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Lasers: Principles and Operations
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Laser Beam Management Detectors

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33 Laser Beam Management Detectors

Alexander O. Goushcha and Bernd Tabbert

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33.1 Introduction
Photodetectors are widely used in laser applications to monitor laser power, beam alignment and shape, laser pulse characteristics and other parameters of radiation generated by laser systems. The principles of the reliable detection of light, in any region of the spectrum, depend on careful consideration of a large number of factors. The importance of signal level, noise and signal-to-noise ratio cannot be underestimated, and these general considerations are discussed in detail elsewhere (see Chapter 9 of this Handbook), together with details of the operating principles of many generic detectors. Some specifics of managing and detection the short laser pulses are discussed in Chapters 18, 19, 21 and 36 of this handbook and the details on design and operation of detectors for laser energy and power measurements are presented in Chapters 21, 34, and 35 of the Handbook.

This chapter focuses on features of the photodetectors used for various beam management applications – position sensing, beam tracking, laser guiding, remote sensing, spot cross-section analysis, imaging and other applications. We will start with briefly discussing design specifics of photodetectors for position sensing and beam tracking. Then we will provide some useful insights into detection of short laser pulses, specifics of the detectors with intrinsic amplifications, detection of multi-colour optical beams and features for the UV and IR light detection. Lastly, we will continue with an overview on how to find the right customization and discuss the latest trends in the development of the next-generation photodetectors.

33.2 Position-sensitive Detectors
Large-area position-sensing detectors (PSDs) can detect and record the position of incident light beams. Many industrial manufacturers and laboratories use PSDs in their daily work. PSDs are able to characterize lasers and align optical systems during the manufacturing process. In conjunction with lasers they can be used for industrial alignment, calibration, analysis of machinery, articulated robotic beam delivery systems, quality control of lasers, pointing stability measurements and other various positioning and beam monitoring systems. They provide outstanding resolution, fast response, excellent...
linearity for a wide range of light intensities and simple operating circuits.

PSD is a photoelectric device that converts an incident light spot into continuous position data. PSDs come in two types: Lateral effect or resistive charge division sensors and Quadrant or the dual-axis detectors. The purpose of these two types is to sense the position of the beam centroid in the X-Y plane orthogonal to the optical axis.

The other type of photodetectors used for position sensing is multi-pixel arrays. Such arrays are used also for optical beam profiling, remote sensing and other imaging applications. In this section, we will discuss properties of the most widely used PSDs and multi-pixel arrays and concentrate primarily on the semiconductor devices.

### 33.2.1 Resistive Charge Division Sensors

The lateral effect semiconductor PSDs take advantage of the resistive division of charges generated by light in the bulk of the detector. They typically offer less positional sensitivity, but much greater dynamic range and faster response time than multi-pixel array detectors. Resistive charge division sensors can be designed as either photoconductive or photovoltaic devices. Considering the most widely used lateral effect PSDs based of a photodiode structure, the active sensing region in PSD is formed by a p-n junction. Electrodes may be arranged on both the anode and cathode of the photodiode so that the photodiode internal resistance forms a series resistance for current between the electrodes.

As an example, semiconductor resistive charge division sensor consists of a segment of photodetective semiconductor (moderately doped $p^+$-layer on the top of $n$-type substrate) with two terminals for signal output and a terminal for application of back-bias voltage – see Figure 33.1a. When the absorbed photons produce charge carriers (electrons and holes) in the semiconductor bulk, the charge carriers move to the appropriate electrode (anode or cathode). However, this means the carriers have to first pass through the resistive semiconductor layer. The photocurrent at each electrode is inversely proportional to the distance $x$ between that electrode and the centroid of the incoming light beam. Thus, the location of the beam centroid can be accurately determined by using the ratio of the signals from the different electrodes.

Position information using such devices is derived by comparing the signal outputs from each terminal. For example, for a four-terminal, two-dimensional PSD shown schematically in Figure 33.1b, the position may be calculated from:

$$
\begin{align*}
    x &= \frac{D_x}{2} \left( \frac{I_B - I_A}{I_B + I_A} \right) \\
    y &= \frac{D_y}{2} \left( \frac{I_C - I_A}{I_C + I_A} \right)
\end{align*}
$$

where $I_A$, $I_B$, $I_C$ and $I_D$ denote photocurrents collected by the respective electrodes and $D_x$, $D_y$ is the active area size in $x$ and $y$ dimensions, respectively.

