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Possible pinning of grain-boundary vortices by neighboring Abrikosov vortices in the nearby grains

Abrikosov 볼텍스에 의한 결정입계 볼텍스의 속박 현상

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The critical currents I_c of the YBCO grain boundaries of 90-degree [100] symmetric tilt showed a hysteretic behavior depending on how the external magnetic fields were applied. Near 77K for fields less than ~1 T, the field-cooled I_c of grain boundaries was larger than the zero-field-cooled I_c. This result is consistent with the model in which the grain-boundary vortices can be pinned by neighboring Abrikosov vortices in the nearby grains.

1. Introduction

To understand the dissipation mechanism in the high-temperature superconductors (HTSC) grain boundaries (GB), a crucial part to the wire development, we studied the temperature and the field dependence of the critical current in YBCO 90-degree [100] symmetric tilt grain boundaries. The result showed an interesting hysteretic behavior in the critical current I_c suggesting an anormalous dissipation mechanism in the bulk grain boundary.

2. Experiment

Samples were grown by the cubic seed growth process described in detail elsewhere [1]. After melt-texture processing, the part of pellet containing GB regions of interest was sectioned and thinned to ~50m. A solid state Nd-YAG laser cutter was used to isolate bars containing the boundaries of 90° [100] symmetric tilt. The bicrystal misorientation angle was verified by electron backscatter Kikuchi patterns that confirmed the boundaries within 1 of 90. For electrical measurements, samples were wired in the four-probe configuration with silver epoxy. The contact resistance was ~ 1 ohm. The samples measured in this work correspond to L-shaped 'tilt3' and I-shaped 'tilt1' in Ref. [2] and they are sketched in Fig. 1. The difference between two samples is the relative orientation of the CuO planes to the macroscopic direction of the current flow. When magnetic fields are applied normal to the sample surface, i.e., parallel to the CuO planes, the current driven vortices in tilt3 should cross the CuO planes, while in tilt1 gliding motion along the CuO planes is possible.

Transport properties were measured in the He-gas flow cryostat using the 150-ms long switched pulse currents to minimize heating and maximize the voltage sensitivity. The critical current was measured in two separate sequences. First the sample was cooled in a zero field from above T_c to a desired temperature, then the field is ramped up and

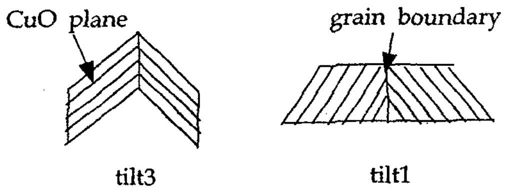

Fig. 1. A sketch of 90° [100] symmetric tilt grain boundaries.

the current-voltage (IV) charateristics were measured. In the other sequence, the field is turned on while the sample is in the normal state, then cooled down and the IV were measured. The GB I_c was determined using 0.1 μV criterion and the intragrain I_c was determined using 1 μV criterion from extrapolating the IV from above (see Fig. 2).

3. Result and Discussion

Figure 2 shows typical current-voltage (IV) characteristics of tilt3 measured in ambient magnetic fields. Sample tilt1 showed a similar behavior but in a certain situation an interesting feature was observed due to the different relative geometry. The details will be described later in the paper. At 92 K, the grain is in the normal state. With decreasing temperature, IV shows two kinds of

