Electron cooling in a normal metal hot electron microbolometer

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Abstract. A capacitive coupled normal metal hot electron microbolometer with two SIN tunnel junctions intended for temperature sensing and two SIN junctions for thermal insulation and electron cooling have been fabricated and experimentally studied. Electron cooling by SIN junctions is analogous to Peltier effect in semiconductors and allows reducing the electron temperature of such a bolometer. Effective electron temperature was estimated from the ratio of dynamic resistance at finite bias to the normal state resistance of SIN sensor. Applying a bias voltage nearly 0.4 mV to the cooling junctions decreases the electron temperature of absorber from 250 mK down to 90 mK. Electron cooling in bolometer improves response and reduces noise and influence of a background power load.

1. Motivation

Normal metal hot electron bolometer with capacitive coupling (CCNHEB) was proposed in [1] and experimentally demonstrated in [2]. Responsivity and noise equivalent power (NEP) of the bolometer are mainly determined by its electron temperature. To improve CCNHEB performance we suggest using direct electron cooling of absorber by a superconductor-insulator-normal metal (SIN) tunnel junction [3]. The effect of electron cooling was demonstrated in [4] and further developed in [5]. For estimation of the actual electron temperature simplest way is to fit IV curve of a real junction by ideal SIN tunnel junction IV curve. The first approximation on kT is:

$$I(V,T) = \frac{1}{eR}\sqrt{2\pi kT\Delta}\cdot\exp\left(-\frac{\Delta}{kT}\right)\cdot\sinh\left(\frac{eV}{kT}\right) \tag{1}$$

in which T is temperature, Δ is energy gap of superconductor, e – electron charge, k – Boltsman constant, V – voltage. A subgap current can affect both shape of IV curve and electron temperature of the bolometer. Such subgap residual conductivity can be due to imperfectness of the tunnel barrier, normal inclusions in superconductor, etc. Another mechanism of subgap conductivity is two-electron tunneling when two normal electrons can be converted into a Cooper pair [6]. Depending on junction geometry, the subgap conductivity is strongly enhanced if the interference effect is essential. It was also analyzed in [7] that reducing insulator thickness and resistivity of junction leads to increase of Andreev reflections. Other parasitic effects are reabsorption and back-tunneling that can dominate at temperatures below 200 mK [8]. Without trap the cooling power is reduced due to electrons that return back from superconducting electrode to the normal metal. Some experiments [9] demonstrated temperature saturation below 300 mK when hot electrons are confined in the normal metal trap.

For practical junctions very important can be presence of a pinhole-type defect in tunnel barrier. Such defect is easy determined by residual conductivity at zero bias. For typical junction with normal resistance 1 kΩ at 350 mK the dynamic resistance at zero bias should be over 1 MΩ and we can take as example the leakage resistance of about the same 1MΩ. The electron temperature under absorbed power is estimated as

$$T_e = \left(T_{ph}^5 + \frac{P}{\Sigma V} \right)^{1/5} \tag{2}$$

in which P is absorbed power, $\Sigma=3{\cdot}10^9$ Wm^{-3}K^{-5} is metal parameter, V=0.18 μm^3 is volume of absorber. For zero phonon temperature at standard dc bias of 400 μV the temperature is increased by about 200 mK. Even if bias voltage is 4 times as low, at 100 μV the temperature increase is still 115 mK. Increased by one order of magnitude leakage resistance to 10 MΩ does not help much and still brings temperature increase by 127 mK at 400 μV. It means that even small probe current increase electron temperature over equilibrium phonon temperature and calibration of electron temperature become rather tricky. Let us consider the zero-bias resistance ratio as electron temperature probe. Adding to equation (1) the parallel conductance of leakage current one can obtain the temperature dependence of relative dynamic resistance of the real junction

$$rds = \left[\left(\sqrt{\frac{2k_b T}{\pi \Delta}} \, \frac{\exp\left(\dfrac{\Delta}{k_b T} \right)}{\cosh\left(\dfrac{eV}{k_b T} \right)} \right)^{-1} + \frac{R_n}{R_s} \right]^{-1}, \tag{3}$$

in which R_n is normal resistance and R_s is shunting leakage resistance. Example of such dependence on bias voltage is calculated in Fig. 1 for parameters of one of our samples.

