Flux Pinning Property in Y-123 Single Crystal

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ABSTRACT

The longitudinal and transverse flux bundle sizes are estimated for a three-dimensional single crystal Y-123 superconductor under a magnetic field along the c-axis and the result is compared with previous results of Bi-2212 and Bi-2223. It is considered that the longitudinal flux bundle size is determined only by the flux pinning strength independently of the dimensionality of superconductor. The number of flux lines in the flux bundle, g^2, which is related to the transverse flux bundle size, is estimated to be larger than 8. This number is much larger than those in Bi-2212 and Bi-2223.

KEYWORD: Flux bundle size, dimensionality of superconductor, single crystal Y-123

INTRODUCTION

The pinning potential, U_0, is an important parameter which determines the irreversible property and is theoretically given by a product of the pinning energy per unit volume of flux lines and the volume of flux bundle. The small pinning potential in the two-dimensional Bi-2212 superconductor is attributed to the weak pinning strength and the small flux bundle size [1]. The volume of flux bundle is given by

$$V = LR^2, \tag{1}$$

where L and R are the longitudinal and transverse flux bundle sizes, respectively. It was shown that L, which is approximately given by the longitudinal elastic correlation length, l_{44}, at low temperatures, is determined only by the flux pinning strength in a Bi-2212 single crystal [1]. Namely, L is independent of the dimensionality of the superconductor. It means that only R depends on the dimensionality of superconductor. If R is expressed as

$$R^2 = g^2 a_{\mathrm{f}}^2 \tag{2}$$

with a_{f} denoting the flux line spacing, g^2 is the number of flux lines in the flux bundle. In fact, $g^2 = 1$ and $g^2 = 1 \sim 2$ were obtained for a Bi-2212 single crystal and a Bi-2223 tape wire, respectively, from the apparent pinning potential, U_0^*, estimated from the relaxation measurement [1, 2].

On the other hand, a much larger g^2 value is expected for the three-dimensional Y-123 superconductor. In this paper l_{44} is directly measured using the Campbell method and g^2 is estimated from the relaxation rate for a single crystal Y-123 superconductor. The result is compared with those on Bi-2212 and Bi-2223 superconductors and discussion is given on the effect of the dimensionality of superconductor on the configuration of flux bundle.

EXPERIMENTS

The specimen used in this study was an untwinned single crystal Y-123 superconductor prepared by a pulling technique. Its size was 0.34 mm thick, 1.22 mm wide and 5.35 mm long and the c-axis was oriented normal to the flat surface. The critical temperature, T_c, was 94.7 K. The longitudinal elastic correlation length and the critical current density were measured using the Campbell method. A DC magnetic field was applied parallel to the c-axis and a small AC magnetic field was superposed parallel to the long axis of the specimen, i.e., normal to the DC magnetic field. The frequency of the AC field was 35.0 Hz. The penetration depth of the AC flux, λ', was measured as a function of the AC field amplitude, b_0, using pick up and dummy coils. The penetration depth took a nonzero constant value in the limit of zero b_0 and this constant penetration depth gives the elastic correlation length, l_{44}. The critical current density, J_c, was also estimated from the slope of a linear part of the λ'-b_0 curve. In addition, the DC magnetization under the magnetic field parallel to the c-axis and its relaxation were measured using a SQUID magnetometer.

RESULTS AND DISCUSSION

The critical current density observed using the Campbell method is shown in Fig. 1(a). Fig. 1(b) shows the results observed in a wide range of temperature using a SQUID magnetometer. In Fig. 1(b), it is found that the peak effect of J_c occurs in the temperatures range of 20–80 K. The single peak of J_c at lower temperatures is split into two peaks at higher temperatures. The mechanism of the double peaks in J_c was argued in reference [3].

Figure 2 represents the magnetic field dependence of l_{44} in the temperature range of 85–90 K. It is of the order of several ten μm and increases with increasing magnetic field and/or temperature. The longitudinal elastic correlation length, l_{44}, can be theoretically estimated from

$$l_{44} = \left(\frac{a_f B}{2\pi\mu_0 J_c} \right)^{1/2} \tag{3}$$

with the observed J_c. The theoretical result is shown in Fig. 3 and it is found that it agrees well with the experimental result shown in Fig. 2. L is given by the same equation with replacing J_c by the virtual value, J_{c0}, in the creep-free case.

