Chapter 1

Introduction

1.1 General Remarks

Sensors that are used to detect optical radiation are usually confined to use in two types of detectors: thermal detectors and photon detectors. Thermal detectors sense the heat generated by the absorbed radiation, so their operation is a two-step process: conversion of the radiation energy into heat, followed by conversion of the heat energy into the energy of an electrical signal. The incident radiation is absorbed to change the material temperature, and the resultant change in some physical property is used to generate an electrical output.

Despite this two-step operation, thermal detectors are relatively simple devices (see Fig. 1.1) that operate primarily at ambient temperature. In general, a thermal detector is suspended on lags that are connected to a heat sink. The signal does not depend upon the photonic nature of the incident radiation. Thus, thermal effects are generally wavelength independent; the signal depends on the radiant power (or its rate of change) but not on its spectral content, assuming that the mechanism

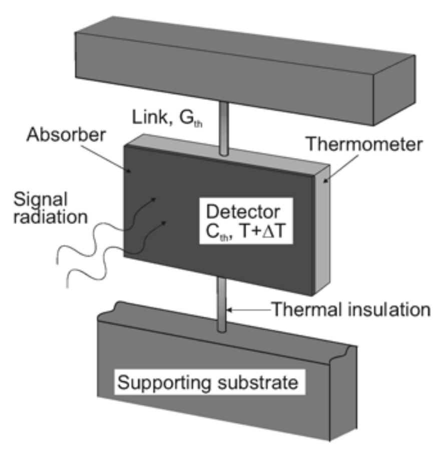

Figure 1.1 The simplest representation of the thermal detector. The detector is represented by a thermal capacitance C_{th} coupled via a thermal conductance G_{th} to a heat sink at a constant temperature T. ΔT is the temperature difference due to the optical signal.

responsible for the absorption of the radiation is itself wavelength independent (see Fig. 1.2).

Three approaches have found the greatest utility in infrared (IR) technology, namely bolometers, pyroelectric effects, and thermoelectric effects. In pyroelectric detectors, a change in the internal electrical polarization is measured, whereas in the case of thermistor bolometers, a change in the electrical resistance is measured. Because they are not selective, thermal detectors can be used in an extremely wide range of the electromagnetic spectrum, from x ray to ultraviolet (UV), visible, IR, and microwave. This is the case for any radiation in which the energy can be readily converted to heat. They have found widespread use in low-cost applications that do not require superior performance and high speed. Their room- temperature operation makes them lightweight, rugged, reliable, and convenient to use. However, they are characterized by modest sensitivity and suffer from a slow response (because heating and cooling of a detector element is a relatively slow process).

Until the 1990s, thermal detectors were considerably less exploited in commercial and military systems in comparison with photon detectors. The reason for this disparity is that thermal detectors were popularly believed to be rather slow and insensitive compared to photon detectors, and useless in scanned thermal imagers. As a result, the worldwide effort to develop thermal detectors was extremely small relative to that of photon detectors. However, during the last decade there has been a revolutionary emergence of focal plane arrays based on thermal detectors.[1] The slow speed of response is no limitation for a staring system covering the whole field of view without mechanical scanning, and thermal detectors' moderate sensitivity can be compensated by a large number of elements in two-dimensional (2D) electronically scanned arrays. With large arrays of thermal detectors, the best values of temperature resolution below 0.05 K can be reached because effective noise bandwidths less than 100 Hz can be achieved. A high sensitivity is also expected by imagers based on superconductor high-temperature bolometers and mechanical cantilever "bimaterial" detectors. Mid-range 10^8 cm Hz$^{1/2}$/W detectivity is typical

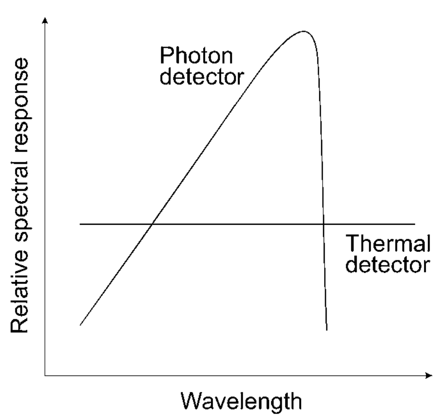

Figure 1.2 Relative spectral response for a photon detector and a thermal detector.

