Organization: Oak Ridge National Laboratory

Project Title: Strategic Research for Coated Conductor Development

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Project Purpose and FY 2001 Objectives: To develop a basic understanding of fundamental issues, and provide guidance for the practical solution of problems, related to coated conductor development for high-temperature and high-field applications. The primary objectives for FY 2001 are:

1. Continue fundamental studies of epitaxial oxide growth on metals, including alloys
2. Increase I_c/width to consistent values >150 A/cm for *ex-situ* processed YBCO coatings
3. Develop solution-based buffer layer deposition on alloy tapes
4. Collaborate with LANL to develop *ex-situ* YBCO on IBAD-MgO substrates
5. Continue studies of thermomechanical processing for improved texture in metals
6. Perform research on fundamental issues of continuous processing with CRADA partners

FY 2001 Performance and FY 2002 Plans: In FY 2001, all milestones were achieved as planned. We have acquired an improved understanding of the important first step of seed-buffer-layer epitaxial growth on metal surfaces from in-situ surface analyses using Auger spectroscopy and reflection high-energy electron diffraction. Thick YBCO coatings prepared on short samples by the BaF_2 ex-situ process have yielded high critical currents greater than 150 A/cm width. A new strengthened nickel-based alloy substrate has been developed in which excellent textures, as good as in the best pure nickel, have been obtained. $La_2Zr_2O_7$ and Gd_2O_3 seed buffer layers have been deposited epitaxially by solution-based process on this alloy substrate. The buffer layer stack was completed by sputtering and high J_c YBCO films were deposited by pulsed laser ablation.

FY 2002 plans include:

1. Develop methods to control the surface superstructure observed to affect oxide film nucleation and growth on pure and metal alloy surfaces.
2. Determine the mechanisms limiting J_c of *ex situ* YBCO with increased coating thickness.
3. Develop viable solution-based epitaxial buffer layers on alloy metal substrates.
4. Refine the level of biaxial texture in Ni and alloy tapes.

FY 2001 Results: Using *in situ* reflection high-energy electron diffraction (RHEED) and Auger electron spectroscopy (AES), we have identified a surface superstructure on Ni, NiCr, and NiW that strongly influences the subsequent heteroepitaxial nucleation and growth of oxide seed layers. The superstructure arises during the high-temperature fabrication anneal, and is due to surface segregation of sulfur contained as a low-level impurity in the metal. Anneals in Ar/4%H_2 are not effective in removing the superstructure or in avoiding its formation. In particular, we find the surface superstructure promotes the (200) epitaxial oxide growth of Y_2O_3-stabilized ZrO_2 (YSZ), CeO_2, and $SrTiO_3$. The ordered and chemically stable S layer forms a two-dimensional net that (completed with O adatoms) matches the (001) oxygen sublattice planes of these oxides, and therefore facilitates the bonding of oxide cations to the surface. These studies have motivated the implementation of in-line AES monitoring of long-length tape processing, since the identification and control of this superstructure may be required for reproducibility in seed-layer deposition.

The most critical step in the synthesis of high-performance YBCO coatings by the BaF_2 process is the *ex situ* anneal, which serves to thermally convert a low-temperature deposited, insulating precursor layer to epitaxial YBCO. Rate-limiting effects associated with this conversion anneal control the efficacy for coated conductor applications, with respect to both the synthesis of thick YBCO coatings and high production rate through a large processing area in a single furnace system. We have obtained valuable new insight into the nature of these rate-limiting effects. Quenching studies on films of various thickness and composition, including layers of the single component BaF_2, highlight the role of reactant and product diffusion through unreacted precursor layer, the nature of chemical reactions at the substrate interface, as well as the process of initial YBCO nucleation. Thick YBCO coatings with the desired c⊥ epitaxy were produced on RABiTS and IBAD-YSZ substrates up to 4-μm thickness, exhibiting J_c >0.3 MA/cm^2 at 77 K. Values for the critical current I_c exceed 150 A/cm-width (77 K) on metal-oxide substrates with adequate biaxial texture. An analysis of rate versus area indicates that for future implementation, reactors need to be designed that are capable of processing conductor areas of 1 m^2 or larger.

