Mem. School. B.O.S.T. Kinki University No. 2 : 14~23 (1997)



# Fabrication of in-plane aligned all $a$-axis $YBa_2Cu_3O_{7-y}$/ $PrBa_2Cu_2TiO_z$ /$YBa_2Cu_3O_{7-y}$ tunnel junctions

Shigeki Hontsu[1], Masaya Nakamori[2] and Junya Ishii[1]


## Abstract

Thin films of $a$-axis oriented $PrBa_2Cu_2TiO_z$ (PBCTO) and multilayers of all $a$-axis oriented $YBa_2Cu_3O_{7-y}$ (YBCO)-PBCTO have been grown by pulsed laser deposition technique. The resistivity of PBCTO film reaches a value of $10^7$ Ωcm at 50K and $10^5$ Ωcm at 100K, respectively. This high resistivity indicates that PBCTO is a good insulating layer and an attractive candidate material for thin film heterostructures made of $a$-axis oriented YBCO film. Using (100) $LaSrGaO_4$ (LSGO) as a substrate and $PrBa_2Cu_3O_x$ (PBCO) as a template layer, the formation of (100) YBCO/(100) PBCTO and (100) PBCTO/(100) YBCO bilayers, and (100) YBCO/ (100) PBCTO/ (100) YBCO trilayer structure have been demonstrated. A $\phi$-scan x-ray diffraction measurements of reflection from (102) YBCO plane display twofold symmetry. Also, the top YBCO film in trilayer structure shows anisotropies of resistance, the resistance in the $c$-axis direction being about two times larger than that in the $b$-axis direction. These results show that the formation of in-plane aligned all $a$-axis SIS epitaxial trilayer is achived in the present structure. Furthermore, we have fabricated SIS tunnel junctions with a trilayer vertical geometry using a YBCO/PBCTO/YBCO, and observed obvious superconductive gap structures at around 26 mV for the junctions with the 400 Å-thick PBCTO interlayer.


## Introduction

The reproducible fabrication of superconductor/insulator/superconductor (SIS) tunnel junctions where S is a high-$T_c$ superconducting oxide is of the utmost important subjects for the electronic devices, such as Josephson junctions and SIS mixer. Additionally, the investigation of tunneling phenomena in high-$T_c$ oxide superconductors yield useful information on the physics, such as large anisotropy energy gap, the density of states (DOS) and the excitation mode related to the superconductivity mechanism. Many experiments have been reported for YBCO/ insulator/YBCO (SIS) junctions of layered structure [(1)-(4)]. In these reports, top and bottom layers are fabricated using (001) or (110)-oriented YBCO films. Several groups have reported SIS (or SNS) junctions of (103) or (013)-oriented YBCO films [(5),(6)]. On the other hand, there are very few reports for SIS junctions of (100)-orientation with its $c$-axis in-plane aligned YBCO films, because it has proven difficult to obtain in-plane aligned $a$-axis YBCO films. Moreover, the good insulator and an attractive candidate material for all $a$-axis oriented SIS structure has apparently not been found. However, $a$-axis films are potentially superior to $c$-axis

1. Department of Electronic Systems and Information Engineering, Kinki University, Wakayama 649-64, Japan
2. Department of Electric Engineering, Kumano Technical College, Mie 519-43, Japan

films for sandwich-type junction applications because of the larger coherence length in the a direction.

Previously, we reported that the *a*-axis oriented YBCO film that grown on (100) $LaSrGaO_4$ (LSGO) substrates were 90° cross domain free and the perfectly in-plane aligned *a*-axis film [7]. Also, we reported the epitaxial growth of all *a*-axis oriented YBCO/$PrBa_2Cu_{3-x}Nb_xO_{7-z}$ (PBCNO) multistructures [8]. In this paper, we report the synthesis of in-plane aligned *a*-axis oriented $PrBa_2Cu_2TiO_z$ (PBCTO) films and YBCO/PBCTO multilayers grown *in-situ* on (100) LSGO substrates with PBCO template layer. Furthermore, we report on the successful growth of all in-plane oriented *a*-axis YBCO/PBCTO/YBCO trilayer structures (SIS junction), and we also observed obvious superconductive gap structures in the junctions.

