×10^8	2.95	0.50	1.66	0.04	2
01	1.09×10^9	1.91	0.43	1.68	0.04	2
10	1.25×10^9	1.72	0.42	2.02	0.04	2
11	2.45×10^9	2.16	0.42	1.65	0.04	2

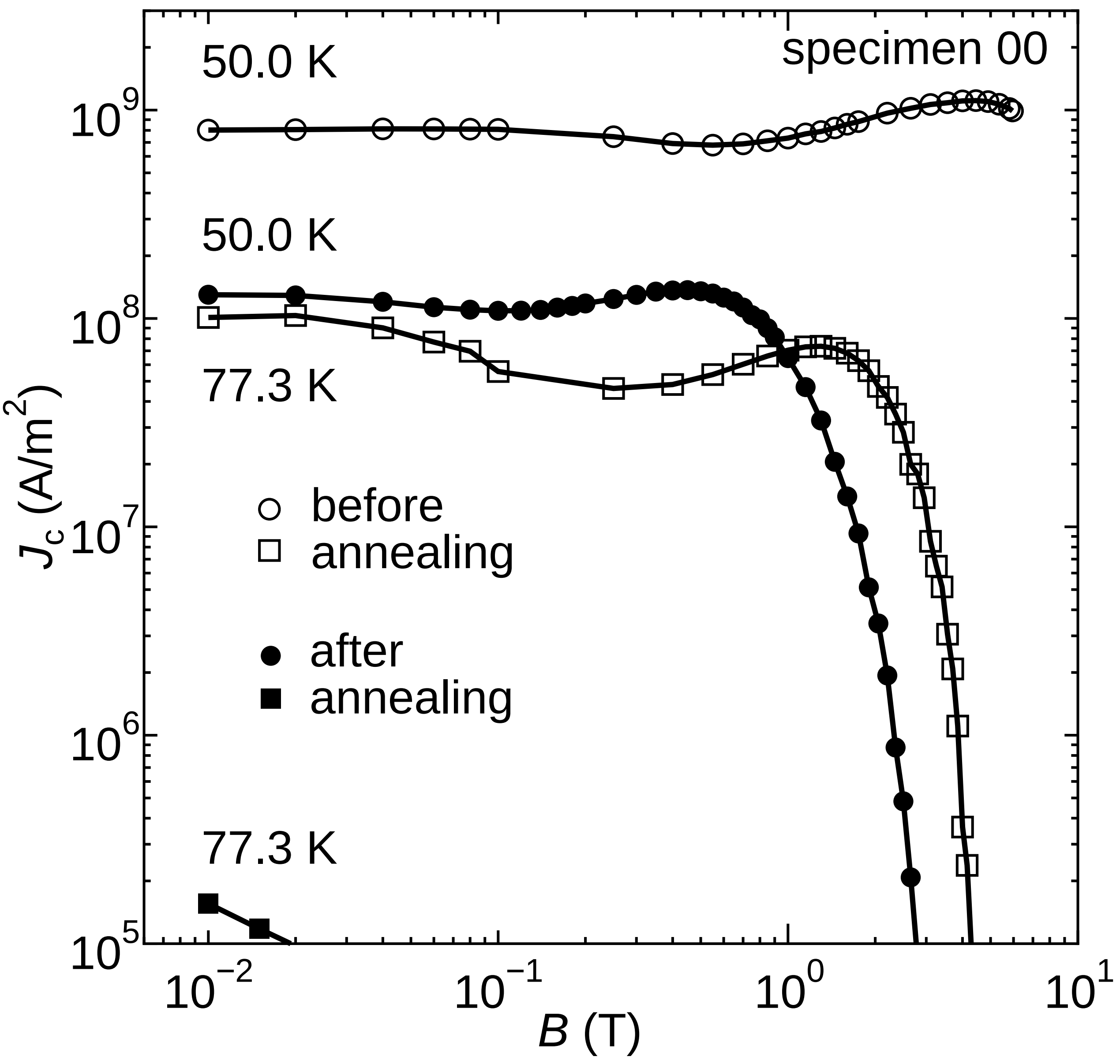
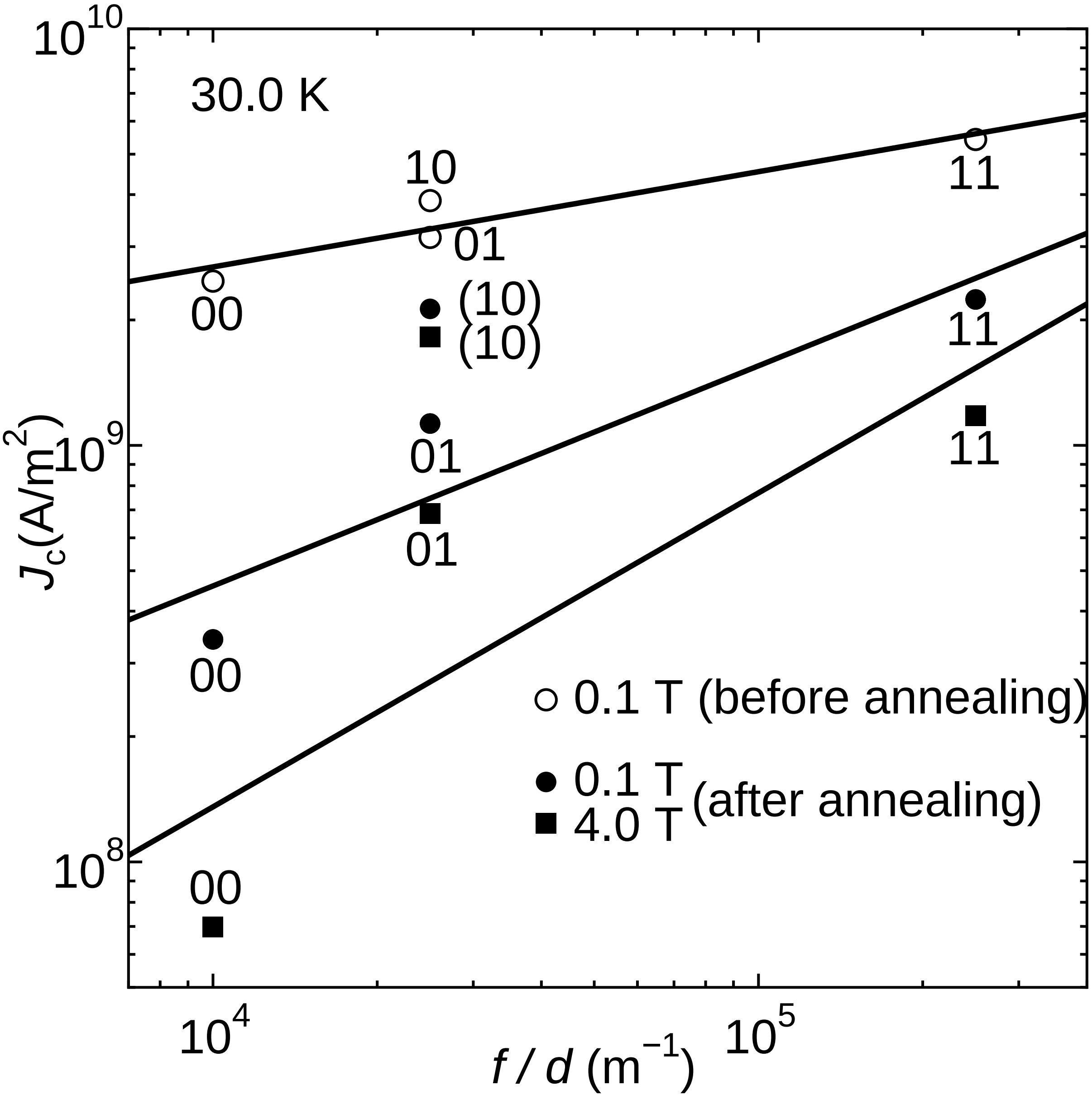


