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Inhomogeneous transport properties in Ag/Bi2223 tapes

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Abstract

In order to elucidate the influence of weak link on the $E–J$ characteristics in the silver sheathed Bi2223 tape, the weak link path model has been applied by using three different stochastic regimes. In general, the growth of non-SC chains proceeds at the low current density region and at the high current density region, the coagulation among non-SC chains takes place and the fast growth rate of percolation network is realized. Comparing three cases, the generating rate of the percolation path becomes lowest for the Markov process. When the correlation becomes stronger, the initial rate of generation of percolated columns becomes faster. The theoretical $E–J$ curves can reproduce the experimental results qualitatively. It is clear that the power-law relationship, $E \propto J^n$, does not hold over the whole range of current. The n value becomes smaller in sequence when the I_c decreases for three cases.

Keywords: Transport properties; Ag/Bi2223 tapes; Markov process

1. Introduction

Several types of crystal imperfections limit transport supercurrent in a specimen. Depending on different fabrication technique, the most prevalent imperfection changes. For the silver-sheathed Bi2223 tapes with critical current density (J_c) larger than 10 kA/cm^2 at 77 K at zero field, J_c is suggested to be limited by weak links at homophase grain boundaries. There is experimental evidence for the dependence of J_c on the volume fraction of Bi2223 phase, the amount of residual carbon and the direction of the applied magnetic field [1]. These results can be explained in terms of the texture of fine plate-like Bi2223 grains and the existence of minor non-SC phases.

In order to elucidate the influence of weak link at grain boundary to the $E–J$ characteristics in the silver sheathed Bi2223 tape, the second differential of the $E–J$ curve has been analyzed using the Weibull distribution function [2]. The four parameters of this function are examined to investigate the microstructural nature of the sample. Further, computer simulation has been carried out based on a new weak link path model consisting of superconducting (SC) and non-SC grains–weak links random network [3]. In the present study, the influence of the distribution of weak links to the $E–J$ characteristics has been precisely investigated and compared with the experimental data.

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2. Experimental

Tape samples of Ag-sheathed Bi2223 have been prepared by using the conventional powder in tube technique. The texture created by this process tends to align the *c*-axis of the Bi2223 plate-like grains perpendicular to the broad face of the tape. The detail of the fabrication process has been described elsewhere [4]. E–J characteristics were recorded by a standard four-point technique. Measurements were made at 77 K in low d.c. magnetic fields up to 0.7 T. Experimental data of J_c with the criterion of 1 μV/cm were analyzed by using Weibull distribution function. The computer simulation has been carried out in the manner of statistical physics.

3. Experimental results and discussion

3.1. E–J characteristics

Fig. 1 shows a log–log plot of the E–J characteristics. Here, the horizontal axis is indicated by the current I. The current density is given by $J = I/S$ where the cross-section S of the oxide layer was 0.078 mm^2. For low magnetic fields, the lines show a downward curvature as the current decreases. This curvature implies a finite critical current. As the field increases, the critical current decreases to zero and the curves become linear, corresponding to the conventional power-law relationship, $E \propto J^n$. Experimentally, the n value has been determined from the

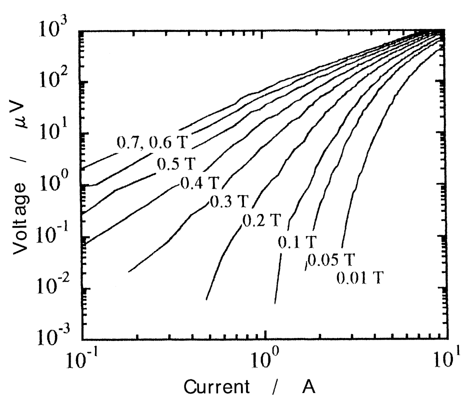

Fig. 1. A log–log plot of the $E-J$ characteristics of Ag/Bi2223 tape as a function of applied magnetic field, where the magnetic filed is perpendicular to the tape surface [2].

E–J curve in the region between 0.1 and 1 μV, where the length between voltage taps was 1 cm. The n value decreased from 16.2 to 5.2 while the magnetic field changed from 0 to 0.7 T. The further detailed analysis of the E–J curves has been reported elsewhere [2].

