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Effect of $BaSnO_3$ Nanoparticle Inclusion on Critical Current Density of $GdBa_2Cu_3O_{7-\delta}$ Thin Films

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Abstract: Effect of $BaSnO_3$ (BSO) nanoparticle inclusion on the critical current density of $GdBa_2Cu_3O_{7-x}$ (GdBCO) thin films was investigated. BSO nanoparticles were prepared on a thin GdBCO seed layer of < 50 nm thick by using pulsed laser deposition (PLD) technique. The GdBCO superconducting layers were deposited on top of the BSO nanoparticles to produce films with the entire thickness of approximately 250 nm. The number of laser pulses was varied from 20 to 320 in order to obtain BSO nanoparticles with different sizes and densities. Magnetization data measured at 65 K showed that: at a small number of laser pulses, the slight enhancement in critical current density (J_c) up to 1.5 T was obtained. Further increasing the number of laser pulses, J_cs were found to be consistently decreased. The increase in J_c was attributed to the addition of BSO nanoparticles serving as artificial pinning centers (APCs) inside GdBCO films. The decreases in J_c was probably caused by to the crystallinity degradation of the BSO-doped GdBCO films which was confirmed by the larger FHWM values.

Keywords: GdBCO thin film, critical current density, $BaSnO_3$, artificial pinning centers.

1. Introduction

$REBa_2Cu_3O_{7-\delta}$ (RE: rare earth)-coated conductors have been reported to have superior field performances than those of standard $YBa_2Cu_3O_{7-\delta}$ (YBCO). Substitution of Gd for Y has been shown to induce the enhanced critical temperature (T_c) which resulted in higher irreversibility field (H_{irr}) and a critical current density (J_c) at 65 K and 77 K [1-3] . For power applications of the second generation of high temperature superconductors, GdBCO has been considered as one of the most promising candidate.

Applications of GdBCO-coated conductors (CCs) require them to be exposed to high fields. Their in-field J_c is determined by the flux-pinning effect which is arisen from defects in the crystal structures

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of GdBCO such as dislocations, grain boundaries, or fine precipitates, and these defects have been found to serve as pinning centers [4]. However, the in-field J_c at 65 K and 77 K is drastically decreased. In order to improve the J_c of GdBCO (or REBCO), different nanoengineering techniques have been developed for introducing and controlling artificial pinning centers (APCs) into the films [4]. One of the most common techniques that satisfy the condition of easily controlled properties of the APCs is the deposition of nanoparticles in which the properties consisting of the average size and density of the nanoparticles are varied by changing the ablation laser pulses.

In this paper, we study the effect of BSO nanoparticle dispersions on the critical current density in the GdBCO thin films. BSO was selected as a dopant material because our previous study had shown that BSO provides the significant J_c improvement via the formation of a BSO nano precipitate [5]. The introduction of the BSO nanoparticles into GdBCO films was carried out by using two separate targets, GdBCO and BSO those were made from the solid state reacted methods. From the microstructural characterizations, the BSO nanoparticle dispersions were found to be located on the GdBCO buffer layer with a distance of ~ 50 nm from film/substrate interface. The field dependence of the J_c data showed that J_c enhancements were obtained for the GdBCO with a dilute doping of BSO nanoparticles.

2. Experiment

The GdBCO thin films with and without the BSO nanoparticle inclusions were deposited on $SrTiO_3$ (STO) single crystalline substrates by separately ablating the two solid-state reacted targets of GdBCO and BSO. The film structure was designed to consist of the two GdBCO layers sandwiched by a BSO pseudo-layer. For GdBCO phase, an energy of 250 mJ and a repetition rate of 8 Hz was used. The first GdBCO layer with a thickness of ~ 50 nm was functioned as a buffer layer for growing BSO nanoparticles. The preparation of BSO nanoparticles on an approximately 50-nm-thick GdBCO buffer layers were performed at a lower energy of 200 mJ with a number of laser pulses varied from 20 to 320. The entire film thickness was maintained at ~ 250 nm. All depositions were carried out at a substrate temperature of 780^{o}C and an oxygen pressure of 150 mTorr. After the depositions, all films were annealed at 500^{o}C in 500 Torr of oxygen for 1 hour and then were freely cooled to room temperature.

