Physica C: Superconductivity and its applications 000 (2016) 1–4

Contents lists available at ScienceDirect

Physica C: Superconductivity and its applications

journal homepage: www.elsevier.com/locate/physc

Flux pinning properties in YBCO films with growth-controlled nano-dots and heavy-ion irradiation defects

T. Sueyoshi [a,*], T. Kotaki [a], Y. Uraguchi [a], M. Suenaga [a], T. Makihara [a], T. Fujiyoshi [a], N. Ishikawa [b]

[a] Department of Computer Science and Electrical Engineering, Kumamoto University, 2-39-1, Kurokami Chuo-ku, Kumamoto 860-8555, Japan
[b] Japan Atomic Energy Agency (JAEA), Ibaraki 319-1195, Japan

ARTICLE INFO

Article history:
Received 31 January 2016
Revised 13 April 2016
Accepted 25 April 2016
Available online xxx

Keywords:
Critical current density
Flux pinning
Irradiation
Columnar defects
Nano-particles

ABSTRACT

In order to clarify the influence of size and spatial distribution of three-dimensional pinning centres (3D-PCs) on hybrid flux pinning, columnar defects (CDs) were installed by using 200 MeV Xe ions along the *c*-axis direction into quasi-multilayered films consisting of $YBa_2Cu_3O_y$ layers and pseudo layers of $BaSnO_3$. The positive effect of the $BaSnO_3$ doping on the hybrid flux pinning stands out for the critical current density J_c around $B \parallel c$ in high magnetic field and/or inclined magnetic field off the *c*-axis, which is more remarkable for the multilayered film grown at higher temperature, possibly due to larger $BaSnO_3$ nano-dots. In the case of the in-plane distributed $BaSnO_3$ nano-dots, the J_c around $B \parallel ab$ is remarkably enhanced, whereas there is a detrimental effect on the J_c around $B \parallel c$. These imply that the tuning of 3D-PCs is one of the keys to improve the J_c at all magnetic field orientations for the hybrid flux pinning.

1. Introduction

For improvement of critical current density J_c in $REBa_2Cu_3O_y$ (REBCO, RE: rare earth elements)-based coated conductors, nano-rods composed of self-assembled stacks of $BaMO_3$ (M = Zr, Sn, Hf, etc.) [1,2] are in common use as practical pinning centres (PCs). Nano-rods are classified as one-dimensional (1D) PCs like dislocations and columnar defects (CDs), which are considerably effective to interrupt motions of flux lines when the magnetic field is applied along the direction of the 1D-PCs. In recent years, a breakthrough in the flux pinning by 1D-PCs has been attempted by adding three-dimensional (3D) PCs like nano-dots [3–5]. The flux pinning by the combination of 1D-PCs and 3D-PCs is referred to as hybrid flux pinning, where 3D-PCs are expected to offset weak-points in the flux pinning of 1D-PCs; 3D-PCs prevent the sliding motion of flux lines for magnetic fields tilted off the direction of 1D-PCs and suppress the motion of double kinks of flux lines due to thermal fluctuation [6]. Therefore, the additional doping of 3D-PCs potentially attaches further improvement of J_c to the 1D-PC pinning over a wide range of magnetic field orientation.

Actually, J_c has been enhanced in every direction of magnetic field by the hybrid flux pinning [4]. As for the relaxation of anisotropy of J_c, however, there has been still a difference between the maximum and the minimum values in the angular dependence of J_c. In addition, the hybrid flux pinning often has a small influence on J_c around $B \parallel ab$ [5,7]. These suggest that the flux pinning by 3D-PCs still is not strong enough to trap the unpinned segments of flux lines in the tilted field and/or the anisotropic J_c behaviour cannot be fundamentally counteracted only by the isotropy of flux pinning of 3D-PCs. Therefore, the flux pinning of 3D-PCs should be extended to further improve the hybrid flux pinning: tuning of 3D-PCs such as control of their size and spatial distribution can result in stronger pinning and anisotropic one for the flux pinning of 3D-PCs.