A strengthened Ni-based substrate with small alloying additions of W(3at%) and Fe(1.7at%) has been developed. By thermomechanical process similar to that used for pure Ni, 100% cube texture can be obtained in this alloy. The alloy shows no sign of secondary recrystallization even upon annealing at temperatures up to 1400C. The yield strength is approximately 3 times that of pure Ni substrates. Surface analysis indicates the surface chemistry is similar to that of our pure Ni substrates, with the formation of an ordered sulfur superstructure. Epitaxial oxide seed layers can be deposited by procedures similar to those used for pure Ni. High J_c's (up to 1.9 MA/cm^2) have been obtained in Pulsed Laser Deposition (PLD) and BaF_2 process YBCO films.

Biaxially-textured seed buffer layers of $La_2Zr_2O_7$ (LZO) and Gd_2O_3 have been grown on these alloy substrates using sol-gel processing. In both cases, the resulting epitaxial films have a strong cube texture and uniform micro-structure. Full RABiTS architectures were completed using rf sputtering to deposit additional YSZ and CeO_2 buffer layers. Resulting coated conductors, where the (YBCO) films were then deposited using PLD, exhibited J_c values in the range 1.6 to 1.9 MA/cm^2 at 77 K. The process has been extended to processing of LZO and Gd_2O_3 buffer layers on meter-long Ni and Ni-W substrates using a continuous reel-to-reel dip-coating unit.

We have continued controlled studies to document the effects of low-angle grain boundaries and the intra-grain properties on electrical transport of YBCO coated conductors. Studies focused on bicrystals with (100) tilt grain-boundary angles in the range of those of coated conductors (<7°). High-resolution measurements on self-assembled current distributions reveal no detectable barriers from 2° boundaries, while suppression is evident for boundaries of 3° or larger. Significantly, however, in the liquid nitrogen temperature range, the suppression of J_c by these low-angle boundaries is supplanted by intra-grain limitations for intermediate values of applied magnetic field that depend on the grain boundary angle. YBCO coatings grown on single crystal (secondarily re-crystallized) Ni tapes show J_c values comparable to those on single crystal oxide substrates, suggesting strong intra-grain properties of coated conductors. These combined results provide insight into previous observations that the high-field performance of coated conductors could be comparable to the best values on control, single crystal oxides. Practical ramifications are the need to further improve intra-grain flux pinning for high-field applications of coated conductors, where the distribution of low-angle grain boundaries will have little consequence.

We have assessed the possible improvement of low-field grain boundary transport through charge-carrier doping by Ca substitutions. Implementing the techniques found effective for improvement of high-angle grain boundaries, we synthesized bi- and tri-layer YBCO/30%Ca-doped-YBCO coatings on RABiTS. No discernible improvement in J_c was found at liquid nitrogen temperatures, while a possible systematic improvement could be observed at low temperatures.

We have conducted experimental studies and analyses addressing issues of coated-conductor thermal stability

during a dissipative transient. Both conductive buffer layers and highly conductive cap layers have been fabricated and assessed for electrically connecting the superconductor coating to a highly conductive shunt. Voltage-current measurements in liquid nitrogen are consistent with calculated stability criteria, and these criteria are found to impose a limit to the achievable engineering current density in stabilized coated conductors.

Advances have been made in achieving a simplified and more useful vapor-deposited buffer layer architecture for RABiTS. A single, 400 - 700 nm-thick electrically conductive buffer layer of $La_{0.7}Sr_{0.3}MnO_3$, deposited by rf magnetron sputtering, has yielded PLD-deposited YBCO films that are electrically well-coupled to the pure Ni tapes, and that exhibit J_c>0.5 MA/cm^2 at 77 K.

Technology Integration: Four CRADA teams are working directly with ORNL staff members to develop the science base for coated conductors. These teams are led by American Superconductor Corporation (AMSC), 3M, MicroCoating Technologies, and Oxford Superconducting Technology. Collaborations are under way with universities and other national laboratories, including University of Wisconsin-Madison, Stanford University, ANL, and LANL. Numerous publications and presentations, including a web-based posting of the 2000 ORNL annual report, help assure transfer of information to industry. A workshop for all patent licensees was held on April 19, 2001. For this, the latest results of ORNL strategic research towards coated conductor development were presented, CRADA team meetings were held, and discussions concerning investments in lab equipment to be made were held. The first personnel exchange was conducted this year, with AMSC placing a scientist at Oak Ridge in April 2001, followed by a site visit to AMSC by an ORNL scientist. Numerous team meetings were held at other CRADA partners' locations, as well. In addition, ORNL established an all-industrial route for CRADA partners to obtain roll textured pure metal and alloy foils, and this information was transferred to all CRADA partners on April 19, 2001.