Performance limitations of photon and thermal infrared detectors

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Investigations of the performance of infrared thermal detectors as compared to photon detectors are presented. Due to fundamental different types of noise (generation-recombination noise in photon detectors and temperature fluctuation noise in thermal detectors), these two classes of detectors have different dependences of detectivities on wavelength and temperature. The photon detectors are favoured at long wavelength infrared and lower operating temperatures. The thermal detectors are favoured at very long wavelength spectral range. The comparative studies of the thermal detectors with HgCdTe photodiodes, doped silicon detectors and quantum well infrared photodetectors are carried out. The considerations are made for different background levels.

Recent trends in infrared detectors are towards large, electronically addressed two-dimensional arrays and higher operating temperatures. The uncooled infrared focal planes may revolutionise development of night-vision IR imaging systems.

1. Introduction

Progress in infrared (IR) detector technology is connected mainly to semiconductor IR detectors, which are included in the class of photon detectors. In this class of detectors the radiation is absorbed within the material by interaction with electrons, either bound to lattice atoms, or to impurity atoms or with free electrons. The observed electrical output signal results from the changed electronic energy distribution. The photon detectors show a selective wavelength dependence of the response per unit incident radiation power (see Fig. 1). They exhibit both perfect signal-to-noise performance and a very fast response. But to achieve this, the photon detectors require cryogenic cooling. Photon detectors having long-wavelength limits above 3 μm are generally cooled. This is necessary to prevent the thermal generation of charge carriers. The thermal transitions compete with the optical ones, making uncooled devices very noisy. Cooling requirements are the main obstacle to the more widespread use of IR systems based on semiconductor photodetectors making them bulky, heavy, expensive and inconvenient to use. The different types of semiconductor photon detectors are listed in Table 1. Depending on the nature of the interaction, the class of photon detectors

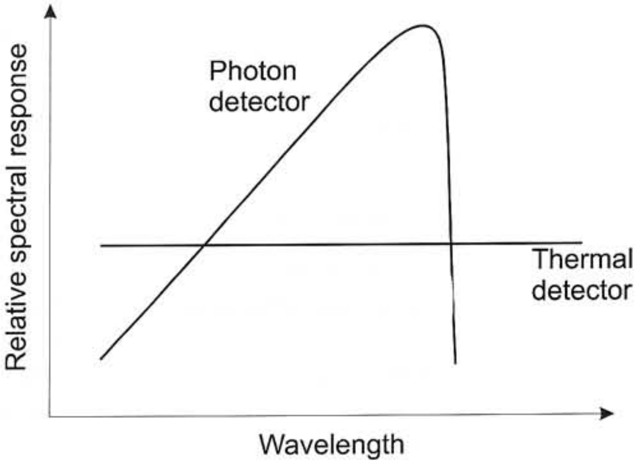

Fig. 1. Relative spectral response for a photon and thermal detector.

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Table 1. Infrared photon detectors

Type	Transition	Electrical output	Example
Intrinsic	Interband	Photoconductive Photovoltaic Capacitance PEM	PbS, PbSe, InSb, HgCdTe InSb, InAs, PbTe, HgCdTe, PbSnTe InSb, HgCdTe InSb, HgCdTe
Extrinsic	Impurity to band	Photoconductive	Si:In, Si:Ga, Ge:Cu, Ge:Hg
Free carriers	Intraband	Photoemissive Photoconductive Photon-drag	PtSi, Pt_2Si, IrSi Schottky barriers, GaAs/CsO InSb electron bolometer Ge
Quantum wells	To and/or from spatially quantised levels	Photoconductive Photovoltaic	HgTe/CdTe, GaAs/GaAlAs, InSb *nipi* InAs/InGaSb SLS

is further sub-divided into different types. The most important are: intrinsic detectors, extrinsic detectors, photoemissive (metal silicide Schottky barriers) detectors, and quantum well detectors.

The second class of infrared detectors is composed of thermal detectors. In a thermal detector shown schematically in Fig. 2, the incident radiation is absorbed to change the temperature of the material, and the resultant change in some physical properties is used to generate an electrical output. The detector element is suspended on lags, which are connected to the heat sink. The signal does not depend upon the photon nature of the incident radiation. Thus thermal effects are generally wavelength independent (see Fig. 1); the signal depends upon the radiant power (or its rate of change) but not upon its spectral content. This assumes that the mechanism responsible for the absorption of the radiation is itself wavelength independent, which is not strictly true in most instances. In pyroelectric detectors a change in the internal electrical polarisation is measured, whereas in the case of thermistor bolometers a change in the electri-

