CHAPTER 9.4
PHOTOCONDUCTIVE AND SEMICONDUCTOR JUNCTION DETECTORS

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INTRODUCTION

Photoconductors and junction devices constitute an important class of solid-state photodetectors that can operate somewhere within the 0.2- to 2-μm spectral region. These detectors convert electromagnetic energy directly into electric energy via the photoconductivity effect that occurs in semiconductors.

PHOTOCONDUCTORS

Operation

The simplest photoconductor detector is a bar of relatively low conductivity *n*- or *p*-type semiconductor (in bulk or thin-film form) with ohmic contacts at its ends (Fig. 9.4.1). The photoconductor varies its electrical resistance in accordance with the light wavelength and intensity it receives. Its operation depends on the photoconductivity that occurs in semiconducting materials. Electrons in bound states in the valence band (intrinsic) or in forbidden-gap levels (extrinsic) absorb the energy of the incident photons and are excited into the free states in the conduction band, where they remain for a characteristic lifetime. Electric conduction may take place either by the electrons in the conduction band or by the positive holes vacated in the valence band. The electrical resistance of the material thus decreases on illumination, and this resistance change can be translated into a change in the current that flows through the output circuit.

Performance

The performance of photoconductor detectors is measured not only in terms of D^* but also in terms of photoconductivity gain, response time, dark current, spectral response, and temperature coefficient. For a photoconductor in which the conductivity is dominated by one carrier (either holes or electrons) the gain is given by the ratio of free-carrier lifetime to the transit time of this carrier. It can also be expressed as

$$\text{Gain} = \tau\mu V/L^2$$

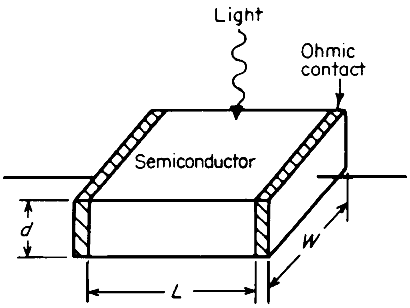

FIGURE 9.4.1 Diagram of a photoconductor detector.

where τ = free-carrier lifetime
μ = mobility
V = applied voltage
L = spacing between ohmic contacts, as shown in Fig. 9.4.1

The maximum D^* and spectral dependence of commercially available CdS and CdSe photodetectors are shown in Fig. 9.4.2. Table 9.4.1 lists typical gains, response times, and dark current.

Properties of Specific Photoconductors. The long-wavelength threshold for photoconductivity is usually determined by the bandgap of the material according to the relationship

$$\lambda_c = 1.24/Eg$$

where λ_c = threshold wavelength (μm) and Eg = bandgap (eV).

Bandgap values of materials commonly used as photodetectors in the 0.1- to 2-μm region are given in Table 9.4.2. The normalized spectral response of some of them is shown in Fig. 9.4.3.

SEMICONDUCTOR JUNCTION DETECTORS

Semiconductor junction detectors (photodiodes and phototransistors) differ from photoconductive detectors in that their operation depends essentially on a reverse-biased diode whose leakage current is varied by electron-hole pairs generated near or at the depletion region by light absorption. Their response time is characteristically short.

Basic Classes of Photodiode Detectors

Photodiodes fall into two general categories, the *depletion-layer type* and the *avalanche type*. The distinguishing feature between them is the existence of a gain mechanism.

The Depletion-Layer Photodiode. The depletion-layer photodiode family includes the *pn*-junction diode, the *pin* diode, the Schottky barrier (metal-semiconductor) diode, the point-contact diode, and the heterojunction diode.

1. *pn-junction diode*. Figure 9.4.4 is a diagram of a *pn*-junction diode. The junction is reverse-biased, and the diode is illuminated either at the *n* or *p* region, away from the depletion region (Fig. 9.4.4*a*), or right at the depletion region (Fig. 9.4.4*b*). Their built-in field enables them to be operated in the photovoltaic mode (i.e., no externally applied bias); however, the photoconductive mode, with a fairly large reverse bias, is usually the more common mode of operation.
2. *pin photodiode*. Figure 9.4.5 shows a cross-sectional diagram of a typical *pin* photodiode. The sensitivity range and frequency response of this type of diode depend principally on the thickness of the intrinsic layer (which defines the depletion layer). Light passes through the *p* region before it arrives at the depletion region, where it excites hole-electron pairs that are very quickly swept out by the large electric field present.
3. *Metal-semiconductor photodiode*. Figure 9.4.6 is a cross-sectional diagram of a metal-semiconductor (Schottky barrier) photodiode. In this case, light passes through a thin (~10 nm) metal film with a suitable antireflection coating to minimize large absorption and reflection losses. As with the *pn* and *pin* diodes, the photogenerated electron-hole pairs in the semiconductor give rise to an output-signal current.

