Superconductivity for Electric Systems 2006
Project Summary

PROJECT TITLE:	**Epitaxial Coatings for Coated Conductors**
ORGANIZATION:	**Oak Ridge National Laboratory**
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FY 2006 FUNDING:	**$ 800 K at ORNL**

Project Purpose and FY 2006 Objectives: To develop a basic understanding and practical synthesis paths of epitaxial buffer layers on RABiTS templates and enhanced properties of YBCO superconductors on practical substrates for improved coated conductor performance. U.S. HTS wire manufacturers are now in a position to produce reasonable quality coated conductors in "pilot-scale" mode. In meeting the DOE cost target, however, it is necessary to increase throughput, decrease the buffer thickness, simplify the conductor architecture, and increase the HTS transport properties. Cost savings via buffer thickness reduction and single buffer architecture will require novel buffer materials with multi-functional properties. Improvements in the properties of the HTS coating require a thorough understanding of the pinning mechanisms and control of a possible combination of nanostructures, in order to further improve the in-field and angular dependent properties in REBCO. FY 2006 objectives were:

1. Continue fundamental studies of epitaxial growth of simplified buffers on textured substrates, including nickel alloys, copper and copper alloys and demonstrate high J_c YBCO films.
2. Further develop nanoparticle additions in the appropriate volume fractions to optimize pinning properties of YBCO at different temperatures (i.e., 77K, 65K, and 40K).
3. Continue optimizing nanoparticle substrate surface modifications for flux-pinning in thick *in situ* and *ex situ* YBCO on RABiTS, and extend to YBCO on IBAD Templates.
4. Fabricate films of REBCO with and without nanoparticle additions and compare pinning characteristics with YBCO with nanoparticle additions.
5. Correlate HTS properties with the level of $BaZrO_3$ incorporated in films as 3D, self-assembled, columnar nanodot arrays.
6. Conduct detailed measurement and analysis of the wide-range thickness dependence of critical currents in *ex situ* YBCO on RABiTS.

FY 2006 Performance and FY 2007 Plans: This project has provided an improved understanding of the fundamental properties of the RABiTS template with alternative buffer layers and YBCO. MOD has been successfully used to grow epitaxial La_3NbO_7 (LNO) and La_3TaO_7 (LTO) seed layers directly on textured Ni-W substrates with improved texture. These seeds could be used towards developing all-MOD buffer/YBCO in FY07. Coordinated effort between materials science and physics with understanding of properties has created paths to improved YBCO materials. Enhanced flux-pinning through a controlled study of substrate surface nano-structure engineering is demonstrated in YBCO films deposited on biaxially textured templates. Epitaxial 0.2 µm thick $NdBa_2Cu_3O_{7-\delta}$ (NdBCO) films with and without the incorporation of self-assembled nanodots of $BaZrO_3$ (BZO) were grown on RABiTS and IBAD substrates by pulsed laser deposition. Compared to epitaxial YBCO films on RABiTS, NdBCO films are found to have superior performance in applied fields at all field orientations, suggesting the presence of an increased density of pinning centers. FY 2007 Plans include:

1. Conduct fundamental studies of epitaxial growth of simplified and multi-functional buffers on textured substrates, including nickel alloys, copper and copper alloys and demonstrate high J_c YBCO films.
2. Fabricate films with minor amounts of site substitution in the Y, Ba, and Cu sites without significant reduction in overall T_c and determine the effects on pinning properties by locally suppressed superconductivity.
3. Fabricate films of REBCO with and without second-phase, nanoparticle additions and compare pinning characteristics with YBCO with nanoparticle additions.
4. Implement results from continued precursor studies to improve I_c in ~2 µm thick YBCO on RABiTS to values > 500 A/cm (77 K; sf).
5. Continue correlation of HTS properties in thicker REBCO films with 3D, self-assembled linear nanodot arrays.
6. Understand the mechanisms of 3D self-assembly of nanodots to enable better control of defect structures to further optimize pinning characteristics.

FY2006 Results: Key Results from the past year include:

- La_3NbO_7 (LNO) and La_3TaO_7 (LTO) type pyrochlore phases have been grown directly on textured Ni-W substrates using MOD with improved out-of-plane textures. Last year, we demonstrated the improvement of textures in MOD $La_2Zr_2O_7$ (LZO) layers by introducing a thin PVD Y_2O_3 seed layer. This was mainly necessary to reduce the lattice mismatch between LZO and Ni-W. This year, we have achieved the improvement in MOD LZO texture by introducing a thin solution deposited LTO seed. Epitaxial growth of LTO or LNO layers with a large lattice mismatch on Ni-W could be attributed to the coherent film growth.

