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Proximity Effect of $YBa_2Cu_3O_x$

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The properties of $PrBa_2Cu_3O_x$ (PBCO) thin films and the proximity effect in $PrBa_2Cu_3O_x/YBa_2Cu_3O_x$ (PBCO/YBCO) double layer films are investigated. The resistivity of the PBCO thin film is changed by modifying the depositing conditions. A metastable state appeared in the PBCO thin film when it is prepared in a rapid cooling process. Such PBCO films show the lower resistivity and anisotropy. The *c*-axis length of PBCO film is related to the resistivity of the film. The superconductivity of YBCO film is improved by PBCO in the *c*-axis oriented double layer film. The diamagnetic moment of YBCO film is increased by lattice matching with PBCO film. The critical temperature of YBCO film is elevated by the oxygen supplied by the PBCO film. Probably the properties of YBCO/PBCO/YBCO type Josephson junctions are determined by the lattice constant and the oxygen content in YBCO and PBCO films.

I. INTRODUCTION

Josephson junctions made of oxide materials, such as $YBa_2Cu_3O_x/PrBa_2Cu_3O_x/YBa_2Cu_3O_x$ (YBCO/PBCO/YBCO) junctions, show superconducting coupling through the PBCO barrier even if the barrier thickness is much thicker than the coherent length of YBCO.[1-4] When the super current flows parallel to the *c*-axis, the junction reveals the flux-flow type current-voltage (I-V) characteristics with no magnetic dependence of the critical current (I_c).[1,2] This means that these junctions link as a superconductor but not as a Josephson junction. On the contrary, when the super current flows perpendicular to the *c*-axis, the junction shows the resistive shunted junction type I-V characteristics with a Fraunhofer-like magnetic response of the I_c.[3,4] Thus these junctions connect as a Josephson junction.

In this paper, we report about the proximity effect of PBCO and YBCO. First, we mention the conductive properties of PBCO thin films to consider the material as barrier layers. Then, we establish the relationship between the PBCO film resistivity and its lattice constant. The proximity effect is related with the PBCO/YBCO double layer structure. We study the crystal structure of the double layer film by analyzing the X-ray diffraction (XRD) spectra and the laser Raman scattering spectra. Finally, we discuss about the contact of PBCO and YBCO films to confirm the proximity effect.

II. CONDUCTANCE PROPERTY OF PBCO

To investigate the properties of PBCO thin films, we prepared them on $SrTiO_3$(STO) substrates by the rf magnetron sputtering method. The orientation of PBCO film was (100) on STO (100) when deposited at 650°C and the thickness was 370nm. The resistivity-temperature (ρ-T) characteristics of PBCO films are shown in Fig. 1. The PBCO film shows the different property from PBCO bulks when PBCO film is sputtered at low pressure (0.5Pa) and cooled rapidly within an hour just after the deposition. The PBCO film in this state has a lower resistivity than a normal state PBCO. The resistivity of PBCO film grows and comes near to the values of orthorhombic phase PBCO bulks[5] after that the PBCO film in the state is oxidized at 300°C in 1 atm. oxygen flowing atmosphere for an hour. Furthermore, the PBCO film gets the highest resistivity, close to the values of tetragonal phase PBCO bulks[5] after reduction at 450°C in vacuum for an hour.

Therefore, we conclude that the PBCO film reaches a metastable state.

From an XRD analysis of PBCO film, we found that the resistivity is related to the *c*-axis length of PBCO film. PBCO film shows low resistivity when the *c*-axis length is short, and high resistivity when it is long.

PBCO (013) films were obtained on STO (110) substrate at 650°C to research anisotropy of PBCO film in the metastable state. The thickness of (013) PBCO film was 370nm. Figure 2 shows the anisotropy of the metastable state PBCO films with the ρ-T characteristics. The PBCO film has the lowest resistivity toward *c*-plane and the highest resistivity toward *c*-axis in

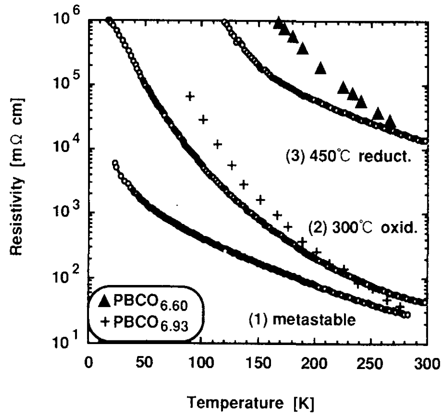

Fig. 1. Resistivity-temperature characteristics of the metastable state PBCO thin film. (1) The metastable state PBCO film shows the lowest resistivity. (2) PBCO film is oxi-dized at 300°C in 1 atm. oxygen flowing atmosphere for 1 hour. (3) PBCO film is reduced at 450°C in vacuum for 1 hour. The cross (+) and solid triangle (▲) curves show the orthorhombic and tetragonal phase resistivities of PBCO bulks, respectively, see Ref. 5.

