CHAPTER 9.6

INFRARED DETECTORS AND ASSOCIATED CRYOGENICS

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DETECTORS

Infrared Detectors

Infrared detectors provide an electrical output, which is a useful measure of the incident infrared radiation. It is usually necessary to cool detectors to cryogenic temperatures to reduce the thermal noise inherent in an electrical transducer. Infrared detectors can be divided into two categories, *thermal detectors* and *quantum detectors*.

Thermal Detectors (Table 9.6.1)

Thermal detectors are of three types. The *bolometer* varies its electrical resistance as a result of temperature changes produced by absorbed infrared radiation.

The *thermocouple* is a junction of two dissimilar metals. When the junction is heated, it produces a voltage across the two open leads. A *thermopile* consists of several thermocouples combined in a single responsive element.

The *pyroelectric detector* produces an observable external electric field when heated by infrared radiation.

Quantum Detectors (Table 9.6.2)

Quantum detectors are of three types. A *photovoltaic detector* is a *pn* semiconductor junction. Absorbed infrared photons produce free charge carriers which, if near the junction, are separated by it, producing an external voltage (open circuit) or an electric current (closed circuit).

A *photoconductor* is a semiconductor in which absorbed infrared photons produce free charge carriers, resulting in a change in the electric conductivity.

A *photoemissive detector* is one in which incident photons impart sufficient energy to surface electrons to free them from the detector surface.

Detector Parameters

The parameters most often used in the description of infrared detectors are as follows.

TABLE 9.6.1 Thermal Detectors

Type	Operating temp, K	Detectivity D^*, cm·Hz$^{1/2}$/W	Wavelength region, μm	Response time, ms	Resistance
Pyroelectric	300	1×10^9	>1	1	10 TΩ
Thermistor	300	5×10^8	1–40	0.1	2 MΩ
Golay cell	300	1.5×10^9	1–2000	15	
Thermocouple	300	1×10^9	>1	10	10 Ω
Germanium bolometer	2.0	1×10^{12}	>10	10	100 kΩ
Tin bolometer	3.7	7×10^{10}	>10	10	100 Ω
Carbon bolometer	2.0	4×10^{10}	>10	1	100 kΩ

Responsivity R is the ratio of the rms signal voltage (or current) to the rms incident signal power, referred to an infinite load impedance or to the terminals of the detector, $R = V_{s,\text{rms}}/P_{s,\text{rms}}$. Spectral responsivity R_λ refers to monochromatic input signal, and blackbody responsivity R_{BB} refers to an input signal having a blackbody spectrum. The units of responsivity are volts per watt (or amperes per watt). Responsivity is a function of wavelength λ, signal frequency f, operating temperature T, and bias voltage V_B.

Impedance times area product ZA is a parameter used to characterize a photovoltaic detector. Here A is the area of the detector, and Z is the dynamic impedance taken from the I-V curve of the diode at some operating point; that is, $Z = \delta V/\delta I$. Usually the zero-bias impedance Z_0 is measured to determine the thermal noise and the proper matching to external electric circuits. The unit of ZA is Ω-cm^2.

TABLE 9.6.2 Quantum Detectors

Material	Type[*]	Operating temp, K	Peak wavelength, μm	Detectivity at peak wavelength, cm·Hz/W	Response time, μs	Resistance (size-dependent)
Si	PV[†]	300	0.9	5.6×10^{12}	10^{-2}	2 kΩ
Si	PV	300	0.9	6×10^{12}	0.2	5 kΩ
Ge	PV	300	1.6	4×10^{11}	1000	
PbS	PC	300	2.4	1×10^{11}	300	1 mΩ
PbS	PC	193	2.8	5×10^{11}	3000	5 MΩ
PbSe	PC	300	3.8	3×10^{10}	2	5 MΩ
PbSe	PC	193	4.8	2×10^{10}	30	50 MΩ
PbSe	PC	77	5.0	2×10^{10}	30	5 MΩ
InAs	PV	300	3.4	7×10^9	1	20 Ω
InAs	PV	195	3.2	1×10^{11}	1	5 kΩ
InAs	PV	77	3.0	7×10^{11}	1	100 kΩ
InSb	PV	77	5.0	1×10^{11}	0.1	1 MΩ
HgCdTe	PC	200	5	5×10^{10}	5	500 Ω
HgCdTe	PC	77	11.5	2×10^{10}	1	40 Ω
HgCdTe	PV	200	4.2	1×10^{11}	0.1	100 kΩ
HgCdTe	PV	77	10.6	2×10^{10}	0.1	1 kΩ
PbSnTe	PV	77	11.5	2×10^{10}	0.1	10 kΩ
Ge:Au	PC	77	5	7×10^9	0.1	300 kΩ
Ge:Hg	PC	28	11	2×10^{10}	0.1	100 kΩ
Ge:Cu	PC	5	25	3×10^{10}	0.1	300 kΩ
Si:Ga		30	15	4×10^{10}	0.1	100 kΩ
Si:In		50	5.6	3×10^{11}	0.1	300 kΩ

