LONGITUDINAL ELASTIC CORRELATION LENGTH OF FLUX LINES ALONG THE c-AXIS NEAR THE PEAK FIELD IN Bi-2212 SINGLE CRYSTAL

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ABSTRACT

The longitudinal elastic correlation length, l_{44}, of flux lines in a single crystal Bi-2212 superconductor is measured in the vicinity of the peak field using the Campbell method with the magnetic field parallel to the c-axis. It is found that l_{44} in this region is of the order of 1 μm and much longer than the distance between the CuO_2 layers. In addition, l_{44} depends on the magnetic field and temperature. These results agree well with the pinning correlation length estimated using the measured critical current density, J_c. The apparent pinning potential estimated from the magnetic relaxation measurement takes a peak near the peak field and agrees well with the result of collective flux creep theory in which the obtained J_c and l_{44} are used. It is concluded from these results that the flux lines are strongly coupled over a fairly long distance along the c-axis even in the vicinity of peak field.

KEYWORDS: longitudinal elastic correlation length, Bi-2212 single crystal, Campbell method, peak effect, apparent pinning potential

INTRODUCTION

The phase diagram of flux lines in the field-temperature plane has been discussed for high-temperature superconductors. The property of flux lines in Bi-2212 superconductors is strongly affected by the two-dimensional electrical property due to the crystal structure. Recently, the peak effect was observed in the magnetization for Bi-2212 single crystals at relatively low fields in the low temperature region. Since this peak effect occurs near the field at which the neutron diffraction pattern of the flux line lattice disappears, it is believed to be related to the dimensional crossover of the flux line system [1]. That is, the flux lines are expected to behave as pancake vortices above this magnetic field. However, the pinning potential estimated from the observed irreversibility field using the collective flux-creep theory suggests that the flux lines are strongly connected between the CuO_2 layers along the c-axis [2]. In addition, the apparent pinning potential estimated from the logarithmic relaxation rate of magnetization differs only by a factor of two or so between most two-dimensional Bi-2212 and three-dimensional Y-123 [3]. On the other hand, the irreversibility field depends sensitively on the thickness of the specimen for two-dimensional Bi-2223 superconductor [4]. These experimental results support the above hypothesis.

Therefore, it is necessary to elucidate which physical picture is correct for the flux lines in the two-dimensional superconductor. In this paper the longitudinal elastic correlation length, l_{44}, of the flux lines along the c-axis of a Bi-2212 single crystal is directly measured in the vicinity of the peak field using the Campbell method. The apparent pinning potential estimated from the logarithmic relaxation rate of magnetization is compared with the prediction of the collective flux-creep theory. The behavior of flux lines along the c-axis near the peak field is discussed based on these results.

EXPERIMENTS

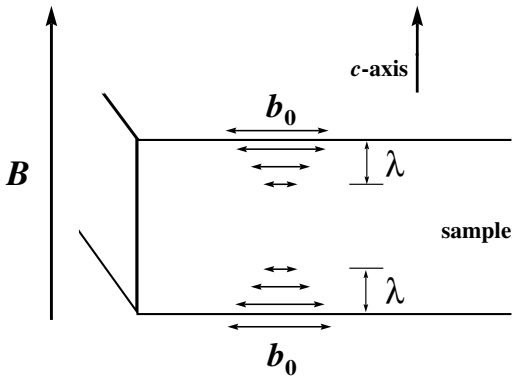

Fig. 1. Schematic view of direction of magnetic fields.

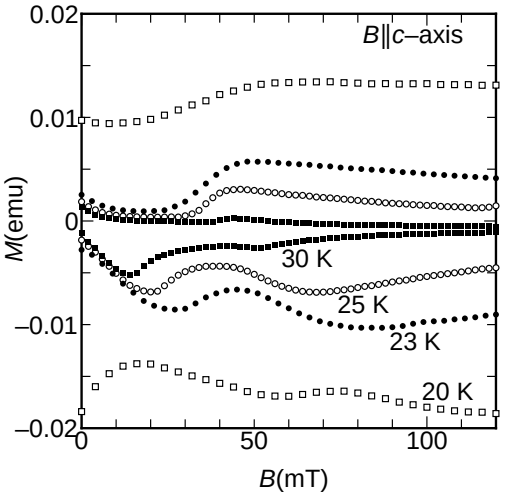

Fig. 2. Magnetization curves at 20–30 K.