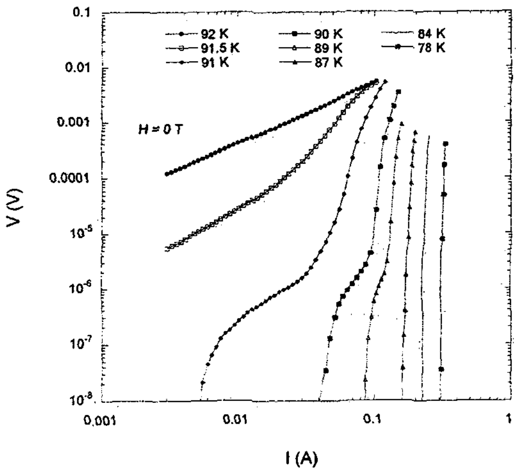

Fig. 2. Current-voltage characteristics of tilt3 in ambient magnetic fields

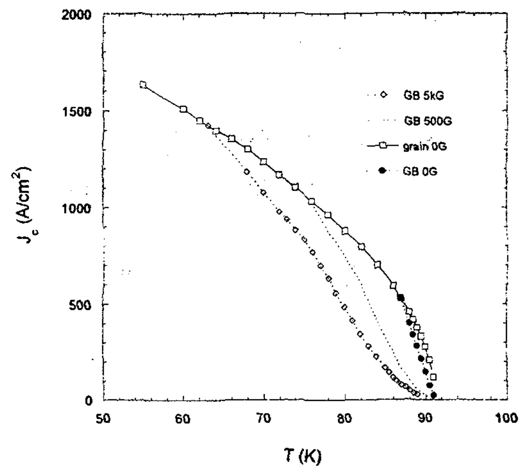

Fig. 3. Temperature dependence of the grain-boundary (GB) and intragrain critical current density of tilt3 in various magnetic fields applied parallel to the CuO planes.

dissipation. The initial dissipation at low currents is from the GB and the sharp increase of voltage on further increment of current is from the grains. For T < 87 K, the step-like feature disappears as the GB critical current is limited possibly due to the heating in the grains as the bias current surpasses the intragrain critical current. The heating at the current contacts can result in a similar increase of the voltage. At this stage, we are working on to figure out the exact dissipation mechanism of voltage uprise at high currents, but whatever the underlying mechanism is, we will call this current as intragrain I_c since its temperature dependence could not be explained solely by contact heating as shown below.

Figure 3 shows the temperature dependence of the GB and the intragrain critical current in various magnetic fields. The magnetic field was applied parallel to the CuO planes of the grains as well as to the GB plane and the I_c was measured while lowering temperature in magnetic fields. The field is parallel to CuO planes. Near T_c, the intragrain I_c is higher then the GB I_c, but at low temperatures the GB I_c is limited by the intragrain I_c. One reason for this crossover in I_c is the larger cross-sectional area for the GB I_c than for the intragrain I_c in tilt3. But note that the increasing rate of the GB I_c with

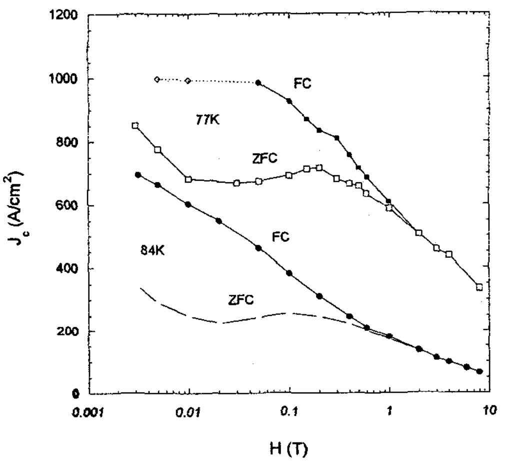

Fig. 4. Magnetic field dependence of grain-boundary critical current density of tilt3 at 77 and 84 K. The GB I_c measured with two different modes, FC and ZFC, are drastically different especially below 1 T.

decreasing temperature is faster than that of the grain I_c. Applying magnetic field shifted the GB I_c toward lower tempeartures, but the intragrain I_c hardly changed in the field range shown in Fig. 3.

Figure 4 shows the field dependence of GB I_c at 84 and 77 K. The magnetic field in this case is applied parallel to the GB plane and CuO layers of the grains. The lower curves (open symbols) were measured with applied field turned on after zero-field cooled (ZFC), and the upper curves were measured with field cooled (FC) from above T_c. The GB I_c measured with two different modes are drastically different from each other with the critical current of FC being much higher than that of ZFC especially below 1 T. In addition, a broad peak in the GB I_c was observed in ZFC branch near 0.1 to 0.2 T. The dotted line in the FC branch of I_c at 77 K denotes that I_c of the GB is limited by intragrain I_c.

We attempt to explain this remarkable hysteretic behavior and the peak in ZFC I_c in terms of pinning of grain-boundary vortices (GBV) by Abrikosov vortices (AV) pinned in the nearby banks. Here the grain-boundary vortex means either a Josephson vortex in low applied field or an overlapped Josephson vortex with its size possibly defined as an elementary length of spatial oscillation of the tunneling current in the high field case.

As introduced by Gurevich et al. [3], the magnetic interaction of GBV in the grain boundary with AV in the grains can provide an additional pinning to GBV on top of the pinning resulted from the inhomogeneities of the tunneling current. This additional pinning requires that AV located close to the grain boundary are strongly pinned, then the local energy barriers resulted by the magnetic fields of AV becomes effective for GBV pinning. Gurevich also derived [3] that J_c will increase with field while the magnetic contribution of pinning is larger than the pinning due to the inhomogeneities of the tunneling current and that pinning by AV becomes ineffective in high fields as the phase cores of GBV overlap. This concept of pinning of GBV by nearby AV is in qualitative agreement with the observed hysteretic behavior of GB I_c.

