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Grain-Boundary Dissipation in High-T_c Superconductors

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Grain-Boundary Dissipation in High-T_c Superconductors

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Thin-film and bulk [001] tilt bicrystal grain boundaries (GBs) in $YBa_2Cu_3O_7$ exhibit a strong dependence of critical current density, J_c, on misorientation angle. What was initially difficult to understand was the 30x smaller J_c in bulk GBs which are microscopically more perfect. We review an explanation of this zero-field data, which is based on the pinning of Josephson vortices by the meandering found in thin-film GBs.

In addition, there is evidence that J_c of GBs does not drop as quickly with applied magnetic field as expected by simple Josephson junction models. The long-wavelength pinning potential due to meandering is less effective at high fields, but Gurevich and Cooley (GC) proposed a new mechanism for an enhanced GB J_c arising from pinned Abrikosov vortices in the banks of a GB which present a static, quasiperiodic pinning potential to pin GB vortices. We find a peak in J_c and an unusual hysteresis which give considerable support to the GC concept. In low fields, the GBs exhibit a larger J_c for field cooling, which is opposite to the usual hysteresis but agrees with GC due to the larger Abrikosov vortex density in the banks. Magnetization data on the same sample are consistent including the identification of the irreversibility field.

1. INTRODUCTION

The pioneering work of Dimos, et al.[1] on thin-film, [001] tilt, grain boundaries (GBs) in $YBa_2Cu_3O_7$ indicated that the critical current density, J_c, is a strong function of misorientation angle, Θ, between the two bicrystal grains. However, the grain-boundary plane for artificially-made thin-film grain boundaries meanders along the path of the underlying straight substrate boundary[2-4]. As such, their value for determining the intrinsic superconducting coupling is questionable. This situation changed after the breakthrough fabrication[5] of bulk bicrystal boundaries in $YBa_2Cu_3O_7$ which has virtually eliminated meandering on all, but atomic, length scales. These symmetrical, bulk boundaries[5,6] are also free of impurity phases. Their J_c values are included with typical thin-film data in Fig. 1 and they both exhibit a similarly strong, exponential Θ-dependence.

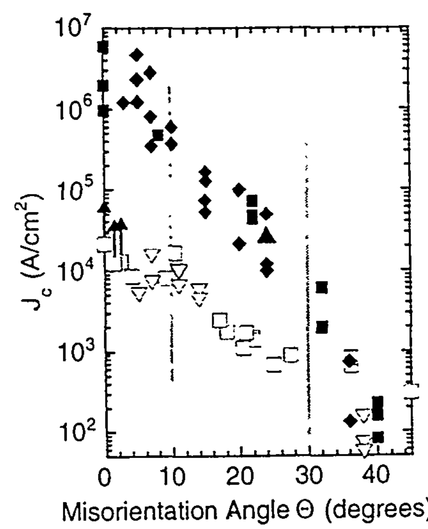

Figure 1. Critical current density for thin-film[7-9] (solid) and flat, bulk[5,10] (open symbols) [001] tilt grain boundaries in $YBa_2Cu_3O_7$.

What is difficult to understand is the thirty-times-*lower* magnitude of J_c in such 'perfect' bulk grain boundaries. A model has been proposed[11] which gives a plausible explanation based on differences in the pinning of Josephson vortices, e.g., by the thin-film meandering GBs.

There is evidence that the GB J_c does not drop as quickly with field as expected by simple Josephson junction models. Although meandering is less effective at high fields, Gurevich and Cooley[12] (GC) proposed a new concept for an enhanced GB J_c arising from pinned Abrikosov vortices in the banks of a GB that present a quasiperiodic pinning potential to pin GB vortices. We find a peak in J_c and an unusual hysteresis which give considerable support to the GC concept.

