Detectors—Figures of Merit

Panos G. Datskos
Nickolay V. Lavrik
Oak Ridge National Laboratory, Oak Ridge, Tennessee, U.S.A.

INTRODUCTION

In order to analyze, quantify, and compare the performance of IR imaging devices, such as various types of focal plane arrays (FPAs), it is essential to have an in-depth understanding of their figures of merit. In this article, we discuss a series of figures of merit that are applicable to both cooled and uncooled IR detectors and systems. We provide a more detailed analysis of these figures of merit for the case of uncooled thermal detectors based on micro-electro-mechanical systems (MEMS). In particular, we discuss and analyze the different sources (and mechanisms) of noise present in MEMS IR detectors. These noises inevitably influence the respective figures of merit for the MEMS IR detectors and ultimately affect the fundamental limits of their performance.

DETECTION MECHANISMS

According to transduction principles, infrared (IR) radiation detectors[1–6] can be classified broadly as either quantum (opto-electronic) detectors[7] or thermal detectors, such as pyroelectric,[8] thermoelectric,[9] thermoresistive (bolometers),[9] and more recently micromechanical (or MEMS) thermal detectors.[10–17] Traditionally, detection of IR photons has relied on quantum absorption phenomena in semiconductor materials at cryogenic temperatures. Quantum IR detectors are based on semiconductor materials with narrow bandgaps, $\varepsilon_g < h/\lambda$, or metal-semiconductor structures (Schottky barriers) with appropriately small energy barriers, $\Delta\varepsilon < h/\lambda$. Because of the nature of photo-excitation and thermal-excitation processes in semiconductors, photonic IR detectors exhibit strong wavelength dependence and only operate efficiently when $k_B T < \hbar/\lambda$, where k_B is the Boltzmann constant, T is the detector temperature, $\hbar$ is the Plank constant, and λ is the wavelength of radiation to be detected. Although quantum IR detectors can have short (sub-nanosecond) response times and very high detectivities (see the definitions later in this article) approaching fundamental limits, they require deep cooling in order to reduce thermal generation of charge carriers and thermal noise that varies as $\exp[-\varepsilon_g/k_B T]$. Cooling of quantum IR detectors down to or below liquid nitrogen temperatures is commonly used for sensitive imaging in the mid-to far-infrared regions using IR photodetectors.

Thermal IR detectors (such as the ones depicted in Fig. 1) are based on measuring the amount of heat produced in the detector upon absorption of IR radiation and can operate at or even above room temperatures. Spectral characteristics that are flat and extended into the far-IR range are typical for thermal IR detectors. A spectral response of a thermal IR detector is primarily defined by the absorbance spectrum of the detector active region, which, in principle, can be close to unity for radiation ranging from the visible to the far-IR. When thermal IR detectors are arranged into FPAs, the long-wavelength roll-off of the spectral characteristics is typically affected by diffraction phenomena (associated with smaller detector sizes) rather than materials properties. Microbolometers and FPA of microbolometers operating at room temperature have already demonstrated sufficient performance, which makes them very competitive with more traditional cooled IR detectors based on narrow-band semiconductors and Schottky barriers. However, uncooled thermal IR detectors tend to have slower response times ($>10^{-3}$ sec) and somewhat lower detectivities, which are limited by relatively high background temperature fluctuations present in any uncooled IR detector.

More recently, a new type of uncooled thermal detectors based on thermal expansion phenomena in micromechanical structures has been introduced and studied.[10–17] Suspended microstructures with bimaterial regions (Fig. 1) provide direct conversion of absorbed heat into a mechanical response and can be referred to as thermo-mechanical detectors. The main advantage of thermo-mechanical detectors with respect to IR detection is that they are essentially free of intrinsic electronic noise and can be combined with a number of different readout techniques. The readout techniques demonstrated to date include capacitive,[18] piezoresistive,[19] electron tunneling,[20] and optical.[15,21] We will discuss the performance of uncooled thermo-mechanical IR detectors in more detail later in this article.

