CRYOGENIC MIMIM AND SIMIS MICROWAVE DETECTORS

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Microwave detectors of the Metal-Insulator-Metal-Insulator-Metal (MIMIM) structure and the Superconductor-Insulator-Metal-Insulator-Superconductor (SIMIS) structure have been designed, fabricated and investigated. The difference of such samples was in external electrodes, MIMIM uses copper external electrodes, while SIMIS uses aluminum. Identical in dimensions MIMIM and SIMIS samples have been fabricated and experimentally studied in the temperature range of 0.1-2.7 K. Voltage and current response were measured at 300 GHz external irradiation using Backward Wave Oscillator (BWO). According to our estimates, the MIMIM current responsivity is $1.1 \cdot 10^3$ A/W in the case of a photon response and $4 \cdot 10^4$ A/W in the case of a bolometric response. The estimated noise equivalent power is in the range $2.5 \cdot 10^{18}$ W/√ Hz to $1.2 \cdot 10^{-19}$ W/√Hz.

Keywords—bolometer, SINIS, MIMIM, quantum efficiency

I. INTRODUCTION

Structures of the metal-insulator-metal-insulator-metal (MIMIM) type can be used as detectors of microwave and infrared radiation. The simplest detection mechanism is bolometric, when the metal absorber in the middle is heated by the radiation power, which leads to the temperature and resistance change. Such detection mechanism is not very sensitive and fast. At low frequencies, a direct detection mechanism is also possible, when the MIM diode functions as a rectifier; in this case, the amplitude of the rectified current is proportional to the second derivative of the IV characteristic of such nonlinear diode. At high frequencies, a third detection mechanism appears when quantum assisted tunneling with absorption of radiation quanta occurs [1]. In recent years, interest in such structures has increased, since it opens up the possibility of creating high-speed photodetectors [2].

To explain the detection effect, the mechanism of formation of surface plasmons is sometimes used, when an electromagnetic wave causes oscillations of carriers on the metal surface. In a metallic absorber, radiation generates hot carriers, which cause a photocurrent. The main parameter of such detectors is the quantum efficiency, which is equal to the ratio of the number of detected electrons to the number of absorbed photons. For such detectors at room temperature, the current responsivity in the optical range usually does not exceed 1 A/W. As an example of the practical implementation of the MIMIM photodetector, in [3] at a wavelength of 1 µm a photoresponse of 1 mA/W was obtained at a dark current of 7 nA. Note that, theoretically, the current responsivity could reach e/hf=0.88 A/W, i.e. three orders of magnitude more. The use of such structures for detecting microwave radiation becomes possible when the MIMIM detectors are cooled down to millikelvin temperatures. In this case, the current responsivity estimates are very attractive. Tunneling of a hot carrier (electron or hole) is called photocurrent or internal photoemission. According to [4], when absorbed in a metal, each photon excites an electron to a higher energy state above the Fermi energy and an equal number of hot holes with the same energy relative to Fermi level. Under the action of the applied potential, hot electrons move to an electronegative MIM junction, and hot holes to an electropositive one, creating a photocurrent (Fig. 1). If the applied potential is small, then the motion of each type of hot particles in different directions is balanced and the total current is zero. In addition, without potential, current is minimal and thermalization (mutual neutralization) of electrons and holes occurs with the emission of a phonon and its escape into the substrate.

Russian Foundation for Basic Research (grant No. 19-52-80023).

II. Estimates of Current Response for SIMIS and MIMIM Structures

The ultimate case of a bolometer based on the superconductor-insulator-normal metal-insulator superconductor (SINIS or SIMIS) structure at a temperature above the critical temperature of superconductor will be the MIMIM (or NININ) structure with normal metals as electrodes and an absorber. The differential resistance is equal to normal and we get a "simple" unsaturated quantum detector. For forward and reverse photocurrent, the expressions are similar. For a bias voltage higher than kT/e, the current response approaches to the value dI/dP=1/V, which is usual for a metal bolometer, so at a bias voltage of kT/e we get the same ultimate bolometric response dI/dP=e/kT. Multiplying by the normal linear resistance of the structure, we obtain a voltage response of dV/dP=eR/kT, which will be 30-50 times less for MIMIM than for SINIS with the same asymptotic resistance, since there is no increase in dynamic resistance. However, by increasing the resistance of the tunnel junctions, equally high voltage response values can be obtained.

