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Influence of the contact resistance of the YBCO/Au interface on the transport and microwave properties of arrays of high-temperature Josephson junctions

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The influence of the contact resistance of the interface of the YBCO/Au structure on the transport and microwave properties of arrays of high-temperature bicrystal Josephson junctions embedded in a coplanar transmission line has been studied. The current-voltage characteristics of Josephson structures fabricated using various technologies are studied: *in situ* and *ex situ* with annealing in an oxygen atmosphere. The results obtained can be used to create a quantum ac voltage generator based on high-temperature Josephson junctions.

Keywords: high-temperature superconductors, Josephson junctions, microwave, contact resistance.

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1. Introduction

The most accurate and reproducible DC voltage standards are based on the superconducting Josephson junctions [1,2]. The modern technology of manufacturing the Josephson contacts from niobium allows to synchronize the external signal of a chain of several tens of thousands of contacts [2]. To implement the AC voltage standard by Benz and Hamilton in 1996, a arbitrary form signal synthesizer based on niobium Josephson contacts was proposed [3,4]. In the synthesizer the chain of Josephson contacts is controlled by current pulses, which allow to generate a variable signal of arbitrary form with quantum accuracy [5–7]. At present, quantum signal synthesizers based on low-temperature superconductors are used in the Jones thermometry, AC voltage standards, temperature converter calibration, etc., [6]. At the same time, the arrays of the bicrystalline Josephson junction from high-temperature superconductors (HTS) are attractive for building a quantum signal synthesizer [8.9]. This is because the operating temperatures for these chips can be achieved with low-power compact cryocoolers. To reduce the dispersion of the characteristic voltages of the bicrystalline Josephson transitions in the chain, it is necessary to bypass them with a layer of normal metal. This allows more Josephon contacts to be synchronized with the external microwave signal. However, to create chips based on high-temperature superconductors a low contact resistance of $\rho_c \approx 10^{-6}–10^{-8}\,\Omega \cdot \mathrm{cm}^2$ is required on the interface between the superconductor and metal [10–15] for the creation of microcircuits based on high-temperature superconductors. This is necessary both for small microwave losses in the transmission line and for the high-quality Josephson contacts based on high temperature superconductors.

This work investigates the effect of the junction resistance of the YBCO(yttrium barium copper oxide)—Au structure interface on the transport properties of bicrystalline junction embedded in the coplanar transmission line. Numerical simulations were carried out to create a chip photo template. The CVC was further investigated without irradiation and in the presence of microwave exposures of the Josephson structures made with the help of various technologies. The developed chip can be used in the future for the construction of a quantum signal synthesizer based on the Josephson contacts from high-temperature superconductors.

2. Numerical simulation

Numerical simulation of the chip was carried out on the basis of the array of bicrystalline Josephson contacts from high-temperature superconductors built into the coplanar transmission line (Fig. 1). The calculations were performed using the Sonnet program. The radiation frequency of the chip varied in the range of 0 to 20 GHz. A fianite (YSZ) with permittivity of 26 and a thickness of $500\,\mu$m was chosen as the substrate material.

The chain of Josephson contacts was modeled by a meander that crosses the bicrystalline boundary (Fig. 1). The width of the meander varied from 10 to $16\,\mu$m. The dimensions of the coplanar transmission line were chosen so that its wave resistance was 50 Ω. The load impedance of the coplanar transmission line was also 50 Ω. To reduce the penetration of microwave power into the measuring path, it was proposed to use a filter in the form of high resistance electrodes electrodes.

Fig. 2 shows the pass ratios of S_{12}, S_{13} and the reflectance S_{11} on the chip depending on the frequency of the microwave signal. The resistance of the filter changed during the modeling process from 6 to 1000 Ω. It has been shown that when 1000 Ω resistance filters are used, there is good S_{12} transmission through the Josephson contact chain and little S_{13} transmission factor into the port *3*. In this case, the microwave power in the chain of Josephson contacts is distributed evenly, which allows to synchronize more contacts and thus increase the value of the output voltage.

Fig. 3 shows the current distribution in the Josephson structure. As you can see from the figure, the current is concentrated near the edges of the central and lateral electrodes of the coplanar line. Therefore, to increase the current at the point of formation of the Josephson contacts, the width of the strip of the central electrode of the coplanar line was reduced to 20 μm.

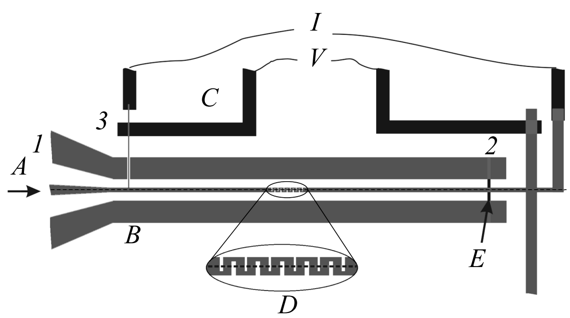

Figure 1. Photo Template for the Josephson Contact Array of High Temperature Superconductors Embedded in Coplanar Transmission Line (*A* — microwave power; *B* – -coplanar transmission line from YBCO—Au, *C* — electrodes from NbN for current transmission and voltage measurement, *D* — meander, *E* — load). The dotted line shows the bicrystalline boundary. The numbers are the port numbers in the simulation.

