LaNiO$_3$ buffer layers for high critical current density
YBa$_2$Cu$_3$O$_{7-8}$ and Tl$_2$Ba$_2$CaCu$_2$O$_{8-8}$ films

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We demonstrate high critical current density superconducting films of
YBa$_2$Cu$_3$O$_{7-5}$ (YBCO) and Tl$_2$Ba$_2$CaCu$_2$O$_{8-8}$ (Tl–2212) using LaNiO$_3$
(LNO) buffer layers. YBCO films grown on an LNO buffer layer have
only a slightly lower $J_c$ (5K, H=0) than films grown directly on a bare
LaAlO$_3$ substrate. It is noteworthy that YBCO films grown on LNO buffer
layers exhibit minor microstructural disorder and enhanced flux pinning.
LNO-buffered Tl-2212 samples show large reductions in $J_c$ at all
temperatures and fields compared to those grown on bare LaAlO$_3$,
correlating to both $a$-axis grain and nonsuperconducting phase formation.
With additional optimization, LNO could be a promising buffer layer for
both YBCO and Tl-based superconducting films, perhaps ideally suited for
coated conductor applications.
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Recently, there has much work on the development of flexible high-temperature superconducting (HTS) wires or tapes to support high currents in the presence of high magnetic fields.\cite{1,2} Such conductors would benefit many applications including high-field magnets, electric generators, and large-capacity power transmission lines. For optimum magnetic field performance, the superconductor must be biaxially textured to avoid high-angle grain boundaries that form "weak links" in the supercurrent flow.\footnote{3} Since this biaxial texture is induced from the growth surface, the buffer layer must provide a biaxially textured template in addition to chemically isolating the superconductor from the substrate. To date, the most successful buffer layers for YBa$_2$Cu$_3$O$_{7.5}$ (YBCO) and Tl-based conductors have been yttria-stabilized zirconia (YSZ) and/or CeO$_2$.\footnote{4-6}

LaNiO$_3$ (LNO) has several properties that make it attractive as a buffer layer for a flexible conductor. It has a pseudo-cubic perovskite structure with pseudo-cubic lattice parameter of 3.83 Å.\footnote{7} This provides a good lattice match with both YBCO and Tl-oxide superconductor materials. The demonstrated ability of LNO to grow epitaxially on a variety of substrates (including YSZ, LaAlO$_3$, SrTiO$_3$, and textured Ni\footnote{8}) makes it potentially useful either as part of a multi-layer buffer\footnote{9} or as a growth surface for a flexible conductor.\footnote{8} Another advantage is that LNO is conductive ($\rho \sim 1$ m$\Omega$ cm at 300 K).\footnote{7,8} If LNO could be made to contact both the metal substrate and the superconductor, then in the event that the superconductor transitioned to the normal state, LNO would contribute to the quench protection by providing a current path to the substrate.

In this letter, we demonstrate the ability of laser-ablated LNO buffer layers to directly support the growth of YBCO and Tl$_2$Ba$_2$CaCu$_2$O$_{8.5}$ (Tl-2212) films with high critical current densities ($J_c$). We used single-crystal LaAlO$_3$ (LAO) substrates in order to study the intrinsic compatibility of the superconductors with LNO. Although growth conditions were not fully optimized, we find that high $J_c$ films of both YBCO and Tl-2212 can be grown on LNO buffer layers.
We grow the LNO films by pulsed-laser deposition (PLD), ablating a stoichiometric multi-phased pellet with a KrF excimer laser (λ = 248 nm) focused to ~ 3 J/cm². LAO substrates are attached to a resistive heater maintained at 700 °C and positioned 8.5 cm directly in front of and parallel to the target surface. LNO films were grown in an ambient of 250-350 mTorr of O₂. The YBCO films were deposited in a separate system using RF off-axis sputtering in an oxygen partial pressure of 10 mTorr with 90 mTorr of Ar. The substrates were mounted with Ag-paint on a heater block held at 850 °C. This heater temperature corresponds to ~ 750 °C at the sample surface. In the case of the Tl-2212, Tl-free precursor films were deposited at ambient temperature using the same RF off-axis sputtering technique. The precursor films were then thallinated in a hybrid two-zone/crucible furnace process described elsewhere. Since neither the YBCO nor the Tl-2212 growth processes were optimized for this study, we simultaneously grew these films on both bare LAO control substrates and on LNO buffered LAO.