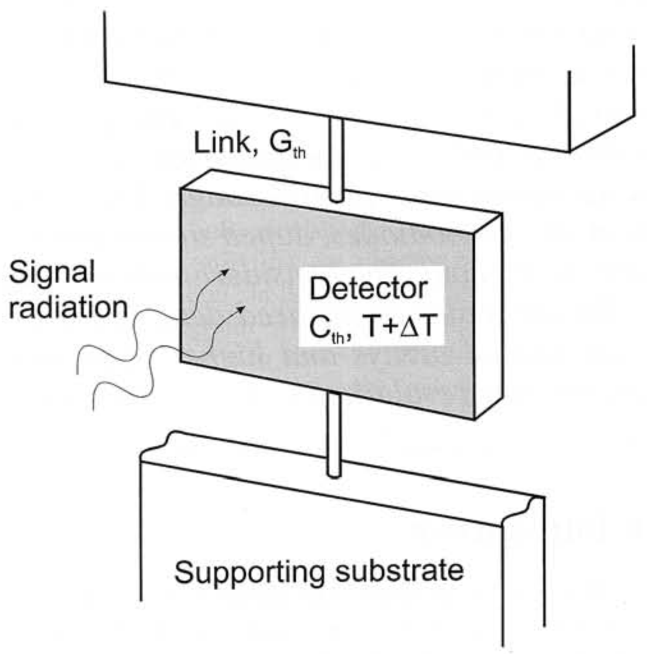

Fig. 2. Thermal detector mounted via lags to heat sink.

Table 2. Infrared thermal detectors

Detector	Method of operation
Bolometer	Change in electrical conductivity
Metal Semiconductor Superconductor Ferroelectric Hot electron	
Thermocouple/Thermopile	Voltage generation, caused by change in temperature of the junction of two dissimilar materials
Pyroelectric	Changes in spontaneous electrical polarisation
Golay cell/Gas microphone	Thermal expansion of a gas
Absorption edge	Optical transmission of a semiconductor
Pyromagnetic	Changes in magnetic properties
Liquid crystal	Changes of optical properties

cal resistance is measured. In contrast to photon detectors, the thermal detectors are typically operated at room temperature. They are usually characterised by modest sensitivity and slow response (because heating and cooling of a detector element is a relatively slow process) but they are cheap and easy to use. They have found widespread use in low cost applications, which do not require high performance and speed. Being unselective, they are frequently used in IR spectrometers.

The greatest utility in infrared technology have found: bolometers, pyroelectric and thermoelectric effects. A list of thermal effects is included in Table 2.

2. Historical background

Historically, the thermal detectors were the first detectors operated in the infrared range of electromagnetic spectrum. Since ≈ 1930 the development of infrared technology has been dominated by the narrow gap semiconductor photodetectors. During the 1950's and 1960's IR detectors were built using single element cooled lead salt detectors primarily for anti-air missile seekers. At the same time, rapid advances were being made in narrow gap semiconductors that would later prove useful in extending wavelength capabilities and improving sensitivity. These developments paved the way for the highly successful forward-looking IR (FLIR) airborne systems developed in the 1970's. In 1970, Boyle and Smith[1] published a paper reporting the charge-coupling principle, which is a simple, extremely powerful concept based upon the transfer of charge packets in a MIS structure. In the area of IR technique, the use of charge transfer devices (CTD) holds the key to substantial improvements in thermal imaging. CTD arrays offer significant advantages for focal plane applications.

In comparison with photon detectors, thermal detectors have been considerably less exploited in commercial and military systems. The reason for this disparity is that thermal detectors are popularly believed to be rather slow and insensitive in comparison with photon detectors. Evaporographs and absorption edge image converters were among the first non-scanned IR imagers.[2] Neither found widespread use. More successful were pyroelectric vidicons. These devices achieved their fundamental limits of performance by about 1970. In the last six years, however, it has been shown that extremely good imagery can be obtained from large thermal detector arrays operating uncooled at TV frame rates.

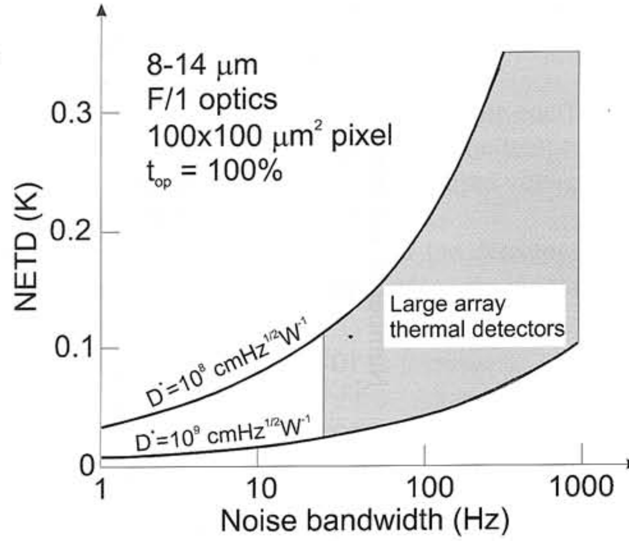

Fig. 3. The NETD versus equivalent noise bandwidth for typical detectivities of thermal detectors (after Ref. 3).

