Spread of Critical Currents in Thin-Film $YBa_2Cu_3O_{7-x}$ Bicrystal Junctions and Faceting of Grain Boundary

Pavel Shadrin, C. L. Jia, and Yuri Divin

***Abstract*—The statistical distributions of critical currents in series arrays of $YBa_2Cu_3O_{7-x}$ grain-boundary junctions have been studied by Low-Temperature Laser Scanning Microscopy. A set of arrays has been fabricated on (110) $NdGaO_3$ bicrystal substrates with misorientation angles from $2 \times 10°$ up to $2 \times 26°$ and patterned to the widths from 1.7 up to 5 micrometers. The critical current values of the individual junctions in the array have been obtained by focusing a laser beam on each junction and measuring the bias current at which the maximum laser-induced voltage response has appeared on the array. The measured critical current distributions have been demonstrated to be close to a log-normal Gauss function. A spread of this distribution has been found to increase with a bicrystal angle. $YBa_2Cu_3O_{7-x}$ grain-boundary topography has been studied by Atomic Force Microscopy. From results of these measurements we suppose that the maximum values of critical current density might be assigned to the symmetrical facets of grain boundary.**

***Index Terms*—Bicrystal boundary, critical current, Josephson junction, meandering.**

I. Introduction

THE key problem in the development of high temperature superconducting electronics is a reproducible fabrication of high-quality Josephson junctions. One of the promising direction in this field is a technology of bicrystal grain-boundary Josephson junctions (GBJJ). By this technique it is possible to produce high-performance junctions with characteristics close to that predicted by the resistively shunted junction (RSJ) model.

Unfortunately, due to a small coherence length in high-temperature superconductors (HTS), electrical properties of GBJJ are very sensitive to defects of any kind. At the same time, a real grain boundary (GB) in HTS film is a complicated 3D object. Due to an island-growth mechanism, the GB in the HTS film is meandering with respect to a bicrystal boundary in the substrate [1] and, as it was supposed, this meandering might result in significant local differences in transport properties along GB. A considerable spread of the critical currents of the 24° $YBa_2Cu_3O_{7-x}$ GBJJ has been found [2]. It is an open question how this spread is related to the meandering of a GB.

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In this report we present the results of our study of the spread of critical currents in the $YBa_2Cu_3O_{7-x}$ GBJJ with different misorientation angles by Laser Scanning Microscopy (LSM) and the results of our study of the topography of these GBJJ by Atomic Force Microscopy (AFM).

II. Experimental Details

We have used the sample layout, which is similar to the previously described one [3]. To study a statistical distribution of the critical current of GBJJ we have prepared a special set of samples. The thin-film $YBa_2Cu_3O_{7-x}$ meander-shaped microstrip is oriented along the grain boundary and crosses a GB many times, forming a GBJJ at each cross. Thus, we have got an array of 100 GBJJ of the same width connected in series. Bicrystal substrates of (110) $NdGaO_3$ with symmetrical misorientation angles $2 \times 10.5°$, $2 \times 12°$, $2 \times 14°$, $2 \times 18.4°$ and $2 \times 26.6°$ [4] were used for preparation of samples.

For all our samples we have used $YBa_2Cu_3O_{7-x}$ thin film deposited on the bicrystal substrate of $NdGaO_3$ by dc sputtering. All the width values in this report are the average width values in the array. A dispersion of the junction width in an array does not exceed ± 0.2 μm. We have measured several arrays consisting of GBJJ with different width from 2, 5 up to 15 μm.

Some GBJJ prepared within the same series as ones used for statistical measurements were examined with HREM to check the fine structure of GB. It was observed with atomic resolution that grain boundary contain no amorphous layer; the meandering amplitude is of order of 0.1–0.5 μm, and elementary facets of symmetrical and asymmetrical microstructures are of order 1–10 nm long.

