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SUPERCONDUCTIVITY

Quantum Response of a Bolometer Based on the SINIS Structure with a Suspended Absorber

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Abstract—Bolometers based on the superconductor–insulator–normal-metal–insulator–superconductor (SINIS) structure with an absorber suspended above the substrate are developed, fabricated, and experimentally studied in the terahertz frequency range. In contrast to the previously studied bolometers with an absorber located directly on the substrate, the real bolometric mode of operation is achieved, i.e., there is more than one excited electron per quantum of electromagnetic radiation (the quantum efficiency is larger than 1). A quantum efficiency of fifteen electrons per quantum of radiation with a frequency of 350 GHz was achieved in the studied bolometers.

Keywords: bolometer, cold-electron bolometer, bolometer based on SINIS structure, quantum efficiency, NETD

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1. INTRODUCTION

The concept of a bolometer based on the superconductor–insulator–normal metal–insulator–superconductor (SINIS) structure emerged as a development of the idea of Andreev's bolometer [1], in which the superconductor–normal metal (SN) contacts were proposed to replace with superconductor–insulator–normal metal (NIS) tunnel junctions [2]. Traditionally, such bolometers were fabricated using the shadow deposition technique, in which the first layer (absorber) was evaporated directly on the substrate. The possibility of direct electron cooling in such structures—owing to which they are also called "cold-electron bolometers" (CEBs)—was an equally important advantage. In addition, a theoretical model based on the heat balance equation [3], which is applicable only to estimate a direct-current sensitivity and inherited from the Andreev receivers, is used to describe the operation of the bolometer based on the SINIS structure. The calculation of the sensitivity from the heat balance equation for SINIS structures (CEBs) does not take into account the quantum nature of absorption, the phonon–electron exchange interaction, and a decrease in the quantum efficiency due to the removal of high-energy electrons.

2. OPERATING MODES OF THE SINIS BOLOMETER

The real description of terahertz radiation absorption in the SINIS structures turns out to be substantially more complicated [4]. If an electron absorbs a photon with an energy that is much higher than the thermal energy, then the electron energy will correspond to electron temperature $hf = kT_e$ of about 17 K for 350 GHz. At this temperature, electron–electron interaction time $t_{ee} \sim 1/T^2$ (1 ns) is much longer than electron–phonon interaction time $t_{\mathrm{eph}} \sim 1/T^4$ (0.1 ns) [5]. As a result, a high-energy phonon is created. It has three opportunities: to go to the substrate, to go to the superconducting electrodes, or to interact with the electronic system. When energy is transferred to an electronic subsystem, an excited electron–excited hole pair with an energy of $hf/2$ is produced. The excited electron with an energy of $hf/2$ generates a phonon with an energy of $hf/2$, which corresponds to an electron temperature of 8.4 K. The phonon gener-

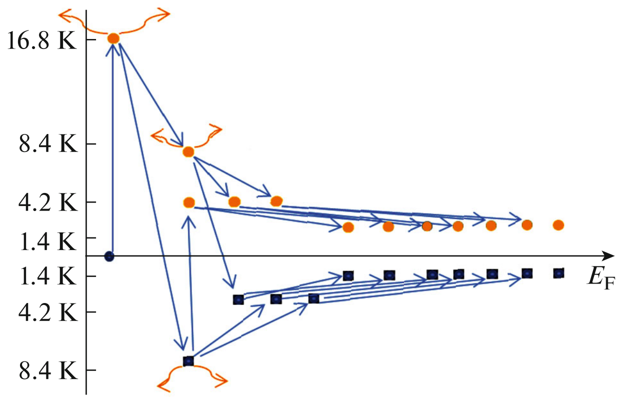

Fig. 1. Schematic diagram of the process of thermalization of a radiation quantum with a frequency of 350 GHz.

ates an electron–hole pair with an energy of $hf/4$, which corresponds to an electron temperature of 4.2 K, and the hole with an energy of $hf/2$ is involved in a similar process with the creation of an electron–hole pair with an energy of $hf/4$.