[*] PV = photovoltaic, PC = photoconductor.
[†] Avalanche.

Chopping frequency f_c is the rate at which the blackbody radiation source is mechanically interrupted to provide a strong periodic signal for separating ac components of the instantaneous power from the dc component.

Noise-equivalent power (NEP) is that value of incident rms signal power required to produce an rms signal-to-noise ratio of unity NEP = $V_{\mathrm{n,rms}}/R$. Spectral noise-equivalent power (NEP)λ refers to a monochromatic input signal, and blackbody noise-equivalent power $(\mathrm{NEP})_{BB}$ refers to an input signal having a blackbody spectrum. The unit of NEP is the watt, NEP is a function of wavelength λ, detector area A, chopping frequency f_c, electric bandwidth Δf, temperature of blackbody T_{BB}, field of view Ω, and background temperature T_B.

Detectivity D is the reciprocal of the NEP. It can also be expressed as the rms signal-to-noise ratio per unit of rms power incident on the detector. Spectral detectivity D_λ and blackbody detectivity D_{BB} are the reciprocals of NEP and $(\mathrm{NEP})_{BB}$, respectively.

D star (D^*) is a normalization of the reciprocal of the noise-equivalent power to take into account the area and electric-bandwidth dependence, $D^* = \sqrt{A\Delta f}/\mathrm{NEP} = \sqrt{A\Delta f}/D$. By using $(\mathrm{NEP})_{BB}$, D^*_{BB} can be determined, and from the definitions of $(\mathrm{NEP})_{BB}$ and R, $D^*_{BB} = \sqrt{A\Delta f}/V_{s,\mathrm{rms}}/V_{n,\mathrm{rms}} P_{BB,\mathrm{rms}}$, where $P_{BB,\mathrm{rms}}$ is the rms power incident on the detector from a blackbody at temperature T_{BB}. Since D^*_{BB} depends on T_{BB}, f_c, and Δf, it is sometimes written as $D^*(T_{BB}, f_c, \Delta f)$. Similarly, D^*_λ depends on λ, f_c, and Δf and is sometimes written as $D^*(\lambda, f_c, \Delta f)$. It can be determined from $(\mathrm{NEP})_\lambda$, $D^*_\lambda = \sqrt{A\Delta f}\, V_{s,\mathrm{rms}}/V_{n,\mathrm{rms}}\, P_{\lambda,\mathrm{rms}}$ where $P_{\lambda,\mathrm{rms}}$ is the rms power incident on the detector from a monochromatic source.

These figures of merit can be used to compare detectors of different types since the detector with the greater value of D^* is a better detector when the terms in the parentheses are identical. This does not hold for detectors limited by noise resulting from fluctuations in background photon flux. For such detectors, field of view and background temperature must be specified. The units of D^* are cm·Hz$^{1/2}$/W.

Quantum efficiency (QE or η) is the ratio of countable output events to the number of incident photons.

Time constant τ is a measure of the speed of response of a detector. It is usually defined as $\tau = (2\pi f_c)^{-1}$, where f_c is that signal frequency at which the responsivity has fallen to 0.707 times its maximum value.

Noise Mechanisms in Infrared Detectors

Noise mechanisms in infrared detectors are usually of five types.

