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THE 700–950 GHz SUPERCONDUCTING RECEIVING STRUCTURES FOR RADIO ASTRONOMY

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We have designed, fabricated, and tested the waveguide receiving element, which is based on the tunnel superconductor–insulator–superconductor structures, for the frequency range 790–950 *GHz. Two Nb/AlN/NbN tunnel junctions are incorporated in a microstrip line consisting of the bottom NbTiN-film electrode with a thickness of about* 300 *nm and the top* 500 *nm-thick aluminum electrode. The production-process optimization allows one to ensure the following characteristics of these junctions: submicron area (*0.5 μm^2 *for each junction), current density about* 30 kA/cm^2*, and band gap width* 3.2 *mV. Such tunnel junctions ensure the receiver operation in a wide frequency range (*700–950 *GHz), which was confirmed by the Fourier transform spectroscopy and the noise-temperature measurements. At a frequency of* 725 *Hz, the corrected noise temperature of the receiver amounts to* 120 *K, which is only threefold greater than the quantum limit* hf/k_B*, where* h *is the Planck's constant,* f *is the frequency, and* k_B *is Boltzmann's constant. In the upper part of this frequency range, the noise temperature increases up to* 390 *K.*

1. INTRODUCTION

Within the framework of the CHAMP project [1], a high-sensitivity receiver has been developed and manufactured for the "Atacama Pathfinder Experiment" (APEX) telescope [2]. This telescope-borne device consists of two seven-pixel matrices, i.e., the heterodyne receivers operated in the frequency ranges 600–720 GHz and 790–950 GHz, which correspond to the atmospheric transparency windows. The mixers based on the superconductor–insulator–superconductor (SIS) tunnel junctions Nb-AlO$_x$–Nb are the high-sensitivity elements of the receivers. However, the receivers of the higher frequency range have a comparatively high noise temperature of about 400 K. To improve the telescope sensitivity, the CHAMP+ project has been launched in order to develop the heterodyne superconductor receiver with a noise temperature of about 200 K, operated in the frequency range 790–950 GHz.

This work is aimed at studying the receiver prototype operated in the range 790–950 GHz on the basis of the mixer SIS structure NbTiN–Nb–AlN–NbN with a submicron dimension and a high barrier transparency (the current density is 30 kA/cm^2).

2. RECEIVING-STRUCTURE PRODUCTION PROCESS

As is known, the junctions with high current density J_C allow one to increase the operation frequency of the SIS receivers and extend their band. However, there exists a limit for the barrier-transparency

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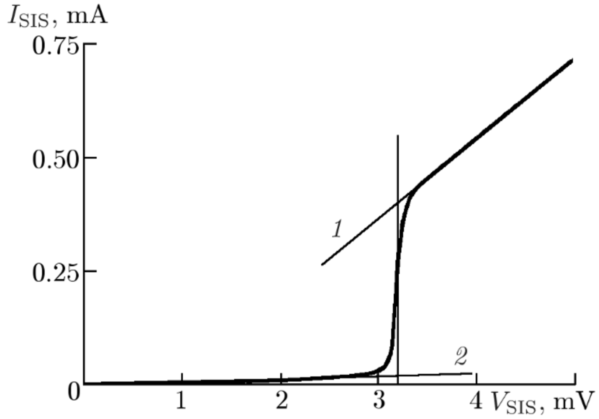

Fig. 1. Current-voltage characteristic of the receiving structure based on two identical SIS junctions. The straight lines *1* and *2* correspond to the CVC regions with the slopes $R_{\mathrm{n}} = 5.9\ \Omega$ and R_{j} ($R_{\mathrm{j}}/R_{\mathrm{n}} = 37$) and the vertical line corresponds to the voltage $V_{\mathrm{g}} = 3.2$ mV.

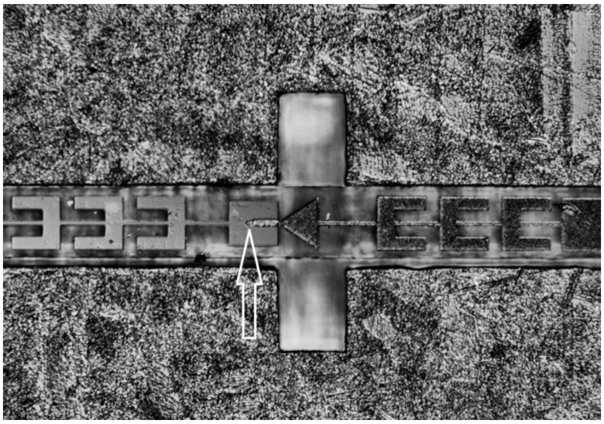

Fig. 2. Microphotograph of the main part of the receiving element. The twin structure is marked by an arrow.

