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Structures and properties of buffer layers with nanometer thickness for PBCMO/YBCO epitaxial multilayers

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Abstract

Insulator buffer layer materials, $\text{PrBa}_2(\text{Cu}_{1-x}\text{M}_x)_3\text{O}_{7-\delta}$ (PBCMO), with $\text{M} = \text{Al}$ and Ga with different portions were synthesized to improve better buffer-layer materials for fabricating superconducting devices from $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ (YBCO) superconductor. Neutron and X-ray diffraction data reveal that the structures of PBCMO and YBCO are the same and their lattice parameters are well matched, while the resistivity shows that PBCMO have much higher resistivity than $\text{PrBa}_2\text{Cu}_3\text{O}_7$ (PBCO). Epitaxial multilayers of PBCMO/YBCO were fabricated by laser ablation to explore the effect of PBCMO layer thickness on YBCO superconducting layers. Superconductivity was not found above 4.2 K for one unit cell thickness of YBCO. As the thickness of PBCMO was varied with constant thickness of YBCO films, the transition temperature of the multilayers remains unchanged even though the PBCMO layer is made as thin as the unit cell of $12.5\text{\AA}$. The difference indicates that PBCMO is better buffer layer and is adequate to insulate YBCO films in the multilayers and to cut off the superconducting coupling between YBCO layers.

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1. Introduction

The discovery of high transition temperature (T_c) superconductors in ceramic compounds of cuprates has excited scientists and engineers in the areas of superconducting electronic devices and power technology. Since the critical

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temperatures of these superconductors are above liquid nitrogen (77 K), the high cost and burdensome facilities for liquid helium cooling are no longer needed. This should make superconducting devices much more engaging for commercial applications. For this reason, great effort has been put into the fabrication of high T_c Josephson junctions or superconductor-insulator-superconductor (SIS) Josephson junctions as parts of superconducting electronics such as superconducting quantum interference devices (SQUID) in medical applications.

Although great progress in high T_c devices has been made, the creation of a digital integrated-circuit technology based on high T_c Josephson junctions remains elusive. At the heart of this problem is the lack of reliability and reproducibility in the fabrication of Josephson junction, primarily due to the lack of ideal insulator layers. To date the majority of work has focused on the fabrication of SNS junctions, yet the devices are still commercially unavailable. The difficulty in making high T_c SIS Josephson junctions is their intrinsic short coherence length. For examples, the coherence lengths of YBCO are 5 Å and 40 Å in c-axis and ab-plane, respectively. The thickness of the insulator layer for the SIS junctions is restricted by these lengths. The ideal insulator layer for SIS junctions has to be made very thin yet still provides sufficient tunneling barrier and critical current for devices. PBMCO where M is Al or Ga is the choice for material insulator layer for the excellent lattice match [1-2] with same process of fabrication and thermal expansion coefficient. The excellent lattice matching reduces the strain of the YBCO film and thus preserves its high T_c . Identical processing conditions make fabrication of the multilayer sample, and the same thermal expansion coefficient prolongs the lifetime of the devices in temperature cycling. Experiments show that the resistivity of the original ceramic PBCO at 77 K is about 200 $\Omega\text{-cm}$ [3] and cannot provide a sufficient potential barrier for YBCO SIS junction unless the PBCO film is made thicker than 2,000 Å. Such an insulator layer will drastically reduce the critical current and makes the SIS junction inapplicable for devices. Fortunately, PBMCO has electrical resistivity of $1.43 \times 10^6 \Omega\text{-cm}$ which is 4 magnitude-orders of that of the ceramic PBCO samples [4]. For this reason PBCAO is considered a better insulator layer material for SIS Josephson junctions.

In this paper, we report the structures and properties of buffer layer materials, PBCMO, and superconductivity of PBCMO/YBCO epitaxial multilayers where M stands for Al or Ga.

