# Introduction

For practical applications of oxide superconductors, it is necessary to understand their current-voltage characteristics in a wide range of the electric field, since the electric field which the superconductor feels strongly depends on the kind of application such as DC or AC equipments. Therefore, it is necessary to measure the current-voltage characteristics of the oxide superconductor in detail in a wide range of the electric field. However, the characteristics have not yet been clarified, and the mechanism of flux motion which generates the electric field under distributed pinning forces is still under discussion. It is well known that the electric field vs current density ($E$-$J$) characteristics of an oxide superconductor is scaled in two master curves as predicted by the vortex glass-liquid transition theory. On the other hand, it has been shown that the scaling of the $E$-$J$ characteristics was also explained by the flux creep-flow model.

In this paper, the current-voltage characteristics in the range of very low electric field were analyzed for a superconducting Bi-2223 tape from a relaxation of the magnetization measured by a SQUID magnetometer. The scaling was examined for the result of $E$-$J$ characteristics at the electric field of the order of $10^{-10}$ V/m. The $E$-$J$ characteristics are numerically calculated using the flux creep-flow model and the results are compared with experimental results.

# Experimental

- specimen

Bi-2223 multifilamentary tape wire

| | |
|---|---|
| cross section (mm) | $3.7 \times 0.27$ |
| length of tape $l$ (mm) | 4.2 |
| number of filaments $f$ | 59 |
| average filament width $w$($\mu$m) | 320 |
| average filament thickness $d$($\mu$m) | 11 |
| critical temperature (K) | 110 |

- measurement

relaxation of magnetic moment measured by SQUID

40–83 K

1.5–900 mT

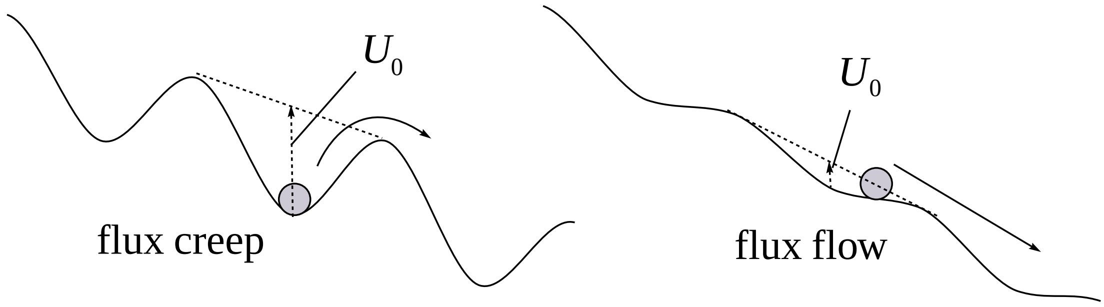
$B \parallel c$-axis

- evaluation of $E$-$J$ curve

$$J = \frac{12m}{w^2 df(3l - w)}$$

$$E = -\frac{\mu_0}{2df(l + w)} \cdot \frac{\mathrm{d}m}{\mathrm{d}t}$$

# Flux creep-flow model




- electric field by flux creep

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

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

$j = J/J_{\rm c0}$: normalized current density
$J_{\rm c0}$: virtual critical current density in the creep free case
$U_0$: pinning potential

- electric field by flux flow

$$E_{\rm ff} = 0; \quad j \le 1$$

$$= \rho_{\rm f}(J - J_{\rm c0}); \quad j > 1$$

$\rho_{\rm f}$: flow resistivity

- total electric field

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

- pinning potential, $U_0$

$$U_0 = \frac{0.835 g^2 {J_{\mathrm{c}0}}^{1/2} k_B}{2\pi^{3/2} B^{1/4}}$$

$g^2$: number of flux line in flux bundle

- scaling low of $J_{\mathrm{c}0}$

$$J_{\mathrm{c}0} = A \left[ 1 - \left( \frac{T}{T_{\mathrm{c}}} \right)^2 \right]^m B^{\gamma - 1}$$

