Reel-to-Reel Continuous Deposition of Ce$_x$Zr$_{1-x}$O$_2$ Single Buffer Layer for YBCO coated conductors

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Abstract. In this paper, a study regarding the epitaxial growth of Ce$_x$Zr$_{1-x}$O$_2$ film on biaxially textured Ni-5at.%W substrate and its use as a single buffer layer of a YBCO coated conductor was reported. Films of Ce–Zr mixed oxide were prepared by direct-current (d.c.) reactive magnetron sputtering with the two sputtering guns arranged symmetrically with respect to the substrate. In sputtering process, d.c. power of Zr was fixed in 200 W while that of Ce was varied with 30 W, 50 W, 75 W, and 100 W, respectively. It was confirmed that the composition of the films could be controlled with modulating power of Ce target. All samples exhibited good epitaxial growth with c-axis perpendicular to the substrate surface. Atomic force microscope revealed a continuous, dense, and crack-free surface morphology for Ce$_{0.32}$Zr$_{0.68}$O$_2$ thin films, which provided themselves as the good single buffer to the YBa$_2$Cu$_3$O$_{7-\delta}$ (YBCO) coated conductors. High quality Ce$_{0.32}$Zr$_{0.68}$O$_2$ buffer layers up to 100-m length could be fabricated with production speed of about 1.2 m/h. X-ray scans have been performed as a function of length to determine the crystallographic consistency of the epitaxial Ce$_{0.32}$Zr$_{0.68}$O$_2$ over length.

1. Introduction

Due to its lower ac loses, better in-field performance and the lower processing costs over first-generation high-temperature superconductor (HTS) tapes, second-generation YBa$_2$Cu$_3$O$_{7-\delta}$ (YBCO) coated conductors have attracted the attention of the researchers worldwide$^{[1-3]}$. However, it is well known that the initial issue for the successful development
of coated conductors for high temperature superconducting (HTS) wire applications is to chemically isolate the HTS film from the metal substrate, preventing diffusion of Ni into the superconductor during high-temperature processing, and also provide an epitaxial template for growth of the HTS coated conductors. Cerium dioxide CeO$_2$ and yttria stabilized Zirconium dioxide (YSZ) films have been widely used as a ‘buffer layer’ for high superconductor \cite{4}. In the case of YBCO coated conductor, CeO$_2$ film is used for seed layer as well as cap layer, while YSZ film plays a major role of diffusion barrier \cite{5-6}. To our knowledge, these multi-layer buffers make the fabrication process complicated and expensive. Many efforts on the use of a single buffer layer in a coated conductors have been done with yttria stabilized zirconia \cite{7}, Y$_2$O$_3$ \cite{8-9}, La$_2$Zr$_2$O$_7$ \cite{10}, La$_{0.7}$Sr$_{0.3}$MnO$_3$ \cite{11}, LaMnO$_3$ \cite{12-13}, and SrTiO$_3$ \cite{14}. As a promising candidate of buffer layer material for YBCO coated conductors, CeO$_2$ has been prepared by many groups due to its excellent chemical compatibility with Ni-based alloy substrates as well as good lattice match with YBCO or ReBCO. However, CeO$_2$ has seldom been used as a single buffer layer due to the existence of a critical thickness of around 50 nm \cite{15-16} beyond which cracks are to generate and micro-cracks to propagate. Consequently, the diffusion of Ni towards YBCO is inevitable, which would greatly reduce the critical current densities. Since the crack formation in cerium oxide layers mainly depends on the stresses introduced by the lattice mismatch with Ni alloy substrate and on the arrangement of the oxygen vacancies in the lattice, it is possible to reduce these stresses by optimizing the doped-Zr in the Ceria layer, thus obtaining very thick and crack-free Ce$_{1-x}$Zr$_x$O$_2$ (CZO) buffer layers.