Photon Noise (Background Noise). Random fluctuations in the arrival rate of background photons incident on the detector produce random fluctuations in its output signal. Photodetectors whose D^* is limited only by this type of noise are called *background-limited infrared photodetectors* (BLIP detectors). This value of D^* is the theoretical limit for a photon detector.

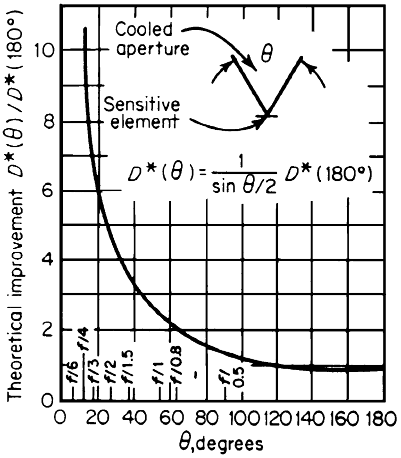

FIGURE 9.6.1 Relative increase in D^* for BLIP detectors obtained by using cold shielding.

Figure 9.6.1 is a plot of relative improvement in D^* versus angular field of view for a BLIP detector. Cooled spectral filters also improve the D^*_λ of a BLIP or near-BLIP detector by attenuating radiation at wavelengths which are not of interest.

Johnson Noise (Nyquist or Thermal Noise). The random motion of charge carriers in a resistive element at thermal equilibrium generates a random electric voltage across the element.

Generation-Recombination Noise (GR). Variations in the rate of generation and recombination of charge carriers in the detector create electric noise.

Shot Noise. Since the electric charge is discrete, there is a noise current flowing through the detector as a result of current pulses produced by individual charge carriers.

I/f Noise. The mechanism involved in this type of noise is not well understood. It is characterized by a I/f^n noise-power spectrum, where n varies from 0.8 to 2.

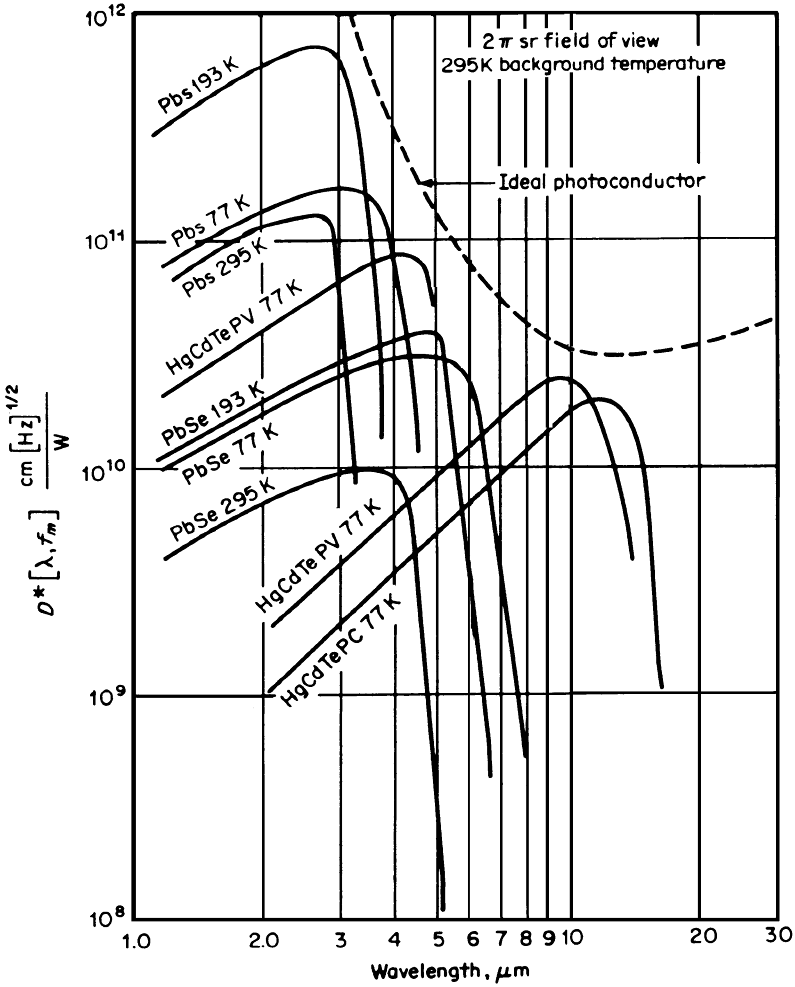

FIGURE 9.6.2 Spectral D^* of photodetectors.

