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Published in:
Journal of Communications Technology and Electronics

DOI:
[10.1134/S1064226916120202](https://doi.org/10.1134/S1064226916120202)

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Document Version
Publisher's PDF, also known as Version of record

Publication date:
2016

[Link to publication in University of Groningen/UMCG research database](#)

Citation for published version (APA):

Rudakov, K. I., Paramonov, M. E., Dmitriev, P. N., Baryshev, A. M., Khudchenko, A. V., & Koshelets, V. P. (2016). Analysis of high-frequency parameters of superconducting planar structures. *Journal of Communications Technology and Electronics*, 61(12), 1395-1399.
<https://doi.org/10.1134/S1064226916120202>

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NOVEL RADIO SYSTEMS AND ELEMENTS

Analysis of High-Frequency Parameters of Superconducting Planar Structures¹

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Received July 18, 2016

Abstract—Planar microwave devices that make it possible to determine parameters of fabricated layers are developed and produced. The parameters are needed for correct numerical simulation based on the Mattis–Bardeen theory and may differ from the tabulated parameters of materials.

DOI: 10.1134/S1064226916120202

INTRODUCTION

Recent interest in the development and study of receivers and sources of terahertz (10^{11} – 10^{13} Hz) radiation with wavelengths ranging from several millimeters to wavelengths of the far-IR spectral range has been driven by topicality of wide-range applications. In this work, we present several terahertz receiving devices developed at the Kotel'nikov Institute of Radio Engineering and Electronics.

A high-sensitivity receiver for the Atacama Pathfinder Experiment (APEX) was developed at the Netherlands Institute for Space Research in the framework of the CHAMP project in 2006. The device that has been mounted on the radio telescope in Chile consists of two seven-pixel arrays [1, 2] of heterodyne receivers that work in spectral intervals of 600–720 and 790–950 GHz corresponding to the atmospheric transparency windows. Mixers based on superconductor–insulator–superconductor (SIS) Nb–AlN–Nb tunneling junctions serve as high-sensitivity elements of the receivers of the higher frequency range [3]. The junctions are located in a microstrip line formed by NbTiN and Al films. Modern receivers of the higher frequency range have a relatively high noise temperature of about 400 K. The CHAMP_HI+ project has been started to improve the sensitivity of radio telescope. The purpose of the project is the construction of a heterodyne superconducting receiver for a frequency interval of 790–950 GHz with a noise temperature of about 200 K.

A fully superconducting integrated receiver (SIR) has been developed at the Kotel'nikov Institute of Radio Engineering and Electronics in the framework of the Terahertz Limb Sounder (TELIS) International Project [4, 5]. The device provides continuous frequency tuning of the integrated oscillator of the heterodyne in a relatively wide frequency interval of 500–650 GHz. At present, the works are aimed at an increase in the working frequencies of the integrated receiver to a level of 1 THz.

Effective parameters of fabricated films are needed for the calculation of microwave circuits [6, 7]: in particular, the permittivity of the insulating layer in the microstrip line, London penetration depth λ_L , conductivity of superconductor with respect to dc current in the normal state in the vicinity of the transition temperature, and superconducting transition temperature T_c . Parameters T_c and dc-conductivity are needed for the models that take into account the frequency-dependent losses [7, 8], whereas parameter λ_L is needed for the models that disregard such losses. Note that the parameters are interrelated.

The above parameters substantially depend on the production technology and often differ from tabulated parameters. For example, an insulator layer may consist of a mixture of silicon oxide and dioxide at unknown relative contents rather than pure silicon dioxide. In addition, the presence of a transition layer between metal electrode and insulator leads to a variation in the effective permittivity.

¹ This work was awarded at the Anisimkin contest of young scientists.

Fig. 1. Scheme of the test planar capacitance.

1. MEASUREMENT OF THE EFFECTIVE PERMITTIVITY

To determine the permittivity, we fabricated several test samples (Fig. 1) that represent plane capacitors based on the Nb–SiO₂–Nb structure. To correct the measurement errors of the permittivity, we fabricate planar capacitors with different areas and identical (for each substrate) thicknesses.

A Tencor Alpha Step 200 Profilometer is used to measure the thickness of dielectric layer. Precision measurements of the area are not necessary, since the relative error of linear sizes of fabricated items is no greater than 1%.