Position sensors of this type have several advantages over, e.g. quadrant detectors or multi-pixel arrays. Because there are no gaps in the active area, the size of the image is not subject to constraints on a minimum diameter. A second advantage is that position information is available as long as the image falls somewhere on the detector’s active area. Among the disadvantages is that frequency response of such detectors tends to be lower than for a conventional semiconductor detector of the same size, because of the series resistance that the photocurrent encounters at the detector surface. The other drawback is the pincushion distortion effect that causes non-linearity in the location determined using equation 33.1 versus the actual centroid of the impinging light beam. Such pincushion distortion occurs due to non-uniformity of the electric field distribution across the active area of the device.

### 33.2.2 Strip Detector and Quadrant Detector

Another way to measure position of the laser beam is obtained by dividing the large-area photodiode into many small, strip-like regions and to read them out separately – see Figure 33.2. The measurement precision depends mainly on the strip spacing and the readout method.
A quadrant photodiode is a variation of a strip detector, the segments of which are the four quadrants that have separate connectors for a signal output. Each quadrant functions and behaves as a regular pin or avalanche photodiode (APD). Quadrant photodiodes are widely used in the tracking systems. Position information is derived from the relative signal output from each segment. When the focused image is centered on the quadrant detector, each segment will receive the same amount of optical radiation, and all four signal outputs will be equal (Figure 33.3, right). As the image moves on the detector surface (corresponding to an angular change of the object being tracked or imaged), more radiation falls on one of the segments and less on the opposite segment (Figure 33.3, centre and left).

The up-down position of the spot is characterized with the relative amplitudes of \((I_A + I_B) - (I_C + I_D)\). Similarly, the term \((I_A + I_B) - (I_C + I_D)\) gives information about the left-right position:

\[
x = \frac{(I_A + I_B) - (I_C + I_D)}{I_A + I_B + I_C + I_D} \quad \text{and} \quad y = \frac{(I_A + I_B) - (I_C + I_D)}{I_A + I_B + I_C + I_D}
\]

(33.2)

Among the important factors that must be considered when designing a position sensing system based on a quadrant or other type of multi-element detector is the relationship between the diameter of the light spot and the dimensions of the detector. If the light spot is smaller than the spaces between the detector elements, then there will be a dead zone where beam tracking will be lost completely. This can be an issue in defraction-limited applications such as data storage. Conversely, the light spot must be smaller than the overall detector dimensions or the signal will be truncated by the edges of the detector, resulting in erroneous position feedback.

The relationship between spot size and detector dimensions is often determined by the trade-off between spatial resolution and range. Tracking range increases with spot size, because once the spot is entirely located within one quadrant, further tracking is impossible. However, positional resolution is inversely proportional to the spot size. This is because a given displacement of a small spot produces a much bigger differential signal than the same movement in a larger spot.

In most tracking and alignment applications, a major parameter of concern is the ability of the detector to supply a precise description of the location of the focused image on the face of the detector. In other words, the change in output signal in relation to a change in the position of the spot is imperative. “Sensitivity” is used in this case to describe the ratio

\[
\text{Sensitivity} = \frac{\text{Change in output signal}}{\text{Change in position}}
\]

(33.3)

### 33.3 Multi-pixel Arrays

Multi-pixel arrays have a virtual monopoly in the fields of light detection and ranging (LIDAR), 3D laser radars (LADAR), laser vibrometers, medical imaging, etc. Among the types of arrays used in different applications are 2D pin photodiode and APD arrays. What makes pin and APD arrays unique is their ability to provide a fast access to any single pixel of the array, high dynamic range, high-frequency bandwidth (up to 1 GHz and even more) and possibility to provide a high-speed parallel read-out regime.

#### 33.3.1 Photodiode Arrays

State-of-the-art pin photodiode arrays with high quantum efficiency in virtually the whole visible and near-infrared (NIR) spectral range were designed using both the front-illumination and back-lit configurations (Holland et al. 1997). In the front-illumination configuration, the light sensitive area of each pixel of the array is formed on the light impinging side of the semiconductor chip, and the electrical connections to each pixel are made on the same side of the chip. Despite the obvious advantage of ease of manufacturing, such arrays have a significant drawback – the requirement to trace signal from each pixel to the edge of the chip to connect to a downstream electronics, which consumes significant portion of the front surface of the chip.

Back-illuminated pin photodiode arrays allowed to overcome this problem. Such arrays feature the bonding pads located on the side of the chip that is opposite to the light entrance side (Figure 33.4), allowing creating arrays with virtually any number of pixels without “dead” spaces between the adjacent pixels. However, for high-resolution applications, the approach with separated pixels each requiring dedicated signal line proved to be not very promising. Instead, different
types of arrays based on charge transfer devices were developed and we will discuss them next.