It is difficult to determine a spread of the critical currents I_c within an array from the dependence of the differential resistance dV/dI from the transport current I through the array due to overlapping of the different peaks. The problem becomes more serious with increasing number of GBJJ in the array. Low-temperature scanning electron microscopy was used to solve this problem [2]. In this work we use a laser probing for the same task. For LSM measurements we have used an experimental set-up similar to the one described previously [3].

The high-T_c samples were mounted on the table of the laser-scanning microscope in a special optical cryostat. Radiation from an Ar-ion laser with a wavelength of 488 nm and a power level of up to 34 mW was focused by a long-distance objective on the surface of the superconducting sample into a spot of around 1.2 μm diameter. The voltage response Δ V of the sample was measured by standard lock-in technique

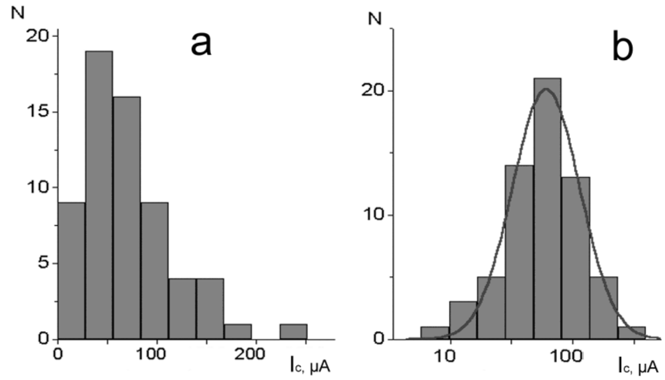

Fig. 1. The statistical distribution of the critical currents I_c in the array of $YBa_2Cu_3O_{7-x}$ GBJJ with the misorientation angle of $2 \times 14^\circ$ and the average width of 2.5 μm. For a linear current scale (a) this distribution looks nonsymmetrical, but for a logarithmic one (b) it fits the log-normal Gaussian curve.

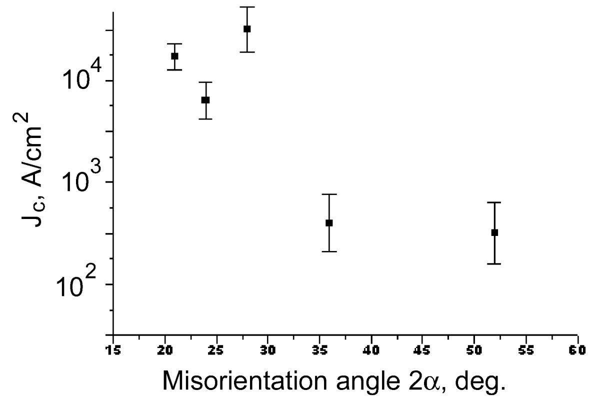

Fig. 2. The average values of critical current density for arrays of 5 μm-wide GBJJ with different misorientation angles at the temperature of 77 K. The spreads of the corresponding Gaussian distributions are shown by bars.

and recorded as a function of the beam position (x, y) on the sample.

Using the LSM electrical imaging technique, it is possible to measure the I_c-value of each junction in the array directly. The focused laser beam induces local heating of the junction from T_1 to T_2 and suppresses the value of critical current from I_{c1} to I_{c2} ($I_{c1} > I_{c2}$). The voltage response $\Delta V(I)$ is equal to the difference of two I–V curves—for T_1 and T_2—at constant bias current I. If the bias current is lower than I_{c2}, we have no response. When bias is equal to I_{c2}, the first response appears and increases with an increase of the bias current. The maximum response is observed when $I = I_{c1}$. With further increase of biasing, we can observe a slow decrease of the response. So, increasing the biasing and observing the amplitude of the laser-beam-induced voltage response for serial array of Josephson junctions, we can find the value of critical current for each of the junctions by recording the bias current that corresponds to the maximum response.

III. Results and Discussion

After measuring the sets of LSM voltage images at the various bias currents we can find a critical current for each of the junction in the array. Typical resulting statistical data are presented in Fig. 1. These data have been measured for an array of 2.5 μm-wide junctions on $2 \times 14^\circ$ substrate.

