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SUPERCONDUCTIVITY

SINIS Bolometer with Microwave Readout

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Abstract—A bolometer, which is based on a superconductor—insulator—normal metal—insulator—superconductor (SINIS) structure, integrated into a twin-slot antenna with a central frequency of 90 GHz, and connected with a superconducting microwave readout resonator, has been designed, fabricated, and experimentally studied. Such an elementary cell is designed for the multi-element array of a high-sensitive radioastronomic receiver, in which the readout from a great number of channels is performed by a single coaxial cable instead of separate wires and amplifier in each channel.

Keywords: SINIS bolometer, microwave readout, frequency-domain multiplexing, twin-slot antenna, coplanar resonator

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1. INTRODUCTION

The active development of radioastromony in the subterahertz frequency range covering the short-wave region of the millimeter and submillimeter ranges of wavelengths increases the requirements to receiving systems, namely, they must have a broad dynamic range and a low noise-equivalent power (NEP) of less than 10^{-16} W/Hz$^{1/2}$ for ground-based observatories and three orders of magnitude better for space missions (10^{-19} W/Hz$^{1/2}$). In this connection, the reduction of intrinsic noises in such systems with the purpose to increase their sensitivity is a vital problem. One of the dominating components of the noise characteristics of a receiving system is the noises contributed by the bolometer signal readout system. The earlier applied readout systems based on field-effect transistors with intrinsic noises at a level of 20 nV/H$^{1/2}$ have no prospects of application in the modern receiving systems for radioastronomic observatories. The creation of a microwave readout system for bolometric structures makes it possible to get rid of low-frequency flicker noise, and the use of a cryogenic amplifier in the immediate proximity to bolometers decreases both amplifier noises and interference noises on long wires, thus improving interference immunity.

In view of this fact, the creation of a radioastronomic receiver based on a superconducting bolometer as a sensitive element with the frequency-domain multiplexing of channels for a bolometer connected to a high-quality coplanar resonator is a relevant problem. This readout method will provide the possibility to read, if necessary, several thousands of channels by a single coaxial line. An example of the practical implementation of such an approach may be the Simons Observatory [1] with 60000 superconducting sensors, the CCAT-prime project [2] with 200000 sensors, and CMB Stage IV [3] with 500000 sensors. Assuming that the mass of one readout amplifier is 1 g, the mass for all channels will be above 500 kg and, in this case, the cryostat must be connected with one million of wires, which disable traditional readout even for ground systems. Almost all the contemporary superconducting multi-array radiation receivers are based on frequency-domain multiplexing. When the number of channels is less than 100, it is possible to use relatively low-frequency megahertz bandwidth systems with SQUID amplifiers [4]. Such systems are used in the POLARBEAR, EBEX, and South Pole Telescope tools. A greater number of channels require a much broader frequency range of several gigahertz. For microwave kinetic inductance detectors (MKIDs), the readout systems with frequency-domain multiplexing have been created and are successfully used.

Among the pioneer implementations, it is possible to mention such tools as MUSIC [5] and NIKA [6]. Another example of such a system is the recent work [7] with the simultaneous readout of 5000 pixels at a temperature of 250 mK. This readout system is described in details in the paper [8].

Table 1. Parameters of four types of resonators

No.	Coplanar resonator length, μm	Design resonance frequency, GHz
1	4800	6
2	6800	4.2
3	8800	3.2
4	13800	2

2. SINIS BOLOMETERS WITH COPLANAR RESONATORS

This paper describes the prototype of an integrated receiver based on bolometers with a superconductor–insulator–normal metal–insulator–superconductor (SINIS) structure with a microwave signal readout system at frequencies of up to 10 GHz, a cryogenic amplifier (4 K) on the basis of a high electron mobility transistor (HEMT), and a noise temperature of 1 K. Among the advantages of SINIS bolometers are a broad dynamic range, NEP of no worse than 10^{-16} W/Hz$^{1/2}$, a high responsivity (of up to 10^9 V/W), and a high operational speed (of less than a microsecond). We have integrated a SINIS bolometer with a superconducting readout resonator. A similar approach was implemented in the works [9, 10] with a SINIS bolometer with a large absorber volume of nearly 5 μm^3. The design of the coplanar resonator and twin slot antenna is identical to the design [11] optimized for a low-resistance superconducting transition-edge transition-edge bolometer. In our case, the topology of coplanar lines for a more high-resistance SINIS bolometer was optimized by numerical modeling to match the impedances. The first batch of samples was fabricated by the traditional technology of shadow evaporation with a suspended resist bridge and a coplanar resonator of 4.8 mm in length.