The speed of thermal detectors is quite adequate for non-scanned imagers with two-dimensional detectors. Figure 3 shows the dependence of NETD on noise bandwith for typical detectivities of thermal detectors. The calculations have been carried out assuming 100×100 μm^2 pixel size, 8–14-μm spectral range, F/1 optics and t_{op} = 100% of IR system. With large arrays of thermal detectors the best values of NETD below 0.1 K could be reached because effective noise bandwidths less than 100 Hz can be achieved. This compares with a bandwidth of several hundred kilohertz for a conventional cooled thermal imagers with a small photon detector array and scanner. Uncooled, monolithic focal plane arrays (FPAs) fabricated from thermal detectors may revolutionise development of thermal imagers. Recently, very encouraging results have been obtained with micromachined silicon bolometer[4,5] and pyroelectric detector[6–8] arrays.

There is a large research activity directed towards 2D "staring" array detectors consisting of more than 10^6 elements. The trend toward higher numbers of detectors per chip is shown in Fig. 4. From this figure we see that the thermal detectors which are relative newcomers are narrowing the gap with photon detectors. Over the last decade, dramatic improvements in detector and readout technology have resulted in a 200× increase in the size of the largest FPAs. Consequently, whereas various 64×64 FPAs were available in the early 1980s, several vendors nowadays produce monolithic FPAs in the TV-compatible 1024×1024 formats.

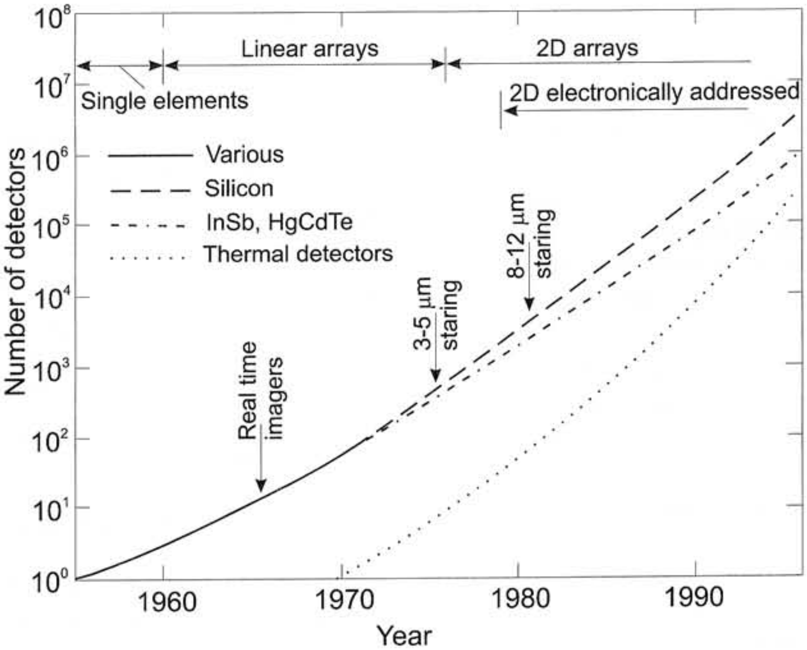

Fig. 4. An illustration of the increasing size of detector arrays with time. The line labelled silicon refers to both Schottky barriers and extrinsic silicon. The line labelled InSb and HgCdTe refers to both monolithic and hybrid technologies. The line labelled thermal detectors refers to both pyroelectric and bolometer detectors (after Ref. 9).

3. Theory of infrared detectors

3.1. Photon detectors

The photodetector is a slab of homogeneous semiconductor with the actual "electrical" area A_e that is coupled to a beam of infrared radiation by its optical area A_o. Usually, the optical and electrical areas of the device are the same or close. The use of optical concentrators can increase the A_o/A_e ratio.

Detectivity D* as the main parameter characterizing normalized signal to noise performance of detectors is equal[10,11]

$$D^* = \frac{\lambda}{hc}\left(\frac{A_o}{A_e}\right)^{1/2} \eta[2(G+R)t]^{-1/2} \quad (1)$$

where G is the generation rate and R is the recombination rate.

For a given wavelength and operating temperature, the highest performance can be obtained by maximizing $\eta/[t(G+R)]^{1/2}$. This means that high quantum efficiency must be obtained with a thin device.