The crystalline structure and texture of GdBCO films were examined by using an X-ray θ-2θ and ω diffractometer with a Cu Kα radiation. The BSO nanoparticle inclusions on a GdBCO buffer layer were observed by using atomic force microscopy (AFM). Cross-sectional scanning electron microscopy (SEM) was employed to characterize the microstructures of the BSO-added GdBCO films. The J_c values of the GdBCO films in magnetic fields applied perpendicular to the film normal were derived from the magnetization data measured by using the magnetic properties measurement system (MPMS) XL-5 SQUID magnetometer.

3. Results and discussion

The preparations of BSO nanoparticles on GdBCO buffer layers that had been deposited on STO substrates by using 20-320 laser pulses. The optimum condition for the impurity nanoparticles to work as APCs has been reported to be the substrate surface decoration. The nanoparticles grown on the bare substrates were observed to induce the dislocation-like defects with some of them thoroughly extended to the top film surface. We have completely done that kind of research using the Gd_2O_3 nanoparticles [6]. With the aim to search another candidate for APCs, we moved to BSO-a perovskite structure-which has been studied to be chemically stable with the REBCO superconductors. The growth of BSO nanoparticles, however, could not be carried out on the bare substrates. Motivated from that point, a thin GdBCO buffer layer was prepared as a basement for BSO.

Figures 1(a) and (b) exhibit two representative AFM images BSO nanoparticle inclusions deposited by 20 and 320 laser pulses, respectively. Randomly-distributed BSO nanoparticles were observed on the GdBCO buffer layer with BSO deposition. Detailed properties of the BSO nanoparticles with respect to the number of laser pulses were automatically analyzed by using the software equipped with AFM system. The resuts are listed in the Table. 1.

Table1. Properties of the BSO nanoparticles with respect to the number of laser pulses

Pulses	Mean diameter (nm)	Mean height (nm)	Density (μm^{-2})	Matching field (T)
20	17.6	0.6	62	0.128
80	26.8	1.1	11.4	0.235
160	30.2	1.6	163	0.337
320	38.2	2.1	183	0.378

The density of BSO particles increased monotonically from ~ 62 to 183 μm^{-2} with increasing number of laser pulses from 20 to 320. In addition, the particles tended to coalesce as the number of the pulses was increased, and as a result, the mean diameter of the BSO particles increased. Nanoscale diameter of < 20 nm was obtained for the BSO particles deposited with 20 pulses only; this diameter was comparable to other reports [7, 8]. Using 160 and 320-pulse BSO depositions, the values of the mean diameters became relatively larger, 30.2 and 38.2 nm, respectively. The influences of the BSO particles on the structural and the J_c of GdBCO thin films will be discussed below.

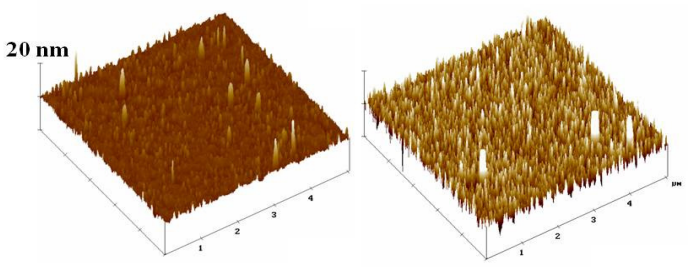

Figure 1. AFM images of BSO nanoparticles deposited on GdBCO buffer layer with 20 (left) and with 320 (right) pulses.

The BSO nanoparticles were first characterized by using AFM, then covered by the GdBCO superconducting phase. In other words, the BSO nanoparticles were preserved inside the GdBCO film. The effect of the BSO nanoparticle inclusions on the J_c was analyzed by using magnetization measurements in a magnetic field applied parallel to the film normal. The calculations of J_c values were done by using the simplified Bean's model: $J_c = 20\Delta M/[b(1-b/3a)]$ [9] where ΔM was the magnetization difference per unit volume, and a and b were, respectively, the length and width of samples, respectively. The field dependences of the J_c for GdBCO films with and without BSO nanoparticle inclusions are exhibited in Figure 2.

