Pinning Property of Bi-2212 Single Crystals With Columnar Defects

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***Abstract*—The critical current density and the irreversibility field were measured before and after nickel ion irradiation for Bi-2212 single crystals in an optimally doped or an overdoped state in a magnetic field parallel to the direction of irradiation. The critical current density was theoretically calculated by using the summation theory and the flux creep-flow model. From the comparison with experimental results the condensation energy density was estimated for each specimen. These results are compared with a similar analysis on three-dimensional Y-123.**

I. INTRODUCTION

COLUMNAR defects nucleated by heavy ion irradiation are known to act as strong pinning centers in various oxide superconductors [1]–[3]. However, the improvement of the pinning properties such as critical current density and irreversibility field depends on the dimensionality of superconductor. That is, the improvement is rather weak in two dimensional Bi-2212 and Bi-2223 in comparison with three dimensional Y-123. This difference seems to be attributed to the difference of the strength of superconductivity in block layers. Therefore, the analysis of the pinning strength is expected to be useful for the evaluation of the strength of superconductivity in block layers in two-dimensional superconductors.

In this study, the critical current density and the irreversibility field were measured for Bi-2212 single crystals irradiated by nickel ions, which were in an optimally doped or an overdoped state. These results were compared with the theoretical calculation based on the summation theory and the flux creep-flow model to estimate the elementary pinning force of columnar defects. The condensation energy density averaged along the c-axis was calculated and the result is compared with that of a three-dimensional Y-123. Discussion is given on the relationship between the condensation energy density and the dimensionality of superconductor.

TABLE I

SPECIFICATIONS OF SPECIMENS

specimen	doped condition	dose	T_c
b-op	optimum	no	89 K
0.4-op	optimum	0.4 T	89 K
1.0-op	optimum	1.0 T	86 K
b-ov	overdoped	no	84 K
0.4-ov	overdoped	0.4 T	83 K
1.0-ov	overdoped	1.0 T	80 K

II. EXPERIMENTAL

A. Specimens

Specimens were Bi-2212 single crystals prepared by KCl flux method [4]. Typical size of the specimens was 2 mm × 2 mm × 4 μm and a wide surface is perpendicular to the c-axis. The state of doping was controlled by changing the partial pressure of oxygen during annealing process and two types of specimens were prepared. Those were in an optimally doped or a slightly overdoped state. These specimens were irradiated along the c-axis by nickel ions with the acceleration energy of 180 MeV. The corresponding matching field for dose, B_ϕ, was 0.4 and 1.0 T. The average radius of the columnar defects is 2.0 nm, as observed by TEM [5]. The nickel ions penetrate through the specimen thickness. Specifications and critical temperature estimated by DC susceptibility of the specimens are listed in Table I. The critical temperature is slightly lower for the overdoped specimen and it decreases with increasing dose of ion irradiation.

B. Measurement

DC magnetization hysteresis was measured in a magnetic field along the c-axis by a SQUID magnetometer (MPMS-7) to estimate the critical current density and the irreversibility field. Strictly speaking, the value of critical current depends on the electric field at which the DC magnetization hysteresis is measured. A relaxation of magnetic moment was observed and the electric field vs. current density (E–J) characteristics was evaluated from the following equations:

$$J = \frac{12\hat{m}}{w^2 t(3l - w)}, \tag{1}$$

$$E = -\frac{\mu_0}{2t(l+w)} \cdot \frac{d\hat{m}}{dt}, \tag{2}$$

where l is length, w is width, t is thickness of the specimen and $\hat{m}$ is the irreversible component of the measured magnetic moment. Then, the critical current density was determined by the current density at which the electric field decreased

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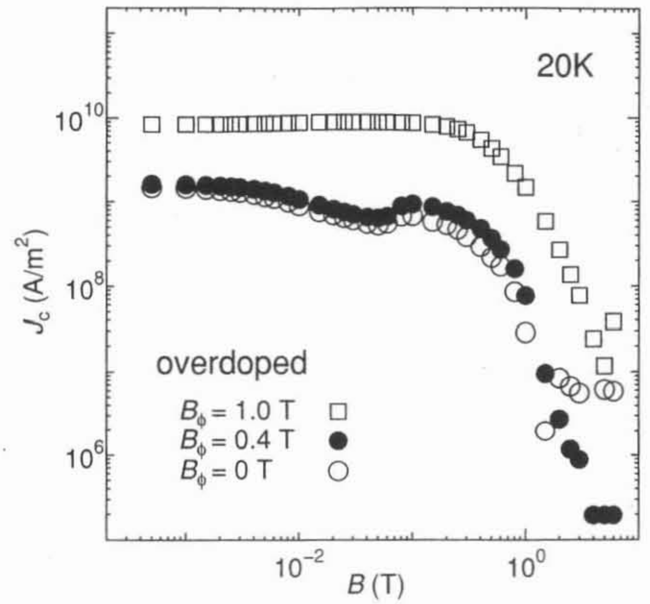