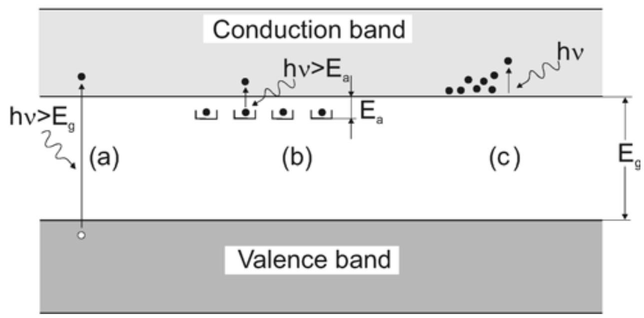

Figure 1.3 Fundamental optical excitation processes in semiconductors: (a) intrinsic absorption, (b) extrinsic absorption, and (c) free-carrier absorption.

for the present microbolometer arrays, while the theoretical limit for radiation heat transfer noise is 1.8×10^{10} cm Hz$^{1/2}$/W at room temperature.

With the second class of IR detectors, photon detectors (photodetectors), the radiation is absorbed within the material by interaction with electrons (see Fig. 1.3) that are either bound to lattice or impurity atoms or are free electrons. The observed electrical output signal results from the changed electronic energy distribution. Photon detectors show a selective wavelength dependence of response per unit of incident radiation power (Fig. 1.2). They exhibit both perfect signal-to-noise performance and a very fast response. But to achieve this, the present photon detectors require cryogenic cooling.

The class of photon detectors is further subdivided into different types based on the nature of the detector's interaction, as shown in Table 1.1. The most important types are intrinsic detectors, extrinsic detectors, photoemissive (metal silicide Schottky barriers) detectors, and quantum well detectors. Depending on how the electric or magnetic fields are developed, there are various modes of operation such as photoconductive, photovoltaic, photoelectromagnetic (PEM), and photoemissive. Each material system can be used for different modes of operation.

A common belief is that an IR photodetector must be cooled to achieve a high sensitivity. The detection of long-wave infrared (LWIR) radiation, which is characterized by low photon energy, requires the electron transitions to be free-charge carriers of energy lower than the photon energy. Therefore, at near room temperatures, the thermal energy kT is comparable to the transition energy. The direct consequence of this is a very high rate of thermal generation by the charge carriers. The statistical nature of this process generates signal noise. As a result, long-wavelength detectors become very noisy when operated at near room temperature. Cooling is a direct, straightforward, and very efficient way to suppress the thermal generation of charge carriers, while at the same time being a very impractical method because it adds considerably to the cost, weight, power consumption, and inconvenience of an IR system. The need for cooling is a major limitation of photodetectors and inhibits the more widespread application of IR technology. Affordable high-performance IR imaging cameras require cost-effective IR detectors that operate without cooling, or at least at temperatures compatible with long-life, low-

Table 1.1 Comparison of IR detectors.

Detector type			Advantages	Disadvantages
Thermal (thermopile, bolometers, pyroelectric)			Light, rugged, reliable, low cost Room-temperature operation	Low detectivity at high frequency Slow response (on the order of ms)
Photon	Intrinsic	IV–VI (PbS, $PbSe$, $PbSnTe$)	Easy to prepare Stable materials	Very high thermal expansion coefficient Large permittivity
		II–VI ($HgCdTe$)	Easy bandgap tailoring Well-developed theory and exper. use Multicolor detectors	Nonuniformity over large area High cost in growth and processing Surface and bulk instabilities
		III–V ($InGaAs$, $InAs$, $InSb$, $InAsSb$)	Good-quality material and dopants Advanced technology Possible monolithic integration	Heteroepitaxy with large lattice mismatch Long wavelength cutoff limited to 7 μm (at 77 K)
	Extrinsic (Si:Ga, Si:As, Ge:Cu, Ge:Hg)		Very long wavelength operation Relatively simple technology	High thermal generation Extremely low-temperature operation
	Free carriers ($PtSi$, Pt_2Si, $IrSi$)		Low cost, high yields Large and close packed 2D arrays	Low quantum efficiency Low temperature operation
	Quantum wells	Type I ($GaAs/AlGaAs$, $InGaAs/AlGaAs$)	Mature material growth Good uniformity over large area Multicolor detectors	High thermal generation Complicated design and growth
		Type II ($InAs/InGaSb$, $InAs/InAsSb$)	Low Auger recombination rate Easy wavelength control Multicolor detectors	Complicated design and growth Sensitive to the interfaces
	Quantum dots	$InAs/GaAs$, $InGaAs/InGaP$, Ge/Si	Normal incidence of light Low thermal generation	Complicated design and growth

power, and low-cost coolers. Thus, it is highly desirable to eliminate or reduce the cooling requirements in an IR system.