From Fig. 1 one can see clear saturation of zero-bias thermometer at temperatures below 200 mK. Accuracy of measurements is decreasing. But for lower temperatures we can use still not saturated region of bias voltages where the dynamic resistance is small compared to leakage shunting resistance. And this region can be used for temperature estimations. The illustration to this can be calculation of the dynamic resistance for the same junction in dependence on temperature for bias voltages 0, 200 and 300 μV presented in Fig. 2. So when temperature is below 200 mK the resistance ratio should be taken for bias voltage 250 μV, and below 100 mK bias should be 300 μV.

With reducing of effective electron temperature a responsivity dV/dT$_e$. can be significantly reduced. According to [9] if the IV curve of SIN junction can be approximated as $I(V) = I_0 e^{\frac{eV-\Delta}{k_b T_e}}$ where $I_0 = \dfrac{\sqrt{2\pi \Delta k_b T_e}}{2eR_N}$

The maximum temperature sensitivity is at zero bias

$$\frac{dV}{dT_e} \cong \frac{k_b}{e} \ln \frac{I}{I_0} = \frac{k_b}{e} \cdot \frac{eV - eV_\Delta}{k_b T_e} = -\frac{V_\Delta}{T_e} \tag{4}$$

In practical junctions such high response is masked by a leakage resistance. For real bolometer with the same junctions for cooling and temperature sensing the bias voltage is about eV_Δ-kT and it brings a constant response $dV/dT=(T/T_e)k/e$. With detuning from the bias voltage optimal for cooling, one can obtain a moderate increase in temperature response. Electron cooling also reduces the Noise Equivalent Power $NEP^2=4kT_e^2G$.

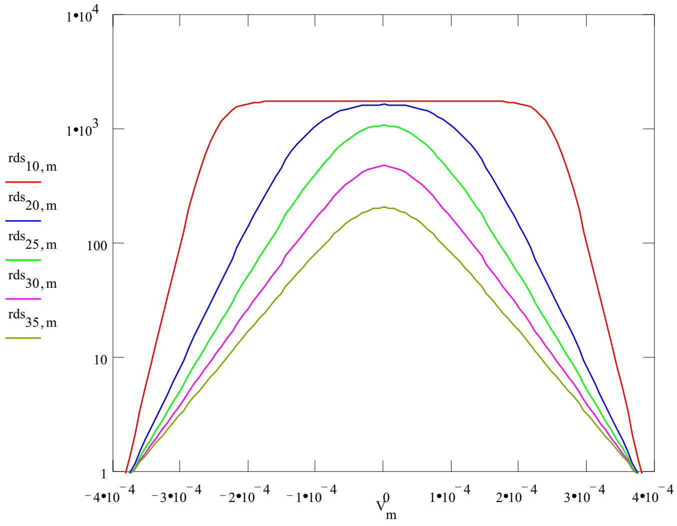

Figure 1. Dependence of dynamic resistance for the model junction on bias voltage for bath temperatures 100, 200, 250, 300 and 350 mK. Junction normal resistance R_n=10 kΩ and leakage resistance 35 MΩ.