Fig. 1. Magnetic field dependence of critical current density of overdoped specimens of before, $B_\phi = 0.4$ T and $B_\phi = 1.0$ T at 20 K.

to 2.0×10^{-8} V/m. The irreversibility field was determined as the field at which the critical current density decreased to 1.0×10^7 A/m^2.

III. RESULTS AND DISCUSSION

Fig. 1 shows the magnetic field dependence of critical current density in the overdoped specimen at 20 K for example. In the case of $B_\phi = 1.0$ T, the enhancement of the critical current density is significant and the peak effect disappears. On the other hand, J_c is not enhanced appreciably in the case of $B_\phi = 0.4$ T. The tendency is almost the same as in the optimally doped specimen. Therefore, hereafter the discussion will be focused only on the case of $B_\phi = 1.0$ T.

Fig. 2 shows magnetic field dependence of the critical current density of the optimally doped specimen of $B_\phi = 1.0$ T. The results on the overdoped specimen are shown in Fig. 3. Fig. 4 represents the enhancement factor of J_c by irradiation of $B_\phi = 1.0$ T for the two specimens. This factor is likely to be high at medium fields and at medium temperatures. The reduction of J_c at high temperatures is attributed to the decrease of T_c by the irradiation.

Fig. 5 shows temperature dependence of the irreversibility field, B_i, for each specimen before and after the irradiation. Before the irradiation, the slope of the curve changes drastically at the critical point between the two-dimensional and three-dimensional vortex states at around $T/T_c \simeq 0.3$. However, this change is smeared out by the introduction of strong pinning centers. Some anomalies may be found at magnetic field about twice as high as the matching field.

Here the critical current density is theoretically estimated. For simplicity we assume an ideal case where thermally activated motion of flux lines does not take place. It is also assumed that columnar defects of radius r_0 which penetrate through the superconductor of thickness t are distributed rather uniformly.

