Evidence for pinning of grain-boundary vortices by Abrikosov vortices in the grains of $YBa_2Cu_3O_7$

Dongho Kim,* P. Berghuis, M. B. Field, D. J. Miller, and K. E. Gray
Materials Science Division, Argonne National Laboratory, Argonne, Illinois 60439

R. Feenstra and D. K. Christen
Solid State Division, Oak Ridge National Laboratory, Oak Ridge, Tennessee 37831-6061
(Received 21 April 2000)

Data as a function of magnetic field on two types of bicrystal grain boundaries (GB's) of high-T_c superconductors show a peak in the critical current and an unusual inverse hysteresis. These results support a mechanism for an enhanced GB critical current, arising from interactions of GB vortices with pinned Abrikosov vortices in the *banks* of a GB, as suggested by Gurevich and Cooley. A substantial fraction of this enhancement (of order a factor of 2 after field cooling) also occurs upon exceeding the critical current of the grains after zero field cooling. A bulk GB and an isolated GB from a coated conductor show qualitatively identical results.

There is evidence that the critical current density J_c of grain boundaries (GB's) in high-temperature superconductors (HTS's) does not drop as quickly[1] with magnetic field H as might have been expected from a simple Josephson junction model, in which the envelope of the Fraunhofer pattern goes as $1/H$. In very low fields, pinning of Josephson vortices by the meandering of thin-film, [001] tilt, bicrystal GB's in $YBa_2Cu_3O_7$ has been demonstrated[2] to enhance J_c. However, as the spacing between Josephson vortices decreases in higher fields, this long wavelength pinning potential due to meandering becomes less effective. Recently, Gurevich and Cooley[3] proposed a new mechanism for an enhanced GB critical current arising from pinned Abrikosov vortices in the *banks* of a GB which present a static, quasiperiodic pinning potential to pin GB vortices. Their calculations, that predict,[3] e.g., a peak in $J_c(H)$, are in the low field limit, but the central concept can be extrapolated to higher fields. This pinning mechanism exhibits optimal effectiveness if the Abrikosov and Josephson vortices have the same spacing, i.e., when the magnetic flux density in the GB and the banks are equal. In that case there is one potential well for pinning per Josephson vortex. A peak in $J_c(H)$ is not uncommon in melt-textured and single crystalline $YBa_2Cu_3O_7$ which are made without intentional GB's, but we are unaware of such direct experimental evidence in GB transport.[4]

This paper reports critical currents, that are extracted from current-voltage curves such as the zero-field data of Fig. 1, on bicrystal GB's that show a peak in the GB critical current $I_{cb}(H)$ and an unusual hysteresis that give considerable support to the central concept of the Gurevich-Cooley model.[3] At high fields, this support comes from the history dependence of $I_{cb}(H)$ and the field profiles found in these bulk materials. We have measured $I_{cb}(H)$ of the GB after either (1) field cooling (FC) the sample in an applied field H to a temperature T from *above* the transition temperature T_c or (2) increasing H after zero-field cooling (ZFC) to T. In low fields, the GB's exhibit a *larger* I_{cb} for FC, which is just opposite to the usual hysteresis for the grains of bulk materials (in which the larger internal fields associated with FC decrease the pinning and thus I_{cg}). However, this is exactly the expectation of the Gurevich-Cooley model for GB's, since FC provides a larger Abrikosov vortex density in the banks that can more strongly pin GB vortices. Magnetization data on the same sample are consistent with features of the I_{cb} hysteresis interpreted in this framework, including the irreversibility field, above which, the internal flux profiles are nearly the same for FC and ZFC. Above the irreversibility field, a necessary expectation of Ref. 3 is that the GB transport should be indistinguishable between FC and ZFC and our data confirm this. Finally, in the ZFC case, after a sufficiently large current is applied such that vortices can both be injected in the banks and exhibit flux creep, the I_{cb} of the GB's is permanently increased thereafter, and by a considerable amount. This is consistent with the additional flux penetration caused by the supercritical current in the banks, although the full I_{cb} value for FC has not been achieved.

Bulk GB's were grown by the cubic-seed-growth melt-texture processing which is described in detail elsewhere.[5] Sections containing 90° [100] symmetric tilt GB's were

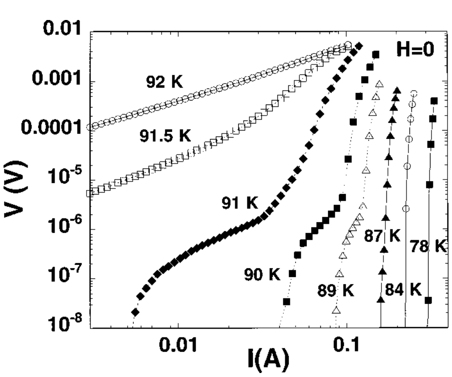

FIG. 1. The current-voltage curves as a function of temperature in ambient magnetic fields (<1 Oe). The separate contribution of the GB (i.e., the foot of the transition) is apparent at intermediate temperatures.

