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Short Note

Anisotropic Transport Properties in Twin-Free $Bi_2Sr_2CaCu_2O_x$ Thin Films on Tilted $LaAlO_3$ (001) Substrates

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Anisotropic transport properties of twin-free $Bi_2Sr_2CaCu_2O_x$ (BSCCO) thin films were studied. Twin-free BSCCO thin films were prepared by molecular beam epitaxy (MBE) on $LaAlO_3$ (001) substrates tilted 6° toward the [110] direction. By postannealing in high vacuum (HV) of 10^{-8} Torr at a temperature of 300–400°C, the carrier density per CuO_2 plane was reduced from 0.5 to 0.3. The anisotropy parameter (γ) was determined to be 38 in the HV-annealed sample.

KEYWORDS: $Bi_2Sr_2CaCu_2O_x$, high-T_c superconductor, Hall coefficient, twin-free thin film, anisotropic transport property, molecular beam epitaxy

Recently, the intrinsic Josephson effect in a high-T_c superconductor has attracted the interest of many reserach groups. It has been found that the intrinsic Josephson effect could be observed in highly anisotropic materials such as Bi- or Tl-based superconductors.[1–4] Kleiner *et al.* observed Josephson coupling between CuO double layers in $Bi_2Sr_2CaCu_2O_x$ (BSCCO) single crystals using direct measurements of the ac and dc Josephson effects for the first time.[1,2] Most research on BSCCO has been focused on single crystals of BSCCO.

Despite a number of studies on the atomically controlled growth technique of BSCCO thin films,[5–9] no clear evidence of the intrinsic Josephson effect has been observed in those thin films, except for those fabricated on granular crystals.[4] For practical applications, the junction should be fabricated with epitaxial thin films.

Since it is known that twin-free BSCCO thin films can be grown on tilted substrates and have oblique a-b planes, there is a possibility of constructing an intrinsic Josephson junction. For this purpose, anisotropic properties of these films should be investigated. Therefore, we studied anisotropic transport properties of twin-free BSCCO thin films grown on tilted $LaAlO_3$ (001) substrates.

The twin-free BSCCO thin films were epitaxially grown by a molecular beam epitaxy (MBE) method with a sequential deposition technique on $LaAlO_3$ (001) with a tilt angle of 6° toward the [110] azimuth. The details of this method are reported elsewhere.[10,11]

The c-axis-oriented BSCCO thin films grown on MgO (001) substrates were used in Hall measurement although they have a twin structure. The estimation of the carrier density in BSCCO on the tilted substrate is thought to be complex, because Hall coefficients show opposite signs for $H \parallel c$ and $H \perp c$ in single crystals.[12] To change the carrier density, postannealing was applied in a high vacuum (HV) of 10^{-8} Torr at a temperature between 300 and 400°C for 1 h. Hall coefficients were measured with the magnetic field of 0–7 T parallel to the c-axis of BSCCO. and at a temperature of between 101 and 202 K.

The resistivity of the BSCCO thin film on the tilted $LaAlO_3$ substrate was measured by the four-probe method. The films of 120 nm thickness were patterned into a line shape with a width of 1 mm.

In Fig. 1, critical temperatures are plotted against the carrier density per CuO_2 plane. In contrast to the bulk BSCCO sample which shows a maximum $1/eR_H$ at 0.1–0.2,[13–15] our as-grown film ($T_c = 50$ K) can be assumed to be in an overdoped region. After HV-annealing at 350°C, T_c was increased to 71 K and $1/eR_H$ was reduced to 0.3 at 202 K. It is clear that the carrier density was reduced by HV-annealing and was optimized.

Twin-free BSCCO thin film on a tilted substrate should exhibit an anisotropic transport behavior, because the a-b planes of these BSCCO thin films are parallel to the (001) plane of the substrate and are inclined to the substrate surface. Therefore, the resistivity along the c-axis could be estimated from the resistivity along the [11 sin 6°] direction which has both a b- and c-axis component. Although $LaAlO_3$ has the twinned structure, the orientation relationship between BSCCO and a tilted $LaAlO_3$ substrate is the same as in the case of $SrTiO_3$

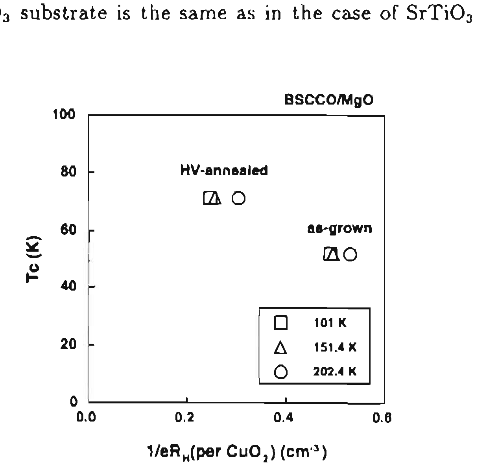

Fig. 1. Critical temperatures depending on $1/eR_H$ for an as-grown sample and HV-annealed sample prepared on MgO (001) substrates.

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reported in refs. 6,10 and 11. The a-axis of BSCCO thin film is parallel to the step edges ($[1\bar{1}0]$ $LaAlO_3$), and the b-axis accompanying incommensurate modulation is perpendicular to the step edges ([110] $LaAlO_3$).

