EFFECT OF CARRIER DOPING ON IRREVERSIBILITY FIELD OF Bi-2212 SUPERCONDUCTORS

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ABSTRACT

The irreversibility field and the critical current density in Bi-2212 superconductors prepared under the conditions of various oxygen pressure were measured in the magnetic field normal and parallel to the c-axis. It is found that the irreversibility field is shifted to higher temperature with increasing carrier doping. The improvement of the irreversibility field is attributed to the improvement of the dimensionality of the superconductor and the strengthening of flux pinning. These contributions to the irreversibility field were separated using the flux creep theory and it is found that the enhancement comes mostly from the variation in the dimensionality of the superconductor.

KEYWORDS: irreversibility field, Bi-2212 superconductor, dimensionality, flux pinning strength, carrier doping

INTRODUCTION

Bi-2212 superconductor is a suitable material for a long wire and high critical current density can be achieved at low temperatures and/or low magnetic fields. It is known, however, that its flux pinning strength is weak and the magnetic property of flux lines is two-dimensional due to the crystal structure. As a result, the flux lines are significantly influenced by the thermal activation at high temperatures. Especially, the irreversibility field along the c-axis is very low. It is desired, therefore, to improve the dimensionality of the superconductor. Recently, it was reported that the dimensionality of Bi-2212 superconductor can be easily controlled by carrier doping and the irreversibility field was improved drastically when it was overdoped [1]. On the other hand, it is known that the irreversibility field depends also on the flux pinning strength and the flux pinning strength itself may also be influenced by the carrier doping. Hence, it is desired to understand the effect only of the variation in the dimensionality by the carrier doping on the irreversibility field. In this paper, the irreversibility field and the critical current density are measured for Bi-2212 superconductors prepared under the various conditions of oxygen pressure. The contributions from the dimensionality and the flux pinning strength to the irreversibility field are separated by a theoretical analysis using the flux creep theory.

EXPERIMENTS

The specimens used in this study are Bi-2212 superconductors prepared by a screen-printed method. The specimens were finally heat treated under the various conditions of oxygen pressure. The c-axis was directed normal to the flat surface of the specimen. The critical temperature, T_c, and the critical current density, J_c, at $T = 4.5$ K and $B = 1$ T of the three specimens are listed in Table 1. The critical current density was estimated from DC magnetization. The irreversibility field was defined by the magnetic field where the critical current density is reduced to $J_c = 1.0 \times 10^5$ A/m^2. The DC magnetic field was applied parallel and normal to the c-axis.

Table 1. Specifications of specimens.

specimen	Condition of oxygen pressure	T_c (K)	J_c(4.5 K, 1 T) (A/m^2)
1	in-air	80.6	5.99×10^8
2	1100ppm	92.5	5.34×10^8
3	100ppm	91.2	1.10×10^8

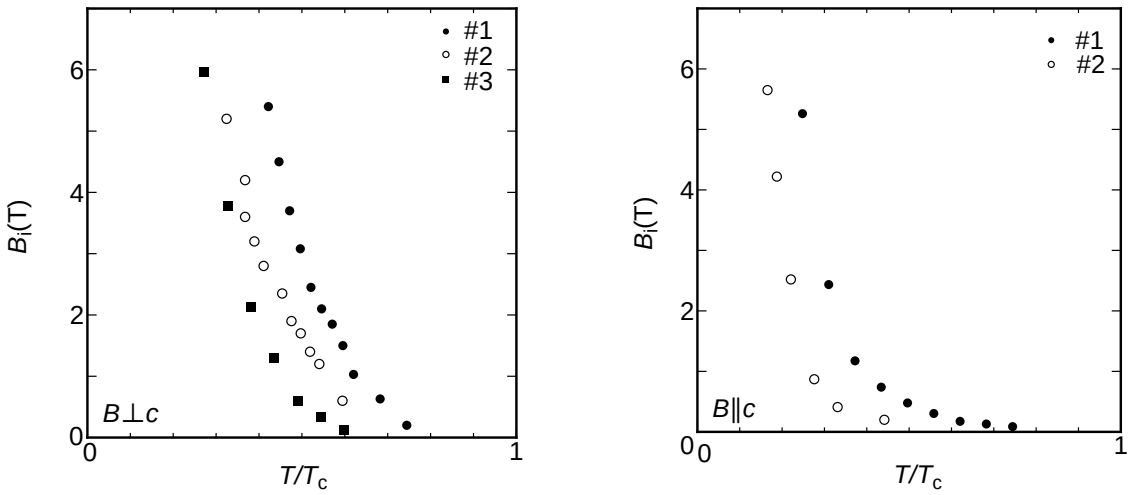

Fig. 1. Irreversibility field of the three specimens for the fields (a) normal and (b) parallel to the c-axis.

