Spread of Critical Currents in Thin-Film $YBa_2Cu_3O_{7-x}$ Bicrystal Junctions.

Pavel Shadrin and Yuri Divin

***Abstract*— A spread of the critical currents in a series array of up to 100 $YBa_2Cu_3O_{7-x}$ bicrystal junction junctions has been studied by Laser Scanning Microscopy. The values of the critical current I_c of individual junctions in the array have been obtained by focusing a laser beam on each junction and measuring the current at which the maximum laser-induced voltage response ΔV on the array has appeared. The distribution of critical currents in logarithmic scale was close to a Gaussian one. The I_c-spread has been found to increase with the increase of misorientation angle of bicrystal substrate and the decrease of the width of the junctions in the array.**

***Index Terms*—Josephson junctions, grain boundary, laser-scanning microscopy, local probing.**

I. Introduction

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

Unfortunately, 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 and, as it was supposed, this meandering might result in significant local differences in transport properties along GB [1]. 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.

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).

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II. Experimental Details

A. AFM Study of Bicrystal Substrates and Junctions

We have examined the quality of $SrTiO_3$ and $NdGaO_3$ bicrystal substrates used for fabrication of HTS GBJJ by AFM and optical microscopy. It was found, that any of these substrates suffer from the defects of different nature. After careful selection and comparison of the substrates the group of the has been chosen with minimum set of defects, consisting from the groove, that arises along the substrate GB during chemo-mechanical polishing, and small voids, due to inclusions of gas or dirt into the GB. A quality of these selected bicrystals can be characterized by 3 parameters: a depth of the groove along the GB, an average size and a linear density of the voids.

Some of the available (110) $NdGaO_3$ bicrystal substrates with misorientation angles 2x10°, 2x12°, 2x14° and 2x18° [3] got relatively small density of the voids, and these substrates have been taken for GBJJ preparation. The AFM topography image of the one of the best 2x14° (110) $NdGaO_3$ bicrystal substrates is shown in Fig.1. The total height modulation in the 2.4x2.4 μm^2 area near the GB of this bicrystal substrate was only 3 nm. The GB in the image is oriented nearly

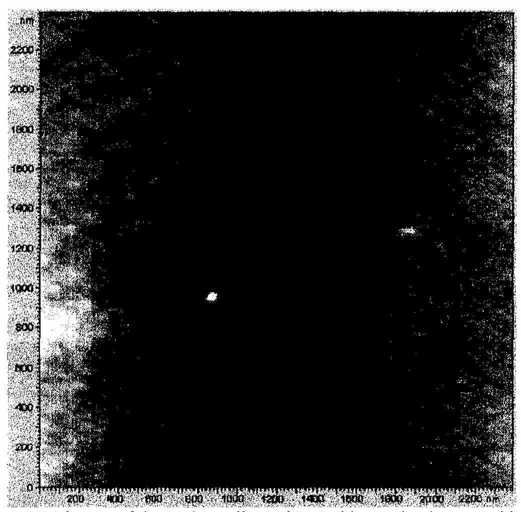

Fig. 1. AFM image of the high-quality $NdGaO_3$ bicrystal substrate with angle 2x14°. Topography is shown by a grayscale with the amplitude from black to white equals to 3 nm. One can see the grain boundary as a dark line - a groove of 40 nm width and 0.7 nm depth. Black spot near the center is a void of 200nm diameter and 1,5 nm depth. The linear density of such voids for grain boundary on this substrate is less then 1 for 100 μm. On the left bank of the bicrystal one can see terraces of $NdGaO_3$ surface with the height of 0,5 nm and the period of 100 nm.