The specimen used in this study is a single crystal Bi-2212 superconductor prepared by TSFZ method. The size of the specimen was about 5 mm long, 1.6 mm wide and 0.11 mm thick and the c-axis was oriented normal to the flat surface. The critical temperature, T_c, was 91.0 K. l_{44} was measured using the Campbell method at relatively low fields at which the peak effect was observed. The arrangement of magnetic fields is illustrated in Fig. 1. The DC magnetic field was applied parallel to the c-axis and the AC magnetic field was superposed parallel to the flat surface giving a bending deformation on flux lines. The frequency of the AC field was 35.0 Hz. The penetration of flux deformation was observed using pick up and dummy coils. The penetration depth of the AC flux, λ', was measured as a function of the AC field amplitude, b_0. The penetration depth took a nonzero constant value in the vicinity of zero b_0. This constant penetration depth corresponded to the elastic correlation length, l_{44} [5]. 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 and its relaxation were measured using a SQUID magnetometer.

RESULTS AND DISCUSSION

Figure 2 shows DC magnetization curves at low fields in the temperatures range of 20–30 K. It is found that the peak effect occurs in this temperature range and becomes vague with increasing temperature. Figure 3 shows the critical current density estimated from the slope of λ'-b_0 curves. It is found that J_c has a peak around the field at which the magnetization shows a peak. The peak effect is clearly seen at 23 K and 25 K and becomes less significant at 30 K. This variation is consistent with the magnetization shown in Fig. 2. Figure 4 shows l_{44} around the field and the temperature at which the peak effect is observed. It is found that l_{44} takes a value larger than 1 μm and is much longer than the distance between the CuO_2 layers. It is concluded, therefore, that the flux lines are coupled over a fairly long length. In addition, l_{44} takes a minimum near the peak field at 23 K and 25 K, while it increases monotonically with increasing magnetic field at 30 K. Thus, l_{44} is closely correlated with the critical current characteristics.

From the mechanism of pinning of flux lines, l_{44} is theoretically predicted as

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

where $C_{44} = B^2/\mu_0$ is the local tilt modulus of flux lines and a_f is the flux line spacing. The theoretically estimated l_{44} from Eq. (1) with J_c in Fig. 3 is shown in Fig. 5. Comparing Figs. 4

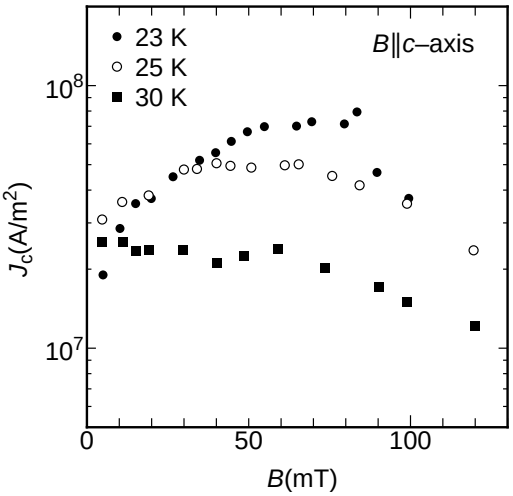

Fig. 3. Critical current density under magnetic field along to the c-axis.

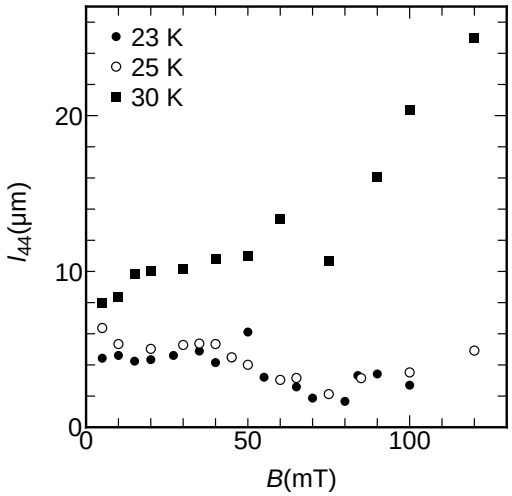

Fig. 4. Magnetic field dependence of observed l_{44} at various temperatures.

and 5, it is found that Eq. (1) explains well the observed result, although the theoretical results are slightly lower than the observed ones. That is, the observed l_{44} is the elastic correlation length determined by the flux pinning mechanism.