RESULTS AND DISCUSSION

Figure 1(a) and (b) represent the observed irreversibility field in the three specimens for the field directions normal and parallel to the c-axis, respectively. It is seen that the irreversibility field is shifted to higher temperature with increasing carrier doping for the both directions of the field. This result is consistent with the previous observation for the field parallel to the c-axis [1].

These results are compared with the theoretical prediction from the flux creep theory. According to the flux creep theory [2], the pinning potential, U_0, in a bulk superconductor is given by

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

where J_{c0} is the virtual critical current density in the creep-free case and g^2 is the number of fluxoids in the flux bundle. g^2 is considered to be determined by the principle of irreversible thermodynamics that the energy dissipation is minimized [3]. This leads to

$$g^2 = g_e^2 \left[\frac{5 k_B T}{2 U_e} \ln \left(\frac{B a_f \nu_0}{E} \right) \right]^{4/3}, \tag{2}$$

where g_e^2 is the number of g^2 when $g a_f$ is equal to

$$l_{66} = \left(\frac{C_{66} a_f}{2\pi J_{c0} B} \right)^{1/2}, \tag{3}$$

where C_{66} is the shear modulus of the fluxoid lattice, ν_0 is the damping oscillation frequency of flux bundle in the pinning potential, E is the electric field and U_e is the virtual pinning potential

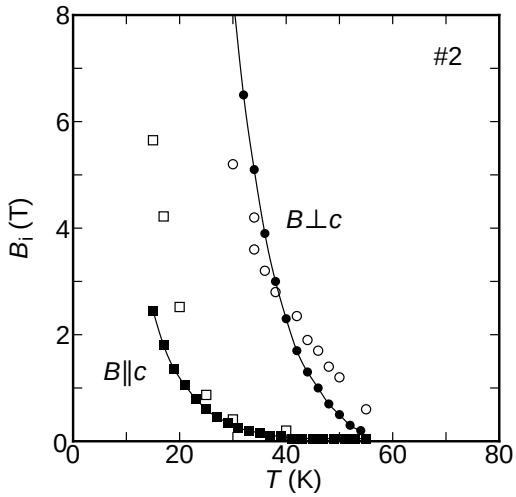

Fig. 2. Irreversibility fields of specimen 2 under the fields normal and parallel to the c-axis: Open symbols (○, □) and solid symbols (●, ■) represent the experimental values and the theoretical values, respectively.

for the case of $g = g_{\rm e}$. We assume the temperature and magnetic field dependences of $J_{\rm c0}$ as

$$J_{\rm c0} = A\left[1-\left(\frac{T}{T_{\rm c}}\right)^2\right]^m B^{\gamma-1}\left(1-\frac{B}{B_{\rm c2}}\right)^\delta, \tag{4}$$

where A, m, γ and δ are the pinning parameters. We carried out a numerical calculation of E-J characteristics for specimen 2. The details of numerical analysis is given in Ref. [4]. The superconducting and pinning parameters used for the calculation are shown in Table 2.

In Fig. 2 the numerically calculated irreversibility fields are compared with the corresponding experimental results. It is found that a quantitative agreement is obtained for the both directions of the magnetic field. That is, the irreversibility field in Bi2212 superconductor including its anisotropy can be explained by the flux creep theory.

Here, the contributions from the dimensionality and the flux pinning strength to the irreversibility field are separated using the flux creep theory [2]. According to the flux creep theory, the relation between $B_{\rm i}$ and $J_{\rm c0}$ is given by $B_{\rm i} \propto g^4 J_{\rm c0}$ for $\gamma = 0.5$. On the other hand, the relations of $g_{\rm e}^2 \propto J_{\rm c0}^{-1}$ and $U_{\rm e} \propto J_{\rm c0}^{-1/2}$ and Eq. (2) derive $g^2 \propto J_{\rm c0}^{-1/3}$. Thus, we have

$$B_{\rm i} \propto J_{\rm c0}^{1/3}. \tag{5}$$

Figure 3(a) and (b) show the relations between the observers irreversibility field and the flux pinning strength at $t = T/T_{\rm c} = 0.59$ in the magnetic field normal to the c-axis and at $t = T/T_{\rm c} =$

Table 2. Assumed superconducting and pinning parameters for specimen 2.

