

## Inter- and intragrain transport measurements in $\text{YBa}_2\text{Cu}_3\text{O}_{7-x}$ deformation textured coated conductors

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Using photolithography, links for transport measurement have been placed across individual Ni grain boundaries and within individual Ni grains on several coated conductor samples. The typical Ni grain size is  $\sim 50 \mu\text{m}$ , while the  $\text{YBa}_2\text{Cu}_3\text{O}_{7-x}$  grains are submicron in size. It is found that the intragrain  $J_c(0 \text{ T}, 77 \text{ K})$  can exceed  $5 \text{ MA/cm}^2$ , thus showing that present coated conductor  $J_c$  values are not significantly limited by the intragrain  $J_c$ . Inter- and intragrain  $J_c$  values ranged from one-half to more than four times full-width measured values, demonstrating that current percolates through the conductor. The misorientation angle dependence of  $J_c$  fits well with previous studies of [001] tilt  $\text{SrTiO}_3$  bicrystals. © 2001 American Institute of Physics. [DOI: 10.1063/1.1425952]

Coated conductors (CCs) using deformation textured substrates such as rolling assisted biaxially textured substrates (RABiTS<sup>TM</sup>) are one of the most suitable conductor forms for applications at 77 K. These substrates are inherently polycrystalline and produce a network of grain boundaries (GBs) in the  $\text{YBa}_2\text{Cu}_3\text{O}_{7-x}$  (YBCO) layer.<sup>1,2</sup> Magneto-optical (MO) studies demonstrate that the vast majority of these GBs have a  $J_c$  value less than that of the intragrain<sup>1,2</sup> regions. Under applied transport currents, MO imaging of the self-field shows a strong GB influence and a clear illustration of percolative current flow.<sup>2,3</sup> The self-field studies have shown that  $J_c$  is usually limited in a local region by a small fraction of GBs, and that the majority of the sample is carrying a current much less than its local  $J_c$ . Here we expand upon that earlier work by quantifying the inter- and intragrain  $J_c$  values of several CC samples. This study shows that the intragrain  $J_c$  is not the limiting factor in present CC technology, and the  $J_c(\theta)$  dependence of GBs in YBCO CCs fits well with previous studies of YBCO grown on [001] tilt  $\text{SrTiO}_3$  (STO) bicrystals.<sup>4,5</sup>

Standard optical photolithography and dry etching was used to pattern inter- and intragrain links in several CC samples. All samples consisted of a deformation textured Ni substrate with a  $\text{Ni/CeO}_2$  or  $\text{Y}_2\text{O}_3/\text{yttria-stabilized zirconia (YSZ)/CeO}_2$  buffer layer structure. The YBCO layers were grown by the barium fluoride<sup>6</sup> or trifluoroacetate<sup>7</sup> methods. All patterned links (inter- and intragrain) were  $10 \mu\text{m}$  wide and  $30 \mu\text{m}$  long. Extended voltage-current characteristics and  $J_c(H)$  dependencies were measured. For intragrain links,  $J_c$  values were determined using an *electric field* criterion of  $1 \mu\text{V/cm}$ . For a  $30 \mu\text{m}$  long link, this yields a voltage criterion of 3 nV, well above our typical measurement noise of 0.3–0.5 nV. For the intergrain links, a *voltage* criterion (3

nV) was used due to the uncertainty in the width of the GBs. Universal use of the  $1 \mu\text{V/cm}$  criterion is crucial to legitimate, quantitative comparisons of  $J_c$  values. Also, it is well known that  $J_c$  increases with decreasing film thickness,<sup>8</sup> and Zhao *et al.* have observed significant overestimates of  $J_c$  for links less than  $10 \mu\text{m}$  wide due to errors introduced in patterning.<sup>9</sup> All these factors need to be considered when comparing  $J_c$  values. For intergrain links, electron backscatter Kikuchi pattern (EBKP) analysis was used to determine the GB misorientation angle  $\theta$ . Where possible this was done in the YBCO layer; however, due to poor EBKP quality most angles were measured in the YSZ. We admit this may not be a true representation of the GB angle in the YBCO. X-ray diffraction and recent EBKP studies<sup>10</sup> have shown that in general, there is an improvement in the *c*-axis alignment of the YBCO relative to the YSZ layer, and this results in a reduction of  $\theta$ .