## Experimental

The PBCTO and YBCO films and PBCO template layer were grown by a pulsed ArF excimer laser deposition technique. The excimer laser (193nm) was used at a repetition rate of 10Hz. The fluence on the target was approximately 1J/$cm^2$. The target for YBCO was a sintered $YBa_2Cu_{3.5}O_y$ pellet and the targets for PBCTO and PBCO was a $PrBa_2Cu_2TiO_z$ and $PrBa_2Cu_3O_z$ pellets. The same deposition conditions were used for YBCO, PBCTO and PBCO, namely, an oxygen pressure of 30 mTorr (containing 8% $O_3$), and a substrate temperature of 700℃. The average deposition rates were approximately 20 Å/min for PBCTO and PBCO, and 18 Å/min for YBCO. Immediately after deposition, the samples were cooled during 1 hr to 100℃ in the same oxygen+ ozone ambient.

## Results and Discussion

Figure 1 shows the temperature dependence of the resistivity for the *a*-axis oriented PBCTO film with that for the *a*-axis oriented PBNCO and PBCO films on the (100) $SrTiO_3$ substrate. The resistivity of PBCTO drastically increases to values of the order of $10^5$ Ωcm at 100 K and $10^7$ Ωcm at 50 K, respectively. This value is 5 orders of magnitude higher than that of the PBCO and one order of magnitude higher than that of the PBCNO film [8]. This high resistivity indicates that PBCTO is a good insulating layer and an attractive candidate material for thin film heterostructures made of *a*-axis oriented YBCO film.

To produce in-plane aligned *a*-axis trilayer structures, we first deposited PBCO of 400 Å as an *a*-axis oriented template layer on the (100) LSGO substrate [7]. Figure 2 shows the X-ray diffraction spectra (XRD) for YBCO/PBCTO and PBTCO/YBCO bilayer structures and YBCO/PBCTO/YBCO trilayer structure. The thickness of YBCO and PBTCO films are 500 Å. Only the (*h*00) diffraction peaks of YBCO and PBCTO can be observed besides the peaks of the substrate, indicating *a*-axis oriented YBCO and PBCTO layers.

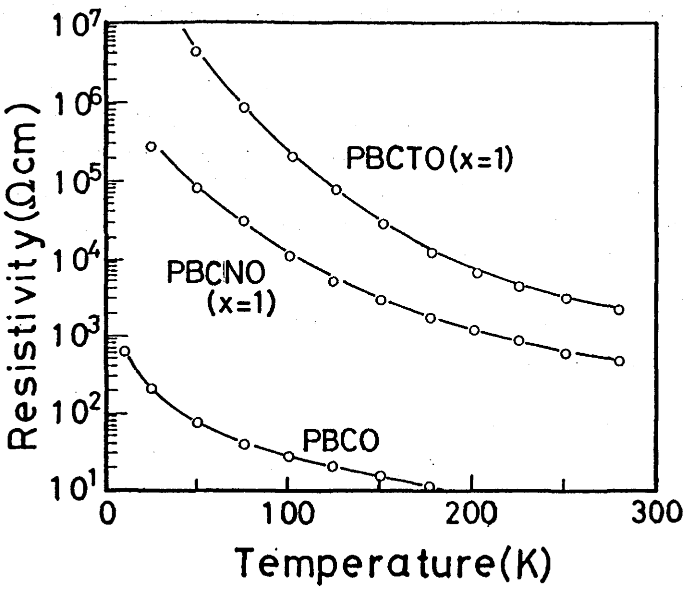


Fig. 1. Temperature dependence of the resistivity for PBCTO film together with the resistivity vs temperature curves for the PBCNO and PBCO films.

A $\phi$-scan [(102)YBCO] for YBCO (1000Å) / PBCTO (500Å) /YBCO (1000Å)/ PBCO (400Å) / substrate heterostructure is shown Fig. 3. The strong peaks 180° apart indicate a twofold symmetry. This proves that the films are a pure *a*-axis oriented one with its *b* and *c*-axes aligned in-plane on the (100) substrate surface. Figure 4 shows the temperature dependence of the electrical resistance for the *c*-axis and *b*-axis directions of the epitaxial top YBCO film in SIS structure, corresponding to the [001] and [010] substrate azimuths, respectively. The zero resistance temperature is 89.0 K in both directions. Both directions show metallic behavior, and the resistance in the *c*-axis direction is about two times larger than that in the *b*-axis direction. These results also show that the formation of in-plane aligned all *a*-axis SIS epitaxial trilayer is achived in the present structure (7).

