Progress Towards A Low-Cost Coated Conductor Technology

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ABSTRACT

Progress in the development of an economically and technically viable YBCO coated conductor technology for HTS wire using deformation-textured buffered substrates and solution-deposited superconductor layers is reported. Biaxially textured Ni substrates have been fabricated using a deformation texturing process. Epitaxial oxide buffer layers have been deposited by a combination of e-beam deposition and magnetron sputtering. Epitaxial YBCO films have been grown using a trifluoroacetate solution precursor. The resulting composite conductors have critical current densities approaching 2 MA/cm^2 at 77K in self-field. Critical current densities of 4.5 MA/cm^2 have been also obtained on CeO_2 buffered YSZ single crystal substrates, demonstrating performance parity with vacuum deposited YBCO films.

INTRODUCTION

Currently, one of the most promising approaches for low-cost HTS wire is based on $YBa_2Cu_3O_7$ (YBCO) coated-conductor in which the superconductor layer is grown epitaxially on a buffered metallic substrate. Critical current density (J_c) values in excess of 1 MA/cm^2 at 77K and self-field are now routinely reported for YBCO films deposited by conventional thin film techniques on metal substrates [1-3]. In addition, Foltyn et al have answered the question of scalability by producing a meter-long, centimeter-wide tape with J_c = 1 MA/cm^2 and a critical current (I_c) of 122 A at 75K and self-field [4]. The greatest obstacle to broad scale HTS commercialization is its price-performance ratio expressed in $/kAm. A stake in the ground has recently been set indicating that price-performance below $10/kAm will be required for broad scale replacement of copper on the electric utility grid [5]. The coated conductor (CC) technology based on YBCO layers deposited by conventional thin-film vacuum deposition techniques will have difficulty in meeting this price-performance target [6]. Consequently, we have proposed a low-cost approach to YBCO coated conductor [7]. It uses an inexpensive biaxially textured, buffered Ni substrate (the RABiTS™ process) initially developed at ORNL [2] and a solution-based metal-organic deposition (MOD) process for the superconductor initially developed at IBM and MIT [8,9].

Solution-based deposition of YBCO films is a low-cost, large-area technique, and offers excellent control of stoichiometry. Moreover it is easily scaleable with existing industrial equipment. The
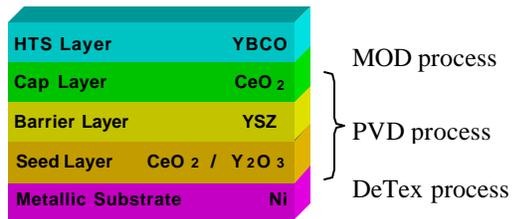
Fig.1 Schematic of a typical conductor architecture.

viability of this approach first depends on whether or not MOD YBCO films can achieve performance parity with vacuum deposited YBCO films. This was only partially answered by previous results for 0.3-2μm thick MOD YBCO films on oxide single crystals with J_c values in excess of 1 MA/cm^2 [5,8,9]. In this paper, we report more substantial progress towards this target on oxide single crystal and buffered metal substrates.

Schematically a low-cost conductor architecture and process path is shown in Figure 1. The biaxially textured nickel substrate is fabricated using a continuous deformation and annealing process [5]. The epitaxial buffer layer, chemically and structurally compatible with the textured nickel substrate, consists of a sequence of oxide layers (e.g. $CeO_2/YSZ/CeO_2$ or "CYC" for short). The CeO_2 seed layers were 20-30 nm thick and were deposited either by e-beam evaporation at ORNL [10] or reactive sputtering at ASC. The Y_2O_3 seed layers were 50-100 nm thick and were deposited by e-beam evaporation either at MIT or ORNL [11]. The YSZ barrier layers were approximately 0.4-0.5 μm thick and deposited on the seed layer by magnetron sputtering. The CeO_2 cap layers were 20-30 nm thick and were also deposited by magnetron sputtering. To avoid NiO formation on the nickel substrate, all the depositions were conducted in a reducing atmosphere relative to NiO (e.g. 4% H_2 in Ar). In some experiments, the metal substrates were replaced by YSZ single crystals and coated with the CeO_2 cap for use as a model system.

The superconductor layer is fabricated using a solution-based deposition technique that has been previously described [5,8,9]. The process uses the two-step decomposition-reaction sequence of the type described by Smith et al. Samples were coated with a solution of the metal trifluoroacetates either by spin-coating or by slot-die coating. The metal trifluoroacetate films were decomposed at a low temperature ($< 400^oC$) to form a film consisting

primarily of mixed oxyfluorides, and then converted to the YBCO phase at a processing temperature of $700 - 800^oC$ [5,12].

For transport measurements, the samples were coated with a thin layer of silver to form contacts; the silver was left over the whole sample surface because its resistance is large compared to that of the superconductor layer. Samples were generally small, ranging from 5x5 mm to 10x20 mm, having been sectioned to maximize the number of different runs and processing conditions. Voltage tap distances ranged from 2 mm to 10 mm without a bridge for the samples on metal substrates and with a 0.7mm wide bridge for the samples on oxide single crystal substrates. The measurements were made at 77K in self-field with a criterion of 1μV/cm.

