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Thermal characterization of a hot-electron micro-bolometer

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Abstract

We report on a hot-electron micro-bolometer fabricated by electron beam lithography consisting of a small normal-metal absorber capacitively coupled to a planar antenna. Both the thermometer and the coupling capacitors are made by sub-micron normal metal–insulator–superconductor junctions. By adding two extra Andreev contacts to the absorber it is possible to characterize the bolometer by dc measurements. © 2001 Elsevier Science B.V. All rights reserved.

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1. Introduction

We are developing a normal metal hot-electron micro-bolometer suitable for the detection of infrared radiation in the mm and sub-mm range. Such a bolometer is designed for high sensitive astronomical observations. The bolometer, which operates at 0.3 K, consists, in the present configuration, of a planar bow tie antenna (3 mm is the length of each lobe) connected to an absorber made by a copper micro-strip (volume $U \simeq 0.1\ \mu m^3$). The temperature rise of the absorber is sensed by an ultra-small thermometer made by two tunnel junctions of normal metal–insulator–superconductor (NIS) type [1]. The junctions are current biased; a change in the temperature reflects into a change of the voltage V_T across the junctions.

In general, at low temperature electrons and phonons are energetically decoupled, so that the temperature of the electron gas T_{el} can be made different from the temperature of the phonon gas T_{ph}. The electrons lose energy to phonons with a rate $P_{el-ph} = \Sigma U(T_{el}^5 - T_{ph}^5)$, where Σ is material dependent and is about $4\ nW/K^5\,\mu m^3$ for a metal on a bulk silicon substrate [2]. Making the volume U small, also the value of P_{el-ph} can be made small, and this mechanism can be used to obtain a hot-electron micro-bolometer provided all the other channels of energy loss are eliminated. In this case, when the metal absorbs a small power P, the electron temperature rises to $T_{el} = (T_{ph}^5 + P/\Sigma U)^{1/5}$. In our case, with an input power of $P = 1$ pW, at a bath temperature (considered equal to the phonon temperature) $T_{ph} \approx 0.3$ K, an electron temperature change of $\Delta T_{el} \approx 45$ mK is expected. The contribution of the electron–phonon mechanism to the total thermal conductance G of the bolometer is given by $G_{el-ph} = dP_{el-ph}/dT = 5\Sigma U T_{el}^4$ ($\approx 2.5\times 10^{-11}$ W/K in our case).

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One possible extra channel of energy loss of the absorber is through the contacts with the antenna. In order to avoid the hot-electron escape, this effect must be minimized by using as coupling contacts either the Andreev reflection mirrors [1] or, alternatively, the capacitive mirrors [2]. With the first type of mirrors, realized by means of two ideal normal-to-superconducting (NS) contacts, the absorber is electrically coupled to the antenna but is thermally insulated from it. The drawback of the Andreev mirrors arises when high frequency photons, with energy larger than the superconducting energy gap Δ (>50 GHz for Al), get into the absorber. In this case, if thermalization of the excited electrons is not efficient, some of them can reach the NS contact with an energy larger than Δ and escape from the absorber increasing in this way the total thermal conductance G. We plan to test both type of mirrors but our present results concern the capacitive coupling of the absorber to the antenna. As stated in Ref. [2] the inconvenience in using this coupling method is that it is not possible to calibrate the bolometer by using dc measurements with currents of low enough amplitude. We overcame this problem by adding two extra NS contacts to the absorber that allowed us to feed small currents in the absorber itself. Again, such Andreev contacts ideally should not spoil the absorber performances with respect to thermal insulation.