It was reported that Y$_2$O$_3$ not only could stabilize high temperature cubic zirconia phase but CeO$_2$ also could stabilize cubic or tetragonal zirconia phases \cite{17-18}. In this study, using reactive sputtering system with two metallic target of simple chemical composition such as Ce and Zr, the preparation and properties of CZO films with adjustable lattice constants for better lattice matching and chemical compatibility are investigated as a single buffer layer for YBCO coated conductors. The growth of subsequent YBCO films by direct-current (d.c.) sputtering is also investigated.

2. Experimental

The short segments (5-15mm), which were cut from a 10m long Ni-5at.%W tape, were manufactured and supplied by evico GmbH. The metal alloy tape had thickness of 70µm and width of 10mm. Prior to deposition the chamber was pumped down to a base pressure below 1x10^{-4}Pa.

Films of Ce–Zr mixed oxide with thickness around 300nm were deposited by d.c. reactive magnetron sputtering with the two sputtering guns arranged symmetrically with respect to the substrate. Two disk type Ce metal (99.99%) and Zr metal (99.95%) target were used. In sputtering process, d.c. power of Zr was fixed in 50 W while that of Ce was varied with 30 W, 50 W, 75W, and 100 W, respectively. It was confirmed that the composition of the films could be controlled with controlling power of Ce target. The samples were heated to 750°C at forming gas pressure (96%Ar+4%H$_2$) of 0.5 Pa, and water vapour for reaction with deposited Cerium and Zirconium atoms was introduced inside the chamber near the NiW substrates to the pressure of about 10^{-3} Pa. When all the parameters for deposition were in
equilibrium, the NiW tape was moved at the speed of 1.2 m/h by the reel-to-reel moving system. To assess the quality of the CZO single buffer layer, YBCO films were deposited by d.c. sputtering on short segments of the coated substrates. Details of the experimental conditions were reported elsewhere [19-20]. Typical YBCO film thicknesses were 500 nm.

X-ray diffraction analysis (θ-2θ, ω-scan and Φ-scan) was used to characterize the phase, structure, texture and lattice parameter of the buffer layers. A Bede D1 X-ray diffractometer with CuKα radiation was used in the present studies. An atomic force microscopy (AFM) and a SEIKO SPA300HV microscope were used to analysis the surface morphology of the samples. The critical current density (Jc) was measured using Jc-scan Leipzig system.

3. Results and discussion

The compositions of CZO films varied with increasing d.c. power to Ce target were analyzed by EDS, the values for x were 0.32, 0.5, 0.6 and 0.75 when d.c. power to Ce target were 30, 50, 75, and 100W, respectively. The epitaxial nature of CZO on NiW tape was investigated using XRD. Figure 1 shows the XRD θ-2θ scans for CZO films with various compositions. For each of the samples, only the (002) CZO peak is observed, indicating that the films are preferentially aligned. Also, the θ-2θ scans clearly illustrate a shift in the (002) peak position as a function of the atomic fraction (x) of Ce in CZO films. Note that the position of the (002) Ni peak (from the substrate) is invariant. The shift in CZO peak positions toward lower diffraction angles indicates an increase in the lattice parameter as the Ce content of the films increases. A linear dependence of the lattice parameter with x is observed shown in Fig. 2. Due to big lattice mismatch more than 50% between CZO and NiW, a 45° rotation of CZO with respect to the NiW was observed. The lattice mismatch between CZO and NiW varies from 7.8% (Ce0.32Zr0.68O2 with x=0.75) to 4.9% (Ce0.32Zr0.68O2 with x=0.32). Considering the effect from lattice match, Ce0.32Zr0.68O2 was used as the buffer layer for the subsequent YBCO coated conductors.

For implementation of Ce0.32Zr0.68O2 single buffer layers into YBCO wire manufacturing, it is important to grow dense and crack-free layers. AFM micrographs of the surface morphology for 300 nm thick Ce0.32Zr0.68O2 films fabricated on biaxially textured Ni-alloy substrates are presented in Figs. 3. The sample exhibits a continuous, crack-free, and dense surface morphology, average roughness around 3.3nm, which should best serve the goal of obtaining high-quality YBCO coatings.

