E-J Characteristics in a Wide Range of Electric Field for a Bi-2223 Silver-Sheathed Tape Wire

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Abstract— **The E-J characteristics are measured for a Bi-2223 silver-sheathed tape wire using the four probe method and a relaxation method of DC magnetization in the high and low electric field regions, respectively. The obtained results in the two regions are approximately explained by a theoretical analysis based on the flux creep-flow model in which the distribution of flux pinning strength is taken into account. It was found that the value of the pinning force density and its peak magnetic field are largely different between the two measurements.**

Keywords— **E-J characteristics, Bi-2223, flux creep-flow model, wide range of electric field**
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I. Introduction

Electromagnetic properties of high-temperature superconducting instruments are strongly influenced by the electric field (E) vs current density (J) characteristics of the superconductors. Therefore, it is necessary to estimate the E-J characteristics in a wide range of electric field. However, the characteristics have not yet been sufficiently clarified. This is ascribed to the lack of a detailed knowledge on the generation mechanism of electric field and on the influence of the distribution of flux pinning strength.

On the other hand, the E-J characteristics in the range of resistive measurements have been successfully explained by the flux creep-flow model with a distribution of the flux pinning strength [1] and by the percolation flow model [2]. In the latter model the flux motion under a significant thermal activation is approximated by an equivalent flux flow by making the pinning potentials shallow. The E-J characteristics are determined by the percolation property which is strongly influenced by the distribution of the flux pinning strength. Hence, the two models are essentially based on the same mechanism.

In this paper the E-J characteristics are measured using the four probe method and a relaxation method of DC magnetization in high and low ranges of the electric field, respectively, for a Bi-2223 tape. The obtained result is compared with the result of the theoretical analysis based on the flux creep-flow model in which the distribution of the flux pinning strength is taken into account.

II. Experimental

Specimen was a superconducting multifilamentary Bi-2223 silver sheathed tape with 59 filaments prepared by the powder-in-tube method. The width and thickness of the tape were 3.7 mm and 270 μm, respectively. The average width, w, and thickness, d, of superconducting filaments were about 320 μm and 11 μm, respectively. The tape was cut in a length of $l = 4.2$ mm for the magnetization measurement. The critical temperature, T_c, was 110 K.

The magnetic relaxation was measured in a magnetic field parallel to the c-axis in a temperature range of 40 to 83 K using a SQUID magnetometer (MPMS-7). The magnetic field of sufficient strength was first applied to the specimen, and then reduced to a certain value, and the relaxation of the magnetic moment, m, was measured. 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.

A four probe method was also used to measure the E-J characteristics in a temperature range of 40 to 77.3 K. The distance between the voltage terminals is about 10 mm.

III. Results and Discussion

The E-J curves evaluated from the both methods at 70 K are shown in Fig. 1. The range of the electric field by the magnetization measurement is of the order of 10^{-10} V/m and 6 to 7 orders of magnitude lower than that by the four probe method.

These observed E-J curves are compared with the theoretical analysis using the flux creep-flow model [1]. According to this model, the E-J characteristics can be calculated when the pinning potential is given:

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

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

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

where A, m and γ are pinning parameters. It is assumed that A is distributed as

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

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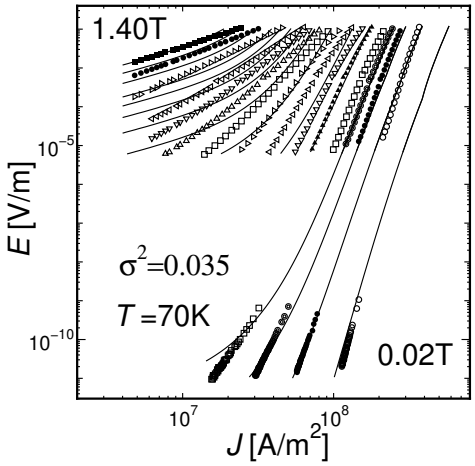

Fig. 1. Comparison of E-J curves between experiment (symbols) and theory (lines) at 70 K. Experimental results are obtained by four probe method (top) and the magnetization method (bottom).

where $A_{\rm m}$ is the most probable value, σ^2 is a constant representing the degree of deviation and K is a constant.

The value of g^2 is assumed to be determined so that the critical current density under the flux creep might take on a maximum value [3], and is given by

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

where $g_{\rm e}$ is the value where flux lines form a perfect triangular lattice, and $U_{\rm e}$ is the value of U_0 when $g = g_{\rm e}$. Strictly speaking, g^2 depend on E as well as on B and T. However, the value of g^2 at $E = 10^{-10}$ V/m is approximately used as a typical value in the present calculation. For example, we used $g^2 = 1.39$ at $B = 0.3$ T and $T = 70$ K. The details of the calculation are described in [1].

The parameters $A_{\rm m}$, m and γ used in the numerical calculation in the whole ranges of temperature and magnetic field are listed in Table 1. On the other hand, σ^2, which is used as a fitting parameter at each temperature.