Assuming a single pass of the radiation and negligible frontside and backside reflection coefficients, the highest detectivity can be obtained for $t = 1.26/\alpha$. In this optimum case $\eta = 0.716$ and detectivity is equal[11]

$$D^* = 0.45\frac{\lambda}{hc}\left(\frac{\alpha}{G+R}\right)^{1/2} \quad (2)$$

To achieve a high performance the thermal generation must be suppressed to possibly the lowest level. This is usually done with cryogenic cooling of the detector. For practical purposes, the ideal situation occurs when the thermal generation is reduced below the optical generation.

At equilibrium the generation and recombination rates are equal, and we have

$$D^* = 0.31\frac{\lambda}{hc}\left(\frac{\alpha}{G}\right)^{1/2} \quad (3)$$

The ratio of absorption coefficient to the thermal generation rate α/G is the fundamental figure of merit of any material for infrared photodetectors which directly determines the detectivity limits of the devices.

The total generation rate is a sum of the optical and thermal generation

$$G = G_{th} + G_{op} \quad (4)$$

The optical generation may be due to the signal or thermal background radiation. For infrared detectors, usually thermal background radiation is higher compared to the signal radiation. If the thermal generation is reduced much below the background level, the performance of the device is determined by the background radiation (BLIP conditions for Background Limited Infrared Photodetector). The background limited detectivity, or so-called "photovoltaic" BLIP detectivity, is given by[12]

$$D^*_{BLIP} = \frac{\lambda}{hc}\left(\frac{\eta}{2\Phi_B}\right)^{1/2} \qquad (5)$$

where, Φ_B is the total background photon flux density reaching the detector.

3.2. Thermal detectors

Thermal detectors operate on a simple principle, that when heated by incoming IR radiation their temperature increases and the temperature changes are measured by any temperature-dependent mechanism, such as thermoelectric voltage, resistance, pyroelectric voltage. The simplest representation of the thermal detector is shown in Fig. 2. The detector is represented by a thermal capacitance C_{th} coupled via a thermal conductance G_{th} to a heat sink at a constant temperature T. In the absence of a radiation input the average temperature of the detector will also be T, although it will exhibit a fluctuation about this value. When a radiation input is received by the detector, the rise in temperature is found by solving the heat balance equation. Assuming the radiant power to be a periodic function, the change in temperature of any thermal detector due to incident radiative flux is[2,13]

$$\Delta T = \frac{\varepsilon \Phi_o}{\left(G_{th}^2 + \omega^2 C_{th}^2\right)^{1/2}} \qquad (6)$$

Equation (6) illustrates several features of thermal detector. Clearly it is advantageous to make T as large as possible. To do this, the thermal capacity of the detector (C_{th}) and its thermal coupling to its surroundings (G_{th}) must be as small as possible. The interaction of the thermal detector with the incident radiation should be optimised while reducing as far as possible all other thermal contacts with its surroundings. This means that a small detector mass and fine connecting wires to the heat sink are desirable.

A characteristic thermal response time for the detector can therefore be defined as

$$\tau_{th} = \frac{C_{th}}{G_{th}} = C_{th} R_{th} \qquad (7)$$

where $R_{th} = 1/G_{th}$ is the thermal resistance.

Typical value of thermal time constant is in the millisecond range. This is much longer than the typical response time of a photon detector. There is a trade-off between sensitivity, ΔT, and frequency response. If one wants a high sensitivity, then a low frequency response is forced upon the detector.

For further discussion we introduce the coefficient $K = \Delta V/\Delta T$, which reflects how well the temperature changes translate into the electrical output voltage of a detector.

The voltage responsivity R_v of the detector is the ratio of the output signal voltage ΔV to the input radiation power and is given by[14]

$$R_v = \frac{K \varepsilon R_{th}}{\left(1 + \omega^2 \tau_{th}^2\right)^{1/2}} \qquad (8)$$

In order to determine the detectivity of the detector, it is necessary to define a noise mechanism. One major noise is Johnson noise. Two other fundamental noise sources are important for assessing the ultimate performance of a detector: thermal fluctuation noise and background fluctuation noise.

Thermal fluctuation noise arises from temperature fluctuations in the detector. These fluctuations are caused by heat conductance variations between the detector and the surrounding substrate with which the detector element is in thermal contact.

The spectral noise voltage due to temperature fluctuations is[2,13]

$$V_{th}^2 = \frac{4kT^2 \Delta f}{1 + \omega^2 \tau_{th}^2} K^2 R_{th} \qquad (9)$$

A third noise source is background noise. It results from radiative heat exchange between the detector at temperature T_d and the surrounding environment at temperature T_b that is being observed. It is the ultimate limit of a detector's performance capability and is given for a 2Π FOV by[2,13]

$$V_b^2 = \frac{8k\varepsilon\sigma A\left(T_d^2 + T_b^2\right)}{1 + \omega^2 \tau_{th}^2} K^2 R_{th}^2 \qquad (10)$$

where σ is the Stefan-Boltzmann constant.