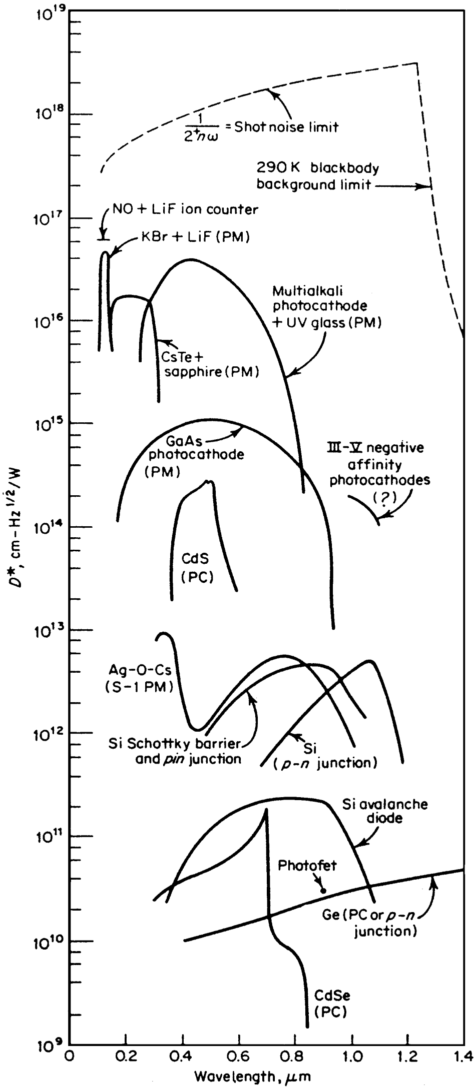

FIGURE 9.4.2 Detectivity vs. wavelength for various photoconductors. PC = photoconductive mode. PM = photomultiplier mode.

4. *Point-contact photodiode*. Figure 9.4.7 shows a diagram of a point-contact detector. Light is incident onto the Schottky barrier through an etched cavity in the semiconductor. This detector is extremely fast because of small dimensions and low capacitance.

5. *Heterojunction photodiode*. A depletion-layer photodiode can be constructed by forming a junction between two semiconductors of different bandgaps. Figure 9.4.8 shows a photodiode made up of n^- GaAs and p^- Ge. Light is absorbed almost completely in the low-bandgap material. Large dark currents could arise owing to spontaneous electron-hole generation in the depletion region from a large density of interface states. This could have deleterious effects on the signal-to-noise ratio at low light levels.

Avalanche Photodiodes. Depletion-layer photodiodes operated at higher-reverse-biased voltages give an increase in output signal. This is because of internal carrier multiplication via the avalanche effect. If the field in the depletion region can impart an energy equal to or greater than the bandgap energy to an electron, this electron can create another hole-electron pair by collision, and this pair can be accelerated to create an additional pair, and so on. This gives rise to carrier multiplication and to internal gain in the photodiode. The avalanche photodiode is therefore the counterpart of the photomultiplier tube, and its multiplication factor M is

$$M = K(1 - V/V_B)^{-1}$$

where K is a constant and V_B is the breakdown voltage.

Figure 9.4.9 shows two types of avalanche photodiodes with guard rings. The guard ring prevents a high-field breakdown region from reaching the surface.

Performance of Photodiodes. The spectral dependence of D^*, gain, speed of response, and dark current of the various photodiodes are shown in Table 9.4.1 and Fig. 9.4.2.

Phototransistors

A *pnp* or *npn* junction transistor can act as a photodetector, with the possibility of large internal gain. An *npn* structure, for example, is usually operated as a two-terminal device with the base floating and the collector positively biased.

Phototransistors are generally fabricated of Ge or Si in the same manner as conventional transistors, except that a lens or window is provided in the transistor to admit light at the base or base-collector junction. Response time of 10^{-8} and peak sensitivities of 30 A/lm are possible. Gains of several hundred have been attained with dark currents as low as nanoamperes.

TABLE 9.4.1 Parameters of Various Photoconductive Detectors

Photodetector	Gain	Response time, s	Dark current
Photoconductor	10^5	10^{-3}	1–10 mA
pn junction	1	10^{-11}	1–10 μA
Metal-semiconductor	1	10^{-11}	
Avalanche diode	10^4	10^{-10}	
Point contact	1	. . .	1–3 mA
Heterojunction photodiode	1	. . .	High
Phototransistor	10^2	10^{-8}	1 nA
Photofet	10^2	10^{-7}	1 μA

TABLE 9.4.2 Bandgap Values for Photoconductor Materials

Material	Threshold λ_c, μm	Bandgap, eV
CdS	0.52	2.4
CdSe	0.73	1.7
ZnS	0.33	3.7
ZnSe	0.48	2.6
GaAs	0.89	1.4
InP	1.03	1.2
Ge	1.77	0.7
Si	1.13	1.1

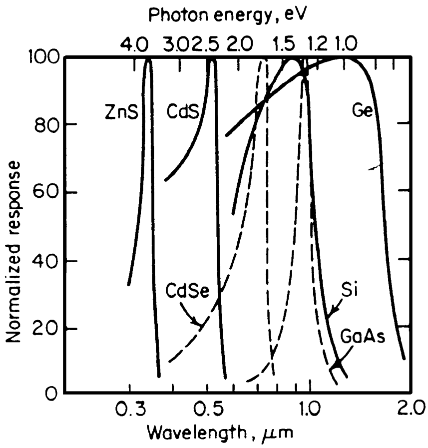

FIGURE 9.4.3 Normalized spectral response of some photoconductors.