If the critical current distribution is plotted in a linear scale of the current currents [see Fig. 1(a)], some nonsymmetrical distribution appears. The situation is different if we use a logarithmic scale for the current axis [Fig. 1(b)]. The resulting distribution was found to be close to the log-normal Gaussian curve

$$P(I_c) = \frac{A}{\sigma\sqrt{\frac{\pi}{2}}} \exp\left(-\frac{\left(\lg\left(I_{c0}\right) - \lg\left(I_c\right)\right)^2}{\sigma^2}\right) \qquad (1)$$

where I_{c0} is an average critical current, σ is a spread of the Gaussian distribution, A is the area under the curve.

The origin of the observed log-normal distribution of the critical current density seems to come from the tunneling mechanism of the superconducting transport between two misoriented high-Tc films. The grain boundary between films with a defined misorientation angle can be considered as a tunnel barrier with some barrier thickness t. The critical current density is exponentially dependent from the barrier thickness with some characteristic thickness t_0.

In the real high-T_c bicrystal junction, due to the faceting of the grain boundary, the local misorientation angles are spread in some range. This might result in the spreading of the real barrier thicknesses t_i and the characteristic thicknesses t_{0i}, which in turn will result in the exponential spread of the local current densities.

The inhomogeneous current distributions with some percolation length l_c of several micrometers have been observed in real $YBa_2Cu_3O_{7-x}$ grain-boundary junctions [5]. Choosing the width of the junctions around the percolation length gives us a possibility to increase an amount of the junctions with RSJ-like behavior [6] but leads to the extended spread of the critical current densities.

Similar situation was observed for all samples under study with the bicrystal angles from $2 \times 10.5^\circ$ to $2 \times 26.6^\circ$ and the widths from 2.5 up to 15 μm. The parameters of measured statistical distributions for a set of arrays of 5-μm wide GBJJ with different bicrystal angles are shown in Figs. 2 and 3.

As one can see in Fig. 2, an average critical current density has a general tendency to decrease exponentially with an increase of the bicrystal angle for the angles $2 \times 10.5^\circ$, $2 \times 12^\circ$ and $2 \times 18.4^\circ$. There are two exclusions from this exponential fall-down, at the angles of $2 \times 14^\circ$ and $2 \times 26^\circ$. A higher value of the average critical current density for the angle $2 \times 14^\circ$, when compared with that of for $2 \times 10.5^\circ$ and $2 \times 12^\circ$ data, may be explained as a result of more well-ordered structure that arises at the coherent angle and a better quality of bicrystal boundary in the substrate. Practically the same values of the average current densities and the spreads for junctions with $2 \times 26.6^\circ$ and $2 \times 18.4^\circ$ might be due to their equal difference from the misorientation angle of 45°, where minimum current density for GBJJ might be expected, e.g., from the d-wave symmetry of the order parameter.

The spread of Gaussian distribution σ, shown in Fig. 3, seems to be more regular characteristic of GBJJ. For junctions of fixed width this parameter depend on the bicrystal angle only. Again, like for the average values of the critical current densities, the angular dependence of the spread σ might have a symmetrical shape with respect to 45°.

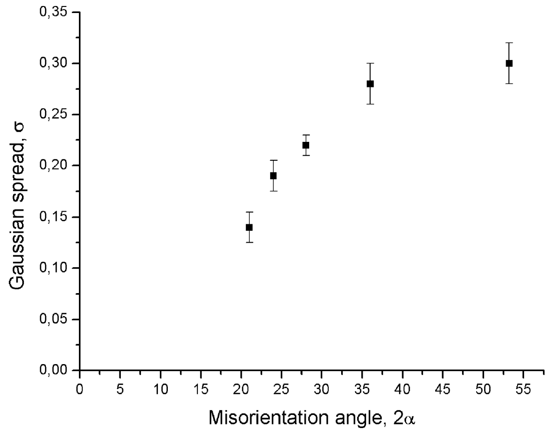

Fig. 3. The spread of the log-normal Gaussian distribution as a function of the misorientation angle of GBJJ for the same set of samples as in Fig. 2.

