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Characteristics of Josephson junctions obtained by the focused ion beam method in $YBCO/CeO_2/Al_2O_3$ structures

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HTS Josephson junctions were made on a sapphire substrate with a sublayer of epitaxial cerium oxide using a focused beam of helium ions. The transport and microwave properties of junctions obtained at different radiation doses of $YBa_2Cu_3O_{7-d}$ bridges have been studied. When exposed to the studied Josephson junctions of radiation with a frequency of about 79 GHz, Shapiro steps are observed on their current-voltage characteristics.

Keywords: substrates with a sublayer of epitaxial cerium oxide, YBCO films, Josephson junctions, focused ion beam.

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Josephson junctions (JJs) are one of the key elements in low-current superconducting microelectronic devices. The technology of fabrication of such contacts for low-temperature superconductors is well proven and offers high reproducibility.

With the advent of high-temperature superconductors (HTSCs), such important instruments as voltage standarts [1], THz signal generators [2], detectors [3], and low-noise amplifiers and mixers [4] were constructed based on HTSC JJs. Although a higher operating temperature is an appealing feature of these junctions, their widespread use is hampered by significant technological difficulties in manufacturing related to the short coherence length in $YBa_2Cu_3O_{7-d}$ (YBCO). Therefore, the search for new methods of HTSC JJ fabrication continues. Studies are currently underway into the possibility of application of a helium ion microscope, which allows one to modify the film parameters in very narrow (units of nanometers) regions and form HTSC JJs [5] in an arbitrary part of the substrate.

Substrates made of various materials (strontium titanate, lanthanum aluminate, neodymium gallate, etc) are used for fabrication of YBCO films and structures. In the present study, JJs formed by a helium focused ion beam (FIB) in a YBCO film deposited onto a sapphire substrate (r-cut) with a cerium oxide sublayer were fabricated and examined. This substrate was chosen for the following reasons. First, low values of the dielectric loss tangent in sapphire are, in general, beneficial for substrates used for the production of electronic circuits. Second, this type of substrate offers new technological opportunities, since a high-quality YBCO film may be grown on sapphire with ultra-thin (down to a few nanometers) layers of cerium oxide [6], while a YBCO film deposited in the same process onto substrate regions without a cerium oxide sublayer does not feature superconducting properties. It is important here that when forming submicron-width YBCO bridges, instead of etching a superconductor film, etching of an ultrathin sublayer of cerium oxide (the so-called formation of „islands“ of cerium oxide on sapphire) can be used, which will then determine the topology of the structure directly during the deposition of YBCO. Third, sapphire substrates have a significant advantage in a combination of their commercial availability and high quality, which stems from their widespread application in various fields of instrumentation engineering (including the production of semiconductor devices).

The studied JJs were fabricated on bridges with a width of $5\,\mu$m and a length of 5 squares. The sequence of operations and parameters of technological processes used to form these YBCO bridges, which make etching of the superconductor film unnecessary, were detailed in [7]. The thickness of the CeO_2 sublayer was 50 nm, and the thickness of the YBCO film was 65 nm. The initial parameters of the c-oriented YBCO film were as follows: critical temperature, 85 K; critical current density, 2 MA/cm^2 at a temperature of 77 K. A JJ was formed at an ion energy of 35 keV and a beam current of 3 pA by a beam of helium ions He^+ using a Carl Zeiss Orion ion microscope fitted with a NanoMaker lithography system. Dose D of helium ion irradiation ranged from 200 to 500 ions/nm.

The superconducting properties of the JJ were studied within the temperature range of $10-100$ K using a measuring microwave probe [8], which was held in a helium cryostat. The main part of this microwave probe is a superdimensional circular waveguide. A circular horn is connected to the waveguide end positioned in the cryostat. A sample with the JJ and a metal mirror are placed beyond the horn. A microwave signal with its frequency ranging from 72 to 79 GHz is applied to the opposite end of the waveguide. This signal is generated by a microwave frequency synthesizer and a solid-state multiplier. The transport characteristics of the JJ were measured in a standard four-point probe setup.