$A, m, \gamma$: pinning parameter

- distribution of pinning force

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

$A_{\mathrm{m}}$: most probable value of $A$

$K$: constant determined by normalization

$$\left( \int_0^\infty f(A) \mathrm{d}A = 1 \right)$$

$\sigma^2$: parameter representing a distribution width

- observed electric field

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

$m$, $\gamma$, $A_{\mathrm{m}}$, $\sigma^2$: adjustable parameters

- number of flux line in flux bundle, $g^2$

> $g^2$ is assumed to be determined so that the critical current density under the flux creep might take a maximum value

$$g^2 = g_{\mathrm{e}}^2 \left[ \frac{5k_{\mathrm{B}}T}{2U_{\mathrm{e}}} \ln \left( \frac{Ba_{\mathrm{f}}\nu_0}{E_{\mathrm{c}}} \right) \right]^{4/3}$$

$$(E_{\mathrm{c}} = 10^{-10}\ \mathrm{V/m})$$

${g_{\mathrm{e}}}^2$: $g^2$ for perfect triangular lattice

$$g_{\mathrm{e}}^2 = \frac{C_{66}^0}{2\pi J_{\mathrm{c0}} B a_{\mathrm{f}}}$$

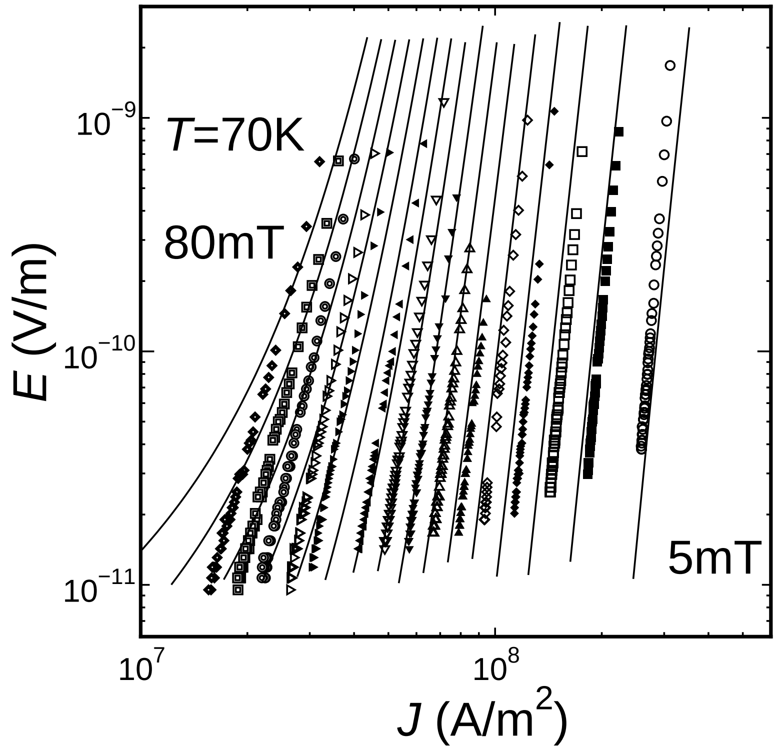
$C_{66}^0$: shear modulus for perfect triangular lattice

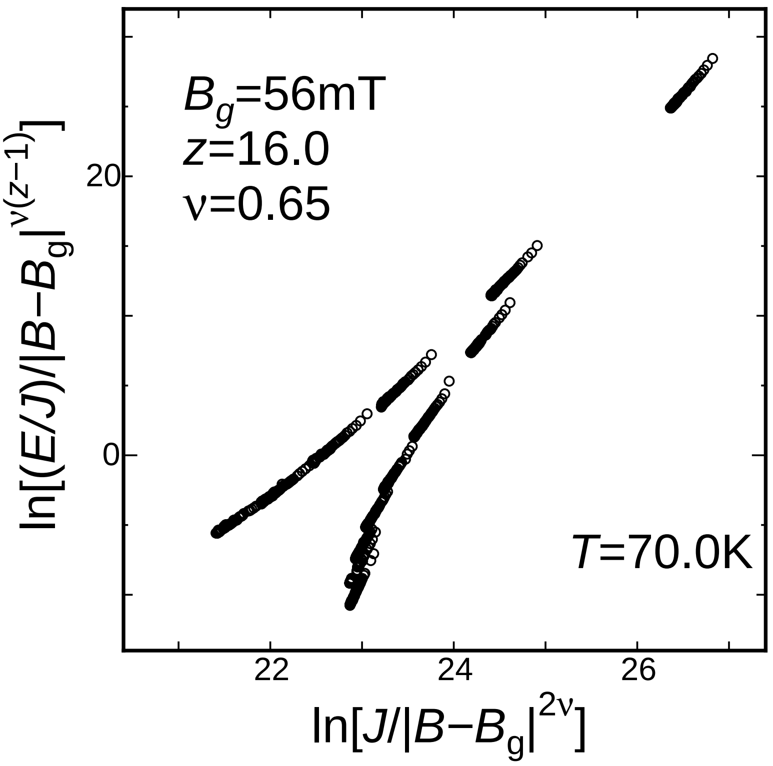
$$C_{66}^0 = \left( \frac{B_{\mathrm{c}}^2 B}{4\mu_0 B_{\mathrm{c2}}} \right) \left( 1 - \frac{B}{B_{\mathrm{c2}}^2} \right)$$