increase for the SIS junctions on the basis of aluminum oxide. This limit corresponds to a current density of about 10–15 kA/cm^2. A further increase in the current density abruptly deteriorates the junction quality. To overcome this restriction, the research workers of V. A. Kotel'nikov Institute of Radioengineering and Electronics of the Russian Academy of Sciences have developed a technology for manufacturing the tunnel SIS junctions Nb/Al–AlN$_x$/NbN with an extremely high tunnel-barrier transparency (up to 70 kA/cm^2 for the corresponding current density) and an acceptable quality parameter $R_{\mathrm{j}}/R_{\mathrm{n}}$, where R_{j} is the SIS-junction resistance measured below the band gap for a voltage of 2 mV and R_{n} is the SIS-junction resistance on the "normal" (above the band gap) part of the current-voltage characteristic (CVC). To obtain a superfine and high-quality alumonitride (AlN) barrier, the aluminum surface was subject to nitriding in the radio-frequency plasma discharge in the pure-nitrogen (N_2) medium. On this basis, the technology of forming multilayered microcircuits was developed and various supersensitive receiving devices operated in the frequency range 100–1000 GHz were manufactured.

The mixer element is manufactured on the quartz substrate using the planar technology and contains a triangle probe antenna in a 300×75-μm waveguide structure, a matching microstrip structure, a system of high-frequency (4–12 GHz) filters in the signal-output circuits, and a detector on the basis of two identical SIS junctions with an area of 0.5 μm^2. The parallel-connected junctions are located at a short distance from each other. Such a structure is used for the capacitance detuning in the wide frequency band and is often called the twin structure, whose typical CVC is shown in Fig. 1, whereas the microphotograph of a part of the mixer element is shown in Fig. 2.

Since the receiver operation frequency exceeds the band gap frequency of niobium, a superconductor NbTiN film with a thickness of 280 nm and a critical temperature of 14.1 K was used as the bottom electrode of the receiving element and a high-quality aluminum film with a thickness of 500 nm was used as the top electrode of this element. The SiO$_2$ oxide with a thickness of 250 nm was used as dielectric in the microstrip line. Although the receivers work under vacuum conditions, the top aluminum layer gradually disintegrates during the tests because of the high chemical activity of the metal. Therefore, some manufactured samples were passivated by a SiO$_2$ layer, which ensured a higher reliability and repeatability of the results of measurements of the SIS-junction characteristics during the thermal cycling.

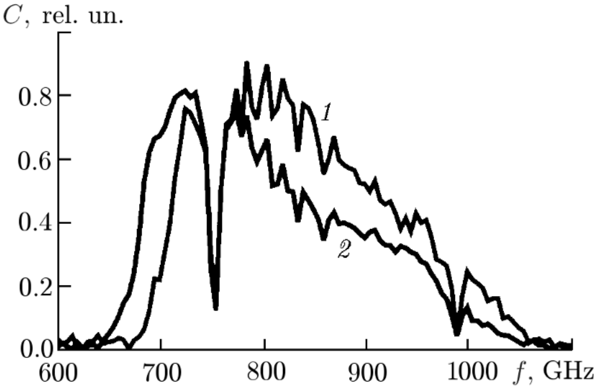

Fig. 3. The frequency dependence of the experimental responses of different types of the receiving elements. Curve *1* corresponds to the element which was tuned to a somewhat higher specific capacitance during the design compared with the element corresponding to curve *2*.

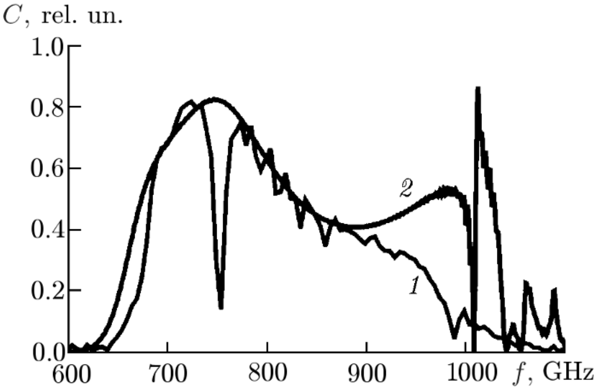

Fig. 4. The measured response (curve *1*) of the receiving element compared with the corresponding theoretical estimate (curve *2*). Two deep and sharp dips on the experimental curve correspond to the water-absorption lines. The artefacts at frequencies exceeding 1 THz on the calculated curve are related to the employed-algorithm feature.

