Influence of the grain boundary network on the critical current of $YBa_2Cu_3O_7$ films grown on biaxially textured metallic substrates

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$YBa_2Cu_3O_7$/YSZ/CeO_2 heterostructures have been grown epitaxially on biaxially textured Ni substrates by pulsed laser deposition. The texture of the film was determined by electron backscattering diffraction, providing information on the propagation of the grain boundary network from the Ni substrate to the $YBa_2Cu_3O_7$ film via the epitaxial growth. The grain boundary network limits the critical current density to 0.3 MA/cm^2 (77 K, 0 T), compared with 1.3 MA/cm^2 (77 K, 0 T) for a film grown on a single crystalline Ni substrate. Transport measurements on the coated conductor sample at different temperatures and magnetic fields show that there is a crossover field between intergrain and intragrain critical current that is shifted to higher magnetic fields as the temperature is reduced.

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I. INTRODUCTION

The RABiTS (rolling assisted biaxially textured substrate) technique is an important approach to obtaining $YBa_2Cu_3O_7$ (Y123) coated conductors (CC's) having high critical current densities in magnetic fields at 77 K.[1] The technique is based on the epitaxial growth of Y123 on a buffered, highly in-plane textured metal tape obtained by recrystallization after heavy cold rolling.[2,3] At present, the most challenging problems facing this technique are the scaling-up to long lengths and the understanding of the current limiting mechanism in the CC's. The two-dimensional grain boundary network (GBN) in the Y123 CC is the main feature responsible for the reduction in the overall critical current density, due to the exponential decrease in J_c with increasing grain boundary misorientation, as observed in bicrystal experiments.[4] Secondary causes of the reduction in J_c can include GB grooving or Ni diffusion from the metal substrate into the Y123 film, but these effects on the maximum obtainable J_c have not yet been quantified.

The GBN in the CC's consists of a large number of grain boundaries with an extended distribution of misorientation angles, resulting in a complex percolative current transport.[5,6] Magneto-optical measurements have shown that the misorientation angle should be below 4° to prevent the percolative flux flow and a resulting reduction in J_c,[7] indicating the importance of well-textured substrates. J_c measurements in magnetic fields should help to clarify the mechanism for critical current limitation by the GBN. It is also necessary to consider some interesting features of low-angle GB's in magnetic fields, such as strong GB pinning,[8] viscous flux flow of line vortices along the GB,[9] and a GB angle dependent crossover behavior from intergrain to intragrain limited J_c with increasing magnetic field at 77 K.[10] Here we report on the temperature dependence of the crossover magnetic field from intergrain to intragrain limited critical current in CC's and the possible implications for future application in magnetic fields.

II. EXPERIMENT

A biaxially textured {100}⟨001⟩ oriented Ni tape was used as substrate for Y123 CC's. The Ni tape had a typical thickness of 80 μm and a sharp biaxial texture with an in-plane full width at half maximum (FWHM) of about 9°. Film deposition onto this substrate was carried out in a conventional on-axis pulsed laser deposition apparatus. The laser beam was focused onto a ceramic target of either CeO_2, yttrium-stabilized zirconia (YSZ) or Y123 with an energy density of 2–3 J/cm^2. Initially, a 50-nm-thick CeO_2 film was deposited at a substrate temperature of 725 °C in 0.02 mbar Ar atmosphere, followed by a 630-nm-thick YSZ film at 700 °C in an oxygen atmosphere of 5×10^{-3} mbar. For the Y123 deposition, oxygen pressure and substrate temperature were increased to 0.3 mbar and 770 °C, respectively, with final cooling to room temperature in 400 mbar oxygen. The Y123 film thickness was 200 nm. The same CeO_2/YSZ/Y123 structure was grown for comparison on a single crystalline Ni film prepared by e-beam evaporation onto an (001) oriented $SrTiO_3$ single-crystal substrate. X-ray θ-2θ diffraction and pole figures from a four circle diffractometer were used for the structural characterization of the heterostructures. Electron backscattering diffraction (EBSD) was used to study the local texture distribution of the films in detail. An inductive T_c measurement setup was used to determine the superconducting transition temperature of unpatterned samples. Transport measurements were performed in a four-point geometry on samples patterned by standard photolithography, with J_c being determined at a voltage criterion of 1 μV on a bridge of width 300 μm and length 800 μm.

