Anomalous in-plane anisotropy of the resistivity on single crystalline 60-K $YBa_2Cu_3O_{7-\delta}$ in high magnetic fields

Tomoyuki Naito [a,1], Seiya Haraguchi [a], Hideo Iwasaki [a], Terukazu Nishizaki [b], Kenji Shibata [b], Norio Kobayashi [b]

[a] *School of Materials Science, Japan Advanced Institute of Science and Technology(JAIST), Tatsunokuchi 923-1292, Japan*

[b] *Institute for Materials Research, Tohoku University, Sendai 980-8577, Japan*

Abstract

We have measured the in-plane anisotropy of the in-plane resistivity on 60-K $YBa_2Cu_3O_{7-\delta}$ single crystals in magnetic fields parallel with the *ab*-plane. In high magnetic fields, the temperature dependence of the resistivity $\rho(T)$ for $H \perp I$ shows the jump near the zero-resistivity transition, while $\rho(T)$ for $H \parallel I$ the gradual behavior. Furthermore, the transition temperature of the latter is lower than that of the former, which is inconsistent with the vortex dynamics induced by the Lorentz force. We discuss the observed anomalous behavior in terms of the phase transition of the Josephson vortex system.

Key words: Josephson vortex; in-plane anisotropy; resistivity; $YBa_2Cu_3O_{7-\delta}$

In the phase diagram of the Josephson vortices(JVs) of 60-K $YBa_2Cu_3O_{7-\delta}$(YBCO) single crystals, the first-order transition line suddenly appears in high magnetic fields above 60 kOe [1]. We pointed out previously that the in-plane anisotropy of the vortex pinning strength exists in 60-K YBCO [2]. It is well known that the pinning strength and the vortex phase transition have a very sensitive correlation. In this paper, therefore, we study the in-plane anisotropy of the Josephson vortex state on 60-K YBCO.

YBCO single crystals were grown by a self-flux method using yttria crucibles. 60-K phase samples were obtained by heat treatment at 680 °C for 168 h in 1 bar oxygen gas, followed by quenching into the liquid nitrogen. The superconducting transition temperature T_c defined at the zero resistivity is 64.2 K. The sample dimensions are $0.8 \times 0.6 \times 0.1$ mm^3. Using the two-axis rotatable device, we can obtain the in-plane anisotropy of the in-plane resistivity, which is measured by a conventional dc four-probe method, as functions of the parallel magnetic field($H \parallel ab$-plane) and the in-plane angle θ between the magnetic field and the current directions; we define the position of $\theta = 0°$ at $H \perp I$ condition. The experimental configuration is schematically illustrated in the inset of Fig. 1.

Figure 1 shows the temperature dependence of the resistivity $\rho(T, \theta)$ for several in-plane angles θ in parallel magnetic fields; to get accurate $H \parallel ab$, we measure the $\rho(\phi)$ curve for each θ, where ϕ is the angle between the magnetic field and the *ab*-plane. One can immediately find that the shape of the $\rho(T, \theta)$ curve for $H=$ 140 kOe changes drastically with θ. The most noticeable feature is that the $\rho(T, \theta)$ curves have a crossing point, in particular the resistivity values for $\theta = 0°$ are smaller than those for $\theta = 90°$ below a certain temperature. On the basis of the normal picture of the vortex dynamics induced by the Lorentz force, this feature is extremely anomalous. Because the resistivity value ought to correspond to the magnitude of the Lorentz force which is naturally a maximum for $H \perp I$ configuration; we note that the Magnus force also cannot explain this phenomenon. To understand the behavior of the $\rho(T, \theta)$ curves, let us consider the JV phase tran-

[1] E-mail:tomon@jaist.ac.jp(T. Naito)

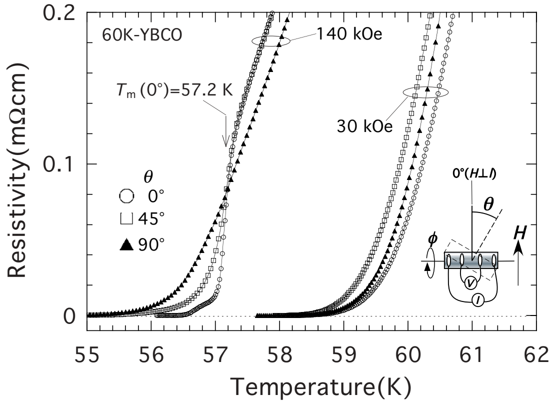

Fig. 1. Temperature dependence of the resistivity for several θ in parallel magnetic fields.

