Effect of Distributon of Flux Pinning Strength on Irreversibility Line and Transition Line

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ABSTRACT

It is known that the irreversibility line and the transition line between the so-called glass and liquid states of flux lines are different, although those are closely correlated to each other. This difference is speculated to be associated with the distribution width of the flux pinning strength. The two characteristic lines are analyzed as a function of the distribution width of the flux pinning strength using the flux creep-flow model for a Bi-2212 superconducting tape. Discussion is given on the difference between the two characteristic lines.

KEYWORDS: Irreversibility line, transition line, vortex glass-liquid transition, distribution of flux pinning strength, flux creep-flow model

INTRODUCTION

It is known that the vortex glass-liquid transition line and the irreversibility line of high-temperature superconductors depend on both the flux pinning strength and the dimensionality of the superconductor and those are closely correlated to each other. However, the difference between the two lines is appreciable. This comes from the difference of the definition. That is, the irreversibility line, $B_{\rm i}(T)$, is determined by the magnetic field at which the critical current density defined using some criterion decreases to some level. The transition line, $B_{\rm g}(T)$, is determined by the magnetic field at which the curvature of the logarithmically plotted current-voltage curve varies from concave to convex [1].

In general the n value, which is the parameter representing the current-voltage characteristic as $E \propto J^n$, is affected by inhomogeneities. Therefore, it is considered that the two characteristic lines are also influenced by inhomogeneities such as a distributed flux pinning strength. In this paper, the effect of distribution width of the flux pinning strength on the irreversibility line and the transition line are investigated for a Bi-2212 superconductor using the flux creep-flow model. Discussion is also given on the difference between the two characteristic lines.

FLUX CREEP-FLOW MODEL

According to the flux creep theory the induced electric field can be calculated as function of the current density, J, and the virtual critical current density in the creep-free case, $J_{\rm c0}$ [2]. The induced electric field is composed of the component of the thermally activated flux motion, $E_{\rm cr}$, and that of the flux flow, $E_{\rm ff}$. $E_{\rm cr}$ is given by

$$E_{\rm cr} = Ba_{\rm f}\nu_0 \exp\left[-\frac{U(j)}{k_{\rm B}T}\right]\left[1-\exp\left(-\frac{\pi U_0 j}{k_{\rm B}T}\right)\right]; \quad j \le 1, \tag{1}$$

$$= Ba_{\rm f}\nu_0\left[1-\exp\left(-\frac{\pi U_0}{k_{\rm B}T}\right)\right]; \quad j > 1, \tag{2}$$

where $j = J/J_{\rm c0}$ is the normalized current density, $a_{\rm f}$ is the flux line spacing, ν_0 is the oscillation frequency of the flux bundle, U_0 is the pinning potential and U is the activation energy. In the above we assumed a sinusoidal washboard pinning potential and $U(j)$ is expressed as

$$U(j) = U_0[(1-j^2)^{1/2} - j\cos^{-1}j]. \tag{3}$$

The pinning potential is proportional to the volume of the flux bundle. The longitudinal flux bundle size in a bulk superconductor is considered to be given by $L = (Ba_{\rm f}/2\pi\mu_0 J_{\rm c0})^{1/2}$. For a

bulk superconductor larger than L, U_0 is given by

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

where g^2 is the number of flux lines in the flux bundle and determined by the condition of the maximum critical current density under the flux creep [4]. If the thickness of the superconducting region, D, is smaller than L, U_0 is given by [5]

$$U_0 = \frac{4.23 g^2 k_{\rm B} J_{\rm c0} D}{(2\pi) B^{1/2}}. \tag{5}$$

When the current density exceeds locally the critical value, the flux flow is expected to occur in this region. The electric field due to the flux flow is given as

$$E_{\rm ff} = 0; \qquad j \le 1, \tag{6}$$

$$= \rho_{\rm f}(J - J_{\rm c0}); \qquad j > 1, \tag{7}$$

where $\rho_{\rm f}$ is the flux flow resistivity. The Bardeen-Stephen model [3], $\rho_{\rm f} = (B/B_{\rm c2})\rho_{\rm n}$ with $\rho_{\rm n} = (T/T_{\rm c})\rho_{\rm n}(T_{\rm c})$ denoting the normal resistivity, is assumed for the flux flow resistivity. Here we approximate that the total electric field is given by

$$E = (E_{\rm cr}^2 + E_{\rm ff}^2)^{1/2}. \tag{8}$$

Thus, the current-voltage characteristics can be calculated when $J_{\rm c0}$ is given. We assume the temperature and magnetic field dependences of $J_{\rm c0}$ as

$$J_{\rm c0} = A \left[1 - \left(\frac{T}{T_{\rm c}}\right)^2\right]^m B^{\gamma-1} \left(1 - \frac{B}{B_{\rm c2}}\right)^\delta, \tag{9}$$

where A, m, γ and δ are the pinning parameters. In the above equation, A is a parameter representing the flux pinning strength of the superconductor and approximately equal to the critical current density at 0 K and 1 T.