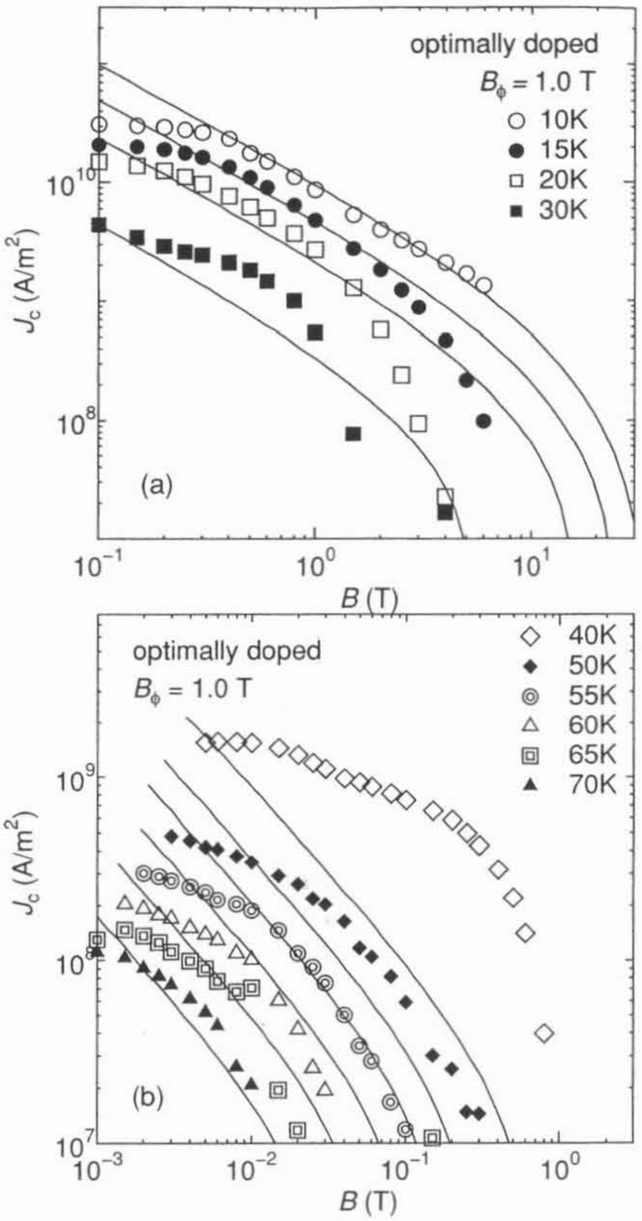


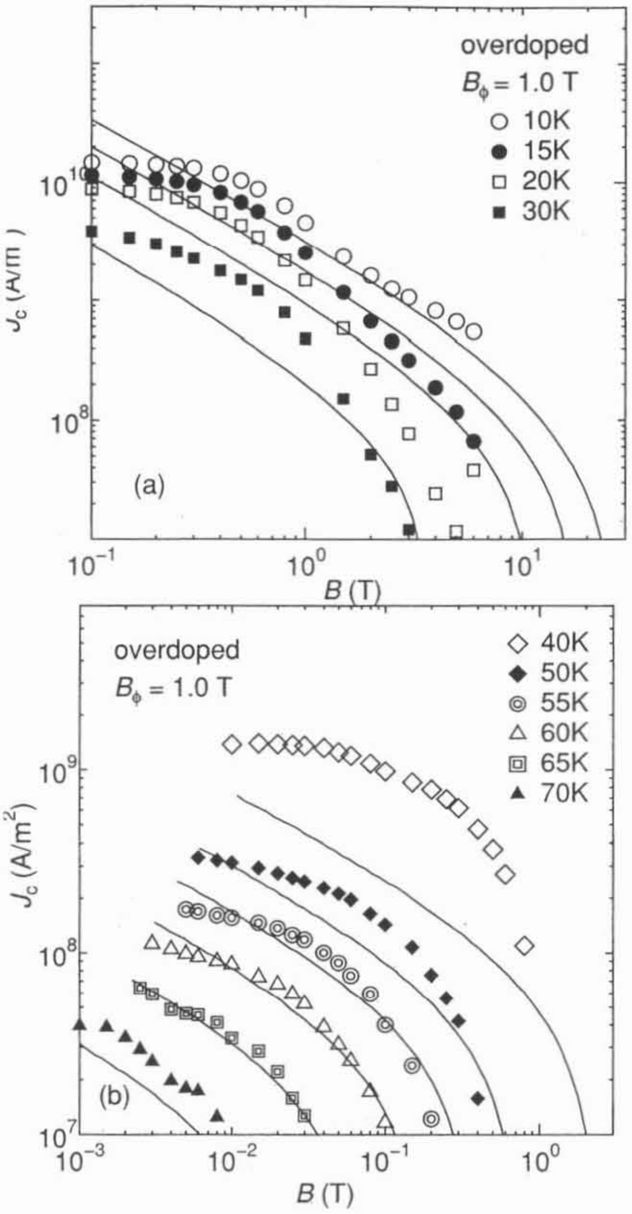
Fig. 2. Magnetic field dependence of critical current density of optimally doped specimen in (a) two-dimensional vortex state at low temperatures and (b) three-dimensional vortex state at high temperatures.

A focus is given on the case where magnetic field is applied parallel to the columnar defects. Since r_0 is larger than the coherence length, the elementary pinning force of a columnar defect is estimated as

$$f_p \simeq \frac{\pi}{4\mu_0} B_c^2 r_0 t, \tag{3}$$

where B_c is the thermodynamic critical field. The effective pin density, N_p', which represents the number density of pinning interactions, is given by a product of the number density of the columnar defects, $N_p = B_\phi/\phi_0 t$, and the probability for a defect to meet a flux line core, $B\pi r_0^2/\phi_0$, as [6]

$$N_p' = \frac{\pi r_0^2 B B_\phi}{\phi_0^2}. \tag{4}$$



3. Magnetic field dependence of critical current density of overdoped
cimen in (a) two-dimensional vortex state at low temperatures and (b) three-
ensional vortex state at high temperatures.

the above ϕ_0 is a flux quantum. Then, the virtual critical cur-
t density in the creep free case is expressed as [6]

$$J_{c0} = \frac{\eta N_p' f_p}{B}, \tag{5}$$

ere η is a pinning efficiency:

$$\eta = \frac{1-\alpha}{1+\alpha}, \tag{6}$$

h

$$\alpha = \frac{-(s+1)+\sqrt{s^2+6s+1}}{2s} < 1, \tag{7}$$

1 $s = \phi_0/\pi^2 r_0^2 B_\phi$.