Detector Data

Tables 9.6.1 and 9.6.2 list commercially available detectors. They include the operating temperature, cutoff wavelength, and peak D^*.

Figure 9.6.2 is a plot of D^*_λ versus wavelength for selected detectors. Since detector noise is a function of operating temperature, D^* will also vary with temperature. Figure 9.6.3 is a plot of peak D^* versus temperature for selected detectors. All values tabulated are data from above-average single-element detectors.

Charge Transfer Devices for Infrared Detection

In applications requiring many infrared detectors, e.g., thermal imaging, the detectors and signal processors have been integrated into a single structure. The signal processor provides rapid and efficient readout of the

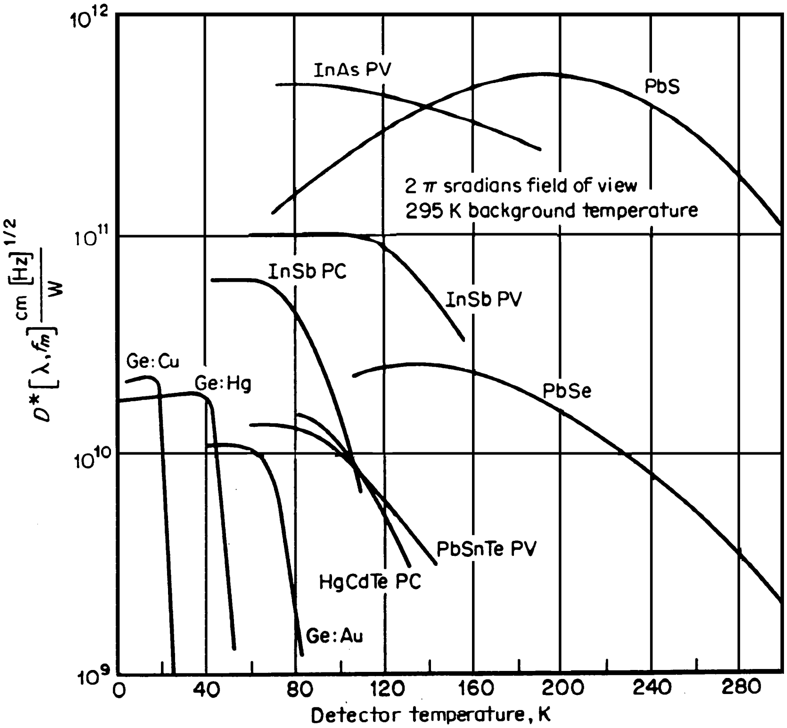

FIGURE 9.6.3 Peak D^* vs. temperature for selected detectors. PC = photoconductive mode, PV = photovoltaic mode.

many detected signals by using charge-coupled devices (CCDs) or charge-injection devices (CIDs). These structures have been fabricated with InSb, extrinsic silicon, and HgCdTe.

Detector Selection

Though no absolute guidelines for the choice of an infrared detector for a specific application are possible, certain criteria can be used to eliminate many of the available detectors. Among them are spectral region of interest, maximum signal frequency, required sensitivity, and available cooling.

COOLERS

Cryogenic Cooling

For BLIP performance, temperatures of 200 K or lower are required for intrinsic infrared detectors, and extrinsic detectors require temperatures of 80 K or less (Table 9.6.2).

The four basic types of cooling systems are:

1. *Open-cycle*, *expendable systems*, which operate by the transfer of stored cryogens
2. *Mechanical coolers*, which are closed-cycle, expansion engines providing cooling at low temperatures and rejecting heat at high temperatures

3. *Thermoelectric coolers*, which operate by using the Peltier cooling effect
4. *Radiation coolers*, which are passive and cool detectors by radiating heat to the low-temperature deep-space environment.