3.2. Weak link path model

The J_c of the silver-sheathed Bi2223 tapes is suggested to be limited by weak links at homophase grain boundaries. When a current is applied, the supercurrent crosses grain boundaries, and branches into several neighboring grains. Supercurrent prefers to flow within *ab* planes, but not easy to pass through the charge reservoir layer along the *c* axis of the crystal lattice. The current flow gives two-dimensional behavior, and the homophase grain boundaries act as weak links. At a grain boundary, weak link breaks from SC to non-SC state, when current density and/or magnetic field applied here are appreciably high. An electric field is generated locally when all weak links break at a whole cross-section of the column perpendicular to the current flow axis.

In order to simplify the discussion, a single grain is treated as an element in the system and a large number of grains are linked by grain boundaries. Each element has Z coordination number with neighboring grains. Here Z is 4. The system consists of M elements in the column and N ones in the row. The procedure of stochastic calculation is given as follows.

The major elements are assumed to be V% in the SC state, and $(100 - V)$% in non-SC state. All elements are connected by weak links. At the first step of calculation, V is fixed to be constant. When the external current increases, some weak links break by P% to non-SC state, where the current density crossing their weak links exceeds a local critical current density $J_{c,w}$. The broken links are selected as to distribute randomly in the system. Supercurrents cross preferentially the SC links. When a fairly large number of weak links break, all links included in a column are in the non-SC state. Thus, the percolation has completed as the supercurrent is disturbed. When the current crosses this percolated column occupied by non-SC links, an electrical field is generated. When the P% of total weak links break, then the

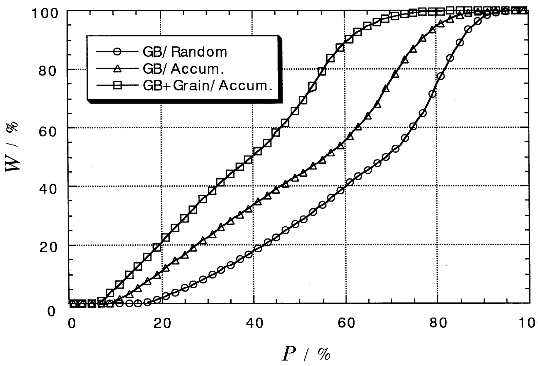

Fig. 2. Change of the degree of percolated columns (W) as a function of the probability of broken links (P) for three cases mentioned in the text.

corresponding W% of total columns are in the non-SC state. In order to consider the effects of grain size, connectivity among grains and so on, a parameter C is introduced, by which the minimum size of elements for keeping SC state is maintained.

Assuming the Weibull distribution for the strength of weak links, the probability P by which weak links break, is expressed as a function of current density crossing the respective weak link;

$$P = k\left(J - J_{c,w}^{min}\right)^{m}, \tag{1}$$

where m is the shape factor. When putting $J_{c,w}^{min} = 0$ for simplicity, then the current density is expressed as

$$J = (P/k)^{1/m}. \tag{2}$$

where k is the constant.

In the present paper, the following three cases are considered.

1. The first case is designated as GB/random. When the current increases, some grain boundary weak links break by P% to non-SC state. Their non-SC links are selected randomly each time from all links. This gives the so-called Markov process in the statistical thermodynamics.
2. GB/accumulation case: When the SC state increases from P% to P + ΔP%, the non-SC links corresponding to ΔP% are chosen from the remaining (100 − P)% SC links. This means that the non-SC link, once achieved, never returns to the SC state.
3. GB + Grain/accumulation case: In addition to case (2), the grains break by αP% to non-SC state simultaneously, when the current increases. Here, α is placed as 0.1.

Fig. 2 shows the P vs. W relation, where $M = 400$, $N = 1000$, $C = 2$ and the three conditions mentioned above. The degree W of percolated columns starts to increase when P becomes larger than about 10%. That means the generation of an electric field. When W becomes 100%, almost all the weak links are in the non-SC state.