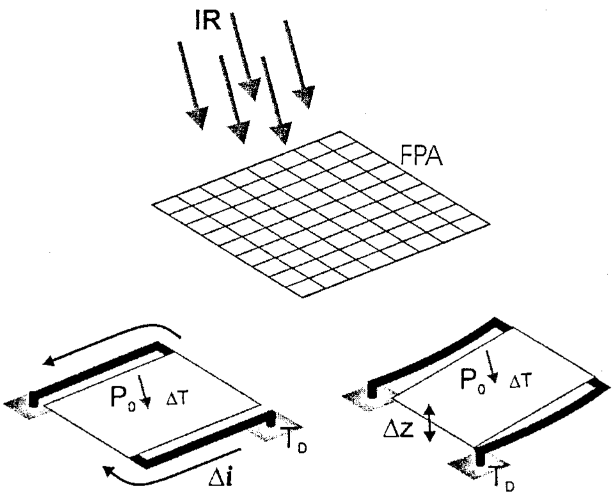

Fig. 1 Microbolometers and thermo-mechanical detectors are the two important classes of thermal IR detectors that comprise uncooled IR-imaging FPAs. Thermal detectors (or detector elements) of each type consist of a micromachined IR absorbing diaphragm suspended above the substrate and connected to the latter with two narrow beams. Absorption of IR power causes a change in the temperature of the detector. This temperature change, in turn, causes a change in the resistance of a bolometer-type detector (bottom left) or a deflection of a thermo-mechanical detector (bottom right).

FIGURES OF MERIT

During the last several decades, a number of different figures of merit have been introduced in order to characterize IR detectors.[3–6,22–25] Although many of these parameters are still in use, the evolution of the IR detectors has been accompanied by the evolution of characterization methods and respective parameters. Some of the previously introduced figures of merit become outdated merely because of the changes in units used to characterize IR detectors. Here we only discuss the figures of merit that are currently accepted and used by the IR community.[4,26]

Although the need for using figures of merit is driven by the desire to compare different detectors, it is important to keep in mind that different assumptions are sometimes made in defining and measuring these parameters. When evaluating the performance of various IR detectors and, especially, those that utilize uncooled thermal detectors, the parameters of major importance[4,25,26] are 1) responsivity, R; 2) noise equivalent power (NEP); 3) normalized detectivities, D^* (and D^{**}); 4) noise equivalent temperature difference (NETD); 5) minimum resolvable temperature difference (MRTD); and 6) response time τ. The definitions of these parameters and their fundamental limits in the case of uncooled thermal IR detectors are provided below. There are a number of additional parameters that can be used for a more detailed and comprehensive characterization of IR detectors. These include linearity of response, cross-talk between detector elements in an FPA, dynamic range, and modulation transfer function (MTF). The linearity of response, cross-talk, and dynamic range are basic parameters amenable to a whole variety of analog devices and transducers, and their definitions are readily available from a number of sources.[22,27] MTF is traditionally used in testing the performance of lenses, imaging systems, and their components and describes how the output contrast changes as a series of incrementally smaller features are imaged.[27]

Responsivity

The responsivity parameter R (applicable to all detectors) reflects the gain of the detector and is defined as the output signal (typically voltage or current) of the detector produced in response to a given incident radiant power falling on the detector[4,25]

$$R_V = \frac{V_s}{P_0} \quad \text{or} \quad R_I = \frac{I_s}{P_0} \tag{1}$$

where V_s is the output voltage (V), I_s is the output current (A), and P_0 is the radiant input power (W). When the definition of the responsivity is expanded to include the frequency dependence and the wavelength (spectral) dependence,[4] then, the responsivity is known as the spectral responsivity, $R(\lambda, f)$. It is worthy to emphasize that very distinct factors define characteristic features of spectral responsivities in the case of quantum and thermal IR detectors. Quantum IR detectors exhibit a cut-off in the spectral responsivity above a certain characteristic wavelength that is related to the photon energy sufficient to generate additional charge carriers (free electrons or electron-hole pairs). Hence, $R(\lambda, f)$ has a long wavelength cut-off defined by the bandgap energy of the semiconductor or the energy barrier at the metal-semiconductor interface used in the device. In the case of thermal IR detectors, however, the far-IR range is readily accessible simply by using appropriate detector absorbing areas and materials with high-absorptivity (either direct or resonant absorption) in this region.

Another derivative of *responsivity* is known as *blackbody responsivity*, $R(T, f)$, and is defined to include the dependence of the detector output signal on the temperature, T, of the blackbody-type source. The responsivity is a useful technical parameter that allows the prediction of the detector signal levels caused by an IR radiation of the given power and wavelength or as a result of thermal radiation from an object at a given temperature and emissivity. Although responsivity provides a good indication about the performance of an IR detector, it does not take into account the level of any intrinsic noise in the device and, therefore, provides little or no information about the threshold sensitivity of the detector. In other words, an IR detector with high responsivity is not necessarily able to detect low-level IR radiation or to distinguish IR sources of nearly the same intensity. It can be concluded that knowing the detector responsivity is important at the stage of designing an IR detection system, while comparative evaluation of different detectors should rely on other figures of merit.

In the case of thermo-mechanical IR detectors, such as microcantilever bimorphs, the intrinsic thermo-mechanical responsivity of the detector should be defined in terms of the mechanical response of the device, i.e., displacement, z_s, per absorbed power, P_0, in units of meters per watts, given by

$$R_z = \frac{z_s}{P_0} \tag{2}$$

Similarly as before, a spectral responsivity $R_z(T, f)$ and a blackbody responsivity $R_z(\lambda, f)$ can be defined.

