5.4 Thermal Detectors

5.4.1 Principle of operation

The scope of thermal detector technology includes a large number of different physical mechanisms, resulting in a wide variety of measurable characteristics. Common to to all these mechanisms is the underlying principle that the absorbed heat increases the temperature of the device (hence the name thermal), which is observed in the change of some observable property of the device. The two major groupings include thermoelectric transducer effects (Seebeck effect and pyroelectric effect) and parametric transducers where the device temperature modulates an electric signal (resistive bolometers, Golay cell, and p-n diodes).[25,33]

The Peltier–Seeback effect (discovered independently by Peltier, Seebeck and Thomson) is the bidirectional conversion between temperature and voltage. This effect is exploited in thermocouple devices and Peltier coolers used to cool detectors and mini-fridges. In a pyroelectric device, temperature variations result in dielectric polarization changes in the material. Pyroelectric detectors are commonly used in IR movement detectors in security applications. In bolometer detectors the temperature change results in a change in the device's resistance. Nanotechnology bolometers are used in low-cost thermal imaging applications.

In addition to the types mentioned earlier, there are several other effects also exploited in thermal detectors.[25] None of these effects require the use of small-bandgap semiconductor materials, thereby not requiring material cool-down for long-wavelength operation. Some of the thermal detectors remain sensitive to temperature effects, such as pyroelectric detectors that lose polarization above the Curie temperature.

A common requirement for all thermal detectors is that the sensing element must be thermally isolated from ambient temperature structures in order to allow minute temperature changes in the sensing element. A conceptual model of a thermal detector is shown in Figure 5.2. The detector-element thermal balance is affected by three heat-flow paths: (a) the incident flux from the object (target), (b) thermally radiated flux from the detector element, and (c) heat conducted from the detector element to the device's substrate. Thermal detector performance optimization entails the careful optimization of the heat balance equation.

Modern thermal detectors employ elements with very small thermal mass (heat capacity) compared to the surface area of the device. For a given amount of absorbed energy, the temperature rise is maximized. Likewise,

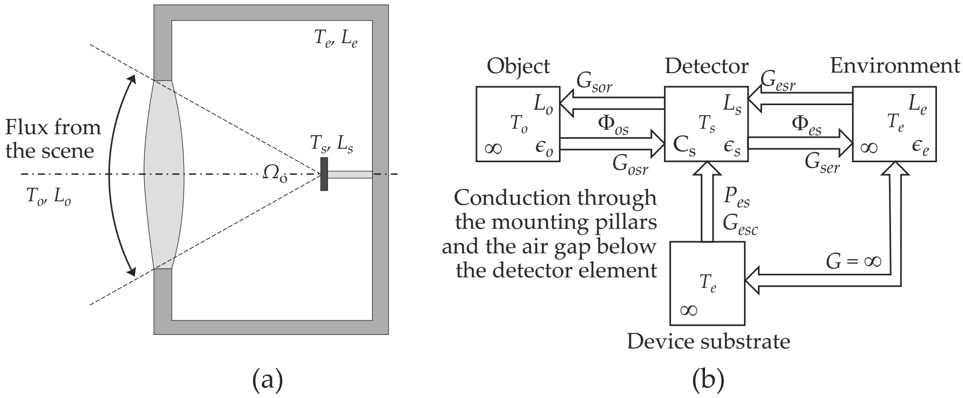

Figure 5.2 Conceptual model for thermal detector: (a) physical layout and (b) flux flow model.

because the radiating area is large compared to the thermal mass of the detecting element, the detector quickly cools down once the incident energy source is removed.

5.4.2 Thermal detector responsivity

In Figure 5.2 the detector element with heat capacity C_s in [J/K] is at a temperature T_s and radiates with radiance L_s into a full spherical environment. The environment is at a temperature T_e, radiates with radiance L_e, and has an infinite heat capacity (it can source or sink an infinite amount of energy without changing temperature). The target object is at a temperature T_o, radiates with radiance L_o, and has an infinite heat capacity. The detector element is fixed by mounting posts to the environment (the readout electronics interface chip). The mounting posts conduct heat P_{es} with conductance G_{esc} in [W/K] from the detector element to the environment. The radiative flux exchange between the object and the detector element is indicated by Φ_{os}. The radiative flux exchange between the detector element and the environment is indicated by Φ_{es}. The mounting posts between the detector element and the environment have a collective heat conductance G_{esc}. In this analysis the detector element is considered a thin disk with area A_d. Under thermal equilibrium the net inflow of power on the detector element is zero, $\Phi_{os} + \Phi_{es} + P_{es} = 0$, where inflowing power is positive:

