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Scaling of pinning forces in $BaSnO_3$-added $GdBa_2Cu_3O_{7-x}$ superconducting thin films

B. Kang [a,*], D.H. Tran [a,b], W.N. Kang [c]

[a] Department of Physics, Chungbuk National University, Cheongju, Republic of Korea
[b] Faculty of Physics, VNU University of Science, Vietnam
[c] Department of Physics, Sungkyunkwan University, Suwon, Republic of Korea

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ABSTRACT

We have investigated the flux pinning force F_p in pure and 2 wt.% $BaSnO_3$ (BSO)-added $GdBa_2Cu_3O_{7-x}$ (GdBCO) superconducting films. Both pure and BSO-added GdBCO films with the thicknesses varying from 0.2 μm to 1.5 μm were prepared by using a pulsed laser deposition (PLD) technique. As BSO is added to the GdBCO films, two changes were observed in the field dependence of the pinning forces. First, the magnitude of the pinning force was greatly enhanced at each corresponding thickness. Second, the pinning forces exhibited an interesting plateau-like behavior. As a result, a universal scaling law of the pinning forces can be applied to the BSO-added GdBCO films which accounts for all variation in thickness. These results suggest an existence of an extra pinning mechanism through the film thickness which is induced by the formation of the BSO nanostructures.

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1. Introduction

The coated conductor development by using $REBa_2Cu_3O_{7-\delta}$ (REBCO) (RE: rare-earth element) has drawn considerable interest due to high expectation of applications to the power-relate area. Among a series of REBCO, $GdBa_2Cu_3O_{7-\delta}$ (GdBCO) is reported to have superior flux-pinning properties than $YBa_2Cu_3O_{7-\delta}$ (YBCO) [1,2], so it is considered as a possible replacement for YBCO. For power applications of GdBCO superconducting films, there is a critical factor which needs to be improved: a drastic decrease of critical current density (J_c) with increasing film thickness and by the application of external magnetic fields [3–6]. The power application of GdBCO superconducting films greatly relies on its capacity for carrying supercurrent in high magnetic fields.

For type II superconductors such as REBCO, magnetic field penetrates into the superconducting film in the form of flux lines that need to be pinned by extra flux pinning in order to have to high critical current. There have been many attempts to introduce additional pinning centers by incorporating impurity to REBCO target [7–13]. Among them, the addition of barium-based perovskite such as $BaZrO_3$ (BZO) and $BaSnO_3$ (BSO) is proven to enhance J_c of REBCO films when magnetic fields are applied [14–17].

The pinning force density F_p ($F_p = J_c \times \mu_0 H$), deduced from the field dependence of J_c, reveals more interesting features than J_c which is a monotonic function of magnetic fields. Therefore, a systematic analysis of F_p is a very effective method to investigate flux pinning mechanism in superconductors. For various high-T_c superconductors, a scaling of F_p was obtained when the normalized pinning forces $f_p = F_p / F_{pmax}$ was plotted as a function of the reduced field $h = H / H_{irr}$, where H_{irr} is the irreversibility field [18,19]. By fitting f_p (h) with a common law of $f_p = Ah^p(1-h)^q$ proposed by Dew-Hughes [20], the fitting parameters p and q are used to characterize a major type of pinning centers. In literature, Dew-Hughes listed several pinning functions f_p (h) depending on the geometry and the type of the pinning [20].

In this paper, we present a comparison of the pinning force density between pure GdBCO and 2 wt.% $BaSnO_3$ (BSO)-added GdBCO films. We have found in previous studies that both the values of J_c and the thickness dependence of J_c of GdBCO in self-field were greatly enhanced by the addition of $BaSnO_3$ (BSO) [21]. In order to obtain a deeper insight into the origin of the improved pinning properties, we performed an extended analysis of F_p. Emphases are made on the field and the thickness dependence of F_p and on the analysis of data with the theoretical model to investigate a change in the pinning mechanism of the GdBCO films

* Corresponding author.
E-mail address: bwkang@chungbuk.ac.kr (B. Kang).