Let us consider simple numerical examples for two typical operating temperatures of 280 mK and 4.2 K. The optimal bias voltages for these temperatures will be $V_{T=0.28}=kT/e=2.3\cdot10^{-5}$ =23 µV and $V_{T=4.2}=kT/e= 3.4\cdot10^{-4}$ =340 µV, from which we get the current responsivity $S_{T=0.28}=1/V_{T=0.28}=4.3\cdot10^{4}$ A/W and $S_{T=4.2}=1/V_{T=4.2}$ $=2.9\cdot10^{3}$ A/W. The noise equivalent power NEP can be estimated as the ratio of the Nyquist noise current In=(4kT/R)1/2 to the current responsivity S=e/kT, i.e. $NEP=(kT/e)\cdot(4kT/R)^{1/2}$ $=(2/e)\cdot(k^3T^3/R)^{1/2}$. For a MIMIM structure resistance of 100 kΩ, the NEP will be down to $2.8\cdot10^{-19}$ W/√Hz at 0.28 K and $1.6\cdot10^{-17}$ W/√Hz at 4.2 K. In this case, the noise current densities will be 12 fA/√Hz and 47 fA/√Hz. For comparison, the noise currents of standard AD743 JFET operational amplifiers and OPA111 MOSFETs are 7 fA/√Hz and 0.5 fA/√Hz, i.e. both are suitable for such measurements.

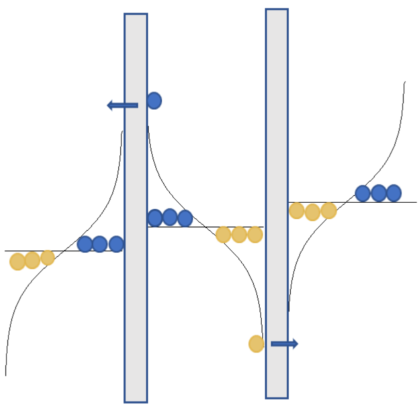

Fig. 1. Energy diagram of a MIMIM structure with electron and hole excitations. With a small constant bias, electrons move to the left, holes to the right (from minus to plus).

III. Experemental

To experimentally prove these considerations, two series of samples were made, one with a classical serial matrix of 100 SINIS bolometers of the metamaterial type [5], and the other with replacing aluminum electrodes with copper ones. The study of these structures was carried out under the same conditions. At a temperature of 275 mK, the curves are very different (Fig. 2.). For the SINIS structure, this is a highly nonlinear curve, with a maximum near zero voltages, with a maximum resistance of about 14 MΩ. For a structure with copper electrodes, the IV curve is practically linear and the dynamic resistance is practically independent of voltage.

The voltage responses (voltage change at a fixed current) to external microwave radiation were actually measured in experiment. The source of radiation in this experiment was a backward-wave oscillator (BWO). The responses for the SIMIS and MIMIM structures were measured at the same temperature of 273 mK, and for the SIMIS structure, the signal was additionally reduced by a factor of 30. In this case, quite similar response curves were obtained (Fig. 3). The maximum response for the SINIS structure is approximately at half of the gap, which for 100 series rings with two SIMIS structures should be around 80 mV (400 µV·2·100). Accordingly, taking into account that the maximum responses for these structures are approximately the same, we can say that SINIS structures have about 30 times better voltage responsivity at the same temperatures.