$$\begin{aligned} 0 \; = \; & \int_0^\infty A_d \Omega_o (\alpha_{s\lambda} L_{o\lambda} - \alpha_{o\lambda} L_{s\lambda}) d\lambda \; + \\ & \int_0^\infty A_d (2\pi - \Omega_o)(\alpha_{s\lambda} L_{e\lambda} - \alpha_{e\lambda} L_{s\lambda}) d\lambda + G_{esc}(T_e - T_s), \quad (5.34) \end{aligned}$$

where Ω_o is the optics FOV, α_e is the environment absorptance (emissivity), α_s is the detector-element absorptance (emissivity), and α_o is the object's absorptance (emissivity). Equation (5.34) applies to the total flux over all wavelengths. Each of the three radiative sources has its own spectral emissivity, requiring a detailed spectral radiometry analysis to find the solution. The following analysis assumes constant spectral absorption and emissivity by applying Kirchhoff's law and setting all values equal to a scalar value $\alpha_o = \alpha_e = \alpha_s = \epsilon = \epsilon_o = \epsilon_e = \epsilon_s = \epsilon$. Next, perform the spectral integrals, resulting in:

$$0 = A_d\epsilon[\Omega_o(L_o - L_s) + (2\pi - \Omega_o)(L_e - L_s)] + G_{esc}(T_e - T_s). \quad (5.35)$$

The two detector heat-loss mechanisms are radiation heat loss and heat conduction to the environment. Consider these two cases separately. Case 1: $L_e = L_s$, no heat loss via radiation to the environment. Then $A_d\epsilon\Omega_o L_o = G_{esc}(T_s - T_e)$, where the object radiance L_o causes a detector-element temperature T_s. Case 2: $G_{esc} = 0$, isolated detector element, with no physical contact with the environment. Then $\Omega_o L_o = 2\pi L_s - (2\pi - \Omega_o)L_e$, where object radiance L_o raises the detector-element temperature such that it radiates at L_s. In general, both radiation and conduction to the environment take place, the relative ratio of which depends on the heat capacity and spectral emissivity values of the three components in this system.

By the Stefan–Boltzmann law, Equation (3.19), the flux radiated (or lost) by a Lambertian object over all wavelengths is

$$\Phi_{\rm SB} = \frac{A\sigma_e T^4}{\pi}, \quad (5.36)$$

where A is the radiating surface area, ϵ in this case is the effective hemispherical emissivity, and T is the temperature. The temperature derivative of the wideband flux is

$$\frac{d\Phi_{\rm SB}}{dT} = \frac{4A\sigma_e T^3}{\pi} = G_r(T) \quad (5.37)$$

with units [W/K], which, by definition, is thermal conductance. $G_r(T)$ can be interpreted that a thermal radiator loses flux by a 'conductance' given by $4A\sigma_e T^3/\pi$ — this is not a physical conductance, but it has the equivalent effect. This 'conductance' varies with temperature.

The derivative of Equation (5.35) with respect to temperature is (keeping in mind that $dL_e/dT = 0$ because T_e is constant)

$$\begin{aligned}
A_d\epsilon\Omega_o\frac{dL_o}{dT} &= A_d\epsilon 2\pi\frac{dL_s}{dT} + G_{esc}, \quad \text{hence} \\
\epsilon\frac{d\Phi_o}{dT} &= \epsilon\frac{d\Phi_s}{dT} + G_{esc} = \epsilon G_r(T_s) + G_{esc}, \quad \text{and finally} \\
\epsilon\frac{\Delta\Phi}{\Delta T} &= G = \epsilon G_r(T_s) + G_{esc}, \quad (5.38)
\end{aligned}$$

which defines a detector thermal conductance for small changes in Φ_o incident on the detector.

In the closed system in Figure 5.2(a), the absorbed flux has two effects: a change in the detector-element temperature $\Phi dt = d(\Delta T)\, C$ as well as a heat loss through conduction to the substrate $P = G\Delta T$. Thus, the temperature of the detector element is given by the solution of the differential equation[25]

$$C\frac{d(\Delta T)}{dt} + G\Delta T = \epsilon(\Delta\Phi)(t), \tag{5.39}$$

where G is given by Equation (5.38). Assuming a sinusoidal input signal $\Delta\Phi(t) = \Delta\Phi e^{i\omega t}$, the responsivity of the detector can be derived as being of the general form[12]

$$\Delta T = \Delta T_0 \exp(t/\tau_\theta) + \frac{\epsilon(\Delta\Phi)e^{i\omega t}}{G + i\omega C}, \tag{5.40}$$

where $\tau_\theta = C/G$ is the thermal time constant of the detector, and T_0 is the initial state of the detector. The transient exponential term becomes zero for large t. The magnitude of ΔT then becomes

$$\begin{aligned}\Delta T &= \frac{\epsilon(\Delta\Phi)}{\sqrt{G^2 + (\omega C)^2}} \\ &= \frac{\epsilon(\Delta\Phi)}{G\sqrt{1 + (\omega\tau_\theta)^2}}.\end{aligned} \tag{5.41}$$