### 33.3.2 Charge-coupled Devices as Tracking/Image Sensors

Charge-coupled device (CCD) is an array of metal-oxide-semiconductor (MOS) capacitors placed close together. A simplified structure and band diagram of the ideal \( p \)-type MOS capacitor in thermal equilibrium and at the so-called flat-band (FB) conditions is given in Figure 33.5a and b. Under this condition, the semiconductor band bending is absent (the electric field strength throughout the semiconductor is zero and potential level shift \( \Psi_s \) at the oxide-semiconductor interface is zero) and the applied to the gate electrode voltage \( V_G = V_{FB} = \phi_m - \phi_i \) corresponds to the difference in the metal (\( \phi_m \)) and semiconductor (\( \phi_i \)) work functions.

Applying a bias to the semi-transparent gate electrode \( V_G \neq V_{FB} \) allows shifting the potential level \( \Psi_S \) of the oxide-semiconductor interface, which drives the MOS capacitor into different regimes. There can be three distinctly different modes of operation dependently on the gate voltage polarity and amplitude: accumulation \( (\Psi_s < 0, \) Figure 33.5c), depletion \( (0 < \Psi_s < \Psi_B, \) Figure 33.5d) and inversion \( (\Psi_s > \Psi_B, \) Figure 33.5e). The Fermi level \( E_F \) remains flat at any regime of operation because of zero current flow. It means that in either depletion or inversion mode, the potential well is created in the semiconductor next to the oxide interface, facilitating non-equilibrium minority carriers’ collection close to the interface (Sze 1981).

Under illumination, the photo-generated minority carriers (electrons for the \( p \)-type semiconductor) tend to collect in the potential well \( \Psi_s \) close to the semiconductor-oxide interface. If the second MOS capacitor is placed next to the illuminated cell on the same semiconductor chip, then the carriers accumulated in the potential well \( \Psi_s \) of the illuminated cell will have the opportunity to leak to the potential well \( \Psi_s \) of the second, neighbour cell if the potential well \( \Psi_s \) is deeper than \( \Psi_s \). If a one-dimensional array of MOS capacitors is placed on a single semiconductor chip, the accumulated photo-generated carriers in the wells can be sequentially transferred from one cell to the other. Applying the proper sequence of gate voltages allows transferring minority carriers across the array, thereby delivering electrical signal proportional to the amount of photons absorbed by each pixel to the output register. The simplified description given above illustrates the basic idea behind the functioning of MOS capacitor-based imaging sensors with charge transfer. The detailed description of the design, structure, and operation of CCD is available in a large number of publications (Janesick 2001, Magnan 2003, Sze 1981). Contemporary cooled CCD can show the photon-limited performance and operate in a single-photon counting mode.

### 33.3.3 Complementary Metal Oxide Semiconductor Detectors

Many of the newer imaging devices use a different chip, one known as a complementary metal oxide semiconductor (CMOS) chip. In a CMOS sensor, each pixel has its own charge-to-voltage conversion, includes MOS transistors providing buffering and addressing capability and may also include the digitizing circuit. The price the designers pay for these additional functions is a reduced area available for the front-side light collection.

Similar to CCD, CMOS detector also performs four-step process: charge generation, charge collection, charge transfer and charge measurement. However, unlike CCD, the first three steps in CMOS sensor are performed within each individual pixel.

To convert two-dimensional spatial information into the serial stream of electrical signals, electronic scan circuits of CMOS photodetector read out each pixel sequentially. First, the vertical scan circuit selects a row of pixels by setting a high DC voltage on all gates of the MOS switches for that row. Next, the horizontal scan circuit selects the pixels in one particular column using the same technique. As a result, only one pixel in the two-dimensional matrix has a high DC voltage on both the row and the column switch, which electronically selects it for read-out. After the pixel dumps its information

---

**FIGURE 33.5** Cross section of a MOS capacitor (a) and simplified energy-band diagram of the ideal MOS capacitor at the gate bias \( V_G = V_{FB} \). (b) Right panels show schematically band diagrams for the accumulation (c), depletion (d) and inversion (e) modes.
Various types; the scattering reflector (Chen and Chou 1997) and distributed Bragg reflector (Emsley et al. 2002) are common examples.