Figure 1: D. Yoshimi *et al.* /BSP-28/ISS2001



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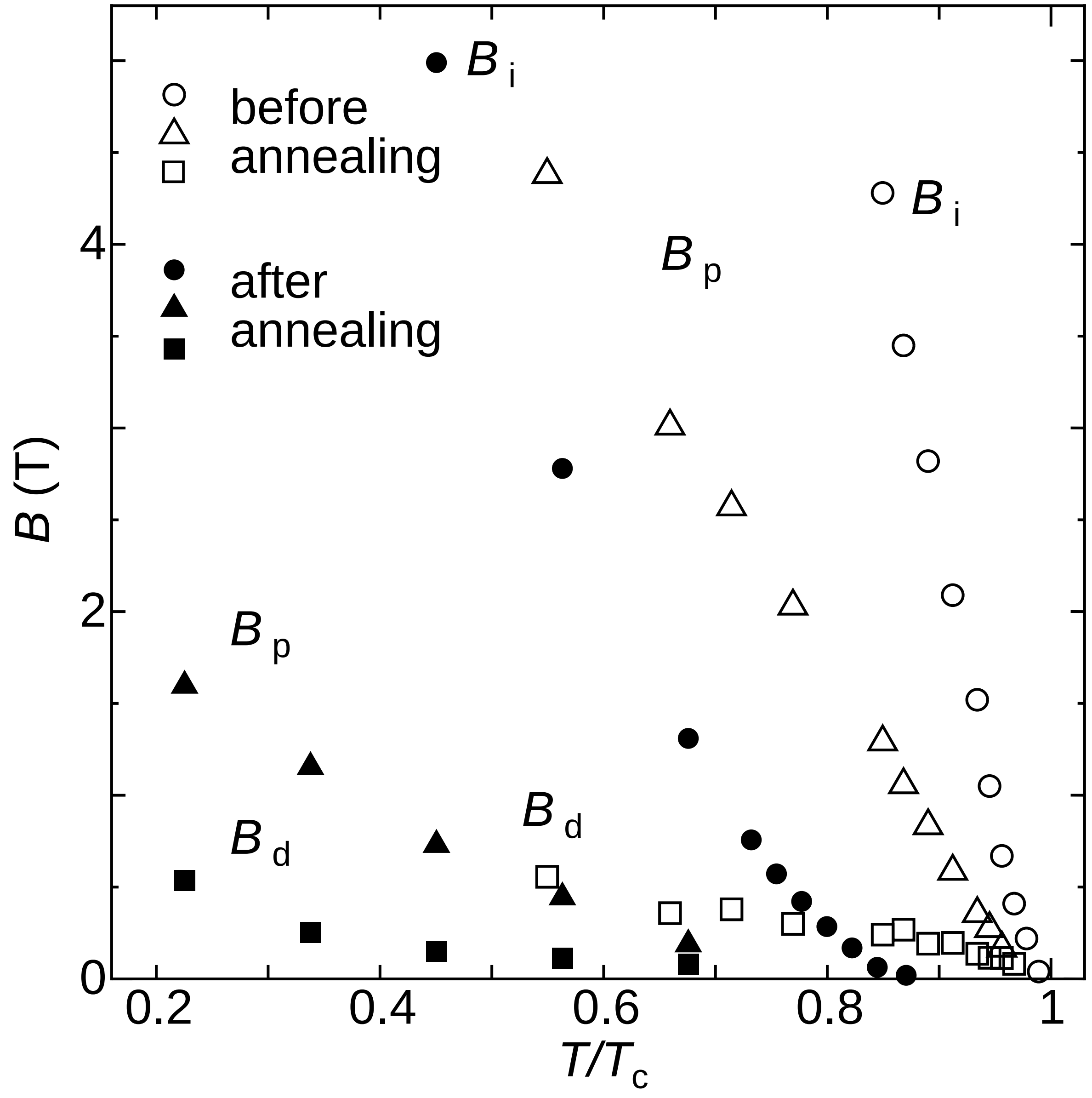

