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# $YBa_2Cu_3O_x$ Josephson junctions on a bicrystal sapphire substrate for devices in the millimeter and submillimeter wavelength ranges

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High-temperature superconducting Josephson junctions on bicrystal sapphire substrates were fabricated and investigated experimentally. The critical parameters of the junctions satisfy the constraints for the design of devices in the millimeter and submillimeter wavelength ranges. The results of dynamic measurements show that in these junctions the superconducting current exhibits a sinusoidal dependence on the phase difference of the superconducting wave functions of the electrodes, and a simple resistive model is used to analyze their microwave properties. At the same time, the temperature dependence of the critical current of the junctions differs appreciably from that typical of tunnel junctions with $s$-superconductors and may be explained as $d$-type pairing of the superconducting electrodes and an SNS junction. © *1999 American Institute of Physics.* [S1063-7850(99)00104-4]

Josephson junctions fabricated using high-temperature superconductors (HTSCs) at liquid-helium temperature $T=4.2\,\mathrm{K}$ have various parameters appreciably superior to those of their low-temperature analogs. These include the normal-state resistance $R_N$, the critical frequency $f_C=\Phi_0 I_C R_N$, where $\Phi_0$ is the magnetic flux quantum and $I_C$ is the critical current, and the capacitance $C$. For comparison we note that for niobium Josephson junctions with $f_C\cong 600\,\mathrm{GHz}$, $R_N\cong 10-30\,\Omega$, and McCumber parameter $\beta_C=2\pi f_C R_N C\approx 1$, which characterizes the junction capacitance $C$ on which the profile of the current–voltage characteristic and thus the presence or absence of hysteresis depend, estimates[1] indicate that shunted Josephson junctions of submicron dimensions $S\approx 0.1\,\mu\mathrm{m}^2$ must be fabricated with a critical current density $j_C\geqslant 10^4\,\mathrm{A/cm}^2$, which is extremely difficult to achieve even with the well-developed technology for fabricating niobium tunnel junctions. The absence of hysteresis on the current–voltage characteristics of HTSC Josephson junctions eliminates the need for shunting, and the potentially high values of $f_C$ allow these junctions to be used at frequencies higher than the niobium gap.

However, aspects involved in the stable fabrication of high-quality HTSC Josephson junctions have not yet been resolved. The most reproducible junctions having a critical current spread of ±12% per chip are fabricated on $SrTiO_3$ bicrystal substrates,[2] but because of their high permittivity $\varepsilon>1000$ they are unsuitable for microwave applications. Single-crystal sapphire having a relatively low permittivity $\varepsilon\approx 9.5$ (parallel to the principal crystallographic axis) and low losses ($\tan\delta\approx 10^{-8}$ at 72 GHz and $T=4\,\mathrm{K}$) (Ref. 3), which is the traditional material used in microwave electronics, is one of the most promising substrate materials. Vale *et al.*[2] and Kunkel *et al.*[4] reported $YBa_2Cu_3O_x$ (YBCO) Josephson junctions on sapphire bicrystals, although the literature contains no information on the correspondence between the parameters obtained from static data on the current–voltage characteristics and those obtained from dynamic measurements nor on the noise parameters, which are particularly important for applications in sensitive detectors in the millimeter and submillimeter wavelength ranges. Here we report the fabrication and measurements of the dynamic parameters of Josephson junctions consisting of YBCO films on bicrystal sapphire substrates having the parameters $f_C=300-700\,\mathrm{GHz}$, $R_N\cong 10-30\,\Omega$, and $\beta_C\approx 1$ at $T=4.2\,\mathrm{K}$.