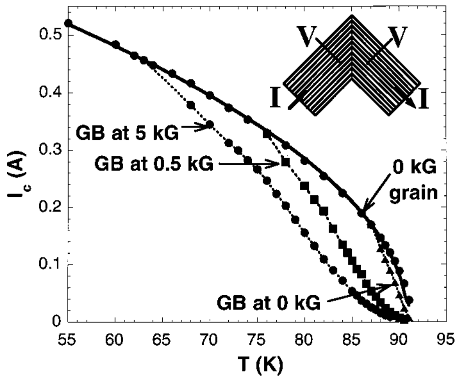

FIG. 2. The temperature dependences of I_{cb} for various applied fields that were perpendicular to the platelike shape (inset) and thus parallel to the GB plane and to the Cu-O planes of each arm. For the grains, the I_{cg} were virtually independent of field. Data were taken while cooling the sample in a field which was applied above the transition temperature, T_c.

thinned to $\sim 75\ \mu$m and the misorientation angle was verified by electron backscatter Kikuchi patterns to be $90° \pm 1°$. A solid state Nd-YAG laser was used to cut these platelike sections into the shape sketched in the inset of Fig. 2. Four electrical contacts with resistance ~ 1 Ohm were attached with silver epoxy, as indicated, with the outermost ones used for applied current I and the innermost for voltage V. For this L-shaped sample, the *macroscopic* applied current direction (thick arrows) is parallel to the Cu-O planes. The widths (lengths) of the arms are $\sim 300\ \mu$m ($\sim 600\ \mu$m).

Transport properties were measured in the He-gas flow cryostat, initially using current pulses of 150 ms duration to reduce heating while retaining sufficient voltage sensitivity (see further discussion of heating below). In ambient magnetic fields (<1 Oe), Fig. 1 shows the current-voltage curves $I(V)$ as a function of temperature, T. The separate contribution of the GB (i.e., the foot of the transition) is apparent at intermediate temperatures, and this gives an independent measure of the GB critical current I_{cb} using a 0.1 μV criterion, and that of the grain I_{cg} using 1 μV criterion after extrapolating the $I(V)$ from higher voltages (see Fig. 1), when necessary. For $T < 87$ K, the measurement was limited by the intragrain I_{cg}, while at 92 K, both arms are in the normal state.

The temperature dependences of I_c are shown in Fig. 2 for various applied fields that were perpendicular to the platelike sample and thus parallel to the GB plane *and* to the Cu-O planes of each arm. Data were taken while cooling the sample in a field which was applied above the transition temperature T_c. This sequence, mentioned above, is known as field cooling (FC). At low temperatures, the data are limited by I_{cg}, and only near T_c can I_{cb} be determined. Larger fields increase the temperature interval over which I_{cb} can be determined, but in all cases the data seem to imply a crossover with $I_{cb} > I_{cg}$ at lower temperatures.

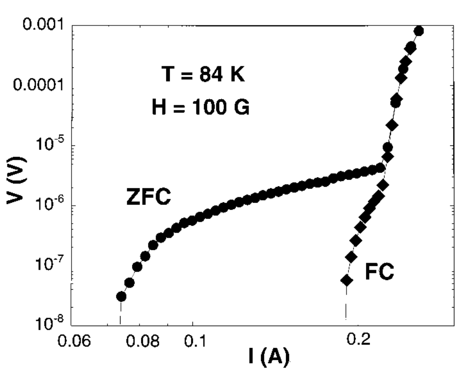

FIG. 3. The differences in $I(V)$ between FC and ZFC for 84 K and 100 Oe.

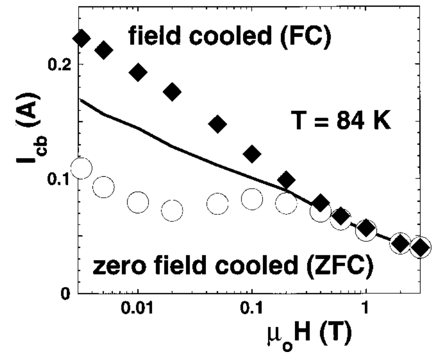

FIG. 4. From data such as Fig. 3, taken as a function of field, the I_{cb} for FC (solid symbols) and ZFC (open symbols) are shown. The solid line is the irreversible (i.e., permanent) change in I_{cb} found upon exceeding I_{cg} after ZFC.