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with BSO addition. It is found that a universal scaling law can be applied to characterize F_p of the BSO-added GdBCO films irrespective of the film thickness.

2. Experiment

Pure and 2 wt.% BSO-added GdBCO films were fabricated on $SrTiO_3$ (STO) single-crystal substrates, supplied by the Crystal Bank at Pusan National University, from homemade solid-state reacted targets by using a conventional pulsed laser deposition (PLD) technique. Both pure and 2 wt.% BSO-added GdBCO targets were ablated by the 248 nm KrF excimer laser with an energy of 250 mJ and a repetition rate of 8 Hz. Film depositions were carried out at an oxygen pressure of 150 mTorr and the substrate temperature was kept at 780 °C. The thickness of GdBCO films varied from 0.2 to 1.5 μm by increasing deposition times whiles the rest of deposition parameters were fixed. Afterwards, all the films were annealed in 500 Torr of oxygen at 500 °C for 1 h, and were cooled to room temperature. The details of deposition condition of the films are reported in our previous papers [21,22].

The J_c's of both the pure and the BSO-added GdBCO films with different thicknesses were deduced from the magnetization data measured at 77 K by using the Quantum Design MPMS XL-5 system in magnetic fields up to 5 T applied parallel to the *c*-axis of the film. The J_c values were calculated by applying the simplified Bean model, $J_c = 20\Delta M/[b(1 - \frac{b}{3a})]$ [17], where ΔM is the difference in the magnetization per unit volume, and *a* and *b* are the dimensions of the rectangular samples.

The possible source of pinning cites inside the film was investigated through consecutive argon-ion-millings of the 1.5-μm-thick films. Ion-milling experiments were carried out by using an argon ion-beam with an energy of 3 keV and at 30° to remove part of the surface layer. After each ion-milling step, the microstructures of the ion-milled films were examined by using scanning electron microscopy (SEM) and cross-sectional transmission electron microscopy (TEM).

3. Results and discussion

The field dependences of the J_c's of the pure and the BSO-added GdBCO films with different thicknesses were investigated at elevated temperatures of 20 K, 55 K and 77 K and those of three representative film thicknesses of t = 0.2 μm, 0.6 μm and 1.5 μm were illustrated in Fig. 1(a)–(c). Although a general field dependence of J_c seems to be similar in both GdBCO films, an obvious enhancement of J_c was observed by the addition of BSO at each thickness. In the literature, the double-logarithmic plot of J_c vs. H is usually separated into two regions: the low-field region and the intermediate field region [23]. In the low-field region, where vortices are individually pinned, field independent J_c's were obtained. As the vortex density becomes greater than the defect density, the intermediate-field region is established and the vortices collectively interact with each other leading to the field dependent J_c. In the intermediate-field region, the flux-pinning mechanism is indicated by the power-law of $J_c \sim H^{-\alpha}$.

For the 0.2 μm- and the 1.5 μm-thick pure GdBCO films, the values of exponent α ranging 0.48–0.52 were obtained regardless of different temperatures. The value of $\alpha = 0.5$ in the intermediate field region implies a relatively diluted distribution of extended defects [24]. This is consistent with the formation of linear defects during the island growth of pulsed laser deposited films. Interestingly, the values of α for the 0.6 μm-thick film was reduced to be $\alpha = 0.35 \pm 0.03$. A smaller value of exponent obtained for the 0.6 μm-thick film pure GdBCO film is considered as a temporary enhancement of pinning which may be originated from an increase in the formation of nanosized dislocation generated by the merging of *a*-axis growth fronts as analyzed in our previous paper [22,25]. Lower film surface temperatures result in generating more dislocations. In our experiment, the 0.6 μm was the thickness at which the *a*-axis growth started to occur.

