Current-Voltage Characteristics in a Superconducting Bi-2223 Tape in the Range of Very Low Electric Field

Edmund Soji Otabe, Takeshi Kodama, Mitsuhiro Fukuda, Teruo Matsushita, Kikuo Itoh

Abstract— **Current-voltage characteristics in the range of very low electric field were analyzed from a relaxation of the magnetization using a SQUID magnetometer in a superconducting Bi-2223 tape. It was found that the observed current-voltage characteristics in this range were scaled well as predicted by the vortex glass-liquid transition theory. However, the obtained transition field was much lower than that obtained from a scaling in the higher electric field range. At the same time, the dynamic critical index, z, was much larger than usual values. Hence, it is concluded that these parameters are not uniquely determined independently of the level of electric field. The experimental result was compared with the theoretical analysis using the flux creep-flow theory in which the distribution of the effective flux pinning strength was taken into account. It was found that the theoretical result explains approximately the observed result. This shows that the essential mechanism which governs the transport property in the superconducting tape is the flux pinning.**

Keywords— **E-J characteristics, Bi-2223, flux creep-flow model, very low electric field**

I. 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[1], [2]. 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[3].

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.

II. Experimental

Specimen was a superconducting multifilamentary Bi-2223 silver sheathed tape with 59 filaments. The width and thickness of the tape were 3.7 mm and 270 μm, respectively. The average width, w, and thickness, d, of the filaments were 320 μm and 11 μm, respectively. The tape was cut in a length of $l = 4.2$ mm for the magnetization measurement. The temperature of the specimen was controlled in a range of 40 to 83 K and the magnetic field was applied parallel to the c-axis. The magnetic field was first applied enough high and then reduced in certain value, and the relaxation of the magnetic moment, m, was measured by a SQUID magnetometer (MPMS-7). The current density, J, and the electric field, E, are estimated by the following equations:

$$J = \frac{12m}{w^2 df(3l - w)}, \tag{1}$$

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

where $f = 59$ is the number of filaments.

III. Results and Discussion

A. Experimental results

The E-J curves at 70 K evaluated from the measured relaxation of the magnetic moment using (1) and (2) are shown in Fig. 1(a). The range of the electric field is of the order of 10^{-10} V/m and is 6 to 7 orders of magnitude lower than that in usual measurements by the four probe method.

According to the vortex glass-liquid theory[1], [2], E-J characteristics can be scaled on two master curves by replotting them in the form of $(E/J)|T - T_{\mathrm{g}}|^{\nu(z+2-D)}$ vs. $J/|T - T_{\mathrm{g}}|^{\nu(D-1)}$. In the above, ν and z are the static

manuscript received September 18, 2000

E. S. Otabe is with Kyushu Institute of Technology, 680–4, Kawazu, Iizuka 820–8502 Japan (Telephone: +81–948–29–7683, e-mail: otabe@cse.kyutech.ac.jp).

T. Kodama is with Kyushu Institute of Technology, 680–4, Kawazu, Iizuka 820–8502 Japan (Telephone: +81–948–29–7683, e-mail: kodama@aquarius10.cse.kyutech.ac.jp).

M. Fukuda is with Kyushu Institute of Technology, 680–4, Kawazu, Iizuka 820–8502 Japan (Telephone: +81–948–29–7683, e-mail: fukuda@aquarius10.cse.kyutech.ac.jp).

T. Matsushita is with Kyushu Institute of Technology, 680–4, Kawazu, Iizuka 820–8502 Japan (Telephone: +81–948–29–7663, e-mail: matusita@cse.kyutech.ac.jp).

K. Itoh is with National Research Institute for Metals, Sakura 3–13, Tsukuba, Ibaraki 305–0003, Japan (Telephone: +81-298-59-5081, e-mail: itoki@nrim.go.jp).