Noise Equivalent Power

The minimum radiant flux that can be measured by different IR detectors with the same responsivity is inversely proportional to the level of total intrinsic noise in the detector. A convenient way to characterize the sensitivity of an IR detector is to specify its NEP, a parameter defined as the radiant power incident on the detector that produces a signal equal to the root mean square (rms) detector noise.[4,25] By this definition, NEP takes into account both gain and noise parameters of the detector and can be related to the detector responsivity, R_V,, R_I, or R_z, and the rms detector noise[4]

$$\mathrm{NEP} = \frac{V_N}{R_V} \quad \text{or} \quad \mathrm{NEP} = \frac{I_N}{R_I} \quad \text{or} \quad \mathrm{NEP} = \frac{z_N}{R_z} \tag{3}$$

where V_N (I_N or z_N) is the rms noise voltage (current or displacement) measured within the whole operation bandwidth. Since NEP depends on R, it also depends on the photon wavelength as well as on the modulation frequency of the IR power and, therefore, can be regarded to as NEP(λ, f). NEP can also be specified as a function of the detector temperature, i.e., NEP(T_D, f).[4] Frequency dependence of NEP is determined by the detector thermal response time, τ, and by the spectral density (i.e., frequency dependency) of the detector noise. It is important to note that even if the noise amplitude is frequency independent (white noise), the rms noise spectral density exhibits a square root dependence on the frequency. NEP(λ, f) and NEP(T_D, f) refer to a 1-Hz bandwidth and have units of W $\mathrm{Hz}^{-1/2}$; NEP without specifying the frequency may have ambiguous interpretation. The units of NEP imply either a full operational bandwidth or a 1-Hz bandwidth.

Normalized Detectivity

The parameter NEP is generally sufficient to evaluate and compare the performance of single (spot) IR detectors by predicting the minimum power. However, a figure of merit that is directly proportional to the detector performance is more convenient. Starting with a parameter known as detectivity, D, which is defined as the inverse value of NEP and taking into account the detector absorbing (active) area, A_d, and the signal bandwidth, B, one can define specific (or normalized) detectivity, D^*, as[4]

$$D^* = \frac{(A_d B)^{1/2}}{\mathrm{NEP}} \tag{4}$$

Normalized (or specific) detectivity D^* is, therefore, the detector output signal-to-noise ratio at 1 Watt of input IR radiation normalized to a detector with a unit active area and a unit bandwidth. The units of D^* are in Jones; 1 Jones = [cm $\mathrm{Hz}^{1/2}$ W^{-1}]. It should be noted that the definition of specific detectivity, D^*, was originally proposed for quantum detectors, in which the noise power is always proportional to the detector area and noise signal (V_n or I_n) is proportional to the square root of the area. However, the noise in thermal IR detectors does not always obey this scaling trend. In fact, neither temperature fluctuations nor thermo-mechanical noise (see the next section) scales up with the detector area. Therefore, D^* should be very cautiously interpreted when applied to thermal IR detector. In fact, D^* tends to overestimate the performance of larger absorbing area thermal detectors and underestimates the performance of smaller ones. In general (even in the case of quantum detectors), D^* ignores the significance of smaller detector elements for high-resolution FPAs.

In order to take into account the possible variability in the efficiency of the optics used for the characterization of IR detectors, the focal ratio F (reciprocal of twice the half angle of the marginal ray from the edge of the optics to the focal point) is included into a modified definition of the normalized detectivity, D^{**}

$$D^{**} = \frac{F(A_d B)^{1/2}}{\mathrm{NEP}} \tag{5}$$

A reasonable approximation of F assumes that the target remains at infinity so that $F = f_0/d$, where f_0 is a focal length of the optics and d is a diameter of the optics.

Noise Equivalent Temperature Difference

NETD is a parameter characterizing the low-signal performance of thermal imaging systems and is more applicable to FPAs of IR detectors. NETD is defined as the temperature of a target above (or below) the background temperature that produces a signal in the detector equal to the rms detector noise.[4,25,28] NETD can be specified for a single detector element or can be averaged for all detector elements in an array. Alternatively, NETD can be defined as the difference in temperature between two blackbodies, which corresponds to a signal-to-noise ratio of unity.[25] When an IR imager produces images, it actually maps the detected temperature variation across a scene or an object. However, the resulting images are also affected by the emissivity of the objects in the scene. Small values of NETD reflect the ability of an IR imager to distinguish slight temperature or emissivity differences of objects. Relationships for predicting NETD have been described elsewhere.[4,5,24,28] NETD can also be determined experimentally for a given detector area, detector absorptivity, optics used, and output signal bandwidth[28] by