[n the practical situation, the critical current density is sig-
icantly deteriorated from J_{c0} due to the flux creep. Such crit-
l current density can be theoretically estimated using the flux

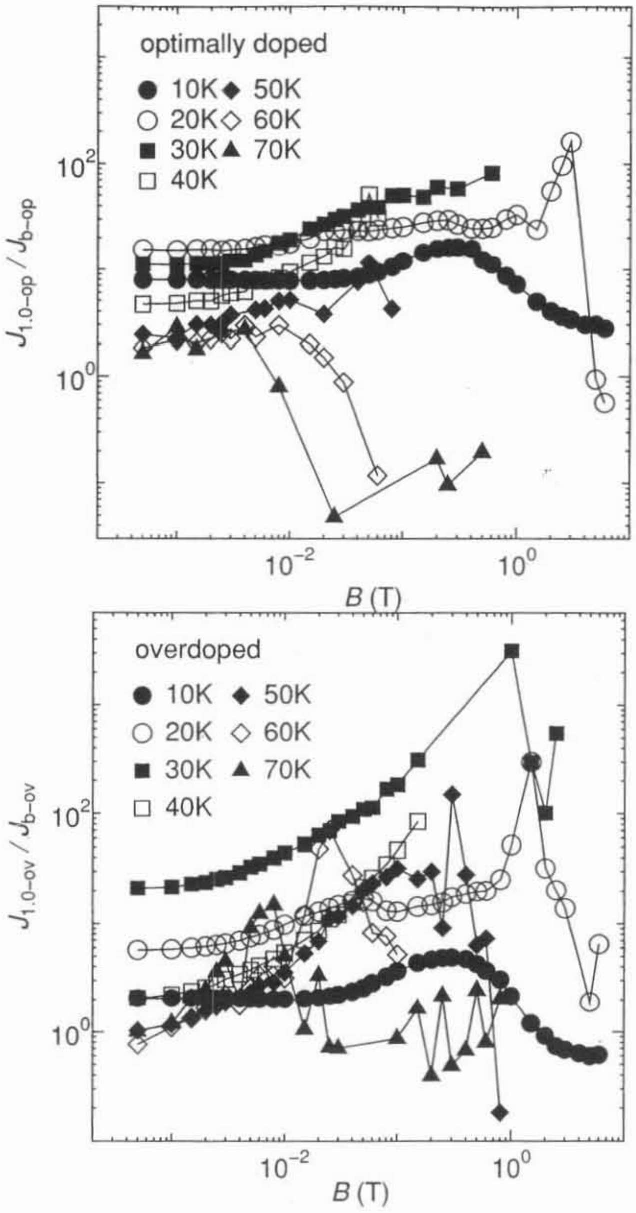


Fig. 4. Enhancement factor of J_c by irradiation of $B_\phi = 1.0$ T.

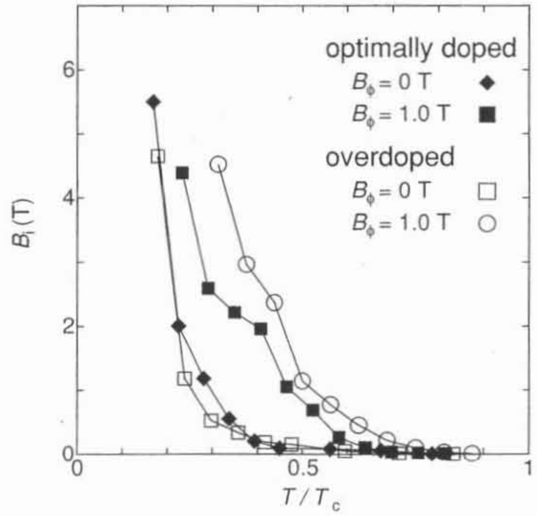


Fig. 5. Temperature dependence of irreversibility field for each specimen.

