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Effect of annealing on the critical current of superconducting YBCO bridges crossing the bicrystalline boundary

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The paper presents the results of a study of the effect of annealing on the critical current of YBCO Josephson junctions obtained by the method of a preliminary topology mask on a bicrystalline substrate. A strong, more than two-fold increase in the critical current of the Josephson junction was detected. This opens up opportunities for managing the current-voltage characteristic of Josephson junctions.

Keywords: Josephson junctions, annealing, YBCO.

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1. Introduction

The non-stationary Josephson effect in high-temperature superconductors has found its practical use in the detection of terahertz (THz) radiation [1]; spectral analysis of absorption and reflection of various substances and electromagnetic structures [2,3]. If the Josephson junction has high electrophysical characteristics and is well described by the resistive-shunted junction model, the procedure for reconstructing the transmission or reflection spectrum of THz radiation can be simple and unequivocal. In addition, to achieve high sensitivity of broadband detectors in a given frequency range, it is necessary to select the optimal parameters for the critical current density (J_c) and normal resistance (R_n) of Josephson junctions [4,5].

For YBCO Josephson junctions on a [100]-tilt bicrystalline substrate, it was shown that low-temperature annealing in atomic oxygen reproducibly increases the critical current and reduces the deviations of the VACs from model predictions [6]. In the case of Josephson junctions with misorientation in the [001] plane, due to the non-homogeneous barrier, the available data were not as reproducible and stable. It was shown in the work [7] that the values of the characteristic voltage remain the same upon annealing of bicrystal junctions. On the other hand, in the work [8] the decrease in the characteristic voltage by 30% and the threefold decrease in the resistance in the normal state after annealing were found for similar transitions.

In this work, the possibility of controlling the value J_c of Josephson junctions fabricated on $Zr_{1-x}Y_xO_2$ (YSZ i.e. phianite) bicrystalline substrate with symmetrical boundary and with misorientation angle 24° in the [001] plane, was studied.

2. Fabrication features of the structure and measurement procedure

The YBCO bridges under study were fabricated as follows. Initially, the sublayer of epitaxial cerium dioxide ($epiCeO_2$) was deposited on the YSZ bicrystal substrate by laser deposition. Then, three rows of bridges were formed on the substrate using the preliminary topology mask (TM) method, which is described in detail in our previous works (see, for example, [9]). Bridge width: 5; 7; 10 and 50 μm. The first and third rows were located on single-crystal parts of the substrate (on so-called „brims"). The bridges of the middle (second) row crossed the bicrystalline boundary and thus included a region of weak coupling, with reduced values of J_c and critical temperature (T_c). The YBCO film was deposited by magnetron sputtering of stoichiometric target [10] and took place in two stages. After the first deposition, the film thickness was 100 nm, after the second one was 200 nm. It should be specially noted here that the TM method makes it possible, preliminary topology to study the dependence of the electrophysical parameters of bridges with fixed lateral dimensions on the thickness of the YBCO film, since the topological pattern of the structure is determined during the formation of the TM before the first deposition of YBCO, and during subsequent cycles of deposition does not change [11]. Silver ohmic bridge contacts were deposited through a mask by thermal evaporation.

After each deposition of YBCO, the resulting structure was annealed at temperature of $T = 500°C$ and oxygen pressure of 27 Pa for 5 min. After that, oxygen was admitted into the annealing chamber to atmospheric pressure, and the structure cooled down to room temperature.

