NORMAL METAL HOT-ELECTRON MICROBOLOMETER WITH ANDREEV MIRRORS FOR THZ SPACE APPLICATIONS

D. CHOUVAEV, L. KUZMIN, M. TARASOV*, P. SUNDQVIST, M. WILLANDER, AND T. CLAESON

DEPARTMENT OF MICROELECTRONICS AND NANOSCIENCE, CHALMERS UNIVERSITY OF TECHNOLOGY, S-412 96 GOTHENBURG, SWEDEN
* INSTITUTE OF RADIOENGINEERING AND ELECTRONICS OF RUSSIAN ACADEMY OF SCIENCES, MOKHOVAYA 11, 103907 MOSCOW, RUSSIA

Abstract

We present a concept and experimental development of an ultrasensitive normal metal hot-electron microbolometer with Andreev mirrors and electronic cooling by superconductor-insulator-normal metal (SIN) tunnel junctions. A value $NEP = 5 \cdot 10^{-18}$ W/Hz$^{1/2}$ for the temperature fluctuations component of noise and the thermal time constant $\tau = 0.2$ μs at 300 mK have been estimated for one of the realized devices with thermal conductance $G \approx 6 \cdot 10^{-12}$ W/K . Such microbolometer is intended as a detector of millimeter and sub-millimeter wave radiation.

1. 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 . This weak thermal coupling characterized by the heat conductance G is mainly responsible for a

substantial temperature rise for very low input power (so-called hot-electron effect).

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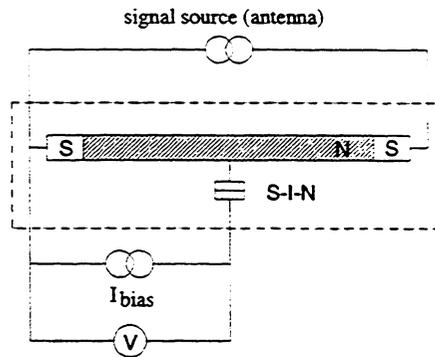
Fig. 1. Schematic of the microbolometer: an SIN junction is biased at a small constant current. A junction voltage depends on the smearing of the IV-curve, which is used to measure the electron temperature in the normal metal absorber (hatched).

An important feature of the NHEB with Andreev mirrors is that the thermal time constant τ equals the electron-phonon relaxation time τ_{e-ph}. The typical values of τ (10 μs at 100 mK and 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 $NEP < 1 \cdot 10^{-17}$ W/Hz$^{1/2}$ and the time constant $\tau < 1$ ms.

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

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

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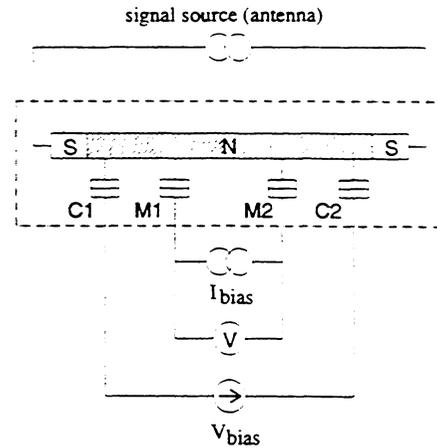
Fig. 2. Schematic of the microbolometer with electronic refrigeration. Two low-resistive SIN junctions (C1 & C2) are voltage-biased and used to decrease the effective electron temperature of the normal metal absorber element (hatched). Two high-resistive SIN junctions (M1 & M2) are biased with a small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

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 sink 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].