We have fabricated a sandwich-type SIS tunnel junction in order to measure the resistance (*R*) versus temperature (*T*) curves for a PBCTO insulator layer embedded between top and bottom YBCO layers and superconductive gap structure. The tunnel junctions were fabricated as follows using an *in-situ* metal mask exchange system. : First, a stripline was prepared as the YBCO bottom layer on the PBCO// (100) LSGO through a metal mask. Then, another metal mask was placed on the YBCO bottom layer, and the PBCTO insulating layer was deposited. Finally, a YBCO top layer was deposited through a metal mask. The detailed composition of the tunneling junction YBCO/PBCTO/YBCO is shown in Fig. 5. The junction area was about 50×50 $\mu m^2$. The junction consists of a 2000 Å-thick YBCO bottom and top layer, and a 500 Å, 450 Å and 400 Å-thick PBCTO insulating layer. Typical *R*-*T* curves of these SIS junctions were shown in Fig. 6. The clear drop in the resistance is observed at 90K, corresponding to the onset of superconductivity in the YBCO top and bottom layers. Also, this figure shows that the insulating quality of the 500 Å-thick PBCTO layer is high, approximately 14 kΩ at 50 K, corresponding to $\rho \cong 10^5$ Ωcm. This value indicates that the PBCTO film is an excellent insulating layer for SIS tunnel junctions. However, that of the 450 Å and 400 Å-thick interlayer are about $10^2$ Ωcm at 50 K, and it can be clearly seen from the insets in Fig. 5 that the residual resistance is due to the PBCTO insulating layers and decreases slightly with a metal-like temperature dependence. This value is three orders of smaller than that of 500 Å-thick PBCTO layer. The low resistivity for PBCTO layer suggests that, possibly interdiffusion occured between the YBCO and PBCTO layers. or a residual oxygen deficiency. Similar behavior has been observed, however, for sandwich structures containing a different material as a barrier layer[3],[4].

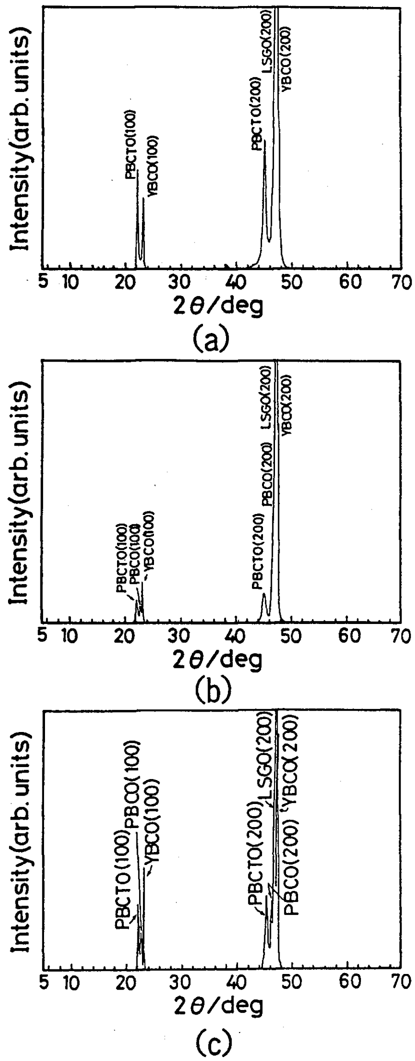


Fig. 2. X-ray diffraction patterns of (a) YBCO/PBCTO // (100) LSGO, (b) PBCTO/YBCO/PBCO// (100) LSGO and (c) YBCO/PBCTO/YBCO/PBCO//(100) LSGO.