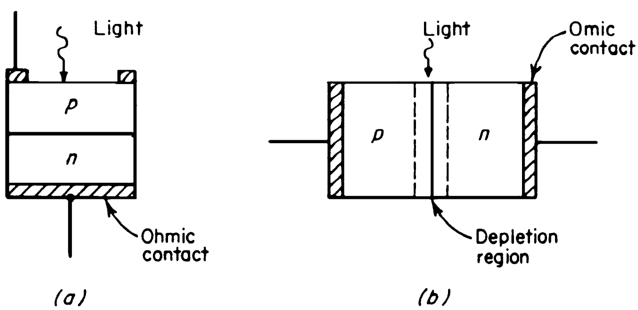

FIGURE 9.4.4 Diagram of a *pn* photodiode illuminated (*a*) away from the depletion region or (*b*) at the depletion region.

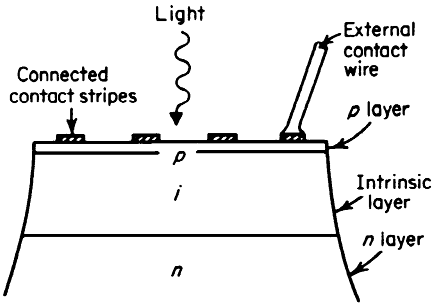

FIGURE 9.4.5 Cross section of a *pin* photodiode.

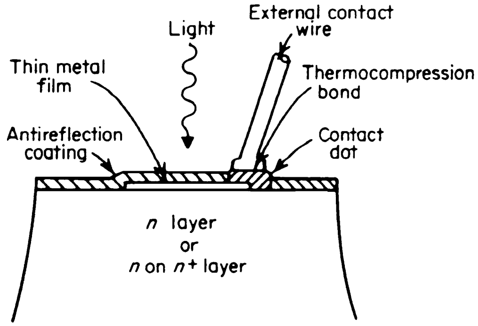

FIGURE 9.4.6 Cross section of a metal-semiconductor photodiode.

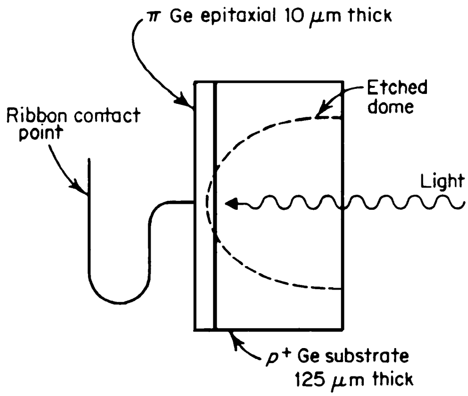

FIGURE 9.4.7 Diagram of a point-contact photodiode.

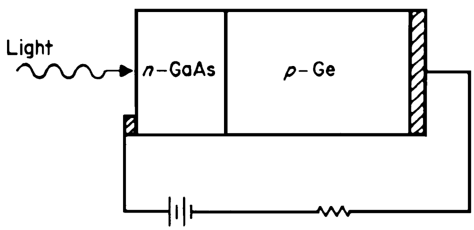

FIGURE 9.4.8 Diagram of a heterojunction photodiode with applied reverse bias.

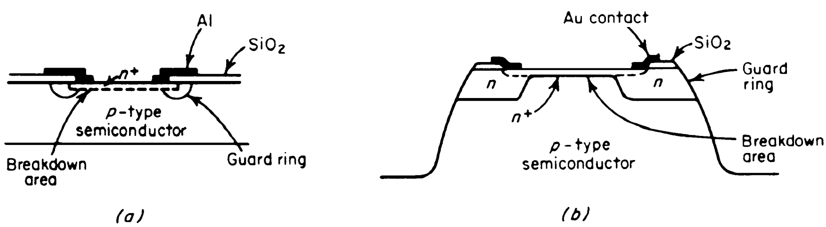

FIGURE 9.4.9 Cross section of avalanche photodiode with guard ring: (*a*) planar type; (*b*) mesa type.

Photofets, SMS Photodetectors, and *pnpn* Devices

The *photofet*, or *photosensitive field-effect transistor*, combines a photodiode and high-impedance amplifier in one device to achieve photodetection with large gain.

A *semiconductor-metal-semiconductor* (SMS) *device* is essentially a Schottky barrier device with gain.

A silicon controlled rectifier (SCR), or *pnpn device*, can be used as a photosensitive switch, with photogenerated current taking the place of the usual gate current.