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Temperature Sensitivity and Noise of an HTSC Josephson Detector on a Sapphire Bicrystal Substrate at 77 K

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In $YBa_2Cu_3O_{7-x}$ films grown on sapphire bicrystal substrates, the Josephson junctions are prepared based on artificial grain boundaries formed by the turn of the crystal lattices about the [100] axis. The films are deposited by the laser ablation method on the buffer CeO_2 layer. The critical film temperature reaches 88.5 K at a transition width of 1.5 K. Junctions from 2 to 3-μm wide are integrated into the planar log-periodic antennas and their characteristics are measured at 77 K. The characteristic voltage I_cR_n reaches 570 μV. With exposure to external radiation at a frequency of 113 GHz, the Shapiro steps were observed on the current–voltage characteristic. The temperature sensitivity of this detector placed in a quasi-optical receiving unit is measured. At the modulation of the input radiation temperature 77 K/300 K, a response of more than 200 nV is observed at the detector output. At the modulation frequency, intrinsic noise is about 1 nV/$Hz^{1/2}$, which corresponds to a temperature resolution of 1 K.

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High-sensitivity microwave receivers are necessary for atmospheric monitoring, biomedical studies, and safety control. Common semiconductor detectors are limited in their frequency and sensitivity. Standard Fourier spectrometers, generators of the oscillators based on backward-wave tubes and far-IR lasers, are cumbersome, hard to control, and expensive. An alternative to all of the above devices may be superconducting receiving devices such as Josephson direct and selective detectors, superconductor–insulator–superconductor mixers with Josephson oscillator generators, Hilbert spectrometers, and SQUID transducers and amplifiers. In contrast to conventional niobium devices with a working temperature of about 4 K, high-temperature superconductors (HTSC) can operate at the liquid nitrogen temperature (77 K) using simple and inexpensive closed-loop cryogenic cooling agents. The HTSC bicrystal junctions on the sapphire substrates seem promising for their use in microwave detectors, generators, and spectrometers.

Sapphire has rather low microwave losses and, thus, could be used as a substrate material in detectors and generators up to terahertz frequencies. Usually, bicrystals with the crystal lattice disorientation formed by the turn about the [001] axis were usually used in the HTSC Josephson junctions on grain boundaries. However, it is known that the curvature of the artificial grain boundary in tilted bicrystal films, where the turn was performed about the [100] axis, was three times smaller than that in conventional bicrystals with the disorientation in the substrate plane. This makes it possible to considerably increase the characteristic voltage of Josephson junctions and to reliably manufacture high-quality Josephson junctions. In this case, the film growth mechanism changes from the island or spiral to the layered one. This makes the surface smoother and increases the current density [1, 2]. As shown in [3, 4], the tilted [100] bicrystal junctions have much better parameters than those with the disorientation in the substrate plane. The boundary in the HTSC film in the former junctions is more rectilinear and better corresponds to the boundary in the substrate; i.e., the deviation from the specified disorientation angle is smaller. The authors of [4] demonstrated values of I_cR_n up to 1.2 mV at 77 K and 8 mV at 4.2 K for strontium titanate substrates. However, these substrates have a high dielectric constant and high microwave losses that limit the sensitivity of feasible detectors and their frequency range. The tilted neodymium gallate bicrystals [5] make it possible to extend the frequency range to the

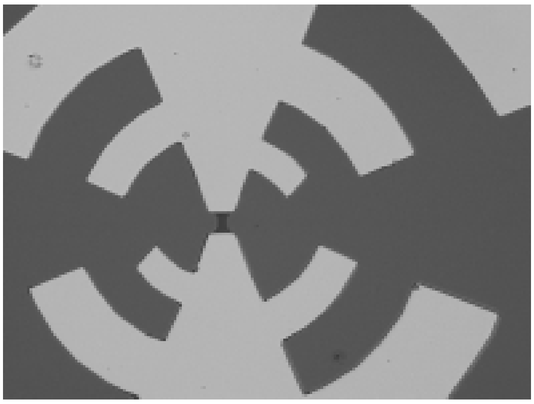

Fig. 1. Photograph of the sample with (dark bridge in the center) the bicrystal Josephson junction integrated with the log-periodic antenna.

