SACSST 2009 Proceedings (ISBN 978-0-620-43865-0)

PBCO/YBCO bilayer growth and optimization for the fabrication of buffered step-edge Josephson Junctions

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***Abstract*— Bilayers of $PrBa_2Cu_3O_{7-\delta}$ and $YBa_2Cu_3O_{7-\delta}$ are grown epitaxially on MgO substrates using Pulsed Laser Deposition. We discuss the entire optimization process in detail, giving quantitative parameter values. Film characterization included X-ray diffraction (XRD), Atomic Force Microscopy (AFM) and susceptance tests. The optimal process yielded bilayer structures which can be utilized in the fabrication of novel buffered step-edge Josephson junctions.**

Index Terms—**bilayer, PLD, step-edge junction, XRD, AFM**

I. INTRODUCTION

$YBa_2Cu_3O_{7-\delta}$ (YBCO) thin film based Josephson junctions are now routinely used in various superconducting electronic devices [1-3]. The deposition techniques for YBCO thin film growth are very well optimized, enabling such junctions to be operated at liquid nitrogen temperatures [4-6]. Of the several junction topologies available, step-edge junctions (SEJ's) are very promising because they can be easily integrated into small and large scale electronic circuits [7]. Optimization of the step-fabrication parameters remains an intriguing research field, which in turn can produce more easily manufacturable SEJ's with improved quality.

The manufacturing process of a step-edge junction involves etching of a step-edge into a suitable substrate (like MgO) before the epitaxial growth of YBCO over the step-edge template. Etch rates of oxide substrates like MgO are very slow as compared to that of typical photoresists used. To overcome this substrate's slow etch rate problem, we proposed a buffered step-edge [8] structure. Essentially a buffer layer which is crystallographically compatible with the YBCO, and which possesses a faster etch rate than the substrates used for film deposition, was used. An ideal buffer layer was found by us in $PrBa_2Cu_3O_{7-\delta}$ (PBCO) [8].

PBCO has a crystallographic structure almost identical to $YBa_2Cu_3O_{7-\delta}$ (YBCO) with comparable values of the lattice parameters. Furthermore, PBCO is not metallic; its resistivity is high at room temperature and increases at low temperature (semiconducting behaviour) without any trace of a transition to a superconducting state. These properties make this material ideal for a buffer layer. The etch rate of PBCO should also be quite similar to that of YBCO, which is much higher than that of oxide-substrates.

Possible problems that can occur when a PBCO buffer layer is used, are Pr/Y interdiffusion, and charge transfer from the YBCO to the PBCO layer. Interdiffusion of Pr may lead to doping at Y-site and depression of T_c. For example a 35% and 50% doping of Pr at Y-site can depress T_c to ~ 50K and 20K respectively [9,10] for the resulting alloy. Charge transfer from the YBCO to the PBCO layer would also result in a decrease of the transition temperature [11]. Fortunately, these effects should not have a significant effect when a reasonably thick YBCO layer is deposited over the PBCO. However, one may encounter several problems during the course of the growth of these bilayers. The thickness of the PBCO/YBCO superlattice could possibly approach critical values where microcracks can start to become a factor. The added surface roughness introduced by using a buffer layer will possibly lead to structural defects in the superconducting YBCO layer, reducing its current-carrying abilities and critical temperature. For this reason, it was necessary to pay special attention to the epitaxy and surface quality of the deposited PBCO layer. In this paper we give complete optimization details of the thin film growth of PBCO/YBCO bilayer structures.

II. PBCO FABRICATION

A. *Pulsed Laser Deposition*

A Pulsed Laser Deposition (PLD) system equipped with a pulsed oxygen valve was used to deposit the PBCO layers onto the MgO substrates. For this purpose, a planar $PrBa_2Cu_3O_{7-\delta}$ target was created using the standard solid state route [8]. A comprehensive study on the deposition conditions of PBCO on MgO substrates could not be found in literature. Consequently, it seemed reasonable to use the deposition parameters similar to those used in a standard YBCO deposition. Optimization of the deposition parameters was restricted to temperature variation due to its dominating effect on surface quality. The temperature variation was over the temperature range 700-800°C. Each deposition was performed for 15 minutes, corresponding to a layer thickness of around 250 nm. Characterization of six buffer layers was done through XRD and AFM analysis.

