# CURRENT-VOLTAGE CHARACTERISTICS IN SUPERCONDUCTING Bi-2212 TAPES

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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 two-dimensional flux line systems. These results are compered with the theorical analysis based on the flux creep-flow model taking account for 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.

## 1. Introduction

It is known that the current-voltage curves of high temperature superconductors collapse on two master curves when those are normalized by proper functions of temperature.[1,2] However, a similar scaling to the prediction of the vortex glass-liquid transition theory 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 this paper the scaling of the current-voltage curves is investigated for Bi-2212 tape wire and the results are compered with the theoretical analysis based on the flux creep-flow model.

## 2. Experimental

The measured specimen was a Bi-2212 tape wire prepared by a dip-coat process. Its size was about 40.0 mm long, 4.7 mm wide and 0.11 mm thick and the $c$-axis 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. Further details of the measurement are given in Ref. 6.

Figure 1 shows the results of scaled current-voltage curves at $B$=1.5 T. In this case the obtained scaling parameters are $T_g$= 28 K, $\nu$=2.6 and $z$= 3.3. The static and dynamic critical indices at various magnetic fields are represented in Fig. 2 and

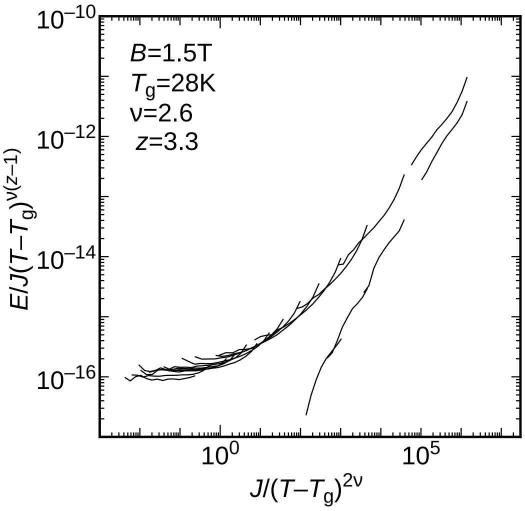


Fig. 1. Scaling characteristics at $B = 1.5$ T.

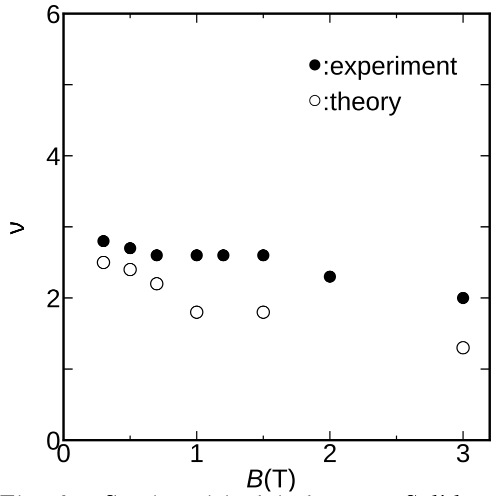


Fig. 2. Static critical index, $\nu$: Solid and open symbols represent experimental and theoretical results, respectively.

Fig. 3, respectively.

## 3. Flux creep-flow model

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

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

where $j = J/J_{\rm c0}$ is the normalized current density by the virtual critical current density, $J_{\rm c0}$, in the creep-free case, $a_{\rm f}$ is the fluxoid spacing, $\nu_0$ is the oscillation frequency of the flux bundle, $U$ is the activation energy and $U_0$ the pinning potential. On the other hand, the contribution from the flux flow is

$$\begin{aligned} E_{\rm ff} &= 0; \qquad j \le 1 \\ &= \rho_{\rm f}(J - J_{\rm c0}); \quad j > 1 \end{aligned} \tag{2}$$

where $\rho_{\rm f}$ is the flux flow resistivity. Here we approximate that the total electric field is given by $E = (E_{\rm cr}^2 + E_{\rm ff}^2)^{1/2}$. This leads to $E_{\rm cr}$ for $j < 1$ and $E_{\rm ff}$ for $j \gg 1$. Since $U_0$ and $U$ are expressed using $J_{\rm c0}$, the current-voltage curve can be calculated when $J_{\rm c0}$ is given.[5] We assume the following temperature and magnetic field dependences of $J_{\rm c0}$:

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

where $A$, $m$, $\gamma$ and $\delta$ are the pinning parameters.

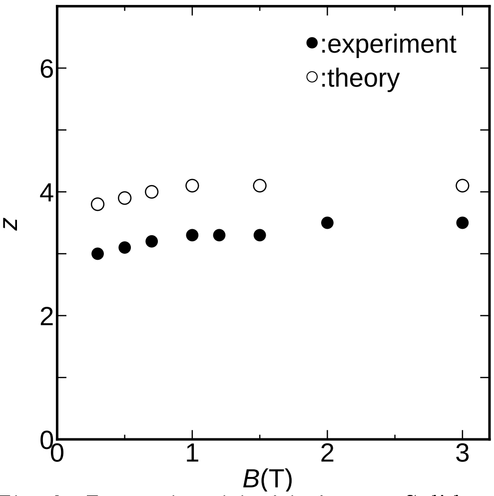


Fig. 3. Dynamic critical index, $z$: Solid and open symbols represent experimental and theoretical results, respectively.