2. Experimental procedures

Polycrystalline samples of YBCO and PBCMO, where M = Al, and Ga were synthesized by the solid state reaction. High-purity Y_2O_3 , Pr_6O_{11} , BaCO_3 , CuO , and Al_2O_3 , and Ga_2O_3 powders were mixed with appropriate amounts. Structural analysis was performed by x-ray powder diffraction (XRD) and neutron diffraction. After being found to be desired phases, the resultant powders were reground and pressed into pellets. High-quality epitaxial YBCO/PBCMO multilayers were grown on polished (110) NdGaO_3 (NGO) and LaAlO_3 (LAO) substrates by pulsed laser ablation. The system was equipped with a multitarget holder allowing different targets to be placed in the beam of KrF excimer pulse laser that might irradiate with wavelength of 248 nm with 30-ns pulses and 2-Hz repetition rate. The laser beam passed through a quartz window and focused on YBCO or PBCMO target inside a high-vacuum chamber. A quartz-crystal-thickness monitor was used to control the deposition process for calibration. The thickness of each layer was monitored during deposition by counting the number of pulses that irradiated on the target. The deposition rate could be varied from 0.2 to 1.0 Å per pulse depending on the intensity of the laser beam and the target-to-substrate distance. The PBCMO template or base layer was deposited first before depositing the YBCO layers and making the multilayers on the top of the PBCMO layers. During the deposition process PBCMO base layers, an ambient O_2 pressure of 200 millitorr was applied. The energy density of the laser beam at the target site was approximately 1.5 J/cm^2 , the temperature of the substrate was set at 700 °C, and the substrate-to-target distance was fixed at 6.00 cm. The 60 Å PBCMO layer was deposited first to serve as the base layer. Second, the substrate temperature was raised to 750 °C at the rate of 25 °C per minute while a varied thickness layer of YBCO was deposited over the base layer. The second layer (YBCO) was deposited at the rate of approximately 1.0 Å per pulse. Finally, 200 Å PBCMO layer was deposited on the top of the second layer. Rotating the targets in multilayer deposition has significantly improved the homogeneity and thickness uniformity of the multilayers. After completing the deposition of each layer, the deposition process was paused to allow the film to relax for 100 seconds. This step improves the surface morphology of the multilayers. After the desired multilayers were completed, the chamber was filled with the pure- O_2 pressure of 1 Torr and the samples in the chamber were cooled

down to room temperature within 30 minutes. Structure and orientation of the multilayers were characterized by X-ray diffraction. The resistivity of the multilayers was measured by a standard four-probe method.

3. Results and discussion

The powder X-ray diffraction patterns of pure PBCO and PBCMO samples are shown in Fig. 1. They mainly show a single phase. The XRD data were analyzed in either orthorhombic Pmmm or tetragonal P4/mmm space group by Rietveld refinement method to obtain lattice parameters. The initial values of structure parameters for refinement were obtained from previous study by Williams et al [7]. The structures of YBCO and pure PBCO were orthorhombic and the lattice parameters a , b , and c of 3.82 Å, 3.88 Å, and 11.68 Å, respectively for YBCO and 3.86 Å, 3.90 Å, and 11.71 Å, respectively for PBCO. The structure of the samples is orthorhombic at low levels of the dopants while the structure of the samples becomes tetragonal at high levels of the dopants.

