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Non-Thermal Absorption and Quantum Efficiency of SINIS Bolometer

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Abstract—We study mechanisms of absorption in two essentially different types of superconductor-insulator-normal metal-insulator-superconductor (SINIS) bolometers with absorber directly placed on Si wafer and with absorber suspended above the substrate. The figure of merit for quantum photon absorption is quantum efficiency equal to the number of detected electrons for one photon. The efficiency of absorption is dramatically dependent on phonon losses to substrate and electrodes, and electron energy losses to electrodes through tunnel junctions. The maximum quantum efficiency can approach \( n = \hbar / kT = 100 \) at \( T = 350 \text{ GHz} \) \( T = 0.1 \text{ K} \), and current responsivity \( dI/dP \approx \hbar / kT \) in quantum gain bolometer case, contrary to photon counter mode with quantum efficiency of \( n = 1 \) and responsivity \( dI/dP = \hbar / hf \). In experiments, we approach intrinsic quantum efficiency up to \( n = 80 \) electrons per photon in bolometer with suspended absorber, contrary to quantum efficiency of about one for absorber on the substrate. In the case of suspended Cu and Pd absorber, Kapitsa resistance protect from power leak to Al electrodes.

Index Terms—Bolometers, nanoelectronics, submillimeter wave integrated circuits, superconducting microwave devices.

I. INTRODUCTION

MICROWAVE detectors of various configurations based on NIS junctions investigated since the 90s, starting with the pioneering work [1]. The detection mechanism usually considered as bolometric [2]. This approach is applicable when the photon energy is rather low. [3]. When the signal frequency increase, the absorption mechanism becomes quantum [4].

At very low frequencies, we can apply a purely classical description, when all conduction electrons receive an energy increment of the order of \( eE\lambda \), where \( E \) is the electric field strength and \( \lambda \) the mean free path. The transition from the classical to the quantum regime considered in [5], [6]. Under the action of an alternating electric field \( E = E_0 \sin \omega t \), a force \( F = eE_0 \sin \omega t \) acts on an electron of mass \( m \) and the equation of motion is \( m^2 \frac{d^2 x}{dt^2} = eE_0 \sin \omega t \) with a solution \( x = (eE_0/m\omega^2) \sin \omega t \). Pulse is \( mx_0/dt = (eE_0/m\omega) \cos \omega t \). Maximum of energy \( E_{\text{max}} = mv^2/2 = (eE_0^2)/(2m\omega^2) \) and average energy is \( E = (eE_0)^2/(4m\omega^2) \).

The criterion for the transition to the quantum regime will be the equality of the energy of the quantum of this energy, i.e., \( (eE_0)^2/(4m\omega^2) = \hbar \omega \). From this we obtain the criterion for the frequency separating the classical and quantum absorption regions \( F_0 = (1/2\pi)(e^2E^2/(4m\hbar)) \). We can estimate the field strength with a power of 1 pW in an absorber strip with a length of 1 \( \mu \text{m} \) and a resistance of 50 \( \Omega \). We get a voltage drop of 7 \( \mu \text{V} \), a field strength of 7 V/m, and the cutoff frequency \( F_0 = 0.25 \text{ GHz} \).

The direct relaxation of the electron energy into phonons is additional relaxation channel that increases effective thermal conductivity and decreases sensitivity. The description of the mechanism of absorption and formation of the response requires calculating the collision integral and solving the kinetic equation [7]. Experimentally, the nonthermal absorption mechanism in SINIS structures with an absorber on a substrate directly observed in [8]. It was shown that, under irradiation, the electron energy distribution has a substantially nonequilibrium form, which differs from the Fermi distribution. Electrons, not having time to come to balance, make the main contribution to the additional tunneling current. In [9], the transition from the quantum gain regime to the unity gain observed when temperature increase from 0.1 to 0.3 K. This transition happens due to the acceleration of energy relaxation processes.

II. THERMAL AND NON-THERMAL ABSORPTION AND QUANTUM EFFICIENCY OF DETECTION

A. Thermal Absorption

SINIS detectors often considered as classical devices, implying that the optical response is equivalent to the electrical response to thermal heating of the absorber by direct current [1], [2], [3], [10]. In practice, the electrical response at dc heating is always significantly higher than the optical response for microwave, terahertz, and IR radiation. In [11] with estimated NEP = \( 10^{-18} \text{ to } 10^{-20} \text{ WHz}^{-1/2} \), whereas the experimental NEP = \( 7 \times 10^{-17} \text{ WHz}^{-1/2} \) is much higher. In [12] the self-noise of

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At a bath temperature of 300 mK, a decrease in the electron temperature down to 100 mK can be obtained [15]. But such cooling with a relatively high cooling current and accompanied by additional thermal conductivity \( G \), should lead to an increase in the noise equivalent power \( \text{NEP}^2 = 4kT^2G \) in which \( T \) is equilibrium temperature and \( G \) is additional thermal conductivity by dc current via SINIS [16]. In the case, with different electron and phonon temperatures, the emission and absorption of phonons are uncorrelated and both processes will give an independent noise contribution \([10],[17]\).