In this work, CDs were installed by using 200 MeV Xe ions along the *c*-axis direction into quasi-multilayered films consisting of YBCO layers and pseudo layers of $BaSnO_3$, where the introduction of $BaSnO_3$ nano-dots was controlled by the growth temperature and the number of the bilayers. The size of nano-dots becomes larger with increasing growth temperature [8], while $BaSnO_3$ nano-dots are randomly distributed over the film or along the in-plane direction in accordance with the number of bilayers. Thus, this work enables us to investigate the influence of the size and the spatial distribution of $BaSnO_3$ nano-dots on the hybrid flux pinning.

2. Experimental details

The quasi-multilayered films consisting of YBCO layers and pseudo-layers of $BaSnO_3$ were fabricated on (100) $SrTiO_3$ substrates by a PLD technique alternating a YBCO target and a $BaSnO_3$ target. A KrF excimer laser with a laser energy density of 1 J/cm^2

* Corresponding author. Fax: +81 96 342 3630.
E-mail address: tetsu@cs.kumamoto-u.ac.jp (T. Sueyoshi).

http://dx.doi.org/10.1016/j.physc.2016.04.011
0921-4534/

Table 1
Samples in this work.

Sample	Number of laser pulse for $BSnO_3$, m	Number of bilayers, n	Growth temperature [°C]	Before irradiation T_c [K]	After irradiation T_c [K]
Pure750	–	–	750	88.9	88.2
Pure770	–	–	770	90.7	89.7
B(1, 100)750	1	100	750	87.1	85.8
B(1, 100)770	1	100	770	89.0	87.7
B(10, 10)770	10	10	770	89.6	88.5

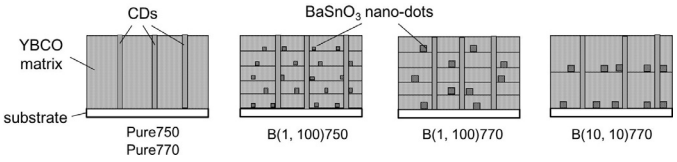

Fig. 1. Schematic illustrations of $BaSnO_3$/YBCO multilayered films after introduction of columnar defects by heavy-ion irradiation.

was used to deposit the films in 300 mTorr oxygen atmosphere. The repetition rate of the laser was 5 Hz for the deposition of YBCO layers, while the pseudo layers of $BaSnO_3$ were deposited at 1 Hz. During the deposition, the growth temperature T_s was 750 °C or 770 °C. After the deposition, the films were cooled down naturally from the substrate temperature to 500 °C and from 200 °C to room temperature in 600 Torr oxygen, while the cooling rate was controlled at 10° C/min from 500 °C to 200 °C.

A series of quasi-multilayered films studied in this work is listed in Table 1. We refer to a sample as B(l, m)T_s, where l and m denote the number of laser pulse on the $BaSnO_3$ target and the total number of $BaSnO_3$ / YBCO bilayers, respectively. A layer of YBCO was always deposited on the top of the multilayered films and the total number of laser pulses on the YBCO target was kept constant at 3600 pulses, resulting in the film thickness of about 300 nm.

The multilayered films patterned in bridge geometry with about 40 μm width and 1 mm length were irradiated with 200 MeV Xe ions along the c-axis at the tandem accelerator of JAEA in Tokai, Japan. The electronic stopping power S_e is about 2.8 keV/Å. This generally creates the CDs of about 8 nm in diameter [9], which was also confirmed by a transmission electron microscopy observation in our previous work [10]. The total density of CDs corresponds to the dose equivalent matching field $B_\phi = 3$ T, assuming the triangle lattice. Fig. 1 illustrates schematically the distributions of $BaSnO_3$ nano-dots and CDs in the multilayered films after the irradiation.

