A novel 2-dimensional artificial pinning center

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Abstract. To increase critical current density (Jc) in magnetic fields (B) parallel to the c-axis, 2-dimensional artificial pinning centers (APCs) are introduced into YBa2Cu3O7-δ (Y123) films. Multilayer films alternately stacked a-axis oriented Y123 and Pr123 (Y123/Pr123 multilayer films) have been grown on SrLaGaO4 substrates by pulsed laser deposition. Magnetic field angular dependences of the Jc showed peaks not only in B//a-axis but also in B//c-axis of the Y123/Pr123 multilayer films. This result indicates that the Y123/Pr123 multilayer films have c-axis-correlated pinning centers. Consequently, it is suggested that the Pr123 layers act as 2-dimensional APCs.

1. Introduction

REBa2Cu3O6.8 (RE: rare earth elements, RE123) has a high critical temperature (Tc) and current density (Jc). Furthermore, RE123 has large anisotropy of electrical transport properties and its crystal structure. The Jc in magnetic fields of B//c-axis of RE123 is much lower than that of B//a/b-axis [1]. Recently, artificial pinning centers (APCs) are introduced into c-axis oriented RE123 films to enhance their Jcs, especially those in B//c-axis. For RE123 films without APCs, magnetic field angular dependences of the Jc show peaks only in B//a-axis. On the other hand, for RE123 films with APCs, Jc increases in B//c-axis.

The field angular dependences of the Jc have been systematically investigated for RE123 films with 0-, 1- and 3-dimensional APCs. However, there are very few reports regarding 2-dimensional (2-D) APCs. Some researchers reported nano-sized grain boundaries of RE123 films act as 2-D APCs [2]. In this case, currents have to pass across the grain boundaries. There are no reports for RE123 films with non-superconducting layers aligned parallel to the c-axis, those layers act as 2-D APCs.
Therefore it is necessary to fabricate the RE123 films with 2-D APCs for investigating the pinning effect of 2-D APCs.

In this study, we propose a new approach to introduce 2-D APCs into Y123 films. Multilayer films alternately stacked $a$-axis oriented Y123 superconducting layers and non-superconducting pinning layers (Y123/Pr123 multilayer films) were grown on a substrate. Furthermore, to investigate the layer thickness dependence of superconducting properties, the films with different layer thickness were also grown.

2. Experimental
A schematic image of a novel 2-D APC is shown in Figure 1. In Figure 1, the superconducting Y123 film is $a$-axis oriented normal to the substrate surface and $c$-axis in-plane aligned. Then, non-superconducting layers are parallel to the $c$-axis. We focused on Pr123 for the non-superconducting pinning layers since Pr123 has the same crystal structure as Y123 and the small lattice mismatch for Y123.

An (100) SrLaGaO$_4$ (SLGO) substrate has been used for the growth of $c$-axis in-plane aligned $a$-axis oriented Y123 films [3]. Gd$_2$CuO$_4$ (Gd214) buffer layers are necessary to grow $c$-axis in-plane aligned $a$-axis oriented Y123 films on the SLGO substrates [4]. Then, we tried to grow Y123/Pr123 multilayer films on SLGO substrates with Gd214 buffer layers.

![Figure 1. A schematic image of a novel 2-D APC.](image)

2.1 The growth of the Y123/Pr123 multilayer films
Both a Gd214 buffer layer and Y123/Pr123 multilayer films were grown by a pulsed ArF excimer laser deposition method (PLD). For the Gd214 buffer layer, the oxygen pressure was 40 mTorr and the pulse frequency was 1Hz during deposition. The growth temperature of the Gd214 buffer layer was fixed at 730°C. The growth time was 5 min.

Figure 2 shows a schematic image of PLD for the growth of the Y123/Pr123 multilayer films. As shown in Figure 2, the target for the Y123/Pr123 multilayer films was a sintered Y123 ceramics containing Pr123 rectangular region. During deposition, the target is rotated.

After the deposition of the Gd214 buffer layer, the target was changed for one shown in Figure 2 to grow the Y123/Pr123 multilayer films. As shown in Figure 2, the target for the Y123/Pr123 multilayer films was a sintered Y123 ceramics containing Pr123 rectangular region. During deposition, the target is rotated.