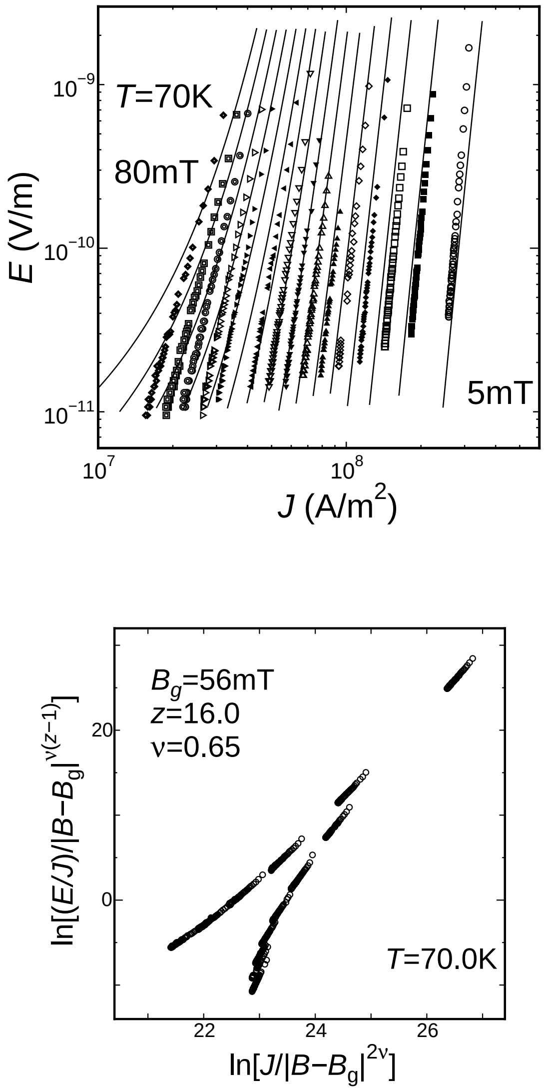

Fig. 1. (a) Observed E-J characteristics at various magnetic fields and at $T = 70$ K and (b) their scaled result in a Bi-2223 silver-sheathed tape wire. Solid lines in (a) represent the calculated result using the flux creep-flow theory.

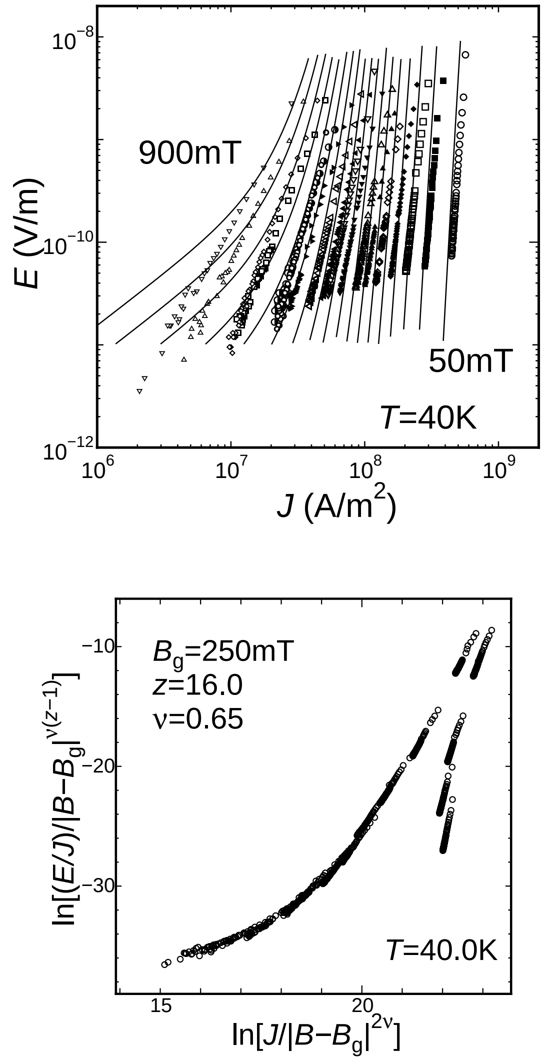

Fig. 2. (a) Observed E-J characteristics at various magnetic fields and at $T = 40$ K and (b) their scaled result.

and dynamic critical indices, D is the dimension of the vortex system and T_{g} is the transition temperature. The similar scaling is predicted [4] for $(E/J)|B - B_{\mathrm{g}}|^{\nu(z+2-D)}$ vs. $J/|B - B_{\mathrm{g}}|^{\nu(D-1)}$ with the same critical indices, ν, z, where B_{g} is the transition field.

Fig. 1(b) shows the result of the scaling of E-J characteristics, where $B_{\mathrm{g}} = 56$ mT, $z = 16.0$, $\nu = 0.65$ and $D = 3$ are assumed. It is clear that the scaling is also obtained in the range of very low electric field. However, the value of z is much larger than predicted by the glass-liquid transition theory. That is, even if we assume $D = 2$, we have $z = 7.5$ (with $\nu = 1.3$), which is still too large. The scaling is also possible at different temperatures as shown in Figs. 2(b) and 3(b) at 40 K and 83 K, respectively.

On the other hand, the scaling in the range of higher electric field by the four probe method gives $B_{\mathrm{g}} = 308$ mT, $z = 11.0$ and $\nu = 0.5$ at 70 K[5]. That is, B_{g} is larger and z is smaller at high electric fields. This result suggests that the E-J characteristics tend to vary from convex upward in the higher E range to concave downward in the lower E range.