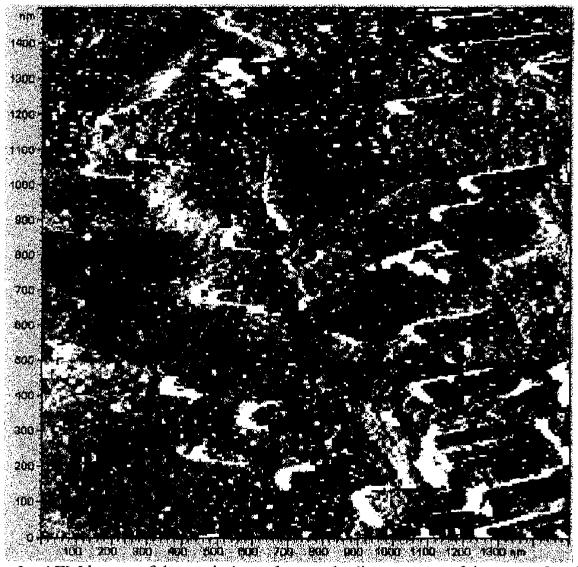

Fig. 2. AFM image of the grain boundary and adjacent area of the $YBa_2Cu_3O_{7-x}$ film, sputtered on the substrate, shown in Fig.1. The grain boundary oriented vertically near the center of the image. One should pay attention to a step-flow growth of YBCO film and small amplitude of meandering - of order of 100 nm.

vertically and it is seen in the image due to a shallow grove along it. A groove of 40 nm width has a depth as small as 0,7 nm. A black spot near the center is the only void observed on more than 100 μm GB length. It has around 200 nm diameter and 1,5 nm depth. On the left bank of the bicrystal one can see terraces of $NdGaO_3$ surface with height of 0,5 nm and the period of 100 nm, which are due to a small miscut (0.3°) of the surface of the substrate. The presence of these terraces demonstrates high quality of the surface of the $NdGaO_3$ substrates used for this study.

The image in Fig.2 shows an AFM signals, proportional to the x-axis derivative of the topography of $YBa_2Cu_3O_{7-x}$ film, that was dc spattered on this substrate (sample YD006141). One can see some brick-like precipitates with different orientation on opposite sides of GB. The GB itself is oriented nearly vertically and located near the center of the image. The film growth demonstrates a step-flow character with clearly observed terraces. The meandering of grain boundary has amplitude of order of 100 nm.

B. LSM set-up

To study a statistical distribution of the critical current of GBJJ, we have prepared special samples in the form of serial array of thin film $YBa_2Cu_3O_{7-x}$ GBJJ. Meander-shaped microstrips along the grain boundary crosses a GB many times, forming a GBJJ at each cross. This structure schematically shown in Fig. 3. Thus, we have got samples consisting from a large number of GBJJ of the same width connected in series.

The exact spread of the critical current values within an array is difficult to determine from the dV/dI versus I curves due to overlay of the different peaks. This problem becomes more serious with increasing number of GBJJ in 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.

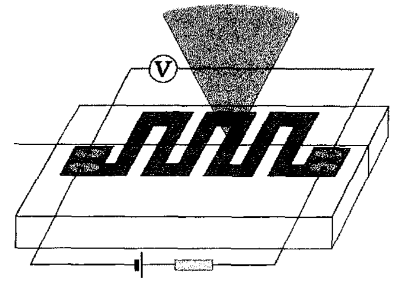

Fig. 3. Schematic view of the principle of measurements. The meander shaped line of width D along the bicrystal grain boundary forms a series array of GBJJ. Voltage response ΔV(x,y) induced by focused laser beam irradiation is measured at constant bias current using standard lock-in technique. Sets of these "snake"-like structures with the width 1.7 - 15 μm on bicrystal substrates with different misorientation angles were prepared.

Schematic view of the principle of measurements is shown in Fig. 3. Laser beam, focused on the surface of the film into a spot of submicrometer size, induces its local heating and changes of the total voltage on the sample. When the position (x,y) of focused beam is scanned across the sample, the corresponding two-dimensional distribution ΔV(x,y) of voltage response is measured and this distribution gives an information about local electrical properties of the sample.

We have used experimental set-up similar to the one described previously [4], but with improved optical and electronic parts. The high-T_c samples were mounted on the table of the laser-scanning microscope in the special continuous-flow 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 ΔV of the sample was amplified and recorded as a function of the beam position (x,y) on the sample. Electrical images ΔV(x,y) consisting of 512 x 512 points with 8 bit signal resolution and spatial resolution of order of 1.5 μm were obtained for all $Y_1Ba_2Cu_3O_{7-x}$ samples under study. The voltage response amplitude is digitized into 256 gray colors scale.