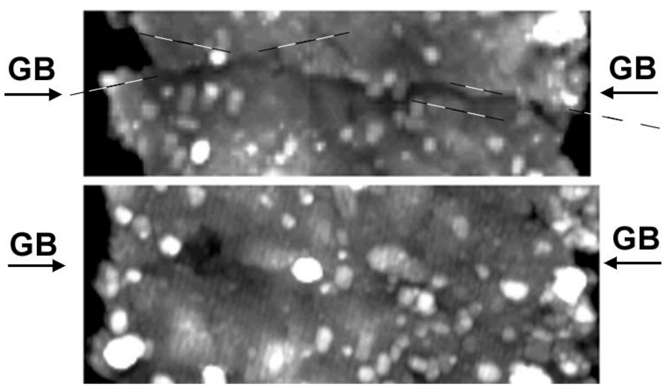

Fig. 4. The AFM topography images of 5 μm-wide GBJJ with the minimal (upper image) and maximal (lower image) values of the critical current in the array of 100 junctions. The bicrystal angle is $2 \times 12^\circ$.

The topography images of junctions with maximal and minimal values of the critical currents in the array of 100 GBJJ with the bicrystal angle $2 \times 12^\circ$ have been measured with AFM. In Fig. 4 one can see an image for junction with minimal current (above) and maximum current (below). The bicrystal boundary in the substrate is oriented horizontally for both images along the arrows. In Fig. 4(a) the grain boundary in the $YBa_2Cu_3O_{7-x}$ film can be seen as a wavy dark line near the center of the image. One can see that most of the GB for this sample has deviations from the orientation of bicrystal boundary in the substrate on the angles close to $\pm 12^\circ$. The orientation of such segments is indicated by dotted lines. It means, that most part of microfacets for this junction has nonsymmetrical orientation: the planes (100) or (010) for one side and the planes with higher indexes on the other side. This profile is very unusual for the c-axis bicrystal GBJJ. Typically, GBJJ profile is much more meandered and has a general orientation along the boundary in substrate. In addition, a presence of dark line on the upper AFM image means that there is some groove along the GB in the $YBa_2Cu_3O_{7-x}$ film.

In Fig. 4(b) one can see the junction with maximum critical current in the same array. It is not so easy to find the position of GB in this image, due to an absence of significant groove along the GB. Hardcopy limitation adds additional difficulties to image analysis. But, at careful consideration, it is possible to identify the profile of GB. In this case the profile of GB is close to a straight line and there is practically no angular deviation from the orientation of bicrystal boundary in the substrate. It means, that most part of the microfacets for this junction has a symmetrical orientation. This profile of GB is also very unusual for the c-axis bicrystal GBJJ.

The observed deviation of the GB profile from the typical one for these two junctions may be used for explanation of their electrical characteristics. One may assume, that the maximum critical current density corresponds to the symmetrical orientation of the microfacets. On the other hand, the microfacets terminated by the planes (100) or (010) from one side of the junction may correspond to the minimal critical current density.

Indeed, from geometrical point of view, the atomic period of $YBa_2Cu_3O_{7-x}$ for both sides is equal only for symmetrical orientation of GB. For nonsymmetrical orientation we will get some irrational ratio of atomic periods at both sides of GB. This fact means, that crystallographic boundary structure of symmetrical facets is more well-ordered and a tunnel barrier is this case might have a smaller thickness with the respect to that of for the asymmetric ones.

IV. Summary

The statistical distributions of critical current densities for the arrays of $YBa_2Cu_3O_{7-x}$ grain-boundary Josephson junctions with different misorientation angles and junction widths were measured with a help of laser local probing technique. The experimental data are in good agreement with the log-normal Gauss distribution.

The profiles of the grain boundaries for the junctions with maximum and minimum critical currents in the array were obtained from AFM topography images. It might be assumed from the comparison of these images, that maximum values of the critical current density in the $YBa_2Cu_3O_{7-x}$ bicrystal junctions correspond to the symmetrical facets of grain boundary.

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