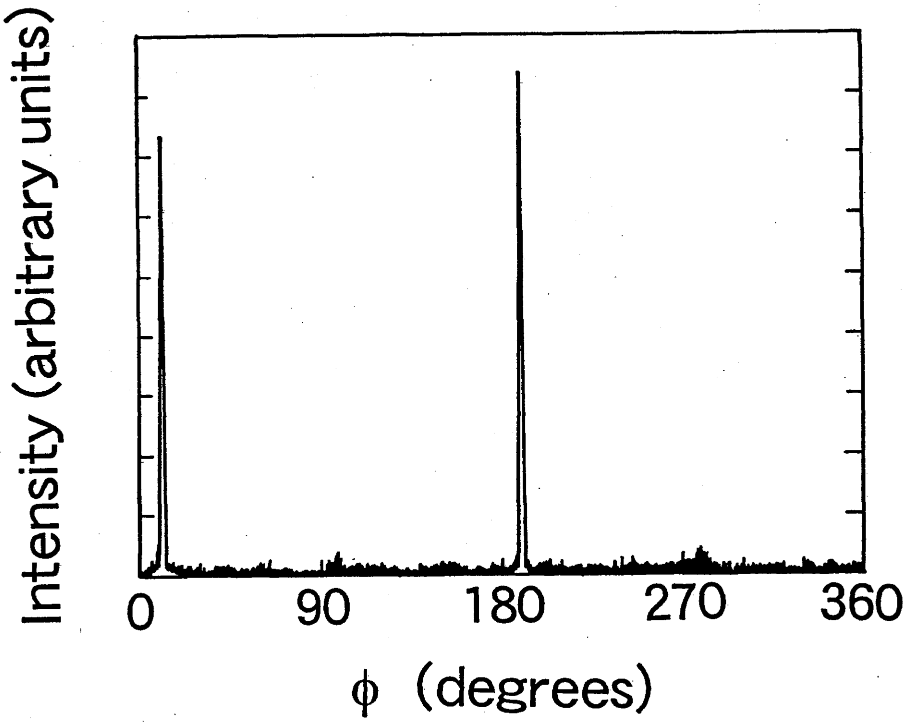


Fig. 3. The x-ray $\phi$-scanned diffraction pattern of (102) peak of YBCO of an $a$-axis YBCO (1000Å)/PBCTO (500Å)/ YBCO (1000Å)/PBCO (400Å) heterostructure on (100) LSGO substrate. Peaks at integer multiples of $\pi$ indicate twofold symmetry.

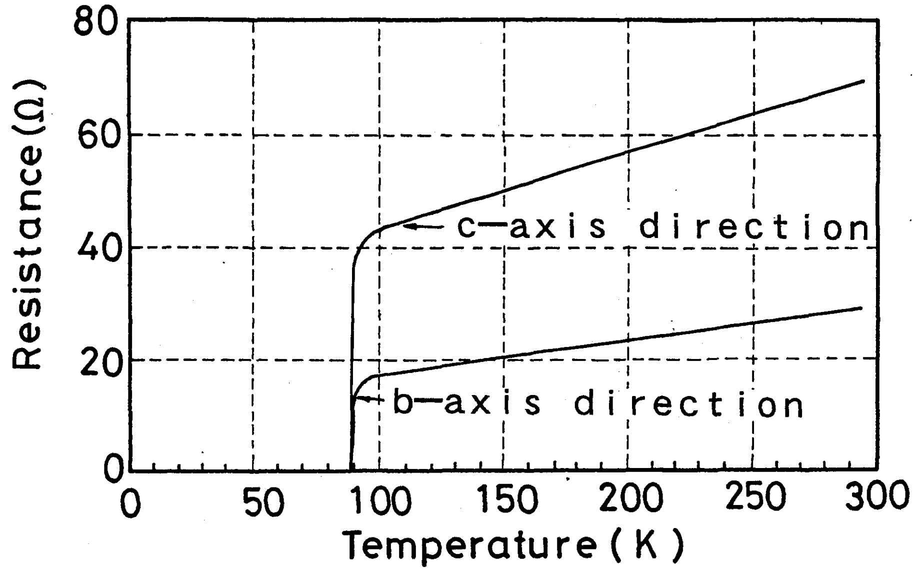


Fig. 4. Temperature dependence of resistance in the $c$-axis and $b$-axis directions for a top YBCO film grown on PBCTO/ YBCO/PBCO// (100) LSGO.