Table I lists several properties of the samples and patterned links investigated. At least two links were patterned per sample, but not all links were suitable for study due to multiple GBs per link or complex GB geometries. Figure 1(a) is a scanning electron microscope (SEM) image of the pair of links patterned in sample No. 3. In this case, both links are entirely within the same Ni grain. However, as can be seen in Table I, their  $J_c$  values are quite different. The  $J_c$  of the  $1.3 \text{ MA/cm}^2$  link was limited by a large *a*-axis grain, highlighted in Fig. 1(b), that extends more than halfway across the link. The YBCO grains are submicron in size. The two intragrain links of sample No. 4 were also within a single Ni grain. There is a 20% difference in the  $J_c$  of these two links, but a SEM investigation revealed no reason for the difference.

The links in Table I yield a large spread in  $J_c(77 \text{ K}, 0 \text{ T})$  of 0.4–5.1  $\text{MA/cm}^2$ . This is in contrast to the full width  $J_c(77 \text{ K}, 0 \text{ T})$  values (where available), which are all  $\sim 1 \text{ MA/cm}^2$ . Thus the links range from one-half to more than

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TABLE I. Comparison of properties of the samples and links in this study. All  $J_c$  values were measured at 77 K.

Sample No.	YBCO thickness (nm)	Full width (nm)	Full-width $J_c$ ( $10^6$ A/cm $^2$ )	$\theta$ /intragrain	Link $J_c$ (0 T) ( $10^6$ A/cm $^2$ )	Link $J_c$ (1 T) ( $10^6$ A/cm $^2$ )
1	310	3.3	1.26	intra	5.1	0.62
2	300	3.3	0.85	2.8°	3.0	0.39
3	380	5	N/A	intra	>3.5	0.41
4	380	5	N/A	intra( <i>a</i> -axis grain)	1.3	0.10
				intra	3.8	0.20
5	380	5	0.9	intra	3.1	0.22
				7.1°	0.7	0.06
6	380	5	0.8	5.5°	0.8	0.07
				9.8°	0.4	N/A
				2.9°	2.6	N/A

four times full width  $J_c$  values. This demonstrates that full width  $J_c$  values must be the result of multiple current paths of both higher and lower  $J_c$ , resulting from variations in the inter- and intragrain  $J_c$ . The very high intragrain  $J_c$  values strongly suggest that the full width values of Table I are not limited by the intragrain  $J_c$ , but rather by the GBs. The full width  $J_c$  values of the best samples, though rare, are in the range $^2$  2–3 MA/cm $^2$ . As all the intragrain links in this study had a  $J_c$  that exceeds these values, even the best samples are not being limited solely by the intragrain.

The  $J_c(77\text{ K}, 1\text{ T})$  values (where available) for both the inter- and intragrain links are reduced by roughly 1 order of magnitude over the  $J_c(77\text{ K}, 0\text{ T})$  values. This is in contrast to the study of Verebelyi *et al.*, where it was found that above 4° GBs were less sensitive to the field than the grains. $^{11}$  While that study was performed on STO bicrystal substrates and not CC GBs, this study could benefit from additional  $J_c(77\text{ K}, 1\text{ T})$  data from intergrain links with  $\theta > 4^\circ$ .

Figure 2 plots the  $\theta$  dependence of the  $J_c$  data from Table I with data from studies using [001] tilt STO bicrystals. The  $J_c(\theta)$  dependence of the GBs in this study and those using (STO) bicrystal substrates all fit very well to an expo-

ponential decay with a critical angle  $\theta_c$  of 2°–3°. The intergrain  $J_c$  values from Table I are slightly higher (for a given  $\theta$ ) than those of the STO bicrystals. This is possibly due to the fact that  $\theta$  was largely measured in the YSZ buffer layer, and  $\theta$  in the YBCO may be less $^8$  by 0.5°–1.5°. While the similarity between the CC and bicrystal data of Fig. 2 may not be surprising, it is interesting to consider that all of the bicrystals were [001] tilt boundaries, and  $\theta$  represents pure in-plane misorientation. Even though there can be a high degree of *c*-axis alignment in the grains of CC substrates, EBKP analysis shows that CC GBs generally consist of both tilt and twist components, and  $\theta$  represents the *total* misorientation between grains, not just in-plane misorientation. Despite this and other potential differences between the CC and bicrystal GBs, the most significant factor in determining  $J_c$  appears to be  $\theta$ . There is a moderate variation of the intragrain data in Fig. 2, but not significantly more than is generally seen in YBCO films grown on single crystal substrates. Also, the intragrain data represent films of different thickness and deposition method, and each Ni grain acts as its own single crystal template (with varying vicinal angle and surface quality), so some variation of the intragrain  $J_c$  is not unexpected. All intragrain  $J_c$  values are high, comparable to the best reproducible values obtained on single crystal substrates. The close correlation between the  $J_c(\theta)$  dependence of the CC