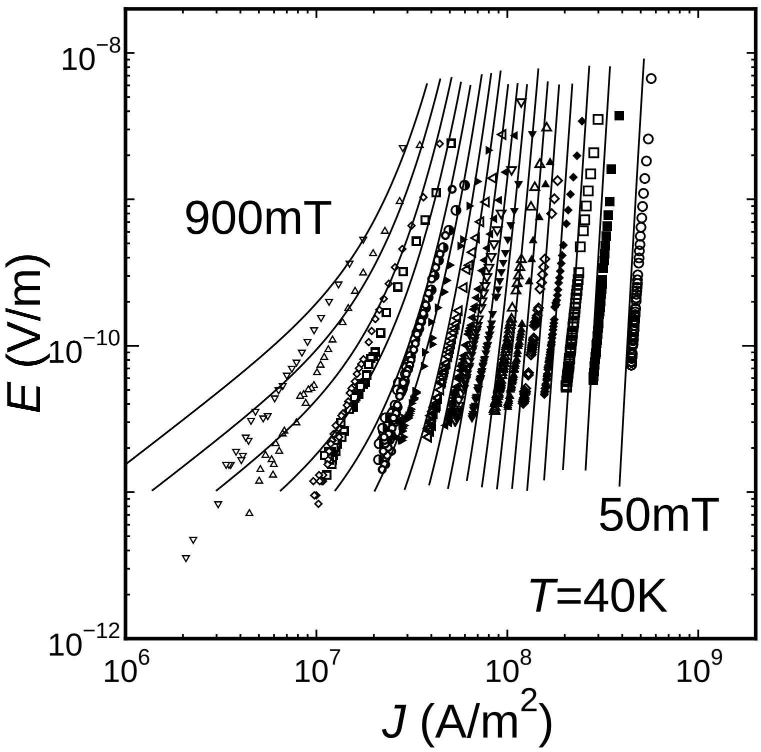
$$U_{\mathrm{e}} = U_0\ (g = g_{\mathrm{e}})$$