Therefore, z and B_{g} are not constant but dependent on the electric field range. This is contradictory to the vortex grass-liquid theory in which those parameters are considered to be intrinsically determined by the characteristic of the flux line lattice. It should be noted that the performance of scaling of E-J curves does not necessarily mean that the vortex glass-liquid transition theory holds. It was shown in [6] that the thermal depinning is a transition of the second order. This predicts the theoretical foundation that the E-J curves can be scaled.

B. Analysis by the flux creep-flow model

These observed results are compared with the theoretical analysis using the flux creep-flow model[3]. According to this model, the E-J characteristics can be calculated in

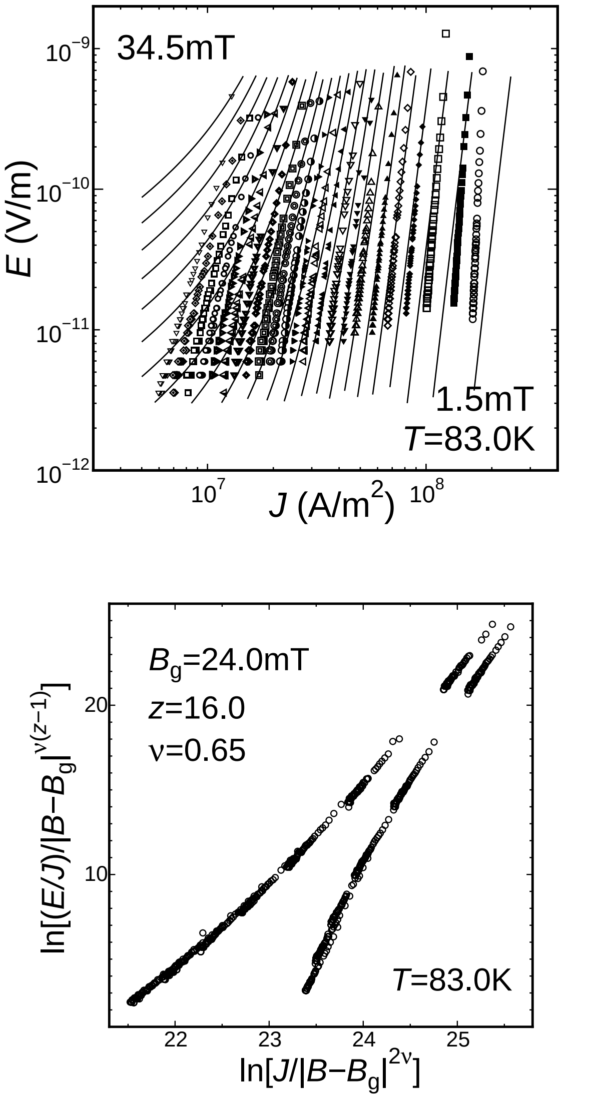

Fig. 3. (a) Observed E-J characteristics at various magnetic fields and at $T = 83$ K and (b) their scaled result.

terms of the pinning potential:

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

where J_{c0} is the virtual critical current density in the creep free case and g^2 is the number of flux lines inside the flux bundle. The magnetic field and temperature dependences of J_{c0} at low fields is assumed as

$$J_{\mathrm{c0}} = A\left[1 - \left(\frac{T}{T_{\mathrm{c}}}\right)^2\right]^m B^{\gamma-1}, \tag{4}$$

where A, m and γ are pinning parameters. It is well known that the magnitude of J_{c0} is widely distributed in oxide superconductors. Here, for simplicity, the distribution of J_{c0} is assumed to originate only from the distribution of A in (4) of the form:

$$f(A) = K\exp\left[-\frac{(\log A - \log A_{\mathrm{m}})^2}{2\sigma^2}\right], \tag{5}$$

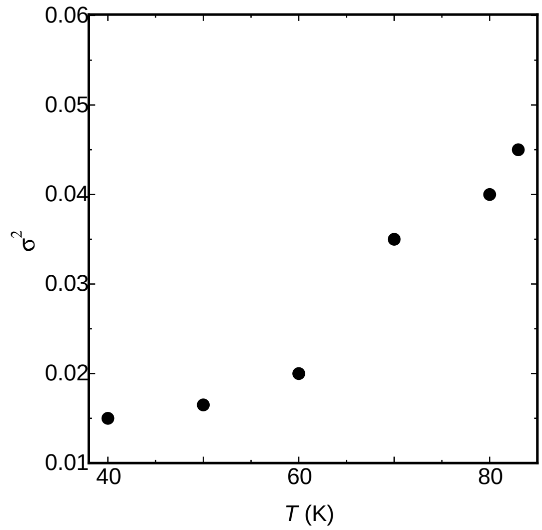

Fig. 4. Temperature dependence of σ^2.

where A_{m} is the most probable value, σ^2 is a constant representing the degree of deviation and K is a constant determined by the condition of normalization.