The second batch of samples was fabricated by the bridgeless technology and incorporated four types with different coplanar resonator lengths and design frequencies from 2 to 6 GHz (Table 1).

3. LAYOUT AND MANUFACTURING TECHNOLOGY

The design is based on a single bolometer integrated into a twin slot antenna with a central frequency of 90 GHz. This central frequency of 90 GHz was selected due to that the first testing site for the developed structures is planned to be the Big Telescope Alt-azimuthal (BTA) [12], and the atmospheric transparency above 100 GHz is much worse in this case. The obtained results will be used to develop the prototype of a receiving system for the telescope under construction on the Suffa plateau [13] and, eventually, for the MILLIMETRON Russian space observatory [14]. The results obtained in the course of this project may also be applied for some other promising developments, namely, the readout system of other types (e.g., for TES and KID) for bolometric arrays, the SQUID structures for quantum-information technologies, and the developed technologies for the fabrication of different micro- and nanostructures.

A planar twin slot antenna has good directivity characteristics in combination with a quasioptical horn or dielectric lens. The antenna (Fig. 1) has two parallel slots in the lower niobium nitride layer. These slots are coherently excited with short sections of the coplanar lines with a SINIS bolometer in the center. One section of a coplanar line is parallel to the slot in the long superconducting section, which functions as a quarter-wave resonator. This resonator is shorted at the far end, and the open end is terminated by the SINIS bolometer in the antenna. The coplanar quarter-wave resonator has a quality factor $Q = 232$ at $f = 5.8$ GHz without the bolometer and $Q = 33$ at $f = 4.95$ GHz with the bolometer (Fig. 2).

The normal metal absorber of the SINIS bolometer has a resistance corresponding to the real impedance part of the antenna, into which it is integrated. The bias current corresponds to the working point with a maximum sensitivity.

The resonator was fabricated from an NbN layer of 50 nm in thickness with estimated kinetic inductance of 4 pH per square. This makes it possible to appreciably reduce the geometric length of a resonator. The first layer contains a resonator, a twin slot antenna, an output resonator, contact pads, and connecting wires. The NbN film was etched in Cl_2/Ar plasma. The bolometers were formed in the second layer with the use of a double-layer resistive mask with further evaporating at the angles of superconducting Al electrodes. The normal metal represents Al, which has a thickness of 20 nm and superconductivity suppressed by the underlying of Fe film with a thickness of 1 nm, and the barrier was formed during the oxidation of this Fe/Al layer.

In parallel with the traditional technology, the development of a technology for the fabrication of submicron SIN and SIS junctions in a resist mask without suspended Dolan bridges is proposed in this paper (the photo of a bolometer fabricated by such technology is shown in Fig. 1b). This technology [15] has many advantages over the earlier applied method, namely, the possibility to fabricate tunnel junctions with an area from 0.01 to 1000 μm^2, to improve the size reproduction accuracy and the electrical and heat conductivity of wiring conductors, and to perform the ion-beam cleaning of a substrate before evaporation. The stages of the new developed technology are schematized in Fig. 3. The essence of this technology consists in the separate evaporation of two films of different metals into two orthogonal deep grooves in a double-layer resist (Figs. 3a and 3b). The evaporation of the first film along the first groove does not lead to its

