Peak Effect in Bi-2212 Single Crystal at Low Magnetic Field

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ABSTRACT

Force-displacement characteristic of flux lines in a superconducting Bi-2212 single crystal was measured using the Campbell method at low temperatures and low magnetic fields where the peak effect of the critical current density was observed. It was found that the interaction distance, d_{i}, had a peak around the peak field, while the Labusch parameter, α_{L}, increased monotonously with increasing magnetic field. The peak of d_{i} means an increment of the reversible limit of motion of pinned flux lines. This seems to be caused by an introduction of some disorder in the flux line lattice at the so-called 3-dimensional to 2-dimensional transition field. However, the characteristic length of the deformation along the c-axis is considered to be much longer than the distance between the CuO_2 planes.

KEYWORD: Peak effect, interaction distance, Labusch parameter, Campbell method, Bi-2212 superconductor

INTRODUCTION

Poor critical current characteristics in Bi-2212 superconductors under a magnetic field along the c-axis are influenced by an anisotropic electric properties due to the layered structure of the superconductor and the pancake vortex model [?] was proposed to explain such characteristics. That is, it is speculated that the flux lines along the c-axis are disconnected at the blocking layer between the CuO_2 planes and the poor irreversibility is attributed to a small pinning potential caused by the small size of pancake along the c-axis. However, the longitudinal elastic correlation length, l_{44}, of flux lines along the c-axis measured using the Campbell method was found to be of the order of 10 μm [?, ?] and four orders of magnitude longer than the distance between the CuO_2 planes even above the peak field. It means that the flux lines are magnetically coupled over a quite long distance and the decoupling of 2-dimensional pancakes assumed in Ref. [?] does not occur. In this paper, l_{44}, the Labusch parameter and the interaction distance are measured using the Campbell method near the peak field and discussion is given on the behavior of flux lines.

EXPERIMENTS

A superconducting Bi-2212 single crystal specimen was prepared by FZ (floating zone) method and annealed at 800 °C for 72 hrs in the air and at 425 °C for 72 hrs in an oxygen atmosphere of 2.1 atm. The size of the specimen was 5.50 mm long, 1.35 mm wide and 0.26 mm thick, and the c-axis was oriented normal to the flat surface. The critical temperature, T_{c}, was 78.3 K. The dc magnetization was measured using a SQUID magnetometer.

The force-displacement characteristic of flux lines was measured using the Campbell method. A dc magnetic field and a superposed small ac magnetic field of 35.0 Hz were applied parallel to the c-axis. The penetration depth of the ac flux, $\lambda^{'}$, was measured as a function of the ac field amplitude,

b_0, using pick up and dummy coils. The elastic correlation length, l_{44}, and the critical current density, J_c, were estimated from a measured $\lambda^{'}$-b_0 curve [?]. The force-displacement characteristic of flux lines is obtained as follows. From the continuity equation of flux lines, the displacement of flux lines at the surface, u, is given by [?]

$$u = \frac{\Phi}{Bw}, \tag{1}$$

where Φ is the amplitude of ac flux and w is the width of the specimen. The restoring force density on flux lines due to the displacement is given by [?]

$$F = \frac{2Bb_0}{\mu_0 \lambda^{'}}. \tag{2}$$

The initial slope of the force-displacement characteristic in the reversible regime gives the Labusch parameter, α_L, which represents the pinning strength. The interaction distance, d_i, i.e., a radius of the averaged pinning potential can also be estimated from a half of the distance at which a tangential line of the initial reversible regime reaches $2J_cB$ in the opposite critical state.

RESULTS AND DISCUSSION

Figure ?? shows the results of dc magnetization curves in the temperature range of 20 to 35 K. It is seen that the peak effect occurs in the range of 75 – 85 mT almost independently of the temperature. The critical current density obtained from the Campbell method in the low magnetic field region at $T = 23$ and 25 K is shown in Fig. ??. The peak effect of J_c occurs near $B = 85$ mT. The correlation length shown in Fig. ?? is of the order of 10 μm and quite longer than the distance between the CuO_2 planes. It depends on temperature and magnetic field. This is the same as the previous result [?].