In Table I, we present data of anisotropic transport properties of as-grown and HV-annealed BSCCO thin films prepared on the tilted $LaAlO_3$ (001) substrate. The anisotropy parameter $\gamma = (\rho_c/\rho_a)^{1/2}$ is given by[16)]

$$\rho_{[11\sin\theta]} = \rho_{[110]}\cos^2\theta + \rho_c \sin^2\theta$$
$$= \rho_{[110]}(\cos^2\theta + \gamma^2 \sin^2\theta), \quad (1)$$

where θ is the tilt angle, $[11\sin\theta]$ and [110] are directions of the substrate, and $\rho_{[11\sin\theta]}$ and $\rho_{[110]}$ are resistivities obtained experimentally. A large anisotropy in resistivity was observed for sample C, as shown in Fig. 2, and the anisotropic parameter was estimated to be 38. This value is larger than those of samples A and B, indicating that the oxygen in the crystal can be removed at a temperature higher than 300°C and the anisotropy parameter can be changed. Tsai et al. estimated γ to be 150 using their model for BSCCO thin films on 4°-tilted $SrTiO_3$ (001).[17)] We recalculated γ using eq. (1) and found the value to be 62. In both cases, these values were small compared to those of single crystals (γ = 50–280).[1,2)] Although a large anisotropy is expected in the twin-free BSCCO thin film having no twin boundary, these results indicate the possibility of the existence of defects and/or intergrowth in the films grown on the tilted substrates.

The transport property in an area of ~1 μm^2 should be investigated taking into account the Josephson penetration depth, and studies for such a structure is now in progress.

The anisotropy parameter γ was estimated to be 38 in the HV-annealed twin-free BSCCO thin film on the tilted $LaAlO_3$ (001) substrate. The anisotropic transport parameters were found to be changed by HV-annealing.

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Table I. Anisotropic transport properties of BSCCO thin films prepared on 6° tilted $LaAlO_3$.

Sample	Anneal temp. (°C)	$\rho_{[11\sin\theta]}$ (mΩ·cm)	ρ_a (mΩ·cm)	γ
A	as grown	7.2	4.2	8.2
B	300	8.0	4.0	9.6
C	400	23	1.4	38

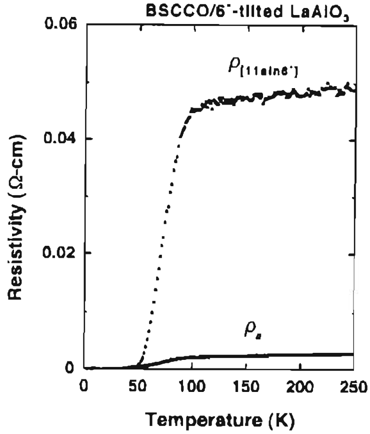

Fig. 2. The temperature dependence of ρ_a and $\rho'_{[11\sin6°]}$ for the twin-free BSCCO thin film HV-annealed at 400°C prepared on tilted $LaAlO_3$ (001) substrates.

1) R. Kleiner, V. Steinmeyer, G. Kunkel and P. Müller: Phys. Rev. Lett. 68 (1992) 2394.
2) R. Kleiner and P. Müller: Phys. Rev. B 49 (1994) 1327.
3) F. Schmid, A. Pfuch, H. Schneidewind, E. Heinz, L. Dörrer, A. Matthes, P. Seidel, U. Hübner, M. Veith and E. Steinbeiß: Supercond. Sci. Technol. 8 (1995) 740.
4) A. Odagawa, M. Sakai, H. Adachi, K. Setsune, T.Hirao and K. Yoshida: Jpn. J. Appl. Phys. 36 (1997) L21.
5) Y. Nakayama, I. Tsukada, A. Maeda and K. Uchinokura: Jpn. J. Appl. Phys. 28 (1989) L1809.
6) J. N. Eckstein, I. Bozovic, K. E. von Dessonneck, D. G. Schlom, J. S. Harris, Jr. and S. M. Baumann: Appl. Phys. Lett. 57 (1990) 931.
7) J. N. Eckstein, I. Bozovic, D. G. Schlom, J. S. Harris, Jr. and S. M. Baumann: Appl. Phys. Lett. 57 (1990) 1049.
8) T. Matsumoto, T. Kawai, K. Kitahama, S. Kawai, I. Shigaki and Y. Kawate: Appl. Phys. Lett. 58 (1991) 2039.
9) T. Ishibashi, Y. Okada and M. Kawabe: Jpn. J. Appl. Phys, 33 (1994) L763.
10) T. Ishibashi, H. Soutome, Y. Okada and M. Kawabe: J. Cryst. Growth 150 (1995) 1094.
11) T. Ishibashi, H. Soutome, Y. Okada and M. Kawabe: IEEE Trans. Appl. Supercond. 5 (2) (1995) 1805.
12) L. Forro, D. Mandrus, C. Kendziora and L. Mihaly: Phys. Rev. B 42 (1995) 8704.
13) A. Maeda, H. Hase, I. Tsukada, K. Noda, S. Takabayashi and K. Uchinokura: Phys. Rev. B 41 (1990) 6418.
14) Y. Koike, Y. Iwabuchi, S. Hosoya, N. Kobayashi and T. Fukase: Physica C 159 (1989) 105.
15) R. Yoshizaki, H. Ikeda, Y. Sato and Y. Abe: Physica C 162–164 (1989) 67.
16) J. Fujita, T. Yoshitake, T. Satoh, S. Miura, H. Tsuge and H. Igarashi: Appl. Phys. Lett. 59 (1991) 2445.
17) J. S. Tsai, J. Fujita and M. Yu. Kupriyanov: Phys. Rev. B 51 (1995) 1627.