$$\mathrm{NETD} = \frac{V_N}{V_s}(T_t - T_B) \quad \text{or}$$

$$\mathrm{NETD} = \frac{I_N}{I_s}(T_t - T_B) \quad \text{or}$$

$$\mathrm{NETD} = \frac{z_N}{z_s}(T_t - T_B) \tag{6}$$

where V_N (I_N or z_N) is the voltage (current or deflection) rms noise, V_s (I_s or z_s) is the voltage (current or deflection) signal, T_t is the temperature of the blackbody target, and T_b is the background temperature. It is important to emphasize that the NETD of optimized thermal IR detectors is limited by *temperature fluctuation noise*, while *background fluctuation noise* imposes an absolute theoretical limit on the NETD of any IR detector. In the next section, we discuss in more detail the factors that affect temperature fluctuation noise and background fluctuation noise, and how the respective fundamental limits of NETD depend on the detector design and its operation regime.

Minimum Resolvable Temperature Difference

MRTD is widely accepted by the infrared community as a measure of the total performance[4,26] of IR imaging systems. The rigorous definition of MRTD involves both the temperature sensitivity and the spatial resolution of a thermal imaging system.[26,28] MRTD is a more informative parameter than NETD when a combination of spatial resolution and temperature sensitivity needs to be taken into account. Although well-established methods have been developed to measure MRTD, it is still one of the most difficult figures of merit to determine.

Response Time

Similarly to other sensor or transducer systems, any IR detector exhibits a characteristic transient behavior when the input IR power changes abruptly. A general definition of the *response time*, τ, for any sensor systems is the time required for a transient output signal to reach 0.707 ($2^{-1/2}$) of its steady-state change. The expressions of the responsivity in the time frequency domain are given by[27]

$$R(t) = R(t = \infty)\left[1 - e^{-\frac{t}{\tau}}\right]$$

$$R(f) = \frac{R_0}{\sqrt{1 + (2\pi f \tau)^2}} \tag{7}$$

where R_0 is the dc responsivity. In the time domain, τ, the cut-off frequency is the half-point or the frequency at which the responsivity is 0.707 of the dc responsivity.

When the transduction of the absorbed IR energy into the output signal is based on photo-electronic excitation (quantum detectors), the intrinsic response time can be less than a nanosecond. Although the response time of quantum IR detectors is often limited by high-impedance electronic readout, their overall response times are commonly shorter than 10^{-3} sec.[9] This satisfies the requirements of the majority real-time IR imaging applications. By contrast, much longer response times (typically in the range of 10^{-3} to 10^{-1} sec) of thermal IR detectors are associated with the required accumulation of heat in the detector active area and are directly related to their transduction mechanism. The response time of a thermal IR detector, τ_{th}, can be calculated as the ratio of the heat capacity of the detector to its effective thermal conductance, viz.,

$$\tau_{th} = \frac{C}{G} \tag{8}$$

where C is the heat capacity of the detector active area and G is the total thermal conductance between the active area of the detector and the support structure (i.e., a heat sink). Eq. 8 provides a convenient way to predict the response time of a thermal IR detector, including thermomechanical devices. In Eq. 8, the heat capacitance, C, is the total capacitance which takes into account the individual capacitances for each of the materials comprising the detector active area given by the products of the specific heat capacitances and their respective masses. The value of G should take into account all the heat loss mechanisms in the detector and in the case of evacuated thermal detectors these are conductive and radiative losses.

NOISE SOURCES IN THERMAL INFRARED DETECTORS

Noise sources may exist within the IR detector itself, as it interacts with its environment or can be introduced by the detector readout system. Micromachining enables batch fabrication of highly efficient transducers that convert very small heat fluxes or temperature differences into conveniently measured output signals. While significantly reduced sizes and heat capacitances improve the sensitivity of thermal and calorimetric sensors, making them useful as IR detectors is governed by the influence of the various noise sources. The noise characteristics of such microscopic devices tend to impose certain fundamental limitations to the performance of thermal detectors. Two of such limitations (background limited and temperature fluctuation limited) are applicable to all types of thermal IR detectors and stem merely from the fact that every object, depending on its thermal mass and the degree of heat exchange with the environment, undergoes certain temperature fluctuations. These spontaneous temperature fluctuations are negligible for macroscopic objects; however, they may become a significant source of noise in the case of highly thermally isolated microscopic detectors, such as microbolometers and micromachined suspended bimorphs (microcantilevers).