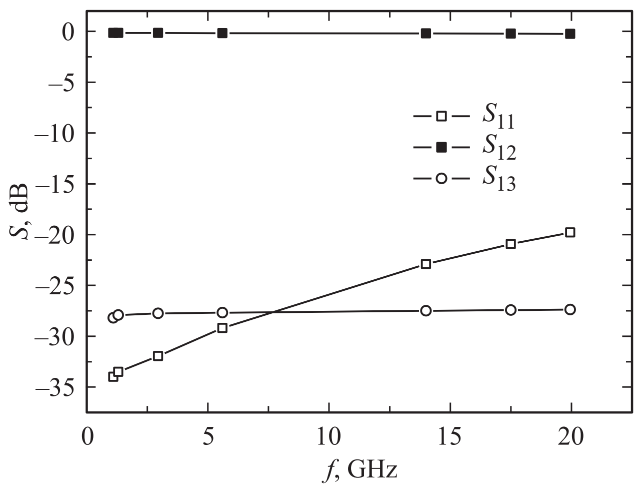

Figure 2. The dependence of the transmission and reflection coefficients S_{12}, S_{13} and the reflectance factor S_{11} on the chip's radiation rate f. Electrode resistance 1000 Ω.

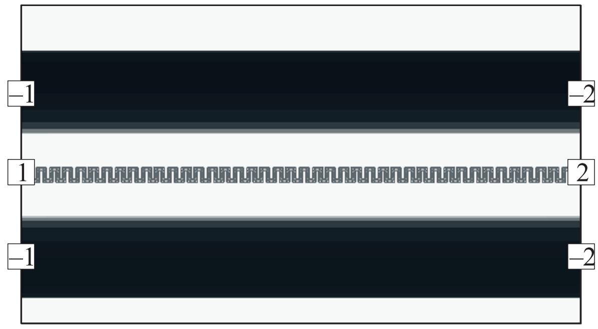

Figure 3. Current distribution in the Josephson contacts embedded in the coplanar transmission line.

3. Samples

On the basis of calculations carried out photo templates of the chip of 10 Josephson contacts with the width of meander 10 μm (Fig. 1) were made. The c-oriented HTS YBCO 250−300 nm films were grown to produce the chips, which were then coated with a thin 30 nm thick gold layer. The first two-layer structure was made on substrate Al_2O_3 with a sublayer of epitaxial cerium oxide in IPM RAS *ex situ* followed by annealing at a temperature of 500°C in the oxygen atmosphere. The second structure on the bicrystalline substrate YSZ was grown at the firm Theva (Germany). The gold film in this case was applied *in situ* at a temperature of 100°C in one vacuum cycle with the YBCO film. The creation of Josephson contact arrays from YBCO—Au two-layer structures was done using standard photolithography and argon ion etching. The explosive lithography was then used to produce high-resistance electrodes and a load of NbN nitride niobium with a thickness of 350 nm.

4. Microwave probe for irradiation of bicrystalline contacts

The microwave probe is used to irradiate bicrystalline contacts. The hermetic stainless steel casing of the probe has a microwave input, which receives a signal from the Agilent 8257D generator in the 9−20 GHz frequency range. The microwave signal then propagates inside the probe via a coaxial cable and enters via a coaxial coplanar transfer the holder and chip lines. Electrical contact between these lines was made by ultrasonic welding. The holder board is made of Arlon foil material with dielectric permeability $\varepsilon = 10$. The waveform resistance of the holder's coplanar line is calculated at 50 Ω. There are several pairs of copper wires on the chip holder for feeding the displacement currents and measuring the CVC of the chip. Measurements take place in the Dewar vessel in a temperature range of 65 to 90 K. On the outside, the probe is covered by a permalloy screen to protect the chip from external magnetic fields. Before measurements are made, helium is applied inside the casing, which provides effective cooling of the chip when the probe is submerged in liquid nitrogen, and also protects the sample from moisture during heating.

5. Discussion of experimental results

First the transport properties at a temperature of $T = 77$ K of the chip manufactured *ex situ* were studied. The current was fed to the external electrodes, and the voltage was removed from the internal electrodes (Fig. 1). In this case in the field of small currents there is a linear section of CVC with resistance of about $50\,\mu\Omega$, which in our opinion is connected with the flowing current in a layer of gold in a narrow HTS electrode of $4\,\mu$m width. The contact between the gold and the superconductor in this case occurs in the direction of the c axis, as the c- YBCO oriented films were used to manufacture the superconducting structure. Using the blending resistance formula R_s [12.15]:

$$R_s(d) = \frac{1}{w_0}\sqrt{\frac{\rho_c\rho_m}{d_m}}\exp\left(-\frac{d}{\sqrt{\rho_c d_m/\rho_m}}\right), \qquad (1)$$

where w_0 — width of the HTS strip, ρ_m – -resistivity of gold, d_m -thickness of gold, d — distance between the current and voltage electrodes, and considering that $\rho_m \approx 10^{-6}\,\Omega\cdot$cm, it is possible to estimate the value of the contact resistance $\rho_c \approx 1.4\cdot 10^{-7}\,\Omega\cdot\text{cm}^2$ at temperature 77 K in the case of samples *ex situ*. This value of ρ_c is well consistent with the Au—YBCO contact resistance data obtained in work [16]. The current flow length is $L = (\rho_c d_m/\rho_m)^{1/2}$ in this case is approximately $7\,\mu$m. Thus, for a sample manufactured *ex situ*, there is no segment on a CVC with a superconducting current due to current flow in a narrow HTS electrode.