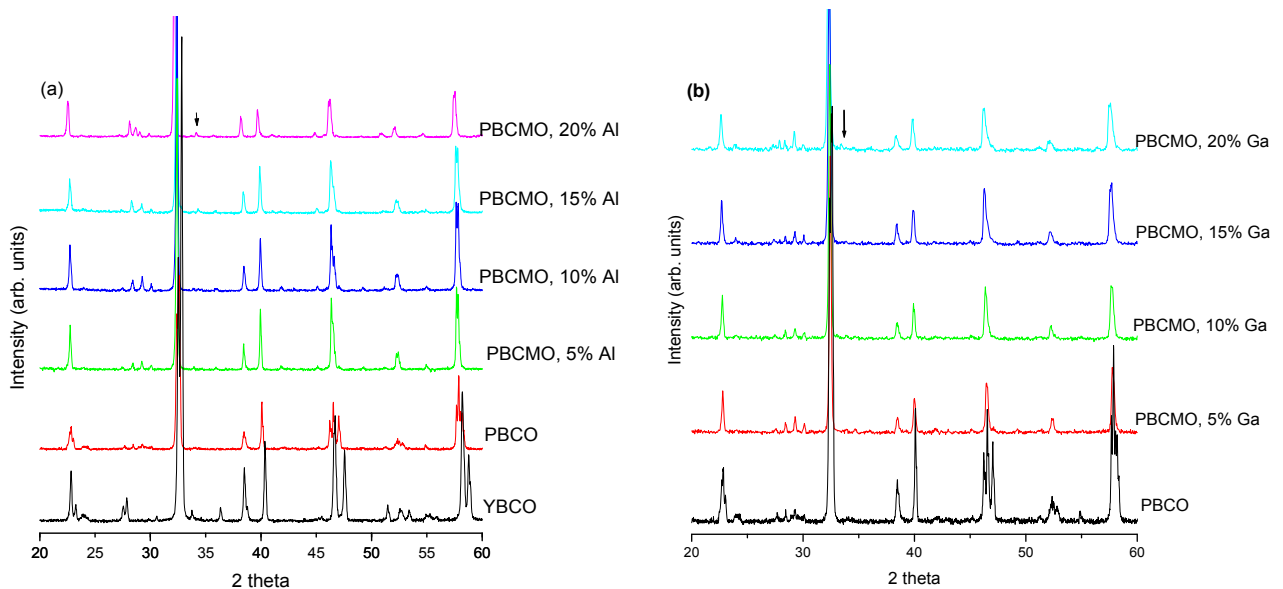


Fig. 1. X-ray diffraction patterns of pure YBCO, PBCO and PBCMO of (a) $M = \text{Al}$ and (b) $M = \text{Ga}$. The arrow indicates the impurity phase.

The PBCMO and YBCO thin films on NGO and ALO substrates show high quality of c -axis epitaxy in our previous reports [4-5]. Previous reports on YBCO/PBCO multilayers [6] showed that for a given thickness of YBCO film, T_c of multilayers decreases when the thickness of PBCO insulator layers increases. This result may be explained by the existence of proximity effect between YBCO superconductor layer and PBCO insulator layer [5, 8]. The decrease of T_c as the decrease of YBCO thickness can also be explained by proximity effect due to the fact that migration of superconducting electrons from YBCO film to PBCO film lowers the density of the superconducting electrons and consequently T_c decreases.

The resistivity data of tri-layers of PBCMO (60Å)/YBCO(dÅ)/PBCMO (200Å), $M =$ with variation of YBCO thickness are shown in Fig. 2. The transition temperatures of different thickness of YBCO layer are almost 90 K. The data show that no superconductivity was observed above 4.2 K for multilayers made of 12.5 Å thick films for both $M = \text{Al}$ and Ga . The measurements on five-layers, seven-layers, and nine-layers of these systems made of 12.5 Å thick YBCO also show no conductivity above 4.2 K. The results show that one-unit-cell thickness, 12.5 Å, of YBCO thin film itself cannot generate superconductivity. YBCO samples made of more than one unit-cell thickness are needed for occurrence of superconductivity. It is not clear whether stress from the substrate destroys the superconductivity or two-dimensional superconductivity does not exist in YBCO superconductor. The transition temperatures of the multilayers are shown in Fig. 3. However, tri-layers, five-layers, and seven-layers of

YBCO/PBCMO with different thickness of PBCMO insulator layers exhibit no different onset T_{cs} indicating the 20% Al and 20% Ga films provide adequate insulating to prevent YBCO superconducting electrons from migrating into the PBCO layers.