In practical superconductors the flux pinning strength is not uniform but is distributed. Here we assume that only A in Eq. (9) is distributed as

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

while the other parameters are constant, where $A_{\rm m}$ is the most probable value, K is a constant determined by the condition of normalization and σ^2 is a parameter corresponding to the width of the distribution. Then, the electric field is calculated from

$$E(J) = \int_0^\infty E f(A) {\rm d}A. \tag{11}$$

The critical current density, $J_{\rm c}$, is determined by the offset method from a level of the 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 $1.0 \times 10^5 {\rm A/m}^2$.

In this paper, we will analyze the result on a Ag-sheathed Bi-2212 tape wire [6]. The parameters associated with the pinning strength, m, γ, δ, $A_{\rm m}$ and σ^2 are determined so as to get a good fit between the experimental and theoretical values of the critical current density in the entire region of temperature and magnetic field. g^2 estimated from the abovementioned condition is smaller than 1 in the vicinity of the irreversibility field. Hence, the minimum value, $g^2 = 1$, is used. These parameters used in the analysis are listed in Table 1. The experimental and theoretical results of $J_{\rm c}$ are compared in Fig. 1, where solid lines and symbols show the theoretical and experimental results, respectively. It is seen that the agreement is fairly good in the entire region of magnetic

Table 1. Pinning parameters of Bi-2212 superconducting tape used in theoretical analysis.

T_c K	$B_{c2\parallel}(0)$ T	$\rho_n(T_c)$ $\mu\Omega$m	D μm	A_m	m	γ	δ	g^2
86.0	34.5	100	50.0	1.7×10^9	3.9	0.9	2.0	1.0

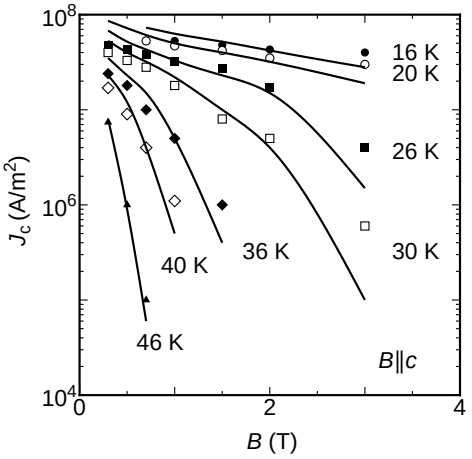

Fig. 1. Experimental (symbols) and theoretical results (lines) of critical current density defined by the offset method.

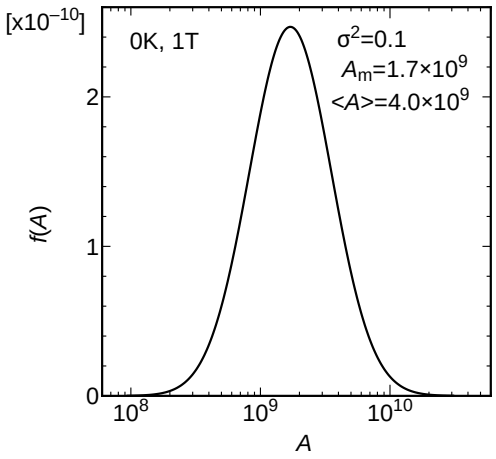

Fig. 2. Assumed distribution of A.

field and temperature. Hence, the calculation of the current-voltage curves is carried out using these parameters. Figure 2 shows the distribution of A assumed here.

DISCUSSION

The scaled result of experimental current-voltage curves at $B = 1.0$ T and the corresponding calculated result are shown in Fig. 3 and Fig. 4, respectively. It is found from comparison of these results that the scaling is similar, although the scaling parameters are slightly different. That is, the transition temperature, the static and dynamic critical indices obtained from numerical calculation are $T_g = 26.0$ K, $\nu = 0.95$ and $z = 9.9$, respectively, where those from experimental results are $T_g = 26.0$ K, $\nu = 0.60$ and $z = 13.0$. The transition lines and the irreversibility lines obtained from experiment and theory are shown in Fig. 5. It can be said from these results that the agreements for the both lines are fairly good.

