Fabrication and characteristics of artificial SNS junctions using three axes orientation-controlled a-axis oriented Y123/Pr123 multilayer films

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**Abstract.** Artificial superconductor/normal conductor/superconductor (SNS) junctions are fabricated using a-axis oriented films. The films are three axes orientation-controlled a-axis oriented YBa\textsubscript{2}Cu\textsubscript{3}O\textsubscript{7-\textgamma}/PrBa\textsubscript{2}Cu\textsubscript{3}O\textsubscript{7-\textgamma} alternately-layered thin films (Y123/Pr123 multilayer films). The multilayer films were grown by a pulsed laser deposition method using a sintered Y123 target with a Pr123 section. The dark contrast parallel to the substrate surface ($bc$-plane), which corresponds to the elemental distribution of Pr, are observed periodically in the transmission electron microscopic cross-sectional image. SNS junctions along a-axis were fabricated using the multilayer films by focused-ion-beam techniques. Nonlinear current-voltage curves with the critical current of $\approx 5\times10^{-7}$ A were obtained at 30 K for a fabricated junction with the area of $\approx 0.2\times0.2 \mu$m$^2$.

1. **Introduction**

High temperature Cu-based superconductors (HTSs) are composed of superconducting CuO\textsubscript{2} double layers coupled along the $c$-axis by a Josephson interaction. Thus multi-connected Josephson junctions (JJs) are naturally grown in the crystal structure, which are called intrinsic JJs (IJJs). In Bi-family HTSs such as Bi\textsubscript{2}Sr\textsubscript{2}CaCu\textsubscript{2}O\textsubscript{8+\textdelta} (Bi-2212), CuO\textsubscript{2} planes are weakly coupled by BiO-BiO insulating layers. IJJs are attractive because the current-voltage ($I$-$V$) property along the $c$-axis has anomalous
nonlinear characteristics. Therefore studies on IJJs using Bi-2212 bulks, single crystal whiskers and films are very active [1-4]. However, for electronics applications of HTSs, the artificial fabrication of JJs is needed. Fabricating superconductor/normal conductor/superconductor (SNS) junctions is one of the indispensable challenges.

In this study, SNS stacks along the $a$-axis were fabricated using three axes orientation-controlled $a$-axis oriented multilayer films which are in alternating layers of YBa$_2$Cu$_3$O$_{7-y}$ (Y123) and Pr123. The Y123/Pr123 multilayer films have artificial JJs due to periodically inserted Pr123 layers, which are non-superconductors. The growing method of the multilayer films, the fabricating procedure of the junctions using the films and $I$-$V$ properties of the junctions are described in this paper.

2. Experimental

2.1. Growth of three axes orientation-controlled $a$-axis oriented Y123/Pr123 multilayer films

A pulsed ArF excimer laser deposition (PLD) method was performed to grow $a$-axis oriented Y123/Pr123 multilayer films. To control the three axes orientation of the multilayer films, SrLaGaO$_4$ (100) substrates with Gd$_2$CuO$_4$ (Gd214) buffer layers were used [5]-[9]. A Gd214 buffer layer was grown at a substrate temperature ($T_s$) of 730 °C in an oxygen pressure ($P(O_2)$) of 40 mTorr under laser frequency ($f$) of 1 Hz for 10 min. Sintered Y123 ceramic partly incorporated Pr123 (see figure 1a) was used as a target for the Y123/Pr123 multilayer film growth. By rotating the target at ~0.6 rpm during the deposition for 20 min in $P(O_2)$ of 400 mTorr under $f = 5$ Hz, the multilayer film was grown on a buffer layer at $T_s = 680$ °C. Twelve Pr123 layers will be inserted into the multilayer film calculated from the rotation speed, growth time and the Pr123 shape in the target.

The crystal phases and orientations of the grown films were determined by the $\theta/2\theta$ X-ray diffraction (XRD). The in-plane orientation of the films was evaluated by XRD $\varphi$-scan using an (102) of Y123. Cross-sectional images of the films were observed using a transmission electron microscopy (TEM) with an energy-dispersive X-ray spectrometer (EDX).

![Figure 1](image.png)

**Figure 1.** (a) A schema of a PLD target for the Y123/Pr123 multilayer film growth and (b) a cross-sectional diagram of the multilayer film.

