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FLUX PINNING BEHAVIOR OF INCOMPLETE MULTILAYERED LATTICE STRUCTURES IN YBa$_2$Cu$_3$O$_{7-y}$

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**14. ABSTRACT**

Magnetization results of YBa$_2$Cu$_3$O$_{7-y}$ films processed with interlayers of CeO$_2$ inclusions are presented. Unexpected flux pinning results that are different from previous observations with nanoparticulate layered inclusions were observed. Flux pinning was found to be in some cases either slightly improved at either low fields <0.5 T or in other cases at high fields >8 T although degraded, sometimes severely, at interim magnetic fields. Most unexpectedly, the pinning performance of the various samples rapidly converges as the temperature is reduced from 77 to 65 K, causing all films to have similar $J_c (H)$ behavior at 65 K even though dramatically different at 77 K.

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flux pinning, lattice structures, YBCO, superconductor

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Flux pinning behavior of incomplete multilayered lattice structures in YBa$_2$C$_3$O$_{7-d}$

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Magnetization results of YBa$_2$C$_3$O$_{7-d}$ films processed with interlayers of CeO$_2$ inclusions are presented. Unexpected flux pinning results that are different from previous observations with nanoparticulate layered inclusions were observed. Flux pinning was found to be in some cases either slightly improved at either low fields <0.5 T or in other cases at high fields >8 T although degraded, sometimes severely, at interim magnetic fields. Most unexpectedly, the pinning performance of the various samples rapidly converges as the temperature is reduced from 77 to 65 K, causing all films to have similar $J_c(H)$ behavior at 65 K even though dramatically different at 77 K. [DOI: 10.1063/1.1809274]

YBa$_2$C$_3$O$_{7-d}$ (YBCO) superconductor films are being developed for a variety of applications since high critical current densities ($J_c$) are maintained in applied magnetic fields of a few tesla. Even though YBCO has good in-field properties, it is of interest to further improve upon this characteristic by incorporating additional flux pinning sites in the YBCO. The intrinsic mechanisms of flux pinning typically occurring in as grown YBCO films are not immediately evident since the coherence length for this high temperature superconductor is quite small, $\xi \approx 1.5–2$ nm.1–2 Because of the small coherence length, a variety of atomic size structures or defects in the film can pin the fluxons.2 The small coherence length suggests that a high density of nano-sized insulating particulates dispersed throughout the superconductor can be an effective pinning structure potentially providing a greater pinning force than these intrinsic mechanisms.

Indeed, a method has been reported by Haugan et al.3 to incorporate nanoparticulate dispersions using pulsed laser deposition into YBCO films.3,4 This was accomplished by the subsequent deposition of YBCO (5–25 nm thick) on top of nonsuperconducting Y$_2$BaCuO$_5$ (Y$_2$11) island-growth particles (~5–10 nm in diameter) dispersed on the previously deposited YBCO layer. The layering was repeated to provide the desired thickness of the composite film, usually 0.3–3 $\mu$m thick. Y$_2$O$_3$ has also been incorporated in this same fashion with effective pinning.3 However, data presented here using lattice matched interlayers of CeO$_2$ provide results that are not readily explained.

Relevant issues regarding the enhancement of pinning and its degradation include: multilayered structures or superlattices, particulate density, particulate size, and displacement of nanoparticulate layers (or, conversely, the thickness of the YBCO nanolayers). In previous multilayered structures, the interlayers were intentionally made continuous and often thick. Regarding particulate density, the higher the density the more fluxons that can be pinned, but a loss in superconducting volume will occur. The size of the particulates should approach a couple times the coherence length.2 The separation between layered nonsuperconducting nanoparticulate inclusions can lower the effective pinning of fluxons, although pinned YBCO samples with layers up to 50 nm thick separating the nonsuperconducting inclusions still showed no significant decrease in effective pinning (largest thickness not yet determined).

Samples were prepared by pulsed laser deposition. A Lambda Physik laser, model LPX 3051, was used at 248 nm, the KrF wavelength. The ablation spot size was ~6.5 mm$^2$. The oxygen deposition pressure was 300 mTorr kept constant by downstream flow control while O$_2$ gas flowed at ~1 l/min. Single crystal substrates of strontium titanate (STO) were attached to the heater using a thin layer of colloidal Ag paint. The heater temperature during deposition was 750 °C. Substrates sizes were approximately 3.2 × 3.2 mm$^2$. The films were oxygen annealed after deposition by gradually cooling the samples in oxygen gas.

To create the multilayered structures, deposition of YBCO was done first for 195 pulses at a 4 Hz rate which results in a ~11-nm-thick film. A CeO$_2$ target was then rotated into place and several pulses of the laser were applied as specified in Table I. The YBCO target was then rotated back into place and the cycle repeated until ~0.3-$\mu$m-thick composite films were made. The sequential PLD depositions were automated by computer control. Film growth was stopped between each layer while the other target was rotated into position. The Y$_2$11 and Y$_2$O$_3$ particulate inclusions referred to were created in the same manner with use of the respective target in lieu of the CeO$_2$ at 780 °C. The experimental conditions used to create CeO$_2$ islands in YBCO samples are listed in Table I.