B. *Film Optimization*

XRD results confirmed that c-axis PBCO favours deposition at lower temperatures than YBCO. The layer deposited at 700°C showed excellent c-axis crystallinity. From Fig. 1 we can clearly see that prominent (00l) peaks

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without any prominent secondary phases or a-axis growth being present.

As the deposition temperature was raised, the introduction of unwanted peaks was observed. This included a prominent (110) peak at 32.7°, others at 60° and 68.12° (see Fig.2).

AFM analysis confirmed the presence of droplets characteristic to the PLD process. A definite difference in growth modes was observed for higher temperatures. It would seem that the presence of edge dislocations are more prominent at higher temperature, which coincides with the rougher surface obtained. This is clearly illustrated in Fig. 3.

The results for the measured AFM roughness are summarized in Table I.

A surface roughness of only 7 nm was obtained for the film deposited at 700°C. This deposition temperature was therefore chosen as optimal from both a crystallinity and surface quality perspective (see Table II for optimal parameter set). A 25° step edge is then milled on the PBCO film and annealed as discussed elsewhere [8]. Over this PBCO step-edge template an YBCO thin film is deposited.

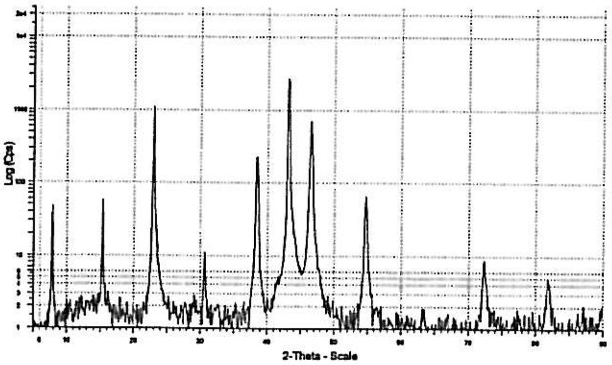

Fig. 1. XRD analysis of a PBCO thin film deposited at 700°C.

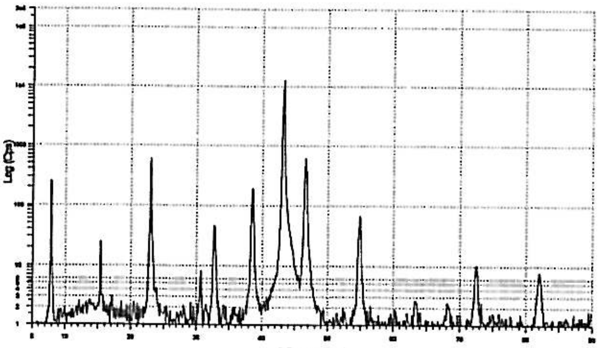

Fig. 2. XRD analysis of a PBCO thin film deposited at 720°C.

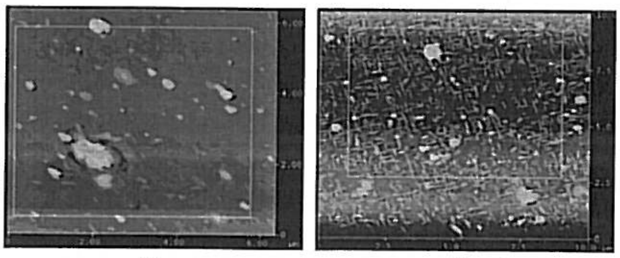
(a) (b)

Fig. 3. AFM analysis of PBCO thin films deposited at (a) 700°C and (b) 720°C.

III. YBCO THIN FILM DEPOSITION

After the step was annealed, a superconducting YBCO layer was deposited by pulsed reactive crossed beam laser ablation [8] [12]. This deposited thin film has to possess certain desirable qualities. These include a T_c as close to 90 K as possible, a small transition temperature range (ΔT), good surface roughness and pure c-axis growth. To ensure proper step coverage and to minimize chip-to-chip parameter drifts, the film thickness should also be uniform over the substrate. PLD is, however, renowned for producing small-area uniformity, necessitating very good alignment of the plume and substrate. Magnetron sputtering was not used for step-edge film coverage due to reports that the growth mechanisms can be unpredictable and not suited for producing step-edge junctions [13]. The unavailability of Transmission Electron Microscopy (TEM) analysis would also have limited characterizing such a process.