# Results and Discussion

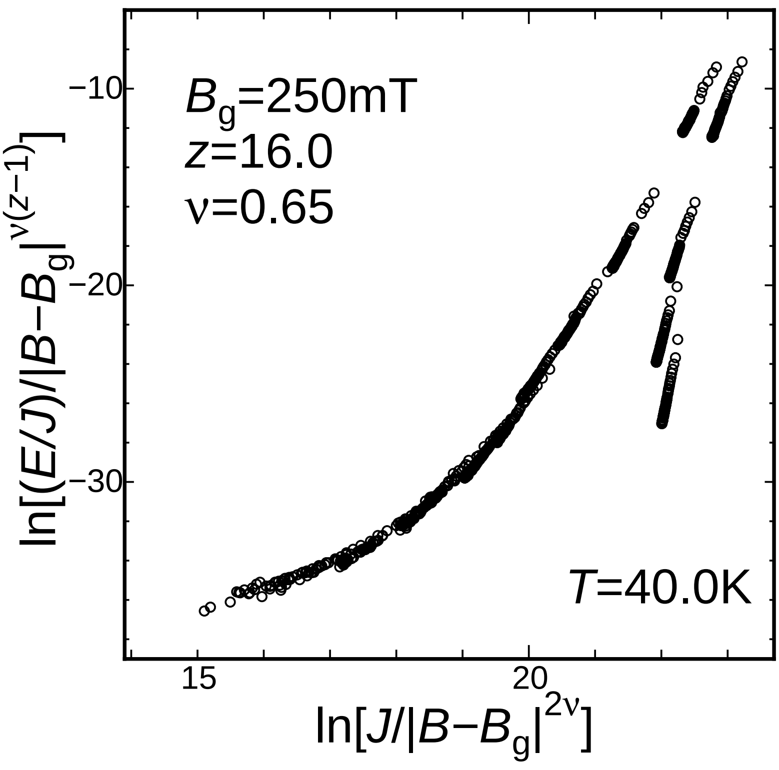
## $E$-$J$ curves and scaled result



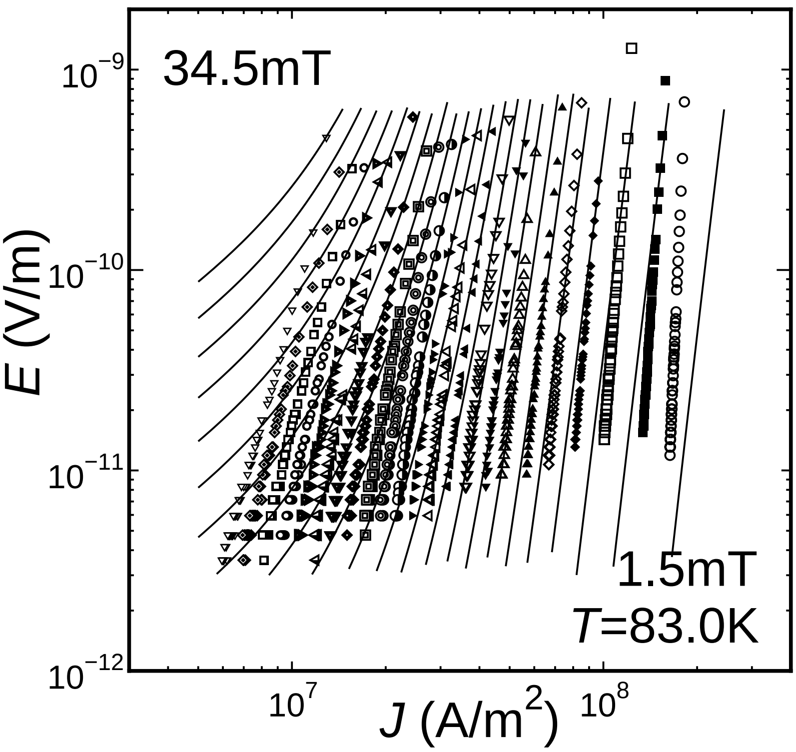



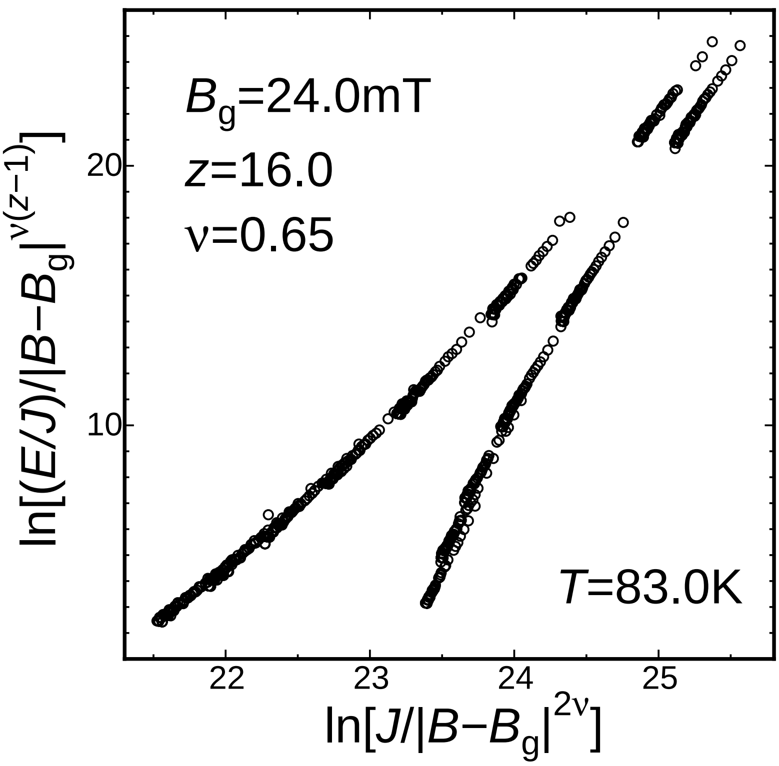


900mT
50mT
T=40K
E (V/m)
J (A/m2)

Bg=250mT
z=16.0
ν=0.65
T=40.0K
ln[(E/J)/|B−Bg|ν(z−1)]
ln[J/|B−Bg|2ν]