Can thermal detectors replace photon detectors in most applications where uncooled operation is essential? The answer is simply—no! Thermal detectors seem to be less suitable for the next generation of IR thermal imaging systems, which are moving toward faster frame rates and multispectral operation; they are completely useless for many imaging and nonimaging applications that require nano- and subnano-second responses.

Photodetectors make it possible to achieve both high sensitivity and fast response (see, e.g., Refs. 2, 3). They are devices that detect radiation by direct interaction of photons with electrons in the detector material. This interaction generates free-charge carriers in intrinsic or extrinsic detectors, or delivers the necessary energy to charge carriers confined within a potential well to overcome the barrier.

A number of concepts to improve performance of photodetectors operating at near room temperatures have been proposed.[4–6] Recent results show that, in principle, the ultimate limits of sensitivity, even for wavelengths exceeding 10 μm, can be achieved without the need for cryogenic cooling.[7, 8]

1.2 Detector Figures of Merit

It is difficult to measure the performance characteristics of IR detectors because of the large number of experimental variables involved. A variety of environmental, electrical, and radiometric parameters must be taken into account and carefully controlled. With the advent of large 2D detector arrays, detector testing has become even more complex and demanding. Numerous texts and journals cover this issue, including: *Infrared System Engineering* by R. D. Hudson;[9] *The Infrared Handbook* edited by W. L. Wolfe and G. J. Zissis;[10] *The Infrared and Electro-Optical Systems Handbook* edited by J. S. Accetta and D. L. Shumaker;[11] and *Fundamentals of Infrared Detector Operation and Testing* by J. D. Vincent.[12] In this volume we have restricted our consideration to detectors whose output consists of an electrical signal that is proportional to the radiant signal power.

The measured data described in this text are sufficient to characterize a detector. However, to provide ease of comparison between detectors, certain figures of merit, computed from the measured data, will be defined in this section.

1.2.1 Responsivity

The responsivity of an IR detector is defined as the ratio of the root mean square (rms) value of the fundamental component of the electrical output signal of the detector to the rms value of the fundamental component of the input radiation power. The units of responsivity are volts per watt (V/W) or amperes per watt (amp/W).

The voltage (or analogous current) spectral responsivity is given by

$$R_v(\lambda, f) = \frac{V_s}{\Phi_e(\lambda)\Delta\lambda}, \tag{1.1}$$

where V_s is the signal voltage due to Φ_e, and $\Phi_e(\lambda)$ is the spectral radiant incident power (in W/m).

An alternative to the above monochromatic quality, the blackbody responsivity, is defined by the equation

$$R_v(T, f) = \frac{V_s}{\Phi_{ebb}} = \frac{V_s}{\int_0^\infty \Phi_e(\lambda) d\lambda}, \tag{1.2}$$

where the incident radiant power is the integral over all wavelengths of the spectral density of power distribution $\Phi_e(\lambda)$ from a blackbody. The responsivity is usually a function of the bias voltage V_b, the operating electrical frequency f, and the wavelength λ.

1.2.2 Noise equivalent power

The noise equivalent power (NEP) is the incident power on the detector generating a signal output equal to the rms noise output. Stated another way, the NEP is the signal level that produces a signal-to-noise ratio (SNR) of 1. It can be written in terms of responsivity as

$$\text{NEP} = \frac{V_n}{R_v} = \frac{I_n}{R_i}. \tag{1.3}$$

The unit of NEP is the watt.

The NEP is also quoted for a fixed reference bandwidth, which is often assumed to be 1 Hz. This "NEP per unit bandwidth" has a unit of watts per square root hertz (W/Hz$^{1/2}$).