2. Bolometer design

Fig. 1 shows the two types (A and B) of bolometers that we fabricated. The type A will be the

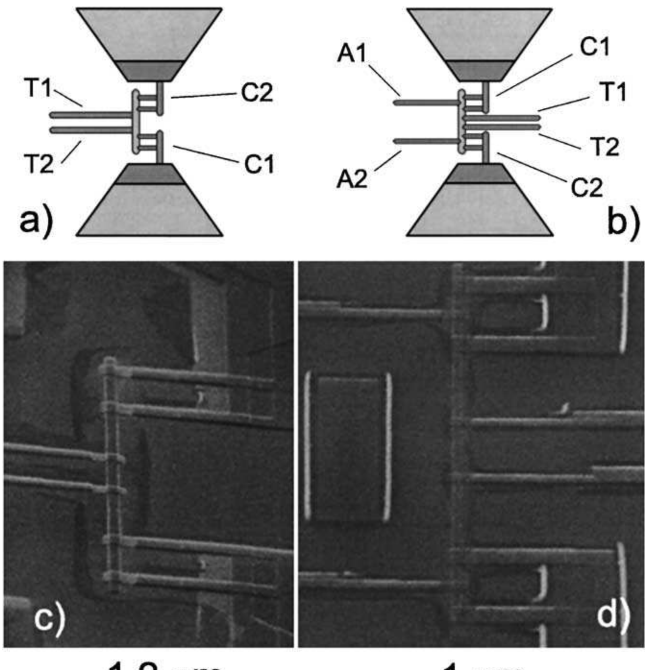

Fig. 1. Top: Schematic drawing of two types of bolometer. (a) Type A bolometer: The bolometer is capacitive coupled (through C_1 and C_2) to the antenna. The thermometer (T_1 and T_2) is made by two NIS junctions. Each coupling capacitor C_i consists of two NIS junctions. (b) Type B bolometer: In this bolometer two extra NS contacts (Andreev A_1, A_2) are added. Bottom: Scanning electron micrographs of the type A (taken at 60° tilting) and type B (taken at 48° tilting) bolometers in the absorber region. (c) Type A bolometer: Absorber and six sub-micron NIS junctions: at each absorber side end there are the coupling capacitors (two NIS junctions each) and in the middle there are the two NIS junctions of the thermometer. (d) Type B bolometer: Absorber and six sub-micron NIS junctions together with the NS contacts (left side).

final bolometer configuration when the absorber characterization, achieved with the type B bolometer, will be completed. In both types, we used the capacitance of the NIS junctions for the thermal insulation of the absorber. This has the advantage that with the same technique and in the same process step we can also make the thermometer (consisting of the two NIS junctions T_1 and T_2). The disadvantage is that NIS junctions are not completely opaque (like an ideal capacitor) allowing the tunneling of the electrons. The transparency of the NIS barrier should be negligibly small for frequencies smaller than 5×10^{14} Hz [2]: in this work we want to test its capability to insulate the absorber from the environment, by measuring the thermal conductance of our bolometers. The evaluation of the total thermal conductance G of the absorber is important in order to determine the figures of merit commonly used to characterize a bolometer. In fact, the power responsivity $S = (\mathrm{d}V_\mathrm{T}/\mathrm{d}T)G^{-1}$ and the phonon noise equivalent power $\mathrm{NEP_{ph}} = (4k_\mathrm{B}T^2G)^{1/2}$, depend from G [3].

Each coupling capacitor C_i consists of two NIS junctions. In the type B bolometer two extra NS contacts (Andreev A_1, A_2) are added to be used for the thermal characterization of the absorber.