The Josephson junctions were fabricated on the $(1\underline{1}02)$ plane of sapphire substrates consisting of two crystals for which the $\langle 11\underline{2}0\rangle$ directions were at angles of $\pm 12^\circ$ to the plane of the interface. The YBCO film was fabricated by first depositing a 40–80 nm thick $CeO_2$ epitaxial buffer layer by rf magnetron sputtering from a metallic Ce target at 750 °C in order to prevent Al atoms from diffusing into the YBCO film. The $CeO_2$ buffer layer was deposited at a pressure of 1.2 Pa in an $Ar-O_2$ gas mixture with a partial pressure ratio of 1:1. A YBCO epitaxial film was deposited on the $CeO_2$ surface by diode sputtering in a dc discharge at a high oxygen pressure of $4\times 10^2$ Pa (Ref. 5). A 50 nm thick YBCO lower layer was then deposited at a lower substrate surface temperature of 725 °C to prevent chemical interaction between the YBCO and the $CeO_2$ (Ref. 5). The 100 nm-thick main upper YBCO layer was deposited at a substrate surface temperature of 780 °C which improved the structure of the film and its superconducting properties. The films were cooled for 1 h in an $O_2$ atmosphere and then coated with a 100 nm polycrystalline $CeO_2$ layer which acts as a mask for the subsequent technological processes. Thin-film YBCO bridges 5 $\mu$m wide and 10 $\mu$m long crossing the bicrystal interface were initially formed in the upper $CeO_2$ layer by rf plasma etching in Ar and the YBCO was then subjected to liquid chemical etching in a 0.5% ethanol solution of $Br_2$ through the $CeO_2$ mask.

Figure 1 shows typical temperature dependences of the

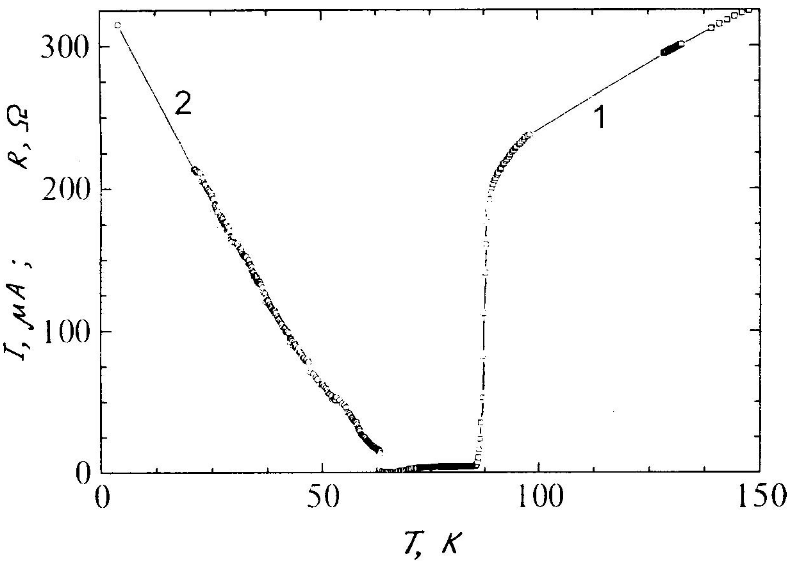

FIG. 1. Temperature dependence of the resistance $R(T)$ (1) and critical current $I_C(T)$ (2) for a YBCO Josephson junction on the $(1\bar{1}02)$ plane of a sapphire bicrystal with a misorientation angle of 24°.

resistance of the Josephson junction $R(T)$ and the critical current $I_C(T)$. It can be seen that at low temperatures a nearly linear dependence $I_C(T)$ is observed, which differs appreciably from the known theoretical dependence for superconductor–insulator–superconductor (SIS) tunnel junctions but is similar to that calculated by Tanaka and Kashiwaya[6] for Josephson junctions fabricated using $d$-type pairing superconductors with an infinitely narrow barrier and a misorientation angle close to the experimental value. It should be noted that for $T \ll T_C$ an almost linear dependence $I_C(T)$ is observed for SNS Josephson junctions where N is a normal metal.[7]