In the case of thermo-mechanical IR detectors, there is an additional fundamental limitation that is related to spontaneous microscopic mechanical motion (oscillation) of any suspended microstructure due to its thermal energy. For the majority of the readout means, these thermo-mechanical oscillations are indistinguishable from the temperature-induced bending and, therefore, directly contribute to the detector noise.

Temperature Fluctuation Noise

All IR detectors that are based on the conversion of IR radiant power into heat are affected by temperature fluctuation noise.[5,24,29] The magnitude of spontaneous temperature fluctuations of the detector can be derived from the fluctuation–dissipation theorem (FDT)[5,24]

$$\langle \delta T^2 \rangle = \frac{k_B T^2}{C} \tag{9}$$

where $\langle \delta T^2 \rangle$ is the mean square fluctuations in temperature of the detector, k_B is the Boltzmann's constant, T is the absolute temperature, and C is the total heat capacity of the detector suspended structure. The frequency spectrum of the temperature fluctuations is given by[5]

$$\langle \delta T_f^2 \rangle = \frac{4k_B T^2 B}{G(1+\omega^2\tau_{th}^2)} \tag{10}$$

where G is the thermal conductance of the principal heat loss mechanism. $\langle \delta T_f^2 \rangle$ in Eq. 9 is the integration over all frequencies f, where $f=\omega/2\pi$, of Eq. 10 and, therefore, the rms temperature fluctuation $\langle \delta T_f^2 \rangle^{1/2}$ can be expressed as

$$\langle \delta T_f^2 \rangle^{1/2} = \frac{2T(k_B B)^{1/2}}{G^{1/2}(1+\omega^2\tau^2)^{1/2}} \tag{11}$$

Eq. 11 shows that thermal conductance G of the principal heat loss mechanism is the key design parameter that affects the temperature fluctuation noise. Fig. 2 shows exemplary temperature fluctuation spectra calculated for a typical IR sensitive micromechanical detector using Eq. 11.

When a thermal detector operates in a vacuum or a gas environment at reduced pressures, heat conduction through the supporting microstructure of the device is usually a dominant heat loss mechanism.[9] In the case of an extremely good thermal isolation, however, the

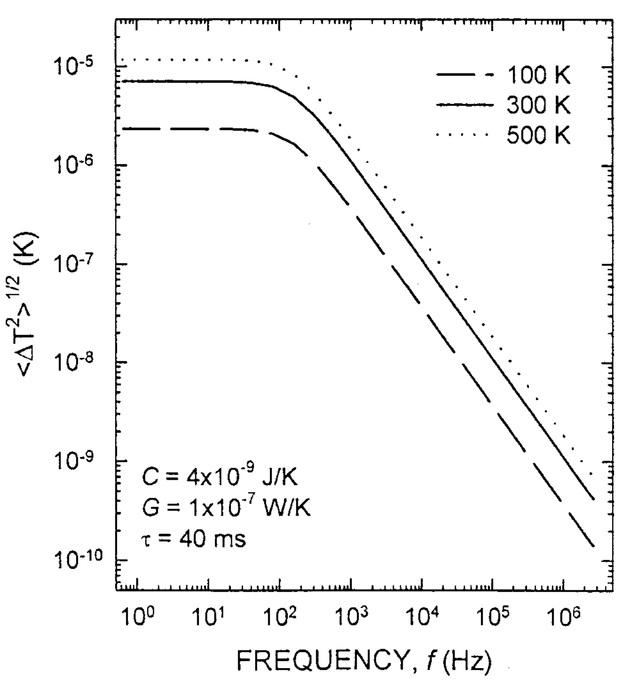

Fig. 2 Spectral density of temperature fluctuation noise (rms values of temperature fluctuation) calculated for a typical thermal IR detector using Eq. 11. Note that the signal follows the same roll-off at higher frequencies as the temperature fluctuation noise does.

principal heat loss mechanism can be reduced to only radiative heat exchange between the detector and its surroundings which is given by $G = 4A_d\sigma T^4$ assuming that the emissivity $\varepsilon = 1$. For micromechanical detectors in the atmospheric environment, heat conduction through air is likely to be dominant heat dissipation mechanism. The thermal conductivity of air at standard temperature and pressure is 2.4×10^{-2} W m^{-1} K^{-1},[9] which yields the respective thermal conductance larger than the thermal conductance through the supporting beams of a typical microcantilever or microbolometer device.