III. RESULTS AND DISCUSSION

Several Y123 CC samples with similar structural and transport properties were prepared as explained above. Pole figures of Ni substrates, buffer layers, and Y123 layers showed a biaxial texture in the films and an excellent epitaxial growth of this system on Ni tape with an improvement in the out-of-plane and in-plane textures of the Y123 layer with respect to the Ni substrate, resulting in an in-plane FWHM of Y123 films around 8°. More detailed texture measurements were carried out on one of the prepared Y123 CC's using EBSD both before and after coating (Fig. 1). In the EBSD

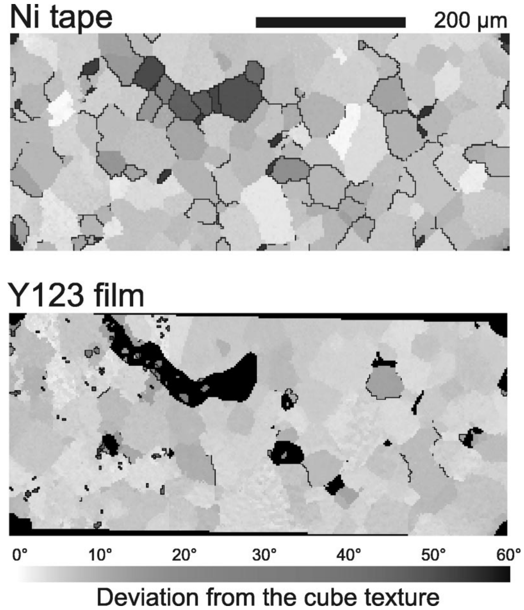

FIG. 1. EBSD measurements of Ni tape and Y123 film carried out in a coated conductor before and after coating. Grain boundaries with misorientation angles (relative to the ideal cube texture) larger than 10° are represented as black lines.

measurement of the Y123 film it is possible to distinguish the grain boundary network of the Ni substrate propagated via epitaxial growth to the Y123 film, but in general an improvement of the out-of-plane texture in the grown Y123 with respect to the Ni grains is observed. GB's with misorientation angles larger than 10° are represented as black lines. The number of GB's with this characteristic is strongly reduced in the Y123 film in comparison to the Ni tape. Black zones in the Y123 measurement represent unindexed points. More details of the measurement are given in Ref. 6.

Transport measurements of the critical current of Y123 CC's revealed in each case values around 0.3 MA/cm^2 (77 K, 0 T). This value of J_c is in agreement with that obtained by computer simulation[6] based on the EBSD texture mappings and the already known angular J_c dependence at 77 K and zero magnetic field.[11] The J_c simulation generated an effective GB angle for the Y123 CC of 7.3° that agrees well with the approximate 8° misorientation obtained from the texture measurements on these samples.

The dependence of J_c on the applied magnetic field was measured on Y123 CC and on the same system grown on a single crystalline Ni film, and found to be different in the two cases (Fig. 2). Y123 grown on the single crystalline Ni film presents an exponential $J_c(B)$ decay over the complete range of measured magnetic fields. Such an exponential decay indicates pinning limitation of J_c by the Y123 grain itself (intragrain J_c). The Y123 CC presents a different dependency: at lower temperatures like 60 K it is found that $J_c(B)$ can be described over the complete range of measured fields by a power-law behavior, but at higher temperatures such as 77 K a transition of the $J_c(B)$ dependence from a power law to exponential decay is seen as the applied magnetic field increases.

Investigations on isolated GB's in Y123 bicrystals[11,12]

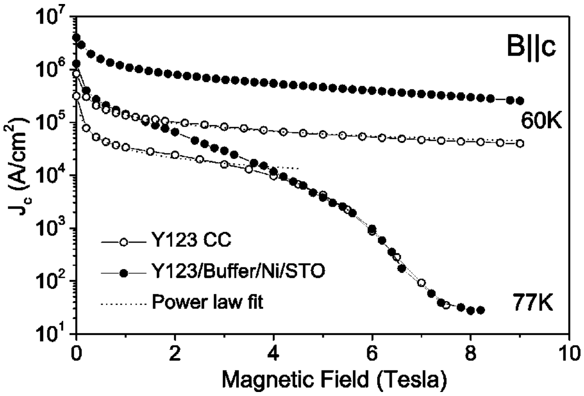

FIG. 2. Dependence of J_c on applied magnetic field ($B||c$) for Y123 on RABiTS (open symbols) and STO/Ni/CeO2/YSZ/Y123 (filled symbols) at 60 and 77 K. The dashed line represents the power-law fit of the measurements.