The fundamental limit to the sensitivity of any thermal detector is set by temperature fluctuation noise, i.e., random fluctuations in the temperature of the detector element due to fluctuations in the radiant power exchange between the detector and its surroundings. Under this condition at low frequencies ($\omega << 1/\tau_{th}$) results

$$D_{th}^* = \left(\frac{\varepsilon^2 A}{4kT_d^2 G_{th}}\right)^{1/2} \qquad (11)$$

It is assumed here that detectivity is independent of wavelength, so that the spectral D^*_λ and blackbody $D^*(T)$ values are identical.

If radiant power exchange is the dominant heat exchange mechanism, then G is the first derivative with respect to temperature of the Stefan-Boltzmann function. In that case, known as the background fluctuation noise limit, we have

$$D^*_b = \left[\frac{\varepsilon}{8k\sigma\left(T_d^5 + T_b^5\right)}\right]^{1/2} \tag{12}$$

Note that D^*_b is independent of A, as is to be expected.

Equations (11) and (12) assume that background radiation falls upon the detector from all directions when the detector and background temperature are equal, and from the forward hemisphere only when the detector is at cryogenic temperatures. The highest possible D* to be expected for a thermal detector operated at room temperature and viewing a backgrounds at room temperature is 1.98×10^{10} $cmHz^{1/2}W^{-1}$. Even if the detector or background, not both, were cooled to absolute zero, the detectivity would improve only by the square root of two. This is basic limitation of all thermal detectors. The background noise limited photon detectors have higher detectivities as a result of their limited spectral responses.

The performance achieved by any real detector will be inferior to that predicted by Eq. (12). The degradation of performance will arise from:

- encapsulation of detector (reflection and absorption losses at the window),
- the effects of excess thermal conductance (influence of electrical contacts, conduction through the supports, influence of any gas – conduction and convection),
- the additional noise sources.

Typical values of detectivities of thermal detectors at 10 Hz change in the range between 10^8 to 10^9 $cmHz^{1/2}W^{-1}$.

4. Comparison of the fundamental limits of thermal and photon detectors

The detectors operated in the 8–14-μm spectral region include cryogenic photon detectors such as HgCdTe photodetectors, doped silicon and germanium extrinsic photoconductors, GaAs/AlGaAs quantum well infrared photodetectors (QWIPs) and uncooled thermal detectors (resistive bolometers and pyroelectric detectors).

The temperature dependences of the fundamental limits of D* of these detectors for different levels of background are shown in Figs. 5 and 6. In comparison with previously published Kruse's paper[15] these dependences are reexamined taking into account updated theories of different types of detectors.[16–21]

From Fig. 5 results that in long wavelength infrared (LWIR) spectral range, the performance of intrinsic IR detectors (HgCdTe photodiodes) is higher than for other types of photon detectors. HgCdTe photodiodes with background limited performance operate at temperature below ≈ 80 K. HgCdTe is characterised by high optical absorption coefficient and quantum efficiency and relatively low thermal generation rate compared to extrinsic detectors and QWIPs. The extrinsic photon detectors require more cooling than intrinsic photon detectors having the same long wavelength limit.

The theoretical detectivity value for the thermal detectors is much less temperature dependent than for the photon detectors. At temperatures below 50 K and zero background, LWIR thermal detectors are characterised by D* values lower that those of LWIR photon detectors. However, at temperatures above 60 K, the limits favour the thermal detectors. At room temperature, the performance of thermal detectors is much better than LWIR photon detectors. Above relations are modified by influence of background, what is

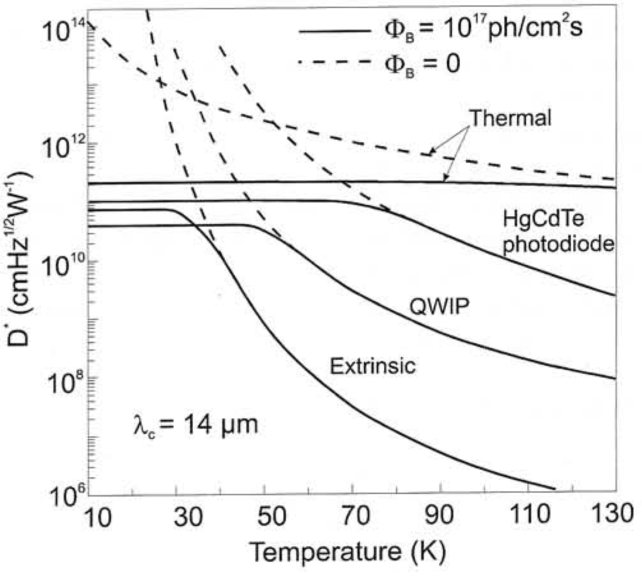

Fig. 5. Theoretical performance limits of LWIR photon and thermal detectors at zero background and background of 10^{17} photons/cm^{2}s, as a function of detector temperature.