2. ZERO FIELD

In zero applied field, dissipation occurs by the motion of GB Josephson vortices which are created by the self field of the current. Strong pinning is expected along thin-film boundaries, partly because their meander wavelength matches the vortex size. However, flat, ideal GBs present little possibility for pinning of spatially extended Josephson vortices, so that J_c just represents the critical flux-entry field, H_{c1}, for the GB. The depinning and flux entry threshholds, J_{cp} and J_{c1}, exhibit different dependences on the intrinsic, small junction Josephson critical current density[11], J_{cj}, as:

$$J_{cp} = \alpha \frac{4}{\pi} J_{cj}, \qquad (1)$$

where α is the strength of pinning defects relative to the maximum possible (α<1), and

$$J_{c1} = \sqrt{J_o J_{cj}}, \qquad (2)$$

where $J_o = c\Phi_o/(\pi^2 w^2 \lambda_{ab})$, Φ_o is the quantum of flux, w is the largest dimension of the cross section and λ_{ab} is the penetration length in the ab plane. Since J_{c1} contains no unknown parameters, the data on bulk GBs determines J_{cj} directly, as seen in the upper line in Fig 2.

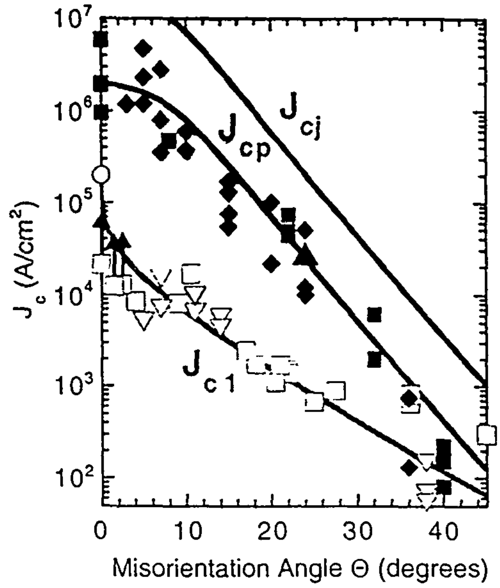

Figure 2. The intrinsic Josephson, J_{cj}, as determined from J_{c1} for the bulk GBs. The lower values of J_{cp} imply an effective pinning strength α of ~0.12.

The ratio of the thin-film J_c to J_{cj} then determines the effective pinning strength, α, of meander boundaries that turns out to be a rather large value of ~0.12.

Very high J_c have been reported[13] on flat GBs of $YBa_2Cu_3O_7$ made by liquid-phase epitaxy. Although they are a factor of 20 times larger than the bulk GBs shown in Fig. 1, they are consistent with J_{c1} of the model since the largest dimension, w, was 30 μm which is 20x smaller than bulk (see Eq. 2).

Thus this flux-pinning model explains the otherwise puzzling differences in J_c shown in Fig. 1 for bulk and thin-film GBs and provides guidelines for *desirable* GBs for various situations. Meandering is highly desirable for biaxially-textured, coated-conductors[14] to enhance J_c, but studies of the intrinsic J_{cj}, e.g., the effects of d-wave superconductivity[15,16], will virtually require planar boundaries[5] to avoid the potentially large variations in J_{cj} and the unknown α.

3. FINITE FIELDS

The close vortex spacing in high fields, reduces the effective pinning by the long-wavelength meandering thin-film GBs. Thus it cannot explain why J_c does not drop as quickly with field as expected by simple Josephson junction models. Gurevich and Cooley[12] (GC) have proposed a new concept for an enhanced GB J_c arising from pinned Abrikosov vortices in the banks of a GB which present a static, quasiperiodic pinning potential to pin GB vortices. We find a peak in J_c and an unusual hysteresis which give considerable support to the GC concept. In low fields, the GBs exhibit a larger J_c for field cooling, which is opposite to the usual hysteresis but agrees with GC due to the larger Abrikosov vortex density in the banks.

