Enhancement of Critical Current Density in the (YBa$_2$Cu$_3$O$_7$-$\delta$/Y$_2$O$_3$) $\times$ N Multilayered Films

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Abstract: The enhancement of critical current density ($J_c$) in the (YBa$_2$Cu$_3$O$_7$-$\delta$/Y$_2$O$_3$) $\times$ N multilayered films was reported. The (YBCO/Y$_2$O$_3$) $\times$ N multilayered films in which N was varied from 0 to 10 were prepared by using the pulsed laser deposition (PLD) technique. Magnetization data measured at 65 K showed that $J_c$ of the (YBCO/Y$_2$O$_3$) $\times$ N multilayered films was enhanced in comparison with that of the pure YBCO film. More interestingly, the $J_c$ enhancement was obtained to increase at small values of N, reach the maximum at N = 5, then decrease with increasing N to 10. The $J_c$ enhancements in the (YBCO/Y$_2$O$_3$) $\times$ N multilayered films with N $\leq$ 5 were attributed to the increases in the number of single YBCO layers. The microstructure degradation in the (YBCO/Y$_2$O$_3$) $\times$ N multilayered films with N $>$ 5 was likely to be reason for the decreases in their $J_c$, which was confirmed by using the scanning electron microscopy (SEM) images.

Keywords: YBCO, critical current density $J_c$, multilayered films.

1. Introduction

In the family of Rare-earth (RE) superconductors, especially REBa$_2$Cu$_3$O$_{7-\delta}$ (REBCO), YBCO was the first materials to be discovered that has been devoted interesting properties for researches [1-5]. Significant efforts have been devoted to YBCO that aimed to its application as the HTS cables require them to process high critical current density ($J_c$) in higher applied fields. To achieve that purpose, the two major methods have been developed: (i) creating artificial pinning centers (APCs) with the sizes are comparable to the coherence of YBCO, and (ii) inserting non-superconducting layers to divide the YBCO film into several single YBCO thin films. The former was performed by directly mixing the non-superconducting phase such as BaSnO$_3$ (BSO), BaZnO$_3$ (BZO), BaNb$_2$O$_6$ (BNO)… to YBCO [6]. The latter was carried out by alternately depositing YBCO and non-superconducting phases such as CeO$_2$, Y$_2$BaCuO$_5$ (Y211).... [7,8]. The completed structure of the films was obtained by repeating the layering process.

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The researches of multilayered processes, however, were mainly focused on the enhancements of $J_c$. The behavior of numbers of non-superconducting phase on $J_c$ was not clearly studied. In this paper, the enhancements of $J_c$ in the (YBCO/Y$_2$O$_3$) × N multilayered films were reported. The Y$_2$O$_3$ was selected as a proper non-superconducting phase since it had been shown a small lattice mismatch (0.6%) and being chemically stable with the YBCO phase [9]. The value of N was varied from 0 to 10 in order to find the optimum N providing the highest enhancement of $J_c$ in the YBCO films.

2. Experiment

The high quality YBCO and (YBCO/Y$_2$O$_3$) × N multilayered films were deposited on the SrTiO$_3$ (STO) substrates by using the PLD technique. The 248 nm KrF excimer laser operated at an energy of 250 mJ and a repetition rate of 8 Hz was applied to ablate the target surfaces. The substrates were heated at 800°C and distanced 4 cm from the targets. The deposits of all the films were carried out in the ambient gas of oxygen at a pressure of 200 mTorr. After that, all of the films were in-situ annealed in oxygen at a pressure of 500 Torr for 1 hour, then freely cooled to room temperature.

The crystalline structure of the films and especially the peaks of Y$_2$O$_3$ second-phase were investigated. The $J_c$ results were deduced from the magnetization curves measured by using the MPMS XL – 5 systems, in which the field was applied perpendicular to the film surfaces.

3. Results and discussion

The XRD patterns for the single YBCO and the YBCO/Y$_2$O$_3$ multilayered films are presented in Fig. 1.

![Figure 1. X-ray diffraction patterns of the YBCO single and YBCO/Y$_2$O$_3$ multilayered films. The c-axis oriented and a-axis oriented properties of the YBCO and Y$_2$O$_3$ phases, respectively, were investigated. Symbol N indicated the number of Y$_2$O$_3$ layers.](image-url)
The dominant (00\(l\)) peaks (where \(l\) ranges from 1 to 7) of the YBCO phase suggested that all of the films were \(c\)-axis oriented. The \(\text{Y}_2\text{O}_3\) (400) peak was observed only in the \(\text{Y}_2\text{O}_3\)/YBCO multilayered films which indicated the addition of \(\text{Y}_2\text{O}_3\) layers. Moreover, the intensity of the \(\text{Y}_2\text{O}_3\) (400) peaks was found to be increased with increasing numbers of \(\text{Y}_2\text{O}_3\) layers. The structural characterization of the YBCO films carried out by using the cross sectional SEM images revealed that the formation of \(\text{Y}_2\text{O}_3\) inside the YBCO phase.