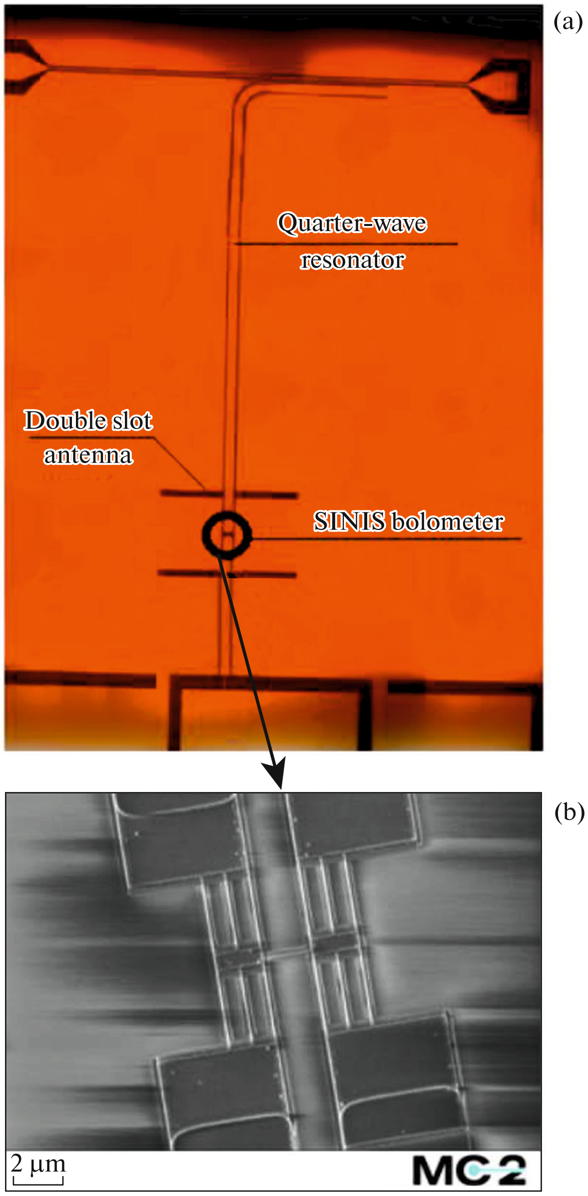

Fig. 1. (a) Optical microscopy photo of the general view of a fabricated sample and (b) SEM image photo of the bolometric structure manufactured by the technology of bridgeless shadow evaporation.

evaporation into the orthogonal groove (Fig. 3c), and the evaporation angle was selected such that evaporation towards the second groove is performed onto the resist wall with further lifting off in the remover. The same also takes place when the other film is evaporated into the second orthogonal groove after the substrate is rotated by 90° (Fig. 3d). The insulator was formed by oxidation of the first film in a deposition chamber (10 Torr, 10 min). The application of separate exposure for the two resist layers makes it possible to perform precise control over the profile of grooves and avoid the formation of vertical metallic walls after the evaporating of films.

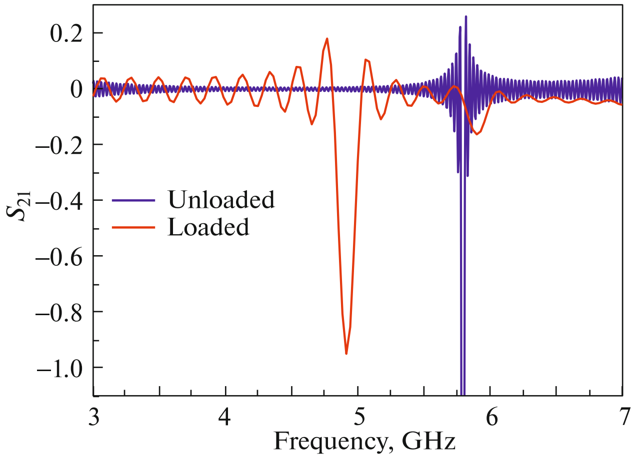

Fig. 2. Resonance of the quarter-wave coplanar resonator without ($Q = 232$, $f = 5.8$ GHz) and with ($Q = 33$, $f = 4.95$ GHz) the bolometer.