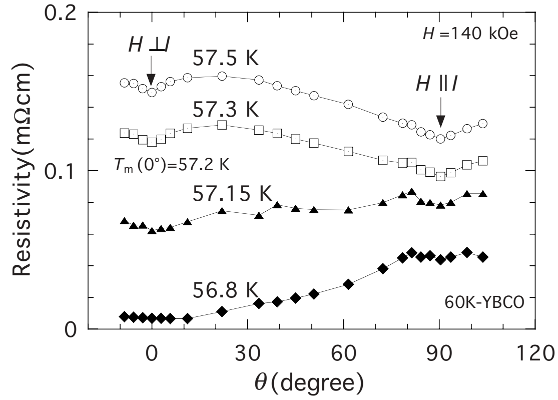

Fig. 2. Angular dependence of the resistivity $\rho(\theta)$ for several temperatures under parallel magnetic field of H=140 kOe

sition in detail. The $\rho(T, 0^\circ)$ curve shows a relatively sharp jump accompanied with a long tail. The resistivity jump comes from the first-order transition in the JV system; the transition temperature $T_{\rm m}(0^\circ)$, defined as the temperature where the $d\rho/dT$ value takes a sharp peak, is of 57.2 K. Since the continuous behavior in the tail region means that the vortex phase transition is a second-order, the transition temperature $T_{\rm g}(0^\circ)$ is estimated to be of 56.2 K using the vortex glass theory [3] giving the relation $\rho \sim (T - T_{\rm g})^s$, where $T_{\rm g}$ is the glass transition temperature and s is the critical exponent. This two-stage transition indicates that the JV slush [4] regime, where a JV liquid containing the short-range ordered JV lattice exists, appears in the temperature range of $T_{\rm g}(0^\circ) < T < T_{\rm m}(0^\circ)$. The resistivity jump becomes unclear with increasing θ, and fully disappears at $\theta = 90^\circ$. Thus the JV transition at $\theta = 90^\circ$ is the second-order, and we estimate $T_{\rm g}(90^\circ)$ to be of about 52.8 K using the same relation mentioned above. As a result of the consideration above, we find that the JV liquid for $\theta = 0^\circ$ has a different nature from that for $\theta = 90^\circ$ below $T_{\rm m}(0^\circ)$. Since the *effective mass* of the JV liquid in the slush regime is expected to be heavier than that in ordinary one, which is consistent the phenomenon, $\rho(T, 0^\circ) < \rho(T, 90^\circ)$ for $T < T_{\rm m}(0^\circ)$. In low magnetic fields, the $\rho(T, \theta)$ curves do not show the discontinuous feature and the shape of those is almost independent of θ, therefore any anomaly does not appear.

Figure 2 represents the angular dependence of the resistivity $\rho(\theta)$ at H= 140 kOe for several temperatures, which are derived from the $\rho(T, \theta)$ curves shown in Fig. 1. Above $T_{\rm m}(0^\circ)$, the $\rho(\theta)$ curves take a minimum with dip structure at around $\theta = 0^\circ$ and 90°. These behaviors seem to be similar to the data for H= 30 kOe reported previously [2]. We succeeded basically in interpreting the data for H= 30 kOe by the theories of the superconducting fluctuation and the in-plane anisotropy of the upper critical field $H_{\rm c2}$; both theories describe the nature of the normal liquid regime. On the other hand, the $\rho(\theta)$ curves below $T_{\rm m}(0^\circ)$ demonstrate a very different angular dependence from the former, indicating that those cannot be described by these theories, i.e., the picture of the ordinary JV liquid. Consequently, we can conclude that the JV phase transition has the in-plane anisotropy on 60-K YBCO.

In 90-K YBCO, it was reported that the in-plane anisotropy of the penetration depth [5] and thermal conductivity [6]; the authors discussed a role of the Cu-O chain on the superconductivity. We speculate that it is a possible origin of the angular dependence of the JV phase transition, because the vortex phase transition lines are affected by the position of the $H_{\rm c2}$ line or microscopic parameters.

In summary, we have measured the in-plane anisotropy of the resistivity under parallel magnetic fields on 60-K YBCO single crystals and found that the phase transition of the Josephson vortex system changes with the in-plane angle.

One of the authors(T. Naito) was financially supported by a Grant for Basic Science Research Projects (Grant No. 000539) from the Sumitomo Foundation.

References

[1] S. N. Gordeev *et al.*, Phys. Rev. Lett. **85** (2000) 4594; T. Naito *et al.*, unpublished.

[2] T. Naito *et al.*, Phys. Rev. B **63** (2001) 172506.

[3] M. P. A. Fisher, Phys. Rev. Lett. **62** (1989) 1415; D. S. Fisher *et al.*, Phys. Rev. B. **43** (1991)130 .

[4] T. K. Worthington *et al.*, Phys. Rev. B. **46** (1992) 11854 .

[5] D. N. Basov *et al.*, Phys. Rev. Lett. **74** (1995) 598.

[6] R. Gagnon *et al.*, Phys. Rev. Lett. **78** (1997) 1976.