Critical Current Densities of Isolated Grains and Grain Boundaries in Coated Conductors

Marcus Weigand, Noel A. Rutter and John H. Durrell
Department of Materials Science and Metallurgy, University of Cambridge, Pembroke St, Cambridge CB2 3QZ, United Kingdom
Susannah Speller, Gareth M. Hughes and Chris Grovenor
Department of Materials, University of Oxford, Parks Road, Oxford OX1 3PH, United Kingdom

***Abstract*—We report on a new technique to isolate grain boundaries and single grains in $YBa_2Cu_3O_{7\circ\pm}$ coated conductors using a focused ion beam microscope. For fields swept in-plane a crossover from a regime where the critical current density is limited by the grain boundary to a regime where it is governed by the properties of the grain was found.**

I. INTRODUCTION

The critical current density J_c of cuprate superconductors is, in most cases, limited by grain boundaries (GBs). J_c decreases exponentially with misorientation angle between adjacent grains [1]–[3]. At low angles the suppression of J_c is due to reduced pinning in the GB region leading to flux channeling [4]–[6].

In order to overcome this detrimental effect of grain boundaries on J_c $YBa_2Cu_3O_{7\circ\pm}$ (YBCO) is grown on textured substrates ("coated conductors" or CCs.). In one of the approaches, called RABiTS (Rolling Assisted Bi-axially Textured Substrates) [7], a Ni alloy with oriented grains is used.

Nonetheless, in wide temperature and field ranges GBs remain the limiting factor, therefore making it necessary to ascertain their electromagnetic properties. Most of this work has been done using model systems consisting of YBCO thin films grown on bicrystal substrates [1], [4], [6] and only recently data obtained on isolated CC grain boundaries has been published [2], [8], [9].

There are two advantages of examining GBs on CCs instead of bicrystals. Firstly, only with these can we analyse the combination of different twists and tilts causing the actual GB [3]. Secondly, it was discovered that certain *ex situ* growth methods lead to meandering GBs (both along their length and through the thickness) [10], which show a higher J_c than planar boundaries [8]. This increase has been explained by their larger cross sectional area [8], [11] and by the suppression of vortex channeling along the boundaries [9].

II. EXPERIMENTAL

A. Sample preparation

Tracks $50\,\pi\mathrm{m}$ wide were patterned by conventional photolithography and ion milling on RABiTS samples grown by TFA-MOD (metal-organic deposition using trifluoroacetates) [12], [13]. Subsequently, EBSD (Electron Backscatter Diffraction) maps of these tracks were acquired, in order to locate grains and grain boundaries of interest as well as to measure their respective misorientation angles. This is a challenging task, particularly after lithographic patterning. Fig. 1a shows an EBSD image of the grain boundary which was isolated.

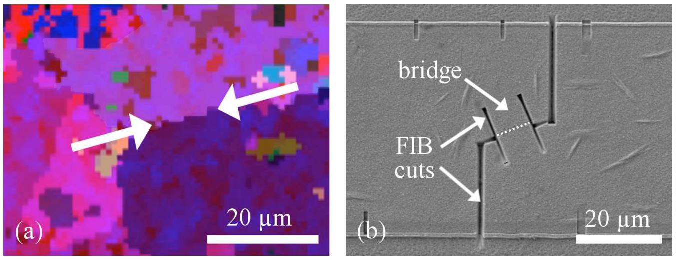


Fig. 1. (a) EBSD map of several grains on an MOD sample. The grain boundary which was isolated subsequently is indicated by arrows. (b) A $50\,\mu\mathrm{m}$ wide track onto which a bridge spanning this GB has been patterned by FIB. The GB is marked by white dots.

In a last step bridges $4{:}5$ and $5\,\pi\mathrm{m}$ wide were patterned across a GB and on a single grain, respectively, using an FIB (Focused Ion Beam microscope, see Fig. 1b). The misorientation angle between the two grains adjacent to the GB was between 4 and $6^{\pm}$ (the scatter being caused by grain mosaicity).

Single grains and grain boundaries have been isolated in CCs before, using EBSD and conventional lithography [2], [8]. In the present work however, this goal has been achieved by the combination of EBSD and FIB for the first time, which allows a more accurate positioning of the patterned bridges. Consequently, specific grains and grain boundaries can be targeted more precisely.

B. Critical current measurements

The critical current densities were measured at $77{:}35\,\mathrm{K}$ for different applied magnetic fields swept in the plane of the film, using a two-axis goniometer [14] mounted in an Oxford Instruments cryostat with an $8\,\mathrm{T}$ magnet. J_c was obtained by a four-terminal measurement with a voltage criterion of $0{:}5\,\pi\mathrm{V}$.

