Enhanced Flux-Pinning in Dy-Doped, MOD YBCO Films on RABiTS

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***Abstract*—Significant enhancements in flux-pinning were obtained for Dy-doped, YBCO films via a metalorganic deposition (MOD) process on rolling-assisted biaxially textured substrates (RABiTS). It has been reported previously that incorporation of excess rare-earth ions during the MOD process, results in improvement of J_c for H//c, however, a decrease in J_c for H//ab is observed. We report here that by altering the processing conditions the reduction in the magnitude of the current peak for H//ab can be minimized while significantly enhancing the random pinning at all field orientations. The result is a YBCO film with significantly reduced anisotropy compared to the typical YBCO films prepared by the MOD process. This is accomplished by incorporating both a high density of stacking faults and $(Dy, Y)_2O_3$ nanoparticles which result in the strong pinning for H//ab and a broad pinning peak for H//c respectively.**

***Index Terms*—Angular dependence, coated conductor, critical current density, flux-pinning, intergrowths, MOD films, nanodots, RABiTS, stacking faults, wires.**

I. Introduction

SECOND-GENERATION HTS conductors or "coated-conductors" consist of a flexible metallic substrate upon which several epitaxial buffer layers and an epitaxial superconducting layer are deposited [1]. The key goal is to have a biaxially textured superconducting layer with few high-angle, weakly conducting grain boundaries. This is accomplished by epitaxial formation of the superconducting layer on biaxially textured oxide surfaces deposited upon the flexible metallic substrate. Three techniques have been developed to accomplish this—ion-beam assisted deposition (IBAD) [2] of biaxially textured buffers on polycrystalline alloy substrates, epitaxial deposition of buffer multilayers on rolling assisted, biaxially textured substrates (RABiTS) [3], and inclined substrate deposition (ISD) [4] of buffers on polycrystalline alloy substrates. For epitaxial YBCO on substrates fabricated using all three techniques, the "inter-granular" critical current density is enhanced due to suppression of weak-links at grain boundaries. However, for practical application of HTS materials, the in-field performance or the "intra-granular" critical current density, also needs to be enhanced further [5].

A promising route to a practical HTS conductor is the use of metalorganic deposition (MOD) of epitaxial YBCO layers on RABiTS [6]. As described in this article, the YBCO MOD process involves four steps: precursor synthesis, coating, decomposition, and reaction. The MOD process is a low-cost and highly efficient process for fabrication of long-lengths of coated conductors. Hence, there is significant interest in optimizing the superconducting properties of MOD films by optimization of the defects structures within the films. It is well established that typical MOD YBCO films are characterized by a strong current peak in fields oriented in the ab-plane of the YBCO with lower pinning for H//c [6]. It is found that at 1T, the J_c drops significantly at field orientations with deviations greater than 20° from the H//ab orientation [6]. Previous work has established that the peak at H//ab in the angular dependence of J_c, for the typical YBCO MOD film, can be attributed to pinning by 124-type stacking faults in the YBCO lattice [7]. It was also shown that the J_c for H//c can be increased by incorporation of excess rare-earth additions such as Dy, Er, etc. [7], which form a fine distribution of nanoparticles throughout the YBCO matrix. However, the addition of the excess Dy results in a decrease in J_c anisotropy for H//ab and H//c from that observed in the typical MOD YBCO film on RABiTS [7]. In this paper, we report how differences in the processing conditions of the Dy-doped YBCO films affects the density of the 124-type stacking faults, resulting in variations in the anisotropy of the films.

II. Experimental Procedure

American Superconductor's 2G manufacturing approach is based on the YBCO(MOD)/RABiTS (Metal Organic Deposition/Rolling Assisted Biaxial Textured Substrates) technology. The coated conductor architecture discussed here is based on textured Ni(5at%W) substrates where heteroepitaxial buffer layers Y_2O_3, YSZ, and CeO_2 are deposited by high-rate reactive sputtering. On top of the buffer layers, a metal trifluoroacetate-based YBCO precursor is deposited by metal organic deposition (MOD) [6]. The precursor film is then dried and decomposed to form a mixture of metal oxyfluorides. A subsequent high-temperature heat treatment is used to convert the precursor into a crack-free, nominally 0.8 μm 123 superconducting film. The critical current was measured by standard four probe method. In-field performance was tested at 65 K and 77 K up to 7T. Phase and textural analysis was done using X-ray diffraction. Microstructural analysis was done by cross-section transmission electron microscopy (TEM).

