Dependence of Irreversibility Field on the Thickness of Superconducting Layer

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ABSTRACT

The irreversibility field was observed for two multilayered Bi-2212 tape wires with different thicknesses of superconducting layers. The irreversibility field does not depend on the thickness of superconducting layers but is determined only by the flux pinning strength. The result agrees well with the theoretical analysis of the flux creep-flow model. The analysis shows that the longitudinal flux bundle size is of the order of a few μm on the irreversibility line. The present experimental result is reasonable, since the flux bundle size is shorter than the thickness of superconducting layers, resulting in the three-dimensional pinning.

KEYWORDS: Irreversibility field, multilayered Bi-2212 tape wire, flux creep-flow model, longitudinal flux bundle size, thickness dependence

INTRODUCTION

It is known that the irreversibility field of a thin film is lower than that of a bulk specimen for a Bi-2223 superconductor. This result suggests that the flux lines are strongly coupled along their length even in such a two-dimensional superconductor. This is explained by the flux creep theory from the viewpoint of the difference of the flux bundle size. That is, for a thin film under a normal magnetic field, the flux bundle size is limited by its thickness, resulting in the pinning potential smaller than in a bulk specimen. It was recently found [1, 2] that the longitudinal elastic correlation length of flux lines along the c-axis was more than four orders of magnitude longer than the distance between the CuO_2 layers in a more two-dimensional Bi-2212 superconducting single crystal. This indicates that flux lines are fairly strongly coupled along their length even in two-dimensional superconductors. This result is consistent with the above thickness dependence of the irreversibility field in the Bi-2223 superconductor. This speculation is quite different from that in the pancake vortex model [3]. It is necessary to investigate directly the thickness dependence of the irreversibility field for the most two-dimensional Bi-2212 in order to ascertain the above speculation. In this paper the irreversibility field is measured for multilayered Bi-2212 tape wires with different thicknesses of superconducting layers and the observed results are compared with the theoretical analysis using the flux creep-flow model in which the distribution of flux pinning strength is assumed.

EXPERIMENTS

The specimens were silver-sheathed multilayered Bi-2212 tape wires with the average thickness of superconducting layers of about 5 μm(specimen 1) and 10 μm(specimen 2). Each specimen contains four superconducting layers. Details of the fabrication process of multilayered tapes are

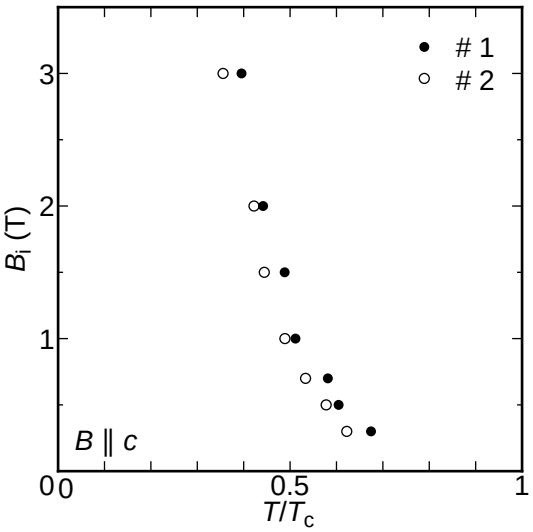

Fig. 1. Irreversibility field of specimens 1(•) and 2(○).

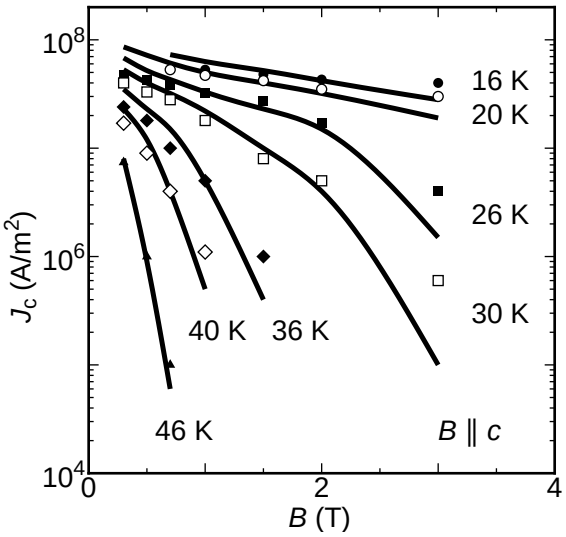

Fig. 2. Experimental (symbols) and theoretical results (lines) of critical current density of specimen 1.

described in Ref. [5]. The critical temperature of specimen 1 and 2 was 86.0 K and 90.0 K, respectively. The critical current densities of specimens 1 and 2 obtained by a SQUID magnetometer at 4.5 K under zero external magnetic field are 1.50 $\times 10^9$ A/m^2 and 5.83 $\times 10^8$ A/m^2, respectively. The higher critical current density in specimen 1 seems to be attributed to a better crystal alignment in thinner superconducting layers.

