Scaling of Current-Voltage Curves of Bi-2212 Tape Wire

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Abstract— **The current-voltage curves are measured for a dip-coated Bi-2212 tape wire at various temperatures under the magnetic field parallel to the *c*-axis. It is found that the current-voltage curves are approximately scaled on two master curves by normalizing as predicted in the vortex glass-liquid transition theory. However, the obtained dynamic critical index was about 3 and too small in spite of the two-dimensional flux line system. These results are compared with the theorical analysis based on the flux creep-flow model taking account of the distribution of pinning strength. It is found that the theorical result approximately explains the experimental result on the scaling behavior, the critical indices and the transition line.**

I. Introduction

It is known that the current-voltage curves of high temperature superconductors meet on two master curves when those are normalized by proper functions of temperature predicted by the vortex glass-liquid transition theory [1], [2]. However, a similar scaling can also be derived from the mechanism of flux creep and flow [3]–[5]. Especially, when the effect of distributed flux pinning strength is taken into account, the critical indices obtained from the mechanism of flux creep and flow are close to experimental results. A satisfactory agreement was obtained between the theoretical and experimental results for a Bi-2223 tape wire [6]. In addition, it was reported [6]–[8] that the critical indices changed with the magnetic field, while it is predicted to be constant if the transformation is really the phase transition. Therefore, it seems to be realistic that such a behavior of the current-voltage curves is different from the phase transition of the second order predicted from the vortex glass-liquid transition theory.

In this paper the scaling of the current-voltage curves is investigated for a Bi-2212 tape wire and the results are compared with the theoretical analysis based on the flux creep-flow model.

II. Experimental

The measured specimen was a Bi-2212 tape wire prepared by a dip-coat process. Its size was about 40 mm long, 4.7 mm wide and 0.11 mm thick and the thickness of the superconducting region was approximately 10 μm. The *c*-axis of the specimen was oriented normal to the flat surface of the tape. The critical temperature, T_c, was 93.0 K. The current-voltage curves were measured by the four probe method under the magnetic field parallel to the *c*-axis. The pulse transport current with the period of 3 s was applied to the specimen to reduce the joule heat at the current leads and 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 only was measured. This was needed for the evaluation of the current-voltage characteristics only of the superconducting region. The critical current density at sufficiently low temperatures was also measured, since the information on the flux pinning strength is necessary for the theoretical analysis based on the flux creep-flow model. For this purpose the Campbell method [9] was used for the cumulated chips of specimens put in the perpendicular magnetic field. Such a geometry was employed to reduce the effect of demagnetization.

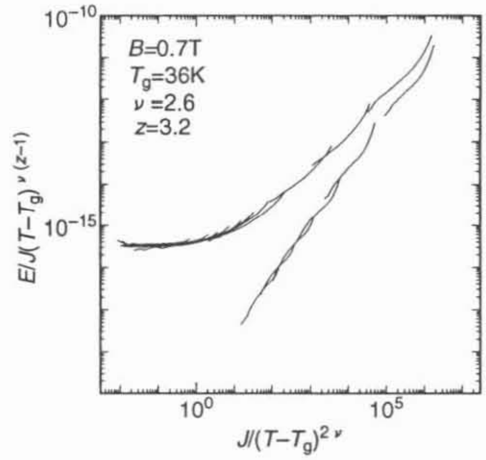

Fig. 1. Scaled current-voltage curves at B = 0.7 T. Obtained parameters are T_g = 36 K, ν = 2.6 and z = 3.2.

According to the vortex glass-liquid transition theory [1], [2], the current-voltage characteristics at various temperatures collapse on two master curves when plotted as $(E/J)/|T-T_g|^{\nu(z+2-D)}$ vs $J/|T-T_g|^{\nu(D-1)}$, where z and ν are the dynamic and static critical indices and D represents the dimension of the fluxoids. In Bi-2223 epitaxial films and tape wires under the magnetic field

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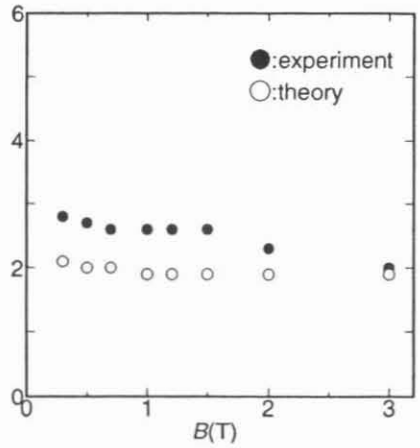

Fig. 2. Static critical index, ν: Solid and open symbols represent experimental and theoretical results, respectively.