In the case of temperature sensitive bimaterial cantilever structures that are used for IR detection, temperature fluctuation noise manifests itself as spontaneously fluctuating deflection of the cantilever tip, δz. Temperature-induced deflections of bimaterial microcantilevers can be expressed as a function of differential stress, δs. The deflection, z, due to differential stress, δs, for a rectangular bimaterial microcantilever is given by[13,30]

$$z = \frac{3l^2}{E^*(t_1+t_2)^2} \times \left[\frac{\left(1+\frac{t_1}{t_2}\right)^2}{3\left(1+\frac{t_1}{t_2}\right)^2 + \left(1+\frac{t_1E_1}{t_2E_2}\right)\left(\frac{t_1^2}{t_2^2}+\frac{t_2E_2}{t_1E_1}\right)}\right]\Delta s \quad (12)$$

where t_1 and t_2 are the thickness of the coating and the microcantilever substrate, respectively, l is the microcantilever length, E_1 and E_2 are the Young's moduli of the coating and microcantilever, respectively, and E^* is the effective Young's modulus of the coated microcantilever defined as $E^* = E_1E_2/(E_1+E_2)$. The differential stress due to thermal expansion of two different materials can be approximated as[13]

$$\Delta s = E^*(t_1+t_2)(\alpha_1-\alpha_2)\Delta T \quad (13)$$

where ΔT is the temperature change and α_1 and α_2 are the coefficients of thermal expansion for the two materials composing the bimaterial microcantilever. Using Eq. 13 we can rewrite Eq. 12 as

$$z = \frac{3l^2}{t_1+t_2}\left[\frac{\left(1+\frac{t_1}{t_2}\right)^2}{3\left(1+\frac{t_1}{t_2}\right)^2 + \left(1+\frac{t_1E_1}{t_2E_2}\right)\left(\frac{t_1^2}{t_2^2}+\frac{t_2E_2}{t_1E_1}\right)}\right] \times (\alpha_1-\alpha_2)\Delta T \quad (14)$$

The temperature rise T of the detector as a result of photon absorption is given by the following solution of the heat flow equation[5]

$$\Delta T = \frac{\eta P_0}{G\sqrt{1+\omega^2\tau^2}} \quad (15)$$

where P_0 is the radiant power falling on the cantilever, η is the absorbance (absorbed fraction) of the radiant power, G is the thermal conductance of the principal heat loss mechanism, ω is the angular frequency of modulation of the radiation, and τ is the thermal response time.

By combining Eqs. 11, 14, and 15, the signal-to-noise ratio, $z/\delta z$, can be written as

$$\frac{z}{\delta z} = \frac{\Delta T}{(\langle\delta T^2\rangle)^{1/2}} = \frac{\eta P_0}{2T(Gk_BB)^{1/2}} \quad (16)$$

By combining the definitions of responsivity, R_z, and NEP (Eqs. 2 and 3), and Eq. 16, temperature fluctuation limited NEP_{TF} can be expressed as function of G

$$NEP_{TF}(f) = \frac{2T(Gk_BB)^{1/2}}{\eta} \quad (17)$$

Temperature fluctuation limited specific detectivity, D^*_{TF}, in turn, is given by

$$D^*_{TF} = \frac{A^{1/2}\eta}{2T(Gk_B)^{1/2}} \quad (18)$$

Fig. 3 shows the dependence of D^*_{TF} on T and G plotted for different detector active areas. As it clearly follows from the data shown in Fig. 3, improved performance of IR thermal detectors can be achieved by increasing the thermal isolation (i.e., a low value of G) between the detector and its surrounding.

The magnitude of thermal fluctuation noise scales up with improved thermal isolation. It reaches its maximum in the case of ideally isolated detectors, i.e., in the case of purely radiative heat exchange. Better thermal isolation, nevertheless, does improve the performance of a thermal IR detector by increasing the responsivity of the detector to an even higher degree: the rms value of temperature fluctuation noise is proportional to $G^{-1/2}$ while the responsivity is proportional to G^{-1}. This yields $G^{-1/2}$ dependency of NEP and $G^{1/2}$ dependency of D^* (Fig. 3b). For very low values of G, these dependencies have a crossover with the background fluctuation limit. By using the first derivative with respect to the temperature of the Stephan–Boltzmann function, Eq. 18 can be rewritten for the case of purely radiative

