Anisotropic Transport Properties Observed in Bi$_2$Sr$_2$CaCu$_2$O$_x$ Single Crystal Films

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We report here a large anisotropic transport phenomena observed in epitaxial Bi$_2$Sr$_2$CaCu$_2$O$_x$(2212) films. In particular, low temperature I-V curves containing inter-layer and intra-layer transports show a large anisotropy. Such anisotropy seems to be intrinsic in Bi-based superconductors.

Single crystal 2212 films were grown on tilted (001)SrTiO$_3$ substrates by using an ion-beam-sputtering technique[1]. The substrate surface normal was tilted about 4° toward [111]SrTiO$_3$, thus the step edges along [110] and {001} terraces were regularly formed on the surface. The epitaxial growth of 2212 film is restricted by the step edges. The a-axis is parallel to [110]SrTiO$_3$ and the b-axis with incommensurate modulation aligned to [110]SrTiO$_3$. Each Cu-O plane was continuous without any grain-boundaries and tilted according to the substrate surface inclination as shown in Fig.1. Therefore, the measured resistivity along [110]SrTiO$_3$ ($\rho_a$) represents the a-axis transport of the film and that along [110]SrTiO$_3$ ($\rho_b$) containing both b- and c-axis components.

Above the superconducting transition temperature(Tc), the resistivity along c-axis($\rho_c$), calculated from the measured value($\rho_b$) and angle of the tilt, was about four orders of magnitude higher than that along a-axis($\rho_a$) as shown in Fig.2, where a geometrical translating formula $\rho_c=\rho_a\sin^2\theta+\rho_b\cos^2\theta$ was used. Below Tc, the critical current density along c-axis($J_c(c)$) was about one tenth of the critical current density along a-axis($J_c(a)$) according to a geometrical translating formula $J_c(c')=J_c(c)\sin\theta+J_c(a)\cos\theta$.

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**References**

[1] [Ion-beam-sputtering technique](http://example.com).

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**Fig.1** Schematic illustration of epitaxial 2212 film on tilted SrTiO$_3$ substrate.
The difference of low temperature I-V curves in two directions was quite remarkable. Compared with the usual flux-flow type I-V curve observed along a-axis (Fig.4(a)), the I-V characteristics containing c-axis component was distinctively different. For the latter case, the non-linear characteristics rather resembled that of a weak-link Josephson coupling, having an IcRn product of about 2.5V observed on a 5μ-wide and 5μ-long strip. It involves about 230 Cu-O/Bi-O/Cu-O coupling layers so each layer is supposed to have about 11mV of IcRn product. This value seems to be reasonable considering $2\Delta=40$mV for this material.

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