34.5mT
1.5mT
T=83.0K
E (V/m)
J (A/m²)
10⁻⁹
10⁻¹⁰
10⁻¹¹
10⁻¹²
10⁷
10⁸


Bg=24.0mT
z=16.0
ν=0.65
T=83.0K
ln[(E/J)/|B−Bg|^ν(z−1)]
ln[J/|B−Bg|^2ν]
20
10
22
23
24
25

- scaling parameters at 70 K

| | $\nu$ | $z$ | $B_g$ (mT) |
|---|---|---|---|
| low electric field | 0.65 | 16.0 | 25 |
| high electric field* | 0.5 | 11.0 | 308 |

(*4 probe method by Shiraishi *et al.*)

$z$ and $B_g$ are not constant but dependent on the electric field range. This is contradictory to the vortex grass-liquid transition theory.

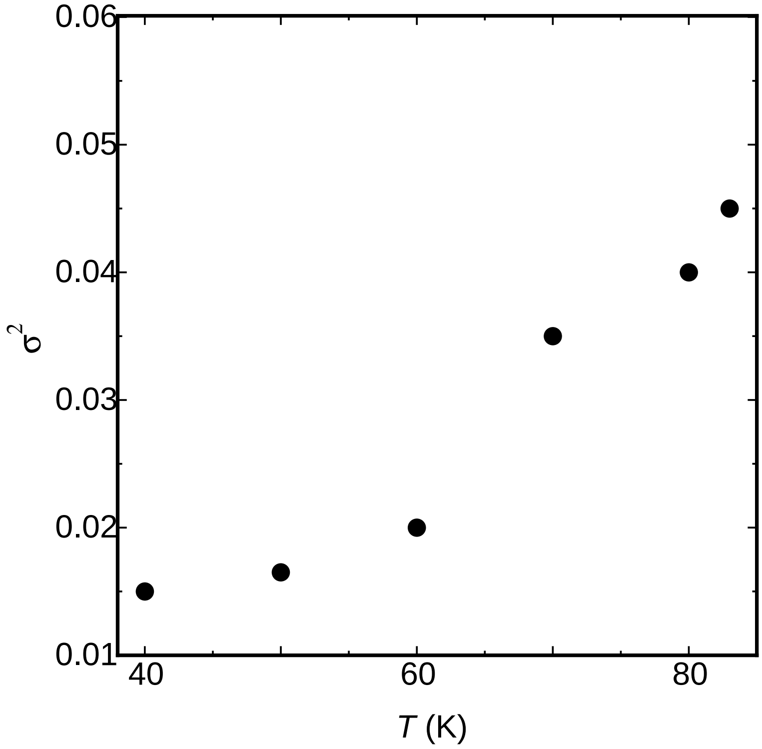
- deviation between theoretical and experimental results

The deviation becomes large at low current densities especially at high temperatures. The reason for this deviation is considered to be attributed to the expression of $g^2$.

- parameters

| $A_m$ | $m$ | $\gamma$ |
|---|---|---|
| $9.0 \times 10^8$ | 2.0 | 0.51 |

- distribution of $J_{c0}$, $\sigma^2$




- The distribution width of $J_c$ increases with temperature. This tendency is consistent with the usual temperature dependence of $n$-value, since $n$ becomes smaller due to the increase of the distribution width of $J_c$ according to increasing temperature.

# Summary

In this paper, the $E$-$J$ characteristics in the range of very low electric field was estimated for a superconducting Bi-2223 multifilamentary tape by analyzing the relaxation of the magnetic moment, and following results are obtained:

- The resultant $E$-$J$ characteristics are successfully scaled in the form predicted by the the vortex glass-liquid transition theory even in the range of the electric field about 6 orders of magnitude lower than in the ordinal four probe method.
- The dynamic critical index, $z$, is too large and is not consistent with the prediction of the glass-liquid transition theory. In addition, $z$ and the transition field, $B_{\mathrm{g}}$, depend on the range of the electric field. Therefore, the thermodynamic phase transition of the second order in the flux line system, which is characterized by the scaling of $E$-$J$ curves, does not originate from the intrinsic nature of flux lines.
- The $E$-$J$ characteristics are approximately explained by the flux creep-flow model over wide ranges of temperature and magnetic field. This shows that the thermal depinning is the basic mechanism which determines the $E$-$J$ characteristics in a wide range of the electric field.
- However, the deviation becomes large at low current densities especially at high temperatures. The reason for this deviation is considered to be attributed to the expression of $g^2$ at low current densities.