To realize an operational Josephson junction, the thickness of the deposited film should also be monitored very carefully. If the film is too thick, the possibility exists that the step-edge would become too rounded. In such a case, the grain boundary close to the step-edge is shunted by a superconducting channel which dominates current transport properties. For this reason, all films thicknesses were about 70% of the step height. The deposition

TABLE I
MEASURED SURFACE ROUGHNESS FOR 6 PBCO DEPOSITIONS

T_{DEP} [°C]	Optimal Value [nm]
700	7.88
720	11.85
740	12.27
760	26.52
780	33.12
800	31.34

TABLE II
OPTIMAL PARAMETER SET FOR PBCO DEPOSITION

Process Parameter	Optimal Value
T_{dep}	700 °C
Laser frequency	16 Hz
Laser fluence	$5x10^{-2}$ mbar
P_{O2}	4.09 J/cm^2
Working distance	60 mm
Focal Distance	15 mm
Deposition Time	15 min
T_{anneal}	30 min

TABLE III
OPTIMAL PARAMETER SET FOR YBCO DEPOSITION

Process Parameter	Optimal Value
T_{dep}	740 °C
Laser frequency	16 Hz
Laser fluence	$5x10^{-2}$ mbar
P_{O2}	4.09 J/cm^2
Working distance	60 mm
Focal Distance	15 mm
Deposition Time	11 min
T_{anneal}	30 min

conditions for YBCO (as optimized for deposition on MgO substrates) are listed in Table III.

Using the optimization conditions as shown in Table 3, an YBCO film was deposited on the PBCO step-edge template. AC susceptance of this structure was then measured.

IV. SUSCEPTIBILITY TESTS

To characterize the superconducting properties of the PBCO/YBCO bilayer structure, a susceptibility test setup was used. Such a test yields the critical temperature, T_C, and illustrate the transition into superconductivity (ΔT) of the thin film. This test is commonly replaced with 4-point probe measurements in literature. The 4-point probe measurement gives the dc resistance of the thin film but requires the deposition of gold pads and wire bonding. The susceptibility test setup does not require prior sample preparation and yields results that are more representative of the entire film. The test setup consists of a cold finger, a two-stage (20 K) cryocooler and a temperature controller. The sample is mounted between two planar coils situated on the cold finger. The primary coil is driven by a 1 MHz sinusoidal waveform, which induces a magnetic field perpendicular to film surface. The secondary, or pickup coil, returns a signal to the controller indicating the percentage signal that is sensed. Below the critical temperature of the sample, it expels magnetic fields according to the Meissner principle. During the process of cooling down the cold finger, the temperature and corresponding percentage susceptibility measurements are sampled and sent serially to a computer where the results are displayed.

The susceptibility measurement on this PBCO/YBCO structure, as shown in Fig. 4, revealed a T_C of about 85 K, but a very poor transient profile with $\Delta T = 20$ K. This is an indication of moderate uniformity in the film quality. Despite this, the film quality is still sufficient to manufacture a Josephson junction.

Such a superconducting PBCO buffered YBCO step-edge junction exhibiting Josephson characteristics has been successfully fabricated using the optimized bilayer structures discussed here [8]. Though there are reports on the usage of PBCO layer along with YBCO to make Josephson junctions [14], they are different class of junctions, as compared to our actual step-edge with PBCO as a buffer step template.

V. CONCLUSION

The novel idea to use an insulative PBCO buffer layer with a faster etch rate as compared to that of MgO, as a template for a step-edge, was attempted. This required the growth of a PBCO thin film and establishing appropriate PLD deposition parameters for this new process. First we have optimized the PLD growth of PBCO layer. After fabricating the PBCO step-edge, YBCO is grown epitaxially on it. Optimization of the entire process was discussed in detail, and we presented a superconducting YBCO layer growth on the PBCO step-edge template which is suitable for actual fabrication of Josephson Junctions.

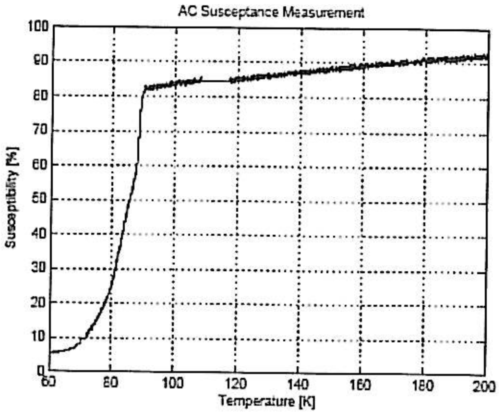

Fig. 4. Susceptance measurement of YBCO film on PBCO step.

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