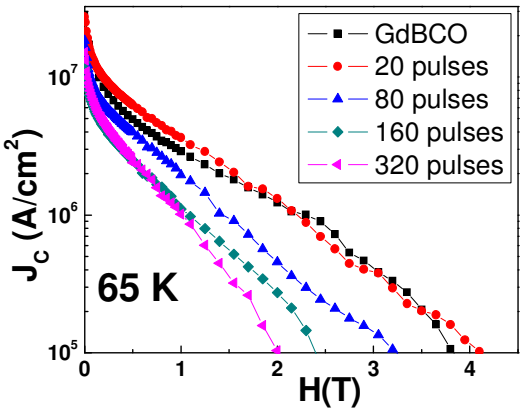

Figure 2. Field dependences of the GdBCO thin films with and without the BSO nanoparticle inclusions. The J_c enhancement was obtained for 20 pulses of the BSO deposition only, which suggested the effect of diluted BSO doping. The decreases in Jc for higher numbers of laser pulses of the BSO deposition might be involved in the changes in the film microstructures.

With the multilayer-like structure of the film in which the negligible change in the thicknesses of the GdBCO buffer layer and GdBCO films, we are focusing on any change in Jc with respect to the BSO nanoparticles. Self-field J_c's of ~ 10^6 A/cm^2 were estimated. J_c values of the GdBCO films with BSO addition using 20 laser pulses of BSO deposition were found to slightly enhanced, compared to that of the GdBCO film without the BSO addition. The relatively small enhancement in the J_c values was corresponded to the low BSO particle density listed in Table 1. The magnetic flux pinning by a second phase dispersion is most effective as the defect size is comparable to 2ξ, where ξ is coherence length of GdBCO [9]. In addition, the low density of the BSO nanoparticles also prepared a large area for the GdBCO superconducting phase. As a result, the J_c enhancement was induced.

Even though the small sizes and increased particles densities were given as increasing the number of laser pulses, the J_c enhancement was disappeared. Instead, the J_c values of the GdBCO with BSO addition using 80-320 pulses were observed to be consistently decreased. The formation of BSO nanoparticle inclusion was still observed with the nanoscale sizes but its effectiveness was reduced, which suggested another involved factors. As far as we know, the superconducting properties of the HTS are closely correlated to their microstructural properties. In order to have the enhanced J_c's along

the *ab* plane of the GdBCO film, the crystal structure of the GdBCO film are required to be highly *c*-axis oriented. The applied currents will probably flow in the CuO_2 superconducting plane of GdBCO the double-perovskite structure with the minimal dissipation. If the GdBCO films are highly c-axis oriented, the ab // CuO2 planes will be provided for the current flowing. The ω-scan XRD rocking curves of (005) reflection of the BSO-added GdBCO films were measured to examine changes in the crystal structures of the GdBCO films with the additions of BSO.

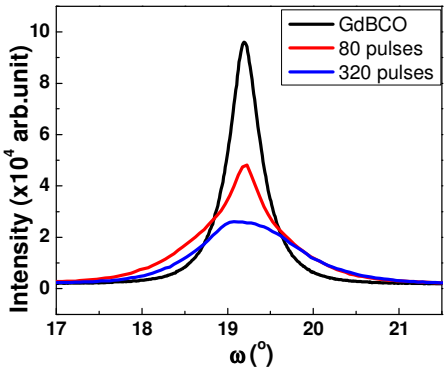

Figure 3. ω -scan XRD rocking curves of (005) reflection of BSO doped GdBCO deposited by using separated targets present that the out-of-plane texture is getting degraded with increasing number of laser pulses for BSO depositions.

From the results illustrated in Figure. 3, it could be said that the values of FHWM increased from 0.44° (pure GdBCO) to 0.82° (80 pulses) and to 1.30° (320 pulses). The higher the FHWM was, the higher the crystallinity degradation was. The larger numbers of the laser pulses might create the dense pseudo-layers, which reduced the crystallinity of the GdBCO films. The formation of the BSO pseudo-layer was observed by using the cross-sectional SEM images as shown in Figure 4.

