Irreversibility Field of Bi-2223 Silver-Sheathed Tape Determined with Different Electric Field Criteria

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Abstract

Dependence of the irreversibility field(B_i) on the electric field criterion (E_c) was measured for a Bi-2223 silver-sheathed tape wire using various measuring methods. It was found that B_i increased monotonically with the electric field criterion. A good agreement was obtained for B_i between experiments and the theoretical analysis using the flux creep-flow model. This implies that the resistive property of superconducting wires can be well described by the mechanism of flux creep

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and flow. The vortex glass-liquid transition field (B_g) was also determined from E-J curves which measured in the low and high electric field regions. It was found that B_g also depends on the ranges of electric field. This is incompatible with the prediction of the vortex glass-liquid transition theory.

Keywords: Irreversibility field, electric field criterion, flux creep-flow model.

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1 Introduction

The irreversibility field (B_i) is an important parameter showing an upper limit of magnetic field for applications of superconductors. Various measuring methods have been used for the measurement of B_i. However, the obtained values are different for different measuring methods. That is, B_i is strongly influenced by both the electric field criterion (E_c) for the determination of the critical current density (J_c) and the criterion of J_c (ΔJ_c). Hence, it is needed to describe B_i as a function of E_c and ΔJ_c.

In this study, we observed B_i in a Bi-2223 silver-sheathed tape wire by various measuring methods:

– imaginary AC susceptibility,

– current-voltage characteristic using a four probe method,

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– DC magnetization hysteresis,

– current-voltage characteristic estimated from the relaxation of magnetization,

and investigated the relationship between B_{i} and E_{c} under a fixed value of ΔJ_{c}. The measured irreversibility field was compared with the vortex glass-liquid transition field (B_{g}) obtained from the scaling of E-J curves. The experimental result was also compared with the theoretical analysis using the flux creep-flow model.

2 Experimental

The measured specimen was a Bi-2223 silver-sheathed tape wire prepared by the powder-in-tube method. The sizes of specimen were 3.7 mm wide and 270 μm thick. The tape was cut in a length of $l = 4.2$ mm for the magnetic measurements. The number of filaments (f) was 59 and the averaged width (w) and thickness (d) of the filaments were 320 μm and 11 μm, respectively. T_{c} determined from a DC susceptibility measurement was 110 K. In all the measurements the magnetic field was applied parallel to the c-axis.

(1)In the AC susceptibility measurement the AC magnetic field was applied parallel to the c-axis at various temperatures. The frequency and the amplitude of AC magnetic field were 35.0 Hz and 0.1 mT, respectively. The irreversibility temperature (T_{i}) was determined by the temperature at which an imaginary AC susceptibility appeared. $B_{\rm i}$ was determined from the magnetic field dependence of $T_{\rm i}$.

(2)In the current-voltage characteristics measurement using a four probe method, $J_{\rm c}$ was determined with the electric field criterion, $E_{\rm c} = 10^{-4},\ 10^{-3}$ and 10^{-2} V/m, and $\Delta J_{\rm c} = 1.0 \times 10^7$ A/m^2 was used for the determination of $B_{\rm i}$.

(3)In the DC magnetization measurement a SQUID magnetometer was used. $J_{\rm c}$ was determined by

$$J_{\rm c} = \frac{6\Delta m}{w^2 df(3l - w)}, \tag{1}$$

where, Δm was the hysteresis width of the magnetic moment. For the determination of $B_{\rm i}$, $\Delta J_{\rm c} = 1.0 \times 10^7$ A/m^2 was used. From the comparison of the magnetic moment with the measurement (4), it was found the DC magnetization measurement was carried out around the electric field of $E \simeq 1 \times 10^{-9}$ V/m.

(4)In the magnetic relaxation measurement, the electric field(E) and the current density(J) were respectively estimated by

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

$$E = -\frac{\mu_0}{2df(l + w)} \cdot \frac{{\rm d}m}{{\rm d}t}. \tag{3}$$

Then, $J_{\rm c}$ was determined with $E_{\rm c} = 10^{-12},\ 10^{-11}$ and 10^{-10} V/m. $\Delta J_{\rm c} = 1.0 \times 10^7$ A/m^2 was used for the determination of $B_{\rm i}$.

The scaling of E-J curves was examined for the results obtained in the measurements (2) and (3) and the vortex glass-liquid transition field (B_g) was determined.