Then the transport properties of the chip made *in situ* on the bicrystalline substrate at a temperature of $T = 81$ K without irradiation and during microwave radiation were studied. Fig. 4 shows CVC of a 10 Josephson contacts chain made on bicrystalline substrate without microwave radiation at a temperature of 81 K. In this case a superconducting current is observed on the CVC. The critical current value of the Josephson contact is $I_c = 0.4$ mA, and the normal resistance value of one contact is $R_n = 0.1\,\Omega$. Since the normal resistance value is mainly determined by the shunt resistance, using the formula for R_n [12]:

$$R_n = \frac{1}{w}\sqrt{\frac{\rho_c\rho_m}{d_m}}, \qquad (2)$$

where w — meander width, you can determine the value of the contact resistance. Considering that the width of the contact is $w = 10\,\mu$m, we get that for this structure $\rho_c \approx 3\cdot 10^{-8}\,\Omega\cdot\text{cm}^2$ at 81 K. The value of the current flow length in this case is $3\,\mu$m.

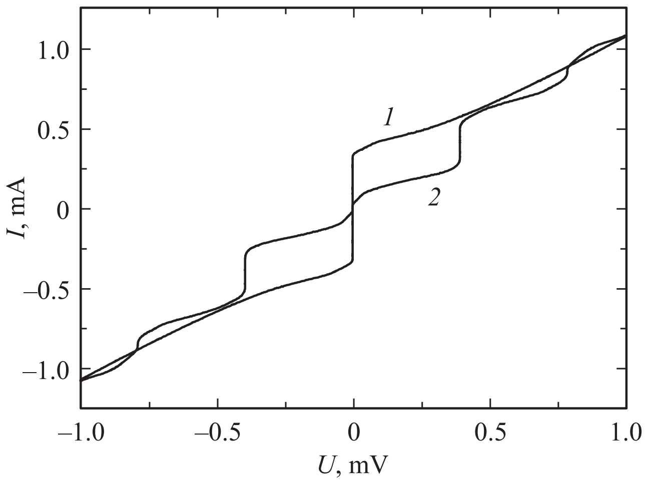

Figure 4. CVC chain of 10 Josephson contacts made on bicrystalline substrate YSZ without irradiation (curve *1*) and at irradiation (curve *2*) by a signal at a frequency of $f = 19.091$ Hz at a temperature of 81 K.

Fig. 4 shows VAC of a 10 Josephson contacts chain made on bicrystalline substrate with radiation at $f = 19.091$ GH and temperature 81 K. The figure shows that at microwave radiation the Shapiro first step is observed on the VAC at a voltage of $394.7 \pm 0.1\,\mu$V (Fig. 4). The value of this voltage corresponds to the synchronization of the chain of 10 Josephson contacts by an external microwave signal. The width of the Shapiro first step current, on which the voltage is constantly $394.7 \pm 0.1\,\mu$V, equals $\Delta I_1 = 0.19$ mA ($\Delta I_1/I_c \approx 0.5$).

Thus, it can be seen from the experimental data that for the contact resistance $\rho_c \approx 3\cdot 10^{-8}\,\Omega\cdot\text{cm}^2$, vo-firstly, the CVC has a superconducting section with a high critical current, and -secondly, when irradiated with a microwave signal, Shapiro steps appear on the CVC. This shows the high quality of the Josephson transitions received.

Later it is planned to synchronize more contacts to increase the output voltage. In addition, to operate at liquid nitrogen temperatures, it is necessary to reduce the characteristic voltage of the Josephson contacts by reducing the resistance of the shunt. It should also be noted that despite the high value of the contact resistance of structures *ex situ*, this method remains also attractive from the point of view of wider technological possibilities. This is why it is planned to obtain structures *ex situ* with lower contact resistance.

6. Conclusion

Numerical simulation of the chip was carried out on the basis of the array of bicrystalline Josephson contacts from high-temperature superconductors embedded in the coplanar transmission line. It is shown that the structure produced it in situ has a low value of contact resistance, which allows to obtain bypass high-quality Josephson transitions from high-temperature superconductors. For the structure produced *in situ*, a synchronization of the chain of 10 Josephson contacts with an external v microwave signal was obtained. The obtained results can be used to create a quantum alternating voltage generator based on the Josephson contacts from high-temperature superconductors.

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Conflict of interest

The authors declare that they have no conflict of interest.

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