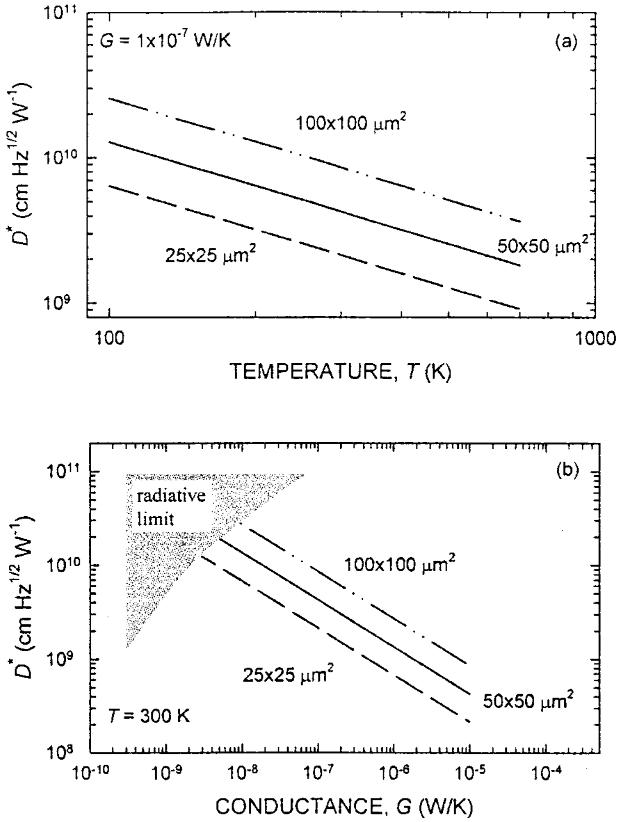

Fig. 3 Temperature fluctuation noise limited specific detectivity, D_T^*, for thermal IR detectors of different areas plotted (a) as a function of the total thermal conductance between the detector and its surrounding and (b) as a function of the detector temperature. Improved performance of IR thermal detectors can be achieved by increasing thermal isolation between the detector and its surrounding.

heat exchange that describes background fluctuation limited detectivity D_B^*[5]

$$D_B^* = \frac{\eta^{1/2}}{[8k_B\sigma(T_B^5 + T_D^5)]^{1/2}} \tag{19}$$

When the performance of a thermo-mechanical IR detector is limited by background fluctuation noise or by temperature fluctuation noise, the respective values of NEDT (regarded as $\mathrm{NEDT_{BF}}$ and $\mathrm{NEDT_{TF}}$) can be expressed analytically as a function of the detector parameters. The background limit, $\mathrm{NETD_{BF}}$, is given by[5,24,29]

$$\mathrm{NEDT_{BF}} = \frac{8F^2[2k_B\sigma B(T_D^5 + T_B^5)]^{1/2}}{t_0(\eta A)^{1/2}(\Delta P/\Delta T)_{\lambda_1-\lambda_2}} \tag{20}$$

where F is the focal ratio of the optics, k_B is the Boltzmann constant, B is the electrical bandwidth, T_D is the detector temperature, T_B is the background temperature, t_0 is the transmission coefficient of the optics, η is the absorptivity of the detector, and $(\Delta P/\Delta T)_{\lambda_1} - \lambda_2$ is the change in power per unit area radiated by a blackbody at temperature T with respect to T, measured within the spectral band from λ_1 to λ_2.

The temperature fluctuation noise limit, $\mathrm{NETD_{TF}}$, is given by[24]

$$\mathrm{NEDT_{TF}} = \frac{8F^2T_D(k_BBG)^{1/2}}{t_0\eta A(\Delta p/\Delta T)_{\lambda_1-\lambda_2}} \tag{21}$$

where G is the total thermal conductance of the detector along the legs of the microcantilever.

Thermo-Mechanical Noise

Sarid[31] has identified a noise source that he referred to as "thermally induced lever noise." The analysis provided by Sarid[31] involves the Q (quality factor) of a vibrating microcantilever, where Q is the ratio of the resonance frequency to the resonance peak width. When the signal angular frequency (ω) is much less than the mechanical resonant frequency, ω_0 (i.e., $\omega \ll \omega_0$), the rms fluctuations in z can be found as[31]

$$\langle\delta z^2\rangle^{1/2} = \sqrt{\frac{4k_BTB}{Qk\omega_0}} \tag{22}$$

where k is the spring constant, defined as the ratio of the force applied to the microcantilever divided by the displacement of the tip. At the resonance (i.e., $\omega = \omega_0$)[31]

$$\langle\delta z^2\rangle^{1/2} = \sqrt{\frac{4k_BTBQ}{k\omega_0}} \tag{23}$$

The latter condition may only become important for a thermo-mechanical IR detector operating at or near one of its resonance frequencies. In Fig. 4a, we plotted the spectral density of thermo-mechanical noise for a suspended micromachined structure. When the responsivity, R_z, of a thermo-mechanical IR detector is known, the low-frequency rms of thermally induced fluctuations defined by Eq. 22 can be used to predict the limits to NEP and the specific detectivity, D^*, of a thermo-mechanical IR detector due to its thermo-mechanical noise:

$$\mathrm{NEP} = \frac{1}{R_z}\sqrt{\frac{4k_BTB}{Qk\omega_0}} \quad \text{and} \quad D^* = \frac{1}{R_z}\sqrt{\frac{4k_BT}{A_dQk\omega_0}} \tag{24}$$

