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Bulk solution techniques to fabricate high J_c YBCO coated conductors

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Abstract

Low-cost, non-vacuum bulk solution technique has been developed to deposit epitaxial Gd_2O_3 and $La_2Zr_2O_7$ (LZO) buffer layers directly onto both textured Ni and mechanically strengthened biaxially textured Ni–W(3 at.%)–Fe(1.7 at.%) (hereafter referred to as Ni–W) substrates. A reel-to-reel continuous dip-coating unit was used to produce meter lengths of highly textured, crack-free Gd_2O_3 and LZO buffers on Ni and Ni–W tapes. Auger electron spectroscopy analysis of the textured Ni–W substrates indicated the presence of sulfur segregation to the surface, which possibly facilitated the growth of solution seed layers directly on Ni–W substrates. On dip-coated seed layers, a reel-to-reel sputtering unit was used to deposit epitaxially 200 nm thick YSZ layers followed by 10 nm thick CeO_2 to complete the RABiTS architecture. Pulsed laser deposition was used to grow $YBa_2Cu_3O_{7-\delta}$ (YBCO) films on these tapes in short lengths. YBCO films with J_c values of 1.2×10^6 and 1.9×10^6 A/cm^2 at 77 K were obtained on Gd_2O_3 and LZO buffered Ni–W substrates, respectively. YBCO films grown by ex situ BaF_2 precursor process on 80 cm long, 1 cm wide CeO_2/YSZ/Gd_2O_3/Ni tapes exhibited end-to-end J_c of 6.25×10^5 A/cm^2 at 77 K and self-field. This demonstrates that the solution layers provide a very good crystallographic template for the growth of high current density YBCO films, with performance approaching that of vacuum-deposited seed layers.
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1. Introduction

In continuation of our efforts to demonstrate the growth of high quality $YBa_2Cu_3O_{7-\delta}$ (YBCO) films on solution buffered biaxially textured Ni-alloy substrates, we have chosen both textured

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Ni and mechanically stronger Ni–W(3 at.%)–Fe(1.7 at.%) (referred as Ni–W) substrates with reduced magnetism for this study. Both Gd_2O_3 and $La_2Zr_2O_7$ (LZO) buffer layers were grown epitaxially on meter lengths of both Ni and Ni–W substrates in a continuous reel-to-reel dip-coating unit. Here we report our successful growth of high current density (J_c) YBCO films on short sections of the solution buffered Ni–W substrates. In addition, we report recent results of high J_c YBCO films over lengths of solution buffered Ni tapes.

2. Experimental

Biaxially textured Ni–W substrates were obtained by mechanically deforming the metal rods by over 95%, followed by annealing at 1250–1300 °C for 1 h in the presence of Ar/H_2 (4%) gas. The substrates used were 1 cm wide and 50 μm thick. Prior to annealing, the substrates were cleaned by sonification in isopropanol. These annealed Ni–W substrates exhibit yield strengths (YS) of 143 and 154 MPa at 0.02% and 0.2% strain respectively, significantly higher than those of pure Ni substrates (YS = 40 and 58 MPa at 0.02% and 0.2% strain respectively). The saturation magnetization, M, of a Ni–W substrate ($M = 40$ G cm^3/g) was found to be lower than that of pure Ni ($M = 57.5$ G cm^3/g). The details of the fabrication of these substrates have been reported earlier [1].