2. 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 $4 \cdot 10^{-2}$ 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.
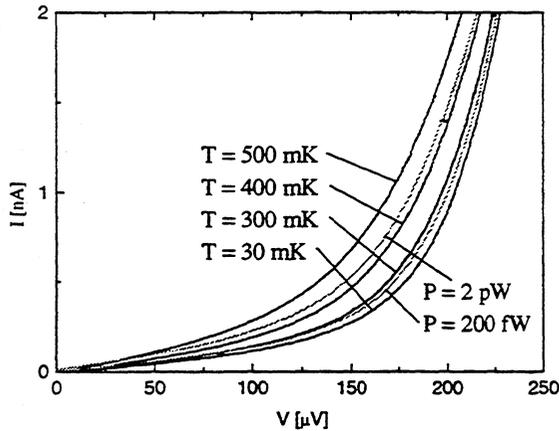
Fig. 3. IV curves of the SIN junction measured for different temperatures without any signal current and for two different powers dissipated by the signal current at the base temperature of 30 mK.

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:

$$P_{e\rightarrow ph} = \Sigma U\left(T_e^5 - T_{ph}^5\right) \quad \Rightarrow \quad (2)$$

$$\Rightarrow \quad \frac{dP}{dT} = 5\Sigma UT^4,$$

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

$$\frac{dV}{dI_{ABS}} = \frac{dV}{dT} \cdot \left(\frac{2I_{ABS}R}{5\Sigma T^4 U}\right) \propto \frac{R}{U}. \quad (3)$$
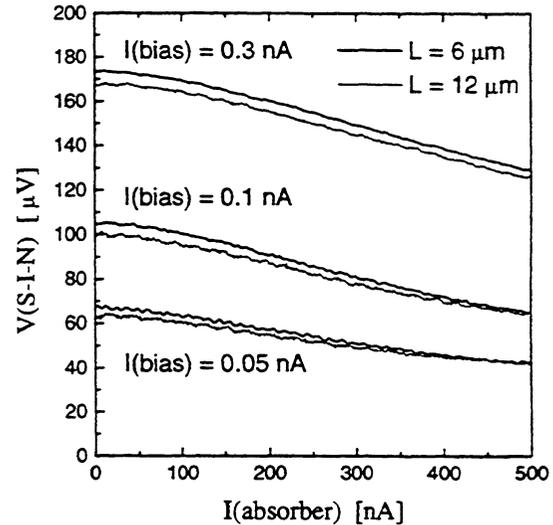
Fig. 4. The junction voltage V at constant bias current I(bias) through the junction as a function of the signal current I(absorber) for two devices with different absorber length 6 μm and 12 μm at $T = 30$ mK.

The overlapping of the curves means then, that increase of dissipated power (P) due to higher resistance (R) has been exactly compensated by 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}·μm^{-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 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].
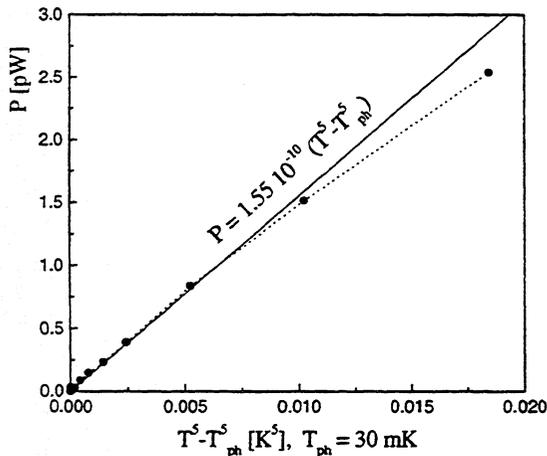
Fig. 5. Power dissipated in the absorber vs. $(T^5 - T^5_{ph})$, where T is temperature of electrons deduced from measurements $V(I_{bias}, T)$, and $T_{ph} = 30$ mK is temperature of the lattice (measured temperature of the sample holder). Linear fit corresponds to the relation (2).

The thermal time constant can be computed as $\tau = C/G$, where C is the electron heat capacity. For the obtained value of Σ we get $\tau \approx 5T^{-3}$ ns. At $T = 300$ mK the time constant $\tau \approx 0.2$ μs, 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, which has had an

IV curve changing its shape substantially only above 300 mK. We believe that such a behavior can be due to the thermal treatment while making the second layer lithography.