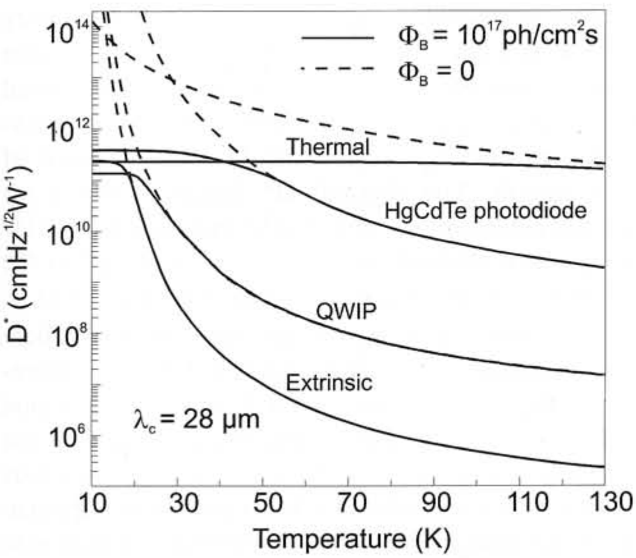

Fig. 6. Theoretical performance limits of VLWIR photon and thermal detectors at zero background and background of 10^{17} photons/cm^{2}s, as a function of detector temperature.

shown in Fig. 5 for a background of 10^{17} photons/cm^{2}s. It is interesting to notice, that for a background of 10^{17} photons/cm^{2}s the theoretical curves of D* for photon and thermal detectors show similar fundamental limits at low temperatures.

The similar considerations have been carried out for very long wavelength infrared (VLWIR) detectors operated in the 14–50 μm spectral range. Results of calculations are presented in Fig. 6. Detectors operating within this range are cryogenic Si and Ge extrinsic photoconductors and cryogenic thermal detectors, usually bolometers. Moreover, in Fig. 6, theoretical prediction for intrinsic detectors (HgCdTe photodiodes) is also included. Figure 6 shows that the theoretical performance limit of a VLWIR thermal detectors at zero and high backgrounds in wide range of temperature equals or exceeds that of photon detectors.

The comparison of both types of detectors indicates that theoretical performance limits for thermal detectors are more favourable as wavelength of operation moves from the LWIR to the VLWIR. It is due to influence of fundamental different types of noise (generation-recombination noise in photon detectors and temperature fluctuation noise in thermal detectors), these two classes of detectors have different dependences of detectivities on wavelength and temperature. The photon detectors are favoured at long wavelength infrared and lower operating temperatures. The thermal detectors are favoured at very long wavelength spectral range. The temperature requirements to attain background fluctuation noise performance in general favour thermal detectors at the higher cryogenic temperatures and photon detectors at the lower cryogenic temperatures.

5. Focal plane arrays

For IR imaging systems, the relevant figure of merit for determining the ultimate performance is not the detectivity D* but the NETD, i.e. the difference of temperature of the object required to produce an electric signal equal to the rms noise voltage. This parameter takes into account the optics, array, and readout electronics. As it is shown e.g. in Ref. 22,

$$\mathrm{NETD} = \frac{4F^2\Delta f^{1/2}}{A_d^{1/2}t_{op}}\left[\int_{\lambda_a}^{\lambda_b}\frac{dM}{dT}D^*(\lambda)d\lambda\right]^{-1} \quad (13)$$

where F is the system f-number, M is the spectral radiant emitance of blackbody (which can be described by Planck's law), and t_{op} is the optics transmission. Regarding the expression (13), the NETD value depends on bandwidth which is determinant for the value of the detector noise. New concepts of large FPAs reduce greatly the noise bandwidth to below 100 Hz.

From fundamental considerations, HgCdTe is the most important semiconductor alloy system for IR detectors. Investigations of the fundamental physical limitations of HgCdTe photodiodes indicate better performance of this type of detector in comparison with other types of IR detectors.[21] The operating temperature for HgCdTe detectors is higher than for other types of photon detectors. HgCdTe detectors with background limited performance operate with thermoelectric coolers in the medium wavelength range, and the long wavelength detectors operate at ≈ 100 K. HgCdTe is characterised by high optical absorption coefficient and quantum efficiency and relatively low thermal generation rate compared to extrinsic detectors, silicide Schottky barriers and quantum well infrared photodetectors (QWIPs). In practice however, the performance of HgCdTe photodiodes is technologically limited (influence of trap-assisted tunneling, leakage current, etc. at temperatures below 77 K).