The apparent pinning potential is estimated from the relaxation rate of DC magnetization as

$$U_0^* = -k_B T \left[\frac{1}{M_0} \frac{\partial M}{\partial (\log t)} \right]^{-1}, \tag{4}$$

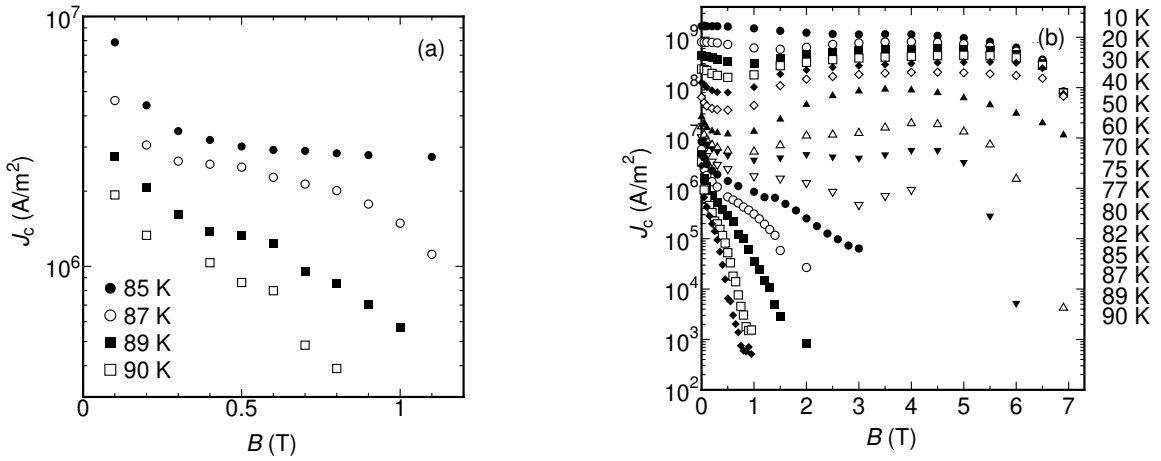

Fig. 1. Critical current density vs magnetic field parallel to the c-axis in the temperature ranges of (a) 85–90 K and (b) 10–90 K.

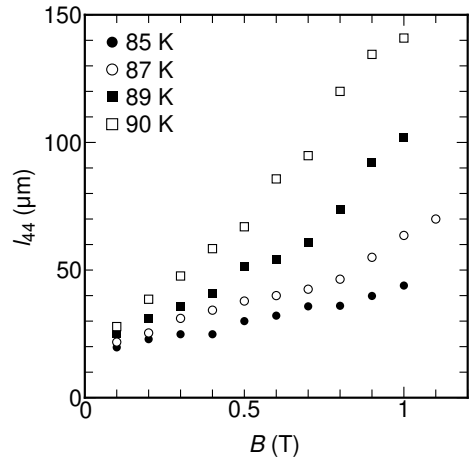

Fig. 2. Longitudinal elastic correlation length vs magnetic field at 85–90 K.

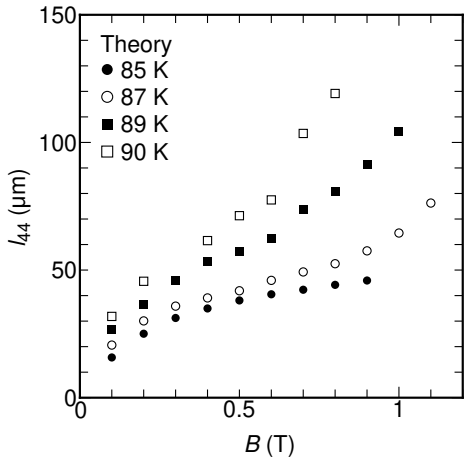

Fig. 3. Theoretically estimated longitudinal elastic correlation length using J_c in Fig. 1(a).

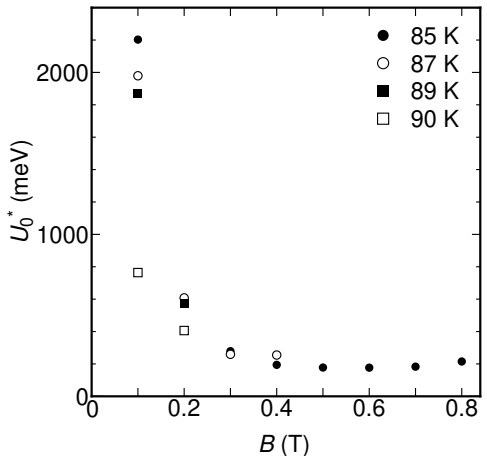

Fig. 4. Apparent pinning potential obtained from relaxation rate of magnetization.

