The Chittagong Univ. J. Sci. 43(1): 21-30, 2021

The Evaluation of E-J (Electric Field-Current Density) Characteristics in Single Crystal Nd-123 Superconductors at Different Temperatures

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Manuscript Submitted on 19/08/2020, Revised manuscript received on 10/01/2021, and accepted on 17/01/2021.

Abstract

The electric field- current density (E-J) characteristics of a Nd-123 single crystal superconductor at different temperatures were estimated from a relaxation of magnetization. For the investigation of flux pinning characteristics of this superconductor, the E-J characteristics were analyzed and compared with theoretical calculations using flux creep-flow model. The pinning parameters such as A_m, g^2, σ^2, m, γ, δ are determined so that a good fit is obtained between the experimental and the theoretical results.

Keywords: *Single Crystal Nd-123 Superconductors, Flux Creep-Flow Model, Magnetic Relaxation Measurements, Pinning Parameters, Flux Pinning Behavior.*

DOI: https://doi.org/10.3329/cujs.v43i1.57331

Nd-123 একক স্ফটিক অতিপরিবাহীর (E-J) তড়িৎক্ষেত্র-প্রবাহ ঘনত্ব বৈশিষ্ট্য বিভিন্ন তাপমাত্রায় চুম্বকন শিথিলকরণ হতে গণনা করা হয়েছে। Nd-123 অতিপরিবাহীর ফ্লাক্স বাঁধা বৈশিষ্ট্য অনুসন্ধানের জন্য তড়িৎক্ষেত্র - প্রবাহ ঘনত্ব বৈশিষ্ট্য বিশ্লেষণ করা হয়েছে এবং ফ্লাক্স হামাগুড়ি - প্রবাহ মডেল ব্যবহার করে তত্ত্বীয় গণনার সাথে তুলনা করা হয়েছে। বাঁধা প্যারামিটার গুলো যেমন - A_m, g^2, σ^2, m, γ, δ এমনভাবে নির্ণয় করা হয়েছে যাতে পরীক্ষামূলক ও তত্ত্বীয় ফলাফল ভালোভাবে মানানসই হয়।

1. Introduction

It is well known that the range of electric field at which the oxide superconductor is used in equipment is considered to be quite different depending on the kind of application. That is, the electric field which is applied to the superconductor is fairly high for AC equipment like a transformer, but is very low for DC ones like an NMR magnet. Thus it is necessary to clarify the E-J characteristics of the superconductor in a wide range of electric fields. Such measurements can be realized by the combination of a resistive method and various magnetic measuring methods [1-3].

For engineering applications, it is common to employ some electric field criterion (typically 10^{-9}) for the determination of J_c value which is used for the design of the superconducting magnetic system. In both high and low T_c materials, it is known that current density J decays logarithmically with time if the pinning force is sufficiently high. In this case, since time decay is logarithmic, one can easily set a practical J_c value with taking account of the safety margin for engineering applications. Persistent super currents in high-temperature superconducting materials decay in time. The time decay of super current or dissipation (due to transport current) is thought to be originated by the thermally activated motion of magnetic flux inside the superconductor.

Theoretical idea of this phenomenon was first described by Anderson and Kim, introducing the concept of thermal activation. This process leads to a redistribution of flux lines or vortices (both flux and circulating current) and hence current loops associated with the magnetic moment which decay in time (so-called magnetic relaxation).

From an applied point of view, the importance of magnetic relaxation lies in the fact that it modifies the current-voltage characteristics of high-temperature superconductors, determines the temperature and time dependence of the current density and dictates limits to the stability of high temperature superconductor devices such as persistent-mode magnets used in levitation or in magnetic resonance (MRI). These properties are central to the successful commercialization of high-temperature superconductor technology.

However, to understand flux pinning behavior in Nd-123 single crystal superconductor, it is necessary to explain E-J characteristics. In this paper, the relations between experimental and theoretical results were investigated from E-J characteristics to find out the pinning characteristics in a single crystal Nd-123 superconductor. For this purpose, the flux-creep flow model was used and the behavior of the pinning parameters was discussed on the pinning characteristics.

2. Experimental Method

Specimen was a flux-grown $NdBa_2Cu_2O_y$ single crystal superconductor. The details of sample preparation conditions were described in reference [4]. The sample dimension was $1.60\times1.45\times0.65$ mm^3.

Magnetic relaxation was measured by monitoring the time decay of DC magnetization [5]. A large negative magnetic field (-7 T) was applied to ensure full flux penetration before starting a measurement. The magnetic field was applied for *H*//*c*. The field was set in no overshoot mode and in persistent current mode. Magnetization measurements were performed immediately after reaching the target field. The scan length was 3 cm. Data were not averaged.