For ZFC and field below H_{c1} of the grains, a magnetic field penetrates into the boundary first forming Josephson vortices in the GB. The initial decrease of the GB I_c up to 0.02 T is mainly related to the increasing number of the Josephson vortices with increasing field. As the external field increases over H_{c1} of grains, the penetration of magnetic field into the grains starts to put the AV into the grains and the field profile inside the grain will be that of the critical state. At the same time, growing number of the Josephson vortices in the boundary will force overlapping of the Josephson vortices resulting in less well defined vortex structure, grain-boundary vortices. In the early stage of the critical state, the penetrating AV are populated near the edge of the sample so that the GBV only near the edge can be effectively pinned by AV. On further increment of field, the deeper penetration of the AV into the grain provides further pinning of GBV, thus increasing GB I_c. But when AV spacing becomes the order of the penetration depth, AV starts to overlap. Then the magnitude of the modulation of magnetic field along the boundary plane becomes smaller resulting in a lower energy barrier against the GBV motion. At the same time the number of the GBV increases, therefore beyond a certain field, a decrease of

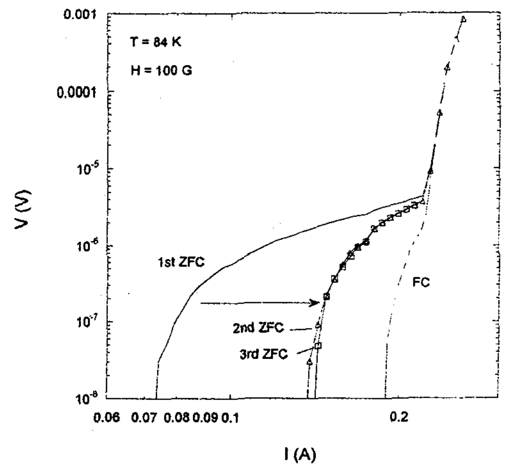

Fig. 5. Traces of several ZFC and FC IV curves of tilt3. After the first ramp of the bias current in ZFC mode, the GB I_c jumps to a higher current but stays there in the subsequent ramps.

GB I_c with increasing field is expected. The peaks in I_c were found around 0.1 - 0.2 T and interestingly this field corresponds to the field that the vortex spacing becomes the order of the vortex size, i.e., the magnetic penetration depth. Even after the full penetration of field into the grains, the field profile is still not uniform compared to FC case until a sufficiently high field, thus the hysteretic behavior persists to reasonably high field e.g., 1 - 2 T in the present temperature range.

In FC case, the homogeneous magnetic field inside the sample above T_c transforms into the uniformly distributed AV upon cooling except very near the edge. Thus, in contrast to the ZFC case, *all* the GBV will experience the pinning by neighboring AV resulting in higher I_c over ZFC case. With increasing field, the GB I_c decreases monotonically as the number of GBV as well as AV increases and eventually two branches of GB I_c collapse to a single line above 1 - 2 T.

One interesting feature that strongly supports the above scenario of the enhanced GB I_c due to pinning by adjacent AV is the progress of ZFC IV with the subsequent measurements. Figure 5 shows the traces of several ZFC IV and one FC IV measured in 100 G at 84 K. The current sweep started at the same current, well below 0.06 A, and finished at the same current for all three IVs. In ZFC measurement, the initial dissipation started just above 0.07 A. But in the subsequent ramp, the dissipation started well over 0.1 A, a big jump from the first I_c. After this jump in I_c, IV hardly changed in the next ramp of the current. On the other hand, the IV for FC remained the same in the second ramp. When the first ramp finishes before the grain becomes normal, for instance up to 1 μV, the I_c jump in the second sweep was not as large as in Fig. 4. The upward shift of the GB I_c in the second ramp of the current is summarized in Fig. 6, and this behavior also can be explained by pinning of GBV by AV. As the current becomes higher than the GB I_c and/or intragrain I_c in the initial ramp, the AV penetrates further into the center of the grains since the local current in the grain may exceed the intragrain critical current. Then, even after reducing the current, some of AV still remain inside the sample and these AV can provide additional pinning to GBV, resulting in a higher I_c in the second sweep. Once the redistribution of AV is set up by the first ramp, a further change in the flux profile seems not likely to occur.