Figure 7 compares NEDT versus F/# for uncooled, TE-cooled HgCdTe, and 120-K HgCdTe FPA technologies. The uncooled devices offer moderate sensitivity at low F/#. The TE-cooled HgCdTe FPA offers higher sensitivity at F/# compatible with inexpensive optics. Instead, the 120-K HgCdTe FPA offers BLIP

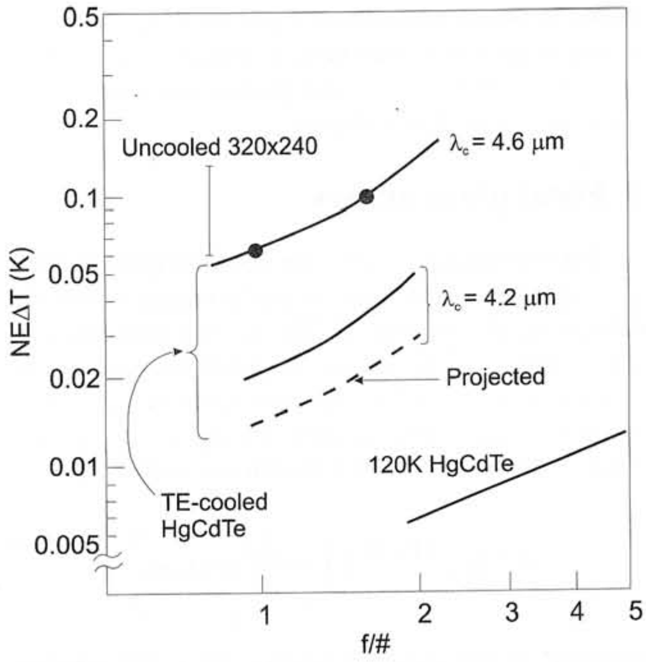

Fig. 7. Comparison of camera NETD versus F/# for uncooled, TE-cooled HgCdTe, and 120-K HgCdTe FPA technologies (after Ref. 23).

medium wavelength infrared (MWIR) sensitivity with NEDT < 0.015 K for F/5 or faster optics.

Figure 8 shows a plot of the thermal detectivity (300 K, 0° FOV) versus operating temperature for the most prominent detector technologies. The thermal detectivity is used here to compare the various technologies for equivalent NETD irrespective of wavelength. The thermal D* figure of merit for photon detectors was obtained by equating the NETD of an ideal thermal detector for a given D* to the NETD of an ideal photon detector with a given $D_{\lambda_p}^*$. The various regions show the appropriate applications including "low cost" uncooled thermal detectors, "high performance uncooled" for night vision enhancement and earth reconnaissance, "tactical" for most imaging uses, and "strategic" for various military-type instruments. For "low cost" applications, the imagery is limited by thermal conduction to the pixels. Photocurrent shot noise should limit the detectivity for other thermal imagers. Strategic sensors generally detect point targets, so the D* must be as high as possible within the constraint that the cooler must not pose overriding size, weight, reliability and cost issue. High performance near infrared has similar performance requirements, but can only provide a minimum of cooling because cost and weight minimisation is critical. The extrinsic silicon