1.2.3 Detectivity

The detectivity D is the reciprocal of NEP:

$$D = \frac{1}{\text{NEP}}. \tag{1.4}$$

It was found by Jones[13] that for many detectors, the NEP is proportional to the square root of the detector signal that is proportional to the detector area, A_d. This means that both NEP and detectivity are functions of the electrical bandwidth and detector area, so a normalized detectivity D^* (or "D-star") suggested by Jones[13, 14] is defined as

$$D^* = D(A_d \Delta f)^{1/2} = \frac{(A_d \Delta f)^{1/2}}{\text{NEP}}. \tag{1.5}$$

The importance of D^* is that this figure of merit permits a comparison of detectors that have different areas. Either a spectral or blackbody D^* can be defined in terms of the corresponding type of NEP.

Useful equivalent expressions to Eq. (1.5) include:

$$D^* = \frac{(A_d \Delta f)^{1/2}}{V_n} R_v = \frac{(A_d \Delta f)^{1/2}}{I_n} R_i = \frac{(A_d \Delta f)^{1/2}}{\Phi_e} (\mathrm{SNR}), \tag{1.6}$$

where D^* is defined as the rms SNR in a 1-Hz bandwidth per unit rms incident radiant power per square root of detector area. D^* is expressed by the unit $\mathrm{cm\,Hz^{1/2}\,W^{-1}}$, which also has been called a "Jones."

Spectral detectivity curves for a number of commercially available IR detectors are shown in Fig. 1.4. Interest has centered mainly on the wavelengths of the two atmospheric windows 3–5 μm (middle wavelength infrared or MWIR) and 8–14 μm (the LWIR region). Atmospheric transmission is the highest in the MWIR and LWIR bands, and the emissivity maximum of the objects at $T \approx 300$ K is at the

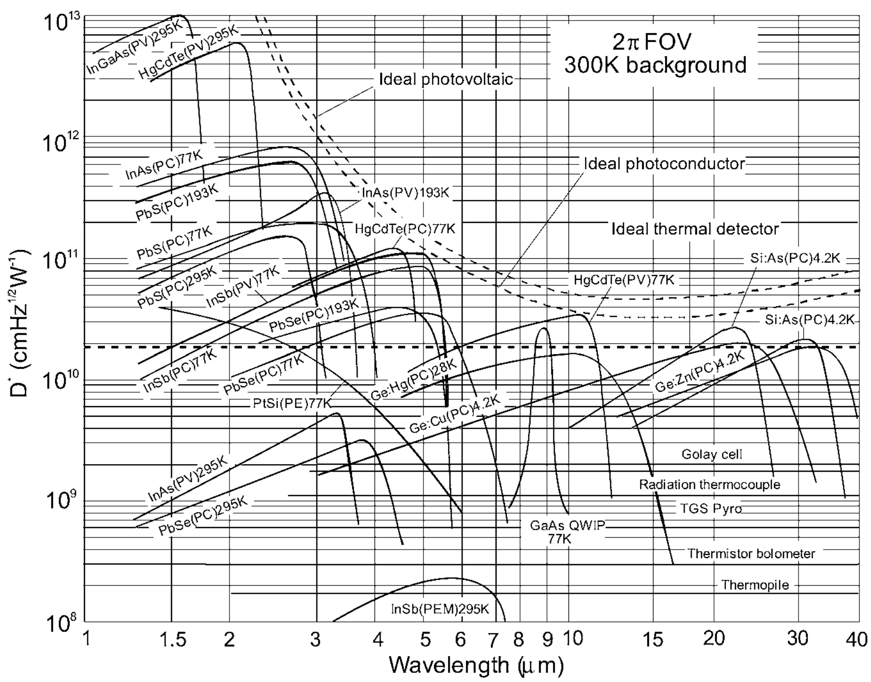

Figure 1.4 Comparison of the D^* of various commercially available IR detectors when operated at the indicated temperature. Chopping frequency is 1000 Hz for all detectors except the thermopile (10 Hz), thermocouple (10 Hz), thermistor bolometer (10 Hz), Golay cell (10 Hz), and pyroelectric detector (10 Hz). Each detector is assumed to view a hemispherical surrounding at a temperature of 300 K. Theoretical curves for the background-limited D^* (dashed lines) for the ideal photovoltaic and photoconductive detectors and for thermal detectors are also shown. Key: PC = photoconductive detector, PV = photovoltaic detector, PE = photoemissive detector, and PEM = photoelectromagnetic detector.

wavelength $\lambda \approx 10$ µm. However, in recent years space applications have increased the interest in longer wavelengths.