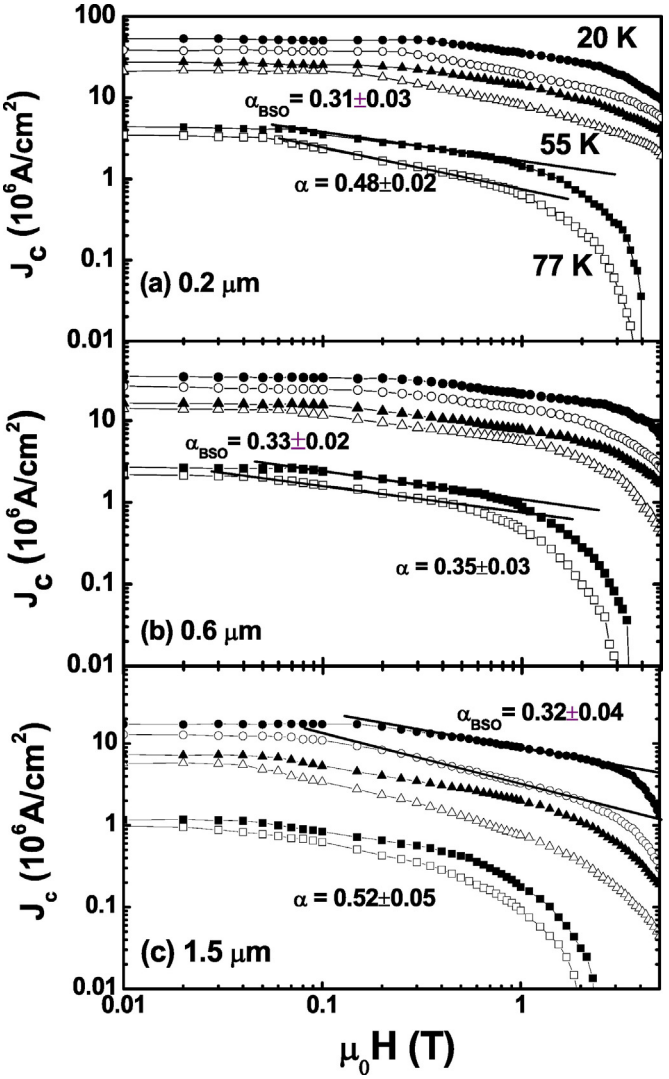

Fig. 1. Field dependence of J_c's of pure GdBCO and BSO-added GdBCO films measured at T = 20 K, 55 K, and 77 K of for (a) 0.2 μm (b) 0.6 μm and (c) 1.5 μm. For the both cases, J_c's in the intermediate-field region exhibited a decrease with the power law of $J_c \sim H^{-\alpha}$, but different values of exponents were obtained.

On the other hand, the double-logarithmic plots of the BSO-added GdBCO films exhibit a consistent feature through a whole thickness range. The values of α for the BSO-added GdBCO films were found to be $\alpha = 0.31$–0.33 regardless of temperature and the film thickness, which are much smaller than those for 0.2 μm- and 1.5 μm-thick pure GdBCO films, and are comparable to the value of 0.6 μm-thick pure GdBCO film. The smaller and constant values of α in the BSO-added GdBCO films imply that the flux pinning is considerably improved and is well maintained through the film thickness.

To examine a possible change in the flux-pinning mechanism between pure and the BSO-added GdBCO films, the flux pinning force density was investigated. Fig. 2(a) and (b) show the flux pinning force density F_p plotted as a function of reduced magnetic field $h = H / H_{irr}$, where H_{irr} is the irreversibility field determined by the criteria of $J_c = 10^3$ A/cm^2 in the J_c vs. H plot [26], at 77 K for the pure and the BSO-added GdBCO films with different thicknesses, respectively. In order to obtain F_p, the definition of $F_p = \mu_0 H \times J_c$ was used. Although J_c is a monotonic function of field, the cross product of J_c and H reveals much more interesting features. For the pure GdBCO, two features were observed. First, the values of F_p decreased with increasing film thickness except at t = 0.6 μm. The inversion of F_p at 0.6 μm-thick film may be attributed to a sudden increase of nanostructure formation as we mentioned in the