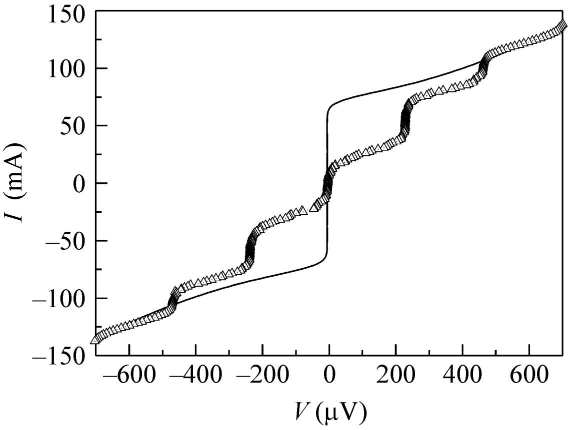

Fig. 2. Current–voltage characteristics of the sample at 77 K (solid line) without a signal and (triangles) with exposure to 113-GHz radiation.

terahertz region. To further decrease losses and to improve the microwave signal timing, we use in this work the tilted sapphire bicrystal substrates having low losses, a high thermal conductivity, and a substrate constant close to that of YBaCuO. In our previous works [6, 7], we investigated the Josephson junctions on such substrates at the liquid helium temperature, obtained sufficiently high values of a characteristic voltage up to 4 mV, and observed emission from this junction at frequencies of up to 1.7 THz. However, the critical current values in these junctions were too low to operate at the liquid nitrogen temperature. In this work, the junction parameters were optimized for operation at 77 K. We note that they cannot operate at 4.2 K, because the critical current is too high and the current–voltage characteristic exhibits hysteresis; i.e., the junction parameters must be optimized within each temperature range.

The epitaxial YBaCuO films were grown by the laser ablation method on the symmetric sapphire bicrystal substrates providing the turn of the crystal lattices of the singe-crystal parts of the film about their common [100] axis with a 11.6° tilt of their principal [001] axes toward the boundary. Initially, the buffer CeO_2 layer was deposited in an oxygen atmosphere of 0.3 mbar and a substrate temperature of 770°C. Then, at 780°C and an oxygen pressure of 0.6 mbar, the 250-nm-thick YBaCuO film was grown, atop of which a thin Au film was deposited without any vacuum breakup. The 50-nm-thick Au layer was formed by magnetron deposition for termination pads and planar antennas. The pads, antennas, and Josephson bridges were shaped using UV lithography followed by ion etching in an argon plasma.

As a result, samples with three Josephson junctions, each integrated into the log-periodic antenna, were obtained on the 5 × 5-nm substrate. One such fragment is shown in Fig. 1.

The samples were placed in a quasi-optical unit. The substrate backside was forced against the elongated hyperhemispherical silicon lens [8]. The hemispherical lens diameter was 13.7 mm and elongation was performed in the shape of a silicon washer so that the antenna was located at a distance of 2.20 mm behind the hemisphere center. A combination of this lens and the antenna had a beam width of about 34° at a level of –30 dB and about 16° at a level of –10 dB. The directional pattern can be approximated by a narrow Gaussian beam propagating from the antenna. The beam was then transformed into a weakly converging one using a plastic lens 50-mm in diameter. This made it possible to use the optical window and cold filters of a relatively small diameter of 25 mm and to considerably reduce exposure to IR radiation and submillimeter background radiation.

The dc characteristics of the junction were measured. At the minimum trapped magnetic flux, the characteristic voltage reached 600 μV, which corresponds to a frequency of 300 GHz. Then, the current–voltage characteristics were measured with exposure to external microwave radiation at a frequency of 113 GHz from a source based on an avalanche flight-time diode. Figure 2 demonstrates the Shapiro steps corresponding to this radiation frequency. The Josephson detector sensitivity to a weak signal was measured by the method of cold and warm loads. To this end, a mechanical modulator and an absorber at the liquid nitrogen temperature were placed in front of the cryostat window. The spectrum of the received thermal radiation was limited by applying the low-frequency cold filters and did not exceed 300 GHz. The modulator blade rotation led to the appearance of black body radiation at the liquid nitrogen temperature of 77 K and at a room temperature of 300 K in front of the window. The modulation frequency was 27 Hz. The signal was isolated by the synchronous detector and recorded as a function of the bias voltage (Fig. 3). The response to a temperature drop of 200 K reached 200 nV. Furthermore, the Josephson junction intrinsic noise was measured when the optical