RESULTS & DISCUSSION

The [111] x-ray pole figure of a typical RABiTS^{TM} Ni substrate showing a full-width-half-maximum ("FWHM") of about 8.0^o and an x-ray
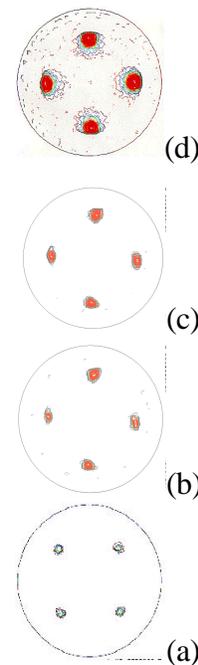

Fig. 2. Typical [111] X-ray pole figures: a) textured Ni substrate, b) CeO_2 seed layer, c) YSZ barrier layer, and d) CeO_2 cap layer (peaks have been truncated to magnify any undesirable low-level texture components.

Table 1
MOD TFA YBCO films deposited on oxide-buffered metal substrates

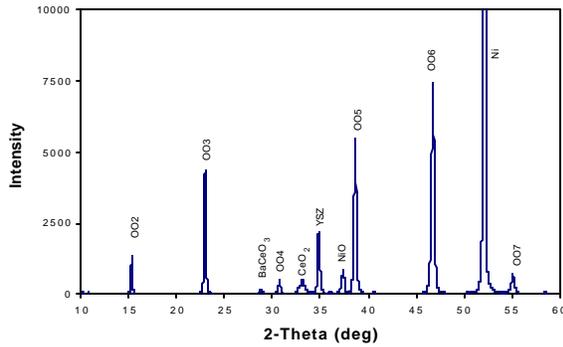| Buffer Architecture	YBCO thickness (μm)	Sample size (mm x mm)	I_c at 77K,sf, 1μV/cm (A)	J_c at 77K, sf, 1μV/cm (MA/cm^2)
Y_2O_3-YSZ-CeO_2	0.4	5 x 5	23	1.0
Y_2O_3-YSZ-CeO_2	0.4	5 x 5	46	1.9
CeO_2-YSZ-CeO_2	0.4	5 x 5	21	1.1
CeO_2-YSZ-CeO_2	0.4	5.5 x 5.5	27	1.2
CeO_2-YSZ-CeO_2	0.4	5 x 5	26	1.3
CeO_2-YSZ-CeO_2	0.4	5 x 5	30	1.5
CeO_2-YSZ-CeO_2	0.4	5 x 5	35	1.8
CeO_2-YSZ-CeO_2	0.27	20 x 10[A]	26	1.1

[A] Voltage tap distance of 10mm

Fig. 3. X-ray ($\theta-2\theta$) diffraction pattern of a 0.4 μm thick TFA MOD YBCO film on a CYC/Ni substrate, showing a small amount of $BaCeO_3$ formation.

Fig. 4 Temperature dependence of resistivity for sample 2 in Table 1.

(200) content of 99.5% is shown in Figure 2a. The surface roughness of the as-annealed substrate is approximately 14 nm R_a as measured by a Zygo Interferometer. The resulting buffer layers have good epitaxy as illustrated by typical pole figures in Figures 2b-d for each of the layers in the buffer architecture; the in-plane FWHM is 8-10°, comparable to the underlying nickel. X-ray diffraction analysis ($\theta-2\theta$) of the full stack shows the YBCO layer with a well-aligned c-axis texture and with good phase purity, Figure 3. A small amount of an interface reaction product, $BaCeO_3$, is formed from the reaction between BaF_2 and the CeO_2 cap layer.

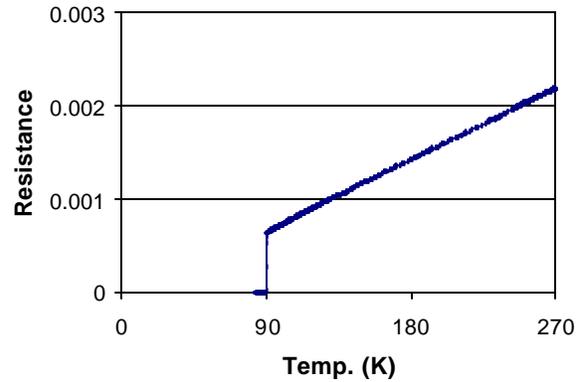Electrical measurements show a reasonable consistency over a range of different buffer architectures as seen in Table 1. J_c values of 1.8-1.9 MA/cm^2 have now been achieved in samples with a YBCO film thickness of 0.4 μm, more than doubling the performance in a previous report [7]. These J_c's compare quite favorably with vacuum based techniques for which maximum J_c values of 1.7-2.9 MA/cm^2 have been reported for a YBCO film thickness of 0.3 μm [13].   The YBCO films produced from the metal trifluoroacetate precursor have T_c onset of ~91K and T_c zero resistivity (determined on a linear scale) of ~90K as shown in Figure 4.

In order to assess performance headroom, solution-based YBCO films were deposited on a near-ideal buffered substrate. In this model system CeO_2 buffered YSZ single crystal substrates were

used. The J_c values of YBCO films grown from TFA precursors are 4.5 MA/cm^2 and 2.5 MA/cm^2 for 0.4 and 0.8μm thick films respectively at 77K in self-field. This performance is comparable to that achieved by vacuum deposition techniques on similar substrates [1] and indicates that there is no intrinsic limitation for solution-deposited YBCO films.

SUMMARY

In this work, progress towards key technologies necessary for the development of an economically and technically viable coated conductor process has been described. Current densities up to 1.9 MA/cm^2 on buffered DeTex Ni substrates have been achieved using low-cost, solution deposited YBCO films, achieving near-parity with vacuum-deposited YBCO films. Thick YBCO films with current densities up to 2.5 MA/cm^2 have been demonstrated on buffered single crystal substrates. The next step is to further develop processes for thicker YBCO and longer lengths of YBCO coated conductors for broad scale commercial application.

ACKNOWLEDGMENTS

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