III. RESULTS AND DISCUSSION

Fig. 2 shows a plot of the critical current densities of the GB and the grain vs. angle between the bridge direction and applied magnetic fields of $0{:}5$, 1, 3 and $5\,\mathrm{T}$ swept in the plane of the film ("$;$-scans"). At $0^{\pm}$ field and bridge are parallel to each other (force-free orientation), while at $90^{\pm}$ they are perpendicular (maximum Lorentz force).

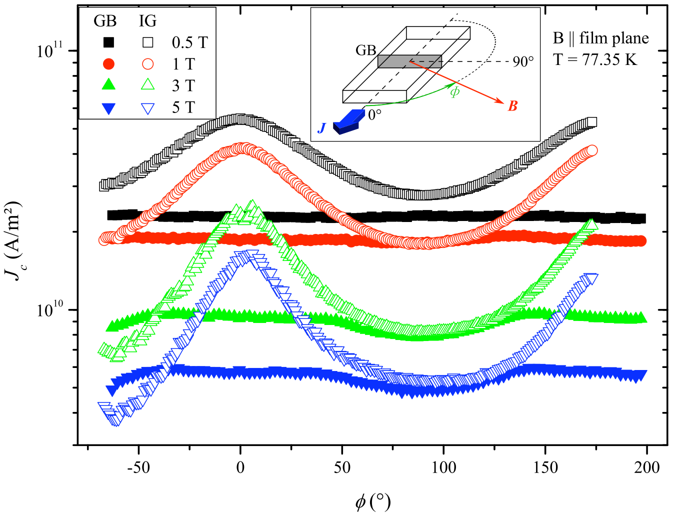
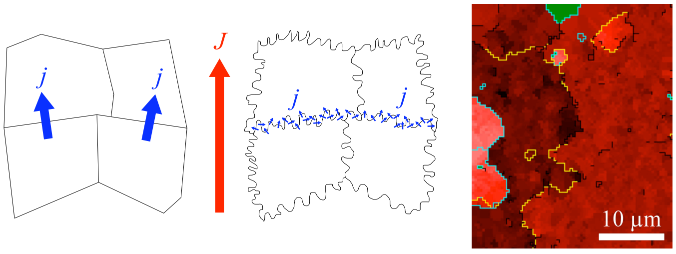


Fig. 2. Critical current densities measured on bridges across a grain boundary (GB) and within a single grain (intragranular, IG) plotted vs. angle between bridge and fields swept in-plane. At $\phi = 0°$ bridge and field are parallel to each other. For $B \geq 1\,\mathrm{T}$ and angles around $90°$ J_c of the grain is lower than that of the GB. The inset shows the measurement geometry.

At $0.5\,\mathrm{T}$ J_c of the GB is lower than that of the grain over the whole angular range and shows virtually no dependence on angle between bridge and field. We explain this flatness by GB meandering [10], which leads to microscopic currents flowing in many different directions, because current always crosses GBs perpendicular to the boundary plane (see Fig. 3, which also shows a high resolution EBSD image of a grain boundary in one of our samples). Consequently, unlike samples grown by PLD (Pulsed Laser Deposition), which have planar GBs, for MOD films there is no orientation where all currents are parallel or perpendicular to the applied field. The result being that the force free maximum (due to a minimum in Lorentz force for $B||J$) is suppressed.



(a)

(b)

(c)

Fig. 3. Schematics showing current flow across (a) planar GBs and (b) meandering GBs (as found in MOD samples). J indicates the direction of macroscopic current flow while j represents microscopic currents. (c) A high resolution EBSD map showing the meandering in one of the samples analysed.

The curves measured on the bridge across the grain on the other hand closely resemble /-scans of a YBCO film grown on a single crystal substrate [15].

At fields from $1\,\mathrm{T}$ upwards at angles around $90^{\pm}$ the critical current densities of the GB and the grain bridges overlap perfectly, indicating that J_c of the GB bridge is actually limited by the properties of the two grains adjacent to the boundary. This means that J_c of the GB exceeds that of the grains. The angular range where this is the case increases with field. A similar crossover from intergrain to intragrain limited critical current density, depending on magnitude of applied field rather than angle between bridge and field, was reported by Fernandez *et al.* [16].

J_c of both the GB and the grain depend strongly on field over the whole angular range. This behaviour is consistent with measurements on GBs isolated by conventional lithography, which showed that J_c of meandering GBs decreases with increasing field more strongly than J_c of planar GBs [9].

IV. CONCLUSIONS AND SUMMARY

We have successfully used a FIB for the first time to isolate a grain boundary and a single grain on a coated conductor. Measurements of the critical current density of the bridge with the GB for fields swept in-plane gave a surprisingly low angular dependence, which can most likely be explained by grain boundary meandering. Comparison with data obtained on a single grain showed a clear crossover from GB to grain limited J_c.

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