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Enhancement of critical current density of $YBa_2Cu_3O_{7-\delta}$ thin films by nanoscale CeO_2 pretreatment of substrate surfaces

X.M. Cui [a,*], G.Q. Liu [a], J. Wang [a], Z.C. Huang [a], Y.T. Zhao [a], B.W. Tao [b], Y.R. Li [b]

[a] *Department of Material Science and Engineering, Panzhihua University, 617000 Panzhihua, People's Republic of China*
[b] *Institute of Microelectronics and Solid State Electronics, University of Electronic Science and Technology of China (UESTC), 610054 Chengdu, People's Republic of China*

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Abstract

$YBa_2Cu_3O_{7-\delta}$ (YBCO) films were prepared on single-crystal $SrTiO_3$ substrates with metal–organic deposition using trifluoroacetates (TFA-MOD). Positive results have been acquired in controlled study to investigate the effects of substrate surface modification on the growth-induced flux-pinning nanostructures in YBCO films. Nanoscale CeO_2 particles were applied to single-crystal $SrTiO_3$ substrate surfaces using pulsed laser deposition before YBCO precursors coating. Superconducting properties of the YBCO films grown on the controlled CeO_2-modified substrates have shown substantial improvement in the critical current densities (J_c) at 77 K over those grown on untreated substrates in almost all the field (78% increment at 1 T, 77 K). We think the reason is that the CeO_2 nanoparticles act as pinning centers.

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Keywords: $YBa_2Cu_3O_{7-\delta}$; Flux pinning; CeO_2 nanoparticles; Metal–organic deposition

1. Introduction

For practical applications, especially power applications, high-temperature superconductors (HTS) such as $YBa_2Cu_3O_{7-\delta}$ (YBCO) need to possess a high critical current density (J_c) under high magnetic fields. However, the ability for HTS such as YBCO to carry currents is significantly reduced with increasing magnetic fields. In order to counteract this effect, various methods to boost the HTS current-carrying abilities in magnetic fields by flux pinning have been developed through the pinning of the quantized flux lines by nanoscale crystalline defects and impurities [1]. Typically, J_c values of epitaxial YBCO thin films are roughly two orders of magnitude higher than those of the high-quality YBCO bulk single crystals, mainly due to their high density of defects that produce strong vortex pinning. However, the majority of these naturally occurring growth defects are either not effective enough to suppress thermal fluctuations or the densities not high enough to maintain the necessary levels of critical currents (I_c) in high magnetic fields [2]. Improving flux pinning within YBCO films is therefore one of the chief concerns for the development of coated conductor technology.

Flux pinning in YBCO thin films can be engineered by materials processing. Columnar defects produced by irradiation and antiphase boundaries produced by miscut substrates provide extended linear defects as strong artificial pinning centers [3,4]. Currently, a few other artificial routes to increase flux pinning have been realized for YBCO films, including multilayering of YBCO with second-phase materials [5,6], mixed rare-earth doping [7,8], target compositional modifications either by second-phase $BaZrO_3$

* Corresponding author. Tel.: +86 812 3362007.
E-mail address: cuixumei@163.com (X.M. Cui).

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inclusions [9] or creation of columnar defects comprised of self-alighted $BaZrO_3$ nanodots and nanorods [10,11], process-induced modifications with excess yttrium [12], and decoration of substrate surfaces by nanoscale particles [13,14].

At present, there are several kinds of processing which can be tried to fabricate the YBCO films, and vacuum deposition methodologies with high cost such as pulsed laser deposition or sputtering can produce high-performance YBCO films at high magnetic fields. So metal–organic deposition using trifluoroacetates (TFA-MOD) as one of the promising ones for low cost also has to produce high-performance YBCO films under magnetic fields for achieving the required goals in terms of cost and performance. So far, however, the flux pinning studies of YBCO are almost for the films grown by pulsed laser deposition, and there is a little study of this kind on films made by TFA-MOD processing. In order to get high-performance TFA-MOD YBCO films, decoration of substrate surfaces by nanoscale CeO_2 particles is tried. In this paper, we report on successful fabrication of epitaxial YBCO films using TFA-MOD method on $SrTiO_3$ single-crystal substrate decorated with CeO_2 particles. The superconducting and structure properties of the films were investigated.