One-meter-long biaxially textured Ce0.32Zr0.68O2 buffer layers were fabricated with production speed of about 1.2m/h. XRD ω- and Φ-scan measurements have been performed in order to examine the uniformity of the Ce0.32Zr0.68O2 buffer layer texture over length. Figure 4 plots the XRD ω-rocking curve FWHM distributions for the Ce0.32Zr0.68O2 (002) peak reflections taken along a 1 m length of NiW alloy tape. Uniform c-axis alignment of the Ce0.32Zr0.68O2 buffer layers can be seen from this figure. Similarly, excellent uniformity for the in-plane texture of the Ce0.32Zr0.68O2 layer is evident from the plot (Fig. 5) of XRD Φ-scan FWHM distribution recorded from the Ce0.32Zr0.68O2 (111) reflection along the tape length. A 1-m Ce0.32Zr0.68O2 film was obtained with Δω of 3-3.5° and ΔΦ of 5-6°. Further, we also observed the texture was uniform along the entire length of the tape.
After optimizing the fabrication process for $\text{Ce}_{0.32}\text{Zr}_{0.68}\text{O}_2$ films on NiW substrate, we deposited the 500nm thick YBCO film by d.c. sputtering. A typical XRD $\theta$-2$\theta$ scan of the YBCO film is shown in Fig.6. The YBCO film exhibits excellent c-axis oriented growth. Weak NiWO$_4$ and NiO impurity peaks are observed at 19° and 37°, respectively, implying minor oxidation of the metal substrate interface. Electrical transport and superconducting property measurements were conducted on the same sample. The self-field $J_c$ measured with $J_c$-scan Leipzig system about 0.75MA/cm$^2$ was obtained at temperature of 77K.

4. Conclusion

Co-sputtered CZO films were obtained by reactive sputtering of Ce and Zr metal targets simultaneously. It has been shown that CZO film with proper composition could used as single buffer layer in the fabrication of YBCO coated conductor. AFM observations demonstrated that CZO buffer layers with thickness up to 300nm were crack-free and dense. XRD $\omega$- and $\Phi$-scans of these buffer layers showed good and uniform out-of-plane and in-plane texture over lengths. YBCO coated conductors have also been prepared by d.c. sputtering on 300nm-thick CZO simple layers, indicating excellent c-axis oriented growth, and a critical current, $J_c$, of about 0.75MA/cm$^2$ at 77K and self-field was obtained.
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Figure captions:

Fig.1 XRD \( \theta \)-2\( \theta \) scans of CZO films deposited with different d.c. power of Ce (a) Ce\(_{0.32}\)Zr\(_{0.68}\)O\(_2\) film (Ce power of 30 W) (b) Ce\(_{0.5}\)Zr\(_{0.5}\)O\(_2\) film (Ce power of 50 W) (c) Ce\(_{0.6}\)Zr\(_{0.4}\)O\(_2\) film (Ce power of 75 W) (d) Ce\(_{0.75}\)Zr\(_{0.25}\)O\(_2\) film (Ce power of 100 W)

Fig.2 Lattice parameters calculated from the XRD data as functions of atomic fraction \( x \) of Ce in CZO

Fig.3 Typical AFM micrograph for Ce\(_{0.32}\)Zr\(_{0.68}\)O\(_2\) film

Fig.4 XRD \( \omega \)-rocking curve FWHM distributions of the Ce\(_{0.32}\)Zr\(_{0.68}\)O\(_2\) (002) reflections as a function of the 1m length tapes.

Fig.5 XRD \( \Phi \)-rocking curve FWHM distributions of the Ce\(_{0.32}\)Zr\(_{0.68}\)O\(_2\) (111) reflections as a function of the 1m length tapes.

Fig.6 Typical XRD \( \theta \)-2\( \theta \) pattern of the YBCO films on Ce\(_{0.32}\)Zr\(_{0.68}\)O\(_2\)/NiW substrate
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Fig. 2: Jie Xiong et al.
Fig. 3 Jie Xiong et al.

Fig. 4 Jie Xiong et al.
Fig. 5 Jie Xiong et al.

Fig. 6 Jie Xiong et al.