EPITAXIAL YBa$_2$Cu$_3$O$_7$ ON BIAXIALLY TEXTURED (001) Ni: AN APPROACH TO HIGH CRITICAL CURRENT DENSITY SUPERCONDUCTING TAPES


ABSTRACT

In-plane aligned, c-axis oriented YBa$_2$Cu$_3$O$_7$ (YBCO) films with superconducting critical current densities, $J_c$, as high as 700,000 amperes per square centimeter at 77 kelvin have been grown on thermo-mechanically, rolled-textured (001) Ni tapes using pulsed-laser deposition. Epitaxial growth of oxide buffer layers directly on biaxially textured Ni, formed by recrystallization of cold-rolled pure Ni, enables the growth of 1.5 micrometer-thick YBCO films with superconducting properties that are comparable to those observed for epitaxial films on single crystal oxide substrates. This result represents a viable approach for producing long-length superconducting tapes for high current, high field applications at 77 kelvin.

INTRODUCTION

Since the discovery of high-temperature superconductivity (HTS) in cuprate materials, significant efforts have focused on developing a high-current superconducting wire technology for applications at 77 K [1,2]. Early in these efforts it was observed that randomly oriented polycrystalline HTS materials have critical current densities, $J_c$, < 500 A/cm$^2$. In contrast, oriented YBCO thin films grown epitaxially on single-crystal oxide substrates, such as (001) SrTiO$_3$, exhibit $J_c$ values > 1MA/cm$^2$ at 77 K [3]. This huge difference between randomly-oriented HTS ceramics and single crystal-like epitaxial films is directly related to the misorientation angles at the grain boundaries in polycrystalline materials. Values for $J_c$ across a grain boundary decrease significantly as the misorientation angle increases, with weak-link behavior observed for grain boundary misorientation angles greater than $\sim$10° [4]. In order to achieve high $J_c$ (\(\sim 10^5\) to \(10^6\) A/cm$^2$, 77 K), the crystallographic orientation of the HTS superconducting wire or tape must possess a high degree of both in-plane and out-of-plane grain alignment over the conductor's entire length. Preferably, this would be achieved with YBCO, because the limits for dissipation-free current at 77 K in an applied magnetic field are most favorable for this material [5,6].

We recently reported on an alternative approach for achieving in-plane aligned, high critical current YBCO films on long-length substrates [7]. A biaxially textured (001) Ni tape, formed by recrystallization of cold-rolled pure Ni [8], is used as the initial, in-plane aligned substrate. A (001)-oriented oxide buffer layer architecture is then epitaxially grown that maintains the sharp crystallographic cube texture of the metal substrate while providing a barrier to chemical interaction with the Ni. Subsequent growth of YBCO on this structure, referred to as a rolling-assisted, biaxially textured substrate (RABiTS), results in c-axis oriented, in-plane aligned films with $J_c$ as high as 700,000 A/cm$^2$ at 77 K. The advantage of this approach over other alternatives, such as IBAD, is in the simplicity of producing the initial in-plane alignment, required for high $J_c$, by a cold-rolling and annealing process that can easily be scaled to produce arbitrary substrate lengths. 
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EXPERIMENTS

The YBCO/yttria-stabilized ZrO₂ (YSZ)/CeO₂ layered architecture used to grow in-plane aligned, high-Jc films on rolled-textured (001) Ni is schematically illustrated in Fig. 1. The Ni substrates have a relatively sharp cube orientation with a FWHM out-of-plane texture Δθ ~ 6° to 10° and an in-plane texture Δφ ~ 6° to 15°, depending on the specific rolling and annealing conditions, as well as material purity, with a grain size ranging from ~ 30–100 μm in diameter. The 125 μm-thick Ni substrates were used as-rolled and annealed with no subsequent polishing. The epitaxial oxide buffer layers, along with the c-axis oriented, in-plane aligned YBCO films, were grown by pulsed-laser deposition (PLD) using a KrF excimer laser.

Typically, the epitaxial growth of a (001)-oriented cubic oxide on a (001) Ni surface is inhibited by the formation of (111) NiO at the oxide/metal interface [9]. The Ni substrates were annealed at 900°C in a 4% H₂/Ar gas mixture prior to film growth to reduce any NiO on the substrate surface. In order to further suppress the formation of NiO and achieve (001)-oriented epitaxy directly on the (001) Ni surface, H₂ gas was introduced into the PLD chamber during the initial stages of CeO₂ growth. Hydrogen is effective in reducing NiO, while having little effect on the CeO₂ film. Consistent (001)-oriented epitaxial growth of CeO₂ was achieved only if the oxide growth was initiated in the presence of the H₂ / Ar mixture. Our results clearly shows that the nucleation of the CeO₂ layer in the presence of H₂ results in the formation of (001) CeO₂, with subsequent growth in either vacuum or a background of oxygen maintains this orientation. This (001)-oriented CeO₂ layer provides an oxide template directly on the metal surface for the subsequent epitaxial growth of additional oxide buffer and HTS layers.

