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Fabrication and optical characterization of the normal metal hot-electron microbolometer with Andreev mirrors

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Abstract

The normal metal hot-electron microbolometer (NHEB) is a direct detector for mm and sub-mm wavelengths. Theoretical estimations indicate that such a device should be able to achieve a sensitivity of around 10^{-17} W/(Hz)$^{1/2}$ at 0.3 K and a time constant less than 1 μs. The temperature of the electron gas is monitored using superconductor–insulator–normal metal (SIN/NIS) tunnel junctions. We have fabricated such an NHEB where the normal metal strip is coupled to a double slot antenna for optical qualification (normal metal strip size $(5.6 \times 0.25 \times 0.03)$ μm^3). The antenna is designed for 300 GHz and has an impedance of 30 Ω at the center frequency. The actual optical responsivity and the response time of our NHEB has been measured at 0.5 K using a hot/cold load (black body radiation at room temperature and at liquid nitrogen temperature). DC-current measurements performed on other samples earlier indicate that our NHEB can achieve an electrical noise equivalent power (NEP) of at least 3×10^{-16} W/(Hz)$^{1/2}$. We conclude that the optical responsivity value obtained in the measurement is consistent with the electrical NEP value at the same temperature and in agreement with the estimated efficiency of the quasioptical coupling.

Keywords: Hot-electron effect; Tunnel junctions; Andreev mirror; Antenna coupled bolometer

1. Introduction

Today most of the detectors for the sub-mm and far-infrared ranges are of the composite bolometer type with a noise equivalent power (NEP) of around 10^{-17} W/(Hz)$^{1/2}$ at 0.1 K and a time constant of $\tau \approx 10^{-2}$ s [1]. This level of sensitivity and reaction time is not considered sufficient for future space applications. One possible way to achieve the required performance has been proposed by Nahum et al. [2]. We are developing such a proposed detector, a normal metal hot-electron bolometer shown in Fig. 1.

The normal metal hot-electron microbolometer (NHEB) is in general a metal island situated between two superconductors (SNS structure). Incident radiation on an antenna coupled to the superconductors will heat the electron gas inside the normal metal. At low temperatures the electron–phonon interaction time ($\tau_{ep} = 10^{-6}$ s at $T =$ 0.3 K) is much longer than the electron–electron inelastic interaction time ($\tau_{ee} \approx 10^{-9}$ s) which allows the electron gas to establish its own thermal equilibrium above the phonon temperature. Andreev reflection at the NS interfaces prevents hot

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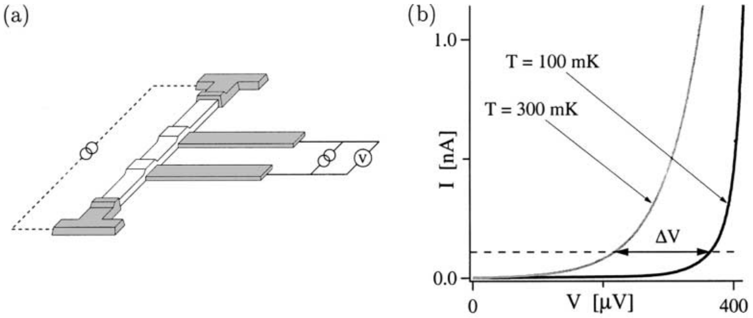

Fig. 1. Schematic picture of the bolometer. Two NIS tunnel junctions in the center are the part of the temperature readout circuit. The side electrodes are the antenna terminals. (b) The electron temperature is read from changes of the NIS junctions' *IV* curve by measuring voltage at a constant current bias.

electrons from escaping back into the antenna. The change in electron temperature is easily measured by NIS tunnel junctions. One can show [3] that the electrons lose energy to the lattice with a rate $P_{\mathrm{el-ph}} = \Sigma\Omega(T_{\mathrm{el}}^5 - T_{\mathrm{ph}}^5)$ where Σ is material dependent (2.5×10^{-9} W μm^{-3} K^{-5} for copper) and Ω is the volume of the normal metal strip. The responsivity S is given by

$$S = \frac{\mathrm{d}V}{\mathrm{d}T}\frac{\mathrm{d}T}{\mathrm{d}P} = \frac{\mathrm{d}V}{\mathrm{d}T}\frac{1}{G}$$

where $\mathrm{d}V/\mathrm{d}T$ is the temperature responsivity of the tunnel junctions and G is the thermal conductance. The value of $\mathrm{d}V/\mathrm{d}T$ for aluminum junctions is almost constant (8×10^{-4} V/K) in the temperature range 0.15–0.45 K (at the optimal bias). The NEP of the bolometer is given as the quotient of the total voltage noise at the output of the bolometer and the responsivity (NEP $= (e_n)/S$).

Several measurements have been made on this kind of bolometer previously (e.g. [4]) but all of them are based on electrical experimental setups using dc currents to heat the metal strip instead of actual optical setups with real incident radiation. One possible problem with this type of bolometer is that the thermalization of the electrons might not be sufficient if the incident photons have an energy well above the energy gap. In this case hot electrons might go over the Andreev mirror and escape into the antenna. Such a problem is not encountered in a dc-current measurement. Another issue to address is how well one can couple the incident radiation into the device. To answer these questions one must perform real optical measurements.