The electron–phonon interaction times are compared with the electron–electron interaction times at electron temperatures about 3.7 K. For simplicity, we assume that the electron–electron interaction with the creation of two electrons and a hole with an energy of $hf/12$ from the initial energy is effective already at 4.2 K, and now the remaining excitations are effectively multiplied as the electron–electron interactions come into force. This process is schematically shown in Fig. 1.

Our approach to estimating of the sensitivity is based on nonequilibrium electronic and phonon distribution functions and mechanisms of quantum absorption of radiation. The quantum efficiency equal to the number of excited electrons per photon is estimated, which can reach a value of $n = hf/kT$. However, if there is a sufficiently strong electron cooling effect near the energy gap, which quickly removes the excitations from the absorber, then the excited electrons do not have time to multiply, and the quantum efficiency does not exceed unity. Therefore, the following two modes of operation of the bolometer based on the SINIS structure are distinguished: the mode of a photon counter and the bolometric mode. The current responsivity ranges from $dI/dP = e/hf$ in the former mode and to e/kT in the latter mode. That is, the efficiency in the photon counter mode drops sharply with an increase in the frequency. In the bolometric mode, the current response is $R_{esp}I = e/2kT = 2.2 \times 10^4$ A/W; the current response at the half gap is $R_{esp}I = e/0.5\Delta = 5 \times 10^4$ A/W. In the photon counter mode, the current response ($R_{esp}I = e/hf$) is 762 A/W at 350 GHz.

The main parameters of the operating modes for a signal frequency of 350 GHz and a temperature of 280 mK are given in Table 1. The maximum voltage response is taken near the half gap at a differential resistance of 35 kΩ for a bolometer with a normal resistance of 1 kΩ. For a practical bolometer, hot electrons are multiplied only up to the level of the half gap, at which there is a divergent density of states from the superconductor side and all excited electrons are tunneled into the readout system.

The bolometric mode with a high quantum efficiency can be achieved using a suspended absorber made of heavy metals, in which the Kapitsa resistance at the interface with aluminum electrodes is high and the electron–phonon interaction is weak. Furthermore, the optimal value of the junction resistance for achieving the quantum operating mode is 5 kΩ, whereas the resistance of the NIS junction in samples with electron cooling is usually about 0.5 kΩ.

3. BOLOMETER BASED ON THE SINIS STRUCTURE WITH A SUSPENDED ABSORBER

Several designs and technologies for the manufacture of bolometers with an absorber made of different materials (hafnium, copper, and palladium) and suspended above the substrate have been developed. The first prototypes of SINIS bolometers with suspended absorbers were fabricated using a simple technology that uses a hafnium absorber and only one wet chemical etching of aluminum under the absorber. Such prototypes had a number of disadvantages, including the negative influence of proximity effect normal metal wire on the superconductivity of aluminum electrodes. The next design already included two etching steps: the first one was conducted in acid to remove copper near the contacts with the antenna and the second one was conducted in alkali to etch aluminum under the absorber [6]. This technology eliminates the partial suppression of superconductivity, but

Table 1. Voltage and current responses in different modes of operation of the SINIS bolometer

Operating mode	Current response	dI/dP (A/W)	dV/dP (V/W)
Photon counter with electron cooling	e/hf	762	2.6×10^7
Practical bolometer with $R_d = 35$ kΩ at half gap	$2/V_\Delta$	5×10^3	1.75×10^8
Quantum bolometer with $R_d = 2$ kΩ near gap	$e/2kT$	2.2×10^4	4.4×10^7
DC response	$2k/(R_{de}\Sigma T^4)$	3.7×10^5	1.3×10^{10}

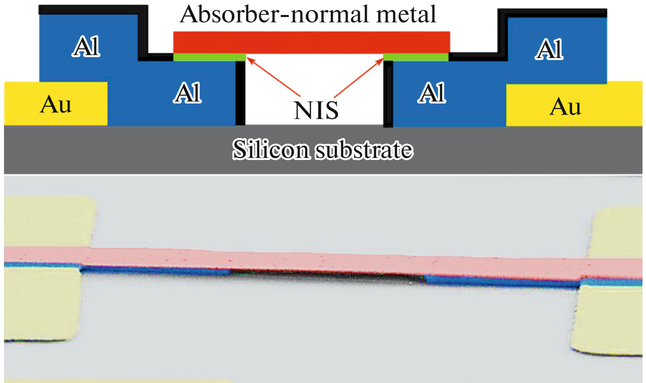

Fig. 2. Schematic representation of the bolometer based on the SINIS structure and the SEM image of the fabricated structure.