After the deposition of the Gd214 buffer layer, the target was changed for one shown in Figure 2 to grow the Y123/Pr123 multilayer films. During deposition, the oxygen pressure was kept at 400 mTorr and the pulse frequency was 5Hz for the Y123/Pr123 multilayer films. The growth of the Y123/Pr123 multilayer films was started at a substrate temperature of 680°C on the Gd214 buffer layer. Then, the substrate temperature was gradually raised to 720°C. The growth time of the Y123/Pr123 multilayer films was 7 min. After the growth, the films were cooled down to room temperature quickly in an oxygen atmosphere. To investigate the effects of layer thickness on superconducting properties, we
prepared two samples. The two samples, YPr-1 and YPr-2, have different layer thickness by controlling the target rotation speed in PLD. Here, the target rotation speed of YPr-1 and YPr-2 were 2 rpm and 0.5 rpm, respectively. Then, about the thickness of each Y123 layer, YPr-1 has thinner one than YPr-2.

![Figure 2. A schematic image of a PLD method using a sintered Y123 ceramics target containing Pr123 rectangular region.](image)

2.2 Evaluation of the grown films
The crystal phases and orientations of the Gd214 buffer layer and the Y123/Pr123 multilayer films were determined by 0-2θ x-ray diffraction (XRD). The in-plane orientation of the Y123/Pr123 multilayer films was evaluated by x-ray φ-scan using an (102) of Y123. Cross sectional images of the films were analyzed by transmission electron microscopy (TEM). The resistivities and the \( J_C \) values of the films were measured by a four-probe method. Varying the angle θ between the \( a \)-axis of the film and \( B \) enabled magnetic field angular dependences of the \( J_C \) to be obtained.

3. Results and Discussion

3.1 Microstructure of the grown films
Figure 3 shows an XRD 0-2θ pattern of the obtained YPr-1 film. An inserted figure shows the magnified XRD pattern around 70°. In Figure 3, peaks at 23° and 74° are determined to be the 100 and 300 peaks of the Y123. Then, the obtained film was \( a \)-axis oriented. Peaks from the Gd214 buffer layer overlapped almost with peaks from the SLGO substrate. Similarly, peaks from the Pr123 overlapped almost with peaks from the Y123. An x-ray φ-scan of YPr-1 is shown in Figure 4. In Figure 4, sharp peaks are located at an interval of 180°, indicating that the \( c \)-axis of Y123 is in-plane aligned. These results indicate that the obtained film is \( c \)-axis in-plane aligned and \( a \)-axis oriented normal to the substrate surface.
Figure 3. An XRD θ-2θ pattern of YPr-1. An inserted figure shows the magnified XRD pattern around 70°.

Figures 5 and 6 are cross-sectional TEM images of the two obtained films, YPr-1 and YPr-2, respectively. In both figures, black and white contrast alternately appears parallel to the substrate surface. From the element distribution map obtained by energy dispersive x-ray spectroscopy - scanning transmission electron microscopy (EDX-STEM), it seems that the distribution of Y and Pr corresponded approximately to the contrast for both films. Then, the results indicate that the obtained both films are Y123/Pr123 multilayer films. The thickness of each Y123 layer is approximately 6 nm from Figure 5 (YPr-1) and 15 nm from Figure 6 (YPr-2), respectively. Furthermore, the contrast is observed in α-direction (vertical to the substrate). The contrast is attributed to stacking-faults [5].

Figure 5. A cross-sectional TEM image of YPr-1, which the target rotation speed is faster than YPr-2.

Figure 6. A cross-sectional TEM image of YPr-2, which the target rotation speed is slower than YPr-1.

3.2 Electrical transport properties of the Y123/Pr123 multilayer films
First, we investigate the $T_c$ of the obtained films. Resistivity - temperature curves ($\rho$-T curves) were measured for the YPr-1 and YPr-2 with the current direction along the $b$-axis of Y123. From the $\rho$-T curves, the $T_c$ of YPr-1 and YPr-2 were about 55K and 79K, respectively.