The results of measurements of the static parameters of the samples at $T=4.2$ K are presented in Table I. The thickness of the $CeO_2$ buffer layer was 80 nm for series BC3 and 40 nm for series BC5. The structures of samples BC3-A and BC5-A consisted of chains of three Josephson junctions connected in parallel. The critical temperature of the YBCO film in the bridges was in the range $T_C \cong 86-88$ K. At $T \approx 77$ K a thermally activated phase slip process was caused by thermal fluctuations (the current amplitude of the fluctuations was $I_t = 4\pi k_B T/\Phi_0 \approx 6$ μA), which broadened the current–voltage characteristic of the Josephson junction[8] and a nonzero critical current was observed at lower temperatures $T<70$ K. The curve $R(T)$ shows a characteristic "shelf" in the range 86–67 K. At temperatures $T \sim T_C$ where thermal fluctuations predominate, the approximated dependence $I_C(T)$ is closer to the quadratic dependence $I_C \sim (1-T/T_C)^2$. This behavior of $I_C(T)$ near $T_C$ may be observed both for $s$-superconductors and in Josephson junctions fabricated from $d$-type superconductors, as was predicted by Barash *et al.*[9] The departure of the HTSC electrodes from $s$-type pairing may be reflected in the functional dependence of the superconducting current $I_S$ on the phase $\varphi$ and thus in the appearance of a nonsteady-state Josephson effect, as was shown by Tanaka and Kashiwaya[6] and Barash *et al.*[9]

TABLE I. Junction parameters measured at liquid helium temperature $T=4.2$ K. The notation is given in the text.

| Sample | $I_C$, μA | $R_N$, Ω | $I_C R_N$, μV | $f_C$, GHz |
|---|---|---|---|---|
| BC3-1 | 93 | 7.5 | 697.5 | 337 |
| BC3-2 | 100 | 13 | 1300 | 628 |
| BC3-A* | 100 | 13.5 | 1350 | 650 |
| BC5-1 | 19 | 36 | 680 | 330 |
| BC5-2 | 64.2 | 23 | 1496 | 723 |
| BC5-A* | 46.2 | 21.4 | 990 | 479 |

*Parameters for a single sample calculated from measurements of a chain of three parallel-connected junctions.

In order to estimate the dependence $I_S(\varphi)$, we measured the current–voltage characteristics of the Josephson junctions at temperatures between the critical temperature $T_C$ and $T=4.2$ K under the action of millimeter external electromagnetic radiation. Figure 2a shows a family of current–voltage characteristics for junction BC5-2 obtained for various powers $P_e$ of the electromagnetic radiation. In this case, the amplitude of the critical current was suppressed by the action of the magnetic field which ensures that the frequencies are approximately equal $f_C \approx f_e \cong 100$ GHz. An analysis of the experimental dependences of the amplitudes $I_C$ and the Shapiro steps $I_n$ $(n=1,2,3)$ on the power $P_e$ (Fig. 2b) showed that the microwave dynamics of these Josephson junctions is accurately described by a simple resistive model.[7] Note that the value $f_C \cong 106$ GHz determined using an independent current–voltage characteristic was also close to its "microwave" analog determined using the maximum of the first Shapiro step $I_{1\,\max}$, $f_{C1} \cong 90$ GHz, and from the zeros of the curves $I_n(P_e)$ ($\chi$-criterion[7]), $f_{C\chi} \cong 100$ GHz. The frequency ratios $f_C/f_{C1}$ for samples BC3-1 and BC5-1 were 337/345 and 330/335 GHz/GHz, respectively. The overall deviation of the frequency $f_C$ from their microwave estimates was of order $\pm 5\%$.

Kleiner *et al.*[10] showed that the deviation of the curve $I_S(\varphi)$ from sinusoidal gives rise to subharmonic (fractional $n/m$) Shapiro steps whose amplitude is proportional to the corresponding harmonic of the Fourier expansion of $I_{S(\phi)}$ with respect to $\sin(n\phi)$. A detailed study of the current–voltage characteristics of the Josephson junctions, including