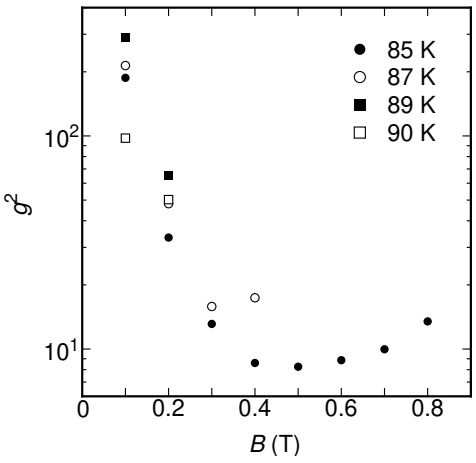

Fig. 5. g^2 in single crystal Y-123 estimated from J_{c0} and U_0^*.

where M_0 is the initial magnetization defined from the value of magnetization extrapolated back to $t = 1$ s after reaching a desired magnetic field. The obtained apparent pinning potential is shown in Fig. 4. U_0^* is of the order of several hundred meV and decreases with increasing magnetic field and/or temperature.

According to the theoretical result of Welch [4], the apparent pinning potential is related to U_0 as

$$U_0^* = 1.65(k_B T U_0^2)^{1/3} \tag{5}$$

for a sinusoidal washboard pinning potential. U_0 in a bulk superconductor is given by [5]

$$U_0 = \left(\frac{g^2 a_f^7 B^3 J_{c0}}{32\pi^3 \mu_0} \right)^{1/2} . \tag{6}$$

Thus, if J_{c0} is given, g^2 can be estimated using U_0^* obtained from the relaxation measurements. The dependences of J_{c0} on temperature and magnetic field are generally expressed in the form of

$$J_{c0} = A \left[1 - \left(\frac{T}{T_c} \right)^2 \right]^m B^{\gamma - 1} \left(1 - \frac{B}{B_{c2}} \right)^\delta , \tag{7}$$

where A, m, γ and δ are the pinning parameters. The critical current density in a wide range of temperature and magnetic field is shown in Fig. 1(b). Fitting the observed results at low temperatures in Fig. 1(b) with Eq. (7) leads to $A = 6.73 \times 10^9$, $m = 2.75$ and $\gamma = 0.72$. We assumed as $\delta = 2$, which does not appreciably influence the present analysis at low fields. At 85 K and 0.5 T estimated J_{c0} and L using these parameters are 8.47×10^7 A/m^2 and 7.2 μm, respectively. The value of L is about one-fifth of l_{44}. The estimated g^2 from J_{c0} and U_0^* is shown in Fig. 5. It is found that g^2 is of the order of 10^2 at low fields and decreases to about 10 with increasing magnetic field.

The value of g^2 in the most two-dimensional Bi-2212 is 1.0 [1] and that in a more three-dimensional Bi-2223 is ranged between 1 and 2 [2]. Hence, the present result of much larger g^2 in the most three-dimensional Y-123 agrees with the expectation. That is, the effect of dimensionality of the superconductor appears only in the transverse flux bundle size and this size becomes larger according as the dimensionality increases, while the longitudinal flux bundle size is independent of the dimensionality. Here we shall argue the reason for the smaller transverse flux bundle size in the more two-dimensional superconductor. Even if the shearing deformation takes place in the flux line lattice, it does not bring about an appreciable energy increase in the insulating blocking layer. Hence, the energy increase is smaller, resulting in the smaller shear modulus of the flux line lattice, for the more two-dimensional superconductor with the thicker blocking layer. The transverse flux bundle size and g are proportional to a square root of the shear modulus. Thus, the above tendency that the smaller transverse flux bundle size in the more two-dimensional superconductor can be explained.

It is shown above that the flux bundle is much larger in the three-dimensional Y-123 superconductor. This contributes to the strong pinning even at high temperatures where the thermal agitation is significant, resulting in the higher irreversibility field.

CONCLUSION

The flux bundle sizes are estimated at high temperatures for a three-dimensional single crystal Y-123 superconductor prepared by a pulling technique. The longitudinal elastic correlation length, l_{44}, of the order of several ten μm is determined only by the flux pinning strength independently of the dimensionality of superconductor. Hence, it is expected that the longitudinal flux bundle size, L, is also independent of the dimensionality. The number of flux lines in the flux bundle, g^2, estimated from the apparent pinning potential, U_0^*, is larger than 8. This value is much larger than those in two-dimensional superconductors such as Bi-2212 and Bi-2223. It is concluded that the effect of dimensionality of superconductor appears only in the transverse flux bundle size and this size becomes smaller according as the dimensionality decreases.

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