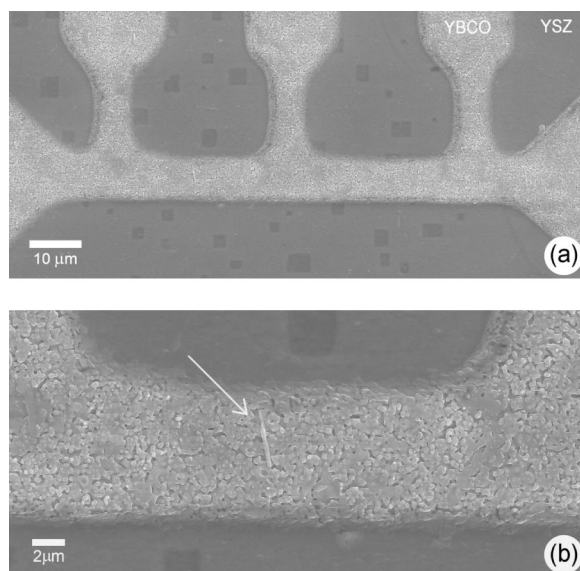


FIG. 1. SEM images of sample No. 3 after patterning. (a) Image of both links of sample No. 3. The tracks run horizontal with three voltage taps coming off the top. This same structure was patterned on all the samples. (b) A closeup of the link on the left in (a), showing the reason for the reduced  $J_c$  of the link. An *a*-axis grain, indicated by the arrow, extends more than halfway across the link.

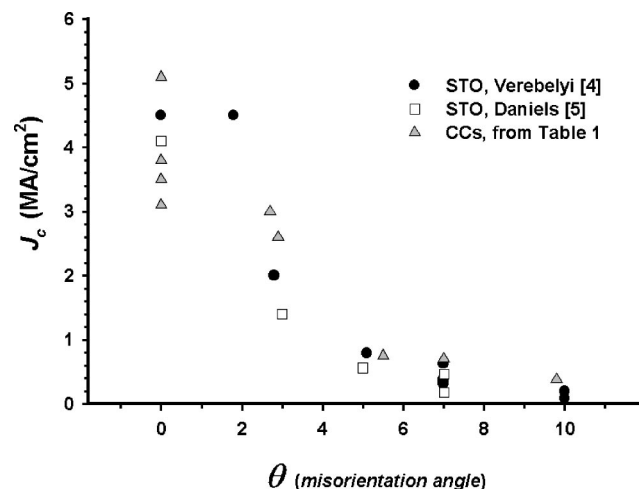


FIG. 2. Plot showing  $J_c(\theta)$  dependence for various inter- and intragrain links. Black circles are data from pulsed laser deposition (PLD) YBCO on STO bicrystals from Verebelyi *et al.* (Ref. 4). Open squares are also PLD YBCO on STO, supplied by G. Daniels (University of Wisconsin). The gray triangles are data from Table I.

GBs and the STO bicrystals implies that application of STO bicrystal studies to CCs is merited.

The consequence of the percolative nature of current flow in CCs and the fact that GBs and not the intragrain will nearly always limit  $J_c$  means that a sharp substrate texture is paramount to obtaining high  $J_c$  tapes. An intragrain  $J_c$  of 5.1 MA/cm<sup>2</sup> in a CC of modest full width  $J_c$  (1.26 MA/cm<sup>2</sup>) implies that local texture is the greatest factor separating “typical” samples from the “best” samples, not film (or intragrain) quality. One question such emphasis on texture raises is “what is the upper limit to  $J_c$  in a CC?” From the plot of Fig. 2, a  $J_c$  value of 2–3 MA/cm<sup>2</sup> is roughly equivalent to that of a 3° GB. While many GBs greater than 3° certainly exist in the “best” samples, such  $J_c$  values indicate an extremely high degree of substrate texture. It is uncertain that substrate textures can be sharpened to a significantly greater degree than those that already produce samples in the range of 2–3 MA/cm<sup>2</sup>. Another means of increasing CC  $J_c$  values is to improve GB properties. While this has been demonstrated in high angle GBs<sup>12</sup> and in low angle GBs at low temperatures,<sup>13</sup> it has yet to be shown in low angle GBs at 77 K.

In summary, the high intragrain  $J_c$  values demonstrate that films of excellent quality can be grown on a metal substrate. The derived  $J_c(\theta)$  dependence indicates that GBs are the most significant factor limiting full width  $J_c$  values in CCs, and that current flow is percolative. This study and previous MO studies<sup>1–3</sup> corroborate each other well on these points. Maintaining good texture over long lengths will be critical to producing commercial tapes, but as pointed out by Verebelyi *et al.*,<sup>11</sup> the influence of the GBs in a CC is reduced at high fields, and the application may dictate the degree of texture required.

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