Using the same field orientation, a second sequence increases the field after cooling to T in zero field (ZFC). The differences in $I(V)$ between FC and ZFC are shown in Fig. 3 for 84 K and 100 Oe. From similar data taken as a function of field, the I_{cb} for FC (solid symbols) and ZFC (open symbols) are collected in Fig. 4. The differences are dramatic in low fields where the GB's exhibit a *larger* I_{cb} for FC. This is just opposite to the usual result for bulk materials (i.e., the larger internal fields associated with FC decrease the pinning and thus I_{cg}). In addition, a broad peak in I_{cb} is seen in the ZFC branch for $\mu_0 H \sim 0.05-0.2$ T.

There is a strong correlation of some of the distinctive features of the data in Fig. 4 with the bulk magnetization of the grains (banks), measured on one half of a GB sample at 77 K and shown in Fig. 5. The transport data at 77 K was qualitatively the same as Fig. 4, except the characteristic fields were about a factor of 2 larger, in excellent agreement

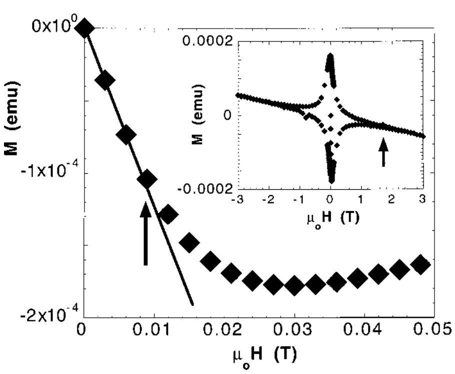

FIG. 5. The bulk magnetization of one half of a GB measured at 77 K. The deviation from the Meissner-like magnetization at ~ 0.01 T (arrow) signals the entry of flux *into the grain* and the inset shows that the grains are reversible above about 2 T (arrow).

with Fig. 5. Thus the deviation from the Meissner-like magnetization at ~0.01 T signals the entry of flux *into the grain* and this corresponds to the beginning of the upturn of *the grain boundary* I_{cb} in the ZFC case. The grains are reversible above about 2 T and so is the GB. These results strongly hint that the GB I_{cb} is connected to the magnetic flux density *in the grains*.

We propose that the Gurevich-Cooley model[3] can explain this remarkable inverse hysteresis in terms of pinning of Josephson-like GB vortices by Abrikosov vortices pinned nearby in the banks. By a Josephson-like vortex, we mean the usual Josephson vortex in low applied fields, but as their density increases, neighboring GB and Abrikosov vortices overlap to significantly alter their structure, e.g., shape.[6] Gurevich and Cooley[3] proposed that sufficiently well-pinned vortices in the *banks* of a GB present a static, quasiperiodic pinning potential to pin such GB vortices, but it also automatically has the optimal spacing *at each field*. This magnetic interaction provides additional longitudinal pinning[3] to that resulting from inhomogeneities[2] of the Josephson current along a GB.

The following scenario provides a possible explanation for the detailed features of the data in Fig. 4. For ZFC, the field penetrates first into the GB, even if $H<H_{clg}$, where $\mu_0 H_{clg} \sim 0.01$ T is the critical flux-entry field of the grains (banks). Then the initial decrease of I_{cb} (for $\mu_0 H<0.01$ T) is likely due to the diluting the average pinning strength as the GB vortex density increases. For $H>H_{clg}$, the surface barrier is overcome so vortices can enter the grains. It is those situated next to the GB that can provide pinning by the Gurevich-Cooley mechanism. It is not clear if these vortices are injected at the outer surfaces of the grains and migrate to the GB, or if their origins are the GB vortices themselves, such that they are injected at the GB interfacial surface (this could be relevant for non-uniform critical-state flux profiles in the grains). However, it is these vortices that likely cause the increase in I_{cb} with field shown in Fig. 4 for ZFC and $\mu_0 H$ 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 each individual grain disappears. For FC, the decrease of the GB I_{cb} with H could result from a dilution of the pinning potential as the vortices move closer together, somewhat analogous to the reduction of the shear modulus in an Abrikosov vortex lattice at high fields.

One may think of two curves of $I_{cb}(H)$: one is the actual FC data in which the field in the grains is at a maximum and approximately equal to H; the other is a hypothetical curve for no vortices in the grains. The latter $I_{cb}(H)$ curve is determined only by inhomogeneities[2] of the Josephson current along a GB and it may be roughly parallel to the first, but exhibits lower I_{cb} than the FC data due to the absence of pinning by Abrikosov vortices in the banks. The beginning of this latter curve is seen as the ZFC curve below ~0.01 T. The ZFC data from ~0.01 to ~0.5 T, including the peak, is then the transition between the two $I_c(H)$ curves as Abrikosov vortices populate the grains and provide pinning for the GB vortices.