The LNO buffer layers (~ 3400 Å) deposited on LAO are highly oriented and have a smooth surface morphology. Theta-2 theta and pole figure x-ray diffraction (XRD) scans confirm that the LNO films are biaxially textured on the substrate with a single cube-on-cube orientation. The LNO films have a root mean square surface roughness < 10 Å, measured by atomic force microscopy.

The microstructural properties of ~ 2000 Å-thick YBCO films grown on LNO buffer layers are similar to those grown directly on LAO. The XRD scans show only (00l) peaks for the YBCO/LAO films, indicating a purely c-axis out-of-plane orientation. For YBCO films grown on an LNO buffer layer, XRD does identify a low-intensity peak corresponding to a plane spacing of ~ 2.6 Å, indicating the presence of a nonsuperconducting minority phase. Pole figure scans for the (113) YBCO peak demonstrate a 4-fold symmetry, confirming a single in-plane orientation in which the a- and b-axes of the YBCO are parallel to the a- and b-axes of the substrate. The surface
morphology of the LNO-buffered samples, shown using scanning electron microscopy (SEM) in Fig. 1, is nominally the same as the control samples on LAO.

The superconducting properties are also similar for YBCO films with and without LNO buffer layers. The onset temperature of superconductivity \( T_c \), as determined by field cooling (20 G), was 76-77 K with broad transition widths of \( \sim 11 \) K for both buffered and un-buffered YBCO. The low value of \( T_c \) compared to the bulk (\( > 90 \) K) was due to our use of an un-optimized YBCO growth process. The critical current density \( J_{cm} \), calculated from SQUID magnetometry data using a modified Bean model,\(^{11}\) shows only a slight decrease for the LNO-buffered YBCO as compared to that on LAO. The effect of LNO itself on the SQUID measurements is negligible since LNO is Pauli paramagnetic.\(^{7}\)

Figure 2 gives the dependence of \( J_{cm} \) on magnetic field for several temperatures. The zero-field values at 5 K are \( 8 \times 10^6 \) A/cm\(^2\) and \( 1.7 \times 10^7 \) A/cm\(^2\) for the buffered and bare substrate samples, respectively. This factor-of-two reduction in the zero-field \( J_{cm} \) may be due to the presence of a nonsuperconducting phase in the buffered sample as discussed above. Interestingly, the improved magnetic field dependence suggests that the LNO-buffered YBCO has better flux pinning than for films grown directly on LAO. Clearly, LNO is a promising buffer layer for the growth of YBCO films with high critical current density.

The situation for Tl-2212 films is not as straightforward. Tl-2212 films grown on LNO and LAO have significant microstructural differences. The XRD patterns from Tl-2212 films (5500 Å) grown directly onto LAO are dominated by the (00\(\ell\)) c-axis peaks. However, the LNO-buffered films (4000 Å) also exhibit two moderately intense diffraction peaks related to planar spacings of \( \sim 3.1 \) Å and \( \sim 2.2 \) Å. These, most likely, result from a reaction between TlBaCaCuO and LNO to form some nonsuperconducting phase(s). Alternatively, it may be indicative of different growth kinetics caused by the presence of the LNO. Such effects of substrate choice on the growth kinetics have been reported previously.\(^{12}\) Pole figure scans of the (105) Tl-2212 peak confirm that the control
film on LAO has a single in-plane orientation with the a-axes of the film parallel to those of the substrate. The same measurements for LNO-buffered Tl-2212 films indicate a second biaxially textured orientation in which the a-axis is perpendicular to the substrate instead of the c-axis. This orientation also appears as a not-readily-resolved shoulder on the LNO peaks in the theta-2 theta scans. Similar evidence for a-axis orientation also appears, to a lesser extent, in thinner (1400 Å) Tl-2212 samples on LNO. Thicker samples (up to 1.7 μm) show that the a-axis grain population increases relative to the c-axis fraction with increasing film thickness. Apparently, the presence of LNO influences the nucleation of a-axis grains, and the relative proportion of this orientation increases with increasing thickness.