The obtained force-displacement characteristic at $T = 23$ K and $B = 70$ mT is shown in Fig. ??. The restoring force density increases initially in proportion to the displacement of flux lines showing an elastic deformation of the flux line lattice and deviates from the linear relation with a plastic deformation. Then, the restoring force density approaches asymptotically the opposite critical state. The magnetic field dependences of α_L and d_i are shown in Fig. ?? and Fig. ??, respectively. Here we shall discuss the result of the longitudinal elastic correlation length, l_{44}. This length is theoretically given by

$$l_{44} = \left(\frac{C_{44}}{\alpha_L}\right)^{1/2}, \tag{3}$$

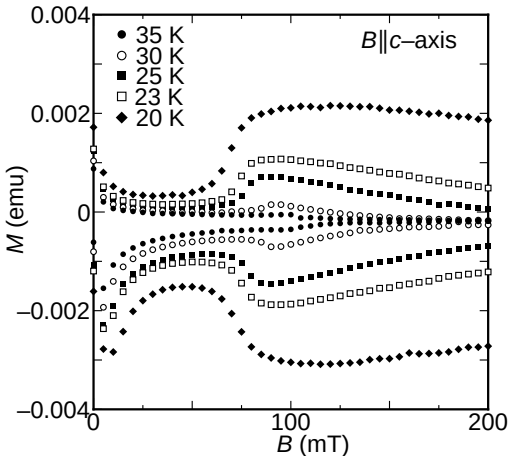

Fig. 1. Dc magnetization curves at 20–35 K.

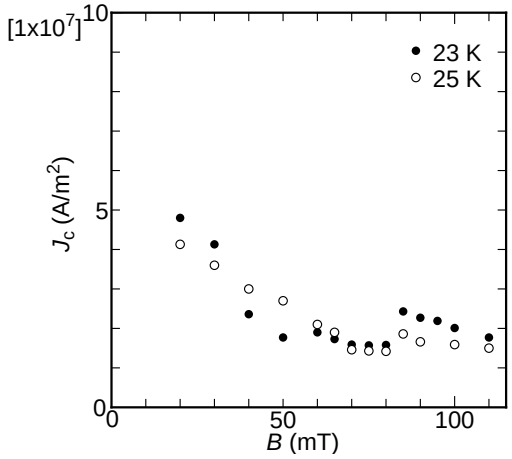

Fig. 2. Critical current density at $T = 23$ and 25 K.

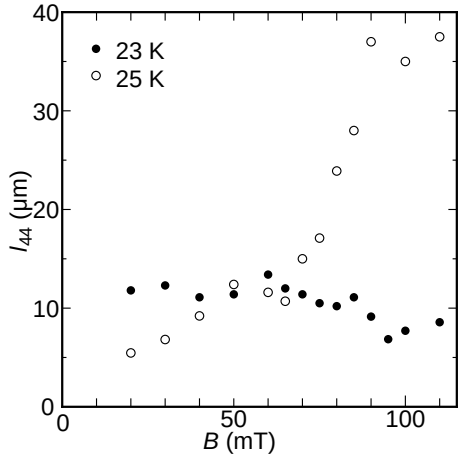

Fig. 3. Longitudinal elastic correlation length at $T = 23$ and 25 K.

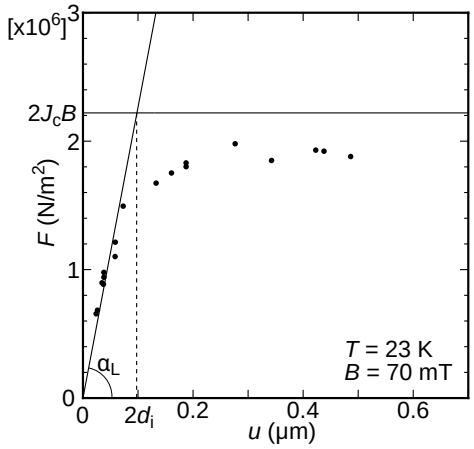

Fig. 4. Force-displacement characteristic of flux lines at $T = 23$ K and $B = 70$ mT.

where $C_{44} = B^2/\mu_0$ is the local tilt modulus of flux lines. l_{44} estimated at $T = 23$ K using the observed α_L in Fig. ?? is shown in Fig. ??. It is found that the agreement is fairly good. Similar agreement was obtained also for the the previous result [?].

Since the specimen does not contain large defects such as normal precipitates, point-like defects such as oxygen vacancies are expected to be dominant pinning centers. If there is no anomaly associated with the peak effect, d_i would be simply proportional to the flux line spacing as predicated theoretically [?] and the critical current density would be constant with respect to magnetic field as usually observed at low temperatures. Thus, we have $\alpha_L \propto B^{3/2}$ and $d_i \propto B^{-1/2}$. These expected magnetic field dependences of α_L and d_i are also shown for comparison in Fig. ?? and Fig. ??, respectively. It is found that the magnetic field dependence of d_i has a sharp peak around the peak field deviating from the above simple expectation, while α_L increases almost monotonously with increasing magnetic field as expect. The result on α_L indicates that the pinning mechanism itself does not appreciably change even at the peak field. But the peak of d_i means that the range of reversible displacement of flux lines inside the pinning potential is widened. That is, the flexibility of flux lines to be pinned by randomly distributed pins is increased near the peak field.

