# Four-fold symmetry of 90K-YBCO single crystals in magnetic fields

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**Abstract**

We have measured the angular dependence of the resistivity $\rho(\theta)$ in 90K-YBCO single crystals, where $\theta$ is the angle between the direction of a magnetic field $H$ and the direction of [010] which is perpendicular to the current $I$ in the single crystal. The obtained $\rho(\theta)$ shows the four-fold symmetry. On the other hand, Kwok et al. had observed only the two-fold symmetry in 90K-YBCO single crystals. The origin of the difference between the symmetry of each case is speculated that it comes from the difference of anisotropy that depends on the concentration of oxygen in the CuO-chains.

*Key words:* In-plane anisotropy; Resistivity; Josephson vortex; $YB_2Cu_3O_{7-\delta}$ single crystal

Recently, the property of Josephson vortex system which forms in the areas between the $CuO_2$ layers has been studied. Moreover, in-plane anisotropy measurements of resistivity under magnetic fields could give information for the symmetry of superconducting electron pairs. Some of the high $T_c$ oxide superconductors have already been studied about the in-plane anisotropy of the resistivity concerning it [1–4]. These implied that the anisotropic parameter $\gamma(=\xi_{ab}/\xi_c)$ has a relation to the in-plane anisotropy, where $\xi_{ab}$ and $\xi_c$ are the coherence length in the *ab*-plane and along the *c*-axis direction, respectively. Particularly, the contribution of the four-fold symmetry is enhanced with increasing $\gamma$ in 60K-YBCO and LSCO systems [5,6]. In those measurements magnetic fields are applied to align precisely parallel to the $CuO_2$ layers. Therefore, we have investigated the in-plane anisotropy about 90K-YBCO single crystals to use the same measurement system and show the results in this paper.

Twin YBCO single crystals were grown by a self-flux method in yttria crucibles. The sample has been annealed in flowing oxygen atmosphere at 450°C for one week, and it is in the slightly over-doped condition [7]. The dimensions are $1.29 \times 0.97 \times 0.06 \mathrm{mm}^3$. The superconducting transition temperature $T_c$ which is defined as a midpoint of the resistivity transition curve is 92.52K and that superconducting transition width $\Delta T_c$ is 440mK.

The current $I$ was applied parallel to the *a(b)*-axis direction and a measurement current density is $1.65 \mathrm{A/cm}^2$. The $\rho_{a(b)}$ is measured by the dc four-probe method. The measurement process has two steps and is performed by using a two-axis rotatable unit. The first step is the measurement of the angular dependence of the resistivity $\rho(\phi)$ with the angle step $\Delta\phi \sim 0.02^{\circ}$, where $\phi$ is defined as an angle between the magnetic field and the *ab*-plane, and it is determined that the position of the *ab*-plane is parallel to the magnetic field. The second one is the measurement of the temperature dependence of the resistivity $\rho(T)$ at $\phi = 0$. This process is repeated for each angle $\theta$ that is defined as an angle between the magnetic field and the direction of [010] which is perpendicular to the current $I$ in the single crystal, and then the angular dependence of the resistivity $\rho(\theta)$ is obtained.

Figure 1 shows the temperature dependence of the

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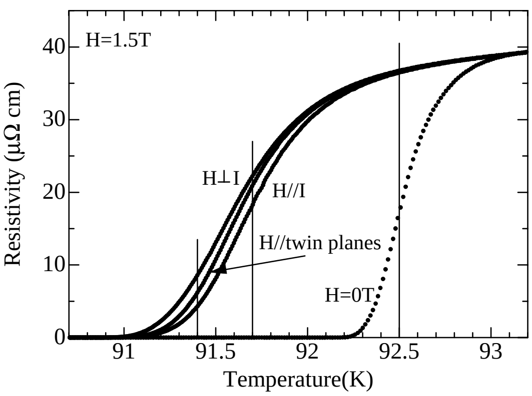


Fig. 1. Temperature dependence of the resistivity of 90K-YBCO at $H$=1.5T for the configuration of $H \perp I$, $H \| I$ and $H \|$twin planes and $H$=0T. The three vertical lines show the scan temperatures of the angular dependence of the resistivity in Fig.2.

resistivity $\rho(T)$ in the $ab$-plane at $H$=1.5T with the current-field orientation $H \perp I$, $H \| I$ and $H \|$twin planes. Any kinks could not be observed, which correspond to the first-order vortex lattice melting transition (VLMT) in the resistivity curve.