For indirect-band gap semiconductors, it is difficult to achieve both high bandwidth and high efficiency with a vertical design since the length of the absorption region is proportional to the carrier transit time. Decoupling of the absorption length from the motion of non-equilibrium carriers is another efficient method to improve the speed and quantum efficiency of Si- and Ge-based photodiodes. Such decoupling is achieved in the lateral surface pin photodiodes on silicon-on-insulator (SOI) substrates, which exploits the idea of a grating coupler on top of the photodiode (Csutak et al. 2002). The coupler promotes the optical beam propagation in a thin, waveguide-type surface layer of Si – see Figure 33.7.

In top-illuminated, direct-band gap semiconductor photodiodes, a reduction of the carriers’ transit time is limited by the surface recombination processes, which decreases the responsivity. The side-illuminated photodiodes, in which the absorption length is decoupled from the carriers’ transit time, overcome the efficiency-bandwidth trade-off of top-illuminated photodiodes (Wake et al. 1991). However, they are not able to operate at high optical power levels, since carrier generation occurs in a very small volume at the diode input facet.

One of the solutions to that challenge is to design evanescently coupled photodiodes monolithically integrated with a waveguide (Takeuchi et al. 2000). The evanescent coupling optimizes the distribution of non-equilibrium carriers along the absorption layer. Due to more uniform light absorption, devices that utilize evanescent coupling can achieve several times higher saturation current than a traditional side-illuminated device. An example of evanescently coupled photodiode is shown schematically in Figure 33.8. The structure is usually based on a classical pin photodiode with a very thin (<0.5 μm) undoped InGaAs absorbing layer of 20–30 μm length and a p+-doped InP layer on the top. The light is delivered from the side and propagates along the undoped diluted waveguide layer, which is a stack of several InP/InGaAsP sandwiches. The bandgaps and the thickness of n+-doped InGaAsP optical matching layers are chosen in a way that they provide a gradual increase of the refractive index from the diluted waveguide towards the thin absorbing layer. As a result of the evanescent wave coupling, the optical wave when propagating along the waveguide is gradually transferred through the optical matching layers to the absorbing layer. The quantum efficiency can be achieved higher than 95% with the bandwidth of over 50 GHz, which should be beneficial for many applications.

FIGURE 33.7 A schematic example of a pin photodiode with the waveguide-grating coupler.
33.5 Photodetectors with the Intrinsic Amplification

To improve the sensitivity, spatial and temporal resolution of optical signal detection, it is advantageous to use photodetectors with intrinsic amplification. There are a few types of photodetectors that are usually considered within this family – phototransistors, APDs, multi-channel plates (MCP), and PMTs are the most common examples. Concerning laser light management and detection, APDs are the prime choice in a vast majority of applications due to their superior performance, quality, form-factor and cost effectiveness. The basic properties of APDs were discussed in Chapter 9 (see also Dereniak and Boreman 1996, Sze 1981). Below we analyse some properties and design consideration important for laser applications.

The choice of APD for each specific application is determined primarily by the spectral range of interest, required frequency bandwidth and acceptable level of noise. Dependent on the required spectral range, the APD design relies on a number of different semiconductor materials available to this technology. The following materials have proved to be appropriate to fabricate high-performance APDs:

- **Silicon.** The spectral range from 400 to 1100 nm. The most commonly used design takes advantage of the reach-through structure, in which the depletion width propagates through the whole thickness of the device.
- **Germanium.** For the wavelengths of up to 1.65 μm. However, since the bandgap in Ge is lower than in Si, the noise is considerably higher and limits the Ge-based APDs application.
- **GaAs-based devices.** The designers usually use the heterostructures like GaAs/Al_{0.45}Ga_{0.55}As, and the large increase in gain occurs due to the avalanche effect in GaAs layers. GaAs/Al_{0.45}Ga_{0.55}As structures are used below 0.9 μm. Applying InGaAs layers allows to extend the sensitivity range to ~1.4 μm.
- **InP-based devices.** For the wavelengths range 1.2–1.6 μm. The example is the double heterostructure with lattice matched layers $n^+-\text{InP}/n^-\text{GaInAsP/p^-}\text{GaInAsP/p^+}\text{InP}$, in which either of carriers may create an avalanche. The other example is APD with separated absorption and multiplication regions $p^+\text{InP}/n^-\text{InP}/n^-\text{InGaAsP/n^+}\text{InP}$, which is similar to the Si reach through devices. The absorption occurs in the relatively wide InGaAsP layers, and avalanche multiplication of the minority carriers proceeds in the $n^-\text{InP}$ layer.