The blackbody $D^*(T, f)$ may be found from spectral detectivity:

$$D^*(T, f) = \frac{\int_0^\infty D^*(\lambda, f)\Phi_e(T, \lambda)d\lambda}{\int_0^\infty \Phi_e(T, \lambda)d\lambda} = \frac{\int_0^\infty D^*(\lambda, f)E_e(T, \lambda)d\lambda}{\int_0^\infty E_e(T, \lambda)d\lambda}, \quad (1.7)$$

where $\Phi_e(T, \lambda) = E_e(T, \lambda)A_d$ is the incident blackbody radiant flux (in W), and $E_e(T, \lambda)$ is the blackbody irradiance (in W/m^2).

The ultimate performance of IR detectors is reached when the detector and amplifier noise are low compared to the photon noise. The photon noise is fundamental in the sense that it arises not from any imperfection in the detector or its associated electronics, but rather from the detection process itself as a result of the discrete nature of the radiation field.

1.3 Detectivity Requirements for Thermal Imagers

For focal plane arrays (FPAs), the relevant figure of merit is the noise equivalent temperature difference (NEDT), the temperature change of a scene required to produce a signal equal to the rms noise. The configuration of a basic thermal imager system is shown in Fig. 1.5.

It can be shown that the NETD of an IR imager is

$$\text{NETD} = \frac{4F_\#^2 \Delta f^{1/2}}{A_d^{1/2} M^*}, \quad (1.8)$$

where $F_\#$ is the optics f-number, Δf is the frequency band, A_d is the detector area, and M^* is the thermal figure of merit, which is dependent on the detectivity of

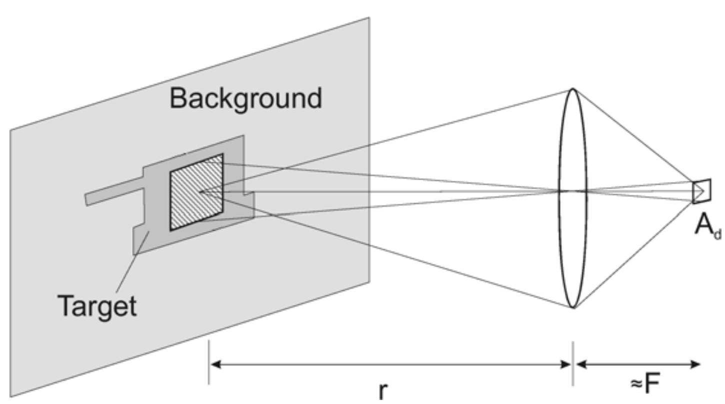

Figure 1.5 Thermal imager system configuration.

detector $D^*(\lambda)$ and spectral blackbody exitance $R(\lambda, T)$, described by the Planck law between two wavelengths λ_1 and λ_2 as

$$M^* = \int_{\lambda_1}^{\lambda_2} D^*(\lambda) \frac{\partial R(\lambda, T)}{\partial T} d\lambda, \tag{1.9}$$

$$R(\lambda, T) = \frac{2\pi hc^2}{\lambda^5}\left[\exp\left(\frac{hc}{\lambda kT}\right) - 1\right]^{-1}, \tag{1.10}$$

where $c = 2.998 \times 10^8$ m/s is the light velocity, $h = 6.6256 \times 10^{-34}$ J s is the Planck's constant, and $k = 1.38054 \times 10^{-23}$ J/K is the Boltzmann's constant.[14, 15]

For nonselective detectors,

$$M^* = D^* \int_{\lambda_1}^{\lambda_2} \frac{\partial R(\lambda, T)}{\partial T} d\lambda. \tag{1.11}$$

Infrared imaging systems with staring arrays demand less bandwidth when compared to scanning systems. Reducing pixel size is important for lightweight imagers, but a higher D^* would be necessary to compensate for NETD deterioration with smaller pixel size [see Eqs. (1.8) and (1.11)].

Table 1.2 shows the $\int_{\lambda_1}^{\lambda_{co}} (\lambda/\lambda_{co})[\partial R(\lambda, T)/\partial T] d\lambda$ and D^* required for NETD $= 0.1$ K as a function of spectral range for a staring IR imager with relatively fast optics ($F_\# = 1$), operating with a standard frame rate (50 frames/sec).

