On the Concept of a Normal Metal Hot-Electron Microbolometer for Space Applications

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Abstract-- We present a theoretical analysis and experimental evaluation of a hot-electron microbolometer with normal metal absorber for ultrasensitive detecting infrared and submillimeter waves. The basic version of the antenna coupled microbolometer makes use of a hot-electron effect in the thin film resistive strip and Andreev reflection of hot electrons at SN interface between the strip and superconducting antenna. A value of $NEP = 5\cdot10^{-18}$ W/Hz$^{1/2}$ for the thermal fluctuation noise and the thermal time constant $t = 0.2$ µs at 300 mK have been estimated for one of the realized devices with thermal conductance $G \approx 6\cdot10^{-12}$ W/K. At 100 mK, the thermal conductance has been decreased to $G \approx 7\cdot10^{-14}$ W/K, that gives estimations for the thermal $NEP = 2\cdot10^{-19}$ W/Hz$^{1/2}$ and the time constant $t = 5$ µs. An advanced version of the microbolometer includes also additional SIN junctions connected to the resistive strip for electronic cooling the absorber. Such microbolometer is intended as a detector of millimeter and submillimeter wave radiation for space applications.

I. INTRODUCTION

The normal metal hot-electron microbolometer (NHEB) with Andreev mirrors has been developed and demonstrated earlier [1],[2]. It has shown very high power sensitivity at operating temperatures around 100 mK. NHEB is designed as a normal metal strip with a very small volume, connected to superconducting electrodes at both ends. A signal current from an antenna fed through those electrodes warms up the electron gas in the strip by dissipated power. The electrons can not give out their energy back to the electrodes because of the Andreev reflection at the NS-interface. They can loose energy by interacting with the lattice, but the thermal coupling gets very weak at temperatures below 1 K.

To detect the changes in temperature of the electrons, an SIN tunnel junction in contact with the normal metal strip forming its N-electrode is used (Fig. 1). The shape of IV curve of this junction depends on the electron temperature in the normal part, and by biasing the junction with a constant current and measuring voltage on it we can get a response $\Delta V(T)$ linear in a rather wide range. An important feature of the NHEB with Andreev mirrors is that the thermal time constant t equals the electron-phonon relaxation time $t_{e\text{-}ph}$.

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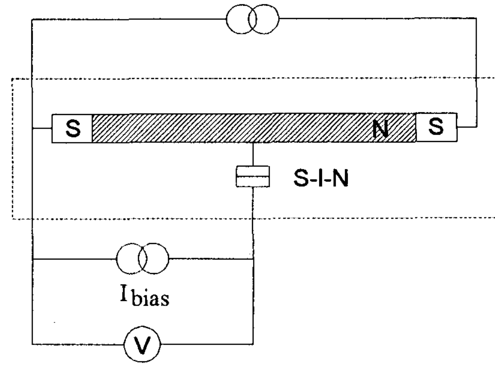

Fig. 1. Schematic of the microbolometer: an SIN junction is biased at a small constant current. A junction voltage depends on the smearing of the IV-curve, which is used to measure the electron temperature in the normal metal absorber (hatched).

The typical values of $\tau \approx 10$ µs at 100 mK and $\tau \approx 0.4$ µs at 300 mK are much smaller than it is usually required for applications [1],[3].

Since ultrasensitive detectors of submillimeter wave radiation are mostly needed for space radioastronomy, a very sensitive device working at a temperature around 300 mK, which can be reached in relatively simple and low-weight He^3-cryostats, seems to be an attractive choice. European Space Agency (ESA) has formulated requirements for bolometer detectors to be used in future far infrared and submillimeter astronomy satellite missions [3]. Such a detector should operate at 300 mK and have the noise equivalent power $NEP < 10^{-17}$ W/Hz$^{1/2}$ and the time constant $t < 1$ ms.

There are three major components contributing to the NEP of NHEB according to the expression

$$NEP = \left[4k_B T_e^2 G + \frac{V_j^2}{S^2} + \frac{V_n^2}{S^2} \right]^{1/2}, \qquad (1)$$

where T_e is the temperature of electrons in the absorber, $G = dP/dT$ is the thermal conductance for the outflow of signal-induced heat, $S = dV/dP = dV/dT \cdot G^{-1}$ is the power responsivity of the detector, V_j is voltage noise of the

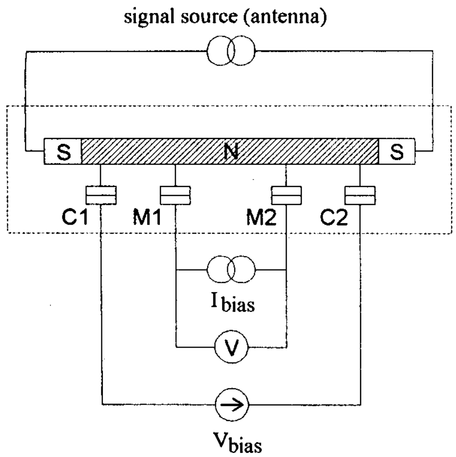

Fig. 2. Schematic of the microbolometer with electronic refrigeration. Two low-resistive SIN junctions (C1 & C2) are voltage-biased and used to decrease the effective electron temperature of the normal metal absorber element (hatched). Two high-resistive SIN junctions (M1 & M2) are biased with a small current and used to measure the resulting electron temperature.

