First Results on Irradiation of Superconducting Elements for Terahertz Receivers in Deep Space

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2022 IEEE 8th All-Russian Microwave Conference (RMC) | 979-8-3503-3206-3/22/$31.00 ©2022 IEEE | DOI: 10.1109/RMC55984.2022.10079335

Abstract – The primary results of assessing of high sensitive receiving structure based on tunnel SIS (Superconductor-Insulator-Superconductor) and NIS (Normal metal-Insulator-Superconductor) junctions to radiation are presented in this paper. It was shown that irradiation with bremsstrahlung radiation with a dose of $5 \cdot 10^6$ rad and gamma-neutron radiation with fluences of 10^{15} cm^2 did not affect the characteristics of receiving devices based on SIS and NIS tunnel junctions

Keywords— *subterahertz waves, superconducting detectors, SIS junctions, NIS tunnel junctions, SINIS detector, radio astronomy, space communications, radiation resistance.*

I. INTRODUCTION

The development of high sensitive subTHz receiving systems requires space and ground-based radio telescopes [1-2], deep space communications, 6G and next generations of mobile communications [3-6] radar [7, 8], for remote sensing of the atmosphere and environmental pollution monitoring. The development of detectors and mixers is a key stage in the creation of a receiving device for modern astronomical research, in particalar the Russian space mission Spectr-M (Millimetron) [9]. Such receivers are required for the international project RT-70 (observatory on the Suffa plateau, Uzbekistan), and can also be widely used for telecommunication systems in deep space.

In the case of space instruments (observatories), the subTHz equipment (and in particular the detection module) it will be under the influence of ionizing radiation (X-ray, γ-radiation, streams of protons, electrons, neutrons, α-particles, ions) what can lead to significant change the properties of materials and functional characteristics of subTHz receivers that are require a detailed study of these consequences, and accurate prediction and reduction of their negative effects. The main task of this paper is to test the operability of detecting devices based on SIS and NIS tunnel junctions under conditions of radiation exposure.

The study was carried out within the framework of the scientific program of the National Center for Physics and Mathematics (project #6 "Nuclear and Radiation Physics"). The equipment of USU "Cryointegral" was used for fabrication of tested subTHz structures; this USU is supported by a grant from the Ministry of Science and Higher Education of the Russian Federation, agreement No. 075-15-2021-667. Development of subTHz receivers for radioastronomy was carried out as part of the state assignment the IAP RAS (No. 0030-2021-0005), in collaboration in the development superconducting detectors with IRE RAS under the project № FFWZ 2022-0005. The work of A. A. Gunbina as the PhD student was supported by the scholarship of the President of RF (СП-4497.2022.3).

As an example, the flight of the balloon subTHz observatory Olimpo around the North Pole from Svalbard. The expedition was prepared and successfully carried out with the participation of the team of authors of this publication. The problems of testing of radiation resistance are described in detail in the joint publication [10]. The problems of radiation resistance during the flight were occurred, but were not of critical importance. In general, the equipment worked well, but due to spikes in the response of the parasitic signal (glitches) a part of the information from hitting the cosmic ray to detector (up to 5%) was lost, which of course is not very good but not critical.

The preferred method of studying of the subTHz receiving structures suitable for space missions is a direct full-scale experiment on board a spacecraft - a space observatory or other object in orbit. Eventually, the receiving systems that are being created should find their place on board of the space observatory the Millimetron, which is being created as part of the Russian Space Program with a planned launch in 2029 (the Spectr-M project). However, given the expected lifetime of the mission, it is no longer possible to test the radiation resistance of the created equipment before the start of the actual space experiment before the beginning of the stages when the composition of the onboard complex of scientific equipment should be fully formed. Having the opportunity to vary the radiation doses, it is possible to simulate in laboratory the conditions of the doses characteristic of the upcoming 5-year mission flight in a short time and to provide, upon completion of this project, reliable confirmation of the operability of the subTHz equipment long before the critical pre-launch dates in the development of the Spectr-M project.

II. INVESTIGATED SAMPLES

In the current work the receiving subTHz superconducting integral structures based on SIS (Superconductor-Insulator-Superconductor) and NIS (Normal metal-Insulator-Superconductor) tunnel junctions were fabricated and investigated.