Figure 1 shows the key electrophysical characteristics of the obtained JJs. Figure 1, *a* presents the current–voltage characteristics (IVCs) of a contact $5\,\mu$m in width at different temperatures. Its IVC features a section with superconducting current. The critical current of the contact at a temperature of 45 K is $I_c = 1.5$ mA, and the normal resistance of this junction is $R_n = 0.5\,\Omega$. Thus, the characteristic voltage is $I_c R_n = 0.75$ mV. Figure 1, *b* shows the temperature dependences of critical current $I_c(T)$ of the JJ $5\,\mu$m in width at different irradiation doses. These contacts are of a fairly high quality. Specifically, at an irradiation dose of 300 ions/nm, the superconducting transition temperature of such contacts is 80 K, and critical current I_c is 4 mA at a temperature of 10 K. These dependences at temperatures close to T_c may be approximated by a power law:

$$I_c(T) = I_c(0)(1 - T/T_c)^n. \quad (1)$$

The best fit between the theoretical curves and the experimental data is observed with an exponent of power n of 1.8–2. It is known that a quadratic temperature dependence corresponds to a superconductor–normal metal–superconductor (SNS) JJ [9]. It should also be noted that the critical current of the contact is suppressed significantly as the ion irradiation dose increases.

Figure 2 shows the temperature dependences of resistivity $\rho(T)$ of the Josephson junction $5\,\mu$m in width at different irradiation doses. It is evident that temperature dependence $\rho(T)$ after the superconducting transition reaches a wide plateau shaped by the JJ. This plateau in the $\rho(T)$ curves for irradiated high-temperature transitions is induced by the thermally activated phase slip (TAPS) effect, which may be characterized using the Ambegaokar–Halperin model [10]. According to this theory, such a $\rho(T)$ dependence forms when thermal energy $k_\mathrm{B}T$ becomes comparable to the Josephson coupling energy at temperatures near the superconducting transition. Figure 2 shows approximation curves $\rho(T)$ obtained within this theory:

$$\rho(T) = \rho_p \left[I_0 \left(\frac{\hbar I_c(T)}{2ek_\mathrm{B}T} \right) \right]^{-2}, \quad (2)$$

where I_0 is the modified Bessel function and $I_c(T)$ is the critical JJ current. The best fit between theoretical curves (2) and the experimental ones is observed with exponent of power $n = 2$. It should also be noted that the plateau widens as the irradiation dose increases. This corresponds to a reduction in the critical current of the JJ.

Figure 3 shows the IVC of the Josephson junction without irradiation and with irradiation by a signal with frequency $f = 78.83$ GHz at a temperature of 45 K. It can be seen that the IVC measured under irradiation features the first Shapiro step with a current swing $\Delta I_1 = 150\,\mu$A ($\Delta I_1/I_c \cong 0.6$) at a voltage of $\sim 163\,\mu$V and a sample temperature of 45 K. The characteristic voltage of the contact at this temperature is on the order of $V_c \cong 180\,\mu$V. It should be noted that since the multiplier cavity, the circular waveguide, and the metal mirror form a microwave resonator [8], the width of the first Shapiro step depends on the microwave signal frequency. Therefore, Fig. 3 presents the IVC at a frequency that corresponds to the maximum current width of the first Shapiro step.