The current-voltage curves were measured under a dc magnetic field along the c-axis, i.e., normal to a wide surface of the tape. The specimen was put in a helium gas and the ambient temperature was controlled. A pulsed transport current with a period of 1 s was applied to the specimen to reduce a heat generation at the current leads which were separated by 3.0 cm. The voltage was measured across the voltage terminals separated by 1.0 cm. After the measurement of the current-voltage curves of the specimen, the superconducting layer was broken and the resistivity of the silver layer was measured. The current-voltage curves only of the superconducting layer were estimated by assuming a simple parallel electric circuit model composed of superconducting and normal layers. The critical current density was determined by the off-set method from a level of electric field of 1.0×10^{-4} V/m. The irreversibility field is defined by the magnetic field at which the critical current density is reduced to 1.0×10^5A/m^2. Figure 1 shows the irreversibility lines of the two specimens. It turns out that the irreversibility field of specimen 1 with the thinner superconducting layer and the higher J_c is higher. That is, this result is opposite to the expected thickness dependence. The critical current density of specimen 1 is shown in Fig. 2.

FLUX CREEP-FLOW MODEL

According to the collective flux creep theory the pinning potential, U_0, is described in terms of the virtual critical current density, J_{c0}, in the creep-free case. That is, we have

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

for a bulk superconductor and

$$U_0 = \frac{4.23 g^2 k_B J_{c0} d}{2\pi B^{1/2}} \tag{2}$$

for a superconductor with the thickness d thinner than the longitudinal flux bundle size, $L = (a_f B/2\pi\mu_0 J_{c0})^{1/2}$. In the above, g^2 is a number of flux lines in the flux bundle. This number is considered to be determined so that the critical current density under the flux creep is maximized [7]. Thus, if J_{c0} is given, the current-voltage curve can be calculated. The dependences of J_{c0} on temperature and magnetic field are expressed in the form of scaling law as

$$J_{c0} = A\left[1-\left(\frac{T}{T_c}\right)^2\right]^m B^{\gamma-1}\left(1-\frac{B}{B_{c2}}\right)^\delta, \tag{3}$$

where A, m, γ and δ are the pinning parameters. In the above A is approximately equal to the critical current density at 0 K and 1 T and represents the flux pinning strength. In practical superconductors the flux pinning strength is not uniform but is distributed. Here we assume that A is distributed as

$$f(A) = K\exp\left[-\frac{(\log A - \log A_m)^2}{2\sigma^2}\right], \tag{4}$$

while other parameters are unchanged. In the above A_m is the most probable value of A, σ is a constant representing the width of the distribution and K is a constant determined by the condition of normalization.

The parameters associated with the pinning strength, m, γ, δ, A_m and σ are determined so as to get a good fit between the experimental and theoretical values of the critical current density in the entire regions of temperature and magnetic field. g^2 estimated at 40 K and 1.5 T is 1.0 and this value is assumed within the entire regions of temperature and magnetic field. Experimental and theoretical results of the critical current density of specimen 1 are compared in Fig. 2, where the used parameters are listed in Table 1. It is seen that the agreement of J_c is fairly good. Thus, these parameters are used in the numerical analysis.

Table 1. Parameters used for analysis for specimens 1 and 2

specimen	d (μm)	T_c (K)	$B_{c2\parallel}(0)$ (T)	$\rho_n(T_c)$ ($\mu\Omega$m)	A_m	m	γ	δ	g^2	σ^2
1	5.0	86.0	34.5	100	4×10^9	3.9	0.90	2.0	1.0	0.10
2	10.0	90.0	34.5	100	1×10^9	3.9	0.90	2.0	1.0	0.08

DISCUSSION

Figure 3 shows the theoretical results of the irreversibility field for specimens 1 and 2. It is found that the theoretical results are in good agreement with the experimental results and the irreversibility field is predicted to be lower for the thicker specimen 2 with the lower J_c. This means that the critical current density determines the irreversibility field in this range of thickness.