A. *Integrated circuit based on SIS tunnel junctions*

Integrated circuits based on Nb-AlOx-Nb and Nb-AlN-NbN tunnel junctions combine in one chip a superconducting local oscillator of the 250-700 GHz band, a SIS detector for monitoring the oscillator signal and circuits for matching of the generator and detector [11-13]. The dimensions of the generator are 400 x 16 μm^2, the area of the SIS junction is 1-2 μm^2. The photo of the central part of the chip is shown in Fig. 1.

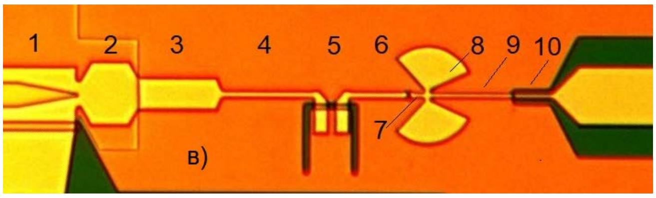

Fig. 1. A photography [12] of the superconducting integrated circuit comprising a generator based on a distributed Josephson junction and SIS detector. 1 – a Josephson generator – so called flux-flow oscillator (FFO); 2, 3, 4 - sections of a three–stage impedance transformer; 5 - DC break for decoupling a FFO and a SIS; 6 - a single-section impedance transformer; 7 - the SIS junction with an inductive section for capacity tuning; 8 – radial stubs for grounding the inductive section at high frequency; 9 - a quarter-wave segment of a microstrip line for connection of SIS junction to IF amplifier; 10 - output coplanar line.

B. *SINIS detectors*

The SINIS detector [14] is a multilayer Superconductor-Insulator-Normal metal-Insulator-Superconductor structure (schematic image – Fig.2). The sensitive element is a submicron strip of normal metal, and two tunnel NIS junctions act as a thermometer. The receiving devices that were studied in this work are 7×7 mm silicon chips with two annular planar antennas with 4 integrated SINIS detectors in each (the photo of SINIS detector – see Fig. 3).

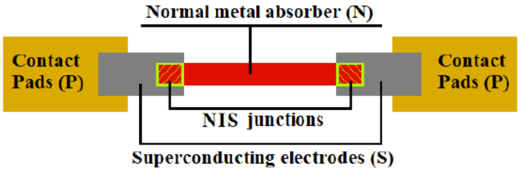

Fig. 2. The schematic view of SINIS detector, figure from [15].

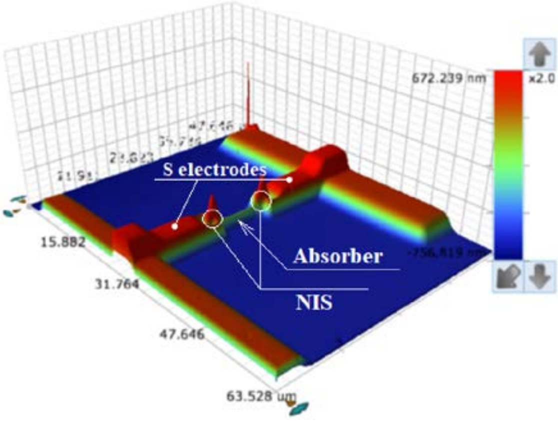

Fig. 3. The 3-d view of SINIS detector made by optical profilometer.

III. EXPERIMENT AND RESULTS

The braking radiation of linear resonance accelerator [16] and gamma-neutron radiation of nuclear reactor [17] were used as a radiation sources which are simulating long-term exposure of cosmic rays in deep space conditions. For the first tests, the following irradiation parameters were used: the exposure dose of bremsstrahlung $5 \cdot 10^6$ P, the fluence of neutrons with an energy of more than 0.1 MeV - 10^{15} cm^{-2}. At the first stage of this project was supposed to study only final states – whether the receiving structure remained functional after irradiation or not.