Figure 2 is the results of the in-plane resistivity $\rho_{a(b)}(\theta)$ at $H$=1.5T. These plotted points are estimated from the $\rho(T)_{a(b)}$ curves for each angle $\theta$. The $\rho(\theta)_{a(b)}$ curves show basically the two-fold symmetry; however, it could be seen a contribution of the four-fold symmetry with a dip at all the plotted temperatures.

This four-fold symmetry has been observed more clearly in 60K-YBCO single crystal which has the anisotropic parameter $\gamma$ of 20 [5]. It has been reported that the symmetry is changed by a variation of $\gamma$ [6]. Kwok et al. had observed only the two-fold symmetry in 90K-YBCO single crystals [4]. It is considered that the difference of the symmetry in 90K-YBCO system comes from the difference of anisotropy that depends on the oxygen content in the CuO-chains. $\gamma$ is able to be controlled by the annealing condition in the present system. Under-doped or over-doped sample has been synthesized by the annealing at higher and lower temperatures than that of the optimally doped one [7]. Because the properties of the vortex system in YBCO show a drastic change by a slight change of the oxygen content for $H \| c$-axis, the difference of the $\rho_{a(b)}(\theta)$ curves between our results and those by Kwok et al. is considered to be due to the oxygen content difference.

In summary, we have observed the four-fold symmetry on the measurement of in-plane anisotropy in 90K-YBCO single crystals on the contrary to the report by Kwok et al. It suggests that the in-plane anisotropy and the behavior of the temperature dependence of the resistivity are strongly affected by the oxygen concentration in the CuO-chains in 90K-YBCO system.

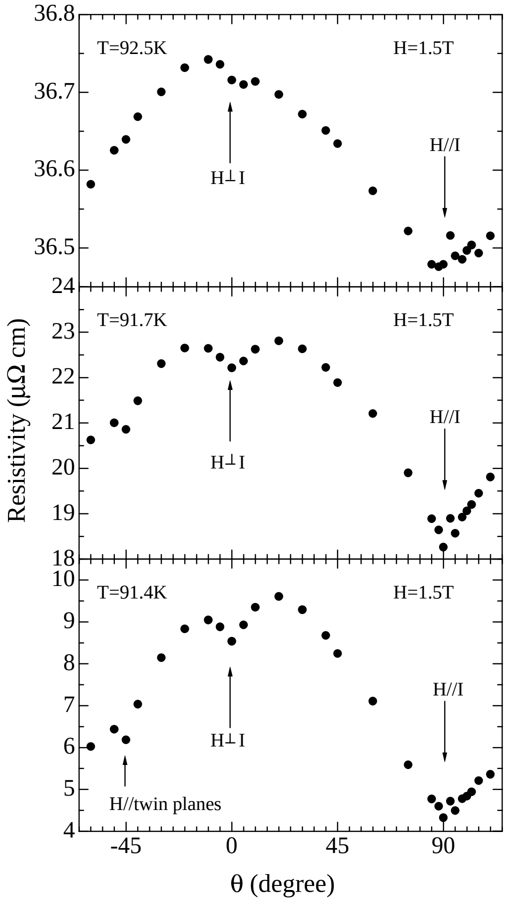


Fig. 2. Angular dependence of the resistivity at three temperatures, from top to bottom, $T$=92.5, 91.7 and 91.4K. $\theta$=0° and 90° indicate $H \perp I$ and $H \| I$, respectively.

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