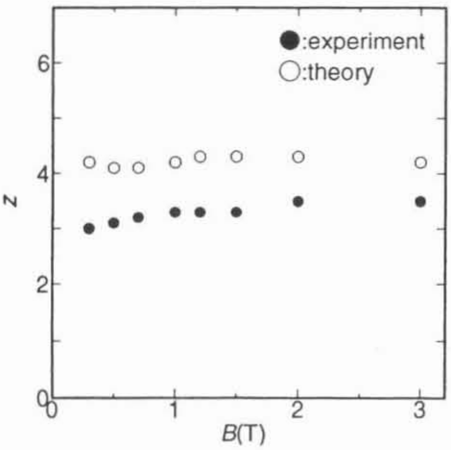

Fig. 3. Dynamic critical index, z: Solid and open symbols represent experimental and theoretical results, respectively.

parallel to the c-axis the fluxoids were assumed as quasi-two-dimensional and $D = 2$ was used in the analysis of the current-voltage characteristics [7], [8], [10], [11]. However, the behavior of fluxoids in Bi-2223 tape wires was found to be three-dimensional for both the magnetic fields normal and parallel to the c-axis from the scaled pinning force density and the irreversibility field [12]. Hence, $D = 3$ is assumed in this paper. Figure 1 shows the results of scaled current-voltage curves at $B = 0.7$ T. In this case the obtained scaling parameters are $T_g = 36$ K, $\nu = 2.6$ and $z = 3.2$. The static and dynamic critical indices at various magnetic fields are represented in Fig. 2 and Fig. 3, respectively. It is found that these indices are not exactly constants but vary slightly with magnetic field.

III. Flux creep-flow model

According to the flux creep model [5], the induced electric field due to the thermally activated fluxoid motion is described as

$$E_{cr} = Ba_f\nu_0 \exp\left[-\frac{U(j)}{k_B T}\right] \times \left[1 - \exp\left(-\frac{\pi U_0 j}{k_B T}\right)\right]; \quad j \leq 1,$$

$$= Ba_f\nu_0 \left[1 - \exp\left(-\frac{\pi U_0}{k_B T}\right)\right]; \quad j > 1, \qquad (1)$$

where $j = J/J_{c0}$ is the normalized current density by the virtual critical current density, J_{c0}, in the creep-free case and a_f is the fluxoid spacing, ν_0 is the oscillation frequency of the flux bundle, U is the activation energy and U_0 is the pinning potential. It is known that the pinning potential depends not only on the the pinning strength but also on the size of the superconductor [13]. The longitudinal flux bundle size in a superconductor is considered to be given by the longitudinal elastic correlation length, $l_{44} = (C_{44}/\alpha_L)^{1/2} = (Ba_f/2\pi\mu_0 J_{c0})^{1/2}$, where C_{44} is the tilt modulus and α_L is the Labusch parameter. If the thickness of the superconducting region, d, is smaller than l_{44}, U_0 is given by [13]

$$U_0 = \frac{4.23 g^2 k_B J_{c0} d}{(2\pi) B^{1/2}}, \qquad (2)$$

where g^2 is the number of fluxoids in the flux bundle and is determined by the condition of maximum critical current density [14]. In the case of d larger than l_{44}, U_0 is given by

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

Within the ranges of magnetic field and temperature for the analysis, g^2 is calculated to be smaller than 1. Hence, we use the minimum value, $g^2 = 1$, in the analysis.

On the other hand, the contribution from the flux flow is

$$E_{ff} = 0; \quad j \leq 1,$$
$$= \rho_f (J - J_{c0}); \quad j > 1, \qquad (4)$$

where ρ_f is the flux flow resistivity. Here we approximate that the total electric field is given by

$$E = (E_{cr}^2 + E_{ff}^2)^{1/2}. \qquad (5)$$

This leads to E_{cr} for $j < 1$ and E_{ff} for $j \gg 1$. Since U_0 and U are expressed using J_{c0}, the current-voltage curve can be calculated when J_{c0} is given [5]. We assume the following temperature and magnetic field dependences of J_{c0}:

$$J_{c0} = A\left[1 - \left(\frac{T}{T_c}\right)^2\right]^m B^{\gamma-1}\left(1 - \frac{B}{B_{c2}}\right)^\delta, \qquad (6)$$

where A, m, γ and δ are the pinning parameters.