A. *Integrated SIS circuits*

Four integrated SIS circuits were irradiated. Table 1 shows data of the type and dose of irradiation for each of the samples, as well as the main characteristics of the SIS junctions before and after irradiation (Rn is the normal resistance of the junction, Rj/Rn is the ratio of the resistance of the junction below the energy gap to the normal resistance). Here the measurement results for one sample from the batch - No. 1 and No. 3 are presented. Fig. 4 shows the IV curves of the SIS detectors (sample No. 1) before and after irradiation. Autonomous IVC as well as under the influence of FFO signals at frequencies of 400, 500, 600 GHz are demonstrated; similar measurements for sample No. 3 are shown in Figure 5. From the presented results, it can be concluded that the irradiation of samples by different sources did not affect characteristics both the SIS and the FFO.

Table 1

Type of irradiation	Radiation dose	Sample №	Type of structure	Rn before irradiation, Ohm	Rn after irradiation, Ohm	Rj/Rn before irradiation	Rj/Rn after irradiation
Bremsstrahlung	$5\cdot10^6$ R	1	Nb-AlOx-Nb	16.63	16.73	16.7	16.0
		2	Nb-AlN-NbN	28.23	28.32	31.9	30.2
Neutrons	10^{15} sm^{-2}	3	Nb-AlOx-Nb	18.94	19.15	11.1	12.8
		4	Nb-AlN-NbN	57.79	not available	11.4	not available

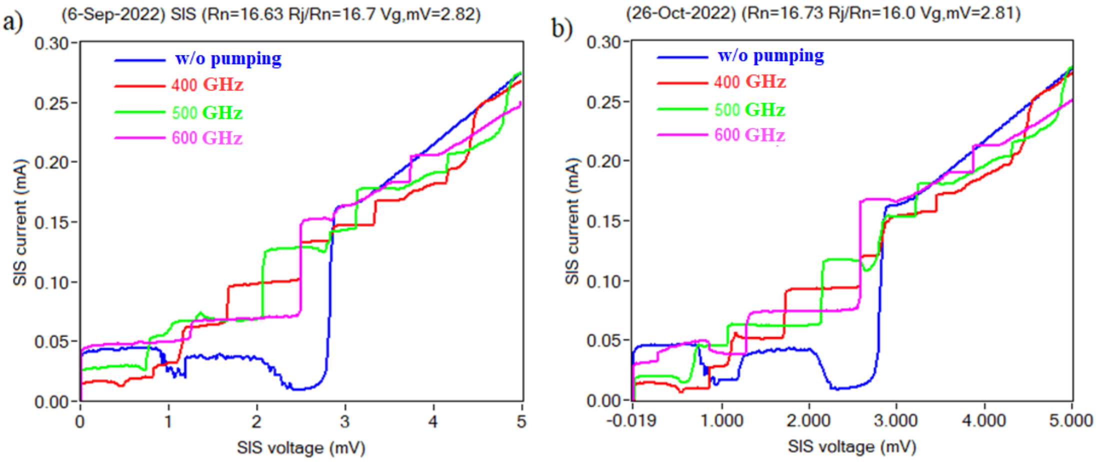

Fig. 4. IV curves of sample No 1 a) before and b) after irradiation. Curves are given without the influence of a signal, as well as under the influence of signals at frequencies of 400, 500, 600 GHz. At voltages that are corresponding to these frequencies ($V_n=n\hbar\omega/2e$) Shapiro's steps are visible.