2.1. Theoretical Method-The flux creep-flow model

The E-J characteristics were evaluated theoretically using the flux creep –flow model [6]. The pinning potential is an important quantity to determine the characteristics and is given by

$$U_0 = \frac{0.835 g^2 k_{\mathrm{B}} J_{\mathrm{c0}}^{1/2}}{\zeta^{3/2} B^{1/4}}. \tag{1}$$

Where J_{c0} is the virtual critical current density in the creep free case.

Here the temperature and magnetic field dependences of the virtual critical current density, J_{c0}, is expressed as

$$J_{\mathrm{c0}} = A\left[1-\left(\frac{T}{T_{\mathrm{c}}}\right)^2\right]^m B^{\gamma-1}\left(1-\frac{B}{B_{\mathrm{c2}}}\right)^{\delta}, \tag{2}$$

Where A, m, γ and δ are pinning parameters. Eq. (2) is usually used in conventional metal superconductor and known as scaling law of the critical current density.

For calculation of E-J characteristics, current density is not always smaller than J_{c0}, electric field E_{ff} is induced by flux flow, and is given by

$$E_{ff} = 0; \qquad j \le 1$$
$$= \rho_f (J - J_{c0}); \qquad j>1 \tag{3}$$

where ρ_f is related with normal resistivity and is given by

$$\rho_f = \frac{B}{B_{c2}} \rho_n \tag{4}$$

ρ_n is approximately given by

$$\rho_n(T) = \frac{T}{T_c} \rho_n(T_c) \tag{5}$$

On the other hand, electric field by flux creep, E_{cr}, is considered to remain and assumed as [12, 13]

$$E_{cr} = Ba_f \nu_0 \exp\left[-\frac{U(j)}{k_B T}\right]\left[1 - \exp(-\frac{\pi U_0 j}{k_B T})\right]; \qquad j \le 1,$$
$$= Ba_f \nu_0 \left[1 - \exp(-\frac{\pi U_0}{k_B T})\right]; \qquad j > 1, \tag{6}$$

Then, the total electric field, E, is obtained from E_{cr} and E_{ff} and is approximately given by

$$E = (E_{cr} + E_{ff})^{1/2}. \tag{7}$$

In the above expression, E is approached to E_{cr} at $j<1$ and to E_{ff} at $j>>1$.

In an usual oxide superconductor, pinning force density is known to be largely distributed. Here only parameter A in Eq. (2) is assumed to have the following distribution:

$$f(A) = K \exp\left[-\frac{(\log A - \log A_m)^2}{2\sigma^2}\right], \tag{8}$$

Where A_m is the most probable value, K is a constant determined by the condition of normalization and σ^2 is a constant representing the degree of distribution width of pinning force density. Therefore, total electric field is given by

$$E(J) = \int_0^\infty Ef(A)dA. \tag{9}$$

The details of the theoretical analysis were described elsewhere [6].

3. Results and discussion

In Fig. 1, the magnetic relaxation in a magnetic field at different temperatures i. e. 40 K, 60 K, 70 K and 88 K are shown.

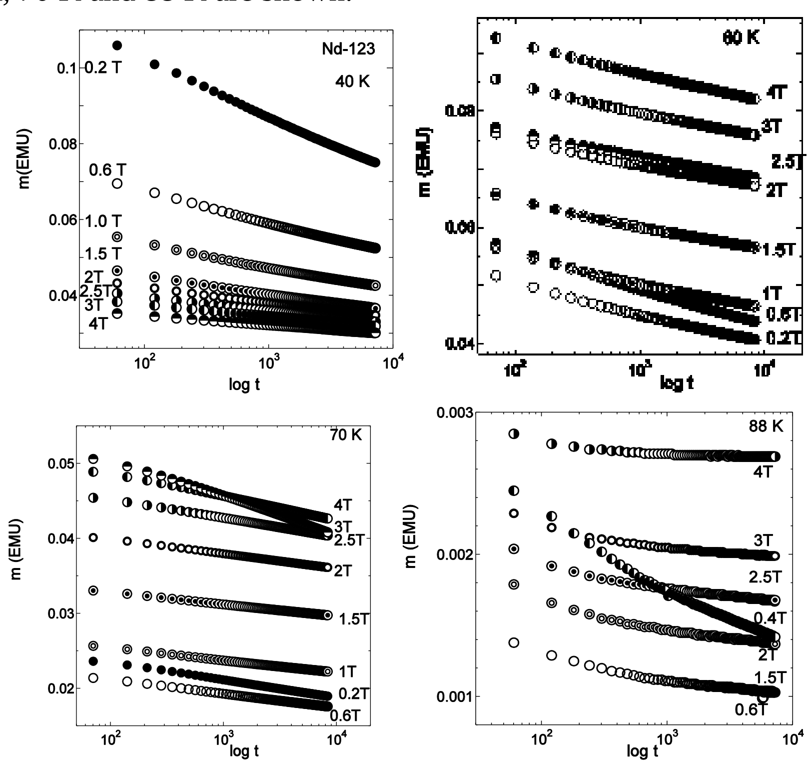

Figure 1: Magnetic relaxation measurement in a magnetic field attemperature of 40 K, 60 K, 70 K and 88 K.