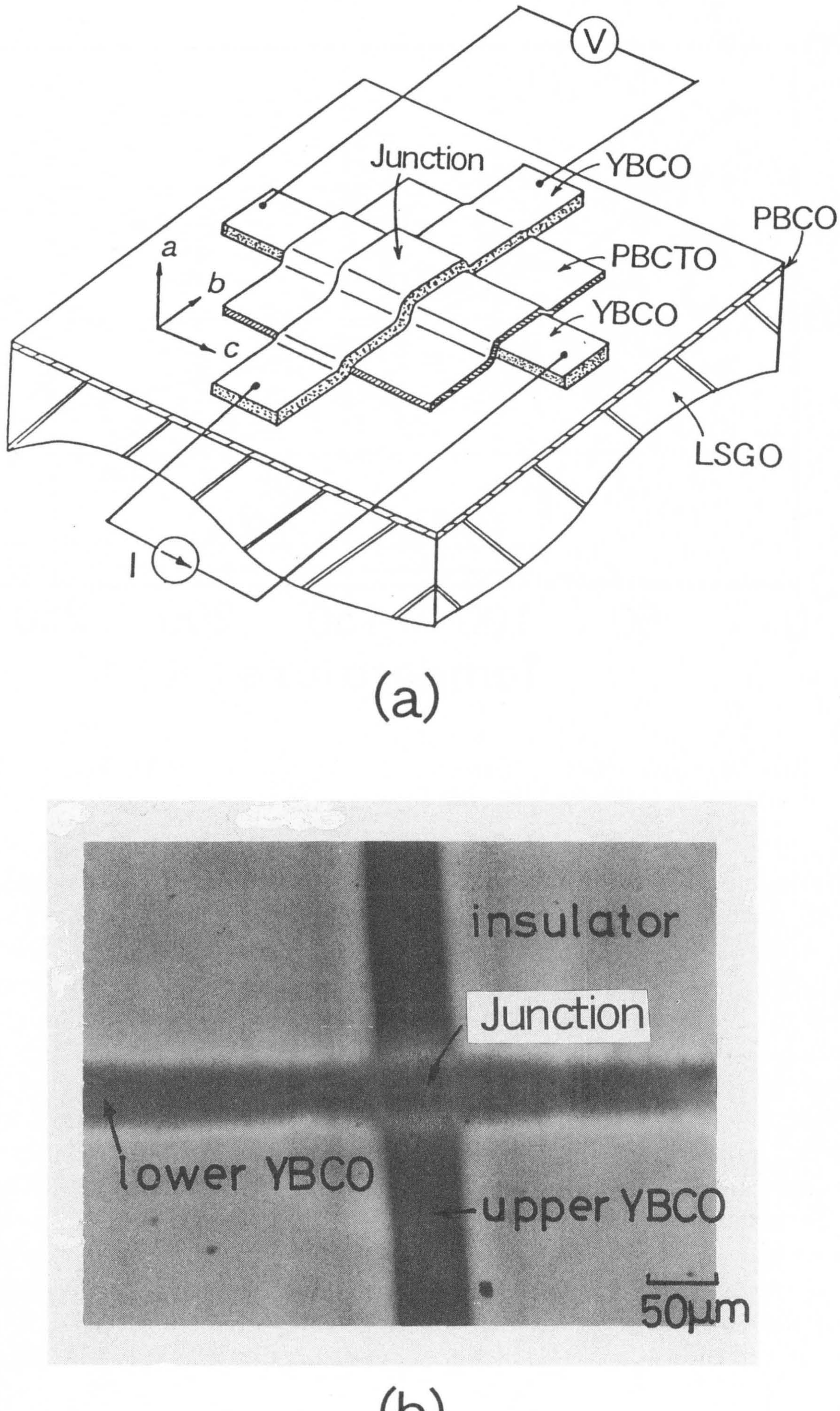


Fig. 5. Schematic composition (a) and micrograph (b) of a YBCO/PBCTO/YBCO junction. The tunneling region is the crossed area of 50×50 $\mu m^2$.