For all our samples we have used $YBa_2Cu_3O_{7-x}$ thin film deposited on the bicrystal substrate of $NdGaO_3$. Width value, pointed everywhere in this report are the average width of the set of junctions, and a dispersion of width for all samples in the set does not exceed ±0.3 μm. We have measured several "snakes" consisting of GBJJ with different width from 2,5 up to 15 μm. In addition, series of samples on the substrates with different misorientation angles (from $2x10^0$ to $2x14^0$) were prepared using exactly the same dc spattering deposition technology. Each of them consists of snakes of different widths – from 1,7 up to 5 μm.

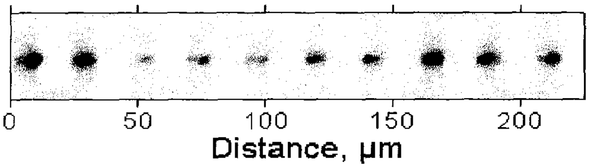

Fig. 4. Response of part of a serial array of 10 μm junctions. T=85 K, I=800 μA. inhomogenuity of the current distribution along the GB is clearly seen for most of junctions.

As an example, one of such images is shown in Fig.4. This is a typical image of low-temperature electrical response for a part of a snake with junctions width 10 μm. The temperature is 85 K, bias current is 800 μA. The snake itself is oriented horizontally; a grain boundary crosses them near the center of the image. Amplitude of the laser-beam-induced voltage response is encoded by gray scale. One can see that the maximum response is located on the grain boundary. Because we are rather close to T_C, some weak voltage response from the $Y_1Ba_2Cu_3O_{7-x}$ film can be observed. It is easy to see, that for most of GBJJ distribution of voltage response (that is proportion to the local current density) along the GB is inhomogeneous. For some junction it is detected, that response is concentrated to one small spot, some have 2 spots.

So, one can say, that a current do not flow throw GB homogeneously, but concentrated at some microshorts with smallest local resistance. If there are 2 such microshorts on one junction, it will works as a SQUID. Due to this fact, for further consideration we have choose arrays of junctions with smaller width of 5 and 2.5 μm. Because Josephson penetration depth λ_J for such junctions at temperatures 77 K and above is bigger than the width, we can neglect magnetic effects.

Using of such LSM electrical images it is possible to directly measure I_C of each junction. It is easy to see that the value of the voltage response is depended upon the bias current I_b and the temperature T. Let us consider a small Josephson junction. Heating by laser beam increases the temperature from T_1 to T_2. The corresponding values of critical current are I_{c1} and I_{c2} ($I_{c1}>I_{c2}$). Our voltage response is equal to the difference at constant current of two I-V curves– for T_1 and T_2. 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 the increasing bias current. The maximum response is observed at $I_b=I_{c1}$. With further increasing of biasing, we can observe a slow decrease of the response. So, changing the biasing and observing the amplitude of the laser-beam-induced voltage response for serial array of Josephson junctions, we can for each of them find the value of critical current, that is the bias current that corresponds to the maximum response.

III. Results and Discussion

After measuring the sets of response distribution images (like in Fig. 4) at different bias current we can combine them to the total pictures (Fig. 5). Here, an array of 2.5 μm GBJJ from the sample YD006141 was measured at 77 K with bias

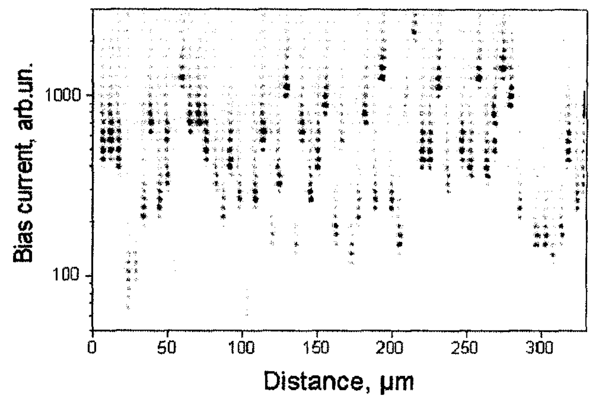

Fig. 5. Combined image for series of electrical images like in Fig. 4 with different bias current. Array of 2.5 μm GBJJ was measured at 77 K with bias current increased in 60 times in logarithmic scale.

current increased in 60 times in logarithmic scale. The array was fabricated on $2x14^0$ $NdGaO_3$ bicrystal substrate, shown. in Fig.1. The scans, recorded at different bias current values are displaced vertically. More dark regions corresponds to larger voltage signal For each of 63 junction under study, looking on the column from down side to upper, one can see no response at bias current below critical, then fast increasing, maximum at critical current and slow decreasing. So, with LSM we were able to find a critical current for each of junction in the snake.