It is considered that the flux pinning strength is distributed in practical superconductors [5]. For simplicity, we assume that only A in (6) is distributed in the form:

$$f(A) = K \exp\left[-\frac{(\log A - \log A_m)^2}{2\sigma^2}\right], \qquad (7)$$

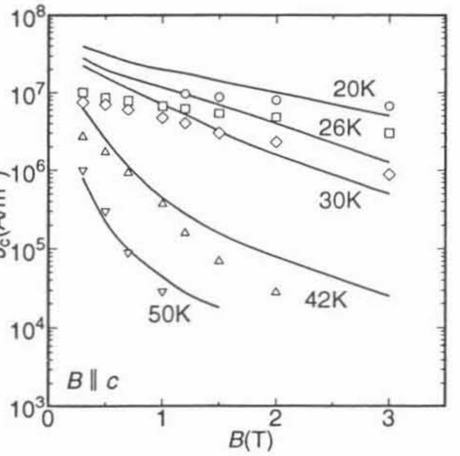

Fig. 4. Experimental (open symbols) and theoretical (lines) results of critical current density.

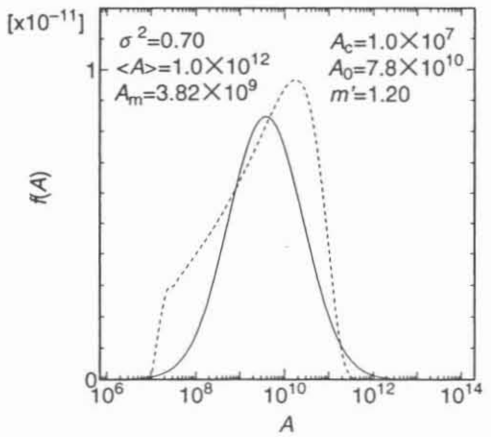

Fig. 5. Two distributions of A. Solid and dashed lines are the distributions given by (7) and (9), respectively.

where A_m is the most probable value, K is a constant determined by the condition of normalization and σ^2 is a constant representing the degree of deviation. Then, the electric field is given by

$$E(J) = \int_0^\infty E f(A) \mathrm{d}A. \tag{8}$$

The parameters used in the numerical calculation are shown in Table I. g^2 is estimated at 40 K and 1.5 T and assumed to be constant for simplicity. The pinning parameters and σ^2 are determined so that a good fit is obtained between the experimental and theoretical values of the critical current density. The critical current density was defined using the electric field criterion of 1.0×10^{-4} V/m. Figure 4 shows the results of critical current density. Its dependences on temperature and magnetic field seem to be approximately explained. However, the value of J_c corresponding to A_m amounts to 2.9×10^9 A/m^2 at $B = 1.5$ T and $T = 26$ K and is larger than the experimental result. It is well known that the distribution of the flux pinning strength can be described by the Weibull function [15].

TABLE I
Superconducting and pinning parameters used in the numerical calculation.

T_c (K)	$B_{c2\parallel}(0)$ (T)	$\rho_n(T_c)$ ($\mu\Omega$m)	A_m	
93.0	34.5	100	3.82×10^9	
m	γ	δ	g^2	σ^2
8.0	0.8	2.0	1.0	0.70

According to the theory, the distribution of the flux pinning strength is given by

$$f(A) = \frac{m'}{A_0}\left(\frac{A - A_c}{A_0}\right)^{m'-1} \exp\left[-\left(\frac{A - A_c}{A_0}\right)^{m'}\right], \tag{9}$$

where m' is the parameter determining the shape of the distribution, A_0 is a scaling factor roughly representing the width of the distribution and A_c is the minimum value of A. These parameters are chosen so as to get a good fit between the two distributions. Here, the two distributions of A are compared in Fig. 5. It turns out that $J_c = 7.6\times 10^6$ A/m^2 estimated at $B = 1.5$ T and $T = 26$ K from A_c is close to the critical current density shown in Fig. 4. Thus, the value of A_m assumed here seems to be reasonable. Hence, the numerical analysis on the current-voltage curves at higher temperatures is carried out using the above parameters. The magnetic field above which l_{44} becomes longer than $d = 10$ μm is $B = 11.9$ T at $T = 20$ K and $B = 4.4$ T at $T = 40$ K.

IV. Discussion

Figure 6 shows the scaled result of numerically calculated curves at $B = 0.7$ T. The scaling parameters obtained from the numerical analysis are $T_g = 30$ K, $\nu = 2.0$ and $z = 4.1$. Comparing the results with the data in Fig. 1, it is found that the scalings are similar although the scaling parameters are slightly different. The obtained static and dynamic critical indices are compared with the experimental results in Figs. 2 and 3, respectively. The present theoretical analysis explains approximately the small z values and the relatively large ν values. These results do not agree with the prediction of the glass-liquid transition theory for two-dimensional fluxoid system. Especially the too small z is speculated to be caused by the large deviation in the pinning strength. In Fig. 7 the transition line is compared between the experimental and theoretical results. This also shows that the agreement is rather good. It is to be noted, that the scaling of the current-voltage curves is not perfect for both the experimental and theoretical results. For this reason, it is considered that the flux pinning strength is very widely distributed in this specimen. This speculation seems to be associated with a broad transition curve of susceptibility.