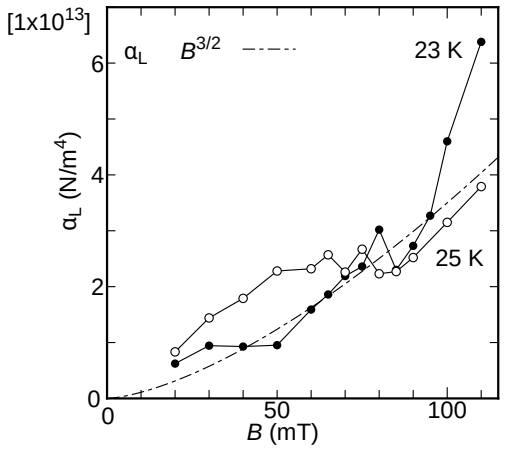

Fig. 5. Labusch parameter at $T = 23$ and 25 K. Dished lines represent the relation of $\alpha_L \propto B^{3/2}$.

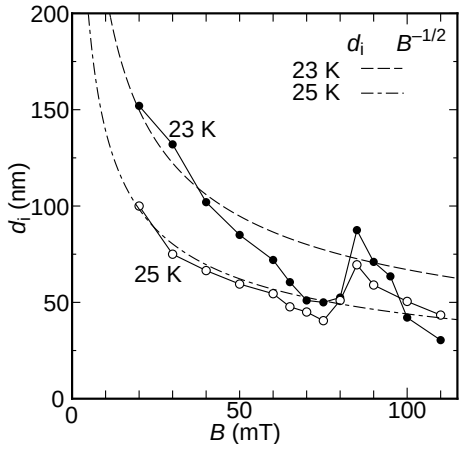

Fig. 6. Interaction distance at $T = 23$ and 25 K. Dished lines represent the relation of $d_i \propto B^{-1/2}$.

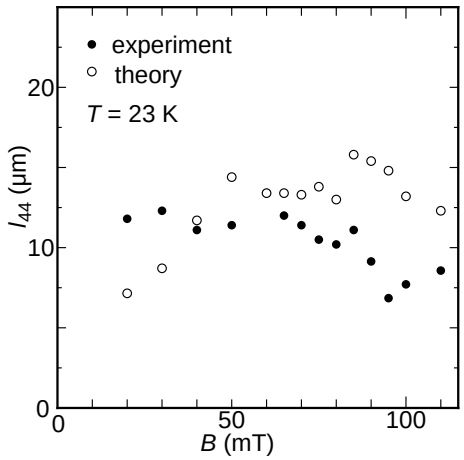

Fig. 7. Comparison of theoretically estimated l_{44} with experimental result at $T = 23$ K in Fig. 2.

This seems to be brought about by the so-called 3-dimensional to 2-dimensional transition of flux lines. However, since the enhancement factor of the critical current density at the peak field is about 2.5, it is speculated that the characteristic length of deformation of the normal core along the c-axis, which is proportional to J_c^{-2}, is reduced by a factor of about 6 at the transition. This variation seems to be too small, if the transition is really the one from the 3-dimensional state to the 2-dimensional state of flux lines. The deformation of the core along the length may be severely restriced by the strong magnetic coupling around the normal core.

CONCLUSION

The longitudinal elastic correlation length, l_{44}, the Labusch parameter, α_L, and the interaction distance, d_i, in a superconducting Bi-2212 single crystal near the peak effect is measured using the Campbell method. The following results are obtained:

1. The observed l_{44} is of the order of 10 μm. This is quite longer than the distance between the CuO_2 planes.
2. The result of α_L indicates that the pinning mechanism itself does not appreciably change even at the peak effect. But the peak of d_i means that the range of reversible displacement of flux lines inside the pinning potential is widened.
3. The enhancement of the critical current density at the peak field is consider to be caused by the so-called 3-dimensional to 2-dimensional transition of flux lines. However, the variation in the characteristic length of deformation along the c-axis estimated from J_c is too small. This may be caused by the strong magnetic coupling around the normal core.

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