Resulting statistical data, which were obtained from these combined pictures, are presented in Fig.6. If the statistical chart of critical current distribution is plotted in linear scale of current (see Fig.6a), some non-symmetrical distribution appears. The situation is different, if we use a logarithm scale for the current axis (Fig.6b). The resulting distribution is close to the classical Gauss curve. The same situation was observed for all samples under study – for all angles and width from 2.5 up to 15 μm We have measured 3 bicrystal snake samples, prepared with exactly the same technological process, but on substrates with different misorientation angles. Resulting parameters of the statistical distribution for 5 μm snakes are shown in the Table I.

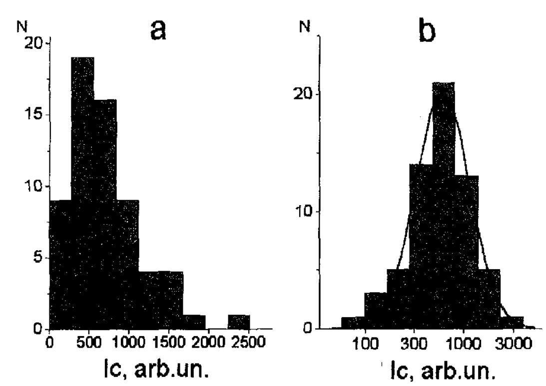

Fig. 6. Statistical distribution of critical currents, obtained from the Fig.5. For a linear current scale (a) this distribution looks non-symmetrical, but for a logarithmic one it fits the Gaussian curve.

TABLE I

SPREAD OF THE I_C DISTRIBUTION FOR ARRAY OF 5μM-WIDE GBJJ.

	YD006142	YD006262	YD006141
bicrystal angle	$2x10,5^0$	$2x12^0$	$2x14^0$
T_c-T, K	4,5	5	4
Center of peak I_C, μA	30	18	37
Spread	29%	37%	44%

An observed results demonstrate that an increasing of the spread is proportional to the increasing of the misorientation angle of the substrate, in spite of a fact that $2x14^0$ sample has higher quality of bicrystal boundary and lower amplitude of meandering.

For a comparison, we have used another sample that was prepared on the substrate from the same series, but with other film preparation procedure (sample YD002222). It was founded by AFM examination, that in this case film has growth islands, and amplitude of meandering is larger, but of the same order. After measuring statistical distribution of critical currents, dispersions of statistical distribution are calculated (see Table II).

It is obvious, that for junctions of larger width the spread of critical current should be smaller, due to an averaging. Not surprising, that for the sample YD006141 with more homogeneous film structure the spread is essentially lower for 2.5 and nearly the same for 5 μm junction arrays. For a sample YD803311 on $2x14^0$ substrate of lower quality for 10 μm junction array dispersion has a value 47%, that close to the data for high-quality substrate, demonstrated above. One can make a conclusion, that for a junction wide enough for averaging of internal junctions inhomogeneities, the spread of distribution depends mostly on the substrate bicrystal angle and only a weak dependence on substrate GB characteristics can be observed.

So, comparing data of Table I and Table II, one can see, that homogeneity of the film structure effects the width of the Gaussian distribution for a small junction width (2.5 μm) only. For more wide junctions (5 μm and more) width of obtained Gaussian distribution depends mostly on the misorientation angle of the substrate.

TABLE II

SPREAD OF THE I_C DISTRIBUTION FOR SAMPLES ON SIMILAR $2x14^0$ SUBSTRATES.

	YD006141	YD002222
2,5 μm	55%	71%
5μm	42%	44%

IV. SUMMARY

Statistical distribution of critical current for high-quality GBJJ with different misorientation angle and junction width were measured with laser local probing technique.

It was demonstrated, that these distributions fit to Gaussian curve with logarithmic scale of bias current axis. The I_C spread was found to be increasing with the misorientation angle of the substrate from 29 % for $2x10,5°$ to 44% for $2x14°$ for junctions of 5 μm width. and does not depends on the growth mechanism of the film.

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