For the beam tracking, positioning and some other applications requiring ultra-low light-intensity detection with a relatively high-frequency bandwidth, the APDs operating in a single-photon counting mode (Geiger mode) promise undisputable advantages (see Chapter 9 for description of the Geiger mode of APD operation). A relatively novel type of avalanche photodetector with Geiger mode operation, known as silicon photomultiplier (SiPM) or multi-pixel photon counter, was developed by several groups, see, e.g. Buzhan et al. (2003). SiPM is an array of microcell APDs operating in the Geiger mode. A typical SiPM may contain several hundreds to thousands of microcells coupled to a common signal output terminal. The size of each microcell is usually ten to hundred square microns. The number of microcells defines the photon-counting dynamic range of SiPM. In each microcell, an arriving photon can trigger an avalanche flow of carriers, leaving the surrounding cells untriggered and ready to record other arriving photons. The output signal of the SiPM is the analogue sum of all individual cell signals. As long as the number of instantaneously impinging photons is less than approximately half the total number of microcells, it can be assumed that a given microcell will be hit by one photon at a time only. Under this condition, the sensor output will depend linearly on the input light flux.

The typical gain of a SiPM is $> 10^6$, providing a signal of a few nanovolts over a 50 Ω load resistor for a single photodiode. The electronic noise of SiPMs is negligibly small due to the very high gain, in contrast to standard APDs, where the gain is typically about 100. The main source of noise, which limits the SiPM’s single photon resolution, is the dark rate, originating from charge carriers thermally created in the sensitive volume.

The overall conversion factor from impinging photons to the number of detectable photocarriers is called photon detection efficiency (PDE). PDE is normally lower than quantum efficiency (QE) $\eta$. The maximum achievable PDE of a SiPM is the product of the following factors: the geometrical efficiency $\varepsilon_{\text{geom}}$ (which is the fraction of total SiPM area occupied by active pixels); the Geiger efficiency (usually close to 100%); wavelength-dependent transport of impinging photons into the sensitive volume of the SiPM; and the intrinsic quantum efficiency $\eta$ of Si. Typical SiPMs can achieve a peak PDE of 50% to 60% in both the yellow-to-green and the blue-to-near-UV ranges.

33.6 Colour-sensitive Detectors

The conventional way for detecting optical beams with multiple wavelengths relies on the idea that the light of different wavelengths can be detected separately. The variety of
Laser Beam Management Detectors

methods exploits two main principles: one uses colour overlay filters on top of the photodetectors active area and the other selects colours using the inherent property of the semiconductor to absorb light of different wavelength on a different depth. In the first type of colour sensors, colour detection is performed by using different bandpass filters, and a corresponding number of individual photodetectors fabricated on the same substrate. The filters allow transmission of one of the selected wavelengths, and the corresponding photodiode measures the intensity of the incident light at that wavelength. A drawback to such methods is that the use of several sensors with their corresponding filters can become complicated and take up excessive space when forming a colour-sensing array.

Another type of multiple wavelength sensors employs more than one sensor in a vertically oriented arrangement. The operation of these devices is based on the intrinsic filtering property of semiconductors that results from the variation of absorption coefficient with the wavelength of light. For example, the blue, green and red photodiode sensors may be formed by the corresponding p/n junctions arranged one below the other underneath the Si sensor surface. The detector layers are individually connected to pixel sensor read-out circuits.

In an alternative design, for the detection of multi-wavelength optical beam the stack of two or more photodetectors may be applied (Figure 33.9). The top-level detector absorbs light in the shorter wavelength spectral range, and the bottom-level detector absorbs light of the longer wavelengths. In particular, the top-level detector may be a thin-layer Si photodiode absorbing primarily within the spectral range below ~950 nm, whereas the bottom detector may be an InGaAs photodiode to detect light in the spectral range above ~900 nm. The advantage of this type of structures is a possibility to tune independently the performance of each channel.

33.7 Detectors for the UV Spectral Range

Detection in the ultraviolet relies on the high energy of the individual photons. The photoelectric effect and the photomultiplier tube (PMT) detectors are still used for this application. The photocathode needs to be appropriate to the region of the spectrum of interest, such that the energy of the photon is greater that the work function of the material forming the cathode. Typical spectral responses of photocathode materials are given in Chapter 9. Care must also be taken to design appropriately the window of PMT due to the high absorption coefficient of many materials in the UV.

Solid-state semiconductor detectors for the UV rely on the same internal process as visible and NIR detectors and, generally, offer a higher quantum efficiency than photoemissive devices (though do not necessarily offer the overall sensitivity of PMT). UV photons have high energies, a wavelength of 200 nm corresponds to a photon energy of ~7.25 eV. This energy implies that any of the solid-state detectors used in the visible or near-infrared can also be used for the UV. However, because of a high value of the absorption coefficient for these materials in the UV, light is absorbed very close to the surface. In addition, the thin passivation layer that is produced on the surface often has high absorption in the UV, and moreover, extended exposure to UV may produce radiation defects degrading the detector’s performance. These drawbacks have to be addressed in designing UV-sensitive semiconductor detectors (Razeghi and Rogalski 1996).