have shown the existence of an intergranular $J_c(B)$ that can be described by a power-law dependence,

$$J_c(B)=J_c(0)[B_0/B]^n. \tag{1}$$

The power-law dependence of J_c on magnetic field is caused by such factors as the presence of flux lines in the GB that are more weakly pinned than the flux lines in the Y123 grains, and the magnetic interaction between the pinned vortices in the GB and the pinned intragrain vortices.[12]

Considering these results in Y123 bicrystals, it is expected that the GBN of the Y123 CC, with a large amount of low-angle GB's, behaves similarly in limiting the critical current. Thus, the power law behavior found in the Y123 CC can be associated with an intergranular limitation of J_c and the exponential decay with an intragranular limitation of J_c. The transition from intergranular to intragranular J_c takes place when the dissipation mechanism due to flux creep within the Y123 grains becomes stronger than the dissipation due to the GBs. The transition point is termed as the crossover magnetic field (B^{cr}). At 77 K, $J_c(B)$ of Y123 CC reveals a B^{cr} of 4 T; above this field $J_c(B)$ reduces exponentially, similar to the Y123 film grown on single crystalline Ni film. At 60 K, the situation is likely the same but B^{cr} is shifted to magnetic fields higher than 9 T. In general, it was found that the

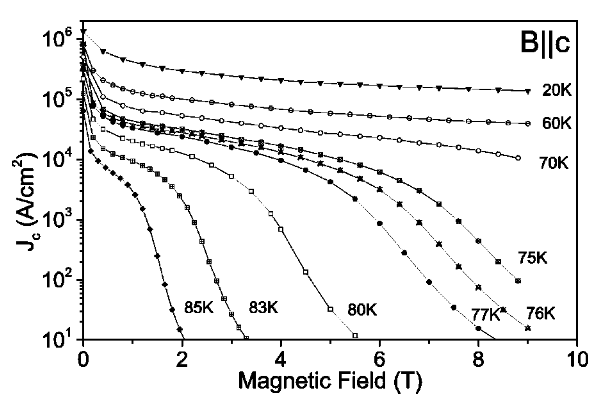

FIG. 3. Dependence of J_c on applied magnetic field ($B||c$) for the CC at various temperatures.

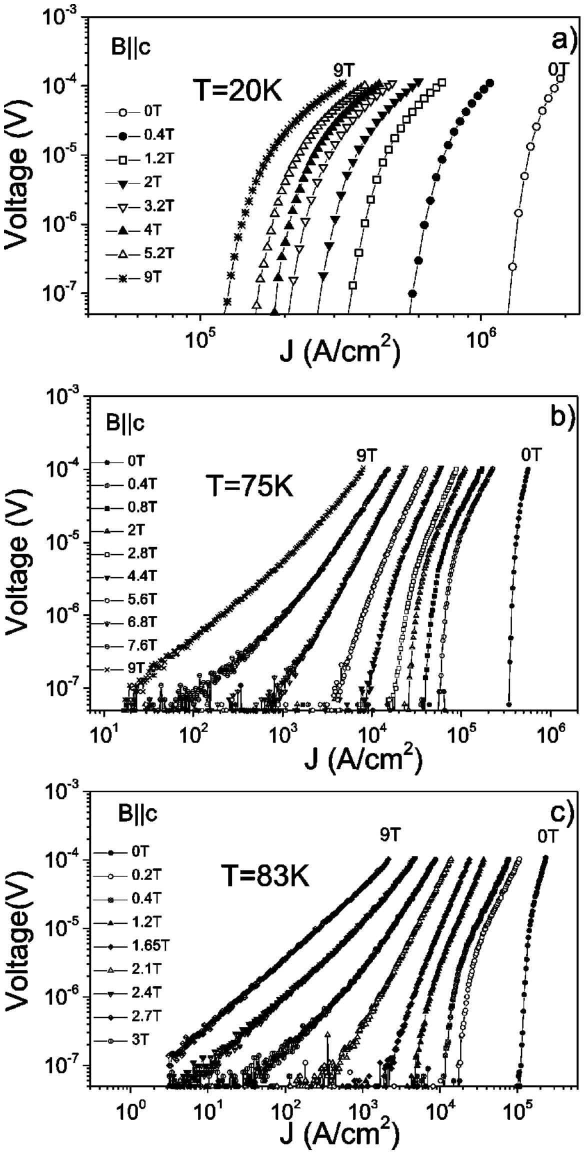

FIG. 4. Magnetic-field dependence ($B||c$) of V-J curves for the CC, at (a) 20 K, (b) 77 K, (c) 83 K.

magnetic crossover field varies with temperature, shifting to lower values as the temperature is increased. At 75 K it has a value of about 5.5 T, reducing to 0.9 T at 85 K (Fig. 3). Crossover fields are also found in the $J_c(B)$ measurements of bicrystal experiments.[11]