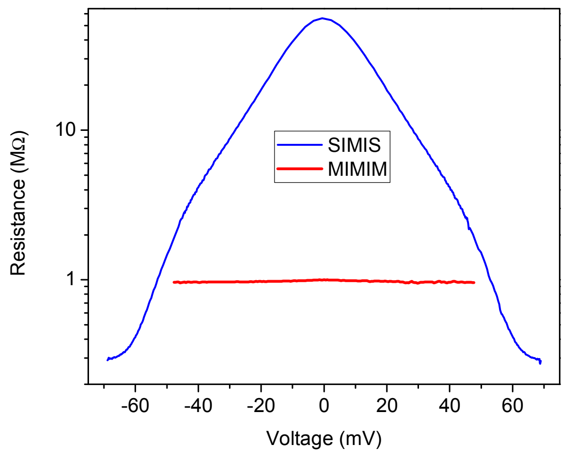

Fig. 2. Dynamic resistance of the SIMIS structure and the resistance of a similar MIMIM at the same temperature of 275 mK in a semi-logarithmic scale.

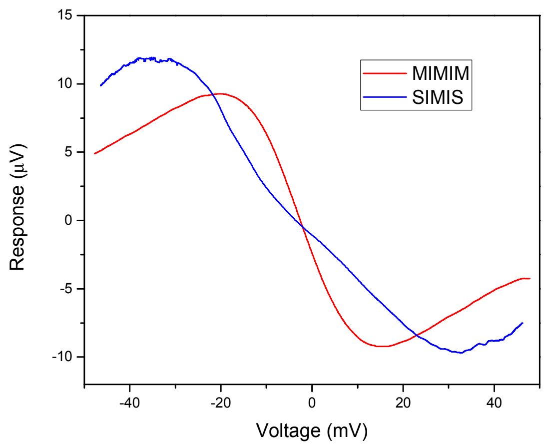

Fig. 3. The voltage response of the MIMIM structure to the BWO radiation at a temperature of 273 mK and for comparison of a similar SIMIS structure for a 1/30 signal.

It is easy to recalculate voltage responses to current responses, taking into account the known dynamic resistances (Fig. 4). Here, even for the MIMIM structure at small bias, one can expect a comparable current response to the SINIS structure.

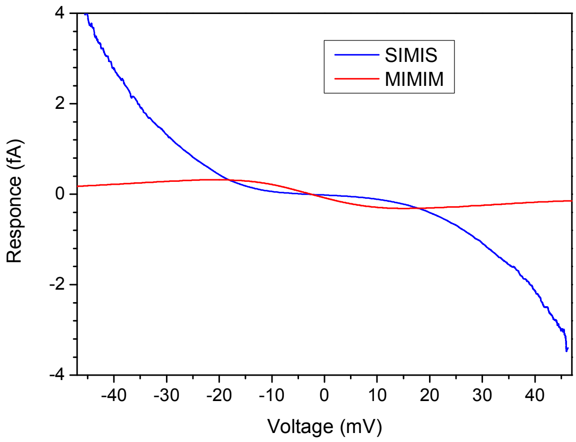

Fig. 4. The current response of the MIMIM structure (recalculated from the voltage response, taking into account the differential resistance) to BWO radiation at a temperature of 273 mK, and for comparison with a structure similar to SIMIS.

IV. Conclusions

Samples of microwave detectors of the MIMIM structure and the SIMIS structure have been developed, manufactured and investigated. It is shown that MIMIM structures can have a current response comparable to SIMIS structures, which is a consequence of quantum absorption of radiation in such structures [6]. It is optimal to read-out such structures in the voltage bias mode by measuring the current changes with a SQUID, which will correspond to a NEP level down to 10^{-19} W/√Hz. For voltage readout and current bias, it is advantageous to increase the resistance of the MIMIM structure to increase the voltage response. This can be done relatively easily by simply reducing the area of the tunnel contacts.

Acknowledgment

The work was carried out within the framework of the RFBR project 19-52-80023 BRICSt. The study of the samples was carried out using UNU 352529, functioning at the expense of the State Research Task at the V. Kotelnikov Institute of Radio Engineering and Electronics RAS.

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