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Nanostructural characterization of artificial pinning centers in PLD-processed $REBa_2Cu_3O_{7-\delta}$ films

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A B S T R A C T

In the context of high temperature superconductors, pulsed laser deposition derived $GdBa_2Cu_3O_{7-\delta}$ sample with $BaHfO_3$ nanoparticles has been reported to achieve high current density and good I_C-B-θ characteristics at high temperatures. Herein, we have carried out a thorough nanostrucural characterization of $BaHfO_3$ nanoparticles embedded in GdBCO matrix using scanning transmission electron microscopy, with an emphasis on the dispersion behavior, morphologies and nanostrain, to understand the role of $BaHfO_3$ nanoparticles.

1. Introduction

The discovery of Ba-La-Cu-O high temperature superconductor (HTS) system by Bednorz and Müller [1], followed by Y-Ba-Cu-O [2] and Bi-Sr-Ca-Cu-O [3] HTSs, have spurred a lot of intensive literature in this field for last three decades. Since then, $REBa_2Cu_3O_{7-y}$ (RE: Rare Earth element, REBCO) superconductors have always been expected as the good candidates for electronic applications, such as transformers [4], magnets [5], motors [6], and power lines [7], operated under high magnetic fields [8,9]. Nevertheless, there are three fundamental necessities for a successful application under high magnetic fields, such as high critical temperatures, T_C, high irreversibility magnetic fields, H_{irr}, and high critical current densities, J_C. Among them, T_C and H_{irr} are mostly dependent on the compositions and structures of HTSs, which can be controlled via starting materials and processes. Additional improvements in microstructures are thus required to achieve high J_C value and to minimize its anisotropy with respect to the direction of magnetic field.

In-field J_C value can be improved further by introduction of flux pinning centers to impede the movements of magnetic flux, such as natural pinning centers (NPCs) and artificial pinning centers (APCs). Typical NPCs in REBCO are oxygen deficiencies [10–12], grain boundaries [13], dislocation cores [13], intergrowths [14], and others [15], wherein pinning strengths are insufficient to reach high enough in-field J_C values. Therefore, intentional additions of APCs has been suggested as the most effective approach for achieving such high in-field J_C value as well as isotropic J_C characteristics [16]. Since the flux pinning effect is the strongest when the applied magnetic field is aligned with pinning centers, introduction of one-dimensional anisotropic APCs has been proposed as the most effective method as c-axis-correlated pinning centers for compensation of the intrinsic field angle anisotropy [17,18]. Hence, the most appropriate one-dimensional APC has always been longed for achieving high and isotropic J_C characteristics. In addition, the pinning strength of APCs can be controlled by controlling their densities, sizes, compositions, and morphologies. A proper optimization of these factors can lead to maximum possible J_C with minimum possible anisotropy [16,19].

Among those REBCO superconductors, $GdBa_2Cu_3O_{7-y}$ (GdBCO) has been receiving great attention, since it has higher T_C and J_C than $YBa_2Cu_3O_{7-y}$[20,21]. GdBCOs with various types of Ba-containing perovskites as APCs have been subjected to minimize the anisotropy of J_C characteristics and to achieve high critical current, I_C, under the magnetic field, such as $BaHfO_3$ (BHO) [22], $BaZrO_3$ (BZO) [17,18], and $BaSnO_3$ (BSO) [23–25]. Among them, BHO was found the most effective APCs to improve the high-field performance of GdBCO coated conductors, with the maximum thickness dependence and an isotropic angular dependence of I_C values [22]. This is attributed to the effective pinning by nanorods and to the enhancement of upper critical field, B_{c2}, by electron scattering at the interface between the nanoparticles and the superconducting matrix [26].