- PVD YSZ has been proven to be an excellent metal diffusion barrier. Based on our work with MOD $Gd_2Zr_2O_7$ (GZO) buffers with improved diffusion properties, we focused on looking into the phase diagram of Gd_2O_3-ZrO_2. Using MOD, we have prepared the entire phase boundary range (0-100%) and identified various structures ranging from monoclinic to fluorite to pyrochlore and to C-type. Both GZO (Gd:Zr = 50:50) and GSZ (Gadolinia stabilized zirconia; Gd:Zr = 20:80) layers have been deposited using sputtering and high J_c YBCO films have been grown using PLD.

- Enhanced in-field J_c performance has been achieved in YBCO films grown on biaxially textured templates pre-treated with preformed suspension based $BaTiO_3$ (BTO) and BZO nanoparticles. Results obtained in this study are compared with our previous investigations on surface modified substrates with sputter and solution processed nanoparticles. Using suspension approach of preformed nanoparticles, YBCO films showed significantly enhanced J_c performance along magnetic field direction parallel to c-axis of the substrate. On the other hand, samples modified through sputter and solution techniques promote the formation of YBCO films with improved and more isotropic pinning dependence with respect to a whole range of field orientations. Analysis of the scaling behavior of pinning force density, F_p, indicates consistency of the pinning mechanism with respect to temperature and provides a powerful tool for predicting J_c at arbitrary field and temperature.

- We have measured and analyzed the superconducting properties for YBCO with columns of self-assembled nanodots of BZO. A model was constructed for the dependence of the critical current density J_c on BZO fraction, *x,* for a series of 0.2 µm films. The model is compared with the magnetization J_c and is in agreement with TEM observations that in going from 2vol% BZO to 4vol%BZO, the aerial density only increases slightly, but the radius of the BZO nanodot columns approximately doubles.

- Epitaxial $NdBa_2Cu_3O_{7-\delta}$ (NdBCO) films have been grown on Rolling-assisted-biaxially-textured-substrates by pulsed laser deposition. At the optimal substrate temperature of 760°C, a J_c of 2.2 ~ 3.4 MA/cm^2 at 77 K, self-field is obtained for films with thicknesses in the range 0.13 ~ 0.25 µm. Compared to epitaxial $YBa_2Cu_3O_{7-\delta}$ (YBCO) film, these NdBCO samples are found to have better field and angular dependences of J_c. When J_c is compared at the field of 1 T, NdBCO samples have more than two times higher J_c than YBCO films with a prominent J_c peak for H//c. Similar enhancements are also observed for other REBCO films. These results strongly suggest the presence of an increased density of *c*-axis correlated pinning centers within NdBCO films. Incorporation of columns of self-assembled nanodots of BZO within the NdBCO films results in further enhancement of the in-field J_c at all field orientations. J_c varies as $J_c \sim H^{-\alpha}$ at intermediate fields, with α values for NdBCO and BZO-doped NdBCO films being ~ 0.37 and ~ 0.43, respectively, which are significantly lower than α ~ 0.52 for a pure YBCO film. Thicker REBCO films are being investigated.

- Yttrium rich BaF_2 *ex situ* YBCO films were prepared with a wide range of thicknesses from 28 nm to 1.5 µm, In a controlled study, the temperature and magnetic field dependencies of J_c were shown to be largely understandable in terms of a theoretical model of strong pinning. For a wide range of temperatures and intermediate fields, we found $J_c \propto H^{-\alpha}$ with $\alpha \sim (0.56 - 0.69)$ for all materials. This feature can be attributed to pinning by large random defects, which theoretically has power-law exponent α = 5/8, and is in semi-quantitative agreement with TEM observations of sparse inclusions of Y_2O_3, etc. This work has appeared (June 2006) as an article in Physical Review B, and the two investigations have been presented in 5 invited talks.

Research Integration: The materials science base for buffer layers for YBCO coated conductors also involves collaborations with universities and other national laboratories, including University of Tennessee, University of Florida, University of Kansas, University of Wisconsin-Madison, University of Houston, Columbia University, NREL, and LANL. Numerous publications (including a Web-based posting of the FY 2006 ORNL annual report) and presentations help assure transfer of information to industry. The work on IBAD substrates is part to ORNL's CRADA with SuperPower. Interaction with other CRADA partners working on RABiTS such as American Superconductor, Oxford and MetOx continues.