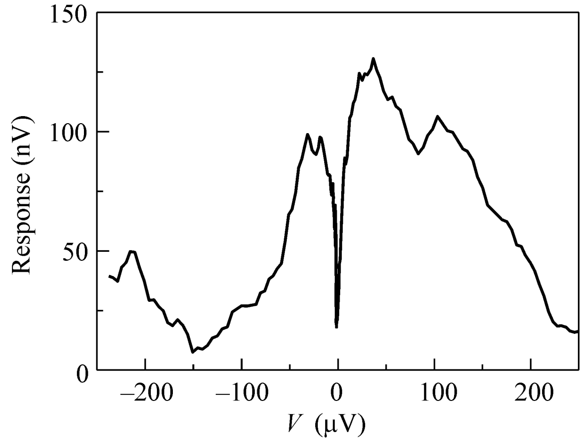

Fig. 3. Detector response to the switching of the input thermal load (300 K/77 K) measured by the synchronous detector at a frequency of 27 Hz.

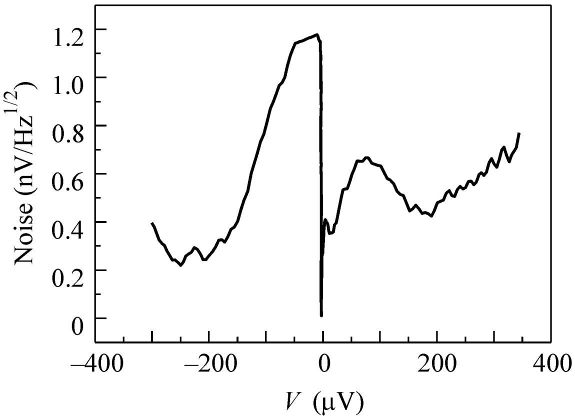

Fig. 4. Intrinsic detector noise measured at the closed optical window.

window was closed (Fig. 4). In the maximum response region, the noise spectral density was ~1 nV/Hz$^{1/2}$. A comparison of these results yields temperature resolution values at a level of 1 K/Hz$^{1/2}$. This value can be compared to the Likharev theoretical estimate [9]

$$\frac{\delta T}{\sqrt{\Delta F}} \approx 20T\frac{\sqrt{F_c}}{\Delta F_\Omega}\omega^2,$$

where ΔF is the integration band at the output, T is the background temperature, F_c is the Josephson junction critical frequency, ΔF_Ω is the input signal transmission band, and ω is the normalized signal frequency. As a result, we obtain a value of 0.01 K, which is much lower than the measured one and relates to mismatching with respect to the signal from the junction of 5 Ω resistance with a planar antenna of 70 Ω resistance and to losses caused by reflection from the silicon lens, plastic lens, and optical window.

We can also estimate the thermal radiation power at the input within the 300-GHz band, which will be 1.2 nW at 300 K and 0.3 nW at 77 K; that is, the power drop will be 0.9 nW. At an output amplitude of 150 nV, we obtain a sensitivity of 170 V/W with respect to the warm input window. If the Hilbert spectroscopy method is directly used, the spectral resolution can be estimated by the semi-empirical formula ΔF[MHz] = $40R[\Omega]T$[K] = 13 GHz at a temperature of 77 K and a normal resistance of 4.4 Ω. To improve the spectral resolution without any loss of sensitivity, we can use a low-inductive resistance shunt and a low-noise current amplifier. This will allow us to obtain a spectral resolution of 1 GHz and better. We note that a modulation frequency of 27 Hz was determined by the use of the mechanical modulator, while the Josephson detector speed can generally reach the junction characteristic frequency and amounts to hundreds of gigahertz.

A microwave quasi-optical HTSC Josephson detector operating at 77 K has been developed, fabricated, and investigated. The characteristic voltage of the Josephson junction reaches 570 μV, which corresponds to the characteristic frequencies up to 300 GHz. The response to the millimeter thermal radiation is 1 nV/K. The temperature resolution is 1 K/Hz$^{1/2}$. Such fast detectors can be used in radio and IR imagers, scanners, and spectrometers for the remote diagnostics of the atmosphere, in biomedical studies, and in passive systems of safety control.

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