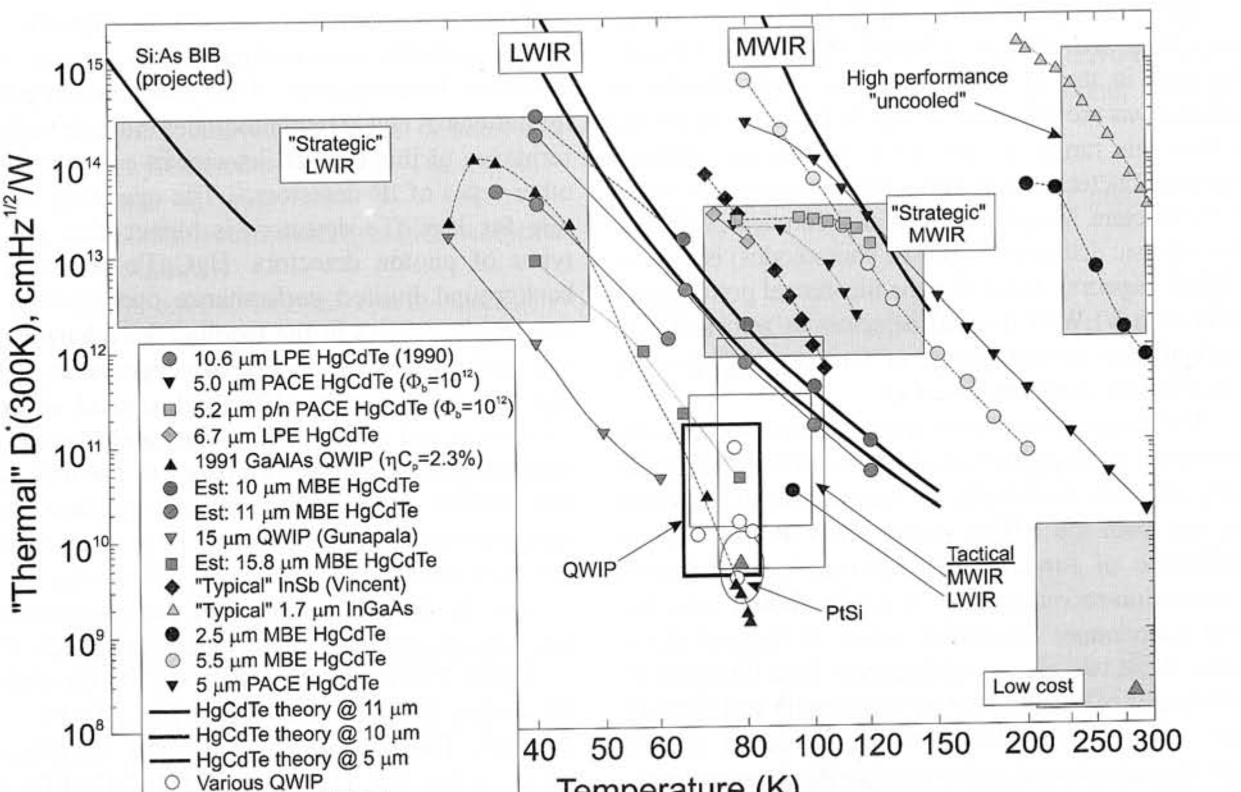

Fig. 8. Comparison of photon detector thermal detectivity D*(300 K, 0° FOV) for various IR technologies for equivalent NETD (after Ref. 24).

Table 3. Comparison of IR imagers (after Ref. 4)

Feature	Present scanned cryogenic imagers	Cryogenic staring imagers	Uncooled silicon microbolometer imagers
Approximate system cost	\$100 000 (military volume production)	\$100 000 (military volume production)	\$1000 (high-volume production)
Typical focal-plane temperature	100 K	100 K	Room temperature
IR sensor	HgCdTe, InSb	HgCdTe, InSb, PtSi, GaAs/AlGaAs	Micromachined silicon
Typical NETD	0.1°C	0.1°C	0.05°C
Applications	Military and specialised industrial applications	Military and specialised industrial applications	Widespread applications for military, commerce, research, industry, etc.

detectors offer very high sensitivity but at the very low operating temperatures which is prohibitive in the most applications. The cryogenically cooled InSb and HgCdTe arrays have comparable array size and pixel yield at MWIR spectral band. However, wavelength tunability and high quantum efficiency have made HgCdTe the preferred material. This material assures the highest possible operating temperature for a given set of operating conditions. Thus, the associated cooling and system power requirements can thus be optimally distributed. The monolithic PtSi Schottky barrier FPAs lead all other technologies with respect to array size (10^6 pixels), however Fig. 4 clearly shows that the thermal mismatch barrier in hybrid FPAs has been recently overcome by developers (InSb and HgCdTe arrays).

Present-day IR semiconductor imagers use cryogenic or thermoelectric coolers, complex IR optics, and expensive sensor materials. Typical costs of cryogenically cooled imagers around \$100000 (see Table 3) restrict their installation to critical military applications allowing conducting of operations in complete darkness (such as tanks and aircrafts).[4] A new revolution in reducing cost of thermal imagers, which is now underway, is caused by very encouraging results obtained with micromachined silicon bolometer arrays and pyroelectric detector arrays.

6. Conclusions

The future development of IR detectors could change dramatically as a result of current research activities in uncooled infrared sensor arrays. It is expected, that the thermal detector arrays will increase in size and improve in thermal sensitivity to a level satisfying high performance applications at ambient temperature. In the next decade, low-cost IR thermal imagers (both pyroelectric devices and bolometers) will likely be used in nonmilitary applications such as drivers aid, aircraft aid, industrial process monitoring, community services, etc.

Despite serious competition from alternative technologies and slower progress than expected, HgCdTe is unlikely to be seriously challenged for high-performance applications, applications requiring multispectral capability and fast response. Currently, no known variable gap material can offer fundamental advantages in terms of performance or cost of production. A challenge may come rather from materials exhibiting higher stability.

7. Acknowledgement

This work was partially supported by the KBN (Poland) under grant number 8–T11B02611

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