According to the collective flux-creep theory [6], the pinning potential is given by

$$U_0 = \frac{g^2 a_{\rm f}^3 J_{\rm c0} B l_{44}}{4\pi}, \tag{2}$$

where g^2 is a number of flux lines in the flux bundle and $J_{\rm c0}$ is a virtual $J_{\rm c}$ value in the creep-free case. g^2 is considered to be determined so that the critical current density under the flux creep might be maximized [7]. It can be shown that g^2 takes the minimum value, 1, throughout the region we investigated. It seems to be reasonable to approximately replace $J_{\rm c0}$ by the observed $J_{\rm c}$, since the measurement was done at relatively low temperatures. Then, the pinning potential, U_0, can be estimated from Eq. (2) with observed values of $J_{\rm c}$ and l_{44}. On the other hand, the apparent pinning potential, U_0^*, obtained from the logarithmic relaxation rate of magnetization is shown by solid symbols in Fig. 6. U_0^* takes a peak at around 50 mT. This seems to be associated with the peak effect. According to the theoretical result of Welch [8] U_0^* is related to U_0 as

$$U_0^* = 1.65(k_{\rm B} T U_0^2)^{1/3} \tag{3}$$

for a sinusoidally varying washboard pinning potential. U_0^* estimated from Eq. (3) is shown by open symbols in Fig. 6. It is seen that the agreement is good. This agreement also shows that the flux lines are coupled over a long length, while they behave independently of each other ($g^2 = 1$). That is, the flux lines are rather one-dimensional than two-dimensional. This is quite different from the usual understanding. The peak effect itself is considered to be caused by some disorder of flux lines. However, the present result shows that this is not the one such as the transition to pancake vortices. Even in the case of much more pronounced peak effect in a metallic superconducting thin film [9], which comes from the dimensional crossover in the pinning, the longitudinal correlation length is of the order of 1 μm and the flux lines are considered to be still strongly couple along their length although those are in the disordered "spaghetti" state. Hence, it is speculated that the flux lines are also strongly coupled along their length in the two-dimensional superconductor, while those may be severely disordered along their length in a shorter scale. This disorder in the shorter scale is considered to influence the determination of the critical current density. However, the characteristic length responsible for more macroscopic

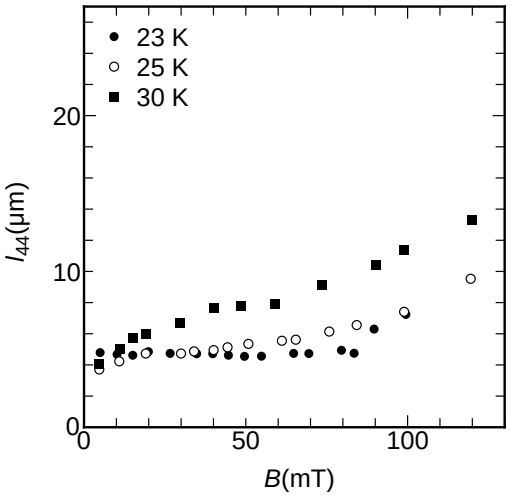

Fig. 5. Theoretically estimated l_{44} from Eq. (1).

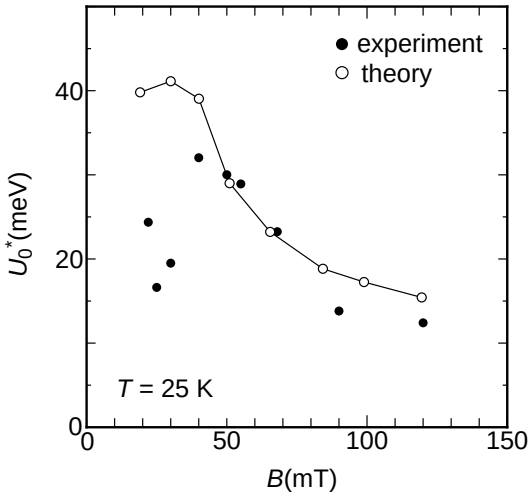

Fig. 6. Apparent pinning potential at 25 K. Solid and open symbols are experimental and theoretical results.

electromagnetic phenomena associated with the flux pinning such as flux creep is the former longer one.

CONCLUSION

The longitudinal correlation length of flux lines parallel to the c-axis of a Bi-2212 superconducting single crystal was measured in the vicinity of the peak effect using the Campbell method. The obtained l_{44} is longer than 1 μm and depends on magnetic field and temperature. It is concluded that the flux lines are strongly coupled over a long distance and are not disconnected at the blocking layer as assumed in the pancake vortex model even in this region. The apparent pinning potential obtained from the magnetic relaxation measurement, which has a peak at around the peak field, can be quantitatively explained by the collective flux-creep theory using the observed l_{44}. This result supports the above conclusion.

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