The detectivity required for a thermal detector operating over the entire spectral range is 0.65×10^8 cm Hz$^{1/2}$/W. Reducing the spectral range to the 8–14 μm atmospheric window increases this detectivity by a factor of ≈ 2.3. Operation in the 3–5 μm atmospheric window would require a significant increase of detectivity—by more than one order of magnitude. This makes thermal detectors not very useful for operation outside the LWIR atmospheric window.

Table 1.2 The $\int_{\lambda_1}^{\lambda_{co}} (\lambda/\lambda_{co})[\partial R(\lambda, T)/\partial T] d\lambda$ and detectivity required for NETD $= 0.1$ K ($F_\# = 1$, $T = 300$ K, detector size 50×50 μm).

Spectral range (μm)	$\int_{\lambda_1}^{\lambda_{co}} \frac{\lambda}{\lambda_{co}} \frac{\partial R(\lambda, T)}{\partial T} d\lambda$ (W/m^{2}K)	D^* (cm Hz$^{1/2}$/W)
0–infinity	6.12	0.65×10^8
0–14	4.25	0.94×10^8
8–14	2.63	1.52×10^8
3–5	0.186	2.15×10^9

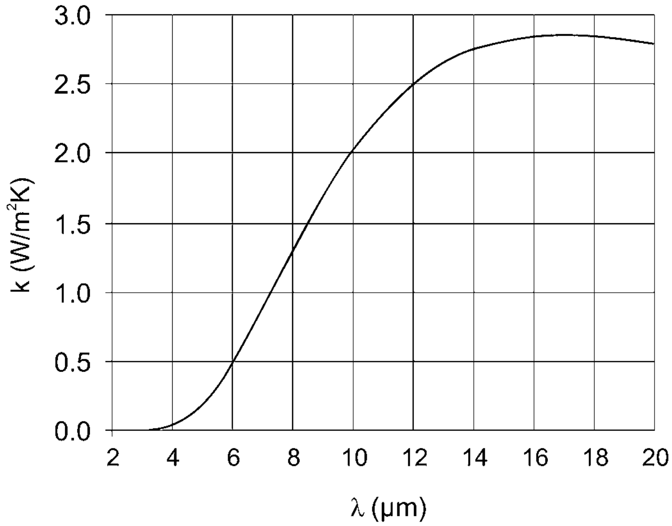

Figure 1.6 Dependence of $k = \int_0^{\lambda_{co}} (\lambda/\lambda_{co})[\partial R(\lambda, T)/\partial T]d\lambda$ on wavelength; $T = 300$ K.

Consider an ideal photon counter detector with cutoff wavelength of λ_{co}. In this case,

$$M^* = D^*(\lambda_{\max}) \int_0^{\lambda_{co}} \frac{\lambda}{\lambda_{co}} \frac{\partial R(\lambda, T)}{\partial T} d\lambda. \tag{1.12}$$

Figure 1.6 shows $\int_0^{\lambda_{co}} (\lambda/\lambda_{co})[\partial R(\lambda, T)/\partial T]d\lambda$ as a function of wavelength. This function initially increases with wavelength, achieving its maximum just above the 8–14 μm spectral range band.

Let's consider NETD = 0.1 K as a minimal requirement for thermal imagers. As Fig. 1.7 shows, detectivity measures of 1.9×10^8 cm Hz$^{1/2}$/W, 2.3×10^8 cm Hz$^{1/2}$/W, and 2×10^9 cm Hz$^{1/2}$/W are necessary for an NETD of 0.1 K for, respectively, the 10 μm, 9 μm, and 5 μm cutoff wavelength photon counter detectors. Very good thermal imaging will require an NETD by a factor 3 to 10 less. Can this be achieved at near room temperature using photodetectors? The answer to this question is given in Chapter 4.

1.4 Cooling of IR Detectors

The method of cooling varies according to the operating temperature and the system's logistical requirements.[16, 17] Various types of cooling systems have been developed including dewars with cryogenic liquids or solids, Joule-Thompson open cycle, Stirling closed cycle, and thermoelectric coolers (see Fig. 1.8). These systems are discussed briefly below.