Fig. 1 describes time dependence of the magnetization due to the thermally activated flux creep obeys the well known logarithmic relaxation with time t. It also speculates the magnetic moments decrease linearly with logt and the decay rate enhances with increasing magnetic field.

From the relaxation measurement, it is estimated E-J characteristics by using the following formulas:

$$J = \frac{12m}{w^2 d(3l - w)}, \tag{10}$$

$$E = -\frac{\mu_0}{2d(l + w)} \cdot \frac{\mathrm{d}m}{\mathrm{d}t}, \tag{11}$$

Where m is the magnetization, l is the length, w is the width and d is the thickness of the specimen, E is the electric field and J is the current density.

The E-J characteristics are calculated from the relaxation of magnetization over an range of electric field from10^{-12} to 10^{-8} V/m at 40 K, 60 K, 70 K and 88 K temperatures, which are shown in Fig. 2.

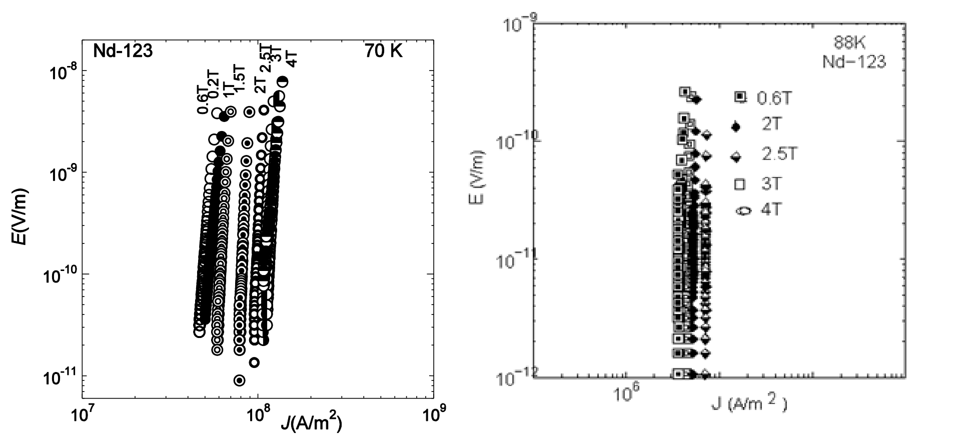

Figure 2: E-J characteristics for Nd-123 at 40 K, 60 K, 70 K and 88 K.

The above E-J characteristics are compared with a theoretical analysis using the flux creep-flow model [6]. In the theoretical analysis of E-J characteristics using the flux creep-flow model, the pinning parameters m, γ, σ^2, ζ, g^2 and A_m are determined so that a good fit is obtained between the experimental and theoretical results.