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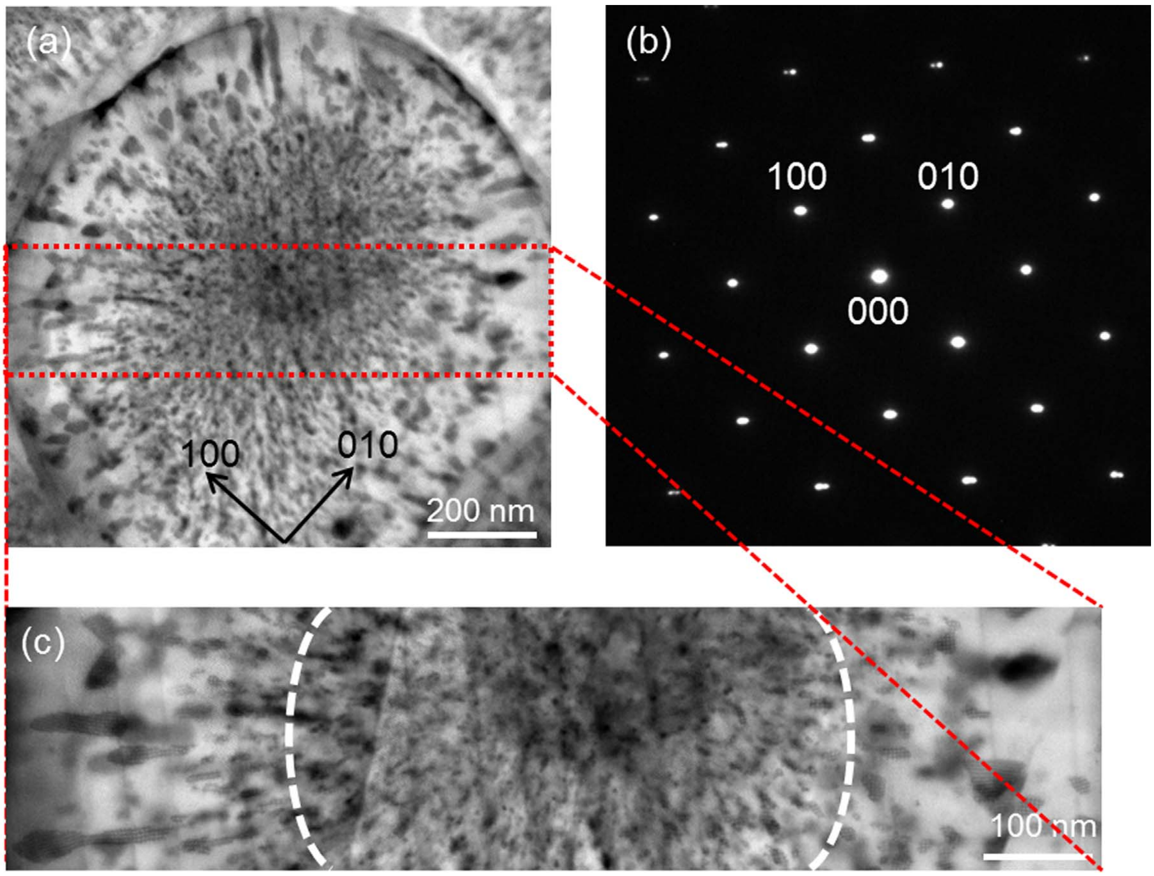

Fig. 1. (a) A plan-view STEM-BF image of GdBCO matrix with nanoparticles, (b) a corresponding selected area electron diffraction pattern, as well as (c) an enlarged image of 1(a).

Recently, the pinning strength related to strains caused by APCs has drawn considerable research interest. Llordés *et al.* demonstrated a mechanism, of APCs in solution derived HTSs through generation of nanostrained regions where Cooper pair formation was possibly suppressed [14]. In addition, Coll et al. reported that there was an effective route to enhance the vortex pinning by generating highly strained local regions in the YBCO, via introduction of small and randomly oriented nanoparticles with highly coherent interfaces [27]. Moreover, the morphology of APCs should be investigated further to understand the relationship between APCs and J_C of in-field for further improvements HTSs.

In this paper, both microstructural and morphological studies of BHO nanoparticles in GdBCO were carried out to understand the role of BHO nanoparticles using Cs-corrected scanning transmission electron microscopy (STEM). Our atomic-scale investigations show that the BHO dispersion varies distinctively in terms of morphology in the interior of the GdBCO grain and at the interface. Also, owing to the strain emerging from the lattice misfit was found to decrease with the size of the embedded BHO particle size.

2. Experimental

2.1. Sample

3.5 mol% of BHO powders were mixed with GdBCO to obtain BHO-doped GdBCO targets. GdBCO with BHO was then deposited on Hastelloy C-276TM tapes with buffer layers of PLD-CeO_2/sputter-$LaMnO_3$/IBAD (ion-beam assisted deposition)-MgO/IBS (ion-beam sputter)-$Gd_2Zr_2O_7$ using a reel-to-reel PLD system with a KrF excimer laser (D 248 nm; Lambda Physik LPX200). The deposition parameters of laser energy and frequency, oxygen pressure, target–substrate (TS) distance, deposition temperature, and tape traveling rate were 280–330 mJ, 120 Hz (two plumes at 60 Hz), 53–80 Pa, 86–94 mm, about 1123 K, and 20 m/h, respectively. The width and length of the coated conductors were 10 mm and about 100 mm, respectively, and showed the J_C value up to 0.3 MA cm^{-2} at 77 K and 3 T.

2.2. Characterization

Samples for high-resolution scanning transmission electron microscopy analysis was prepared by focused ion beam (FIB) method (Quanta 3D 200i, FEI, The Netherland) operated at 30 kV and followed by Ar ion-milling, NanoMill Model 1040 (FISCHIONE, U.S.) operated at 1 kV. Both TEM and STEM characterizations were carried out in a JEM-ARM200F (JEOL, Japan), operated at 200 kV and equipped with a CEOS aberration corrector (CEOS, Germany). In particular, high-angle annular dark-field was performed to record incoherent images, in which the intensity of atom columns directly reflected their mean square atomic number (Z) [28], so that the elements consisting of the atomic columns would be estimated from the intensity profiles. In addition, partially discrete-tomography was performed to investigate the morphology of APCs at atomic resolution. Local strains caused by the intentional addition of APCs were characterized by geometrical phase analysis (GPA) software (HREM, Japan) from high-resolution TEM/STEM images, capable of determining the local strain at atomic scale with 10^{-2} of strain resolution [29]. The radius of the mask for selecting reflection spots in GPA was set to be 1.0 nm^{-1}, which results 1.0 nm of spatial resolution to the strain map. Several authors have