An alternative explanation which shares some of the characteristics noted above is flux focusing along the GB, caused by field expulsion from the banks. While flux focusing can explain the low-field (~0.01 T) hysteresis in granular materials,[7] the hysteresis in our data extends to much higher fields. Interpreting our data as due to flux focusing requires mapping our ZFC data points onto the FC curve (at a presumed higher GB field, that is amplified by flux focusing). This implies, e.g., at $I_{cb} \sim 0.1$ A in Fig. 4, that a focused field of ~0.2 T is found at the GB for applied fields of only ~0.004 T. Our direct bulk magnetization data in Fig. 5, and also measurements with Hall-effect microprobes, dispel that possibility. In addition, the peak in I_c seen in our GB's for ZFC was not seen in the earlier study,[7] and flux focusing offers no obvious explanation of it. Thus we suggest that flux focusing cannot explain our data.

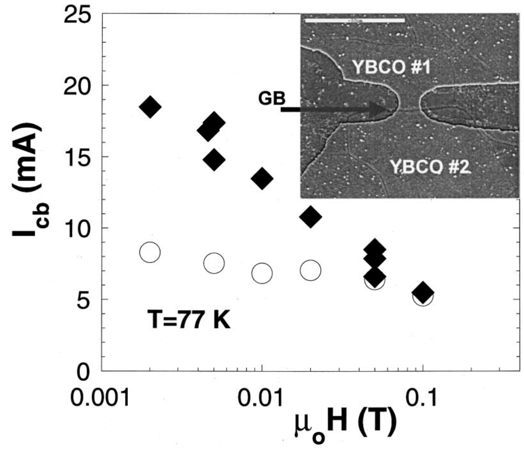

FIG. 6. Similar I_{cb} data as in Fig. 4, but here taken on a patterned GB on a coated conductor (inset), for FC (solid symbols) and ZFC (open symbols).

The bulk, flat 90° [100] symmetric tilt GB's used above are somewhat special ones that are relevant to step-edge film junctions (devices), but not so important for coated-conductor applications. In addition, the field was applied *parallel to the ab planes* resulting in an anisotropic pinning potential for the Abrikosov vortices. To test the generality of the Gurevich-Cooley concept (i.e., the enhancement of I_c by decorating the banks of GB's with Abrikosov vortices), we also isolated a GB by lithography from a coated conductor sample made by the RABITS process.[8] This thin-film, [001] tilt, bicrystal GB (determined by electron backscatter to be ~11°) was measured with the applied field *parallel to the c axis*, that implies an isotropic pinning potential for the Abrikosov vortices (note that the current flow is still perpendicular to the field). The data, shown in Fig. 6, are remarkably similar to those of Fig. 4 for the bulk, flat 90° [100] symmetric tilt GB, so this mechanism appears to be a general property of GB's. In addition, previous data[9] on artificial thin-film bicrystal GB's showed the same qualitative hysteresis as in Figs. 4 and 6.

We have discovered another method, in addition to FC, to introduce Abrikosov vortices into the grains and enhance I_{cb}. Starting from the ZFC case, if the current exceeds the threshold for flux creep, i.e., at I_{cg} in Fig. 3, Abrikosov vortices are injected into the bulk grains. These can play that same pinning role as the Abrikosov vortices introduced by FC, and thus increase I_{cb} of the GB. The increase, shown as the solid line in Fig. 4, is irreversible (i.e., permanent) and can be a considerable fraction (~1/2) of the increase found by FC. However, by analyzing the temporal voltages during current pulses that exceeded I_{cg}, evidence was found for heating effects. Thus the injection of vortices into the grains could be akin to FC. Shorter pulses ($\sim 2\ \mu$sec) eliminated heating, so the much smaller, but definitive, enhancements of I_{cb} must be due to *Lorentz-force driven* vortex injection. The enhancements depended mostly on the pulse current magnitude (up to 1.4 A) and only weakly on the number of pulses.

In summary, we have presented strong support for the conceptual model of Gurevich and Cooley[3] in which GB vortices are pinned by Abrikosov vortices in the banks of the GB. This conclusion has some interesting and possibly important consequences. It provides a mechanistic basis to understand the high-field behavior of granular high-T_c superconductors. It also points to the potential for improved performance (i.e., higher I_c), in applications where I_c is affected by GB's, by decorating the GB banks with pinned Abrikosov vortices.

The authors thank A. Gurevich for stimulating discussions and D. Larbalestier for the use of the laser cutting facility at the University of Wisconsin. This work was partially supported by the U.S. Department of Energy, Basic Energy Sciences-Materials Sciences and Energy Efficiency and Renewable Energy, Office of Power Technologies as part of a program to develop electric power technology, under Contract No. W-31-109-ENG-38 at Argonne and under Contract No. DE-AC05-96OR22464 with Lockheed Martin Energy Research Corp. at Oak Ridge. Earlier stages of the Argonne effort were funded by the National Science Foundation Office of Science and Technology Centers under Contract No. DMR 91-20000.

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*Permanent address: Dept. of Physics, Yeungnam University, Kyungsan 712-749, Korea.

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