To determine the resulting pinning effect, samples were mounted in a vibrating sample magnetometer. The samples

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<th>Energy (mJ)</th>
<th>Rep rate (Hz)</th>
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<th>Pulses (total No.)</th>
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<tr>
<td>1</td>
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</tr>
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<td>5</td>
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were mounted such that the field was applied perpendicular to the wide face of the sample with currents induced in the $a-b$ planes of the HTS films. $M-H$ loops were obtained collecting data every second with a 100 Oe/s ramp rate and vibration frequency of 40 Hz. The resulting $M-H$ loops were volume normalized and then the magnetization critical current density $J_c = 30 \frac{\Delta M}{d}$, where $\Delta M$ is the hysteresis loop width and $d$ is the average sample size in the film plane. The onset superconducting transition temperature $T_c$ was measured using an ac susceptibility technique with the amplitude of the magnetic sensing field varied from 0.025 to 2.2 Oe, at a frequency of approximately 4 kHz.

The films were of good quality as determined from ac susceptibility. $T_c$ for the samples were 88–90 K, which is slightly depressed from plain YBCO ($T_c$ of 90–92 K) using the same processing conditions. This is typical of all previous nanoparticulate layering. The spread of the magnetic field lines in the ac loss data were narrow indicating good films and showed a sharp single phase transition. Self-field $J_c$ values of most samples were high $\gtrsim 1$ MA/cm$^2$.

An initial deposition of CeO$_2$ resulted in almost complete planar inclusions of $\sim 2-3$ nm thick within the YBCO layer. In this case, in-field pinning was severely degraded compared to plain YBCO and pinning by Y211 nanoparticles, although self-field values of each are comparable. This can be ascribed to the nature of the pancake vortices within the high temperature superconductor copper-oxide planes being weakly coupled together. The CeO$_2$ interlayers help decouple the vortices degrading pinning. Lower deposition times of CeO$_2$ were used to avoid a continuous layer; however, the size of inclusions is affected more by the lattice matching of the nonsuperconducting inclusions to YBCO and the pinning density by length of deposition. Figure 1 shows the difference between Y$_2$O$_3$ nanoparticle inclusions (upper) and that of the larger nanopatches of CeO$_2$ (lower) for longer (left) and shorter (right) deposition times. It can be seen that Y$_2$O$_3$ particles are much smaller as compared to CeO$_2$ inclusions. Y$_2$O$_3$ inclusions in a separate study showed slightly smaller particle formation than Y$_2$O$_3$ likely due to a different growth mechanisms based on lattice mismatch.

With the CeO$_2$ patchwork interlayers, it is expected the pinning will be less due to the large size of the inclusions (see Fig. 2). However, significant exceptions occur in the resulting data for the nanopatches of CeO$_2$ at either very low or very high fields. At fields greater than 8 T, three CeO$_2$/YBCO samples match plain YBCO and Y211/YBCO sample performance and appear to become better although not clear. In other samples minor improvement over YBCO occurred for $<0.5$ T. Generally, samples fell into the category of low field improvement, high field improvement, or no improvement. All films displayed severely degraded performance at moderate magnetic fields. Of greater interest is the difference in temperature dependence of the CeO$_2$/YBCO samples. Figure 3 shows the field dependence at 65 K. In-field performance rapidly converges together at this temperature for all CeO$_2$/YBCO specimens, even losing the high field advantage of the two samples. This is contrary to typical YBCO and nanoparticulate pinning by Y211 or Y$_2$O$_3$. The natural assumption is that the CeO$_2$ nanopatches result in decoupling of many of the pancake vortices in the YBCO degrading pinning, but this does not explain the unexpected behavior. Also, the high self-field performance of most samples indicates that the chemical degradation due to barium cerate formation is not significant. Potential doping of the superconductor in combination with the nanolayered structure may be possible.

In conclusion, the use of CeO$_2$ in interlayer inclusions within YBCO provide unexpected flux pinning behavior. In some samples, pinning improvement over plain YBCO oc-

**FIG. 1.** Scanning electron micrographs of the surface following deposition on YBCO of Y$_2$O$_3$ (upper SEMs) and CeO$_2$ (lower SEMs).

**FIG. 2.** $J_c$ vs applied magnetic field at 77 K for the samples with CeO$_2$ islands.

**FIG. 3.** $J_c$ vs applied magnetic field at 65 K for the samples with CeO$_2$ islands.
occurred at low fields, <0.5 T, and in others with apparent improved pinning observed at high fields >8 T while \( J_c \) is severely degraded at moderate fields. Most significant is that the pinning performance of the various samples rapidly converges as the temperature of measurement is lowered, with all CeO\(_2\)/YBCO films behaving similarly at 65 K even though substantially different at 77 K.


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