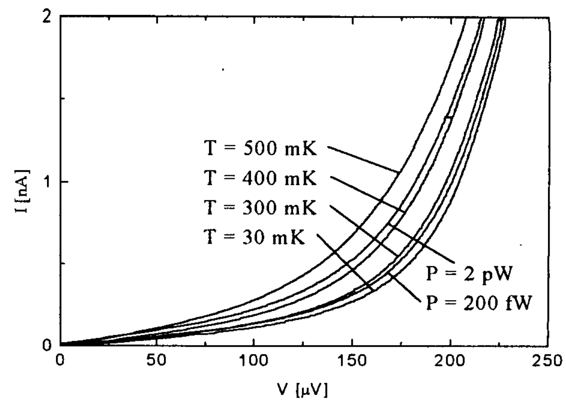

Fig. 3. IV curves of the SIN junction measured for different temperatures without any signal current and for two different powers dissipated by the signal current at the base temperature of 30 mK.

SIN junction and V_n is voltage noise of an amplifier. The first term describes the electron temperature fluctuations in the absorber and sets the fundamental noise limit for a given device at a given temperature. It is clear from the expression above, that it is mostly the small G that provides comparatively low NEP in this type of bolometer.

We suggest using an already demonstrated [4] mechanism of electronic cooling to decrease the NEP further by decreasing the temperature T_e of the electron gas in the absorber of the microbolometer while leaving the physical temperature of the lattice above 300 mK [5]. Such a device would balance the heating power transfer from phonons to electrons and the cooling power transfer by high-conductive tunnel junctions biased around the gap voltage, thus removing the most energetic electrons (Fig. 2).

According to the preliminary estimates [5] the total thermal conductance G can not be decreased by the electronic cooling even though it is very temperature dependent, since an additional channel for heat out-flow is then added. The electronic cooling should improve the overall performance of NHEB by reducing T_e in the first term in (1) and by increasing the temperature responsivity dV/dT (giving higher S) in the second and third terms of the NEP [5].

II. The Power Detector

We have made several experimental steps in realization of an NHEB and developing it further by attaching SIN junctions for cooling. First, we have made a microbolometer with a single tunnel junction for measuring the electron temperature in the absorber [6]. The absorber has been fabricated together with the superconducting electrode of the junction using electron beam lithography and the shadow evaporation technique. The superconducting electrode (40 nm-thick aluminum film) has been evaporated first and oxidized in $4\cdot10^{-2}$ mbar of O_2 for 2 min to form the tunnel barrier. Subsequently 3 nm of chromium and 35 nm of silver have been evaporated to form the 6 μm long 0.25 μm wide absorber strip. Two superconducting leads (120 nm of lead) were then attached using one more lithography and deposition cycle. An ion etching *in situ* before the deposition was used to remove any oxide or contamination, which could otherwise make the Andreev reflection at the interface inefficient.

We performed measurements of IV-curves of the SIN junction at different temperatures and with different dissipated power from the signal current (Fig. 3). The dependence of the voltage V at constant bias current through the junction on the signal current I_{ABS} in the absorber was measured at constant temperature for two devices with different absorber lengths. The corresponding curves $V(I)$ for the two devices almost overlapped (Fig. 4). The derivative dV/dI_{ABS} directly related to the form of the curve can be expressed via temperature responsivity, inverse thermal conductivity, and dP/dI_{ABS}:

$$\frac{dV}{dI_{ABS}} = \frac{dV}{dP}\cdot\frac{dP}{dI_{ABS}} = \frac{dV}{dT}\cdot\left(\frac{dP}{dT}\right)^{-1}\cdot\frac{dP}{dI_{ABS}}.$$

One can find from the Joule law

$$P = P_{Joule} = I_{ABS}^2 R \quad\Rightarrow\quad \frac{dP}{dI_{ABS}} = 2RI_{ABS}.$$

The inverse thermal conductance can be found from the expression for the heat exchange in case of the hot-electron effect:

$$P_{e\to ph} = \Sigma U\left(T_e^5 - T_{ph}^5\right) \quad\Rightarrow\quad \frac{dP}{dT} = 5\Sigma U T^4 \qquad (2)$$