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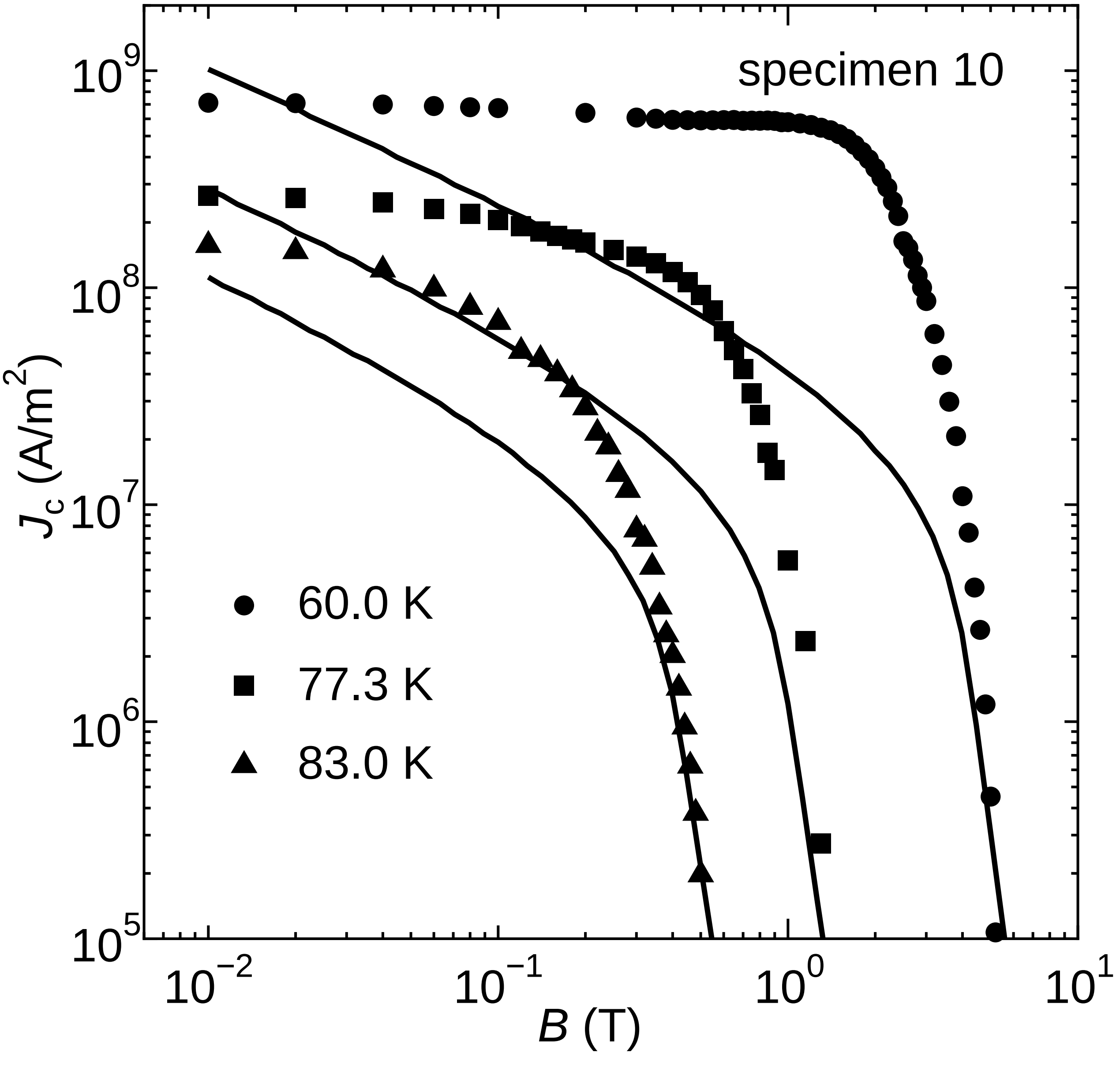