The transport properties were measured using a four-probe method. The J_c was defined by a criterion of electrical field, 1 μV/cm. The n-values were extracted from linear fits to the log E versus log J plots in the range of 1 ~ 10 μV/cm. The transport current was always applied in the direction perpendicular to the magnetic field.

3. Results and discussion

Fig. 2 shows the angular dependence of J_c at 65 K for 1 T and 5 T in the multilayered films before the irradiation, where θ is defined as the angle between the magnetic field and the c-axis of the films. For the samples with 100 bilayers, upward shifts in J_c can be observed over the entire magnetic field directions, compared to the non-doped samples. This suggests that the randomly distributed $BaSnO_3$ inclusions in the films work as effective 3D-PCs. The angular behaviour of J_c, however, is very different between B(1, 100)750 and B(1, 100)770, especially around B || c: a broad peak of J_c centered at $\theta = 0°$ emerges for the film grown at higher temperature, B(1, 100)770, whereas a flat-like angular dependence can be observed for B(1, 100)750. One possible reason for the J_c behaviour depending on the growth temperature is the difference in the size of nano-dots composed of the $BaSnO_3$ inclusions. The growth temperature largely contributes the migration of adatoms on a surface of the films during the crystal growth [11], so that the diameter of $BaSnO_3$ inclusions becomes larger for higher growth temperature [8]. Yamasaki *et al.* found that a high and broad J_c peak appears around B || c in YBCO films with a high density of larger particles whose typical diameters are larger than 2ξ (~ 7 nm, ξ is the coherence length), whereas very small particles less than 2ξ cause a smoother angular variation of J_c around B || c where the J_c shows a minimum [12]. Hence, nano-dots of larger or smaller size were introduced in the multilayred films by controlling the growth temperature, which is also supported by the presence of a broad J_c peak around B || c.

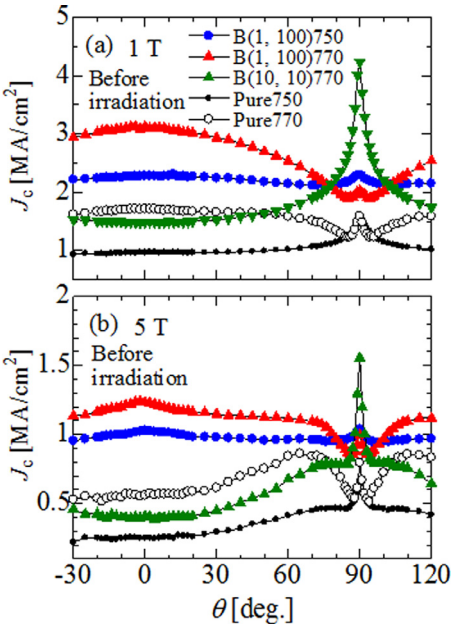

Fig. 2. Angular dependence of Jc in multilayered films before irradiation at 65 K for (a) 1 T and (b) 5 T.

For B(10, 10)770, on the other hand, J_c at B || ab exhibits more abrupt peak than any other samples, although the J_c around B || c is slightly lower than the non-doped film, Pure770. This is attributed to the correlated pinning by the row of $BaSnO_3$ nano-dots along the in-plane of the film, which work as more effective PCs at B || ab. The normal conducting layers composed of $BaSnO_3$ nano-dots, however, promote the flux motion at B || c, resulting in the non-effective PCs. In this manner, the anisotropic feature can be added to the flux pinning of 3D-PCs by controlling the spatial distribution of nano-dots.

It should be noted that the J_c peak at B || ab for B(10, 10)770 has a long tail at 1 T, whereas the width of the J_c peak becomes considerably narrow and thin at 5 T. When the magnetic field is tilted off the ab-plane, flux lines is composed of pancake vortices

Please cite this article as: T. Sueyoshi et al., Flux pinning properties in YBCO films with growth-controlled nano-dots and heavy-ion irradiation defects, Physica C: Superconductivity and its applications (2016), http://dx.doi.org/10.1016/j.physc.2016.04.011