The value of g^2 is assumed to be determined so that the critical current density under the flux creep might take a maximum value [7], and is given by

$$g^2 = g_{\mathrm{e}}^2\left[\frac{5k_{\mathrm{B}}T}{2U_{\mathrm{e}}}\ln\left(\frac{Ba_{\mathrm{f}}\nu_0}{E}\right)\right]^{4/3}, \tag{6}$$

where g_{e} is the value where flux lines form a perfect triangular lattice, and U_{e} is the value of U_0 when $g = g_{\mathrm{e}}$. In the present calculation $g(B, T)$ is obtained by (6), while $E = 10^{-10}$ V/m is assumed as a typical value of the electric field. Further details of the calculation are described in [3].

The parameters A_{m}, m and γ used in the numerical calculation in the whole range of temperature and magnetic field in the present measurement are listed in Table. 1. On the other hand, σ^2, which is used as a fitting parameter at each temperature, is shown in Fig. 4. 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.

The calculated results are compared with the experimental results in Figs. 1(a), 2(a) and 3(a). It is found that the theoretical result explains approximately the observed re-

TABLE I

Parameters used in the numerical calculation.

A_{m}	m	γ
9.0×10^8	2.0	0.51

sults in the range of very low electric field. Since the E-J characteristics in the higher range of electric field can also be explained by the theory [8]–[10], it can be said that the flux creep-flow model can approximately describe the E-J characteristics in wide ranges of temperature, magnetic field and electric field. This shows that the essential mechanism which governs the transport property in the superconducting tape is the flux pinning.

However, the present theoretical model cannot explain the details of the observed E-J characteristics. That is, the theoretical prediction leads to an E-J curve concave downward with a much larger value of E at very low J value. This becomes more remarkable at higher temperatures. This deviation seems to be attributed to the assumption of the constant value of $E = 10^{-10}$ in (6) for simplicity. In fact, this deviation is qualitatively explained by the electric field dependence in (6). That is, when E becomes small, g^2 takes a larger value and the effect of flux creep is expected to become weak. However, the estimated results at 40 K, 900 mT and 70K, 80 mT are almost unchanged even by this treatment.

Another reason for the deviation may exist in the assumption on which (6) is derived. This equation was derived for the current density far above the TAFF region. On the other hand, the deviation becomes large around the region where TAFF starts to take place in the theoretical model. Hence, it seems to be necessary to derive a correct expression of g^2 in such a range of low current density.

IV. Conclusions

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_{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.

Acknowledgments

The authors would like to acknowledge Mr. K. Shiraishi, Drs. M. Kiuchi and T. Kiss of Kyushu University for helpful discussions.

References

[1] M. P. A Fisher, "Vortex-glass superconductivity: A possible new phase in bulk high T_c oxides", Phys. Rev. Lett., vol. 62, p. 1415, 1989.

[2] D. S. Fisher, M. P. A. Fisher and D. A. Huse, "Thermal fluctuations, quenched disorder, phase transitions, and transport in type-II superconductors", Phys. Rev. B, vol. 43, p. 130, 1991.

[3] T. Matsushita, T. Tohdoh and N. Ihara, "Effects of inhomogeneous flux pinning strength and flux flow on scaling of current-voltage characteristics in high-temperature superconductors", Physica C, vol. 259, p. 321, 1996.

[4] T. Kiss, T. Matsushita and F. Irie, "Relationship among flux depinning, irreversibility and phse transition in a disordered HTS material", Supercond. Sci. Technol. vol. 12, p.1079, 1999.

[5] K. Shiraishi, S. Nishimura, M. Kiuchi, T. Kiss: private communication.

[6] T. Matsushita and T. Kiss, "Thermal depinning of flux lines in superconductors", Physica C, vol. 315, p.12, 1999.

[7] T. Matsushita, "On the flux bundle size in weakly pinned superconductors", Physica C, vol. 217, p. 461, 1993.

[8] M. Kiuchi, K. Noguchi, T. Matsushita, T. Kato, T. Hikata and K. Sato, "Scaling of current-voltage curves in superconducting Bi-2223 silver-sheathed tape wires", Physica C, vol. 278, pp. 62, 1997.

[9] M. Kiuchi, K. Noguchi, M. Tagomori, T. Matsushita, and T. Hasegawa, "Scaling of current-voltage curves of Bi-2212 tape wire", IEEE Trans. Appl. Supercond., vol. 7, pp. 2114, 1997.

[10] T. Matsushita, M. Tagomori, K. Noguchi, M. Kiuchi and T. Hasegawa, "Irreversibility and vortex glass-liquid transition fields of silver-sheathed Bi-2212 superconducting tapes", Adv. Cryog. Eng. Mater., vol. 44, pp. 609, (Plenum, New York, 1997)