	$T_{\rm c}$ (K)	$B_{\rm c2}(0)$ (T)	$\rho_{\rm n}(T_{\rm c})$ ($\mu\Omega$m)	A	m	γ	δ	g^2
$B \perp c$	92.5	690	100	5.34×10^8	7.0	0.6	2.0	2.8 (5.1 T, 30 K)
$B \parallel c$	92.5	34.5	100	2.13×10^8	7.0	0.6	2.0	1.0 (0.41 T, 30 K)

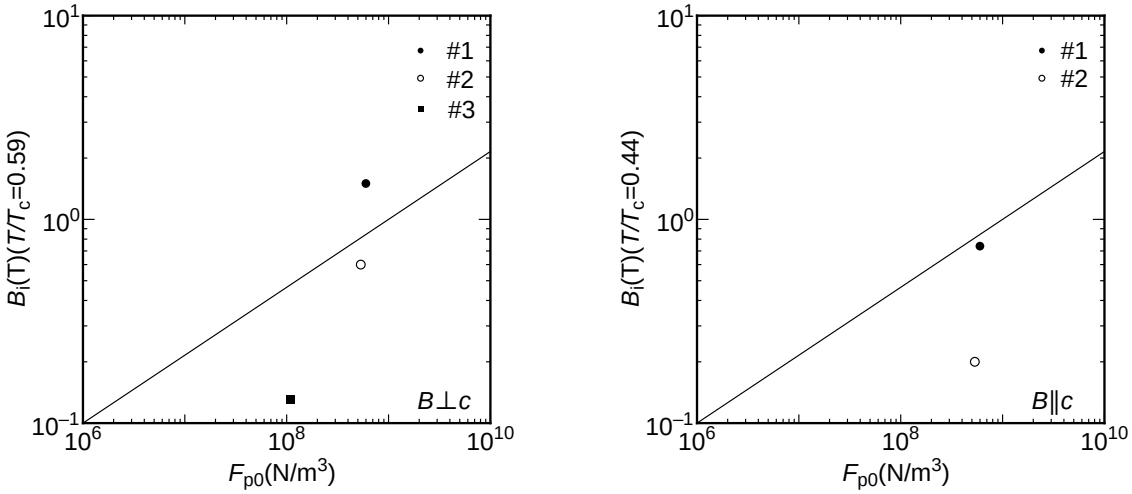

Fig. 3. Dependence of irreversibility field on the flux pinning strength (a) at $t = T/T_c = 0.59$ in normal field to the c-axis and (b) at $t = T/T_c = 0.44$ in parallel field to the c-axis, respectively. Straight line shows Eq. (5).

0.44 in the magnetic field parallel to the c-axis, respectively. The pinning force density at 4.2 K and 1 T is used as a parameter representing the flux pinning strength. Comparing the results of specimens 1 and 2, it is found that the anisotropy factor in the irreversibility field decreases with increasing the amount of doped carrier. The straight line shows Eq. (5) and it is known that this characteristic line is different from material to material depending on the dimensionality [5]. It is found that the increase in the irreversibility field is larger than the increase in the flux pinning strength. Hence, it is concluded that the improvement of the irreversibility field due to overdoping comes mostly from the improvement of the dimensionality, although the improvement of flux pinning has also some effect. The reason why the flux pinning is strengthened by overdoping is not clear now.

CONCLUSION

The effect of carrier doping on the irreversibility field is investigated for Bi-2212 superconductors prepared under the various conditions of oxygen pressure and the following results are obtained:

1. The irreversibility field is shifted to higher temperature and the anisotropy in the irreversibility field decreases with increasing doped amount of carrier.
2. The improvement of dimensionality has a larger contribution than the improvement of flux pinning strength to the irreversibility field. Thus, the improvement of the irreversibility field due to overdoping comes mostly from the improvement of dimensionality.

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