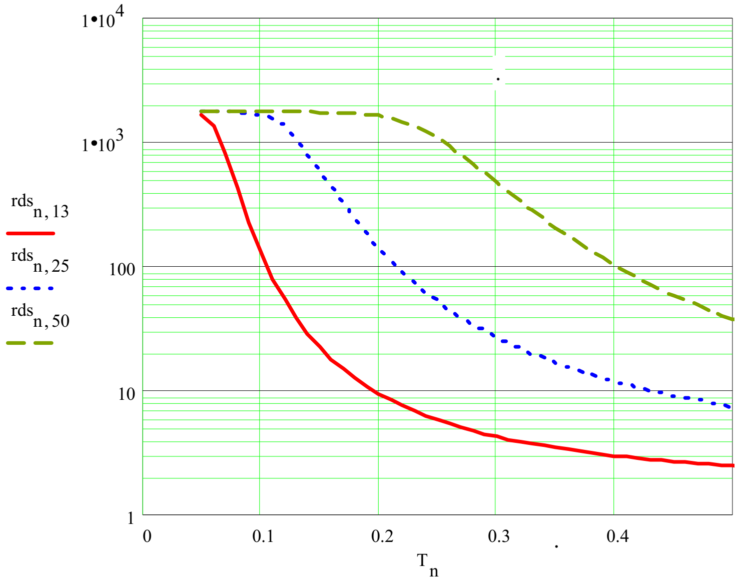

Figure 2. Zero bias resistance ratio calculated for sensor normal resistance R_n=10 kΩ and leakage resistance 35/45 MΩ (dashed line), resistance ratio for bias 200 μV (dotted line) and for 300 μV bias (straight line).

2. Experimental

The illustration for the above estimations could be example of dynamic resistance of sensor junctions at different cooling voltages measured at 20 mK (Fig. 3, curves V0T20 and V400T20). One can see that the largest resistance of 45 MΩ is observed only at cooler zero bias. With any other voltage via refrigerator the resistance is below 37 mΩ that corresponds to electron temperature above 187 mK from zero-bias dependence. Large increase of sensor resistance in the region 200-350 μV with cooling bias 400 μV can be explained according to resistance ratio at finite voltages and corresponds to cooling down from overheated level of 98 mK down to 88 mK. The similar dependence measured at 250 mK (curves V400T250 and V150T250) shows increase of a zero-bias sensor resistance from 12 MΩ to 36 MΩ with increase of cooling bias. The resistance of junction in this case is not so much shunted by leakage and temperature can be estimated from the zero-bias resistance ratio dependence calculated for shunted SIN junction according to equation (3). This temperature dependence is presented in Fig. 4. The resistance ratio at 300 μV sensor bias brings temperature change from 250 mK down to 88 mK or by 162 mK. Theoretical values calculated according to equation (3) are presented as boxes for sensor bias voltages 0, 200, and 300 μV. Sharp maximum of dynamic resistance at zero bias at 20 mK can be due to Coulomb blocade effect that is not accounted in our estimations.

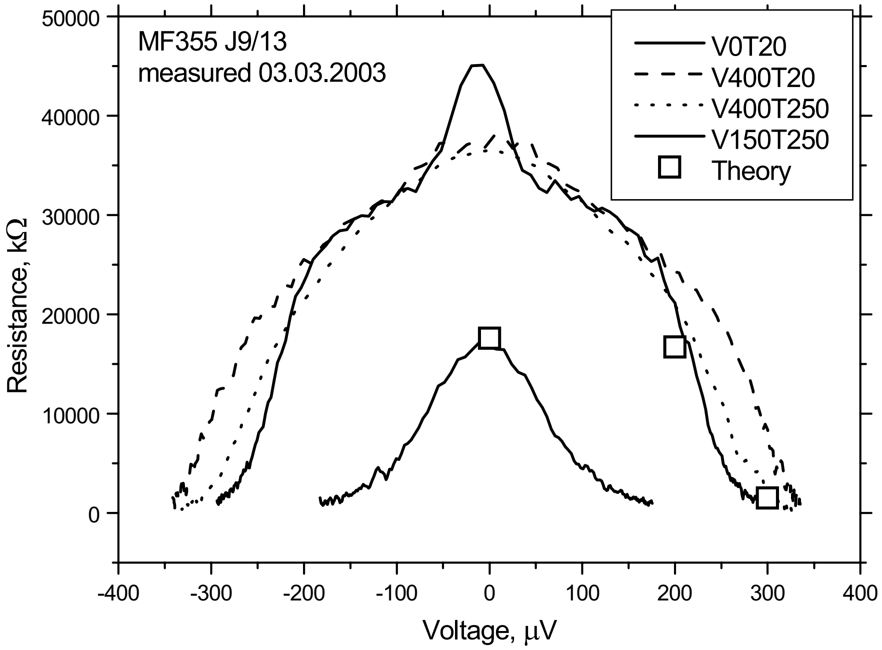

Figure 3. Dependencies of dynamic resistance of sensor junction on its bias voltage measured at 20 mK and 250 mK for cooling junction voltage off and at 400 μV. Theoretical values are presented as boxes for thermometer bias voltages 0, 200 and 300 μV.