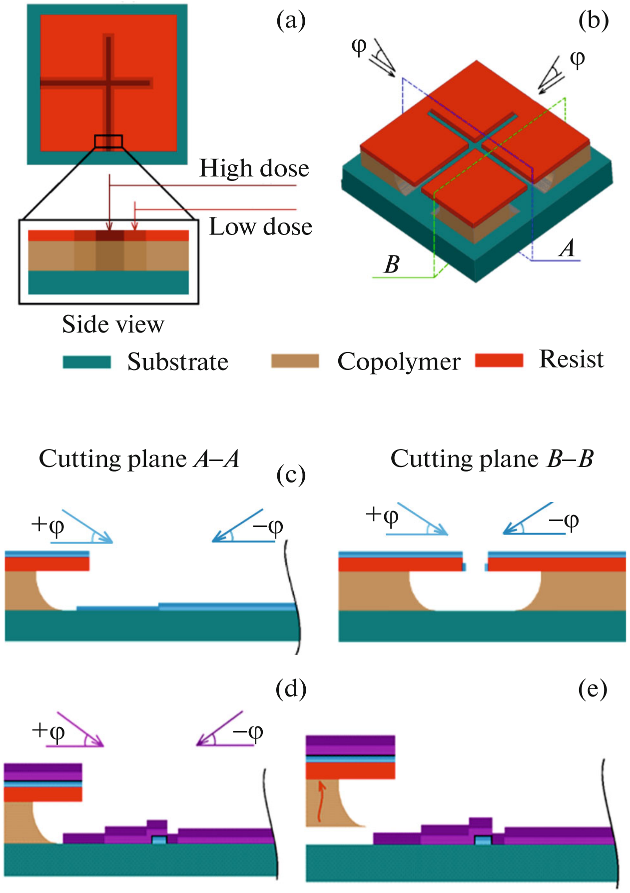

Fig. 3. Stages of the developed technology for the fabrication of tunnel junctions: (a) exposed structure before development, (b) exposed structure after development, (c) evaporating of the first film at angles of ±45°, (d) evaporating of the second film into the orthogonal groove, (e) lifting off of the resist in the remover.

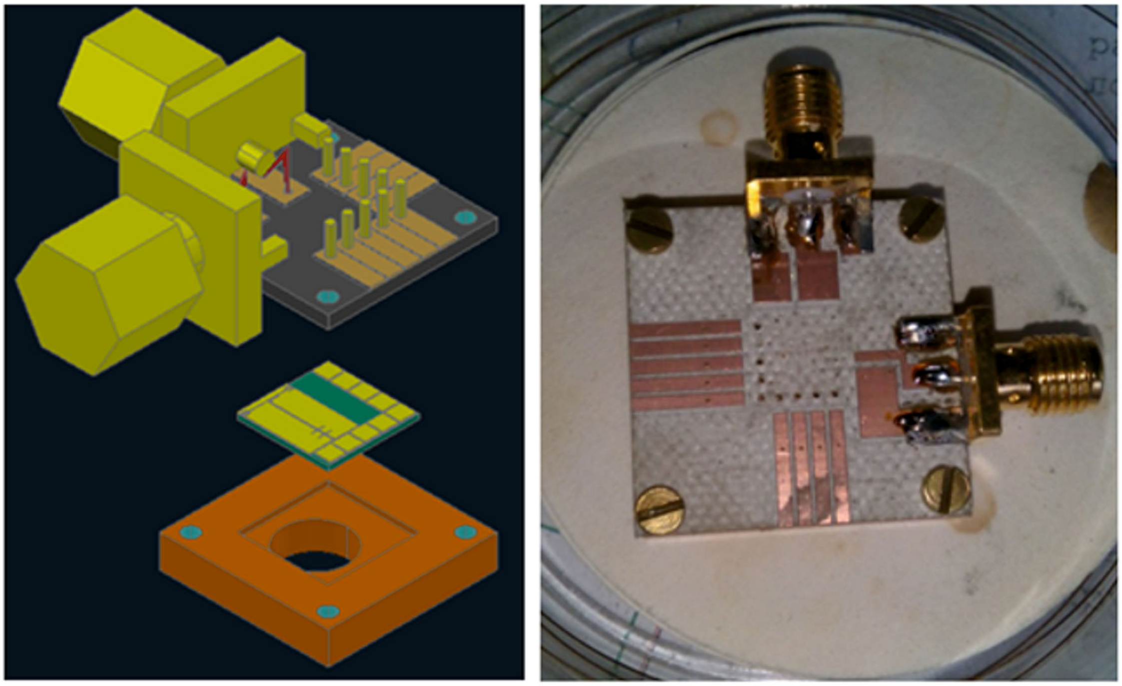

Fig. 4. Sample holder with SMA connectors.

4. EXPERIMENTAL SETUP AND RESULTS OF MEASUREMENTS

The measurements of current-voltage (IV) characteristics were performed in an Oxford Instruments Heliox AC-V cryostat at a temperature of 300 mK. The photo and scheme of the sample holder developed for such measurements are shown in Fig. 4. The spectral response of a studied sample was also measured with the use of a tunable backward-wave oscillator (BWO) within a range of 75–100 GHz (Fig. 5). The radiation power was normalized to a signal from the reference channel with a pyroelectric receiver. For the spectral response of the developed structures to be more precisely estimated, the additional normalization of a received signal to the reference signal (the signal received from the ruthenium resistor installed inside the cryostat near the studied sample) and the signal from the chain of NIS (thermometer) structures was applied. Such calibration provides the partial “elimination” of multiple rereflections inside the cryostat and substrate heating. The specific features of such a calibration method are detailed in our work [16].