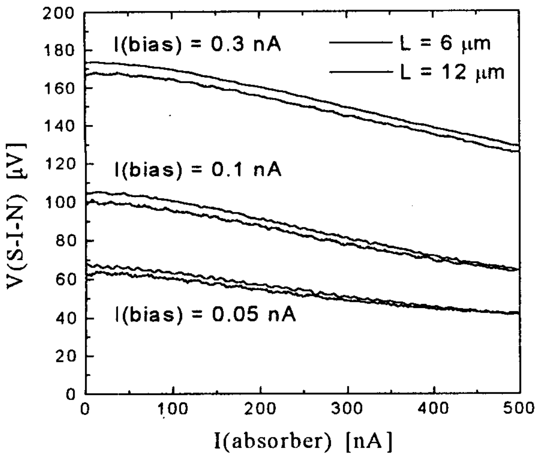

Fig. 4. The junction voltage V at constant bias current I(bias) through the junction as a function of the signal current I(absorber) for two devices with different absorber length 6 μm and 12 μm at T = 30 mK.

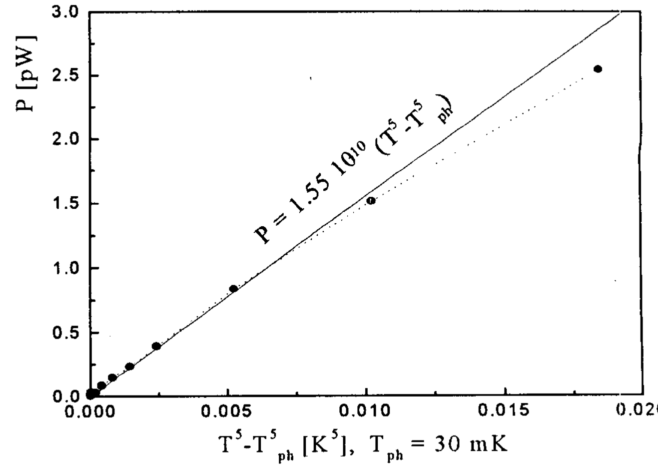

Fig. 5. Power dissipated in the absorber vs. (T^5-T^5_{ph}), where T is temperature of electrons deduced from measurements $V(I_{bias},T)$, and T_{ph} = 30 mK is temperature of the lattice (measured temperature of the sample holder). Linear fit corresponds to the relation (2).

where Σ is a material-specific parameter and we assume equilibrium, $P_{Joule} = P_{e\rightarrow ph}$. After substitution we get

$$\frac{dV}{dI_{ABS}} = \frac{dV}{dT}\cdot\left(\frac{2I_{ABS}R}{5\Sigma T^4 U}\right) \propto \frac{R}{U} \,. \qquad (3)$$

The overlapping of the curves means then that the increase of dissipated power (P) due to higher resistance (R) has been exactly compensated by the increase of heat conductance due to larger volume (U), i.e. no substantial thermal transport through the NS-contacts has been present. The dependence $V(I_{ABS})$ was then re-calculated to give $V(P)$. Maximal power responsivity at an optimal I_{bias} = 0.3 nA was found to be $S_{max} = |dV/dP| = 3\cdot 10^7$ V/W. Combining the data $V(I_{bias}, T)$ and $V(I_{bias}, P)$ the dependence $P(T_e)$ could be calculated (Fig.5).

From a fit to the expression (2) we could determine the material parameter $\Sigma \approx 3\cdot 10^{-9}$ nW·K^{-5}·mm^{-3} and, consequently, the thermal conductance $G \approx 6\cdot 10^{-12}$ W/K at 300 mK. This value is twice as low as the one which can be calculated using the data from [2]. This decrease was due to the smaller volume of the absorber in our case. The thermal fluctuation component of the NEP (1) calculated for this value of G is about $5\cdot 10^{-18}$ W/Hz$^{1/2}$, which is well below the ESA requirements for the total NEP for future spaceborn bolometers [3]. At 100 mK, the thermal conductance has decreased to $G \approx 7\cdot 10^{-14}$ W/K. This value of G gives a thermal fluctuation noise component of the total noise equivalent power NEP $=2\cdot 10^{-19}$ W/Hz$^{1/2}$.

The thermal time constant can be computed as $t = C/G$, where C is the electron heat capacity. For the obtained value of S we get $t \approx 5T^{-3}$ ns. At T = 300 mK the time constant $\tau \approx 0.2$ μs, and at T = 100 mK the time constant $t \approx 5$ ms, which is considerably shorter as what is typically required.

When operated at temperature 100 mK and below the NHEB did not show significantly better power sensitivity. The performance was apparently limited by the quality of the measuring tunnel junction – its IV curve stopped sharpening at 300 mK. We believe this nonideality was due to the thermal treatment during the second stage lithography.