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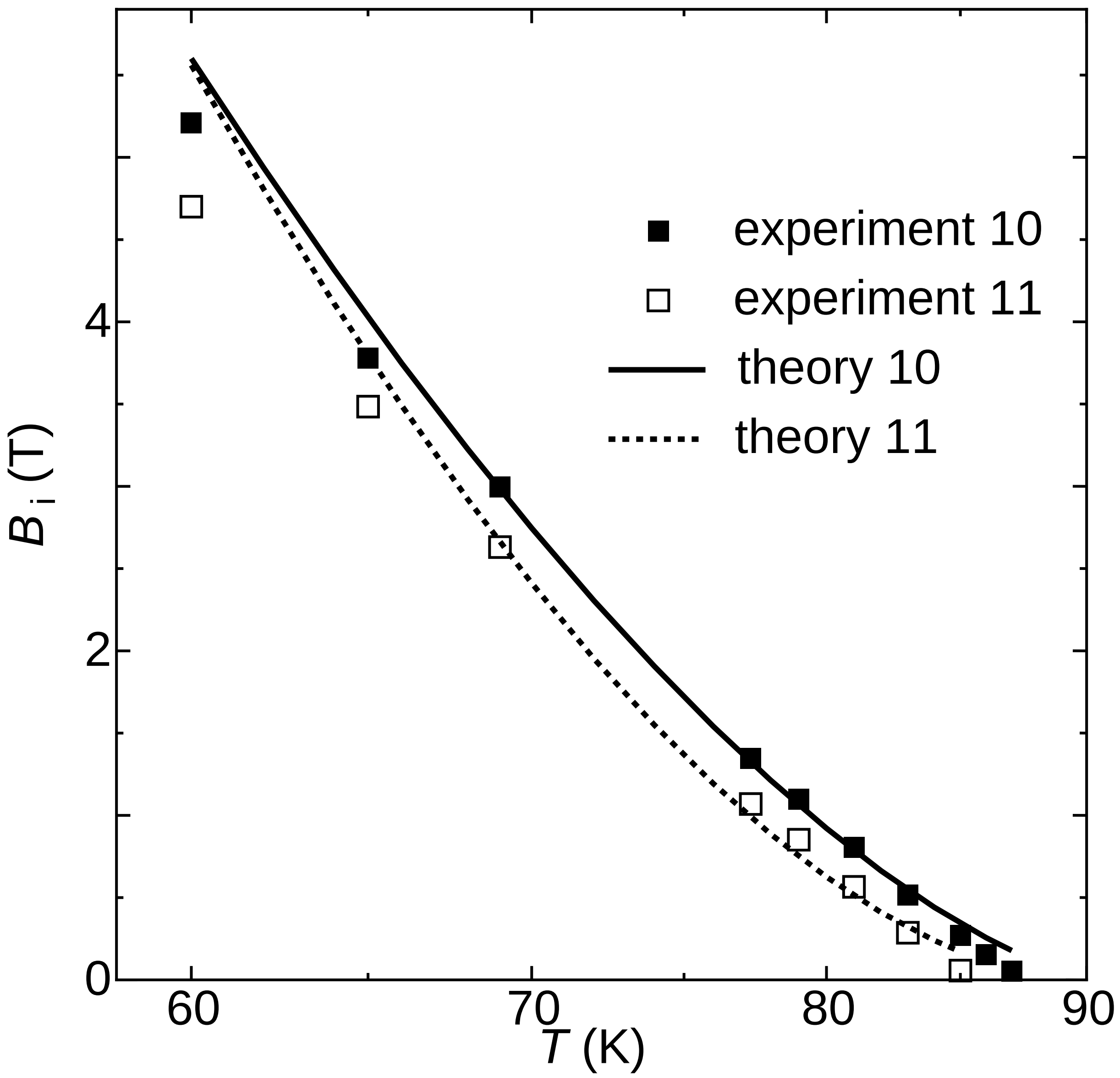

Figure 5: D. Yoshimi *et al.* /BSP-28/ISS2001

Figure captions

Fig. 1. Magnetic field dependence of critical current density of specimen 00 at 50.0 K and 77.3 K.

Fig. 2. Critical current density at 30.0 K and at 0.1 T and 4.0 T vs effective surface area of 211 phase particles in a unit volume.

Fig. 3. Irreversibility field ($B_{\rm i}$), peak field ($B_{\rm p}$) and dip field ($B_{\rm d}$) in specimen 00 versus temperature.

Fig. 4. Magnetic field dependence of critical current density of specimen 10 at 50.0 K and 77.3 K.

Fig. 5. Irreversibility lines of specimens 10 and 11.