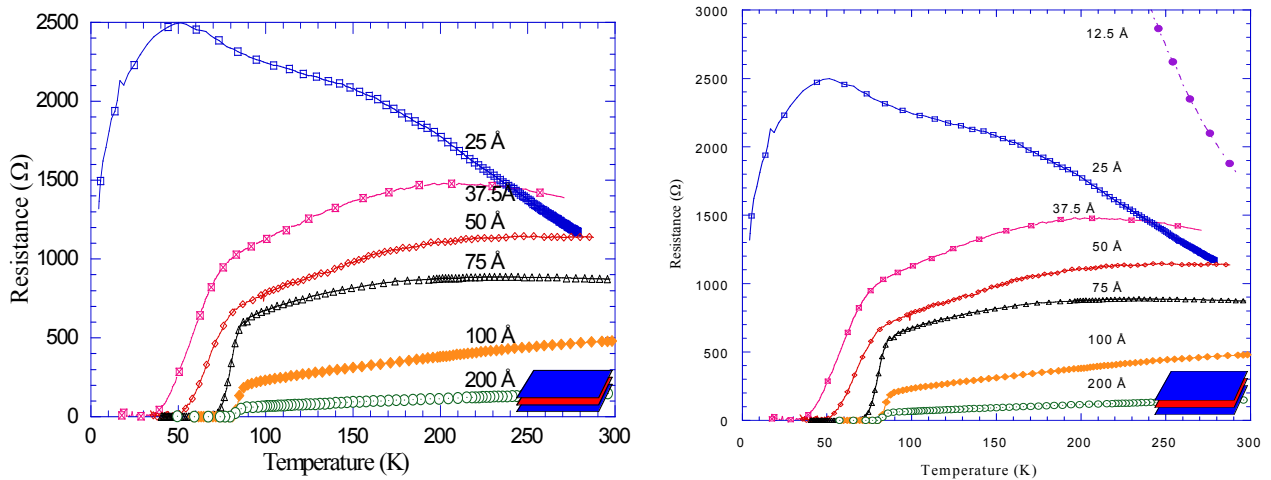


Fig. 2. Plots of Temperature versus dc resistance for 3 layers PBCMO/YBCO(d Å)/PBCMO with the variation of YBCO thickness d = 25, 37.5, 50, 75, 100, and 200 Å (a) M = 20% Al and (b) M = 20% Ga.

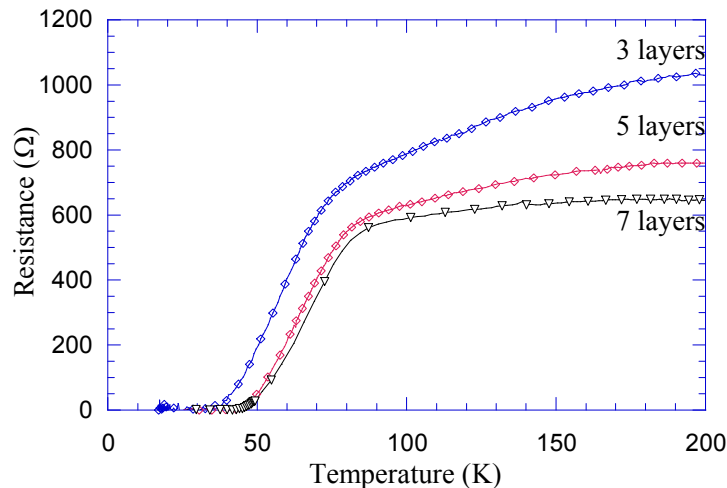


Fig. 3. Plots of temperature versus dc resistance for 3, 5, and 7 layers with YBCO and PBCMO thickness of 37.5 Å and 60 Å, respectively: 3-layers as shown, BCMO/YBCO/ PBCMO, 5-layers, PBCMO/YBCO/PBCMO/ YBCO/PBCMO, and 7-layers PBCMO/ YBCO/PBCMO/YBCO/ PBCMO/ YBCO/ PBCMO. The onset T_{cs} of multilayers are not different.

4. Conclusion

The target materials of insulator layers, $\text{PrBa}_2(\text{Cu}_{1-x}\text{M}_x)_3\text{O}_{7-\delta}$ (PBCMO), with M = Al and Ga, and x = 0.20 were prepared by solid-state reaction. XRD and neutron diffraction data show that the structure of the targets is orthorhombic and their lattice parameters match those of YBCO superconductor. We also fabricated multilayers of PBCO/YBCMO by laser deposition and the films show c-axis epitaxy. PBCMO film can prevent YBCO superconducting electrons from penetrating into PBCMO layers. Therefore, the PBCMO films will be an ideal insulator layer for making high-temperature superconductor Josephson junctions.

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