Superconductivity for Electric Systems 2006
Project Summary

PROJECT TITLE:	Development of texture and critical currents in 3-4 micron thick YBCO films on RABITS substrates.
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PRESENTERS:	Vyacheslav Solovyov, Masaki Suenaga
FY 2005 FUNDING:	$400k
FY 2006 FUNDING:	$320k

Overall Project Purpose and FY2006 Objectives:
This project is focused on developing a knowledge base for the *ex situ* processing of high performance multi-micrometer-thick YBCO films. A thick high-J_c YBCO film is the essential component of a coated conductor (CC) and further improvements in performance on the YBCO film are required to make CCs more attractive for various applications. Progress in the J_c of CCs has come from two directions: enhancement of flux pinning and improvement of the texture and structure quality of the YBCO film. The BNL group has applied its expertise and understanding of the thermodynamics of YBCO growth and epitaxial nucleation to develop methods to improve the structure of *ex situ* processed CCs. Additional improvements have come about through the understanding of the thermodynamic phenomena underlying the formation of c-axis oriented texture in thick YBCO films. The work performed at BNL for the Superconductivity for Electric Systems Program nicely complements the flux-pinning-oriented research at other laboratories (LANL, ORNL).

FY 2006 Results and Accomplishments:
1) We have demonstrated record critical current densities for 3 μm thick YBCO films on RABITS substrates: 1.9 MA/cm^2 in zero field and 0.66 MA/cm^2 at 1 T, H||c orientation, at 77 K. The J_c angular dependence of similar films was nearly isotropic up to 3 T. In addition these YBCO layers combine high J_c with a T_c exceeding 92 K. For these studies the substrates were cut from 4-cm-wide RABITS tapes, produced in large quantities by AMSC. It should be emphasized that thick film processing is more sensitive to the quality of the buffer layer due to the retardation of epitaxial c-axis YBCO nucleation caused by the thick precursor layer.

2) The dominance of exceptionally strong isotropic flux pinning centers in these films, inferred from the angular dependence of J_c, is one of the most intriguing observations of FY2006. This type of pinning emerges in samples processed at low temperatures, <750 ºC, and fast growth rates, >5 Å/s. In addition to having strong pinning, films grown in this regime have an unusually high T_c, over 92 K. Qualitatively, angular dependences of J_c are very reminiscent of those typically observed in single crystals with pinning by oxygen vacancies. However, the pinning strength in these films is an order of magnitude higher than that caused by the oxygen vacancies. Analysis of TEM data provides little evidence that the pinning is caused by non-superconducting inclusions, such as Y_2O_3, since there is little correlation between density of the Y_2O_3 precipitates and J_c. Understanding the origins of this pinning may have important consequences opening up new high-field applications for CCs. At this point several possible candidates are under consideration for the pinning centers. We envision this as a new exciting area of research in FY2007.

3) In processing thick, >2 μm, YBCO films at fast growth rates, > 5 Å/s, by the BaF_2 process, it was found that the nucleation was initiated at the top surface of the precursor as well as the precursor/substrate interface. Randomly oriented YBCO growth at the top surface dramatically reduced J_c. These grains grew when the nucleation of c-axis YBCO at the interface was delayed (long incubation periods). This occurs when an as yet unidentified condition of the surface of the oxide buffer layer was unfavorable (low catalytic efficiency) for c-axis YBCO nucleation. Limiting the nucleation of YBCO at the top surface required changes in the processing protocol so that the nucleation and growth of the YBCO layer could be independently controlled. At the start of YBCO film growth the overall pressure in the reactor is set high in order to slow down the growth rate and promote epitaxial c-axis nucleation at the precursor substrate interface. After the c-axis nuclei have established themselves the pressure is gradually reduced to speed up the growth of desired c-axis oriented phase. Fast growth was discovered to be essential in order to reduce granularity in the c-axis oriented YBCO and achieve J_c's well over 1 MA/cm^2. We consider this understanding and control our most important result for FY2006.