2. Experimental

The nanoscale CeO_2 particles are deposited on $SrTiO_3$ single-crystal substrates with (0 0 1)-orientation using a CeO_2 stoichiometric target by PLD with KrF excimer laser. Deposition parameters were 248 nm laser wavelength, 108 mJ laser energy, 1 Hz laser repetition rate, 4 cm target-to-substrate distance. And the deposition temperature and oxygen partial pressure are 650 °C and 20 Pa, respectively. Deposition time of nanoscale CeO_2 particles was controlled between 20 s and 2 min. Subsequently, YBCO films were grown by TFA-MOD on the substrates decorated with CeO_2 particles.

For the preparation of the precursor solution of TFA-MOD process, yttrium trifluoroacetate, barium trifluoroacetate and copper trifluoroacetate were chosen as starting substances, and methanol as the solvent. The solution were coated on the CeO_2-decorated and undecorated $SrTiO_3$ single-crystal substrates by spin coating at 4000 rpm for 2 min at room temperature and then the samples were put in a quartz tube within a horizontal furnace and heat-treated to 400 °C in 2.1% humid oxygen at a flow rate of 1 l/min. Finally the films were annealed at a fixed temperature of 840 °C with annealing time 70 min in 2.1% humid Ar/O_2 (200–400 ppm O_2) gas at a flow rate of 3 l/min. Water pressure and gas flow rate greatly affect the growth rate and microstructure of the films so we fixed them in the study [15].

The phase content and texture of the YBCO films were examined by high-resolution X-ray diffraction (HRXRD) using a Bede D1 diffractometer with Cu Kα source. Omega (ω)-scans were used to evaluate out-of-plane texture. The surface structure of the CeO_2 decorated on $SrTiO_3$ single-crystal substrates was observed with atomic force microscopy (AFM). J_c in zero field was measured using J_c-scan Leipzig system [16]. The DC magnetization measurements were carried out with a Quantum Design MPMS 7 SQUID magnetometer in magnetic fields parallel to the c-axis of the specimens. Measurements were made up to 7 T in the temperature range of 65–77.3 K. And the J_c values of the YBCO films in magnetic fields were determined by application of the Bean critical state model formula [17], $J_c(H) = \frac{20\Delta M(H)}{a\left(1-\frac{a}{3b}\right)}$, where ΔM is the vertical width of the magnetization hysteresis (emu/cm^3), a and b (cm) are the cross-sectional dimensions of the sample perpendicular to the applied field with $b \geqslant a$.

3. Results and discussion

With the increase of deposition time of CeO_2, the number density of CeO_2 particles and its size increased, which is consistent with the increase of deposited material. Fig. 1 shows the AFM images of CeO_2 particles deposited on $SrTiO_3$ single-crystal substrates with different deposition time. The white-image nanoparticles are assumed to be CeO_2 phase. We can get the size of the CeO_2 particles through AFM analysing. The mean size of the CeO_2 particles with 2 min deposition time is about 184 nm, while that of CeO_2 particles with 20 s deposition time is about 59 nm which is the order of the coherence length, $\xi \sim 10$ nm, and so they can be acting as flux pinning centers. So we think the 20 s deposition time in our experiment condition is proper in order to get the flux pinning centers for YBCO thin films.

Chemical and structural characterization of the YBCO films deposited on CeO_2-decorated $SrTiO_3$ single-crystal substrates was determined using XRD analysis. Fig. 2 shows the XRD patterns of the YBCO films. We can see that all films display the (0 0 1) diffraction peaks of YBCO, which indicates a well-textured, c-axis oriented grain structure. In addition to the strong (0 0 1) peaks of YBCO, we can also find the (1 1 1) and (2 0 0) diffraction peaks of CeO_2 particles in the figures. According to the figures, the intensity of CeO_2 (1 1 1) peak is lower than that of the (2 0 0) peak while the theoretical value of CeO_2 (1 1 1) peak is much higher than that of the (2 0 0) peak, indicating CeO_2 particles exists with the mainly (2 0 0) orientation. Because the content of CeO_2 particles is much lower than that of the YBCO, the intensity of CeO_2 particles diffraction peaks is very low in comparison with that of the YBCO films. But with the increase of deposition time of CeO_2 particles, we can found that the ratio of the area intensity of CeO_2 (2 0 0) peak to that of YBCO (0 0 5), $I_{CeO_2(200)}/I_{YBCO(005)}$, is increasing and it shows more CeO_2 particles with bigger size are formed. The XRD patterns of the YBCO films indicate that there is no additional phase formed due to CeO_2 particles decoration. This is much different from the metallic Ir-doped YBCO films, wherein a heterogeneous perovskite phase such as $BaIrO_3$ is always present instead of the original doping phase