Here we shall argue the effect of the distribution width of the flux pinning strength on the transition temperature, T_g, and the irreversibility temperature, T_i. For simplicity we assume that A_m is unchanged ($A_m = 1.7 \times 10^9$). The results are shown in Fig. 6. It is shown that T_i and T_g become small, and the relative difference between T_i and T_g becomes large according to broadening the distribution width. The decrease in T_g and T_i is caused by the decrease in the minimum value of J_c. The decrease in T_i with increasing σ^2 is slower than that in T_g. The former seems to reflect directly the variation in the physical property. That is, the slower decrease in T_i is considered to be attributed to an overestimation of T_i by the use of a finite threshold level for the determination of J_c. Therefore, in order to decrease the relative difference of the two characteristic temperatures, the distribution width should be lowered as that of metallic superconductors. However, it is very difficult to fabricate such a homogeneous tape wire in present stage. Therefore, it is necessary to use a more severe criterion for the determination of the irreversibility line to make it a more reliable limit for the application of the superconductor.

CONCLUSION

The irreversibility line and the vortex glass-liquid transition line of a Ag-sheathed Bi-2212 tape wire are investigated using the flux creep-flow model with taking account of the distributed pinning

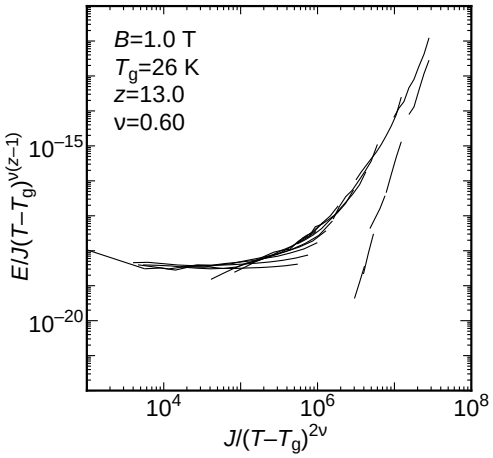

Fig. 3. Scaling of observed current-voltage curves at $B = 1.0$ T.

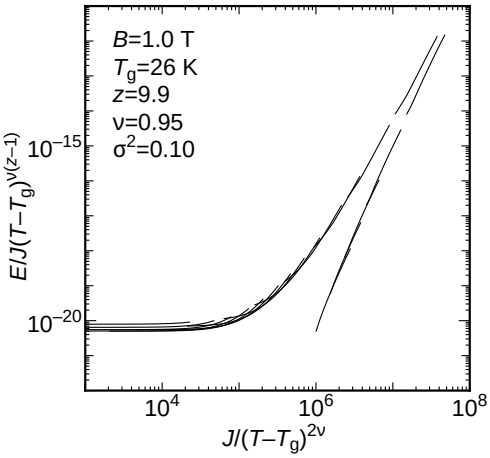

Fig. 4. Scaling of calculated current-voltage curves at $B = 1.0$ T.

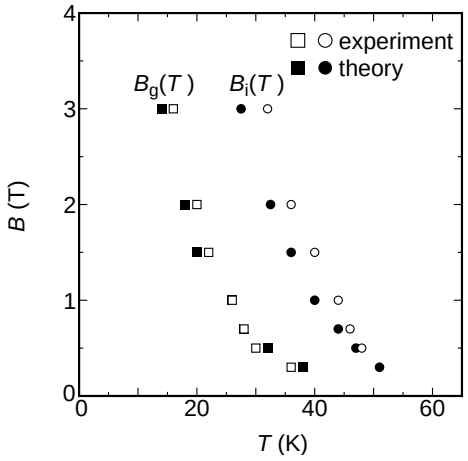

Fig. 5. Theoretical (solid symbols) and experimental results (open symbols) of transition and irreversibility lines.

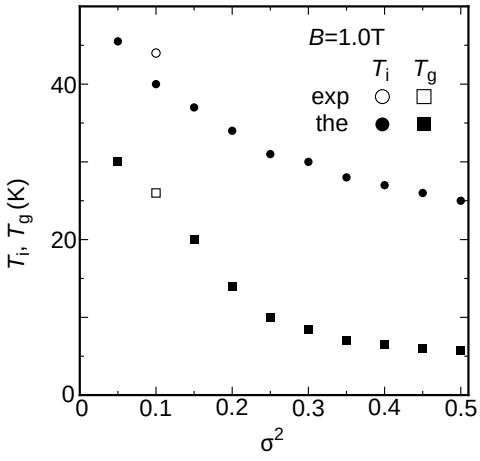

Fig. 6. Transition and irreversibility temperatures vs σ^2. Open symbols represent experimental results.

strength and the following results are obtained:

1. The observed irreversibility and transition lines are well explained by the flux creep-flow model with taking account of the distributed pinning strength.
2. The irreversibility and transition temperatures become small and the relative difference between the two characteristic temperatures becomes large according to broadening the distribution width. The decrease in the two characteristic temperatures is due to the decrease in the minimum value of the critical current density.
3. The slower decrease in the irreversibility temperature seems to be attributed to its overestimation by the use of a finite threshold level for the determination of the critical current density. It is necessary to use a more severe criterion for the determination of the irreversibility line to make it a more reliable limit for the application of the superconductor.

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