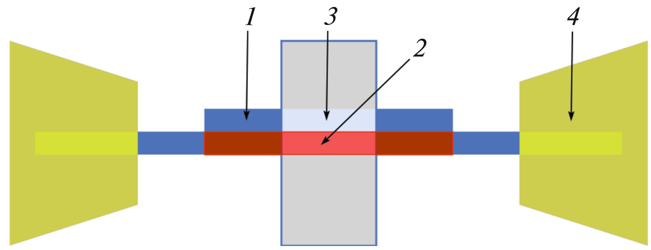

Fig. 3. Scheme of fabrication of the SINIS bolometer with the absorber evaporated at an inclined angle.

does not allow one to use noble metals in the absorber, since they can hardly be etched by acid. A schematic representation and an electron microscope view of the structure of such a bolometer are shown in Fig. 2.

Instead of additional etching of the upper layer of normal metal, the absorber in the last series of prototypes was evaporated at an angle to form a layer of normal metal only in a certain region. The scheme of fabrication of such a SINIS structure is shown in Fig. 3: (*1*) first, gold wires and antennas are evaporated; (*2*) next, an Al layer is evaporated at a right angle through a resist mask and then oxidized to create a barrier; (*3*) after that, normal metal (for example, Pd) is evaporated through the same mask, but at an inclined angle and only in the region of the wide window of the resist mask; (*4*) and finally, the lower Al layer is selectively etched.

The response of bolometers integrated into a twin slot antenna or log-periodic antenna to external radiation at a frequency of 350 GHz was measured at temperatures of 100–500 mK in the dilution cryostat [7] using the black body (BB) as a radiation source. The source was a NiCr film on a sapphire substrate. To