2.2. Fabrication of SNS junctions using the $a$-axis oriented Y123/Pr123 multilayer films

SNS junctions were fabricated using the three axes orientation-controlled $a$-axis oriented Y123/Pr123 multilayer films. Figure 2a shows a schema of the junctions fabricated using the multilayer films. A three-dimensional focused-ion-beam (3D FIB) etching technique [10, 11] was performed for fabricating the junctions. Near the junction, a fine aperture with a beam current of 9 pA was used for final etching process and other apertures with beam currents of 50-200 pA were used for rough etching processes. The accelerating voltage was 30 keV. The substrate stage is tilted up to ~90° automatically in the 3D FIB method. The steps of the fabrication process using the 3D FIB etching are shown in figure 2b-2d. The multilayer film is grown on a substrate as shown in figure 2b. The width of the...
junction and the full depth of the film were etched by Ga ions in a microscopic area from perpendicular-direction to the film surface (see figure 2c). After tilting the sample stage up to 90°, two grooves were etched in the microscopic bridge from the cross-sectional direction of the film to fabricate the required junction size (see figure 2d).

Resistance-temperature \( R-T \) and \( I-V \) properties of the junctions were measured by a conventional four-probe method. The current was passed along the \( b \)-axis of the films to obtain \( I-V \) curves of the fabricated junctions.

![Figure 2](image)

**Figure 2.** (a)A schema of the stacked junctions fabricated using the \( a \)-axis oriented Y123/Pr123 multilayer film. (b)-(d) Schemata of fabrication steps for preparing SNS stacks by a 3D FIB method.

3. Results and Discussion

3.1. Microstructure of the grown films

Only \( h00 \) peaks of Y123 were observed in the XRD \( \theta/2\theta \) pattern. The result of \( \varphi \)-scan using an (102) of Y123 showed sharp peaks at intervals of 180 degrees. Therefore the grown film is \( a \)-axis oriented and \( c \)-axis in-plane aligned. As a result, three axes of the film are controlled. Figure 3 shows a cross-sectional bright-field TEM image (BFI) of the grown film. The contrast differences in the BFI correspond to the distribution of Y and Pr obtained by EDX analyses. According to the EDX analysis results, the brighter contrast is Y123 layers and the dark contrast is Pr123 layers, respectively. The XRD results and the TEM observations revealed that the grown film is three axes orientation-controlled \( a \)-axis oriented Y123/Pr123 multilayer film. The Pr123 layer thickness, which is estimated from the BFI, is approximately 6 nm. The Pr123 thickness may not preclude coupling between the superconducting layers since the junctions are fabricated along the \( a \)-axis with the coherence length of 2-3 nm [12].
3.2. The current dependence on the voltage of fabricated junctions using the three axes orientation-controlled a-axis oriented Y123/Pr123 multilayer films

Figure 4 shows an angular scanning ion microscope (SIM) view of the fabricated junction on the 600-nm-thick Y123/Pr123 multilayer film. The junction area is \(0.2 \times 0.2\) \(\mu\text{m}^2\) and four junctions are included.

In figure 5, the \(R-T\) curve of the junction shows the onset temperature at 85 K and the zero-resistance temperature at \(\sim 30\) K, respectively. The semiconducting behavior below the critical temperature \((T_c)\) is observed in the \(R-T\) curve. This may have been caused by damage of a Ga ion beam during the fabrication process of the junction by FIB etching. The oxygen around the junction area may be lost. To avoid the damage, the junction size should be increased. The \(I-V\) curve along the a-axis measured at 30 K is shown in figure 6. A nonlinear characteristic is found in the curve. The critical current \((I_c)\) is estimated at \(\sim 5 \times 10^{-7}\) A. Shapiro steps were not observed under the microwave irradiation in the range from 1 to 40 GHz at a power level of -15 to 15 db and a temperature of 30 K. If \(I-V\) properties under the microwave irradiation were measured at a very low temperature, Shapiro steps will be observed.
Conclusion

Three axes orientation-controlled $a$-axis oriented Y123/Pr123 multilayer films were grown by PLD methods. SNS stacks were fabricated on the multilayer film by 3D FIB. The nonlinear $I$-$V$ curve with $I_c \approx 5 \times 10^{-7}$ A was obtained at 30 K for the fabricated SNS junction with the size of $0.2 \times 0.2$ µm$^2$. The Pr123 non-superconducting layer thickness is approximately 6 nm. The $R$-$T$ curve showed the semiconducting behavior below the $T_c$, which may have been caused by damage of a Ga ion beam during the FIB process. The junction size should be increased to avoid the damage.

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