The longitudinal flux bundle size, L, at 1.0 T for the most probable value, A_m, is estimated as about 2 μm in the vicinity of the irreversibility line. Hence, the above speculation is proved to be valid. That is, it can be said that the present specimens are in the regime of three-dimensional pinning in the entire region below the irreversibility line. It means that the irreversibility field is not influenced by the thickness of the superconducting layer but determined only by the flux pinning strength.

Here, the numerical analysis is carried out for the dependence of the irreversibility temperature on the thickness of superconducting layers. The assumed parameters used in the numerical analysis are the same as those of specimen 1: $A_m = 4.0\times10^9$, $m = 3.9$, $\gamma = 0.9$, $\delta = 2.0$, $g^2 = 1.0$ and

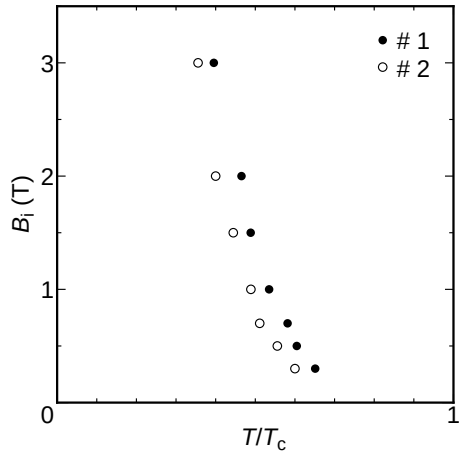

Fig. 3. Theoretical results of irreversibility fields of specimens 1(•) and 2(○).

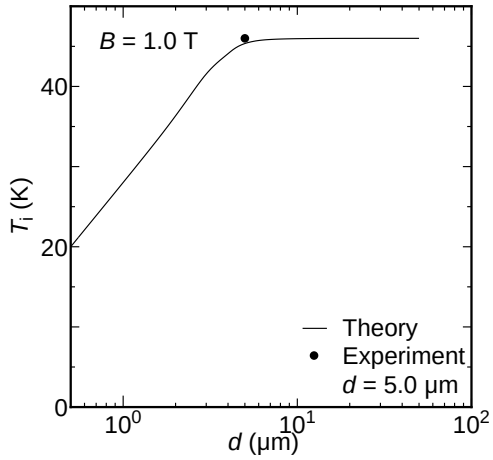

Fig. 4. Dependence of irreversibility temperature on thickness of superconducting layers at $B = 1.0$ T. Solid symbol is experimental result of specimen 1.

$\sigma^2 = 0.10$. Figure 4 shows the calculated result at $B = 1.0$ T. It is found that the irreversibility temperature increases according to increasing thickness of superconducting layers up to 4 μm and is saturated a constant value. It is considered to be necessary to reduce the thickness below 2 μm to observe the thickness dependence of the irreversibility temperature.

CONCLUSION

The dependence of the irreversibility field on the thickness of superconducting layers was investigated for Bi-2212 multilayered tape wires. The results were compared with the numerical analysis based on the flux creep-flow model with taking account of the distributed pinning strength. The following results are obtained:

1. The observed irreversibility field does not depend on the thickness of superconducting layers but on the flux pinning strength.
2. The estimated longitudinal flux bundle size for the most probable value of the pinning strength is about 2 μm in the vicinity of the irreversibility line at 1.0 T and the irreversibility field is predicted to be independent of the thickness when the thickness is less than 4 μm. This is consistent with the experimental results.
3. The theoretical model of flux creep-flow explains the experimental result well.

REFERENCES

1 Kiuchi M, Yamato H, Matsushita T (1996) Physica C 269: 242
2 Matsushita T, Kiuchi M, Yamato H, Hirano T, Koshizuka N (1997) Physica C 277: 185
3 Clem JR (1991) Phys Rev B 43: 7837
4 Ihara N, Matsushita T (1996) Physica C 257: 233
5 Noguchi K, Kiuchi M, Tagomori M, Matsushita T, Hasegawa T (1997) Advances in Superconductivity IX: 625
6 Kiuchi M, Noguchi K, Tagomori M, Matsushita T (1997) IEEE Trans Appl Supercond 7: 2114
7 Matsushita T, Tagomori M, Noguchi K, Kiuchi M, Hasegawa T (1997) Proc of Int Cryog Mater Conf, (to be published.)
8 Matsushita T (1993) Physica C 217: 461