Measurements of the J_c of the bridges at temperature of $T = 77$ K were carried out both immediately after YBCO

Table 1. Characteristics of bridges crossing a bicrystal boundary

Sequence of operations	Critical current, mA / Critical current density, 10^5 A/cm^2		
	Bridge 7 μm	Bridge 10 μm	Bridge 50 μm
1. Deposition of YBCO (Thickness 100 nm)	0.15/0.21	0.18/0.18	2.25/0.43
2. Annealing	0.75/1.07	1.0/1.0	3.0/0.59
3. Deposition of YBCO (Thickness 200 nm)	1.0/0.71	1.5/0.75	5.3/0.51
4. Annealing	1.75/1.25	2.5/1.25	7.3/0.7
5. „Aging“	0.49/0.35	1.0/0.45	3.5/0.34

deposition and after annealings. In this part of the experiment, the time interval between measurements was no more than two days. Since the important characteristic of YBCO structures is the temporal stability of their electrophysical parameters, the final measurements were carried out after storage of the sample for 200 days in Petri dish („aging“).

The bridges were tested in the dipstick placed in transport Dewar vessel with liquid nitrogen. Since the dipstick was not shielded from the magnetic field, the measured critical current of the bridge crossing the bicrystal boundary varied strongly depending on its orientation relative to the Earth's magnetic field. When the dipstick was moved in the Dewar vessel, a family of VACs was obtained with different values of the critical current. As the value of critical current of the bridge, its maximum value, for each family of VACs, was taken to be.

In addition, for a more complete characterization of the obtained sample, its surface morphology was studied by scanning electron microscopy. Electron microscope CarlZeiss EVO 10 was used.

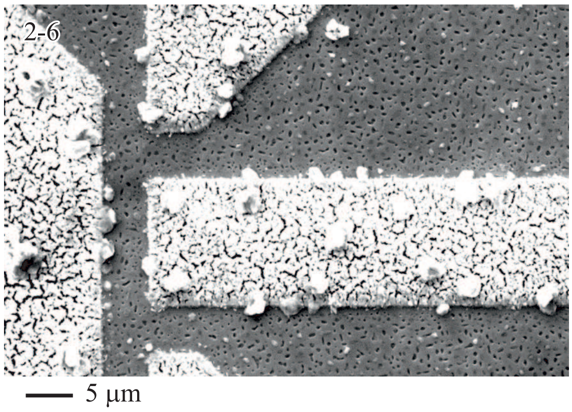

Photo of a 5 μm wide YBCO bridge after the second deposition cycle (film thickness of 200 nm) obtained by the TM method. The superconductor film grows on the epiCeO2/YSZ substrate in the windows of the topology mask, i.e. dark region. Light areas is insulator formed during the deposition of YBCO on a mask of amorphous cerium dioxide [9]. Magnification 15 500. The silver contacts are outside the scanning area.

3. Discussion of results

The figure shows the secondary electron images of one of the bridges under study. The YBCO film has considerable surface relief, it contains precipitates of CuO, i.e. light particles of irregular shape with sizes of $\sim 0.5\,\mu$m on the film surface, and Y_2O_3, which are formed on the surface of the substrate and are visible in the photo as pores, since the YBCO film does not grow over such precipitates [12]. As has been well known for a long time, the presence of such precipitates is characteristic of YBCO films with high electrophysical characteristics [13]. Indeed, the obtained sample has very high values of T_c and J_c (see below). In particular, the critical temperature of the YBCO film on „brims“ after both deposition cycles is $T_c \sim 88.5$ K. After annealing, it increased to $T_c \sim 89.5$ K. In this case, the ratio of the resistance of the bridges at temperature of 300 K to the resistance at temperature of 100 K is $\gamma \sim 3$.

Table 1 presents values of the critical current and the critical current density for three bridges of different widths crossing the bicrystal boundary (Josephson junctions). It can be seen that the increase in the critical current due to annealing is very significant. It can be five times or more for bridges 7 and 10 μm after the first deposition of YBCO and is at least 25% for the bridge 50 μm after the second deposition. Further, as can be seen from Table 1, for the 50 μm bridge, the effect of annealing is due to annealing less significant than for narrower bridges. Note that the obtained values of the critical current $1.25 \cdot 10^5$ A/cm^2 for bridges 7 and 10 μm wide are comparable with the best worldwide results for Josephson junctions on bicrystal substrates with such a misorientation [14]. The degradation of the critical current of bridges as a result of „aging“, i.e. prolonged „annealing“ at room temperature, is also most noticeable for narrow width bridges a decrease by a factor of 3.6 for the bridge 7 μm, and by 4 times for the bridge 10 μm, and 2.1 times for the bridge 50 μm.