However, the approximate scaling of the current-voltage curves obtained from the mechanism of flux creep and flow seems to be attributed to the divergence of some correlation length at the transition temperature, T_g. The cor-

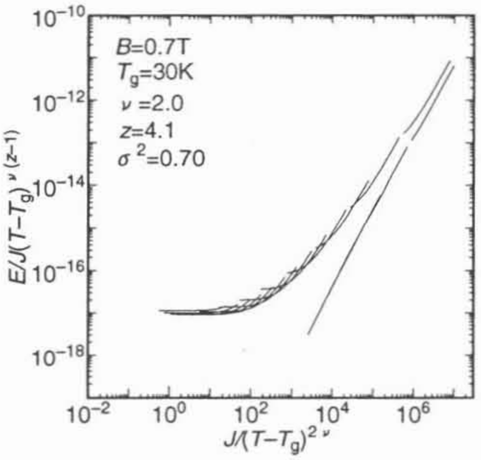

Fig. 6. Calculated scaled characteristics at B=0.7 T

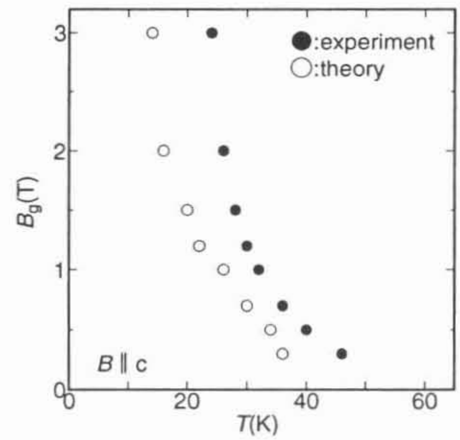

Fig. 7. Experimental (open symbols) and theoretical (solid symbols) results of transition line.

responding correlation length will be $l_{11} = (C_{11}/\alpha_L)^{1/2}$ along the direction of the Lorentz force, where C_{11} is the uniaxial compression modulus. Since α_L is proportional to the pinning force density, F_p, if we assume the scaling law as $F_p \propto (1 - B/B_g)^{\delta'}$ in the vicinity of the transition line, we have $l_{11} \propto (1 - B/B_g)^{-\delta'/2}$. This means that the temperature dependence of l_{11} is given by $l_{11} \propto (1 - T/T_g)^{-\delta'/2}$ near T_g. Thus, $\delta'/2$ corresponds to the static critical index, ν. The scaling of the pinning force density is shown in Fig. 8. From this result we obtain $\delta' = 5.4$ and $\nu = 2.7$ is expected. The static critical index, ν, takes about 2.7 in the range of 38 K–50 K ($B < 0.7$ T) for the measurement in Fig. 8. It is found, therefore, that the static critical index can be explained by the mechanism of flux pinning.

V. Summary

The scaling of the current-voltage curves is investigated for a dip-coated Bi-2212 tape wire and the following results are obtained:

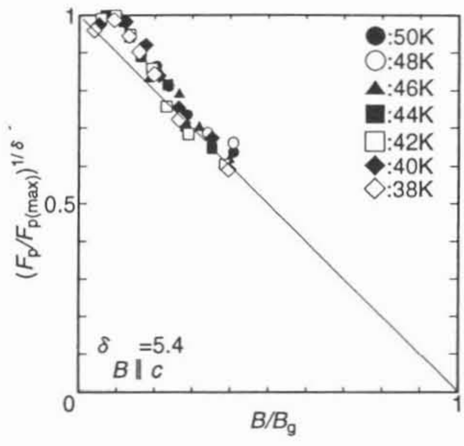

Fig. 8. Pinning force density normalized by the maximum value vs magnetic field normalized by B_g.

1. The current-voltage curves are approximately scaled on two master curves. However, the scaling is not perfect. This seems to be ascribed to be the widely distributed inhomogeneity of the specimen.
2. The scaling of the current-voltage curves, the two critical indices and the transition line are approximately explained by the flux creep-flow model. Especially, the dynamic critical index is too small in spite of two-dimensional flux lines. This is caused by the inhomogeneous distribution of pinning strength.

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