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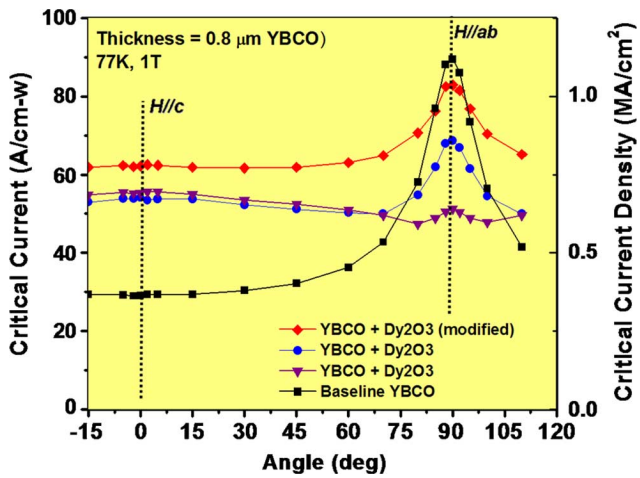

Fig. 1. Angular dependence of J_c at 77 K, 1T for several MOD YBCO films on RABiTS. The y-axis on the left of the figure is I_c in A/cm-width and the right of the figure is J_c in A/cm^2. The black squares and curve correspond to a baseline YBCO film on RABiTS. Only a strong peak for H//ab is observed. No Dy additions were made to this sample. The blue and purple symbols and curves are for YBCO films with excess addition of Dy in the starting MOD precursor corresponding to a total composition of $Y(Dy_{0.5})Ba_2Cu_3O_x$. For these samples, there is a very broad peak centered at H//c; however, the strong peak for H//ab which was present in the baseline sample has significantly decreased. The red symbols and curve are for a defect-optimized sample with same overall composition as the samples corresponding to the blue and purple curves. A massive enhancement in J_c is seen for most angles without any substantial drop in J_c for H//ab field orientation.

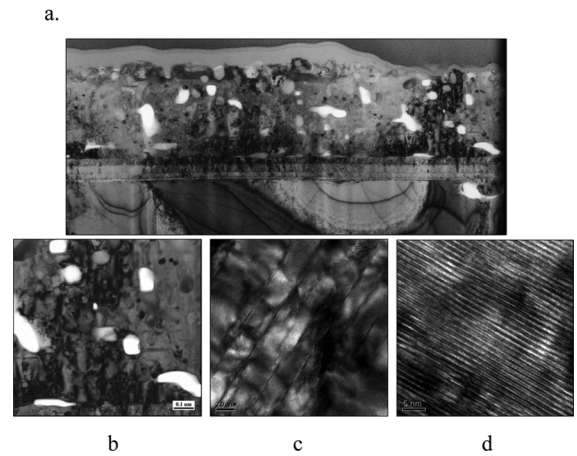

Fig. 2. Cross-section TEM image of sample corresponding to the red curve in Fig. 1. (a) low magnification image showing strong diffraction contrast within the HTS film due to defects; (b) higher magnification image of the HTS film showing the presence of high density of nanoparticles. These have been confirmed to correspond to the composition $(Dy, Y)_2O_3$; (c) higher magnification image showing the presence of high density of planar defects comprised of stacking faults. (d) still higher magnification images of stacking faults within the YBCO lattice. These have been determined to correspond to an extra CuO plane resulting locally in the formation of a Y-124 cell.

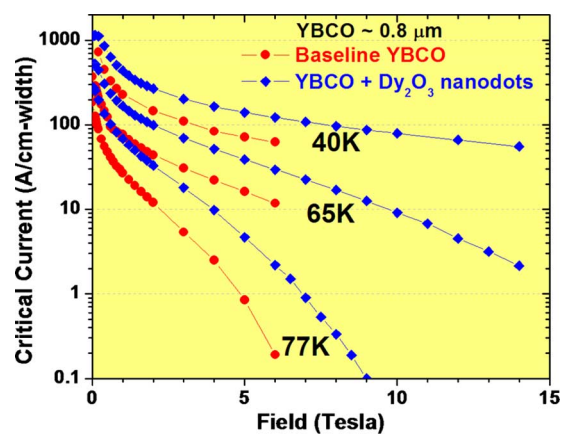

Fig. 3. J_c versus H at 40, 65 and 77 K for a baseline YBCO sample and a defect-optimized YBCO sample with 50 at% addition of with excess addition of Dy in the starting MOD precursor corresponding to a total composition of $Y(Dy_{0.5})Ba_2Cu_3O_x$. Significant enhancement of J_c is seen for field up to 14T at all temperatures.