3 Flux Creep-Flow Model

The observed results are compared with the theoretical analysis using the flux creep-flow model. According to this model, E-J characteristics can be calculated in terms of the pinning potential:

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

where J_{c0} is the virtual critical current density without flux creep and g^2 is number of the flux lines in the flux bundle. The magnetic field and temperature dependencies of J_{c0} at low field are assumed as

$$J_{c0} = A \left[1 - \left(\frac{T}{T_c} \right)^2 \right]^m B^{\gamma - 1}, \tag{5}$$

where A, m and γ are pinning parameters. The distribution of J_{c0} is approximated by that of A given by

$$f(A) = K \exp \left[- \frac{(\log A - \log A_m)^2}{2\sigma^2} \right], \tag{6}$$

where A_m is the most probable value of A, 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 on a maximum value [1], and is given by

$$g^2 = g_{\mathrm{e}}^2 \left[\frac{5k_{\mathrm{B}}T}{2U_{\mathrm{e}}} \ln \left(\frac{Ba_{\mathrm{f}}\nu_0}{E} \right) \right]^{4/3}, \tag{7}$$

where g_{e} is the value of g when flux lines form a perfect triangular lattice, U_{e} is the value of U_0 when $g = g_{\mathrm{e}}$, a_{f} is the flux line spacing, and ν_0 is the oscillation frequency of flux bundle. Further details of the calculation of the E-J characteristics are described in [2].

The parameters A_{m}, m, and γ are assumed to be constant in the whole ranges of temperature and magnetic field in the measurement and are listed in Table 1. On the other hand, σ^2 is used as a fitting parameter at each temperature.

4 Results and Discussion

An example of the estimated E-J characteristics using Eqs. (2) and (3) 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. Fig. 2. shows B_{i} determined with various measurements in which different electric field criteria are used and B_{g} estimated from the current-voltage characteristics in the low and high electric field regions. It is seen that the value of B_{i} is completely different from measurements and that B_{g} also depends on the range of electric field. The B_{i}'s are generally higher than $B_{\rm g}$'s.

Fig. 3. shows $E_{\rm c}$ dependence of $B_{\rm i}$ at $T = 70$ K under the condition of $\Delta J_{\rm c} = 1.0 \times 10^7$ A/m^2. It is found that $B_{\rm i}$ depends largely and systematically on the electric field criterion for the definition of $J_{\rm c}$. $B_{\rm i}$ is different almost by one order of magnitude between the usual resistive and magnetic measurements between which the electric field criterion is different by several orders of magnitude. In the figure $B_{\rm g}$ is also shown for comparison. It is found that $B_{\rm g}$ also depends on the range of electric field similarly to $B_{\rm i}$. This is consistent with the previous measurement on a Y-123 thin film [3] and incompatible with the prediction of the vortex glass-liquid transition theory.

In the AC susceptibility measurement, the conditions of the determination of $B_{\rm i}$ are about $E_{\rm c} = 3.5 \times 10^{-6}$ V/m and $\Delta J_{\rm c} = 1.0 \times 10^5$ A/m^2. Hence, the value of $B_{\rm i}$ is strongly influenced by the choice of these conditions. If we express the relationship between E and J as $E \propto J^n$, we have $n = 2.82$ in the vicinity of the irreversibility field. Hence, a similar relationship $E_{\rm c} \propto \Delta J_{\rm c}^n$ holds, and if the same condition of $\Delta J_{\rm c} = 1.0 \times 10^7$ A/m^2 is chosen, the corresponding value of $E_{\rm c}$ is estimated as $E_{\rm c} = 1.0 \times 10^{-2}$ V/m. Thus, if $B_{\rm i}$ could be obtained in the same conditions as in other measurements, $B_{\rm i}$ from the AC susceptibility measurement would be located as shown by the solid triangle in Fig. 3. Therefore, all the measurements seem to systematically change with the electric field criterion.

The E-J characteristics are theoretically analysed using the flux creep-flow model in a wide range of electric field. The theoretically analysed results in the low electric field region are compared with the experimental results from the magnetic measurement in Fig. 1. The theoretical results explains fairly well the experimental result except in the low current density region. From the calculated results B_i can be estimated with the same E_c and ΔJ_c as in experiments.