3. Fabrication details

Contact pads, antenna, absorber and NIS junctions are fabricated on a silicon substrate coated with about 300 nm SiO_2. The planar antenna and the contact pads, made by 80 nm thick Nb with a 20 nm thick Au capping layer, are defined by photolithography. In this layer we also define the markers that will allow the realignment in the successive lithography step. The NIS junctions and the absorber are obtained by electron beam lithography and shadow mask evaporation through a mask made by a bilayer of electronic resists [4]. The evaporation was made at three different large angles θ. We deposited a first Al layer, 30 nm thick, at $\theta = +52°$, a second Al layer, 30 nm thick, at $-52°$ and on top of them a 30 nm thick Cu layer at 0°, where $\theta = 0°$ is the direction normal to the substrate plane. We avoid in this way the supernumerary isolated islands due to the shadow mask evaporation [5,6]. In the type A bolometer, before the copper film evaporation, we oxidize both the first and the second aluminum film by exposing them to pure oxygen, making in this way both the thermometer junctions T_i and the coupling capacitors C_i. In the type B bolometer, we oxidize just after the deposition of the first aluminum layer to form the barrier for the NIS junctions of T_i and C_i, successively we deposit the second aluminum layer to form the base electrode of the Andreev NS contact A_i and, at the end, the copper is evaporated on top of them. The area of a single NIS junction of the thermometer is about 0.04 μm^2, while that of the coupling capacitor is 0.1 μm^2. The absorber, ≈13 μm long and ≈0.25 μm wide, is made by the copper film.

4. Measurements and discussion

At each side end of the absorber there are two NIS junctions (see Fig. 1): we can estimate their sum capacitance $C_i \simeq 10$ fF, considering for the AlO_x insulator a specific capacitance of about 50 fF/μm^2. The effective high frequency coupling to an external signal is determined by the total impedance seen by a travelling signal in the bolometer antenna. We consider the impedance of the antenna $Z_\mathrm{a} \simeq 80\ \Omega$ and frequency independent [7]. The absorber has a total impedance $Z_\mathrm{t} = [R_\mathrm{abs}^2 + (\omega L_\mathrm{abs} - 1/\omega C_\mathrm{t})^2]^{1/2}$, where $C_\mathrm{t} = [(1/C_1) + (1/C_2)]^{-1} \simeq 5$ fF is the total capacitance and $L_\mathrm{abs} \simeq 45$ pH is the strip inductance of the absorber (considering in our case a specific inductance of about 3.5 pH/μm). The absorber resistance $R_\mathrm{abs} \simeq 15\ \Omega$ was determined by the four wire measurement using the contacts A_i of the type B bolometer. The capacitive coupled bolometer has a band-pass response, centered at $f_0 = 1/(2\pi\sqrt{L_\mathrm{abs}C_\mathrm{t}}) = 330$ GHz with $Q = 1/\omega C_\mathrm{t}R_\mathrm{abs} = 6.5$. A predefined frequency range can be achieved by changing the total capacitance C_t. The measurements were carried out in an unshielded environment by using a ^{3}He refrigerator. Filtering was obtained by feed-through capacitive filters and thermocoax cables