III. Results and Discussion

Fig. 1 shows the J_c versus angle at 77 K for a typical, undoped MOD YBCO film on RABiTS. The measurements were made in the maximum Lorentz force configuration so that the field was always applied perpendicular to the direction of current flow. A dominant peak for H//ab is observed. As reported previously using an X-ray technique and examination via transmission electron microscopy (TEM), the strong peak for H//ab can be ascribed to pinning by planar stacking fault defects which are also parallel to the ab plane. Since the total length of defects in the ab-plane at any location in the sample is large, a significant portion of flux-line is trapped, resulting in strong peak for H//ab. Fig. 1 also shows J_c versus angle for three other samples in which excess addition of Dy in the starting MOD precursor was made corresponding to a total composition of $YDy_{0.5}Ba_2Cu_3Ox$. Two of the samples were processed identically to the undoped YBCO sample, the processing details for which have been discussed previously [6]. For these samples, indicated in red and purple in the figure, while there is enhancement in J_c at all field orientations upon addition of 50% Dy there is a significant decrease in J_c in the angular range $\pm 20°$ from H//ab. As has been shown previously, this occurs because of the reduction in the density of stacking faults parallel to ab-plane upon rare-earth addition as confirmed by high-resolution X-ray scans coupled with TEM observations [7]. The last curve in Fig. 1 corresponding to the red symbols is for a 50% Dy-doped sample wherein the processing has been changed to preserve the stacking faults. For this sample, enhancement of J_c at most field orientations is observed and the decrease in pinning for H//ab is only minor.

Fig. 2 shows a cross-section TEM image of the optimized sample shown in Fig. 1. Both Dy containing nanoparticles as well as planar defects can clearly be observed. Fig. 2(a) shows a low magnification cross-section image of a sample prepared using the focused-ion-beam (FIB) approach. Strong diffraction contrast throughout the thickness of film can be seen. A higher magnification image shown in Fig. 2(b) shows the presence of high density of nanoparticles, which from energy dispersive spectroscopy (EDS) have been identified to be $(Dy, Y)_2O_3$. Fig. 2(c) shows a still higher magnification image showing the presence of stacking faults. Fig. 2(d) which is still a higher magnification shows that these stacking faults are indeed present in high density than in the sample with a reduced ab-plane peak. The disruption of the lattice fringes clearly indicate the presence of the stacking faults which have previously been identified to correspond to an extra CuO plane resulting in the local formation of $YBa_2Cu_4O_8$. Cross-section TEM images of the sample corresponding to the J_c versus H

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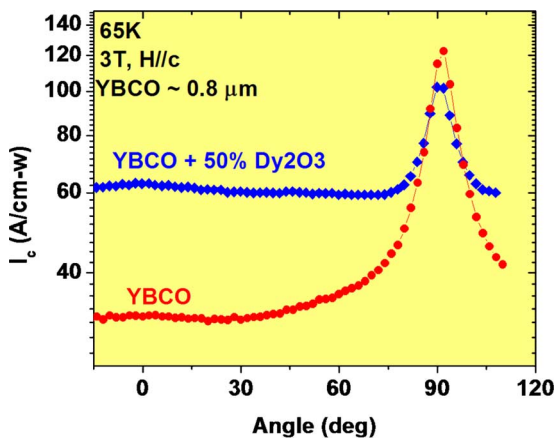

Fig. 4. Angular dependence of J_c at 65 K, 3T for the baseline YBCO sample and a defect-optimized YBCO sample with 50 at% addition of excess addition of Dy_2O_3 in the starting MOD precursor corresponding to a total composition of $YDy_{1.5}Ba_2Cu_3O_x$. Similar to the data shown in Fig. 1 for 77 K measurements, a massive enhancement in J_c is seen for all angles without any substantial drop in J_c for H//ab field orientation.

shown in Fig. 1 wherein the peak for H//ab is suppressed, show a very low density of planar stacking faults [7].

It is noted that although this is minimal reduction in the magnitude of the ab-plane peak, the anisotropy of the $Y(Dy_{0.5})Ba_2Cu_3O_x$ sample is significantly reduced compared to the YBCO sample. This reflects the increase in the random pinning due to the Dy-based nanoparticles addition and the reduction in stacking fault density compared to the undoped YBCO.

The improved pinning in perpendicular fields seen in Fig. 1 at 77 K is also seen at lower temperatures. Fig. 3 shows J_c versus H for H//c for 77, 65 and 40 K for fields up to 14T. Clearly the enhancement in pinning is substantial at all fields and temperatures. At 77 K, beyond 3T, the enhancement is greater than a factor of 4. Similar enhancement at high fields is also seen at lower temperatures. Fig. 4 shows the angular dependence of J_c at 65 K, 3T. This field and operating temperature is of significance for defense or military applications. As can be seen from the angular dependence, much like the 77 K data shown in Fig. 1, the peak at H//ab is only reduced slightly while the J_c is enhanced significantly at all other angles and almost by a factor of 2 for H//c.

IV. Conclusion

In summary, significant enhancements in flux-pinning were obtained for Dy-doped, YBCO films via a metalorganic deposition (MOD) process on rolling-assisted biaxially textured substrates (RABiTS). Massive enhancement of J_c for all field orientations and without a significant decrease in pinning for H//ab was accomplished by incorporating both a high density of stacking faults and $(Dy, Y)_2O_3$ nanoparticles which result in the pinning for H//ab and a broad pinning peak for H//c respectively.

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