Among the most popular materials and solutions used for UV detectors are as follows:

- Silicon carbide (SiC) with the peak responsivity at around 280 nm and reasonably good sensitivity within the range from ~220 to 380 nm. Both photocathode and photovoltaic structures have been developed with SiC.
- Gallium phosphide that is often used for the blue/green light detection. Its sensitivity also extends into the UV down to ~200 nm.
- The nitride III–V semiconductor materials also have large bandgaps suggesting suitability for application in the UV. Gallium nitride is the most developed and is used in the 240–380 nm spectral range. Other III–V nitrides have been studied in detail, for example, aluminium nitride (AlN) with a bandgap of 6.2 eV at 300 K and AlGaN that allows tailoring the peak responsivity by adjusting the content of Al and Ga (Moustakas and Paiella 2017).
- Semiconductor diamond as a UV detector is attractive as it has the largest bandgap and has good UV optical properties. In addition, it has high thermal conductivity and a small dielectric constant, bringing together properties that are ideal for UV optical detectors. However, getting high-quality devices did not allow good production yield.
- Schottky (metal-semiconductor) barrier devices can be used as photovoltaic detectors for many discussed above materials. The Schottky barrier creates a depletion layer between the metal contacting the semiconductor and the semiconductor material (see also chapter 9 and Dereniak and Boreman 1996, Sze 1981). Thus, the sensitive region of the device is brought very close to the surface, allowing secure absorption and photoelectric conversion of high-energy photons. The drawback of the Schottky barrier photodetectors is a high noise level.

33.8 Detectors for the IR Spectral Range

IR detectors cover the wavelength from approximately 1 to 14 µm. The radiation up to the lower end of this range can be satisfactorily detected by standard Si, Ge and InGaAs
33.9 Common Customizations

Some laser applications may need a photo detector that is optimized regarding one or more features. Solid-state photodetectors based on semiconductors allow significant level of customization. Since wafer fabrication processes are mostly independent of the features of the design layout, it may be advantageous to use a custom design for each particular application.

33.9.1 Active Area Sizes, Shapes and Apertures

Aside from the choice of a semiconductor material, the active area size and shape are among the most important design features of a photodetector. Larger detector areas collect more light but also exhibit higher dark noise and capacitance. For low-noise and high-speed applications, the designs with small sensitive active areas are commonly used. For silicon photodiodes, active areas can range from a fraction of to tens of square millimetres. Devices made of other materials are typically limited to smaller designs. InGaAs detectors, for instance, rarely exceed about 25 mm² due to defects in the base material that cause low yield for large photodiodes. SiC or GaN are typically limited to about a millimetre diameter of active area also because of the crystalline defects and wafer uniformity issues.

For many photoconductive applications, the designs capable of high-performance operation at high-voltage bias conditions are important. Since the probability of voltage breakdown and highly increased dark current is much higher around the sharp corners of the p/n junction, the circular shaped active areas are preferable for the photoconductive operations at high reverse bias.

The active area size of semiconductor detectors is one of the determining factors of the device capacitance. Therefore, to achieve a fast response time, the active area size has to be minimized. For example, to design Si photodetector with below 1-ns response time, the active area size should be smaller than 0.5 mm in diameter.

For some applications, it is imperative to ensure that there is no signal detected if light is falling on regions of the photodetector outside its active area. For the semiconductor photodetectors, all metal-covered surfaces provide protection against non-useful light sensitivity. But semiconductor chip surfaces covered with metal often produce the unwanted light reflection. Therefore, other materials like black polyimide or a stack of Chromium with Chrome oxide (Cr/CrOx) may be used to create apertures on the chip. Such coatings may provide both, less than 5% reflectance and better than OD3 transmittance blocking within the required spectral range.

33.9.2 Coatings and Filters

Semiconductor photodetectors often use a protective passivation layer (typically a thin layer of silicon oxide or silicon nitride or their combination) which also serves as anti-reflection coating. This layer can reduce the front surface reflection of the active area down to less than 1% but only for a part of the spectrum that is narrow compared with the spectral range of most common semiconductor materials. More sophisticated multilayer coatings can be applied allowing coarse wavelength selection for simple applications like low-cost RGB sensors.
For better spectral filtering, dielectrically coated glass sheets can be attached to the active area of a detector or be installed as part of a package window assembly.