[8]. We electrically tested the thermal properties of our normal metal hot-electron micro-bolometer by feeding a small ac signal i_{abs} at a frequency $f = 8$ Hz into the absorber through the NS contacts A_i and measuring the corresponding thermometer voltage change ΔV_T at $2f$ (this is because the thermometer response depends from the power $P = i^2_{abs}R_{abs}$). For this measure a spectrum analyzer was used. The thermometer was current biased approximately in the middle of the superconducting gap to get the maximum of the temperature responsivity, $dV_T/dT \simeq 480$ μV/K, a figure quite typical for our NIS junctions [9]. The plot of the voltage change across the thermometer ΔV_T versus the power deposited in the absorber P at $T_{ph} = 330$ mK (see Fig. 2a) allows us to estimate both the power responsivity $S = dV_T/dP \simeq 6.2 \times 10^6$ V/W and the total thermal conductance $G = dP/dT = S^{-1}dV_T/dT \simeq 7.7 \times 10^{-11}$ W/K. The latter is about three times larger than the theoretical electron–phonon thermal conductance $G_{el-ph} \simeq 2.4 \times 10^{-11}$ W/K calculated with a volume $U = 0.1$ μm^3. To understand if the energy losses are due to mechanisms other than the electron–phonon thermal coupling, we considered the electron temperature dependence (in the form $T^5_{el} - T^5_{ph}$) as a function of the deposited power P (Fig. 2b) at $T_{ph} = 330$ mK. The linear dependence of this plot indicates that: (a) the electron–phonon energy coupling is the basic mechanism of the energy escape from the absorber, (b) the product $\Sigma U \simeq 1.1$ nW/K^5. This suggests that the absorber has an effective volume about a factor 3 larger than $U \simeq 0.1$ μm^3, maybe because of the imperfect energy decoupling of the NIS capacitors C_i. Nevertheless, this can be stated for sure after an independent measure of Σ (here assumed equal to 4 nW/μm^3 K^5) fabricating an absorber not connected to the antenna. Scaling the thermal conductance value G from the measured value at 0.33 K to the value at 0.30 K, considering the demonstrated T^4 temperature dependence, we can predict at this temperature a phonon $\mathrm{NEP_{ph}} = (4k_BT^2_{ph}G)^{1/2} \simeq 1.6 \times 10^{-17}$ W/Hz$^{1/2}$. This figure, however, cannot be directly measured because it is overhelmed by the noise of the voltage preamplifier, even with the best voltage preamplifier available (with a voltage noise $V_{n_A} \simeq 0.3$ nV/Hz$^{1/2}$), our total NEP is dominated from the preamplifier contribution. In fact, the total NEP is the quadratic sum of the $\mathrm{NEP_{ph}}$ plus the contribution coming from the preamplifier, $\mathrm{NEP} = (4k_BT^2G + V^2_{n_A}/S^2)^{1/2}$ (other terms are neglected [3]) which in the best case gives NEP $\simeq 5\times 10^{-17}$ W/Hz$^{1/2}$. In conclusion, we showed that also using the capacitive coupling between antenna and absorber it is possible to characterize the bolometer by the dc measurements by adding two extra Andreev contacts. Improvement of the NEP can be achieved if the contribution coming from the amplifier can be made small. This can be obtained considering that dV_j/dT is the temperature responsivity of a single NIS junction biased in current and $dV/dT = N(dV_j/dT)$ is that of the thermometer (in the present case $N = 2$). By increasing the number of the junctions we can

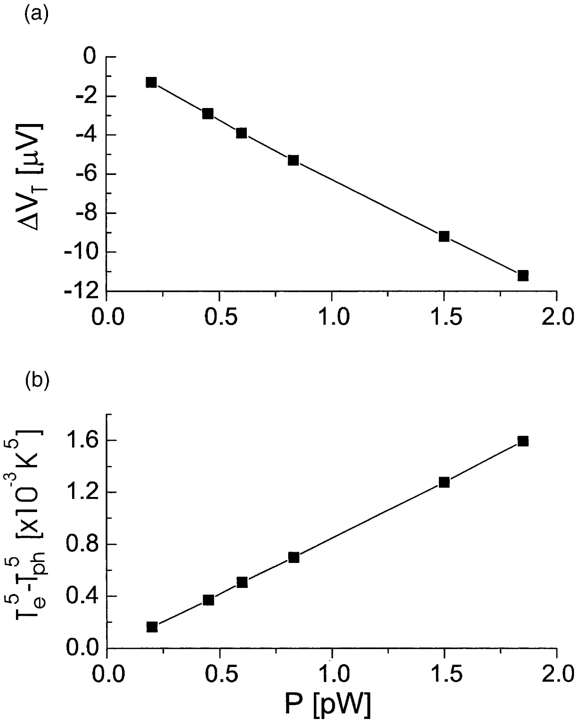

Fig. 2. (a) Thermometer voltage change ΔV_T versus the power dissipated in the absorber P. (b) Plot of $T^5_{el} - T^5_{ph}$ versus the power deposited in the absorber P. Both measurements are taken at a bath temperature $T_{ph} = 330$ mK.

increase N times the power responsivity $S \propto \mathrm{d}V/\mathrm{d}T$, while the noise is increasing $N^{1/2}$ times.

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