According to [3] the whole NEP can be estimated as \( \text{NEP}^2 = 2kG(T_c^2 + 2kG)T_p^2 = 10k\Sigma\nu(T_c^6 + T_p^6) \), in which \( T_c \) and \( T_p \) are electron and phonon temperatures. Thus, even in the ideal case of a decrease in the electron temperature to zero, the total NEP cannot decrease by more than 1.4 times. Thus, cooling of only electrons is much less efficient than the simultaneous cooling of both the electron and phonon systems.

For the numerical calculation of the sensitivity, the heat balance equation is often used \([1],[3]\), which takes into account heat sources and relaxation mechanisms \( P_{\text{sys}} + P_{\text{bg}} = \Sigma\nu(T_c^2 + T_p^2) + P_{\text{cool}} \), in which \( P_{\text{sys}} \) is signal power, \( P_{\text{bg}} \) is spurious background power, \( \Sigma\nu(T_c^2 + T_p^2) \) power flow from electron to phonon system, and \( P_{\text{cool}} \) is electron cooling power. From this equation, for samples with an absorber volume of \( \nu = 10^{-20} \) m\(^3\), the voltage responsivity should be higher than \( 10^9 \) V/W at 300 K and more than \( 10^{10} \) V/W at 200 mK. In the case of heating the absorber with a direct current or at low frequencies, responsivity values close to these estimates achieved in experiment, but at frequencies of the order of 300 GHz, the experimental results are more than an order of magnitude worse. At low resistances of SINIS junctions and strong electron cooling, excited electrons are effectively removed from the absorber, their multiplication does not occur, and the current response decreases from \( \text{dI/dP} = e/kT \) down to \( \text{dI/dP} = e/hf \) in the case of the so-called cold electron bolometer CEB. The role of electron cooling on the response of SINIS detectors was experimentally investigated in [18], where it was shown that electron cooling does not provide the same sensitivity as the cooling of the receiver as a whole. Current quantum response efficiency for bolometer integrated in a twin-slot antenna [8] is in the range of 0.52–1.1 for signal power 4.8–0.11 pW.

**B. Quantum Absorption Mechanism**

In the case of absorption of a photon by an electron with an energy much larger than the gap, for example, with a frequency of \( f \sim 350 \) GHz, the energy of an excited electron (hole) can be in the range from 0 to \( hf \), i.e., reach an equivalent electron temperature up to 16 K. The time constant of the electron-electron interaction at this temperature is much larger than the electron-phonon relaxation time. As a result, first in a time \( \tau_{\text{sp}} \approx 12 \) ps a phonon with energy up to 16 K created. For this phonon, there are three relaxation channels: escape into the substrate, escape into superconducting electrodes, or interact with an electron with time \( \tau_{\text{pe}} \approx 1 \) ps. In the latter case, an electron-hole pair created with characteristic energies \( \pm hf/2 \) above and below the Fermi level. An excited electron with energy
hf/2 creates a phonon with an equivalent temperature of 8 K, and then an electron-hole pair again created, now with energy hf/4 each, or an equivalent temperature of ∼3 K. At this energy and below, the time of electron-electron interaction, changing as $T^{-2}$ becomes dominant in comparison with the electron-phonon one, proportional to $T^{-4}$, energy redistributed only between electrons without noticeable generation of phonons. The process of relaxation of the energy of electrons proceeds until their characteristic times reach the tunneling time determined by the NIS parameters - the transparency of the barrier, the thickness of the normal metal film, and the diffusion rate of electrons in it. For commonly used structures, this time is of the order of tens nanoseconds.

The process of phonon escape is very important in the case of high frequencies. For transverse phonons propagating normal to absorber surface, the escape from the absorber to the substrate is $\tau_{tr} = t_{abs}/v_{sound} = 5-10$ ps, and for longitudinal phonons propagating along the absorber, it can reach $\tau_{l} = l_{abs}/v_{sound} = 0.1-0.2$ ns for a longitudinal size of 1 µm and the speed of sound 3-5 $\times 10^3$ m/s. For an absorber on a substrate, $\tau_{tr}$ and a fast escape of phonons into the substrate will prevail, while for a suspended absorber that does not have contact with the substrate, only a slower process with a time constant $\tau_{l}$ remains. Moreover in the case of different materials phonons partly reflected from the boundary.