Cooling Specifications

The particular application and detector type determine the best-suited cooling system. Variables used for cooler specifications include cooling capacity, cooling temperature, cooldown time, temperature stability, reliability, duty cycle, environment, weight, configuration, noise (acoustical, electromagnetic, mechanical), and power (ac, dc, limits).

Open-Cycle Expendable Systems

Open-cycle systems include the use of high-pressure gas combined with a Joule-Thomson (J-T) expansion valve, cryogenic liquids, or solid cryogenics.

Joule-Thomson. The J-T cooling process exploits the cooling effect obtained by the adiabatic expansion of a high-pressure (1000 to 6000 lb/in.^{2}) gas through an orifice. The cooled, expanded gas is used to cool incoming gas. This process of regenerative cooling continues until liquid forms at the orifice. Figure 9.6.4 shows a typical J-T cooler. Self-regulating throttle valves can be placed in the orifice of the J-T cooler to maintain constant temperature, reduce clogging, and improve gas economy. Some gases, e.g., helium, hydrogen, and neon, require precooling before the J-T cooling effect can occur.

Liquid-Cryogen Storage. Cryogens can be stored as liquids in equilibrium with their vapors (subcritical) or as homogeneous fluids at high pressure and temperatures (supercritical). There are two basic types of storage, direct-contact and liquid-feed. In the direct-contact (or integral) system, the detector is built into a cryogenic dewar which stores the liquid cryogen. In the liquid-feed method, the cryogen is fed to the detector from a remote storage tank. The liquid is transferred by gravity or by gas pressure resulting from the natural pressure buildup in the storage tank.

Solid-Cryogen Storage. Stored solid cryogen sublimes, causing an increase in pressure and temperature. The detector temperature and the dewar pressure are maintained at constant levels by venting the gas through specially designed ducts. Such coolers have operated successfully in space for a year or more.

Mechanical Coolers

Closed-cycle, expansion-engine refrigerators (described below) are used to cool infrared detectors. Cooling is produced by the expansion of a gas from a high pressure to a low pressure, with consequent reduction of working gas temperature. The figure of merit for coolers is the coefficient of performance (COP), the ratio of the produced cooling power to the power supplied. The Carnot cycle is used as a standard of comparison because for given temperature limits its COP is maximum. For a Carnot engine operating between the temperatures T_a and T_c, COP = $T_c/(T_a - T_c)$, where heat is absorbed at T_c and heat is rejected at a higher temperature T_a.

Stirling. In the Stirling cycle, cooling is obtained by cyclic out-of-phase motion of a compression piston and a displacer-regenerator. The working gas is compressed while occupying the ambient space, at temperature T_a, by an upward motion of the compression piston, reducing the gas volume. Heat of compression is rejected to ambient. The COP for an ideal working gas is equal to that of the Carnot engine. This refrigeration cycle is well developed. Stirling cycle refrigerators have the best COP in practice (10^{-3} to 5×10^{-2}) and the best ratio of total weight per watt refrigeration compared with other refrigerators.

Vuilleumier (VM). This is a heat-driven cycle which is exploited for its long life and low vibration, owing in part to inherently very low dynamic forces on moving parts. Coolers have been built that provide refrigeration at 10 K. Cooling is obtained by cyclic out-of-phase motion of two displacer-regenerators. The working gas throughout the entire cooler is compressed by downward motion of the hot displacer-regenerator as it transfers part of the gas at the ambient end into the heated end. COP is equal to that for two Carnot heat engines in series: COP = $(T_c/T_h)(T_h - T_a)/(T_a - T_c)$. Typical COP values of 3×10^{-4} to 2×10^{-2} are obtained.

Gifford-McMahon (GM) and Solvay. By separating the expander from the compressor, a refrigeration system can be constructed that consists of a simple, lightweight cooling unit and a compressor which can be located remotely, connected to the expander with pressure lines. A piston displacer-regenerator is pneumatically moved up and down by timed valving of the high and low working-gas pressure. Cyclic charging and discharging of the expander working-gas pressures with time piston motion will pump heat from the cold to the ambient end. Heat pumped from the cold end using the GM cycle is rejected at the ambient end of the expander. Heat pumped from the cold end using the modified Solvay cycle is rejected along pressure lines and at the compressor. For these coolers COP values of 2×10^{-4} to 10^{-2} are measured.