Table 2. Characteristics of bridges outside the bicrystal boundary

Sequence of operations	Critical current, mA / Critical current density, 10^6 A/cm^2	
	Bridge 5 μm	Bridge 7 μm
1. Deposition of YBCO (Thickness 100 nm)	24/4.8	34/4.9
2. Annealing	27/5.4	40/5.7
3. Deposition of YBCO (Thickness 200 nm)	47/4.7	66/4.7
4. Annealing	48/4.8	69/4.9
5. „Aging“	–	65/4.6

For comparison, Table 2 presents the values of the critical current of two control bridges located outside the bicrystal boundary. It can be seen that the effect of annealing on these bridges is significantly less, i.e. maximum 16% for a bridge 7 μm wide after the first deposition of YBCO. In addition, it can be seen that the film is quite stable outside the weak coupling, as far as the drop in the critical current density of the 7 μm wide bridge over the storage time was $\sim 6\%$.

The maximum values of the critical current density for the bridges crossing the boundary were obtained after the second annealing (YBCO film thickness 200 nm), and for the bridges located on the „brims“ — after the first annealing (YBCO film thickness 100 nm). It should also be noted that the absolute values of the critical current density of bridges on „brims“ — $\sim 5 \cdot 10^6$ A/cm^2 at $T = 77$ K are high, i.e. the structure under study was obtained in a technological mode that provides the optimal electrophysical characteristics of the YBCO film outside the weak link region.

Thus, from the results presented in Tables 1 and 2, we can conclude that the dynamics of the change in the critical current density as a result $T = 500^\circ$C annealing and during storage is radically different for bridges crossing the bicrystalline boundary, and for bridges located on „brims“ for ones located- outside the bicrystalline boundary. It can be assumed that the observed dynamics is determined by the high mobility of oxygen in the YBCO film near the bicrystalline boundary, i.e. in the region with broken crystal structure. Moreover, the observed dependence of the degree of influence of annealing on the width of the bridge indicates that oxygen diffusion occurs both perpendicular to the film surface and along the boundary. The crystal structure of the near-boundary region apparently improves with increasing film thickness from 100 to 200 nm. This may be due to a noticeable decrease after the second cycle of YBCO deposition in the degree of influence of annealing on the critical current of the bridges crossing the bicrystal boundary, as well as the maximum values of the critical current density for these bridges.

4. Conclusion

Strong effect of short-term (5 min) annealing at temperature of $T = 500^\circ$C and oxygen pressure of 27 Pa (with subsequent increase to atmospheric pressure) on the YBCO parameters of bridges crossing the bicrystal boundary is found. The critical current of such Josephson junction can increase several times as a result of annealing. For narrower (7 and 10 μm) bridges, the effect of such annealing is more significant than for wide (50 μm) ones. Annealing in the described mode is accompanied by intense diffusion of oxygen along the weak link of the superconducting „brims“ and changes the boundary region without significantly affecting the „brims“ themselves, which retain high superconducting characteristics. Therefore, such annealing leads to a significant increase in the critical current of Josephson junctions, which can be used for controlled selection of the parameters of Josephson junctions.

At the same time, the high mobility of oxygen in the weak link region also leads to faster degradation of the critical current of the bridges crossing the bicrystalline boundary as compared to the bridges outside the boundary. As the thickness of the YBCO film increases, the sensitivity of the critical current to annealing decreases both for the bridges on the „brims“, and especially for bridges with weak link. Apparently, this is due to a decrease in the width of the region with broken crystal structure near the bicrystalline boundary as the film grows.

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Conflict of interest

The authors declare that they have no conflict of interest.

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