The temperature dependence of B_i, i.e. the irreversibility line is compared between the experiment and the theory in Fig. 4. The theoretical prediction of the E_c-dependence of B_i is shown in Fig. 3. It is seen that the flux creep-flow model can describe B_i in a wide range of the electric field.

5 Summary

The electric field criterion dependence of the irreversibility field was measured for a Bi-2223 silver-sheathed tape wire and the following results were obtained:

(1)B_i depends largely on the electric field criterion and this behavior can be well described by the flux creep-flow model in a wide range of the electric field.

(2)The vortex glass-liquid transition field depends also on the range of electric field. This is incompatible with the prediction of the vortex glass-liquid transition theory.

References

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Table 1

Parameters used in the numerical calculation.

A_{m}	m	γ
9.0×10^8	2.0	0.51

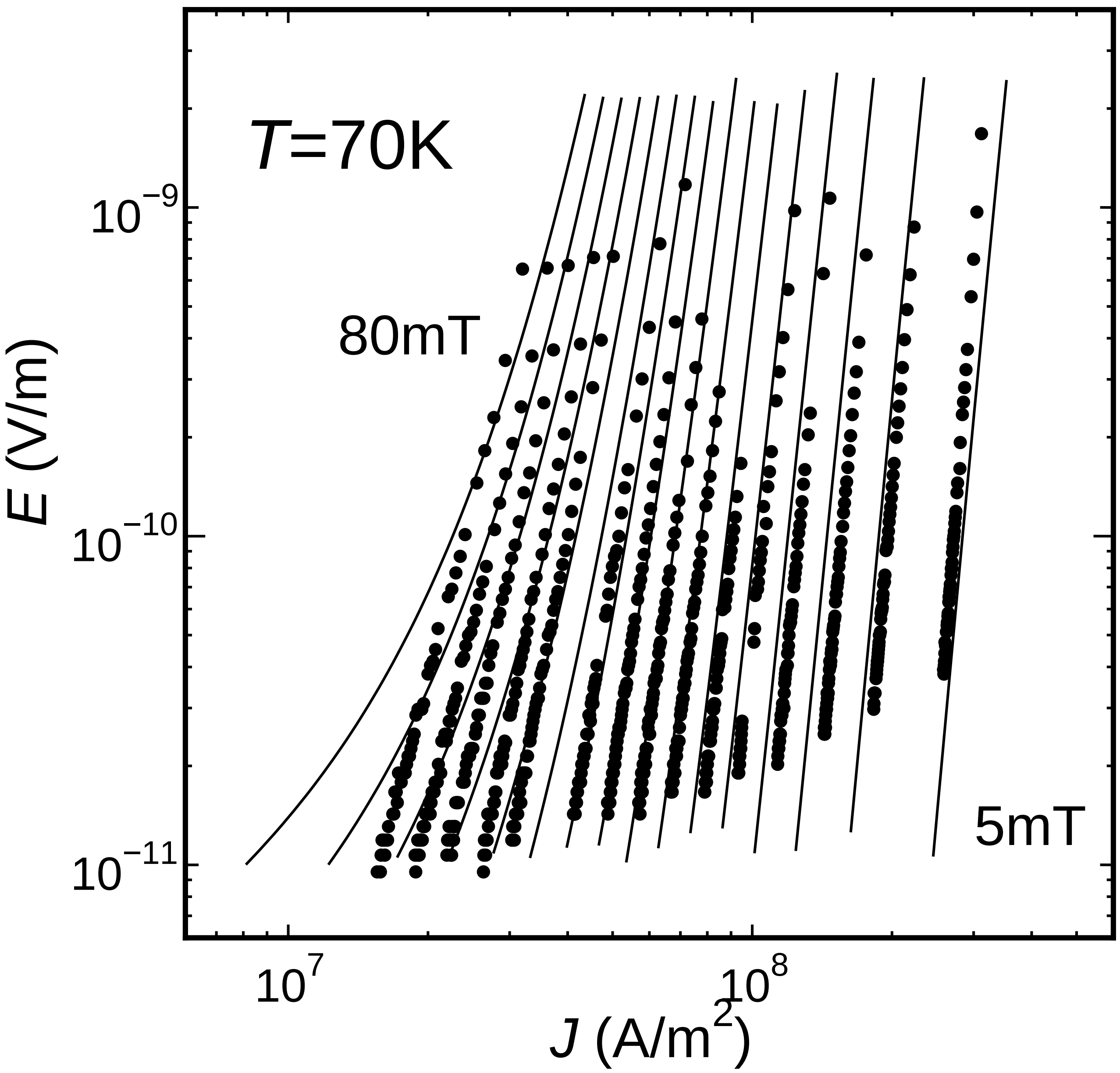

Figure 1: M. Fukuda *et al.*

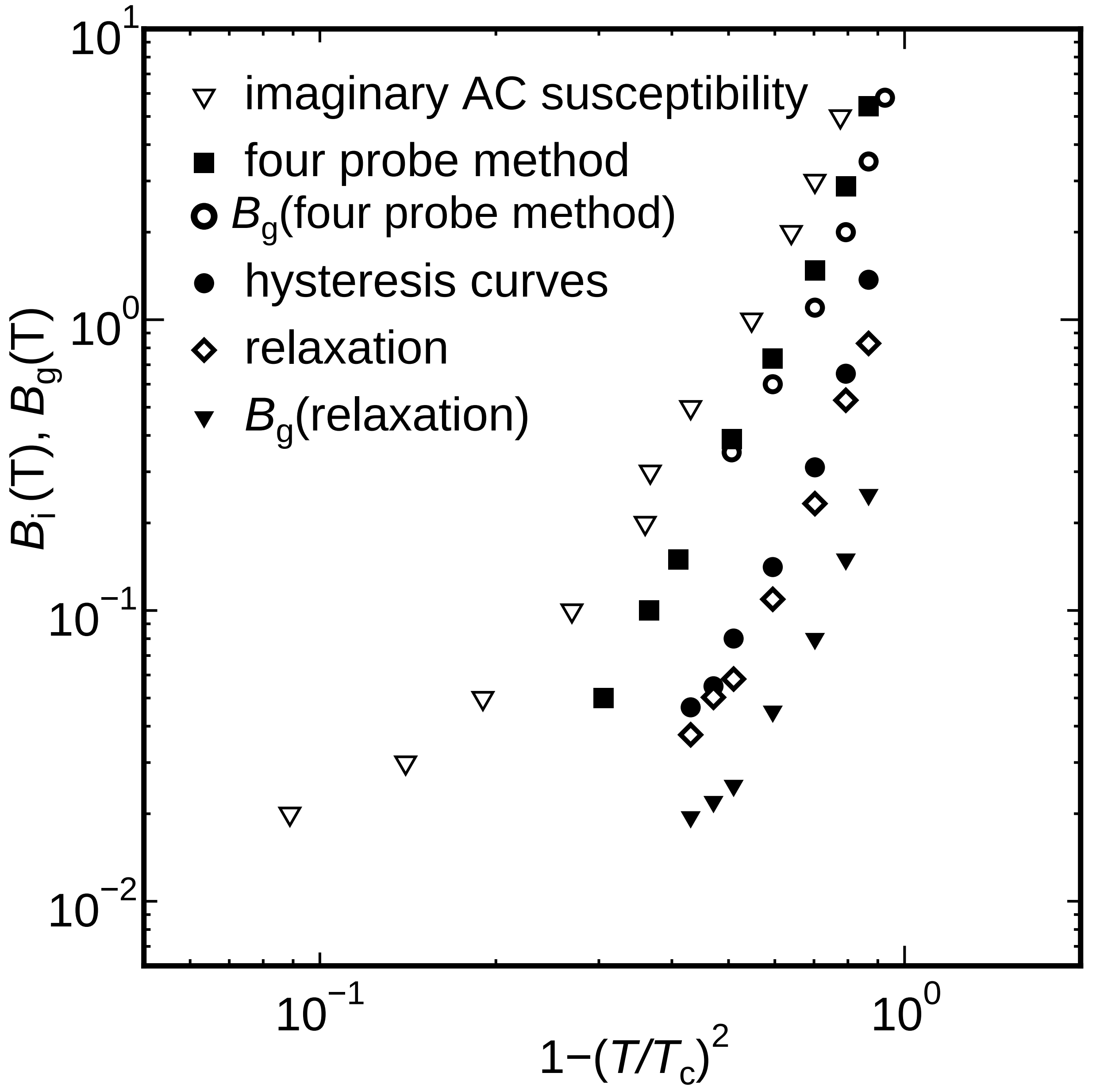

Figure 2: M. Fukuda *et al.*

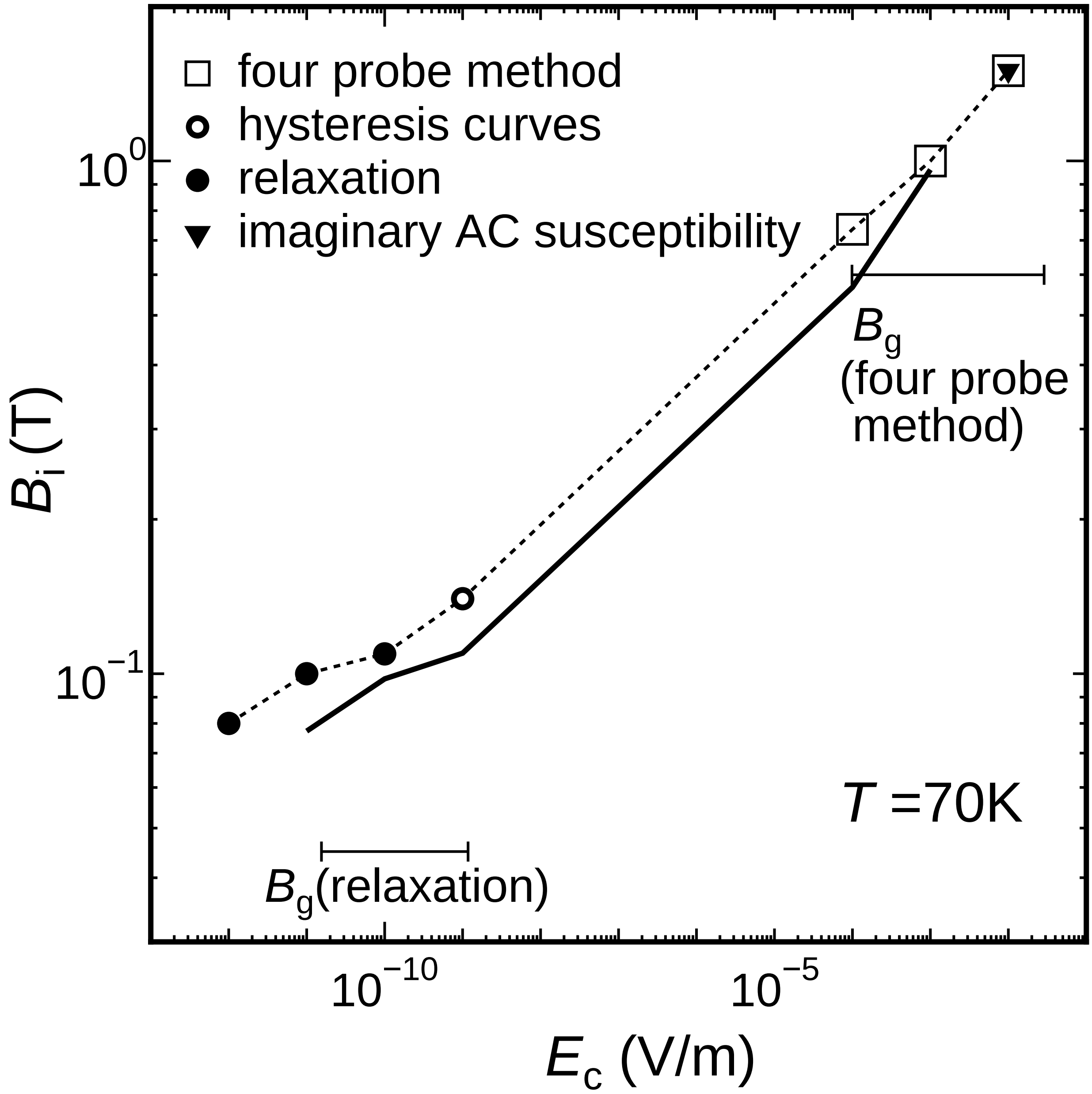

Figure 3: M. Fukuda *et al.*

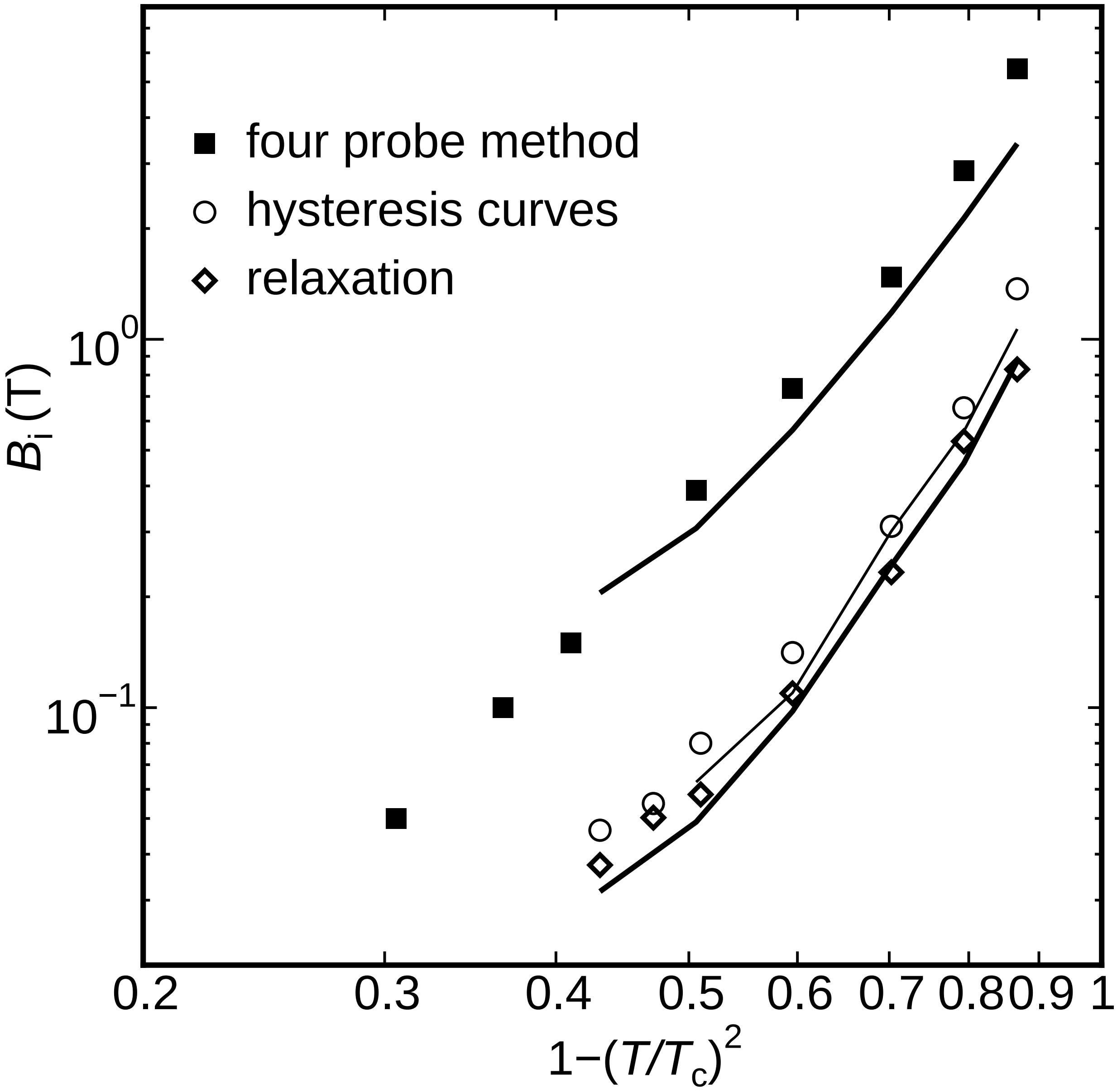

Figure 4: M. Fukuda *et al.*

Figure caption

Fig. 1. Observed E-J characteristics at $T = 70$ K from the magnetic relaxation measurement(symbols) compared with theoretical analysis(solid lines).

Fig. 2. Irreversibility field of Bi-2223 silver-sheathed tape wire determined with different electric field criterion and transition field.

Fig. 3. Dependence of irreversibility field on electric field criterion at $T = 70$ K.

Fig. 4. Theoretically analysed B_{i}(solid lines) compared with experimental results(symbols).