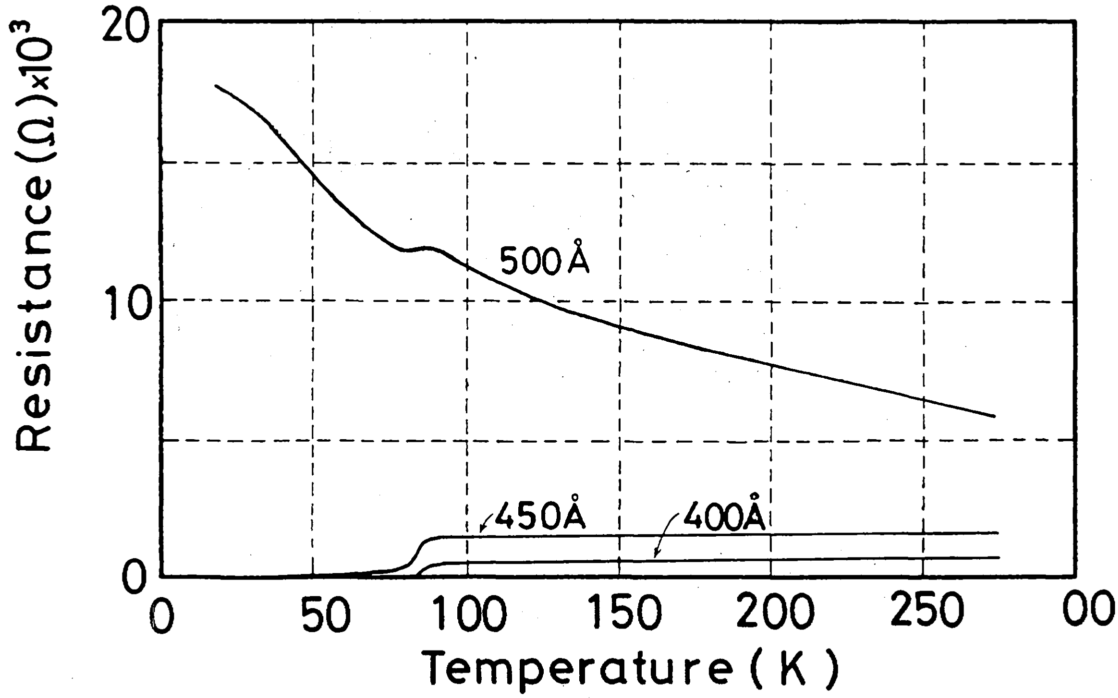


Fig. 6. Resistance ($R$) versus temperature ($T$) curves of an YBCO/PBCTO/YBCO junctions on a PBCO//(100) LSGO.

The differential conductance of the barrier, *i.e.*, $dI/dV$ vs. $V$, was studied as a function of temperature for the YBCO/PBCTO/YBCO junction. The typical result for a 400 Å-thick insulating layer is shown Fig. 7. In general, the observed gap structures did not resemble the typical BCS curves, however, a gap structures with $2\Delta=26$mV (indicate by the arrow in figure), denoted by $V_g$ developed below 45K, significantly lower than the $T_c$ of ($T_c$=90K). We also observed a zero-bias conductance peak (ZBCP) develops rapidly below 90K, and the gaplike structure opens at about 45K and lower. The ZBCP is often observed in high-$T_c$ superconductor tunnel junction spectra [9], [10]. Although several models to explain the ZBCP have been discussed [11]-[14], it is not yet clarified. Note that the ZBCP disappeared above $T_c$. Thus the observed phenomena can be explained in terms of a transmission processes of $d_{x^2-y^2}$ wave superconductor with $\alpha \neq 0$ [13] [14], where $\alpha$ is the angle between the normal to the interface and the $a$-axis of the superconductor. In the case of sandwich-type SIS tunnel junction, these condition ($\alpha \neq 0$) happen to roughness at the interface or tunnel process from the side-edge of junction.