J-T Closed Cycle. In this system a compressor is used to supply high-pressure gas to the J-T throttling valve. After expansion, the gas is recycled through the compressor. COP values of 3×10^{-3} to 10^{-2} are obtained for this system.

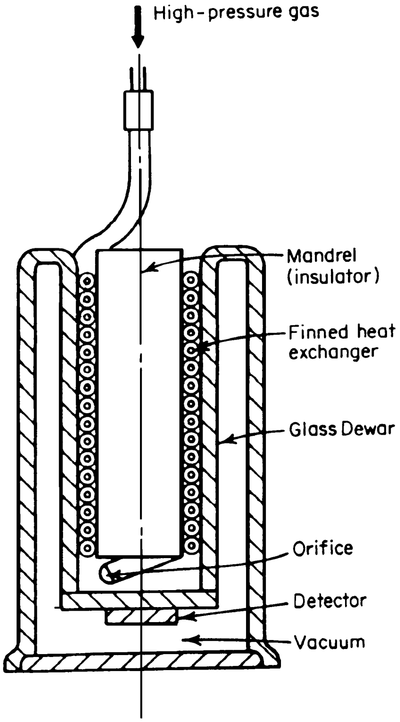

FIGURE 9.6.4 Single-stage, open-cycle Joule-Thomson cooling system.

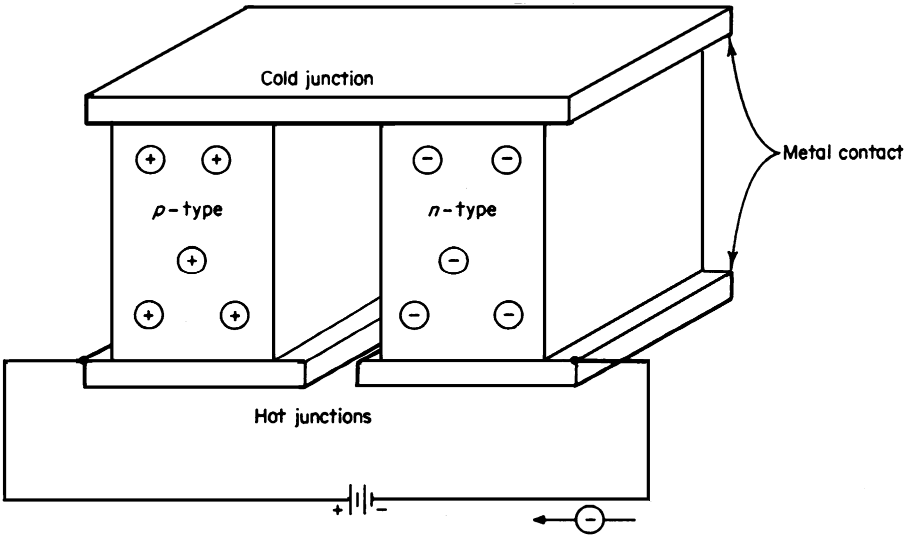

FIGURE 9.6.5 Single-stage thermoelectric refrigeration.

Thermoelectric (TE) Cooler

The basic operating principle of the thermoelectric cooler, the Peltier cooling effect, is the absorption or generation of heat as a current passes through a junction of two dissimilar materials (Fig. 9.6.5). Electrons passing across the junction absorb or give up an amount of energy equal to the transport energy and the energy difference between the dissimilar-materials conduction bands. Cryogenic temperatures are reached using heat rejected from one thermoelectric cooler stage to supply thermal input to the stage below. The maximum temperature difference attainable on a practical basis is about 150°C, which implies a minimum attainable temperature of approximately 150 K.

Radiation Coolers

Radiation coolers are used in spaceborne applications. These systems are passive and cool by radiating heat from the detector into the low-temperature (4-K) sink of deep space. The radiators consist of a suitably sized cold plate of high emissivity connected to the detectors. The high-vacuum in-space environment minimizes convective heating, but the radiator must be shielded from sunlight and (for near-earth orbits) from thermal emission and reflected sunlight from the earth and its atmosphere. Radiation coolers have been designed for cooling milliwatt-level loads at 85 K and 5-W loads at 135 K.

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