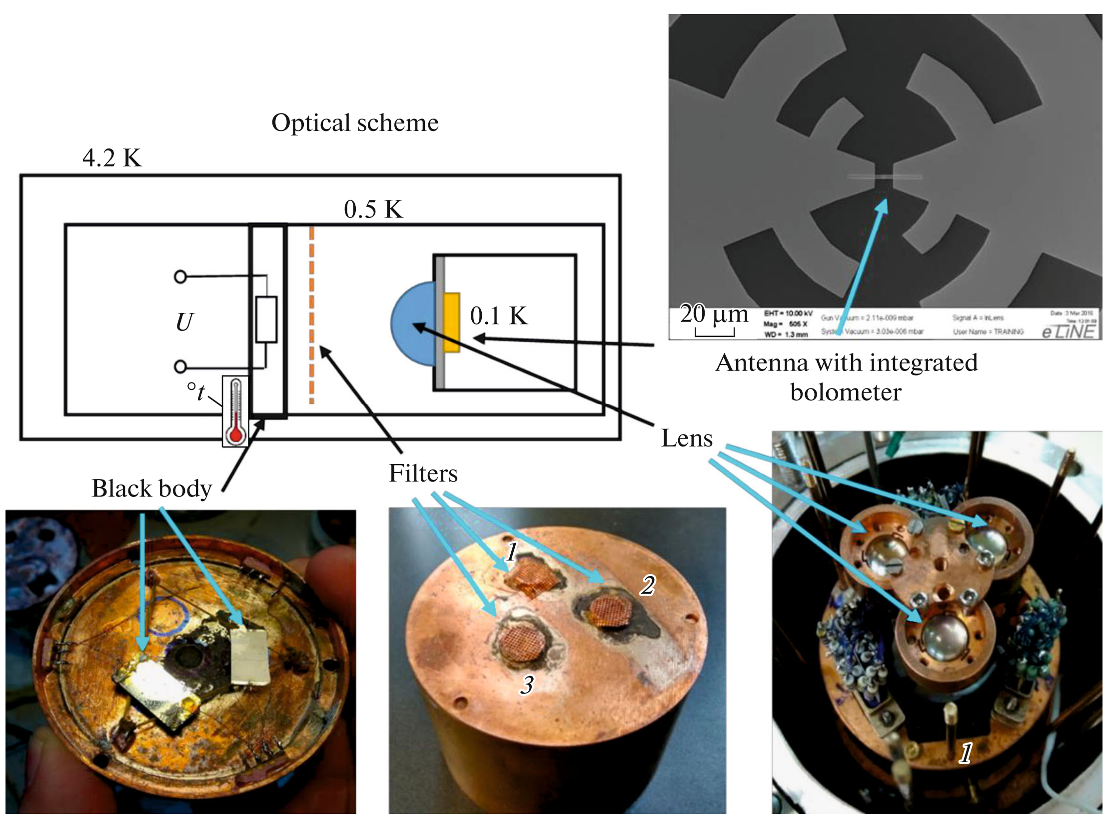

Fig. 4. Optical scheme of measuring the response to external radiation and photos of elements.

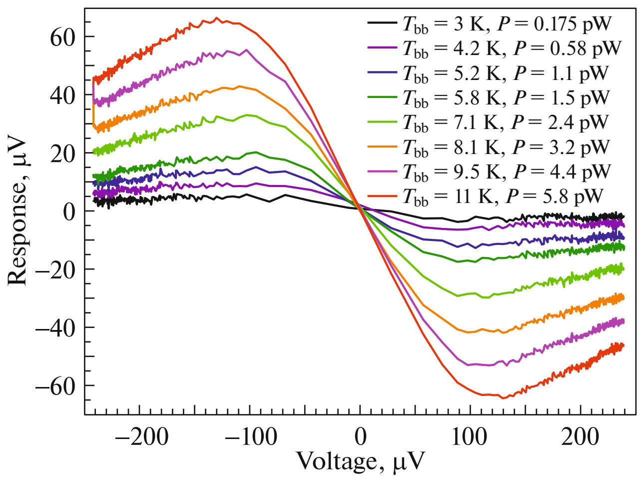

Fig. 5. Voltage responses to BB radiation with different powers at a temperature of 120 mK.

eliminate the exposure of the sample by background radiation power, an aperture and a band-pass filter with a central frequency of 350 GHz were additionally placed between the source and the sapphire lens, on which the chip was placed [8] (Fig. 4).

Voltage and current responses were measured at different black body temperatures (different radiation powers coming to the antenna with a bolometer) (Fig. 5). The Noise Equivalent Temperature Difference (NETD) calculated from these measurements was 1.6 $\mathrm{mK}/\sqrt{\mathrm{Hz}}$, but it is limited by a fairly simple DC-operated readout system and room-temperature amplifiers. The current response of the bolometer with a copper absorber was 0.7 nA at a calculated radiation power of 0.06 pW, which corresponds to a current response of 1.1×10^4 A/W. A current of 0.7 nA corresponds to 4.3×10^9 electrons per second, and a power of 0.06 pW corresponds to 2.8×10^8 quanta with a frequency of 350 GHz per second. The quantum efficiency at a frequency of 350 GHz was more than fifteen electrons per radiation quantum.

Our measurements of SINIS bolometers with suspended absorbers made of copper, hafnium, and palladium confirmed the validity of the model of quantum absorption at 350 GHz and demonstrated a high quantum efficiency that reached fifteen electrons per radiation quantum, i.e., the bolometric mode with high quantum efficiency is achieved in such SINIS bolometers.

4. CONCLUSIONS

Bolometers based on the SINIS structure with a suspended absorber have been developed and studied, which show a current responsivity of more than 10^4 A/W at a radiation frequency of 350 GHz. The NETD is 1.6 $\mathrm{mK}/\sqrt{\mathrm{Hz}}$ and is limited by the readout system. Measurements with SINIS bolometers with suspended absorbers made of copper, hafnium, and palladium confirm the model of quantum absorption at a frequency of 350 GHz and reveal a high quantum efficiency that reaches fifteen electrons per radiation quantum, i.e., the bolometric mode with high quantum efficiency is achieved in these SINIS bolometers.

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CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest.

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