The surface of the textured Ni–W substrates was analyzed using Auger electron spectroscopy (AES). The substrates were heated in an ultra-high vacuum at various temperatures ranging from 200 to 900 °C. A reel-to-reel continuous dip-coating unit was used to deposit both Gd_2O_3 and LZO seed layers using a 2-methoxyethanol solution of gadolinium methoxyethoxide/acetate or lanthanum zirconium methoxyethoxide. The dip-coated tapes were annealed in a furnace, which had been preheated to 1050–1150 °C. The flow rate of Ar/H_2 (4%) gas purging the furnace was 2–4 l/min. The heat-treatment times typically varied from 10 min to 1 h in the hot zone. After heat treatment, the tapes were spooled onto the take-up reel for subsequent processing. The typical film thicknesses of these seed buffer layers are 20–30 nm. The details of the process conditions have been reported elsewhere [2–4]. The optimized process conditions for Gd_2O_3 seeds are: coating speed: 20 cm/h; annealing speed: 20 cm/h; temp.: 1150 °C. Similarly, for LZO seed layers: coating speed: 3 m/h; annealing speed: 30 cm/h; temp.: 1050 °C. For comparison with solution seed layers, vacuum-process Y_2O_3 seed layers were also grown on Ni–W substrates using reactive evaporation. The details of the Y_2O_3 deposition were published earlier [5]. A reel-to-reel rf magnetron sputtering technique was used to grow both YSZ and CeO_2 layers on long solution seeds at 780 °C in a sputter-gas mixture of 10 mTorr Ar/H_2 (4%) gas and 2×10^{-6} Torr H_2O. Typical film thicknesses for these YSZ and CeO_2 layers were around 200 and 10 nm, respectively. On short lengths of these structures, pulsed laser deposition (PLD) was used for YBCO deposition, conducted at 780 °C and p_{O_2} of 120 mTorr. Ex situ YBCO precursor coatings were deposited on CeO_2 buffered YSZ/Gd_2O_3/Ni tapes using electron beam co-evaporation of Y, BaF_2, and Cu in a reel-to-reel setup. The YBCO precursors were then post-annealed at 740 °C in a mixture of oxygen and water vapor, using conditions reported earlier [6].

The films were analyzed by X-ray diffraction techniques. SEM micrographs were taken using a Hitachi S-4100 field emission microscope. The thicknesses of both buffers and YBCO films were determined by Rutherford backscattering spectroscopy and alpha step profilometer scans. The resistivity and transport critical current density, J_c, were measured using a standard four-probe technique. The voltage contact spacing was 0.4 cm. Values of J_c were calculated using a 1 μV/cm criterion. The Auger data were collected using a physical electronics model 590 scanning Auger microprobe with a beam voltage of 5 keV. The data were collected in the voltage to frequency conversion mode and smoothed and differentiated using commercial software and a personal computer. Sensitivity factors published by the equipment vendor were used to approximately quantify the results. The concentration of the values are certainly not absolute due to the various escape depths of the Auger electrons and the thickness of the sulfur layer and possible errors in the sensitivity factors,

but relative measurements between samples and sample conditions should be appropriate.

3. Results and discussion

The data obtained from the AES analysis of the textured Ni–W substrates are shown in Fig. 1. At 200 °C, the presence of C (~18%) and O_2 (~32%) concentrations indicates the presence of hydrocarbons and possibly WO_3 or NiO. After heating the substrate to 550 °C, the hydrocarbons were absent and O_2 was decreased to 10% and the presence of S (~20%) was observed. Further heating ($\geqslant$ 600 °C) increased the sulfur concentration to ~22% and O_2 was absent. This Auger coverage is similar to the complete coverage of a sulfur $c(2 \times 2)$ superstructure, observed previously on textured-Ni substrates [7]. Detailed X-ray studies indicated the presence of epitaxial Y_2O_3 (vacuum seed), Gd_2O_3, or LZO (solution seed) layers on Ni–W substrates. Detailed SEM and AFM studies indicated the presence of smooth, crack-free solution seeds. Meter lengths of solution Gd_2O_3 and LZO seed layers were produced. Very recent attempts to grow YBCO films directly on the solution seeds are encouraging, and details will be published elsewhere. The field dependence of J_c for short-length YBCO films deposited by PLD on all the seed layers with sputtered YSZ and CeO_2 cap layers is shown in Fig. 2. A high J_c of 1.9×10^6 A/cm^2 at 77 K and self-field was obtained on both Y_2O_3 and LZO seed layers. YBCO films with a J_c of 1.2×10^6 A/cm^2 were obtained on Gd_2O_3 seed layers. This demonstrates that the performance of solution seed layers approaches that of vacuum seed layers. Efforts are being made to grow YBCO films in lengths on solution buffered Ni–W tapes.