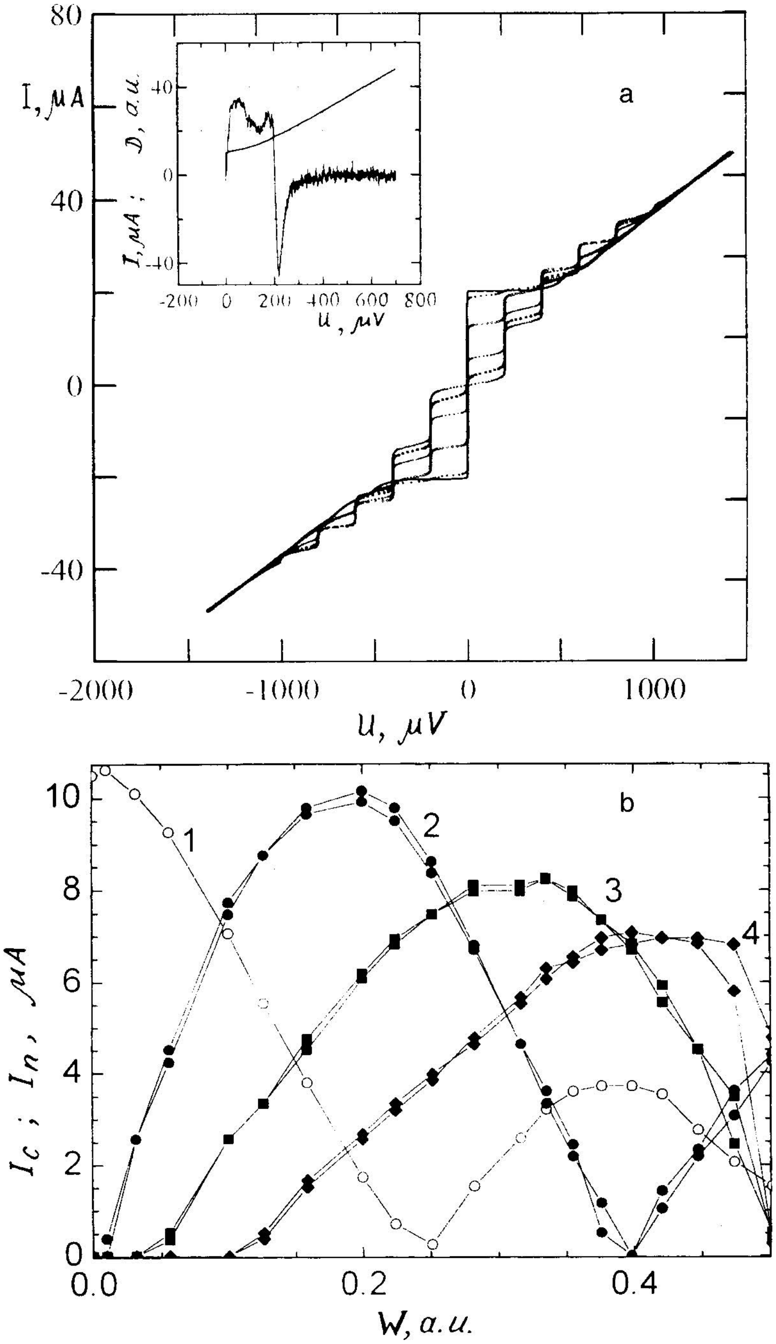

FIG. 2. Influence of microwave irradiation at power $P_e$ and frequency $f_e \cong 100$ GHz on junction BC5-2 of width $w = 5$ μm, $R_N \cong 23\ \Omega$, and $I_C \cong 11$ μA (suppressed by the action of a weak static magnetic field) at $T = 4.2$ K: a—family of current–voltage characteristics at various power levels $P_e$ (the inset shows the detector response of the Josephson junction ($D$) to a weak signal at the same frequency); b—power dependence of the critical current (1) and the amplitudes of the Shapiro steps $n=1$ (2), $n=2$ (3) and $n=3$ (4) on the right and left branches of the current–voltage characteristic.