III. The Electronic Cooling

Using similar routines we have also fabricated an NHEB with four tunnel junctions as shown in fig. 2 and fig. 6. The absorber has been in this case a 40 nm thick 0.25 μm wide and 7 μm long copper strip. Junctions used for cooling need to have normal resistance of the order of 1 kΩ each to make this process efficient. At the same time, the junctions used for measuring the electron temperature should have normal resistance at least over 10 kΩ to keep the biasing current low. To get this combination we used junctions with very different areas (0.2 μm^2 for large and 0.01 μm^2 for small ones). In practice we have got the ratio of normal resistances much larger than 20, presumably because of oxidation from the edges affecting the small junctions much more than the large ones.

To demonstrate the electronic cooling action in the microbolometer we measured the voltage drop over the small junctions at a constant biasing current as a function of voltage over the large junctions. Then we calibrated this voltage drop as a function of temperature in a cryostat with the large junctions not connected.

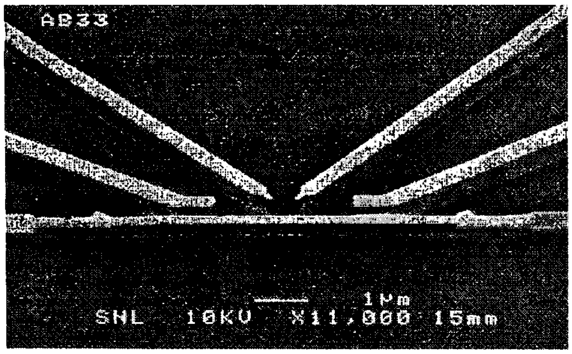

Fig. 6a. SEM picture of a microbolometer with electronic microrefrigeration fabricated by double shadow evaporation.

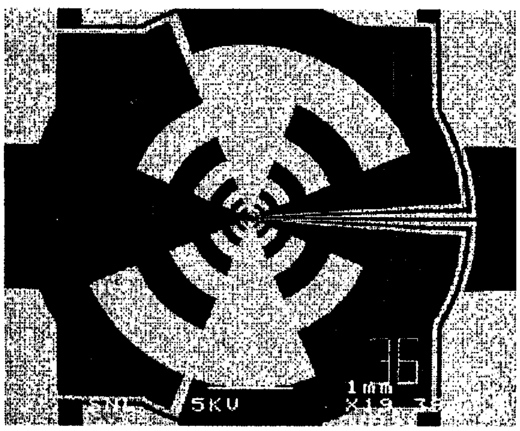

Fig. 6b. View of a chip with a planar log-periodic antenna designed for device tests at 100-1000 GHz.

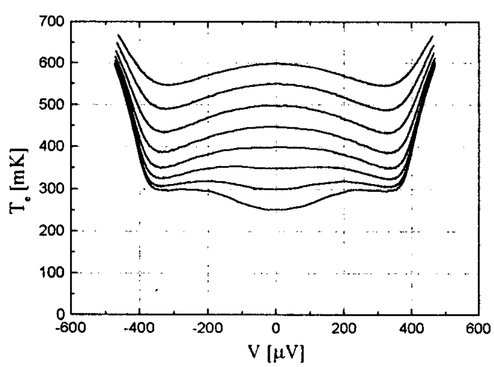

Fig. 7. Temperature of electrons T_e in the absorber as a function of voltage applied over two large SIN junctions at various starting temperatures.

The resulting curves with different starting temperatures $T_{ph} = T_e$ at $V = 0$ are presented in fig. 7. We can see both the cooling action and its unexpected suppression below 400 mK. At present we do not have a clear understanding of this limitation. We had a suggestion that this effect could be due to the Joule heating from the bias current flowing between the tunnel junctions. To check this we put those large junctions as close as only 0.5 µm from each other, but the behavior of the system remained the same.

IV. Conclusion

We have fabricated a normal metal hot-electron bolometer (NHEB) with an absorber of very small volume, connected to an antenna by the Andreev NS-contacts. Experiments where the absorbers have had different lengths show that the thermal conductance is mainly determined by the electron-phonon interaction and almost no heat losses through the NS-contacts have been present. Thermal conductances of $6\cdot10^{-12}$ W/K and $7\cdot10^{-14}$ W/K have been measured for the microbolometer with the shorter absorber at 300 mK and 100 mK, respectively. It gives the time constants $t = 0.2$ µs and $t = 5$ µs and $NEP = 5\cdot10^{-18}$ W/Hz$^{1/2}$ and $NEP = 2\cdot10^{-19}$ W/Hz$^{1/2}$ for the temperature fluctuation noise component. These parameters, especially the time constant, are considerably better than similar parameters of a voltage-biased superconducting transition edge bolometer [7]. We have fabricated also an extended version of NHEB where the electronic cooling by two SIN tunnel junctions has been applied to decrease the total NEP of the detector.

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