As shown in Fig. 2, the degree W of percolated columns increases with increasing P. In order to treat this statistical distribution, the Weibull function $f(J_{c,w})$ is introduced. The original Weibull distribution is defined as the cumulative distribution giving the weakest links in the one-dimensional mechanical chain [5]. In the present paper, the Weibull function is applied to the similar percolated columns as given by the equation,

$$W(J) = \int_0^{\infty} f(J_{c,w})\,\mathrm{d}J_{c,w}. \tag{3}$$

The Weibull function $f(J_{c,w})$ can be obtained from the first derivative of Eq. (3) as shown in Fig. 3, where the horizontal axis indicates the current by Eq. (2). The function is apparently found to comprise two parts. One appears at the lower current density region with rather broad distribution. Another is a sharp function appearing at the higher current density region. Their characteristics can be seen in Fig. 2 as the linear part with increasing P and the

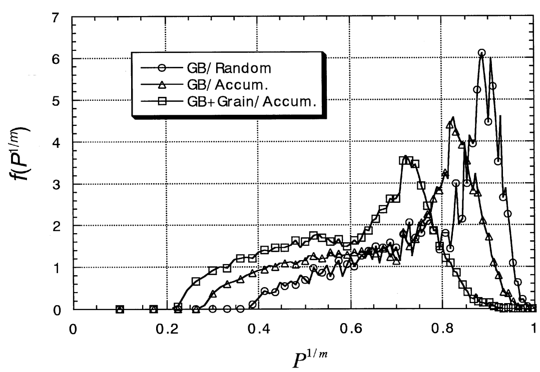

Fig. 3. Change of Weibull distribution function as a function of the current $(P^{1/m})$ for three cases mentioned in the text.

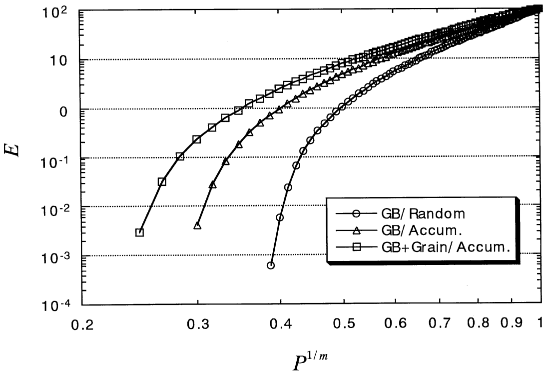

Fig. 4. Change of electric field as a function of current ($P^{1/m}$) for three cases based on the weak link path model.

accelerated and saturated one. Looking at the steps during computer simulation, the growth of non-SC chains is observed at the lower current density region. At the high current density region, the coagulation among non-SC chains takes place and the fast growth rate of percolation network is realized.

The electric field appearing in the terminals of the sample is proportional to the integration of $W(J)$ with respect to J, the electric field is given by the equation,

$$E = R_{\mathrm{f}} \int_0^{\infty} W(J)\,\mathrm{d}J. \tag{4}$$

where R_{f} is the resistivity per non-SC link. Thus, it is possible to estimate the E–J relationship theoretically. Fig. 4 shows the change of electric field (arbitrary unit) as a function of current for three cases mentioned just above as shown in Figs. 2 and 3. The present E–J curves can reproduce qualitatively the experimental results shown in Fig. 1. It is clear that the power-law relationship, $E \propto J^n$, does not hold over the whole range of current.

In practice, the critical current due to the SC to non-SC transition is determined by using an empirical criterion. According to International Standard IEC61788-1, two values of I_c are determined at criteria of 10 and 100 μV/m. Their electric fields are as small as they can be measured experimentally. The electric field of Fig. 4, on the other hand, is expressed in arbitrary unit. It is natural that the onset of electric field with increasing J corresponds to the range for the electric field criteria. When the power law is applied partially in the onset region of E between 10^{-1} and 10^{-2}, the n value becomes smaller in sequence when the I_c decreases for three cases. The reason for the small n value is recognized from the distribution function shown in Fig. 3. Comparing two cases of GB/Random and GB/Accum., the generating rate of percolation path becomes lowest for the Markov process. When the correlation becomes stronger, the initial rate of generation of percolated columns becomes faster.

4. Summary

In the present weak link path model, three cases due to different stochastic regime have been examined to study the E–J characteristics of Ag-sheathed Bi2223 tapes. In general, the growth of non-SC chains proceeds at the lower current density region. At the high current density region, the coagulation among non-SC chains takes place and the fast growth rate of the percolation network is realized. Comparing three cases, the generating rate of percolation path becomes lowest for the Markov process. When the correlation becomes stronger, the initial rate of generation of percolated columns becomes faster. The theoretical E–J curves can reproduce qualitatively the experimental results. It is clear that the power-law relationship, $E \propto J^n$, does not hold over the whole range of current. The n value becomes smaller in sequence when I_c decreases for three cases.

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