TABLE II
PINNING PARAMETERS IN BI-2212 SINGLE CRYSTAL

temperature region	specimen	A_m	m	γ	σ^2
< 40 K	1-op	6.5×10^{11}	10	0.01	0.10
< 40 K	1-ov	8.0×10^{10}	5.0	0.05	0.10
> 40 K	1-op	4.8×10^{9}	3.6	0.10	0.15
> 40 K	1-ov	1.8×10^{10}	3.0	0.60	0.10

creep-flow model [7]. According to this model, the pinning potential for bulk superconductor is given by

$$U_0 = \frac{0.835 g^2 k_B J_{c0}^{1/2}}{(2\pi)^{3/2} B^{1/4}}, \tag{8}$$

where g^2 is the number of flux lines inside the flux bundle. The magnetic field and temperature dependence of J_{c0} at low fields is assumed as

$$J_{c0} = A \left(1 - \frac{T}{T_c}\right)^m B^{\gamma - 1}, \tag{9}$$

where A, m and γ are pinning parameters.

TEM observations revealed that the distribution of columnar defects is not uniform but random. Hence, it is necessary to introduce a wide distribution of the parameter A in J_{c0} because of such a distribution of N_p' in (5). Then, a numerical simulation is carried out. Pinning centers are distributed randomly on a square flux line lattice containing 10×10 flux lines. Since g^2 for two-dimensional Bi-2212 is considered to be 1, the maximum pinning force which each flux line experiences during a travel by one lattice spacing is estimated. From a histogram of this force, a distribution function of A is approximately fit to the form:

$$f(A) = K \exp\left[-\frac{(\log A - \log A_m)^2}{2\sigma^2}\right], \tag{10}$$

where A_m is the most probable value, σ^2 is a parameter representing the degree of deviation and K is a constant. It is found that this distribution function with $\sigma^2 = 0.10$ approximately fits to the result of simulation.

The value of g^2 is estimated such that the critical current density under the flux creep takes on a maximum value [8]. Derived theoretical g^2 value is less than unity in wide regions of magnetic field and temperature, as was so in previous cases of Bi-2212 [7]. Thus, we used the theoretical minimum value, $g^2 \doteq 1$. The critical current density is determined from calculated E–J characteristics with the electric field criterion $E_c = 2 \times 10^{-8}$ V/m, which corresponds to the experimental analysis.

Table II lists pinning parameters obtained by fitting the theoretical result to the experimental result in two-dimensional and three-dimensional vortex states at temperatures lower and higher than 40 K, respectively. The radius of the columnar defects is $r_0 = 2.0$ nm and the thickness of the specimen is $d = 3.0$–6.0 μm. Solid lines in Figs. 2 and 3 show theoretical results of the critical current density. It is found that the agreement is fairly good except for the results around the boundary temperature of 40 K.

In the case of optimally doped specimen, we estimate as $\alpha = 1.84 \times 10^{-2}$ and $\eta = 0.96$. Thus, J_{c0} at 1 T and at $T/T_c = 0.8$ is calculated as 1.18×10^7 A/m^2 by (9) and parameters in Table II, where the most probable value is used for A. From this value, we have $B_c = 5.8 \times 10^{-2}$ T with the aid of (3)–(5), resulting in $B_c^2/2\mu_0 = 1.3 \times 10^3$ J/m^3. In the case of the overdoped specimen, we have $B_c = 1.8 \times 10^{-1}$ T and $B_c^2/2\mu_0 = 1.3 \times 10^4$ J/m^3 in the same condition. Therefore, the condensation energy density in the overdoped specimen is 10 times as large as that in the optimally doped specimen. The condensation energy density of an Y-123 single crystal [6] at 1 T and at $T/T_c = 0.8$ is estimated as 4.8×10^4 J/m^3 from the same analysis. Thus, the condensation energy density of three-dimensional Y-123 is much larger even than the overdoped Bi-2212. Such difference of the condensation energy density originates from the difference of the superconductivity in the block layer and the layer thickness. It should be noted that much larger value of the irreversibility field in Y-123 is attributed to such a large condensation energy density and to large g^2.

IV. SUMMARY

From the observed critical current density of Bi-2212 specimens with columnar defects, the condensation energy density was estimated. The condensation energy density of overdoped specimen is found to be 10 times as large as that in the optimally doped specimen. The condensation energy density of Y-123 single crystal is further larger than that of the overdoped Bi-2212. Such difference of the condensation energy density originates from the difference of the superconductivity in the block layer and the layer thickness.

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