After the CeO₂ film is deposited, a YSZ layer was grown in situ using PLD. The YSZ layer appears to alleviate cracking of the oxide layers that can occur due to the thermal...
expansion mismatch between the Ni substrate and the oxides. The CeO$_2$ and YSZ layers are each \( \sim 500 \text{ nm} \) thick. A thick (> 0.5 \( \mu \text{m} \)) YBCO film is then deposited at 780\(^\circ\text{C}\) in an oxygen pressure of 185 mTorr. After deposition, the films are cooled at 10\(^\circ\text{C}\) per minute, with the oxygen pressure increased to 700 Torr at 400\(^\circ\text{C}\).

A \( \theta-2\theta \) x-ray diffraction (XRD) scan of a YBCO/YSZ/CeO$_2$ composite structure (Fig. 1) reveals that the CeO$_2$ and YSZ buffer layers, as well as the YBCO layer, are (001)-oriented relative to the surface normal. The intensity ratio of the CeO$_2$ (111)/(200) peaks is \(< 10^{-2}\), indicating a very small volume percentage of (111)-oriented oxide. The out-of-plane crystallographic texture for the YBCO, YSZ, CeO$_2$, and Ni was determined by XRD rocking curves (\( \varphi \)-scans). The rocking curve through the Ni (002) peak shows a significant amount of structure, due to the coarse-grained nature of the rolled-textured substrate, yielding an out-of-plane FWHM of \( \sim 6^\circ \). Subsequent rocking curves through the (002) peaks for the CeO$_2$ and YSZ layers indicate an out-of-plane FWHM of 5.5\(^\circ\) and 5\(^\circ\), respectively. Some structure was also observed in these rocking curves, reflecting the good epitaxial relationship between the oxides and the underlying Ni grains. A significant narrowing in the out-of-plane texture is observed for the YBCO, with the rocking curve through the (005) YBCO peak yielding an out-of-plane FWHM of only 1\(^\circ\). This improvement in the out-of-plane alignment relative to the underlying Ni results from the low (001) surface energy and the anisotropic film growth nature commonly observed for YBCO. This high degree of out-of-plane texture is important in realizing a high \( J_c \), as it virtually eliminates the [100] tilt boundary contribution to the total grain boundary misorientation angle.

The in-plane crystallographic alignment of the epitaxial YBCO/YSZ/CeO$_2$/Ni structure was determined by XRD \( \varphi \)-scans through the YBCO (226), YSZ (202), CeO$_2$ (202), and Ni (222). The in-plane FWHM for all of the layers is \( \sim 6.8^\circ \), indicating excellent epitaxy of the oxide layers with the biaxially textured metal. If the grain-to-grain misorientation angles are uncorrelated with a normal distribution, \( \sim 90\% \) of the Ni grains have in-plane misorientation angles of 7\(^\circ\) or less [10]. The in-plane (100) CeO$_2$ and YSZ principal crystallographic axes are rotated 45\(^\circ\) relative to the in-plane (100) Ni axis, whereas the a- and b- axes of the YBCO are rotated 45\(^\circ\) with respect to the YSZ axes, all of which are in agreement with near-coincidence site lattice models [11].

The superconducting transition temperature, \( T_c(R=0) \), for the YBCO films was typically \( \sim 88 \text{ K} \). The temperature dependence of \( J_c \), measured in magnetic fields of 0, 3, and 8 T applied parallel to the YBCO c-axis, is shown in Fig. 2. At zero field, this YBCO film has a \( J_c(77 \text{ K}, \ H=0) \) of 575,000 A/cm$^2$. We have produced several films with \( J_c(77 \text{ K}, \ H=0) \) greater than 600,000 A/cm$^2$, with the highest
value obtained thus far being 700,000 A/cm². The \( J_c(T) \) behavior for the YBCO films on the rolled-textured Ni tapes is comparable with that observed for epitaxial films on oxide single crystals, which is consistent with the absence of high angle grain boundaries in the YBCO film. For comparison we also show data for conventional low \( T_c \) superconducting NbTi and Nb₃Sn wires [12], as well for Bi-2212/Ag [13], Bi-2223/Ag [14], and Tl-1223/poly-YSZ [15], HTS wires and tapes. Clearly, the performance of the epitaxial YBCO on rolled-textured Ni tape is far superior, in terms of \( J_c \), to these other superconducting wire technologies, both for zero-field and high-field applications. In particular, the zero-field \( J_c \) of the YBCO on rolled Ni at 77 K is significantly higher than the \( J_c \) of state-of-the-art Bi-2223, Bi-2212, or Tl-1223 wires and tapes at 4.2 K. In addition, \( J_c(T, H=8 \text{T}) \) for the YBCO/RABiTS is higher than \( J_c(T, H=0) \) for the Bi-2223/Ag and Tl-1223/YSZ wires in zero field at all \(< 65 \text{K} \). At \( T < 40 \text{K} \), \( J_c(H) \) for these films is greater than for conventional low \( T_c \) superconductors, such as NbTi and Nb₃Sn, operating at 4.2 K. Thus, the use of rolling textured metal substrates, coupled with the epitaxial growth of appropriate buffer layer architectures and superconducting films, represents a viable means for producing long-length superconducting tapes for high current, high field applications at 77 K, particularly if high values of the "engineering" \( J_c \), defined as the critical current per total conductor cross-sectional area (including substrate thickness), can be realized with thinner substrates and/or thicker YBCO films.

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REFERENCES