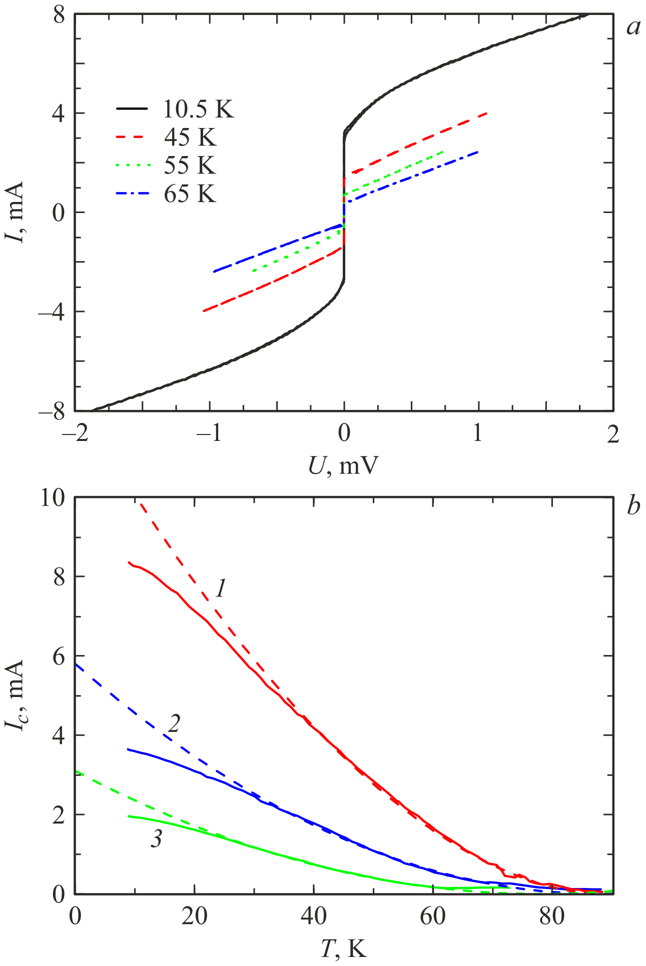

Figure 1. *a* — Current–voltage characteristics of a JJ $5\,\mu$m in width at different temperatures. Contact irradiation dose $D = 300$ ions/nm. *b* — Temperature dependences of the critical current of the JJ $5\,\mu$m in width at irradiation doses $D = 200$ (*1*), 300 (*2*), and 500 ions/nm (*3*). Dashed curves represent power-law approximations.

Thus, HTSC JJs with fine electrophysical parameters were fabricated using the FIB method with various irradiation doses on a sapphire substrate (*r*-cut) with an epitaxial cerium oxide sublayer. It was found that the manufactured superconducting structures are SNS-type transitions. When the produced JJ was exposed to radiation with frequency $f = 78.83$ GHz, the first Shapiro step with a voltage of $\sim 163\,\mu$V formed in the contact IVCs. The obtained results demonstrate that further development of the technique of JJ

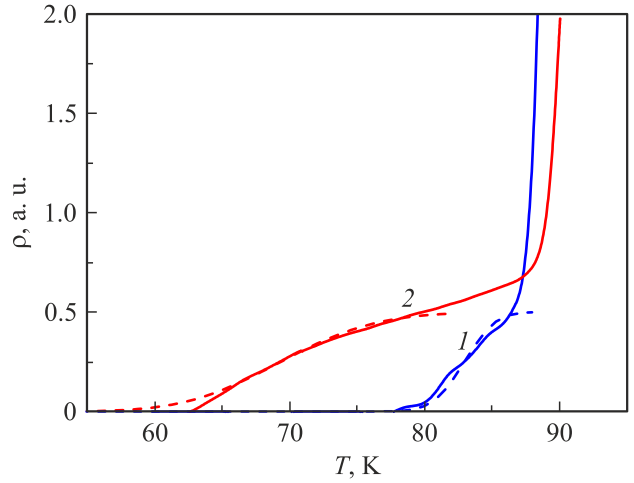

Figure 2. Temperature dependences of resistivity of the JJ 5 μm in width at irradiation doses $D = 200$ (*1*) and 300 ions/nm (*2*). Dashed curves represent the approximation obtained within the Ambegaokar–Halperin model [10].

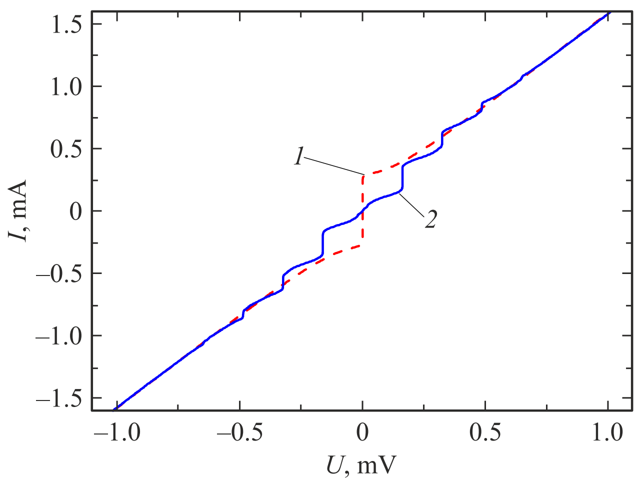

Figure 3. Current-voltage characteristics of the JJ 5 μm in width without irradiation (*1*) and under irradiation (*2*) with a microwave signal at $f = 78.83$ GHz and a temperature of 45 K. Contact irradiation dose $D = 500$ ions/nm.

fabrication by a focused beam of helium ions on sapphire substrates with an epitaxial cerium oxide sublayer is a promising line of research. This should eventually allow one to produce arrays of uniform JJs with well-reproducible electrophysical parameters, which is a prerequisite for their use in various fields.

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Conflict of interest

The authors declare that they have no conflict of interest.

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