2. Optical qualification

The concept of our optical setup was described in detail in [5]. A helium dewar with an optical window and a closed-cycle ^{3}He cryocooler mounted at the cold plate was the main component in our setup. We have used a twin slot antenna to couple the incident radiation into the normal strip. The dimensions of the antenna were calculated using a procedure developed at Caltech [6]. The bolometer is situated in the center and is connected to the slots by coplanar transmission lines with a characteristic impedance of 30 Ω, which matches that of the antenna at 300 GHz. The size of the normal strip on the measured sample was ($5.6 \times 0.25 \times 0.03$) μm^3. There were four junctions present on the sample instead of the two designed. The two extra might have been the result of a disruption of the superconducting layer at the bend of the electrode wires. The total resistance of the four junctions in series was 5.0 kΩ, with the left and the right temperature measuring junctions symmetrical in resistance. The sample was precalibrated (with respect to temperature) in a dilution refrigerator where one could expect the lattice and the electron gas to be in equilibrium. These calibration curves were used extensively to monitor the temperature of the electron gas throughout the whole experiment. The lowest electron temperature

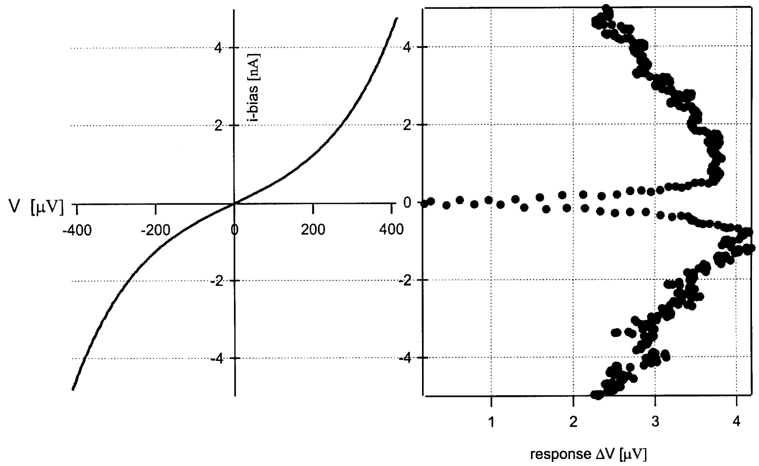

Fig. 2. *IV* curve of the SINIS tunnel junctions that measures the temperature change of the electron gas. The working temperature of the bolometer was estimated to 500 mK. Right panel: Voltage response corresponding to the alternating hot/cold load. The vertical axis is the bias current (in both panels).

reached during the measurements was estimated to 460 mK. The main principle of the experiment was to expose the detector to either a hot load (room temperature 297 K) or a cold load (liquid nitrogen temperature 77 K). A rotating chopper was used to switch between the two loads. The junctions were biased by a constant current and the change in voltage across them was measured using a lock-in amplifier at 35 Hz. The result can be seen in Fig. 2.

A maximum response of 4 μV is observed at the optimal bias of 1 nA. To estimate the optical sensitivity $S_{opt} = \Delta V/\Delta P$ one must know the change of input power ΔP. We used the simplified Plank's formula for black body radiation in the limit of high temperatures and low frequencies to estimate this parameter according to

$$\Delta P = \eta k_b (T_2 - T_1)\Delta f$$

where η is the coupling efficiency, k_b is Boltzmann's constant, and Δf is the bandwidth of the system. The losses in the setup have been calculated to be above 21 dB taking into account Dewar windows (teflon, ≈0.4 dB), various filters (mainly neutral density filter, ≈19 dB) and lenses (dielectric TPX and Silicon, ≈1.6 dB) [5]. The bandwidth has theoretically been estimated to 180 GHz. A scale model of the circuit was tested with a scalar network analyzer and the results supported the theoretical estimations. Given the assumed bandwidth we obtain $\Delta P = 4.3 \times 10^{-12}$ W and $S_{opt} = \Delta V/\Delta P = 9 \times 10^5$ V/W. This is consistent with the value obtained for the sample in dc-measurements using the dilution refrigerator which means that the unaccounted losses were small. We also performed measurements of the voltage noise arising from the NHEB as well as the noise of the preamplifier in order to calculate the NEP. We found the noise level to be $e_{tot} = 15$ nV/(Hz)$^{1/2}$. Combining this result with the value for S_{opt} we get an NEP of 1.4×10^{-14} W/(Hz)$^{1/2}$ at 35 Hz. The noise contribution from the bolometer was $e_{bol} = 2$ nV/(Hz)$^{1/2}$ which means that the intrinsic NEP was 2×10^{-15} W/(Hz)$^{1/2}$. It is important not to mix intrinsic and technical NEP when comparing detectors.

3. Conclusion

We have performed optical measurements of an NHEB at an electron temperature of 500 mK and the sensitivity achieved at this temperature corresponds to a sensitivity of 1.8×10^{-15} W/(Hz)$^{1/2}$ at 0.3 K. This is consistent with the electrical NEP value we got during the calibration of the sample in the dilution refrigerator. The results arc also in agreement with the estimated efficiency of the quasioptical coupling. However, we are still missing an order of magnitude in sensitivity as compared to the electrical NEP obtained for other samples earlier (3×10^{-16} W/(Hz)$^{1/2}$). One possible reason for this poor sensitivity might be that the Andreev mirror on the measured sample does not work properly. This improper behavior of the mirror might be the result of ferromagnetic contamination in the superconductor. Previous bolometers did not have this problem but they were fabricated using slightly different parameters (different evaporation angles, different size, etc.). Hence we are led to believe that the problem will be solved in the nearest future.

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