On long lengths of solution Gd_2O_3 buffered Ni tapes, YBCO films were grown using the reel-to-reel BaF_2 precursor approach. The resulting end-to-end J_c, over a 0.8 m length, was 6.25×10^5 A/cm^2 at 77 K. The complete, section-by-section data of J_c are shown in Fig. 3. The average J_c is 7.5×10^5 A/cm^2 with the standard deviation of

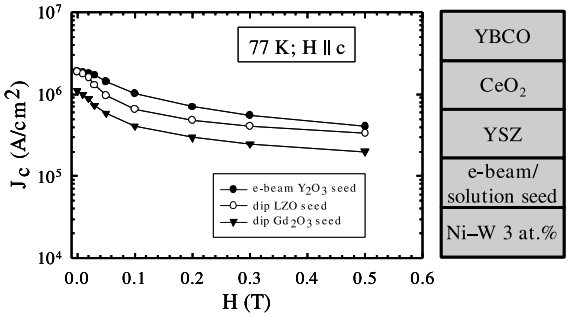

Fig. 2. The magnetic field dependence of critical current density, J_c, for short-segment YBCO films grown on various seed layers using PLD. The buffer layer architecture is shown on the right.

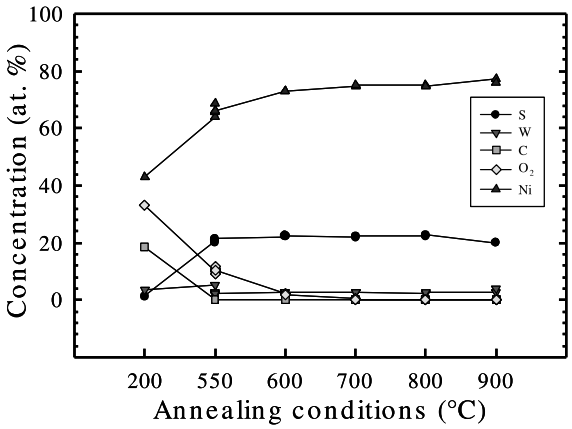

Fig. 1. AES analysis containing various atomic percentage of elements present at the textured Ni–W surface, after annealing at each temperature for 60 min in a high vacuum.

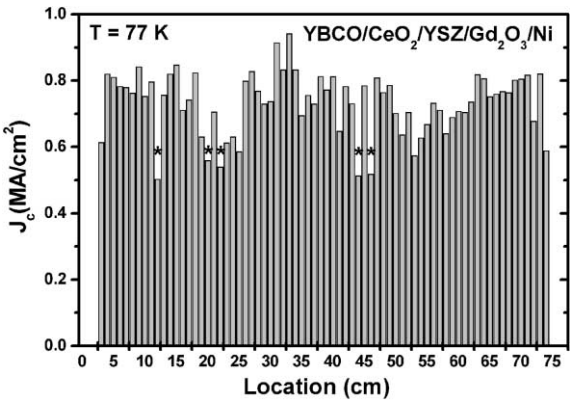

Fig. 3. Sectional J_c values at 77 K and self-field for the YBCO film obtained on a 1 m long CeO_2/YSZ/Gd_2O_3 (dip-coated)/Ni tape. Visible line features marked by (*).

only 10.5%. In some sections, the J_c is even approaching 1×10^6 A/cm^2. This is the highest J_c YBCO film reported so far in lengths using the RABiTS approach. It is worth noting that the low J_c sections marked with, "$*$", are associated with the visible line features along the YBCO thickness, resulting from the variations in the composition of YBCO precursor films. Despite the existence of these flaws, this result demonstrates that high J_c YBCO films can be grown on the solution seed layers in lengths. This also promises a route for producing long lengths of YBCO coated conductors using both vacuum and non-vacuum buffer layer technologies.

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