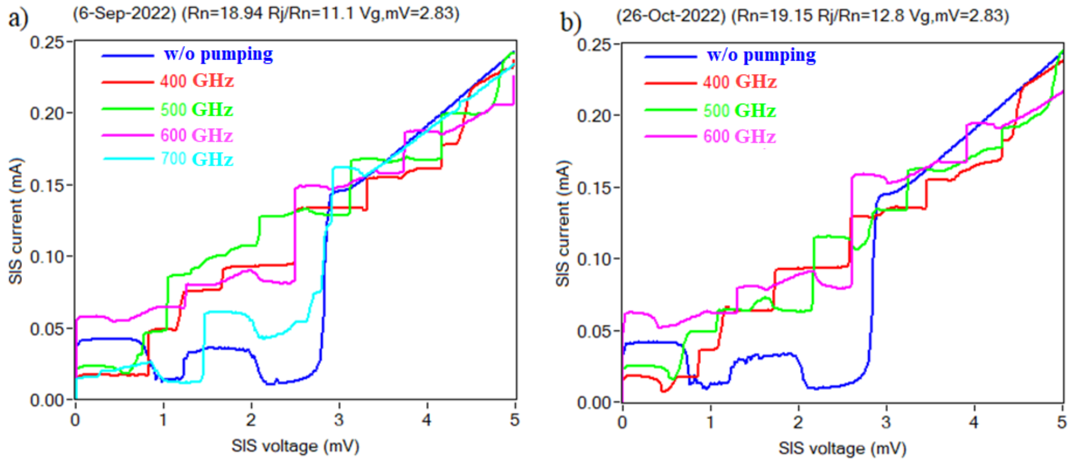

Fig. 5 IV curves of sample No 3 a) before and b) after irradiation. Curves are given without the influence of a signal, as well as under the influence of FFO signals at different frequencies. At voltages that are corresponding to these frequencies ($V_n=n\hbar\omega/2e$) Shapiro's steps are visible.

B. SINIS-detectors

Samples of the SINIS detectors were irradiated with the same doses and in addition one of the samples was irradiated with both the first and second source, we will give the results for this sample. In this case, the characteristic of the sample quality is the resistance ratio, which at an operating temperature of 300 mK was more than 100, as it was before irradiation (Fig. 6). In this regard, it can be concluded that the SINIS detectors at the first stage of research are resistant to radiation and it is possible to proceed to detailed studies.

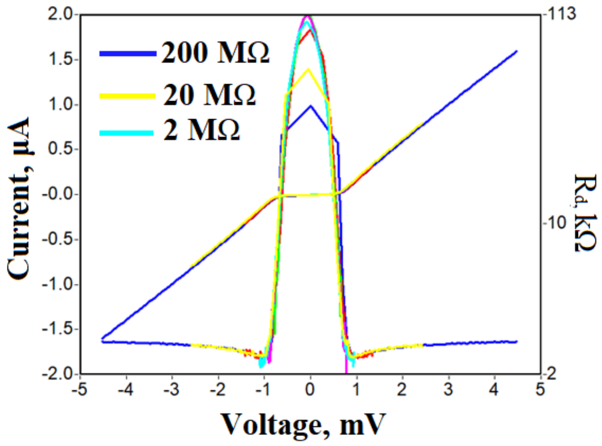

Fig.6. Measured IV curves and dynamic resistance of a sample of a SINIS detector irradiated with two sources. Curves are taken with bias resistances from 2 MΩ to 200 MΩ.

IV. CONCLUSION

Initial test studies of receiving devices based on tunnel SIS and NIS junctions showed that irradiation of them by various radiation sources did not affect their characteristics. At the next stages, it is assumed to study structures with a different number and layout of detectors (which is required primarily for multi-matrix receivers). Also, different additional doses, corresponding 5 years doses in the L2 point may be considered. At the final stage of the project, it is of interest to study the whole receiving system under irradiation, which, in addition to the detecting module, includes readout electronics and a portable 0.3 K cryogenic system. The presented first tests bring some optimism that the final stated goals of development of receivers for deep space are achievable; at least the initial exposures did not make dramatic changes in the characteristics of the samples.

The initiated project for the development of radiation-resistant receiving equipment in the subTHz range involves the fabrication of a series of receiving systems for deep space, which will be tested on the unique VNIIEF equipment complex [18-19]. To do this, prototype devices will be developed, the first batch of which is being tested as part of the initial stage of the project presented here. Subsequently, the receivers will be tested in real operation under the influence of ionizing radiation. Now a set of initial data has already been prepared for designing a mobile 0.3 K cryoelectronic hardware and software complex for testing the characteristics of receiving systems in operating mode with simultaneous exposure to cosmic rays.

ACKNOWLEDGMENT

The study was carried out within the framework of the scientific program of the National Center for Physics and Mathematics (project #6 "Nuclear and Radiation Physics").

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