The sample is fixed in the measurement unit at the end of a long metal tube and immersed in liquid helium. The measurements are performed using a two-point method/scheme, so the resistance and spurious, so that the resistance and spurious capacitance of wires in the metal tube that is dipped in liquid helium must be taken into account. A multimeter is used to generate a low-frequency signal with a fixed amplitude that is needed for the measurement of the resistance of

external circuit. The estimated capacitance of the capacitors is several hundreds of picofarads, and the effect of the resistance of connecting wires and contacts at a frequency of 100 Hz is insignificant. To take into account spurious capacitances, we perform the measurements on the setup with liquid helium in the absence of the sample under study. Then, we measure a reference capacitance of 330 pF at the liquid-helium temperature (spurious capacitance of connecting wires, metal tube, and measurement unit is 100 pF). Based on the experimental results, we determine the permittivity of the dielectric layer to be 4.1. Such a result is physically consistent, since the permittivities of pure silicon oxide and dioxide are 5.6 and 3.8, respectively.

2. DC-CONDUCTIVITY OF THE Al, NbTiN, AND Nb FILMS

We must also determine dc-conductivity of superconductor (Nb or NbTiN) and normal metal (Al) in the vicinity of the transition point of Nb and NbTiN and temperature T_c . To determine the parameters, we fabricate several test stripes with different thicknesses based on the Nb and NbTiN films deposited on the Al₂O₃ or SiO₂ buffer sublayer on the silicon substrate. The thickness and width of the samples are measured using a profilometer, and the resistance is measured with the aid of four-point scheme. Table presents the resulting conductivities. A semiconductor thermometer in the measurement unit is used to determine temperature T_c (see table).

3. LONDON PENETRATION DEPTH DETERMINED WITH THE AID OF THE RESONANCE METHOD

The physical principle of the method [9, 10] is based on the fact that the natural frequencies of the microstrip resonator are determined by its geometrical sizes, capacitance per unit length (calculated in the previous experiment), and inductance. Thus, the calculations of the resonance frequency can be performed with allowance for the London penetration depth that provides the best agreement of the calculated resonance frequency and experimental results. A single Nb–AlO_x–Nb tunneling SIS junction located at the center of the resonator is used as the source and receiver of microwave signal. In accordance with the second Josephson law, the SIS junction generates the microwave radiation. When the generation frequency coincides with the frequency of the eigenmode of the microstrip resonator, significant variations in the boundary conditions for the tunneling junction lead to specific I – V characteristic. Figure 2 shows a typical scheme of the structure, and Fig. 3 presents the scheme of the chip with several resonators.

Conductivities of superconductor and normal metal

Sample	T , K	DC conductivity, S/m	T_c , K
Nb	10	2.21×10^7	9
NbTiN	15	9×10^5	14
Al	4.2	1.89×10^8	—

Fig. 2. Topology of the microstrip resonator with a length of $308\ \mu\text{m}$ for the measurement of the London penetration depth.

To implement the above approach, we must correctly insert the tunneling SIS junction in the microstrip resonator and choose the parameters of the tunneling junction providing a relatively low plasma frequency. Thus, the resonances can be detected at relatively low frequencies. For this purpose, we must choose the optimal sizes and density of the tunneling junction and provide its matching with the impedance of the microstrip line, since the generator of microwave current is used to excite the SIS junction. General physical principles show that the generator of current in resonant structures must be located at the minimum. Thus, we choose the scheme in which the tunneling SIS junction is connected in the series-type resonance. The critical current density in the SIS junction is chosen in such a way that the estimated frequency of plasma oscillations is lower than the needed resonance frequency, and the microstrip resonator sizes are chosen in such a way that the impedance of one half of the resonator and the differential resistance of the junction at the resonance frequency of the structure are on the same order of magnitude. The measurement contacts must be correctly connected to the microstrip resonator to provide its maximum Q factor. Thus, the microstrip resonator outputs are connected to the contact pads via radial closing contactor. The structure for the dc-current measurements is constructed in such a way that a relatively low impedance of electromagnetic wave in the region of the radial closing contactor is transformed into a relatively high impedance (virtual disconnection) in the vicinity of the connection to the microstrip resonator at the working frequency of the microstrip resonator. In this case, the conducting lines also form an additional cavity but its resonance frequencies are significantly higher than the frequencies of the main microstrip resonator (MC in Fig. 2).

The I – V characteristics of the tunneling SIS junction in the cavity are measured at fixed current or voltage at several temperatures and magnetic fields. The magnetic field is generated by an external coil located inside a magnetic shield in the liquid-helium container.