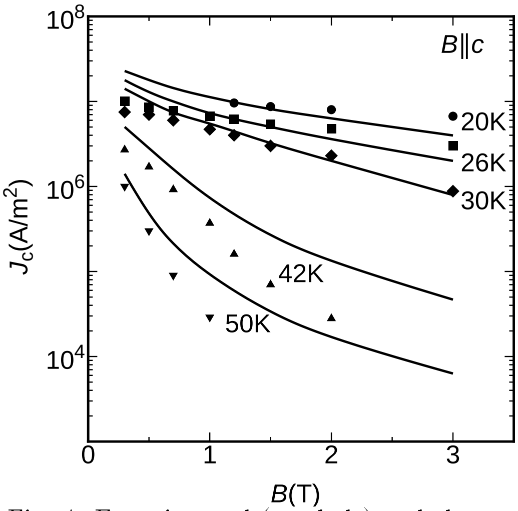


Fig. 4. Experimental (symbols) and theoretical (lines) results of critical current density.

In is considered that the flux pinning strength is distributed in practical superconductors.[5] For simplicity, we assumed that only $A$ in Eq. (3) is distributed in the form:

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

where $A_{\mathrm{m}}$ is the most probable value, $K$ is a constant determined by the condition of normalization and $\sigma^2$ is a constant representing the degree of deviation. Then, the electric field is given by

$$E(J) = \int_0^\infty Ef(A)\mathrm{d}A. \tag{5}$$

The parameters used in the numerical calculation are; $T_{\mathrm{c}} = 93.0$ K, $B_{\mathrm{c2}\|}(0) = 34.5$ T, $\rho_{\mathrm{n}}(T_{\mathrm{c}}) = 100\ \mu\Omega$m, $A_{\mathrm{m}} = 2\times 10^{12}$, $m = 7.0$, $\gamma = 0.67$, $\delta = 2.0$, $g^2 = 1.0$ and $\sigma^2 = 0.90$. In the above $g^2$ is estimated at 40 K and 1.5 T and assumed to be constant. The pinning parameters and $\sigma^2$ 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 $1.0\times 10^{-4}$ V/m. Figure 4 shows the results of critical current density. The agreement seems to be qualitatively good. Hence, the numerical analysis is carried out using the above parameters.

## 4. Discussion

Figure 5 shows the scaled result of numerically calculated curves at $B$=1.5 T. The scaling parameters obtained from the numerical analysis are $T_{\mathrm{g}} = 24$ K, $\nu = 1.8$ and $z = 4.1$. Comparing the results with Fig. 1, we find that the scalings are similar although the scaling parameters are slightly different. Static and dynamic critical indices are compared with experiments in Fig. 2 and 3, respectively. Although the results do not agree well, the present theoretical analysis explains approximately small $z$ values and relatively large $\nu$ values. In Fig. 6 the transition line is compared

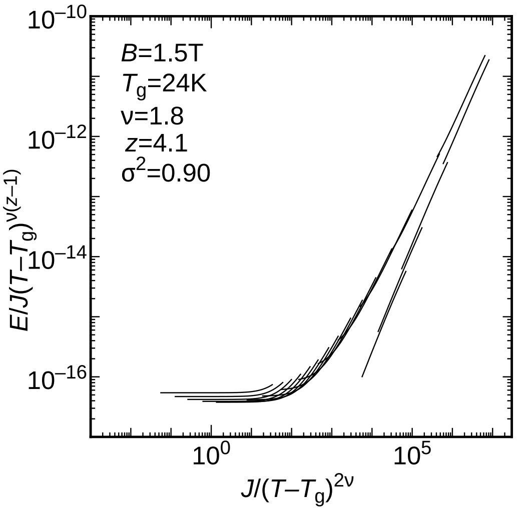


Fig. 5. Calculated scaled characteristics at $B$=1.5 T

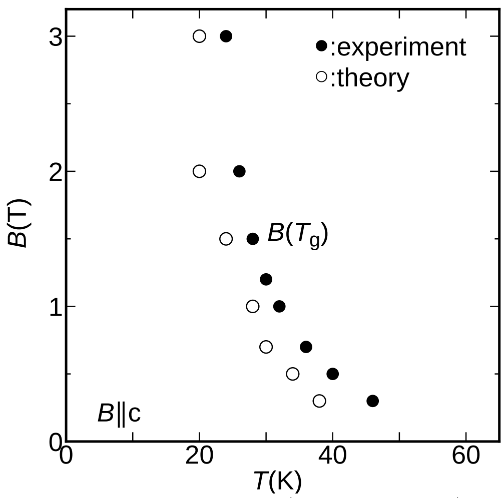


Fig. 6. Experimental (open symbols) and theoretical (solid symbols) results of transition lines.

between the experimental and theoretical results. Although the experimental result is slightly higher than the theoretical one, the agreement is rather good.

It is to be noted, however, 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 the transition curve of susceptibility.

## 5. Summary

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

1. The current-voltage curves are approximately scaled on two master curves. However, the scaling was 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 was too small in spite of two-dimensional flux lines. This is caused by the inhomogeneous distribution of pinning strength.

## 6. References

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