Perform ance of cryogenic microbolometers and calorimeters with on-chip coolers

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Astronomical observations of cosmic sources in the far-infrared and X-ray bands require extreme sensitivity. The most sensitive detectors are cryogenic bolometers and calorimeters operating typically at about 100 mK. The last stage of cooling (from 300 mK to 100 mK) often poses significant difficulties in space-borne experiments, both in system complexity and reliability. We address the possibility of using refrigeration based on normal metal/insulator/superconductor (NIS) tunnel junctions as the last stage cooler for cryogenic themal detectors. We compare two possible schemes: the direct cooling of the electron gas of the detector with the aid of NIS tunnel junctions and the indirect cooling method, where the detector lattice is cooled by the refrigerating system, while the electron gas temperature is decreased by electron-phonon interaction. The latter method is found to allow at least an order of magnitude improvement in detector noise equivalent power, when compared to the direct electron cooling.

A themal detector system, such as a bolometer or a calorimeter, consists of a themal sensing element (TSE) which is connected to a heat sink. The TSE typically consists of an absorber and a themal element. The themal element can be a transition-edge sensor (TES) or a normal metal/insulator/superconductor (NIS) tunnel junction themal element. In this paper we address the fundamental question of whether one should cool the electrons of the detector directly, i.e., cool the TSE below the heat sink temperature, or alternatively cool the heat bath of the TSE. The principle of the NIS cooler has been introduced in Refs. 3 and 4.

The sensitivity of themal detectors is strongly in uenced by the detector temperature. The goal of most detectors is the noise equivalent power (NEP). To calculate this quantity for themal detectors coupled to on-chip coolers, we have to evaluate the ucations of the electron gas temperature due to the power exchange with the lattice, with the superconductor of the cooler (in case of direct cooling), and due to the bias of the themal element (see Fig. 1). We can then derive the NEP as the optical input power (the power to be detected) needed to produce a change in the temperature of the electron gas equal to the square root of the mean square of these ucations. In the following calculations the noise introduced by the bias power $Q_b$ is supposed to be very small.

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ponents of the Fourier transformed shot noise fluctuations (in quantities transferred randomly at a constant average rate) of the power transfer \( Q_{\text{ep}} \) and particle flux \( N_{\text{ep}} \) (through the NIS junctions), respectively. The other notations are explained in Fig. 1. We can now observe that in the case of indirect cooling, the two terms in Eq. (1) (let us call them \( \text{NEP}_{j} \)) disappear, since there are no NIS refrigerating junctions on the detection side. Moreover, if in a three-dimensional system we write \( Q_{\text{ep}} = Q_{\text{ep}} [T_{g}^{2} T_{d}^{2}] \) and \( N_{\text{ep}} = \kappa S [T_{g}^{2} T_{h}^{2}] \), then

\[
\begin{align*}
\text{h}^2 Q_{\text{ep, phot}} (t) & = 5 \kappa \kappa S [T_{g}^{2} + T_{h}^{2}] (\text{the error of the approximation is within } 2\% \text{ for any } T_{g} > T_{e}) \\
\text{h}^2 Q_{K, \text{phot}} (t) & = 8 \kappa \kappa S (T_{g}^{2} + T_{h}^{2}),
\end{align*}
\]

where \( \kappa \) is the Riemann function, \( S \) is the area of the TSE, \( \kappa \) is the contact area between the TSE and the heat bath, while \( \text{ep} \) and \( \kappa \) are coupling constants. In the case of indirect cooling, \( T_{g} = T_{h} \), while for direct cooling \( T_{g} < T_{h} < T_{g} \), the exact values depending on the coupling constants and geometry. Due to the high power in the temperature dependence of the noise term, slightly higher temperature of the lattice or of the heat bath would have a huge effect on the TSE. To make this point more clear, let us discuss two extreme cases. In the first case suppose that the thermal resistance between the lattice and the heat bath (Kapitza resistance) is much smaller than the one between the lattice and the phonons: \( B_{Q_{g}} = \Theta_{T_{g}} T_{g} \) and \( B_{Q_{h}} = \Theta_{T_{h}} T_{h} \), while in the second the inequality is reversed. We define a critical frequency \( \omega_{c} = \Theta_{T_{g}} T_{g} \), where \( \omega \) is the transmission coefficient for a phonon between the lattice and the heat bath, \( T_{g} \), \( T_{h} \) and \( T_{c} \) are the temperatures of the TSE. For typical devices \( \omega_{c} \) is of the order of \( 10^{10} \text{ s}^{-1} \). Therefore we can neglect in general the dependence of the two terms in Eq. (1). Under such assumptions, in case 1 the NEP reduces to

\[
(2) \quad \text{NEP}^2 \quad \text{h}^2 Q_{\text{ep, phot}} (t) \quad \text{h}^2 Q_{K, \text{phot}} (t) \quad \frac{\Theta_{Q_{g}}}{\Theta_{T_{g}}} \quad \frac{\Theta_{Q_{h}}}{\Theta_{T_{h}}} \quad \text{NEP}^2_{j}
\]

where the last approximation holds if \( (T_{g} - T_{h})^{2} \) is much smaller than the ratio between the electron-phonon and the Kapitza resistance \( \Theta_{Q_{g}} = \Theta_{T_{e}}^{2} (T_{g} = \kappa S) 1 \), which is certainly the case for indirect cooling. In the second case we have the approximation

\[
(3) \quad \text{NEP}^2 \quad 4 \quad \text{h}^2 Q_{\text{ep, phot}} (t) \quad \text{h}^2 Q_{K, \text{phot}} (t) \quad \text{NEP}^2_{j}
\]

Using Eqs. (4) and (5), we can write in general the ratio between the noise equivalent power in the case of direct cooling \( \text{NEP}_{d} \) and in the case of indirect cooling \( \text{NEP}_{i} \):

\[
\text{NEP}_{d} = \frac{S}{T_{g}^{2} + T_{h}^{2}} + \text{NEP}^2_{j} + \text{NEP}_{i}^2.
\]
far-infrared bolometers in terms of background saturation.

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