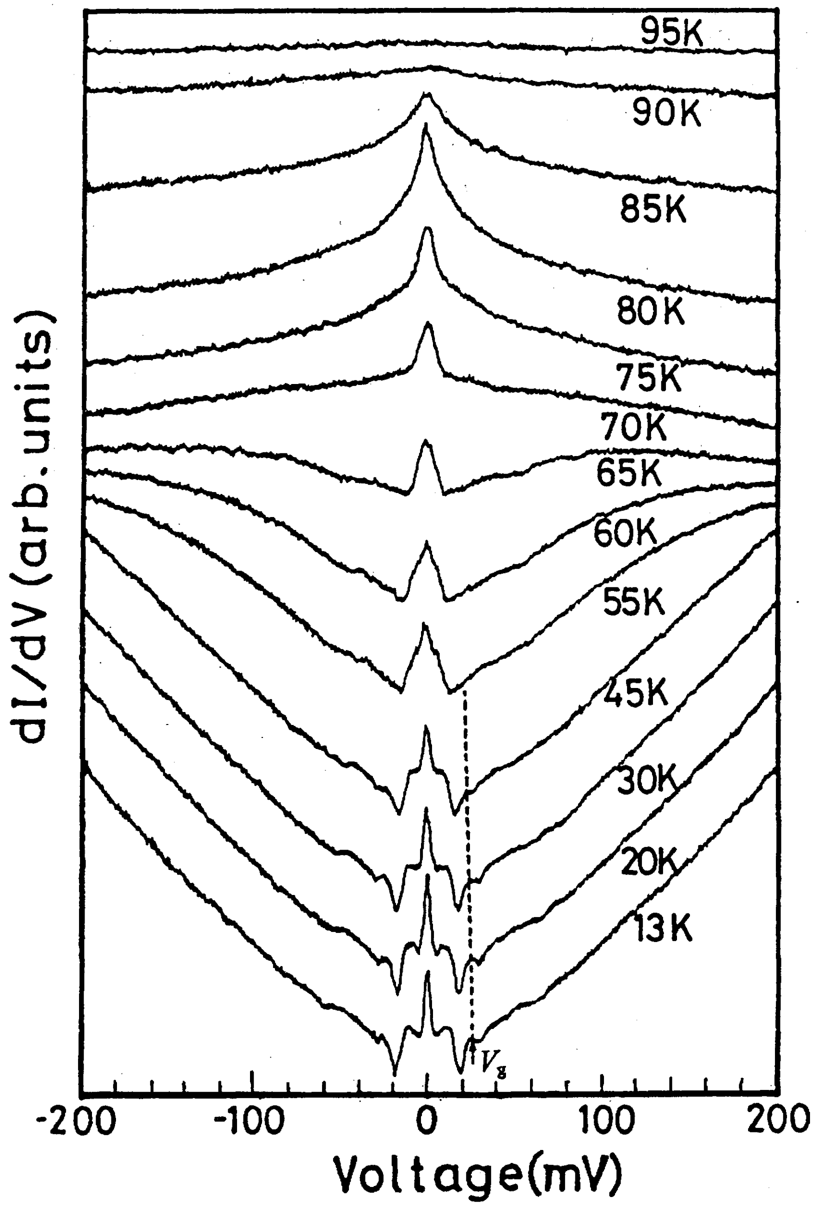


Fig. 7. Typical characteristics of $dI/dV$ - voltage ($V$) in tunnel junction fabricate on PBCO⫽(100) LSGO for various temperatures.

## Summary

In summary, we have successfully grown $a$-axis oriented films of PBCTO that have a high resistivity ($\rho \cong 10^5$ $\Omega$cm at 100 K), and heteroepitaxial structures of (100) YBCO/ (100) PBCTO and (100) PBCTO/ (100) YBCO bilayers, and (100) YBCO/ (100) PBCTO/ (100) YBCO trilayer, using an pulsed laser deposition technique. These YBCO/PBCTO multilayers have in-plane aligned $a$-axis oriented structures. Also, a sandwich type YBCO/ PBCTO/ YBCO (SIS) tunnel junction with 400 Å-thick PBCTO insulating layer shows a clear gap structure at temperature below 45K. We conclude that PBCTO is compatible with YBCO and is a good candidate as an insulator in YBCO multilayer systems.

## References


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## 和文抄録


面内配向 all-$a$ 軸 $YBa_2Cu_3O_{7-y}$／$PrBa_2Cu_2TiO_z$／$YBa_2Cu_3O_{7-y}$
トンネル接合の作製

$a$-軸配向 $PrBa_2Cu_2TiO_z$（PBCTO）薄膜と all-$a$ 軸配向 $YBa_2Cu_3O_{7-y}$（YBCO）-PBCTO の積層膜をパルスレーザー成膜法によって成膜した。PBCTO 膜の抵抗率は50K で $10^7$ Ωcm、100K で$10^5$ Ωcm の値に達した。この高い抵抗率は PBCTO が良好な絶縁体であり、そして $a$ 軸配向 YBCO と薄膜ヘテロ構造をつくるための魅力的な材料であること示している。基板として（100）$LaSrGaO_4$（LSGO）を、テンプレート層として $PrBa_2Cu_3O_x$（PBCO）を用いることにより、（100）YBCO／（100）PBCTO と（100）PBCTO／（100）YBCO の 2 層構造と（100）YBCO／（100）PBCTO／（100）YBCO の 3 層構造を作製した。（102）YBCO 面からの反射を用いた $\phi$ スキャン X 線測定は、2 回の対称性を示した。また、3 層構造の上部の YBCO は電気抵抗の異方性を示し、$c$- 軸方向の抵抗値は $b$- 軸方向の抵抗値の約 2 倍大きかった。これらの結果は、面内配向 all-$a$ 軸 SIS の形成が現在の構造で実現できたことを示している。さらに、YBCO／PBCTO／TBCO の 3 層構造をもつ SIS トンネル接合を作製し、そして400Å 厚の PBCTO の中間層をもつ接合に対して26mV 付近に明白な超伝導ギャップ構造を観測した。