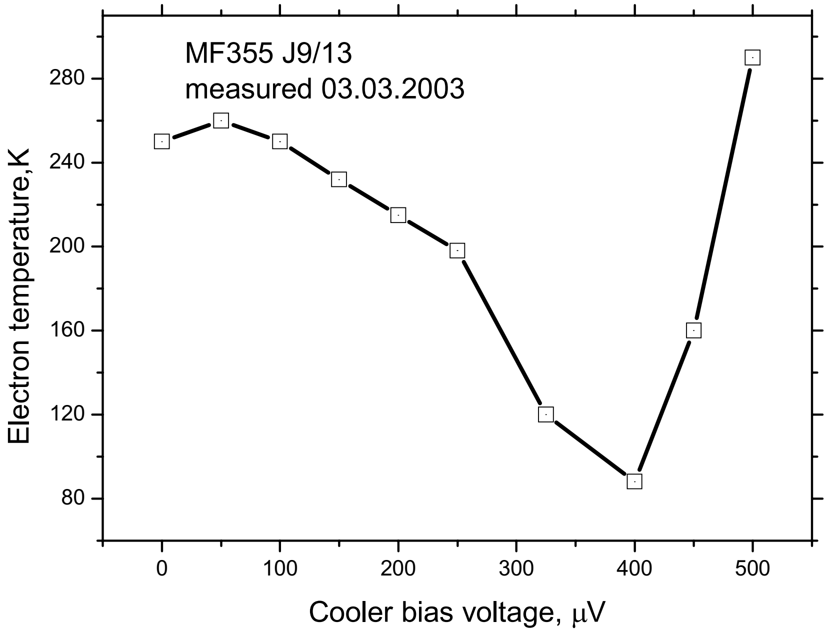

Figure 4. Equivalent electron temperature dependence on cooler bias voltage.

3. Discussion

The performance of bolometer is strongly affected by external overheating from the background power load and also from normal conducting channels in the tunnel barrier itself. The actual electron temperature without electron cooling can have excess level above the phonon temperature of the order of 100 mK. We can numerically model both processes of overheating via shunting resistance plus background power load and electron cooling. The simplified analytic expression for cooling power is

$$P_{cool}(\tau,V)=\frac{\sqrt{2\pi\Delta k_b\tau}}{2eR_N}\left(\frac{\Delta}{e}-V\right)\exp\left(-\frac{\Delta-eV}{k_b\tau}\right) \tag{5}$$

and the effective electron temperature τ is determined from equation

$$\left(T_{ph}^5-\tau^5\right)\Sigma\Lambda=P_{cool}(\tau)-P_{bgn}-\frac{V^2}{R_s} \tag{6}$$

in which T_{ph} is phonon temperature, V is dc bias voltage, R_s is shunting resistance, $P_{bgn}=0.5hf\Delta f=6\cdot10^{-14}$, $\Sigma=3\cdot10^9$ is material parameter, $\Lambda=1.8\cdot10^{-19}$ is absorber volume. The example of graphic solving of equation (6) is presented in Fig. 5 in which T200-T300 are terms of electron-phonon power exchange $P_{ep}=(T_{ph}^5-T_e^5)\Sigma\Lambda$ at different phonon temperatures, and terms Q_{mn} correspond to cooling and overheating power balance in bolometer $Q_{mn}=P_{cool}-V^2/R_s$. One can see that for leakage resistance of 30 MΩ one can obtain cooling by ΔT=160 mK at 250 mK.