4) Films were processed at low $p(O_2)$ to retard the growth of randomly oriented YBCO. The films became granular and J_c was reduced dramatically. To understand how granularity of the c-axis oriented layer negatively affects J_c, we examined the microstructure of individual YBCO nuclei. Specially prepared plane-view samples allowed for both optical and TEM observation of YBCO nuclei. TEM contrast was observed to change from the center to the edge of the nuclei, possibly reflecting changes in the degree of YBCO disorder. This aspect of our TEM effort will receive more attention in

FY2007.

5) The effects of a magnetic substrate on the ac losses of superconducting films were investigated by measuring the losses for single and stacks of octagonal disks of $YBa_2Cu_3O_7$ film grown on a magnetic Ni-5 at. % W substrate. The specimens were received from AMSC and the measurements were performed at 77 K in perpendicular ac magnetic fields at 20 Hz. At low fields the loss dependence on ac magnetic field amplitude, B, and film thickness, t, varied as B^3/t instead of the B^4/t^3 dependence, observed for superconducting films on a nonmagnetic substrate. These results are well described by considering the formation of a virtual-infinite stack of superconducting films due to the magnetic mirror effect. The implications of this study for critical currents, I_c, is that I_c of the film on a soft magnetic substrate will be higher than that of a same film on a nonmagnetic substrate. This applies to thin superconducting films in low magnetic fields measured by magnetic hysteresis.

FY 2007 Plans and Expectations

1) In FY2005-2006 we established a strong correlation between J_c and the growth rate of the YBCO layer. Achieving high J_c required fast growth at low temperature. Thermodynamically this means that the precursor -> YBCO conversion reaction has to be shifted as far from equilibrium as far as possible. In FY2007 this limit will be explored. So far the only limitation has been the formation of randomly oriented YBCO in the films. Since we now have effective strategies to suppress randomly oriented grain nucleation, growing c-axis oriented films at rate faster than 10 Å/s at 735 ºC is possible. An interesting trend is increase of T_c with the growth rate and the discovery of new meta-stable phases with interesting properties cannot be ruled out. The research also has important practical implications, because faster processing is essential for making the manufacture CCs less expensive.

2) An extensive analysis of structural data collected in FY2005-2006 is an important part of our plans for FY2007. During these 2 years over 200 3-4 μm thick YBCO samples have been synthesized, measured, and characterized. So far we have examined only the intensities of (006) and (103) YBCO reflections to prove that the structure quality is a primary limitation of J_c. In FY2007 it is planned to extend this analysis to other reflections of the XRD spectrum and search for new structure-performance correlations. One direction that would be interesting to pursue is the role of the cubic perovskite phase that develops in these samples after the conversion of the precursor to YBCO.

3) Establishing the nature of defects for flux pinning in these samples poses a significant challenge. The isotropic nature of these defects makes them difficult to detect by traditional TEM methods and may require some specialized time-consuming techniques, e.g., analysis of diffuse scattering and high-resolution EELS. However, we believe that the exceptionally strong high-field pining caused by these defects justifies the effort. To succeed in this we will require a close collaboration with an experienced and motivated TEM group.

Research Integration:

FY 2006 was marked by productive collaboration with research groups at LANL, ANL, AMSC and Superpower.
Dr. Civale's group at LANL extensively studied transport critical-current densities of our samples. Results of these measurements, which were mentioned above, provided deep insight into character of the pinning centers. Correlations between results of J_c measurements and TEM and XRD data might reveal the origins of exceptionally strong pinning in these samples and provide guidance for further enhancements of the pinning strength and consequent improvements in high-field performance of CCs.

In FY2006 we started collaboration with ANL with a goal of elucidating the type of structural disorder accumulated in large YBCO grains. Samples of films were supplied with large well-defined nuclei to the ANL group for characterization by RAMAN microscopy (Vic Maroni) and SEM, FIB TEM (Dean Miller). Composition maps of nuclei imbedded in the precursor films show differences in elemental concentrations of the YBCO nuclei and the precursor.

Our group at BNL has traditionally strong ties with AMSC, which is pursuing a similar fluoride-based *ex situ* process for large-scale production of CC's. We use buffered substrates manufactured by AMSC and exchange information on performance of the thick YBCO films deposited on these substrates.

We offered our expertise in composition analysis of YBCO layers to Superpower and assisted in the installation and set-up of an inductively coupled plasma analysis system at the Superpower facility in Schenectady, NY.