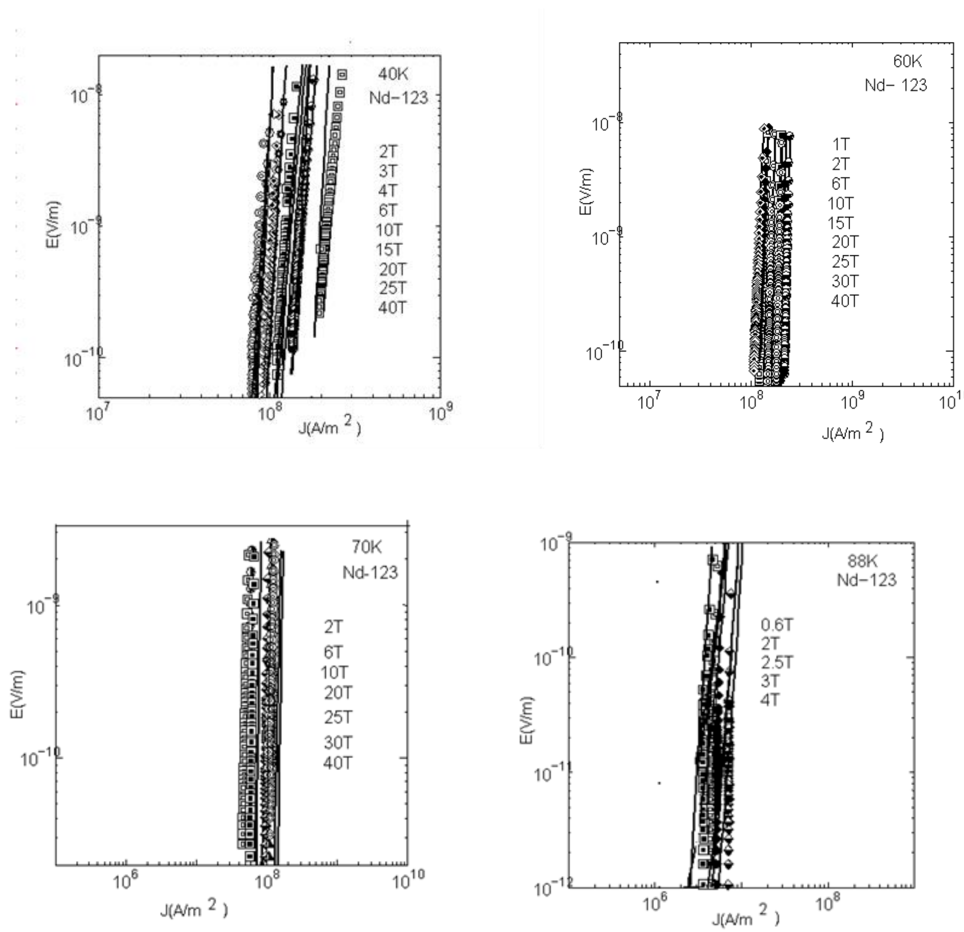

Figure 3: Theoretical fitting of E-J characteristics with experimental results at 40 K, 60 K, 70 K and 88 K for Nd-123 superconductors.

The parameters used in the theoretical calculation are given in table 1.

Table 1: Pinning parameters used for theoretical calculations.

Temperature(K)	**Field, B(Tesla)**	$\mathbf{g^2}$	$\mathbf{A_m}$	$\boldsymbol{\sigma^2}$	**Γ**	**m**	**Δ**
Low Temperature (40 K)	0.2	1.16	9.73×10^8	0.01	0.87	2.05	2.0
	0.6	1.58	9.73×10^8	0.01	0.87	2.05	2.0
	1.5	2.53	9.73×10^8	0.01	0.87	2.05	2.0
	2.0	3.01	9.73×10^8	0.01	0.87	2.05	2.0
	3.0	6.03	9.73×10^8	0.01	0.87	2.05	2.0
	4.0	8.56	9.73×10^8	0.01	0.87	2.05	2.0
High Temperature (60 K, 70 K and 88 K)	0.2	4.18	1.03×10^9	0.001	0.85	2.05	2.0
	0.6	6.03	1.03×10^9	0.001	0.85	2.05	2.0
	1.5	7.12	1.71×10^9	0.006	0.85	2.05	2.0
	2.0	7.05	1.94×10^9	0.001	0.85	2.05	2.0
	2.5	7.95	1.82×10^9	0.001	0.85	2.05	2.0
	3.0	9.25	1.71×10^9	0.001	0.85	2.05	2.0

In the following, we have discussed the behavior of the pinning parameter such as A_m, g^2, σ^2, m, γ, δ which are determined so that a good fit is obtained between the experimental and the theoretical results. In, general, g^2 (the number of flux lines in the flux bundle) is expected to be determined so that the maximum critical current density, J_c, is obtained under the flux creep [7]. From the table, it was found that g^2 increased with increasing magnetic field. At high temperature it was rather large in comparison with low temperature.
The most probable value, A_m, is used for the flux pinning strength. It was found from the table that the value of A_m was lower at low temperature in comparison with high temperature. The relationship between g^2 and A_m is satisfied.

The value of the distribution width, σ^2 associated with the parameter of the most probable value A_m. Hence, the value of σ^2 is 0.01 at low temperature, which is small in comparison with the value at high temperature (i. e. 0.001). Other parameters m, γ, δ are almost the same for all temperatures.

It was found that the agreement between the experimental and the theoretical results was fairly good.

4. Conclusion

E-J characteristics were estimated for a Nd-123 single crystal superconductor from the magnetic relaxation measurements and compared with theoretical results based on the flux creep-flow model. The pinning parameters such as A_m, g^2, σ^2, m, γ, δ were determined so that a good fit was obtained between the experimental and theoretical results. From the discussion of the pinning parameters, it can be concluded that the theoretical results explained experimental results well.

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