The measured V-J curves on the Y123 CC at different magnetic fields also show a change in form with increasing temperature (Fig. 4). At the low temperatures (20 K) the V-J curves present a characteristic shape over the full range of accessible fields, similar to the NOLD (non-Ohmic linear differential) behavior resulting from viscous flux flow along low-angle GB's.[9] In general, we do not observe in the Y123 CC a pure NOLD signature at higher current densities. We suggest that the percolation of flux flow through multiple flux flow channels in the GBN can cause this deviation from pure NOLD behavior. At higher temperatures (75 and 83 K) the V-J curves reveal a change in form as the magnetic field is increased. This change takes place at exactly the same

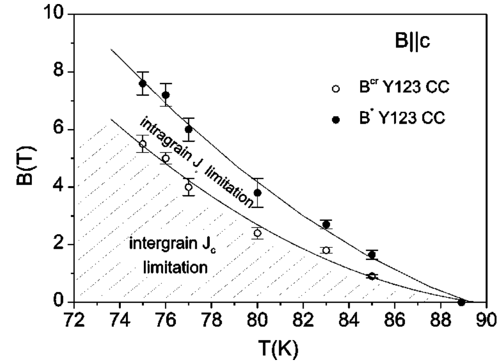

FIG. 5. Irreversibility and crossover fields of the Y123 CC at different temperatures close to T_c.

crossover magnetic field B^{cr} as in the $J_c(B)$ measurements. Viscous flux flow is deducible from the V-J curves until the applied magnetic field reaches the crossover field. At this point the dissipation in the Y123 grains overcomes that in the GB's and viscous flux flow no longer occurs. Then the V-J curves show a power-law behavior, representing flux creep effects at currents very close to or above the critical current. As a reference, the V-J curves of Y123 grown on single crystalline Ni (not shown) were measured, showing in all cases an apparent power-law behavior.

For application of CC's it is fundamental to consider both the crossover field B^{cr} and the irreversibility field B^*. B^{cr} separates the region where the critical current is limited by the GBN of the CC from that where the critical current is completely intragranular, while B^* determines the maximum limit for high-field applications of the CC. Above B^*, flux pinning is no longer effective and Ohmic resistance arises. To determine B^* in the CC the E-J curvature method was used.[13] Figure 5 shows the temperature dependence of B^* and B^{cr} in the Y123 CC. From this figure, it is possible to evaluate if the GBN in the Y123 CC really constitutes a limitation for a given application that works in a fixed range of magnetic field. We see that the range of higher magnetic fields corresponds to areas of complete intragrain limitation, for example at 77 K J_c is completely intragranularly limited if the required magnetic fields are higher than 4 T (B^{cr}).

For high J_c CC's above 1 MA/cm^2 at 77 K the B^{cr} field is shifted further to lower values due to the smaller GB angles in the sample [e.g., at 77 K $B^{cr} \approx 2$ T (Ref. 14)] and the GBN J_c limitation is only valid at low magnetic fields.

IV. CONCLUSIONS

$J_c(B)$ in Y123 CC has been studied and different mechanisms of limitation of the critical current density depending on temperature and applied magnetic fields observed. At low magnetic fields, up to B^{cr}, the critical current is limited by the GBN (intergrain critical current). This is reflected in a power-law dependence of $J_c(B)$ and NOLD-like signature of the V-J curves. At magnetic fields above B^{cr}, $J_c(B)$ is limited by pinning witin the Y123 grain (intergrain critical current) with a typical exponential decay dependence. It was found that the transition from intergrain to intragrain critical current limitation is shifted to lower magnetic fields as the temperature is increased. This crossover behavior can have important implications for CC applications. For applications that require the presence of higher magnetic fields, the GBN of the Y123 CC does not limit the critical current and hence J_c is completely intragrain. The irreversibility field represents in this case the upper limit for applications in high magnetic fields with the GBN having no influence. A better in-plane texture of the CC with smaller GB angles does not avoid this problem since the crossover field is only shifted to lower magnetic fields, leaving the exponential J_c decrease at high fields unchanged. Only in the case of applications that require magnetic fields lower than the crossover field, an improvement of the GB angles in the samples can be useful. We conclude that in fact the GBN strongly limits the critical current in the Y123 CC but only in the range of magnetic fields below the crossover field. The GBN does not present an obstacle for applications that require fields over this transition point and improvements in J_c can be obtained by optimization of the intragrain pinning properties.

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