3. VARIATIONS IN THE RECEIVING-STRUCTURE CHARACTERISTICS

The receiving-element response in a frequency band of 790–950 GHz was experimentally measured using the Michelson Fourier transform interferometer. The resistance heater (Globar) was used as a wideband source of terahertz radiation. An operation voltage of 2.5 mV was specified on the twin junctions for measuring the receiving-element response. The Fourier-transform spectroscopy results are given in Fig. 3. To ensure good suppression of the critical current of the tunnel junctions, it is sufficient to move to the first maximum of the critical-current dependence on the external magnetic field. Usually, the second or even the third minimum of this dependence is used as an optimal suppression level. The critical-current suppression is improved and the electric noise decreases with increasing order of the minimum. However, the high magnetic field reduces the energy band gap of superconductors, which leads to a decrease in the band-gap voltage on the CVC and, thus, a pronounced decrease in the upper boundary of the operation range.

For correct calculation, we should exactly know the specific capacitance of the junctions with a tunnel layer of aluminum nitride (AlN). According to [3], a specific capacitance of 60 $\text{fF}/\mu\text{m}^2$ is reached for a critical current density of 56 kA/cm^2, whereas in [4], a specific capacity of 85 $\text{fF}/\mu\text{m}^2$ for a critical current density of 50 kA/cm^2 is mentioned. To reduce the uncertainty and definitely realize the required input band, the samples calculated for various specific capacitances were included to the manufactured series. Analysis of the test series of the samples described in [5] allowed us to determine the specific capacitance of the SIS junction for the used current density, which was found to be equal to 80 $\text{fF}/\mu\text{m}^2$.

Complete three-dimensional simulation of the manufactured structures, including the adjustment elements and the chip-sample location in the waveguide, was performed. As is evident from Fig. 4, the experimental response of the receiving structure is lower than the calculated one in the frequency range 900–1000 GHz. With allowance for the high quality of the employed SIS junctions, it is assumed that disagreement with the calculated results in the upper part of the frequency range is caused by a larger loss in the films than that estimated using the Mattis–Bardeen theory [6]. For the studied sample series, as a result of the structure formation, the NbTiN-layer thickness was smaller than the calculated one (up to the values that are close to the London penetration depth). Such a variation can lead to the electromagnetic-field penetration to the lower NbTiN-film layers, whose structure and properties differ from the thick-film characteristics, and even into the substrate. Probably, this is the cause of the observed fast increase in the

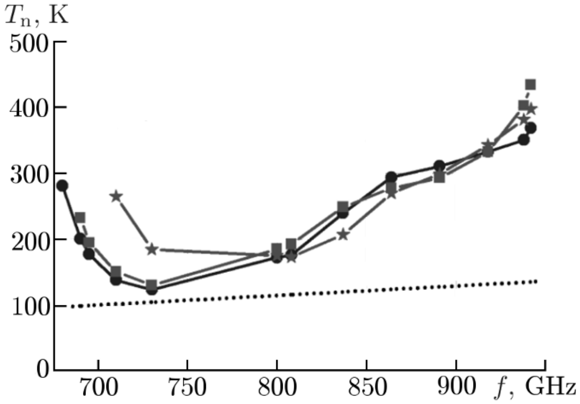

Fig. 5. Corrected noise temperature of various receiving elements as a function of frequency. Mixers *1* (●) and *2* (■) have identical adjustment structures and mixer *3* (★) has a design that differs from those of mixers *1* and *2*. The dots show the noise temperature which corresponds to $3hf/k_B$.

loss at a high frequency. The features of the calculated curve at frequencies above 950 GHz are the artefacts of the employed calculation models [6, 7]. Two deep dips on the experimental curve in the lower and upper parts of the frequency range are the water-absorption lines in the interferometer quasioptical channel.

The noise temperature was measured by the standard method of the "hot" and "cold" loads (Y factor). The absorbers at 300 and 77 K were used to simulate the "hot" and "cold" loads, respectively. Figure 5 shows the frequency dependences of the noise temperature for various types of the receiving elements. The presented data are corrected for the quasioptical-beam Mylar divider with a thickness of 12 μm and a transmission factor of 88%. In the range 700–950 GHz, the noise temperature increases from 120 to 390 K. Figure 5 shows the noise-temperature dependences on frequency for various receiving-element samples and the dependence $3hf/k_B$ (the quantity hf/k_B is called the quantum limit). The obtained results in the major part of the studied frequency range are comparable with the data for the tenth range of the ALMA radio telescope [8].

4. CONCLUSIONS

The measured noise temperature of the receiving elements in a significant part of the frequency range 790–950 GHz is smaller than a similar parameter for the high-frequency CHAMP+ receivers mounted on the APEX telescope. When optimizing the production processes, we reached a high quality of the tunnel junctions with an area of 0.5 μm^2 and a current density of 30 kA/cm^2. However, at high frequencies, one can observe a fast increase in the noise temperature. Calculations of the experimental response show that the high-frequency loss in the metal of the used films increases with increasing frequency faster than it follows from the theoretical estimates. It is assumed that the noise temperature can still be further reduced by improving the quality of the employed films and increasing the NbTiN-film thickness to 350 nm, which allows one to improve the propagation conditions of the high-frequency electromagnetic radiation.

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