3. 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.
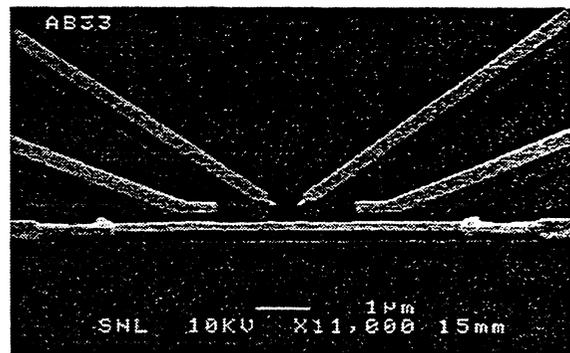
Fig. 6a. SEM picture of a microbolometer with electronic microrefrigeration fabricated by double shadow evaporation. The upper strip is made of copper and forms the absorber. The darker layer is aluminum; two large and two small tunnel junctions are formed where the absorber strip covers the oxidized aluminum electrodes. The ends of the absorber are contacted to aluminum electrodes, which has been fabricated using a separate lithography process.
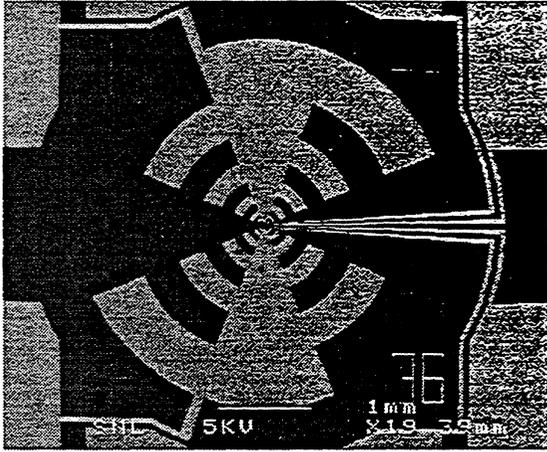
Fig. 6b. View of a chip with a planar log-periodic antenna designed for device tests at 100-1000 GHz.

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.
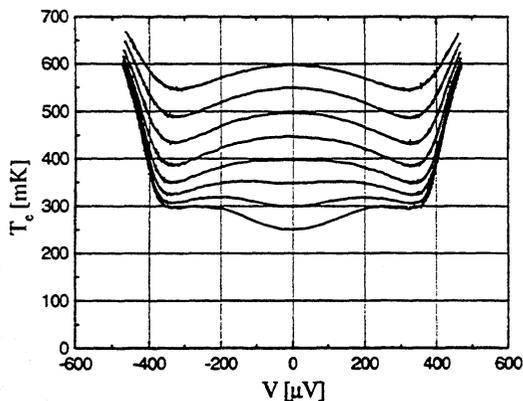
Fig. 7. Temperature of electrons T_e in the absorber as a function of voltage applied over two large SIN junctions $(R_n[M1] + R_n[M2] = 62 \text{ k}\Omega + 116 \text{ k}\Omega)$ at various starting temperatures. T_e is computed from the voltage drop over two smaller tunnel junctions $(R_n[C1] + R_n[C2] = 625 \ \Omega + 645 \ \Omega)$ biased at a small constant current using a calibration curve obtained in a separate measurement.

The resulting curves with different starting temperatures $T_{ph} = T_e$ at $V = 0$ are presented in the 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 contradiction to the previous results from [4]. 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 had put those large junctions as close as only 0.5 μm from each other, but the behavior of the system remained the same.

4. 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. The thermal conductance of $6 \cdot 10^{-12}$ W/K has been measured for the microbolometer with the shorter absorber at 300 mK. It gives the time constant $\tau = 0.2 \ \mu s$ and $NEP = 5 \cdot 10^{-18}$ 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 eventually be able to decrease the total NEP of the detector.

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