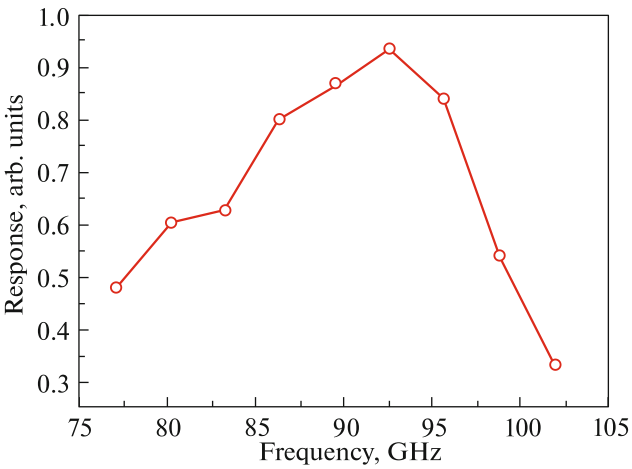

Fig. 5. Spectral response of the bolometer to BWO radiation.

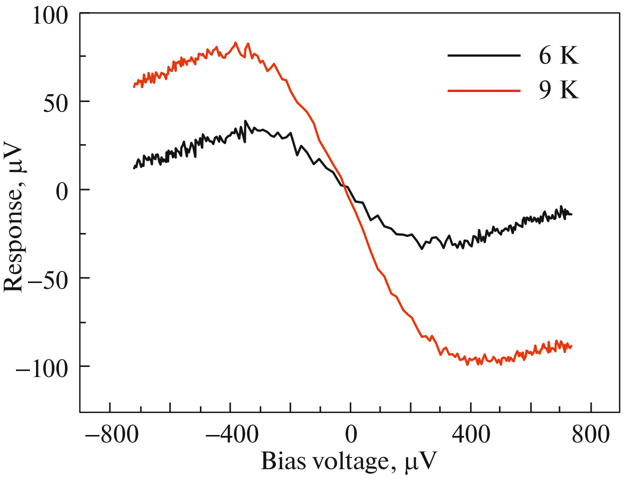

Fig. 6. Response to black body radiation at temperatures of 6 and 9 K.

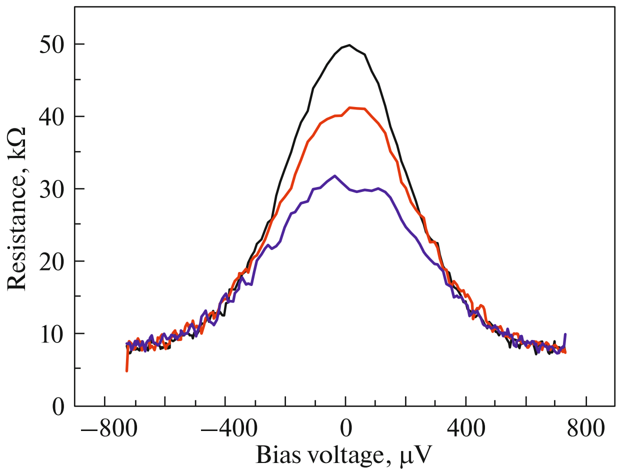

Fig. 7. Dynamic resistance at three signal power levels.

We have also measured the response of a sample to black body radiation at temperatures of 6 and 9 K (Fig. 6) in an immersion dilution cryostat at a temperature of 100 mK [17]. The corresponding dynamic resistance maximum variates from 50 to 30 kΩ. The experimental dynamic resistances at three radiation power levels are plotted in Fig. 7. For the coplanar line with a resistance of 50 Ω, such a load corresponds to the Q-factor of 1000 and 300 for the dark and irradiated cases, respectively. The impedance change from 30 to 50 kΩ can be easily detected from the change in the resonance frequency and Q-factor and enables microwave readout with the frequency division of channels.

5. CONCLUSIONS

The SINIS bolometer designed for the use with a microwave readout system was designed, fabricated, and experimentally studied. The spectral response was measured at a signal frequency within a range of 90 GHz. The electrical response and dynamic resistance of such a bolometer to black body radiation were measured at temperatures of 6 and 9 K. In this case, the dynamic resistance variates from 50 to 30 kΩ, which corresponds to the change in the Q-factor from 1000 to 300.

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CONFLICT OF INTERESTS

The authors declare that they have no conflicts of interests.

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