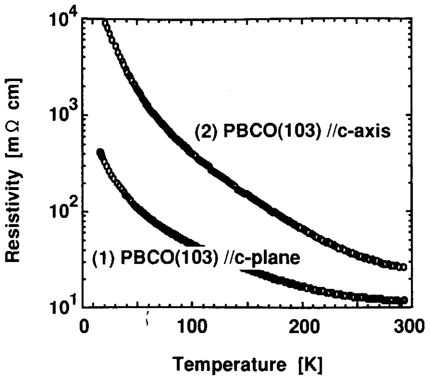

Fig. 2. The anisotropy of the metastable state PBCO thin films with the resistivity-temperature characteristics. (1) the resistivity toward *c*-plane in (013) film is the lowest. (2) the resistivity toward *c*-axis in (013) films is the highest.

(103) films. The anisotropy of the metastable state PBCO film is similar to that of the stable state PBCO film.

III. SUPERCONDUCTIVITY OF YBCO IN DOUBLE LAYER

In a YBCO/PBCO/YBCO type junction, micro-holes in the barrier layer and inter diffusions are the issues to discuss. On the contrary, in a PBCO/YBCO double layer structure, there is no need to consider micro-holes and there is no inter diffusions, as learned from Auger electron spectroscopy measurement. This allows to study the proximity effect.

PBCO and YBCO films were deposited on MgO (100) substrate by rf magnetron sputtering at 660°C and 650°C, respectively. The orientation of the film was (001) and the thickness of YBCO film was 300nm. We measured the AC susceptibility of the double layer film to inquire the proximity effect. The peak value of the magnetic field was 2A/m and the frequency was 313 Hz. The diamagnetic moment (μ) of superconductor is estimated from the measured voltage, since μ is proportional to the product of the susceptibility and the sample volume, that is, superconductivity varies with μ. The normalized diamagnetic moment (μ/μ_0) of YBCO film increases according to the PBCO film thickness, as shown in Fig. 3. The normalized critical temperature (T_c/T_{c0}) of YBCO film shows a constant increase of

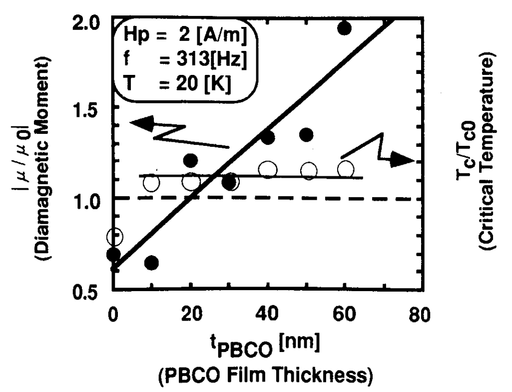

Fig. 3. Diamagnetic moment and critical temperature of YBCO film in PBCO/YBCO double layer structure, versus PBCO film thickness. Solid circles represent the normalized diamagnetic moment, and open circles the normalized critical temperature. The diamagnetic moment increases with the PBCO film thickness while the critical temperature remains constant with PBCO.

about 1.15 by the PBCO film deposition. As shown in Fig. 3, μ and T_c decrease at the point where PBCO film thickness equals 0nm, i.e., the YBCO film is taken just annealing without PBCO film deposition. These facts show that the superconductivity of YBCO film is improved by the PBCO film but weakened by the annealing.

For a detailed characterization of the crystal structure in PBCO/YBCO double layer films, XRD spectra and Raman spectra were measured. Figure 4 shows XRD spectra of (1) the single YBCO film, (2) the single PBCO film and (3) the PBCO/YBCO double layer film. From this figure, we have that the *c*-axis length is 1.187nm for the single YBCO film and the single PBCO film. The *c*-axis lengths of the PBCO/YBCO double layer films are 1.192nm for PBCO and 1.179nm for YBCO film. The *c*-axis length of YBCO film is reduced by PBCO film in the double layer film. On the other hand, the *c*-axis length of the PBCO film is enlarged by the YBCO film in the double layer film. These results suggest that the change of the *c*-axis length comes from a lattice matching between PBCO and YBCO or from oxygen diffusion of PBCO film to YBCO film. The Raman shift around 500cm^{-1} points out oxygen content in YBCO.[6,7] As shown in Fig. 5, the single YBCO film has just a 500cm^{-1} peak. The peak shifts to a higher value for the annealed YBCO film. This means that the YBCO film is provided with oxygen by annealing. The peak shifts to much higher values with double layer films. We conclude that the YBCO film is supplied with more oxygen by the PBCO film than by annealing but the content of oxygen does not depend on the PBCO film thickness. From this result, we consider that oxygen supply is not the cause of μ increase but the reason of T_c increase. Namely, the oxygen annealing causes the improvement of T_c and the lattice matching