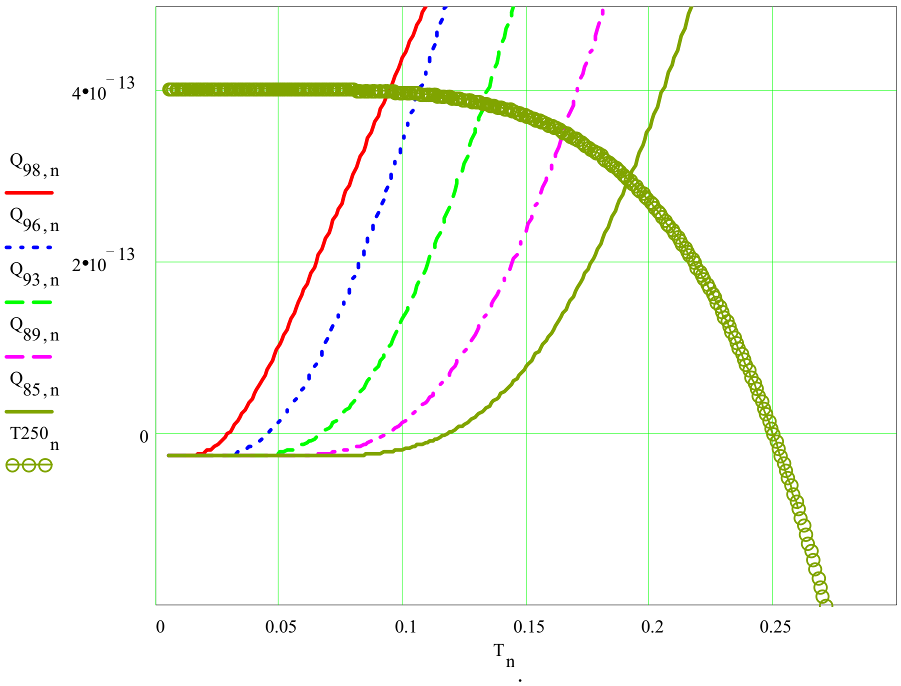

Figure 5. Curve T250 present electron-phonon power exchange $P_{ep}=(T_{ph}^5-T_e^5)\Sigma\Lambda$ at phonon temperature 250 mK, and curves $Q_{mn}=P_{cool}-V^2/R_s-P_{bg}$ correspond to cooling and overheating power balance in bolometer at bias voltages 392 µV – 340 µV. Intersection corresponds to electron temperature T_n in balance.

In our junctions the temperature responsivity at phonon temperature 250 mK was 1.6 mV/K, and at 185 mK 2.1 mV/K. For low-resistive junctions with substantial electron cooling or at lower temperatures the response could be even higher. Finite bias resistance ratio is very sensitive to electron temperature variations and provides absolute temperature value without measuring phonon temperature. For temperatures below 200 mK a constant voltage bias about 200 µV for sensor junction brings sensitive region without saturation, and below 100 mK the bias should be increased to about 300 µV.

4. Conclusion

We have designed, fabricated and measured a normal metal hot-electron bolometer with electron cooling. Electron cooling allows increasing the dynamic resistance and response of the bolometer. For estimations of effective electron temperature the ratio of finite-bias resistance to the normal resistance can be used as a figure of merit. Electron cooling at bath temperature 250 mK brings 3 times increase in zero-bias resistance in the limit of shunting resistance. The maximum electron cooling was observed from 250 mK down to 90 mK.

Acknowledgements

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References

[1] Kuzmin L 2000 Physica B 284-288 2129-2130

[2] Tarasov M Fominsky M Kalabukhov A and Kuzmin L 2002 JETP Lett. 76 507-510

[3] Kuzmin L Devyatov I and Golubev D 1998 Proc. Of SPIE 3465 193-199

[4] Nahum M Eiles T M Martinis J M 1994 Appl. Phys. Lett. 65 3123-3125

[5] Leivo M Pecola J and Averin D 1996 Appl. Phys. Lett. 68 1996-1998

[6] Hekking F W J and Nazarov Yu 1993 arXiv:cond-mat/9302034 1-12

[7] Bardas A and Averin D 1995 Phys. Rev. B 52 12873-12877

[8] Jochum J Mears C Golwala S et al. 1998 J.Appl. Phys. 83 3217-3224

[9] Quirion D Lefloch F and Sanquer M 2002 Physica E 12 934-937