The responsivity is then

$$\mathcal{R} = \left(\frac{\Delta T}{\Delta\Phi}\right)\left(\frac{i_d}{\Delta T}\right) = \frac{g}{G\sqrt{1 + (\omega\tau_\theta)^2}}, \tag{5.42}$$

where $\mathcal{R}$ is the responsivity in [A/W], and g depends on the conversion mechanism for the type of thermal detector. Responsivity can be similarly defined in terms of voltage output.

One technique to improve the frequency response of the detector is to increase the detector conductance G. This would, however, result in a reduced responsivity, as shown in Equation (5.42). The better way to improve the frequency response is to reduce the detector-element heat capacity C. The heat capacity is $C = c\rho V$, where $c = dC/dm$ is the detector material specific heat in [J/(g·K)], ρ is the material density in [g/m^3], and V is the detector-element volume in [m^3]. The material properties c and ρ are fixed; the only design freedom is the volume. The detector area must be maximized; therefore the detector-element thickness must be minimized to reduce the element's heat capacity — this can be done with no other detrimental effect on performance. The only requirement on the detector-element thickness is to achieve mechanical stability and rigidity.

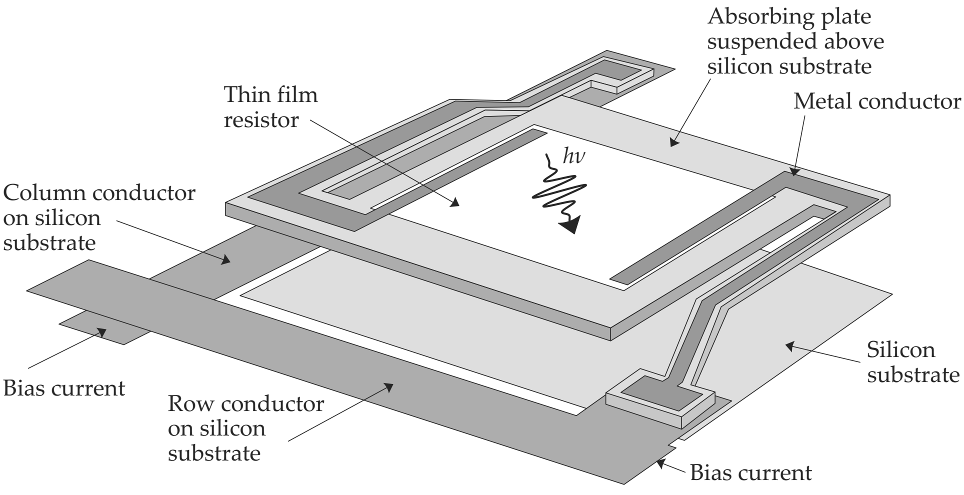

Figure 5.3 Resistive bolometer construction (adapted[34]).

5.4.3 Resistive bolometer

The resistive bolometer senses a change in electrical resistance of the device when the device temperature changes as a result of changing absorbed radiant energy. The bolometer consists of a thin, absorbent, metallic or semiconductor layer on a structure that is thermally isolated from the substrate material (low conductance). Different materials, ranging from metals to semiconductors, can be used for the resistive element in these detectors. The structure is designed to maximize absorption and the associated temperature increase but minimize heat loss to the substrate. Microbolometer detector elements are constructed using nanotechnology processes, achieving elements with very good thermal performance.[25,33,35–37] Figure 5.3 shows the construction of one type of microbolometer detector, used in modern staring array detectors. The readout electronics is located underneath each detector element.

The metallic element bolometer has a positive temperature coefficient of resistance (resistance increases when temperature increases). The temperature coefficient of resistance α_B in [K^{-1}] is defined as

$$\alpha_B = \frac{1}{R_B}\frac{dR_B}{dT_s}, \tag{5.43}$$

where R_B is the bolometer resistance. The detector-element resistance is given by the parametric equation

$$R_B(T) = R_{B0}\left[1 + \alpha_B(T - T_0)\right], \tag{5.44}$$

where R_{B0} is the resistance at temperature T_0.