It should be pointed out that alternative models exist to adequately describe the thermo-mechanical noise of a

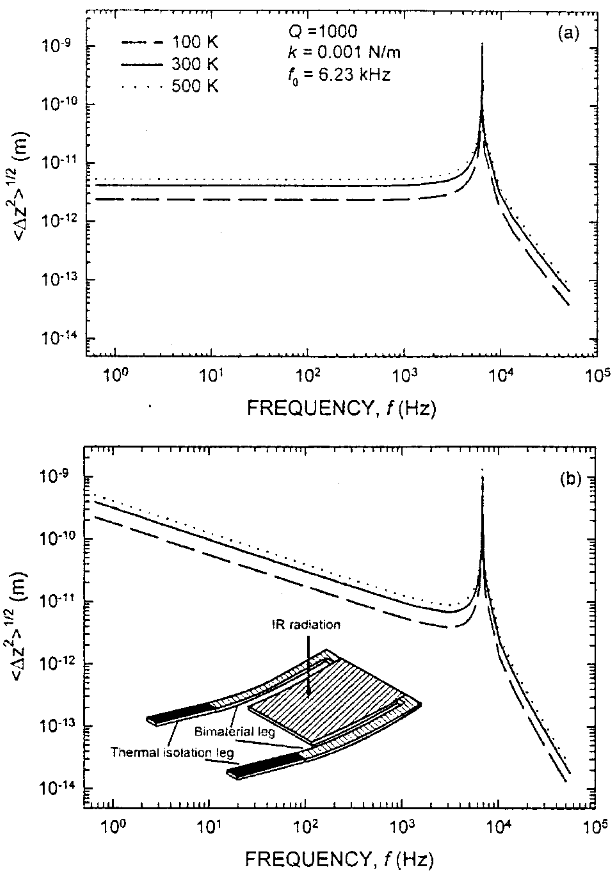

Fig. 4 Spectral density of thermo-mechanical noise for suspended micromachined structured calculated using alternative models. According to Sarid,[31] thermo-mechanical noise of microcantilevers is frequency independent at low frequencies (a). When the damping is due to intrinsic friction processes rather than due to viscous damping of the medium, the theory predicts a $f^{-1/2}$ trend for the density of thermo-mechanical noise below the mechanical resonance (b).

mechanical oscillator below its resonance.[32] For instance, when the damping is due to intrinsic friction processes rather than due to viscous damping of the medium the density of thermo-mechanical noise follows a $1/f^{1/2}$ trend below the resonance (see Fig. 4b).

CONCLUSION

Using figures of merit allows assessing, quantifying, and comparing the performance of various IR detectors, especially focal plane arrays (FPAs). Over the years a number of parameters (figures of merits) have been introduced and used to characterize different types of IR detectors. Although some figures of merit are more informative than others, the explicit and implicit assumptions made should always be kept in mind. With the development of uncooled thermal detectors, a challenge arises in the efforts to define parameters that are both applicable to thermal detectors and consistent with parameters used to describe cooled photon detectors. In this chapter we provided a detailed analysis of figures of merit that apply to a class of uncooled thermal detectors based on MEMS.

The performance of uncooled IR systems is often limited by the detector intrinsic noise. Fundamental mechanisms of heat exchange and dissipation induce spontaneous temperature fluctuations of all thermal IR detectors and impose two important fundamental limits to their performance, referred to as the background fluctuation noise limit and the temperature fluctuation noise limit. In addition, thermo-mechanical IR detectors exhibit spontaneous oscillations in a wide range of frequencies well below their fundamental mechanical resonance due to a combination of their nonzero thermal energy and intrinsic mechanical losses. Although these fundamental limits are independent of readout means, they do depend on several properties of the detector. Theoretical relationships between the figures of merit and the detector properties can be used to rationally design thermal IR detectors with optimized performance.

The performance of a thermal IR detector can reach its absolute theoretical limit when the thermal isolation between the detector and its surrounding is so high that the dominant heat loss mechanism is radiation exchange between the detector and its surrounding. Although the thermal conductance of the support structure can be almost infinitely reduced, this would also affect the thermal response time, which is inversely proportional to the thermal conductance. Optimization of thermal IR detectors may therefore involve a tradeoff between an acceptable time-constant and their sensitivity. Since the response time is directly proportional to the heat capacity, the limitations of this tradeoff can be eliminated in part by reducing the heat capacity of the detector.

GLOSSARY

R	Responsivity
NEP	Noise equivalent power
D^*	Normalized detectivity
NETD	Noise equivalent temperature difference
τ	Response time
z	Micromechanical deflection (bending)
C	Heat capacity
G	Heat conductance
k_B	Stephan-Boltzmann constant

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