### 33.10 Photodetector Integration

Photodetectors for specific applications do not work alone. In most of the cases, they are coupled to signal measuring and processing electronics or even integrated with other optoelectronic and/or electronic devices to provide useful input for a higher-level processing systems. This section describes some important properties and features of semiconductor photodetectors’ assembly and integration.

#### 33.10.1 Packaging

Regardless of the type of package of a detector assembly, the active area has to be aligned to other optical components in the system for most applications. Within the semiconductor surface, the alignment tolerance is typically better than 5 µm. The semiconductor chip then is placed onto a substrate, either a printed or flex circuit board, a ceramic, a metal header, a lead frame or another semiconductor chip. The tolerance for this placement depends on the tooling used during the attachment process. Manual placement will result in tolerance between ±75 and ±150µm depending on materials and operator skill. With contemporary die placement, equipment tolerances better than 10 um can be achieved under high-volume production conditions.

Optoelectronic packages can be divided in hermetic and non-hermetic types. Over the years many different solutions have been developed. Below, we will outline the basic types only.

Hermetic packages have typically a cavity that contains the photodetector chip and, in many cases, other active and passive components. The cavity is sealed by a lid or cap that has to provide optical access to the active area. True hermeticity in the interpretation of aerospace standards is achieved if all interfaces are either soldered, brazed, welded or consist of a glass or ceramic to metal seal. One of the still popular package types is “transistor outline” packages or the TO-cans. These cans consist of a cap and a header made of a nickel–cobalt ferrous alloy (Kovar) or steel with a sealed borosilicate, quartz or sapphire window. Since no epoxy is involved in the sealing process, these packages generally exhibit the best hermeticity and lowest leak rates. Moreover, if all materials are chosen carefully, these packages can withstand temperatures in excess of 200°C and other stress conditions like shock, vibration and temperature cycling. However, the storage and operating temperature of such devices may be limited to lower values due to the use of epoxies and low-temperature solders for the attachment of components inside the package. Figure 33.10 shows typical configurations for simple devices assembled in TO-type packages.

Epoxy seals, over-moulded components or plastic encapsulated microcircuits are generally not considered hermetic. The materials and processes commonly used to assemble such components can be ruggedized to some extent as, for instance, for the use in many modern automotive parts. Examples of photodetectors in non-hermetic packages are shown in Figure 33.11.

#### 33.10.2 Hybrids and Detectors for Fibre-coupled Lasers

Many applications require bringing the initial signal processing circuitry as close as possible to the output terminals of the photodiode chip. This not only allows more compact packaging of the overall assembly but may improve the noise and frequency bandwidth of the assembled photodetector. The simplest version of a hybrid is a photodiode chip with

![FIGURE 33.10 Examples of semiconductor photodiodes assembled in hermetically sealed TO packages: (a) two-leads package with a flat window, (b) three-leads package with isolated photodiode and a light focusing lens, (c) photodiode with the attached filter and a window cap with a filter, (d) sealed simple TO package and (e) quadrant detector in a large TO can.](image)

![FIGURE 33.11 1D photodiode arrays assembled in non-hermetic packages: (a) array on single chip assembled on a substrate; (b) array of individual chips placed on a substrate.](image)
the transimpedance amplifier (TIA) assembled in either TO or surface mount package. The purpose of a transimpedance circuit is to convert the input current from a photodiode into an output voltage $V_{out}$ that can be approximated as $V_{out} = I_{ph}R_f$, where $I_{ph}$ and $R_f$ are the photodiode photocurrent and feed-back resistance of TIA, respectively (see Figure 33.12 for an example electrical schematics). The TIA gain $R_f$ and the 3dB cut-off frequency $f_{3dB}$ are defined as:

$$
R_f = \frac{V_{out}}{I_{ph}} \quad \text{and} \quad f_{3dB} = \frac{\text{GBP}}{2\pi R_f C_{total}} \quad (33.4)
$$

where GBP is the Gain-Bandwidth-Product of the operational amplifier and $C_{total}$ is the total capacitance of the circuit, equal to the sum of the photodiode capacitance and input capacitance of the operational amplifier and feedback capacitance $C_f$. Obviously, increasing TIA gain $R_f$ causes a decrease in the cut-off frequency value $f_{3dB}$. Therefore, selection of operational amplifier and photodiode chip is critical to provide a desired photodetector performance.