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### TABLE I

**DYNAMICS OF 350 GHz PHOTON RELAXATION**

| Process | Equiv. temp. | Time constant | Number of particles | Phonon and electron escape from absorber |
|---------|--------------|---------------|---------------------|-----------------------------------------|
| el-ph   | 16 K         | $\tau_{e}=12$ ps | 1                   | Transvers phonons 10 ps, Lateral phonons 1 ns |
| ph-el   | 8 K          | $\tau_{e}=0.2$ ns | 2                   | Transvers phonons 10 ps, Lateral Phonon 1 ns |
| el-ph   | 4 K          | $\tau_{e}=3.2$ ns | 4                   | Transvers phonons 10 ps, Lateral Phonons 1 ns |
| ph-el   | 2 K          | $\tau_{e}=51$ ns | 24                  | Electron escape $\tau_{eq}=40$ ns |
| ph-el   | 0.6 K        | $\tau_{e}=0.5$ ns | escape              | Transvers phonons 10 ps |
| el-el   | 0.3 k        | $\tau_{e}=700$ ns | escape              | Electron escape $\tau_{eq}=40$ ns |
| el-el   | 0.1 K        | $\tau_{e}=6.4$ ns | escape              | $\tau_{eq}=40$ ns |

### III. EXPERIMENTAL RESULTS

#### A. Conventional Bolometer on Substrate

IV curves and dynamic conductivity dependencies on bias voltage for 3 SINIS bolometers with FeAl absorber on the substrate at different temperatures and at 350 GHz irradiation presented in Fig. 2, Fig. 3. IV curves without radiation correspond to Fermi distribution and can be correctly described with negligible electron cooling, the level of nonequilibrium is higher and the number of detected electrons is much larger.

In addition, in [7], the detection efficiency dependence on the NIS junction resistance was calculated for various levels of nonequilibrium. According to these calculations, the maximum non-equilibrium achieved at the optimal resistance of the NIS junction asymptotic resistance $\sim 5$ kΩ. In this case, the quantum efficiency reaches 30 and the current responsivity is $dI/dP = 30e/hf$. For lower resistance values, the rate of energy escape into the electrodes is significantly higher, the thermal conductivity is higher, and excited electrons quickly leave the absorber without having time to multiply. In this case, the quantum efficiency does not exceed unity.

In conventional SINIS bolometers with NIS junction resistance less than 1 kΩ and an absorber on the substrate, the power loss to the substrate and superconducting electrodes can reduce the current responsivity even below the photon counter limit. In contrast to an absorber on a substrate, for a suspended absorber made of heavy metal and high-resistance NIS junctions, it is possible to realize high values of the current responsivity $e/kT$ predicted in [7] for the bolometric mode.

The effect of electron cooling at a bias voltage in the region of half the gap cannot significantly improve the response. In [14] the dependences of the electron temperature and voltage response experimentally studied at characteristic temperatures in the range of 0.1 K and 0.3 K. Experimentally the expectation of significantly improve responsivity without reducing the phonon temperature of the SINIS receiver was refuted.
Fig. 3. Dynamic resistance (1) at 0.07 K, (2) at 0.22 K; and (3) at 0.07 K with radiation from black body source at 9 K with filters at 350 GHz and bandwidth 70 GHz.

Fig. 4. Equivalent electron temperature of absorber without radiation (1), and with radiation through filter at 350 GHz with bandwidth 70 GHz at black body radiation source temperature of 3 K (2), 5.8 K (3), 8 K (4), and 10.5 K (5).

by equivalent electron temperature. Shape of curves measured at 9 K radiation clearly differs from equilibrium case. It is even clearer in dynamic resistance dependencies in Fig. 3. The important feature of dark curve at 220 mK bath temperature is that the equivalent electron temperature is 235 mK. At bath temperature of 70 mK the equivalent electron temperature is 208 mK. It means that electron system of absorber is overheated due to spurious room-temperature radiation and this device is clearly hot-electron bolometer, not a cold-electron bolometer as it was sometimes referred in literature [14], [19].

B. Suspended Bolometer

We fabricated series of bolometers with absorber suspended above the substrate; see [22], [23], [24], [25]. The fabrication process is following: after first laser beam lithography patterning, a three-layer superconductor/insulator/normal metal structure is deposited in one vacuum cycle and lifted-off. Film thicknesses are: aluminum about of 70 nm, and normal metal – 30 nm. In the next step, the window in resist is patterned by e-beam lithography at the area where it is intended for aluminum etching under the absorber. The aluminum etching is made in a weak alkaline solution (for example, 10% KOH or photoresist developer like MF-CD-26). After that the resist is removed in acetone. In bolometer with suspended Pd, Cu, or Hf absorber with high-resistance NIS junctions it is possible to approach the bolometric mode with high quantum gain, see Fig. 5. In experiments, we usually measure voltage response for current bias. Maximum of response observed at voltage corresponding to about half energy gap. For asymptotic resistance of 1 kΩ the dynamic resistance at a half-gap bias is about 35 kΩ at bath temperature of 280 mK. With current response of 760 A/W, the voltage response is $2.6 \times 10^7$ V/W. At bath temperature of 0.1 K the voltage response increase up to $1.4 \times 10^9$ V/W just due to increase of dynamic resistance.

IV. C. Conclusion

Presented model of microwave photons non-thermal absorption and estimations of quantum efficiency in SINIS detector could be applicable for different types of cryogenic Terahertz sensors such as Transition Edge Sensors, Hot Electron Bolometers, Josephson detectors, etc. It is favorable for nonequilibrium, non-Fermi energy distribution cases, when electron temperature does not describe relaxation dynamics in the device.
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