The calculated results are compared with the experimental results in Fig. 1. The theoretical results explain approximately the experimental results except in the region of low current density. It is seen that the critical current density is different between the resistive and magnetization methods because of the filament sausaging. That is, the magnetic $J_{\rm c}$ shows an average value and is larger than the resistive $J_{\rm c}$ which is determined by narrow area of filaments. The theoretical results show the higher electric fields than observed in very high range of the electric field. This deviation comes from the sharing flow of the current to the silver sheath in the experiment.

TABLE I
PARAMETERS USED IN THE NUMERICAL CALCULATION.

$A_{\rm m}$	m	γ
9.0×10^8	2.0	0.51

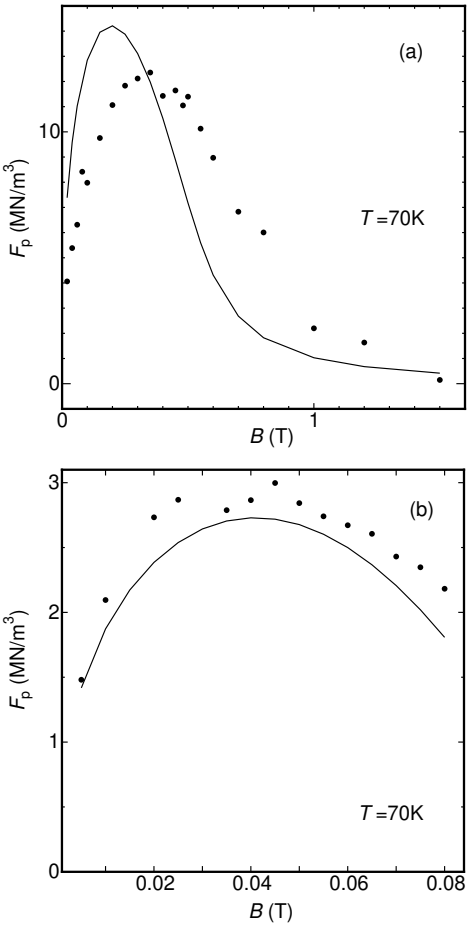

Fig. 2. Pinning force density at 70 K defined at (a) high and (b) low electric fields. Symbols and lines show experiment and theory, respectively.

Thus, 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 thermal depinning is the basic mechanism which determines the E-J characteristics in a wide range of the electric field.

Fig. 2 shows the pinning force densities, $F_{\rm p}$, at 70 K defined at (a) $E = 1.0 \times 10^{-4}$ V/m and (b) $E = 1.0 \times 10^{-10}$ V/m in the resistive and magnetic measurements, respectively. The value of $F_{\rm p}$ and the peak magnetic field are largely different between the two cases, suggesting a large effect of flux creep.

Fig. 3 shows the distribution width of $J_{\rm c}$ 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 $J_{\rm c}$ according to increasing temperature.

Although, the present theoretical model approximately explains the observed E-J characteristics, the details cannot be explained. That is, the deviation becomes large at low current densities. The reason for this deviation is considered to be attributed to the expression of g^2 at low current densities. That is, the dependence of g^2 on the electric field was disregarded. In addition, Eq.(6) was derived for the region far from the TAFF(thermally activated

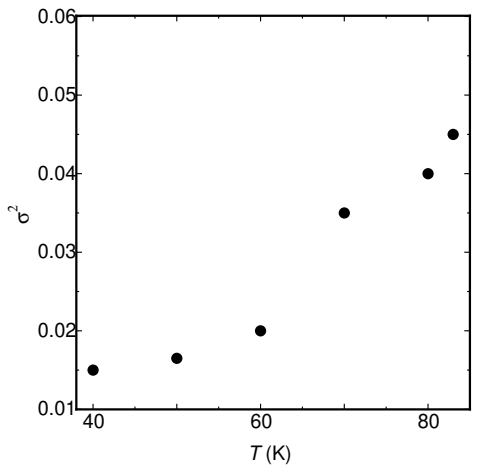

Fig. 3. Temperature dependence of σ^2.

flux flow) state, while the theoretical prediction shows the typical behavior in the TAFF state as can be seen from Fig. 1. Thus, the theoretical expression of g^2 should be obtained in a self-consistent manner.

IV. Summary

The E-J characteristics are approximately explained by the flux creep-flow model over wide ranges of temperature, magnetic field and electric field. This shows that the thermal depinning is the basic mechanism which determines the E-J characteristics.However, the deviation becomes large at low current densities. The reason for this deviation is considered to be attributed to the expression of g^2 at low current densities.

V. Acknowledgments

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References

[1] T. Matsushita, T. Tohdoh and N. Ihara, Physica C **259**(1996) 321.
[2] K. Yamafuji and T. Kiss, Physica C **258** (1996) 197.
[3] T. Matsushita, Physica C **217** (1993) 461.