Table 1 shows the target rotation speed, the layer thickness of Y123 and Pr123, $T_c$ and $a$-axis length for each sample. Table 2 shows the theoretical lattice parameters of Y123 and Pr123 for purpose of comparison with measured results. From Table 1, $T_c$ of YPr-1 was much lower than that of pure Y123 films. We focused on two possible reasons for $T_c$ degradation. One is the $a$-axis length of the films and another is the Y123 layer thickness. The $a$-axis length of both films was longer than 0.382 nm of pure Y123 films. Therefore the replacement of Y with Pr can cause $T_c$ degradation. Here, we defined the thickness of Y123 layer as “APC spacing”. Then, the coherence length along the $a$-axis of Y123 is range from 1 to 3 nm. The APC spacing of YPr-1 was almost the same thick as twice of coherence length along the $a$-axis. It is expected that $T_c$ decreases if the APC spacing is less than twice of coherence length. $T_c$ was improved from 55K to 79K by increasing the thickness of Y123 layer (APC spacing) from 6 nm of YPr-1 to 15 nm of YPr-2.

Table 1. The target rotation speed, the layer thickness of Y123 and Pr123, $T_c$ and $a$-axis length for each sample.

| sample name | target rotation speed (rpm) | thickness of an Y123 layer (nm) | thickness of a Pr123 layer (nm) | $T_c$ (K) | $a$-axis length $a^o$ (nm) |
|-------------|-----------------------------|---------------------------------|---------------------------------|-----------|--------------------------|
| YPr-1       | 2                           | about 6                         | about 2                         | 55        | 0.3830                   |
| YPr-2       | 0.5                         | about 15                        | about 5                         | 79        | 0.3828                   |

$a^o$ The $a$-axis length of the films was calculated from the $h00$ peaks of XRD 0-2θ pattern using a Nelson-Riley function [6].

Table 2. The $a$-axis length for materials used in this study.

| sample name | $a$-axis length (nm) | theoretical/ measured |
|-------------|----------------------|------------------------|
| Y123        | 0.382                | theoretical            |
| Pr123       | 0.387                | theoretical            |
| YPr1        | 0.3830               | measured               |
| YPr2        | 0.3838               | measured               |

Next, we investigate the $J_c$ of the obtained films. The field angular dependences of $J_c$ ($J_c$-$B$-$\theta$ curves) for the YPr-2 and a pure Y123 film are shown in Figure 7. In Figure 7, the horizontal axis $\theta$ represents the angle between the substrate azimuth and the magnetic field. As indicated in inserted figure, $\theta=0^\circ$ corresponds to $B$ // $a$-axis, and $\theta=90^\circ$ corresponds to $B$ // $c$-axis. The vertical axis represents the normalized $J_c$ [$J_c/\langle J_c (B // a) \rangle$]. These curves were measured around 60K in magnetic fields of 1 and 3T. As shown in Figure 7, for the pure $c$-axis in-plane aligned $a$-axis oriented Y123 films, the $J_c$ in $B$ // $c$-axis is much lower than that in $B$ // $a$-axis. Therefore the peak is observed only in $B$ // $a$-axis in $J_c$-$B$-$\theta$ curves. However, for the YPr-2, $J_c$-$B$-$\theta$ curves show peaks not only in $B$ // $a$-axis but also in $B$ // $c$-axis. Therefore the Y123/Pr123 multilayer film has $c$-axis-correlated pinning centers. As a result, it is concluded that the Pr123 layers act as 2-D APCs in magnetic fields. In addition, for pure Y123 films, the $J_c$s in $B$ // $c$-axis generally decrease as magnetic fields increase as shown in Figure 7. However, for the Y123/Pr123 multilayer film, the $J_c$s in $B$ // $c$-axis increase as magnetic fields increase.
4. Conclusions
We proposed a novel structural approach to introduce 2-D APCs into Y123 films. It was a multilayer alternately stacked $a$-axis oriented Y123 superconducting layers and non-superconducting Pr123 layers grown on SLGO (100) substrates with Gd214 buffer layers by PLD. In all samples, it was confirmed from TEM and the element distribution map that the Pr123 layer grows alternately with the Y123 layer. The superconducting properties showed the thickness dependence of Y123 layer. For the Y123/Pr123 multilayer film with thinner Y123 layers, $T_C$ was decreased. The field angular dependences of the $J_C$ for the film with thicker Y123 layers showed peaks not only in $B // a$-axis but also in $B // c$-axis. This result suggested that the Y123/Pr123 multilayer film has $c$-axis correlated pinning centers. For the Y123/Pr123 multilayer film, the $J_C$s in $B // c$-axis increased as magnetic fields increased.

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