SEM easily detects the presence of these a-axis grains. Figure 3 is an image of an un-buffered Tl-2212 film and shows the melt growth typically observed in Tl-oxide superconductors13 with some off-composition surface particles. Figure 4 is an SEM of a buffered Tl-2212 film showing high aspect ratio microstructures that correlate to the a-axis grains detected in the pole figures. While the thallination process used to grow these Tl-2212 films was not optimized at the time of these experiments, the presence of both a-axis grains and the significant unidentified diffraction peaks described above only in films grown on LNO-buffered substrates strongly implies an interfacial reaction between LNO and TlBaCaCuO. Further study is required to determine the nature of this interaction and its relevance for various thicknesses of the LNO-buffer and Tl-superconductor layers.

This degraded microstructure is reflected in the superconducting properties of the LNO-buffered Tl-2212 films. Similar to the YBCO films, the Tl-2212 films also had superconducting onset temperatures that were lower than the bulk $T_c (> 100$ K) due to the un-optimized growth. However, $T_c$ for the buffered sample (80 K) was substantially lower than for the control (94 K). This is consistent with the presence of the additional nonsuperconducting phase seen in the diffraction scans. For the same reason, the transition widths, although comparable, were quite wide ($\sim 40$ K). Therefore, $J_{csf}$
measurements are relevant only for temperatures below ~ 40 K, shown in Fig. 5. While the zero-field $J_{cm}$ at 5 K is respectable at $1.4 \times 10^6$ A/cm$^2$ for the LNO-buffered film, it is nearly an order of magnitude less than the $J_{cm}$ of $1.0 \times 10^7$ A/cm$^2$ for the control sample. The field dependence of the buffered sample is also significantly worse, even at 5 K. These results are consistent with the presence of $a$-axis grains and/or the non-superconducting phases discussed above. Such microstructural features form "weak links" that limit the percolative current flow.$^3$

It should not be assumed that the $a$-axis orientation is an inevitable consequence of growing Tl-2212 on LNO. These films were grown in air at 800 °C, the lowest temperature limit for Tl-2212 films. Such a condition has led to the observation of $a$-axis grains for films 1 μm thick, even on bare LAO. This $a$-axis nucleation is greatly reduced by increasing the growth temperatures to 825–850 °C.

In summary, we find that LNO is a promising buffer layer for the growth of YBCO and Tl-2212 superconducting films with high critical current density. YBCO films grown on LNO buffer layers show negligible microstructural differences with films grown directly on bare LAO, resulting in similar $T_c$ and low-field critical current densities, and with significantly enhanced flux pinning properties. Despite requiring further optimization, our results clearly show that LNO has potential as a buffer layer for Tl-2212 (and perhaps other Tl-based superconductors).

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Figure Captions:

FIG. 1. SEM image of an LNO-buffered 2000 Å-thick YBCO film. The morphology is similar to YBCO on bare LAO.

FIG. 2. Magnetization critical current density vs. applied magnetic field at several temperatures for (a) LNO-buffered YBCO and (b) YBCO on bare LAO. The field is applied normal to the substrate. The solid lines are guides to the eye.

FIG. 3. SEM image of a 5500 Å-thick Tl-2212 film on bare LAO showing evidence of the melt growth typically observed in Tl-oxide materials with some additional surface particles.

FIG. 4. SEM image of an LNO-buffered 4000 Å-thick Tl-2212 film exhibiting a-axis-oriented grains.

FIG. 5. Magnetization critical current density vs. applied magnetic field at several temperatures for (a) LNO-buffered Tl-2212 and (b) un-buffered Tl-2212. The field is applied normal to the substrate. The solid lines are guides to the eye.
Figure 2
Figure 3
Figure 5