those at $T = 4.2$ K ($T/T_C \approx 0.05$), under the action of a microwave field reveals no $\sin(2f)$ and $\sin(nf)$ components in $I_S(\phi)$ to within 5%. Note that for the case of a Josephson junction fabricated of $d$-type superconductors calculated in Ref. 6, for which $I_C(T)$ is linear, the dependence $I_S(\phi) \approx \sin(\phi)$ is also predicted. We note that the appearance of subharmonics may also be caused by an inhomogeneous current distribution over the junction width[7,11] and/or by the high capacitance of the Josephson junction. In our case, the uniformity of the current distribution was also confirmed experimentally by the "Fraunhofer" dependence $I_C(H)$ and the absence of hysteresis on the current–voltage characteristic indicates the junction has a low capacitance $C$. Using the resistive Josephson junction model we estimate $\beta_C \approx 1$ and therefore $C = \varepsilon\varepsilon_0 S/t$ from the independent current–voltage characteristic, where $t$ is the thickness of the junction tunnel barrier and $S$ is the area of the junction. We obtain $C \cong 13.5$ fF and the ratio $t/\varepsilon \approx 2.7$ Å. Note that this value of $C$ agrees with the data given in the literature for other types of HTSC Josephson junction (see Ref. 12, for example) where $C$ was estimated from the resonant Fiske characteristics in the tunnel junction model.

The noise properties of these samples were estimated by measuring (using a procedure similar to that described by Ovsyannikov *et al.*[13]) the line width $\Delta f$ of the natural Josephson oscillation from the profile of the selective detector response $\eta(V)$ at 100 GHz. This dependence is shown in the inset to Fig. 2a. The values of $\Delta f \approx 15$ GHz were four times broader than the theoretical values predicted by the resistive model. This line broadening has frequently been observed in the literature (see Refs. 4 and 13, for example). Note that for $V > 300\,\mu\text{V}$ the curve $\eta(V)$ approaches zero. In this case, measurements of the noise response using a cryogenic low-noise amplifier at 1.5 GHz revealed a linearly dependent increase in the noise level as a function of the junction voltage caused by the presence of shot noise whose level, according to our estimates, was insufficient to explain the observed broadening of the oscillation line.

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[1] V. N. Gubankov, K. I. Konstantinyan, and V. P. Koshelets, Zh. Tekh. Fiz. **53**, 1639 (1983) [Sov. Phys. Tech. Phys. **28**, 1009 (1983)].

[2] L. R. Vale, R. H. Ono, and D. A. Rudman, IEEE Trans. Appl. Supercond. **7**, 3193 (1997).

[3] V. B. Braginsky and V. S. Ilchenko, Phys. Lett. **120**, 300 (1987).

[4] G. Kunkel, G. Hechtfischer, M. Frommberger *et al.*, Tech. Phys. Lett. **7**, 3339 (1997).

[5] A. D. Mashtakov, I. M. Kotelyanskiĭ, V. A. Luzanov *et al.*, Pis'ma Zh. Tekh. Fiz. **23**(19), 8 (1997) [Tech. Phys. Lett. **23**, 738 (1997)].

[6] Y. Tanaka and S. Kashiwaya, Phys. Rev. B **56**, 892 (1997).

[7] K. K. Likharev and B. T. Ul'rikh, *Systems with Josephson Junctions* [in Russian], Moscow State University Press, Moscow (1978), 446 pp.

[8] C. L. Lin, W. J. Chang, M. Y. Li *et al.*, Physica C **269**, 291 (1996).

[9] Yu. S. Barash, A. V. Galaktionov, and A. D. Zaikin, Phys. Rev. B **52**, 665 (1995).

[10] R. Kleiner, A. S. Katz, A. G. Sun *et al.*, Phys. Rev. Lett. **76**, 2161 (1996).

[11] K. I. Konstantinyan, A. D. Mashtakov, G. A. Ovsyannikov *et al.*, Zh. Éksp. Teor. Fiz. **107**, 1742 (1995) [JETP **80**, 971 (1995)].

[12] H. R. Yi, D. Winkler, and T. Claeson, Appl. Phys. Lett. **66**, 1677 (1995).

[13] G. A. Ovsyannikov, A. D. Mashtakov, I. M. Kotelyanski *et al.*, in *Extended Abstracts of ISEC 97*, Germany, Vol. 2 (1997), p. 76.

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