In the case of tilt1, a similar, but weaker

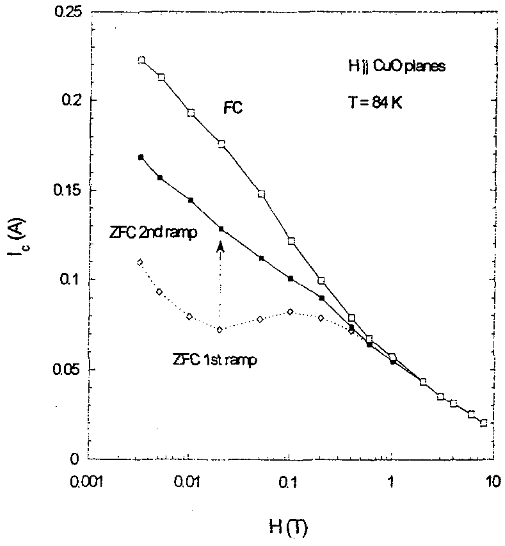

Fig. 6. The upward shift of the GB I_c in the second ramp of the bias current in tilt3.

hysteretic behavior in GB I_c was observed, but the jump of I_c in the second ramp of the bias current in ZFC mode was much larger than that of tilt3, essentially reaching the FC I_c curves. This difference can be understandable considering the relative orientation of the CuO planes to the edge of the sample. In tilt1, the CuO planes intersect the edge with an angle, but the CuO planes are parallel to the edge (Fig. 1). When the magnetic fluxes infiltrate into grains near the end of the first ramp in ZFC mode, it is easier in tilt 1 than in tilt3 since the vortices should overcome the additional pinning barrier by CuO planes in tilt3. This basically assumes that the whole grain does not turn into normal simultaneously, instead a few weak spots become normal first and the heat propagates through the sample. The time trace of the voltage record showed such a behavior.

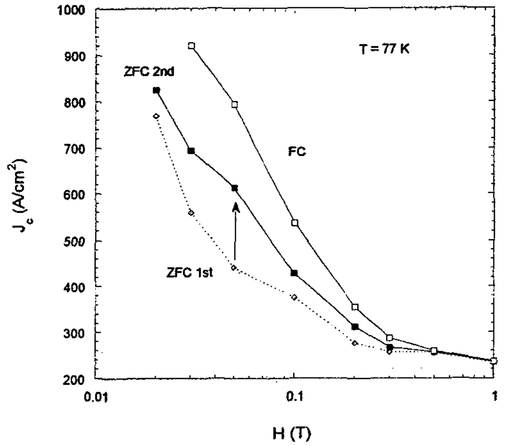

Fig. 7. Hysteretic behavior in the GB I_c persists when a magnetic field is rotated 90° in the boundary plane.

When the field is rotated 90° in the boundary plane from the above configuration, a weaker hysteretic behavior in the GB I_c was also observed. Figure 7 shows the GB I_c of ZFC and FC as well as the GB I_c from the second ramp in ZFC mode as a function of field measured at 77 K. In this configuration, there is a field component parallel to the c axis of the grains so that field penetrates into the grains rather easily. Thus the difference in I_c between FC and ZFC is relatively small because the field profile in ZFC at a given field would be more uniform compared to the case of Fig. 4. The I_c peak in ZFC branch is not so obvious as in Fig. 4, but this could be due to the rapidly decreasing I_c with field due to the critical current anisotropy. Also the fact that two I_c branches collapse at ~5 kG smaller than the other case is consistent with the weaker bulk pinning in this configuration.

One of the alternative explanations on the hysteretic behavior is that in ZFC as the field increases diamagnetic flux exclusion will increase the field density inside GB so that I_c in ZFC is smaller [4]. This model was suggested to explain the hysteretic behavior in I_c of polycrystalline YBCO. Applying that to the present case, it requires that flux compression should result ~6 kG inside GB if 0.2 kG is applied field according to Figs 4, 6, and 7. Although we cannot rule out the flux focusing effect completely, but 30 times larger field inside GB is unreasonable. Further local field measurements using magneto optic or micro Hall array never showed such a large enhancement at the edge of any kinds of HTSC samples.

4. Conclusion

The critical currents I_c of the YBCO grain boundaries of 90-degree [100] symmetric tilt showed a hysteretic behavior depending on how the external magnetic fields were applied. We interpret this result as an evidence of the grain-boundary vortex pinning by nearby Abrikosov vortices in the grains.

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