Bulk GBs were obtained by the cubic-seed-growth melt-texture processing[5], and sections containing 90° [100] symmetric tilt GBs were thinned to ~75 μm. In ambient magnetic fields, the current-voltage curves, I(V), show a separate contribution of the GBs at intermediate temperatures, and this allows us to determine independent measures of the GB critical current, I_{cgb}, and that of the grain, I_{cgr}. At low temperatures, the data are limited by I_{cgr} and only near T_c can I_{cgb} be determined. Larger fields increase the temperature interval over which I_{cgb} can be determined, but in all cases the data seem to imply a crossover with $I_{cgb}>I_{cgr}$ at lower temperatures.

Data were taken while cooling the sample in a field which was applied above T_c in a sequence called field cooling (FC). A second sequence increases the field after cooling to T in zero field (ZFC). The differences between FC (solid symbols) and ZFC (open symbols) are shown in Fig. 3 for 84 K and they are dramatic in low fields where the GBs exhibit a *larger* I_{cgb} for FC. This is just opposite to the usual result for bulk materials (in which the larger internal fields associated with FC decrease the pinning and thus I_{cgr}). A broad peak is also seen in I_{cgb} for the ZFC branch.

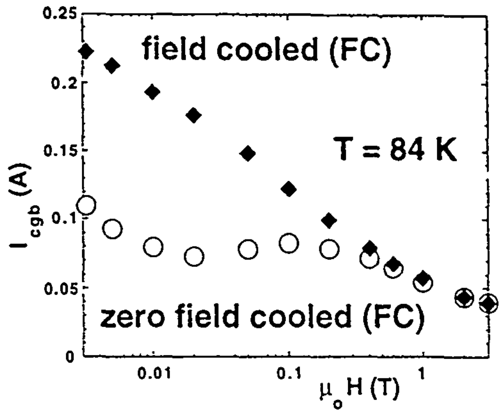

Figure 3. Hysteresis in the GB I_{cgb} and peak effect for ZFC data.

We propose an explanation of this remarkable hysteric behavior in terms of pinning of Josephson-like vortices (JLV) in the GB by vortices pinned in the nearby banks, in a manner suggested[12] by GC.

The following provides a possible scenario for the detailed features of the data in Fig. 3. For ZFC, the field penetrates first into the GB if $H<H_{c1gr}$, where H_{c1gr} is the critical flux-entry field of the grains. Then the initial decrease of I_{cgb} (for H<0.02 T) is likely due to a reduction of the average pinning strength as the vortex density increases. For $H>H_{c1gr}$, the surface barrier is overcome so vortices can enter the grains and those situated next to the GB can provide pinning by the GC mechanism. It is not clear whether these vortices are injected at the outer surfaces of the grains or if their origins are GB vortices which are injected at the GB interfacial surface (this would be relevant for non-uniform critical-state flux profiles). However, these vortices likely cause the increase in I_{cgb} with field shown in Fig. 3 for H between 0.02 and 0.1 T. For the FC curve the vortex density in the grains is near or at its maximum, so the ZFC curve cannot cross it, but instead merges with it as the irreversibility of the individual grains disappears. The decrease of the GB I_{cgb} with H for FC could result from a smaller pinning potential as the vortices move closer together, somewhat analogous to the behavior of the shear modulus in an Abrikosov vortex lattice. Magnetization data on the same sample are consistent including the identification of the irreversibility field.

An alternative explanation, used on very low field (~10 mT) data[17] in polycrystalline $YBa_2Cu_3O_7$, invokes flux focusing into the GB caused by field explusion from the grains. Here, the fields are significantly larger than H_{c1gr} of the grains. For example, the focused field at the GB, for ZFC at 3 mT, would have to be ~100 mT to match the FC data for the same I_{cgb}. This seems implausible, but direct measurements of the focused field will be necessary to completely rule this out.

4. SUMMARY

Experiments and modelling show, not surprisingly, that the pinning of vortices rules the roost for GBs, just as it does for dissipation in bulk superconductors. The GC mechanism implies that trapped flux can improve I_c if it is dominated by the GBs.

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