![Cross-sectional SEM images of (a) the YBCO single and (b) YBCO/\(\text{Y}_2\text{O}_3\) multilayered films. The 5 \(\text{Y}_2\text{O}_3\) layers were observed to uniformly distribute inside the YBCO film.](image)

Fig. 2 (a) showed the cross section of the pure YBCO film. It could be seen that the film were highly \(c\)-axis oriented evidenced by a dense layer and a relatively smooth film surface. The film thickness was estimated to be \(~534\) nm, which was compared to be lower than the thickness of \(~600\) nm for growth of the \(a\)-axis oriented grains [9]. Fig. 2 (b) indicated the \(\text{Y}_2\text{O}_3\) layers uniformly separated inside the YBCO film with the thickness of each YBCO single layer was approximately \(91\) nm. Though \(\text{Y}_2\text{O}_3\) layers were found to be difficult to resolve at these magnifications, these cross sectional SEM images clearly presented the separation between the YBCO single layers. As mentioned in the experiment part, the multilayered structure was obtained by alternatively ablating the
two targets or YBCO and Y\(_2\)O\(_3\). The smoothness of the Y\(_2\)O\(_3\)/YBCO film surface with 5 Y\(_2\)O\(_3\) layers was also observed to slightly reduce. The big particulates on the Y\(_2\)O\(_3\)/YBCO film surface were identified to be Cu or Ba-rich phases – the typical property of PLD- films [10].

The field dependence of \(J_c\) of the YBCO and Y\(_2\)O\(_3\)/YBCO films was investigated. The \(J_c\) values were estimated by applying the simplified Bean model, \(J_c = 20\Delta M / [b(1-b/3a)]\) [11], where \(\Delta M\) is the difference in the magnetization per unit volume, \(a\) and \(b\) are the dimensions of the rectangular samples. A general decrease in the \(J_c\) with increasing the applied filed was observed. The \(J_c\) values were observed to be highest of ~ 3 \(\times\) 10\(^7\) A/cm\(^2\) at self-field and decreased with increasing the applied fields. The self-field \(J_c\) of the YBCO and Y\(_2\)O\(_3\)/YBCO films were compared to be similar, which was reasonable due to the fact that the artificial pinning center (APCs) induced by the addition of Y\(_2\)O\(_3\)
effectively worked in the applied field only. That idea was examined by analyzing the in-field $J_c$ at different applied fields as shown in Fig. 3 (b). The addition of Y$_2$O$_3$ was found to generate the $J_c$ enhancements for $N \leq 5$. The possible reason for that might be attributed to the following: the architecture of YBCO/Y$_2$O$_3 \times N$ films was prepared to reduce the formation of microstructural defects including porosity, voids, or the a-axis oriented grains those occurred in thick REBCO films. The interfaces between Y$_2$O$_3$ and YBCO served as templates for the growth of subsequent high-quality REBCO layers. It has been well-known that the microstructure evolution at the surface of REBCO thick film was significantly different from that of a thinner one [9], and the REBCO films became rougher with increasing the film thickness. By inserting the Y$_2$O$_3$ layers between the YBCO layers, such phenomena were expected to be reduced, and $J_c$'s were enhanced consequently.

![Figure 4](image-url)

Figure 4. Surface morphologies of (a) the YBCO single and (b) YBCO/Y$_2$O$_3 \times 10$ multilayered films. The a-axis oriented grains were grown on the surface of YBCO/Y$_2$O$_3 \times 10$ multilayered films which was attributed to the decreases in $J_c$ enhancement as shown in Fig. 3.

Contrary to the enhanced $J_c$ performances were observed for $N \leq 5$, the decreases in $J_c$ with further increasing N from 5 to 10 were exhibited. The results suggested that another mechanism might occur. It has been widely studied that the superconducting and microstructural properties of REBCO films are closely correlated [9]. The surface morphology of the YBCO single and YBCO/Y$_2$O$_3 \times N$ films
was examined as presented in Fig. 4. Strikingly, the YBCO single film exhibited a relatively smooth surface (Fig. 4(a)) with only few droplets (or outhgrowths) which were typical for the PLD-films. The observation confirmed that the YBCO single film was highly c-axis oriented as revealed in Fig. 1. By the addition of 10 Y$_2$O$_3$ layers (Fig. 4(b)), the smoothness of the film surface was reduced by the formation of the rectangular shapes which were identified to be the a-axis oriented grains. The YBCO/Y$_2$O$_3 \times N$ films with N > 5 were then concluded to be a-axis oriented. The degradation in $J_c$ in the a-axis oriented YBCO films was probably explained by using the electronic structure of YBCO. The YBCO unit cell consisted of the two perovskite-structures sandwiched by the Y element. The two CuO$_2$ superconducting planes were alternated by two BaO insulating planes. The four layers were located parallel to the $(ab)$ plane of the perfectly/or highly c-axis oriented films which provided the largest opportunity for the horizontally applied currents to flow the CuO$_2$ planes. If the films were a-axis oriented, the flowing of mentioned current might be blocked at BaO planes which led to the degraded $J_c$'s. The further $J_c$ enhancements in the YBCO/Y$_2$O$_3 \times N$ films with N > 5 might be achieved by reducing or avoiding the formation of the observed a-axis oriented grains.

4. Conclusions

The YBCO single and YBCO/Y$_2$O$_3 \times N$ multilayered films were successfully fabricated by using the pulsed laser deposition (PLD) technique. The values of N were varied from 1 to 10 to systematically study the effect of N on the field performance of $J_c$ in these YBCO films. Magnetization results measured at 65 K revealed two different effects depending on N. The $J_c$ was enhanced by using small values of N, reach the maximum at N = 5, then decrease with increasing N to 10. Two possible reasons for them were provided. The $J_c$ enhancements in (YBCO/Y$_2$O$_3$) $\times N$ multilayered films were attributed to the increase in the number of YBCO single layers, in which the formations of microstructural defects such as porosity, voids, or the a-axis oriented grains were eased. These formations, however, were found to remain in the (YBCO/Y$_2$O$_3$) $\times N$ multilayered films with N > 5 which possibly blocked the super-current flowing along the $(ab)$ planes of the films.

5. References