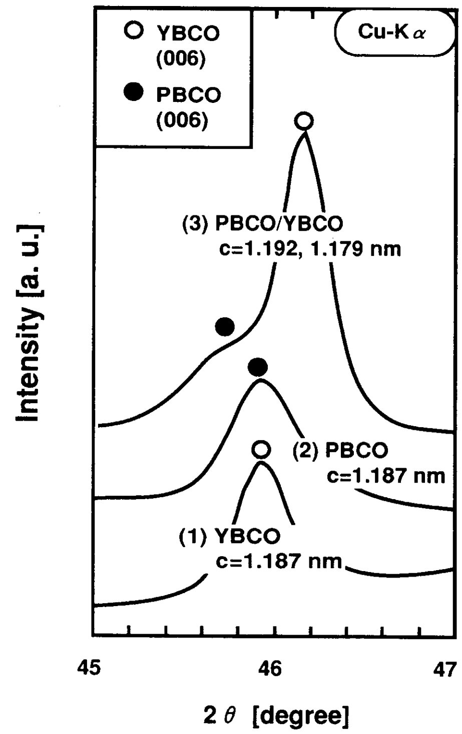

Fig 4. XRD spectra of thin films. (1) (006) peak of single YBCO film indicates a 1.187nm *c*-axis length. (2) (006) peak of single PBCO film also shows a 1.187nm *c*-axis length. (3) (006) peaks of PBCO/YBCO double layer film are at 1.192 and 1.179nm *c*-axis lengths, respectively.

causes the improvement of μ.

IV. CONTACT BETWEEN PBCO AND YBCO

In this section, we would like to discuss what happens at the interface between PBCO and YBCO films. In case of contact

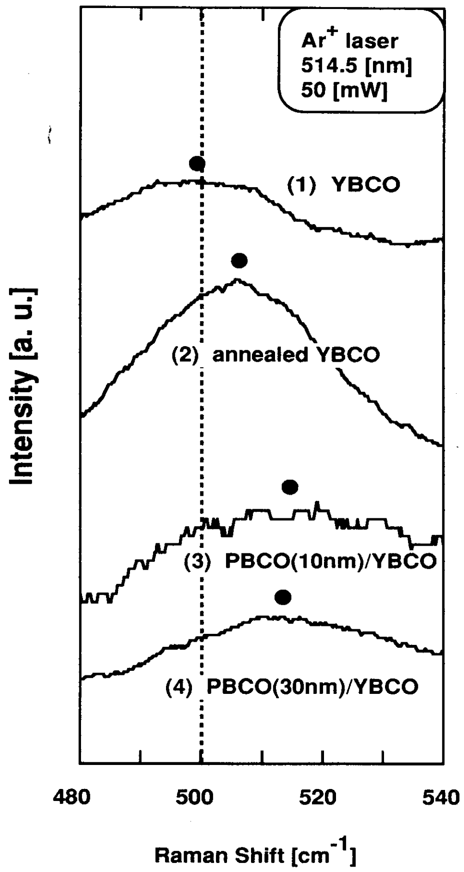

Fig. 5. Raman spectra of thin films. (1) the single YBCO film has a $500cm^{-1}$ peak that reveals oxygen content. (2) the annealed YBCO film is supplied with a little oxygen. (3) the YBCO film which is the base of a 10nm PBCO film is supplied with more oxygen than the annealed YBCO film. (4) the YBCO film which is the base of a 30nm PBCO film has the same oxygen content as the 10nm PBCO/YBCO film.

between PBCO and YBCO, we must concern lattice matching and oxygen diffusions.

A-axis and *b*-axis lattice length should match each other for the *c*-axis oriented PBCO/YBCO double layer films. From this view point, *a*-axis and *b*-axis lengths of PBCO films are shortened and those of YBCO films are enlarged. Because a unit cell in PBCO and YBCO films tries to preserve its volume, the *c*-axis length of PBCO film is stretched and that of the YBCO film is reduced. At the same time, PBCO films release oxygen and YBCO films receive oxygen. The superconductivity of YBCO film is enhanced by PBCO film and the resistivity of PBCO film must grow in the double layer film. Therefore, there are few possibilities that YBCO/PBCO/YBCO junctions have the Josephson coupling along to *c*-axis.

On the contrary, *c*-axis lattice length should match each other for the non *c*-axis oriented PBCO/YBCO double layer films. The *c*-axis length of PBCO film is shortened and that of YBCO film becomes longer. In this case, the resistivity of PBC-O film decreases or PBCO film reaches the metastable state in a double layer structure. Hence, YBCO/PBCO/YBCO junctions might have Josephson coupling along to *c*-plane.

V. CONCLUSIONS

We measured the PBCO thin film and the PBCO/YBCO double layer film to explain the mechanism of the proximity effect in YBCO/PBCO/YBCO type Josephson junctions. The PBCO thin film had a metastable state and the PBCO film in that state showed a lower resistivity than in a stable state PBCO. The *c*-axis length of PBCO film affects the PBCO film resistivity. A metastable state PBCO film showed that the anisotropy of its resistivity depends on its crystal directions. When PBCO and YBCO films touch each other, there occur a lattice matching and oxygen diffusion. In the case of *c*-axis oriented films, the lattice matching improved the diamagnetic moment of the YBCO films, and the oxygen diffusion made the critical temperature of YBCO films higher. Thus, PBCO films enhanced YBCO films and increase its resistivity parallel to *c*-axis. In the case of non *c*-axis oriented films, on the contrary, the resistivity of PBCO films were reduced. There is a possibility of the proximity effect parallel to *c*-plane.

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