To improve frequency bandwidth and still ensure high gain of the photodetector, the hybrid may include two or more amplification stages. The first stage may TIA with a relatively low feedback resistance that ensures high-frequency bandwidth of the first stage. The second amplification stage may be a simple voltage amplifier also having a relatively low feedback resistance. The resulting frequency bandwidth of such hybrid will be rather high and determined by the 3dB cut-off frequency of the first amplification stage, whereas the total gain determined by the product of gains of the two stages will also be high.

Multi-element photodetector arrays can also be packaged in hybrids with TIA or even higher level processing components. It is common to add comparators, analogue-digital converters and even ASIC (application-specific integrated circuit) chips in the same package with a primary photodetector to save space and improve performance parameters. However, with increased functionality of a hybrid other considerations like heat dissipation have also to be taken into account.

In applications that require detection of optical signals delivered via fibres, a special type of hybrid assemblies called optical receivers is usually used. An example of the receiver assembled in a ceramic package is shown schematically in Figure 33.13. A single-mode optical fibre with the core diameter of $\approx 10\ \mu m$ and cladding diameter of several hundreds of micrometres is fed through the input port of the package. The core of the fibre is brought close to the photodiode ($\approx 50\ \mu m$ or less) and aligned with its centre to obtain maximum photocurrent from the photodiode. The package may contain TIA and other components to bring the output signal to a required level.

### 33.11 Future Directions in Detectors

**Technology and Applications**

Recent advances in optoelectronics and photonics challenged researchers developing optical detectors with improved performance and facilitated application of new materials and principles in their design. Significant efforts were employed in the field of short-wavelength IR (SWIR, approximately 0.8–3 $\mu m$), MWIR (3–8 $\mu m$) and long-wavelength IR (LWIR, 8–14 $\mu m$) detectors (see Tan and Mohseni 2018 for the most recent review). Impressive advances were reached with the structures employing quantum wells, quantum dots (QD) and nanowires. Among new emerging photodetectors, graphene-based and other 2D structures with carrier multiplication and devices utilizing photonic crystals (PC) to couple incoming light to the absorbing medium were developed. We will discuss some representative examples in this sections.

PCs are periodically arranged structures with the periodicity scale proportional to the wavelength of light. In analogue to the periodically arranged atomic structures forming crystalline atomic lattice with electronic energy zones and bandgaps, the structure of PC is characterized with a forbidden bandgap (also known as a photonic stopband, PSB) where light cannot propagate or escape from it. If light with the wavelength within the range of PSB enters PC, it will experience multiple Bragg’s reflection, which creates an effect of light retardation inside PC and may eventually stop light against further propagation through PC. Incorporating nanocrystals or other nanoscale materials within the pores of PC or optically coupling such nanoscale materials with PC in an appropriate alternative way allows enhancing interaction of light with those embedded materials due to multiple light-scattering effects in PC.
creating thereby favourable pre-requisites for an efficient wavelength-selective photo detection.

The effect of PC cavity enhancement of absorption was used to tune the graphene photodetector’s responsivity by coupling of the graphene sheet to a planar PC prepared using SOI wafer with 450nm pitch-etched cavities. As is known, graphene as an atomic layer material is characterized by rather low absorbance. However, integrating graphene with PC boosts graphene’s absorption allowing to achieve high responsivity at ~1550nm (Shiue et al. 2013). A comprehensive review on optoelectronics in silicon-based PC (including photodetectors) for MWIR is given in the most recent article (Lin et al. 2018).

A promising solution for SWIR and MWIR detectors was proposed recently based on the hybrid structures of graphene integrated with QD layers (Koppens et al. 2014). The design of such photodetectors is based on a multilayer structure, in which the top layers may perform a wavelength selection role. After passing these top layers, the MWIR optical beam enters the layer with QD in which light absorption and initial charge separation occur. The carriers of one polarity (electrons) are trapped by QD, whereas the other polarity carriers (holes) are transferred to the bottom graphene layer. This causes electrostatic perturbation of the graphene conductance and leads to a photo-gating effect changing the graphene resistance through capacitive coupling and allowing charge carriers in graphene to recirculate many times due to extremely high carrier’s mobility in the graphene while the other polarity carriers remain trapped by QD. This structure is in fact the analogue of an efficient phototransistor with high photodiode gain produced due to charge trapping in the QD layer. The devices of such type promise very high value of specific detectivity $D_\text{s}$ of over $10^{14}$ cm$^2$/Hz$^{1/2}$/W. In addition, selecting of QD material and size allows fine-tuning the spectral sensitivity range from slightly above 1μm for QD made of PbS to virtually any wavelength within the interval from 2 to above 6μm for lead salts PbSe,Te$_x$, with varied values of $x$.

REFERENCES


FURTHER READING