A variation in the magnetic field leads to a variation in the critical current of the tunneling SIS junction

Fig. 3. Scheme of the test sample for the measurement using the resonance method in the presence of external magnetic field.

and, hence, variations in the impedance and plasma frequency. The experiments performed at optimal magnetic fields and well-matched tunneling SIS junction and cavity show that specific features emerge on the I – V characteristics at voltages that correspond to the Josephson generation at the eigenfrequencies of the cavity. The current of superconducting carriers provides the Josephson generation, so that an increase in the magnetic field, resulting in a decrease in the critical current, causes a decrease in the amplitude of the generated microwave signal. In the presence of strong magnetic fields the specific features on the I – V characteristics are hardly detectable (Fig. 4a).

An alternative method for the observation of the specific features of the I – V characteristics employs the heating of the sample. An increase in the temperature of the SIS junction leads to a decrease in the plasma frequency and exponential increase in the leakage current, which cause a variation in the impedance of the SIS junction and provide the observation of resonances. Note that even minor variations in the temperature may lead to significant variations in the matching of the SIS and cavity. When the SIS and microstrip line are perfectly matched, the specific features of the I – V characteristics are observed even in the absence of external magnetic field (Fig. 4b).

Fig. 4. I – V characteristics of the SIS junction in the cavity with a length of 308 μm in the current regime (rising branch) measured (a) in the presence of external magnetic field (the magnetic field increases from upper to lower curves) and (b) at several temperatures (the temperature increases from upper to lower curves).

4. CALCULATION, MEASUREMENT, AND OPTIMIZATION OF THE CHAMP_HI+ RECEIVING UNIT

The determined above parameters and specific capacitance of the tunneling SIS junction C_{sp} are needed for the development and simulation of the receiving unit. The exact value of capacitance C_{sp} was unknown in the course of development of the first prototype. Several units were designed and fabricated on a single substrate, and each unit was optimized with respect to a certain value of capacitance C_{sp} .

A Fourier-transform spectrometer (FTS) based on the Michelson interferometer is used to experimentally measure the response of each receiving structure. A global resistive heater serves as the broadband source of the terahertz radiation. Atmospheric conditions in a significant part of the quasi-optical path lead

Fig. 5. (1) Theoretical and (2) experimental responses R of the receiving unit and (3) and (4) theoretical responses R of the two tunneling junctions in arbitrary units.

to two sharp dips on the FTS spectra caused by the absorption of water vapor.

The parameters of the layers determined with the aid of the above methods make it possible to decrease the number of unknown variables in the numerical model from six to one, so that a variation in the specific capacitance in the calculation model can be used to reach the best agreement of the theoretical model and experimental response curves. Figure 5 shows the experimental and theoretical responses of the receiving unit based on the structure with two SIS junctions and the relative contribution of each tunneling junction in the total response. The analysis of the results shows that the receiving element based on a single SIS junction has a lower noise temperature due to better matching and a decrease in the shot-noise level but in a narrower frequency band in comparison with the receiving unit based on two tunneling junctions. Nevertheless, the width of the response of the receiving unit based on a single SIS junction is sufficient for operation in a frequency interval of 790–950 GHz.

A receiving unit based on a single SIS junction is designed and fabricated using the above parameters. The first experiments show that such a receiving unit is extremely sensitive to deviations in technological process, so that the desired response band can hardly be reached in a working interval of 790–950 GHz. Figure 6 presents the results of the first measurements of the noise temperature of receiving units fabricated on a single substrate and based on one and two tunneling junctions.

The receiving unit based on two tunneling junctions is less sensitive to technological deviations of the sizes of elements. The optimization of technological procedures of fabrication of the receiving unit based on two SIS junctions makes it possible to reach even lower noise temperature of the receiver (120 K at a fre-

Fig. 6. Noise temperatures of the receiving units based on (1) one and (2) two SIS.

quency of 725 GHz) that is higher than a quantum limit of hf/k_B only by a factor of 3 [11].

CONCLUSIONS

The electrophysical parameters of the films that are used for fabrication of supersensitive terahertz receiving units are measured. The parameters are employed in the calculations of newly designed microwave receiving units of the terahertz frequency range.

ACKNOWLEDGMENTS

This work was supported by the Ministry of Education and Science of the Russian Federation (project no. 14.607.21.0100, identification no. RFMEFI60714X0100).

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Translated by A. Chikishev