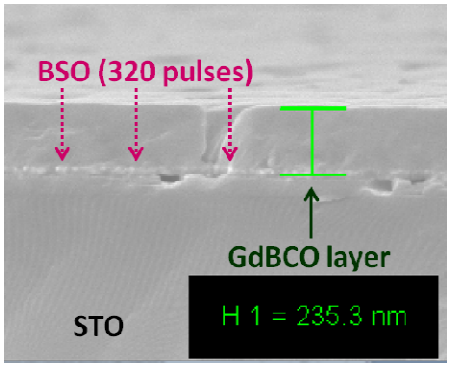

Figure 4. Cross sectional SEM images of the GdBCO film for the 320 pulses of the BSO deposition. The BSO nanoparticles were observed to be located ~ 30 nm near the film/substrate interface.

4. Conclusions

We have studied the critical current density J_c of GdBCO thin films through a systematic addition of BSO nanoparticles, leading to BSO nanoparticle inclusions. The BSO nanoparticles were prepared on a GdBCO buffer layer by using the PLD technique before the GdBCO film deposition. The diameter and density of BSO nanoparticles were controlled by varying the number of laser pulses from 20 to 320 pulses. J_c enhancement was obtained for 20 pulses of BSO deposition, suggesting that effective pinning is obtainable in dilute BSO addition. Decreases in J_c were observed for higher number of laser pulses of BSO deposition, which might be explained by the crystallinity degradations of the BSO-added GdBCO films, which was confirmed by the cross-sectional SEM analysis.

5. References

[1] Y. Xu, M. Izumi, K. Tsuzuki, Y. Zhang, C. Xu, M. Murakami, N. Sakai and I. Hirabayashi, Thickness dependence of critical current density in GdBa2Cu3O7−δ thin films with BaSnO3 addition, Supercond. Sci. Technol, 22, 095009, (2009).

[2] S. Rosenzweig, J. Hänisch, K. Iida, A. Kauffmann, Ch. Mickel, T. Thersleff, J. Freudenberger, R. Hühne, B. Holzapfel and L. Schultz, Thickness dependence of critical current density in GdBa2Cu3O7−δ thin films with BaSnO3 addition, Supercond. Sci. Technol, 23, 105017, (2010).

[3] M. Murakami, N. Sakai, T. Higuchi and S.I. Yoo, Melt-processed light rare earth element-Ba-Cu-O Supercond. Sci. Technol, 9, 1015 (1996).

[4] K. Matsumoto and P. Mele, Artificial pinning center technology to enhance vortex pinning in YBCO coated conductors, Supercond. Sci. Technol, 23, 014001 (2010).

[5] D.H. Tran, W.B.K. Putri, C.H. Wie, B. Kang, N.H. Lee, W.N. Kang, J.Y. Lee, and W.K. Seong, Thickness dependence of critical current density in $GdBa_2Cu_3O_{7-\delta}$ thin films with $BaSnO_3$ addition, J. Appl. Phys, 111, 07D714 (2012).

[6] D.H. Tran, W.B.K. Putri, C.H. Wie, B. Kang, N.H. Lee, W.N. Kang, J.Y. Lee and W.K. Seong, Enhanced critical current density in GdBa2Cu3O7-δ thin films with substrate surface decoration using Gd2O3 nanoparticles ", Thin Solid Films 526, 241 (2012).

[7] P. Mele, K. Matsumoto, T. Horide, O. Miura, A. Ichinose, M. Mukaida, Y. Yoshita, and S. Horii, Control of Y_2O_3 nanoislands deposition parameters in order to induce defects formation and its influence on the critical current density of YBCO films, Physica C, 426-431, 1108 (2005).

[8] P. Mikheenko, A. Sarkar, V.S. Dang, J.L. Tanner, J.S.Abell, and A. Crisan, c-Axis correlated extended defects and critical current in $YBa_2Cu_3O_x$ films grown on Au and Ag-nano dot decorated substrates, Physica C, 469, 798 (2009).

[9] P. N. Barnes, T. J. Haugan, C. V. Varanasi and T. A. Campbell, Flux pinning behavior of incomplete multilayered lattice structures in $YBa_2Cu_3O_{7-d}$, Appl. Phys. Lett, 85, 4088 (2004).