Spectrum Selective Narrowband Optical Detectors*

Saravanan Rajamani and Mahesh Kumar

Optical detection is the basic underlying principle of many optoelectronic systems like image sensors, optical communications, biomedical imaging, motion detection, surveillance, machine vision, etc. Applied research in optoelectronics has invested a lot towards the development of photodetectors with a wide spectral response (UV, visual and IR), as well as narrowband spectrum selective photodetectors for special applications. Spectral discrimination is required for colour-selective detection, but current commercial systems use broadband photodetectors combined with optical filters. This approach increases the complexity of the system and degrades the quality of colour detection. In this article, we explain briefly the basics of photodetectors and a method for tuning the spectral response to achieve filter-free, narrowband photodiodes.

Introduction

Photodetectors are the central component of optoelectronic platforms such as imaging, communications, remote sensing, and biological sensing. Depending on the applications, the photodetectors may be classified as a broad or narrow band determined by the response window of the photosensitive material. Broadband detectors, such as visible imaging systems (400–700 nm), are implemented in applications such as surveillance, machine vision, industrial inspection, and spectroscopy. Other examples of broadband detectors are ultraviolet (UV) detectors and infrared (IR) detectors, which find applications in astrophysics, food and pharmaceutical industries, and phototherapy. Narrowband photodetectors, on the other hand, respond to a particularly narrow

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1Nanometer-sized semiconductor particles that confine the motion of conduction band electrons and valence band holes in all three spatial directions.

2The distance between the valence band and the conduction band, where electrons cannot exist.

3Mainly deals with energy of confined electrons, which have discrete energy levels.

Spectrum of light (with a small response window of wavelength). They are desired in special applications such as missile detection, ozone damage monitoring, and night vision systems, where the visible light response needs to be excluded. Broadband imaging is largely facilitated by GaAs, Si, InGaAs in UV, visible and IR spectrum. Narrowband detection in commercial photodetectors is currently realized using broadband semiconductor photodiodes in combination with spectrum selective optical filters or a dichroic prism. However, this approach increases the system complexity, cost and decreases image sharpness. A filter-free narrowband light detection scheme is a viable solution to avoid such complexities. Several filter-free spectrum selective photodetectors are emerging, employing alternative strategies such as narrowband absorbers in the active area, organic/hybrid structures and manipulating charge collection lengths with thick absorbing layers. A promising approach to narrowband detection is using quantum dots (QDs) taking advantage of their tunable bandgap and quantum confinement. The bandgap of the semiconductor materials in the nanometer range depends on the size of the nanomaterials. At low dimensions, due to the quantum confinement of the charge carriers, the edge of the valence and conduction bands split into discrete energy levels similar to atomic energy levels. The energy difference between the discrete levels depends on the size of the quantum dots. The bandgap increases with reducing the size of the QDs. The bandgap can be tuned in a certain range by changing the dimension of the materials. Using this phenomenon, a filter-free narrowband photodetector can be developed.

**Photodetector Fundamentals**

When a semiconductor with bandgap \( E_g \) is illuminated by an optical beam of wavelength \( \lambda \), if the energy of the incident photons (\( E_{ph} = hc/\lambda \), where \( h \) is Planck’s constant and \( c \) the speed of light) exceeds the energy bandgap of the semiconductor, one electron is excited to the conduction band for each photon absorbed. Photodetectors, in principle, are categorized into two main classes: photoconductors and photodiodes (Figure 1). A photoconductor...
is a two-terminal device, typically consisting of a semiconducting material between two metal contacts (ohmic). When illuminated, the conductivity of the semiconductor changes due to the change in mobility\(^4\) and or carrier density caused by the generated electron-hole pairs. Like diodes, photodiodes are based on the formation of a p-n junction in a semiconductor using doping (homojunction), or a junction between a semiconductor and a metal contact (Schottky junction), or a junction between two different semiconductors (heterojunction) with different bandgaps.

A simple form of a junction photodiode is a p-n junction detector, whose reverse current increases when photons are absorbed. Consider a reverse-biased p-n junction as shown in Figure 1(b), where photons are absorbed all over the diode with absorption coefficient\(^5\) \(\alpha\). Whenever a photon is absorbed, an electron-hole pair is generated, but only where an electric field is present the charge carriers can be transported in a particular direction. Since a p-n junction can support an electric field only in the space charge region, photo-carriers are desirably generated in this region. The space charge region is formed around the junction because of the immigration of holes from the p-side to the n-side and electrons from the n-side to the p-side. The photocurrent\(^6\) here is associated with two fundamental mechanisms: drift and diffusion. When carriers move under an electric field, the current is called drift current. Diffusion current is associated with the flow of carriers due to concentration gradient.

\(^4\) The ability of an electron to move through a metal or semiconductor under the influence of external electric field.

\(^5\) The rate of decrease in the intensity of light, as it passes through a substance.

\(^6\) An electric current produced by photosensitive device under light.
In both cases, the main contribution is the drift current associated with the carriers generated in the space charge region. Here, the generated electrons and holes are transported by the electric field, and they recombine with the majority carriers from the electrodes. Such a transport process induces an electric current in the external circuit converting the optical signal into an electric signal. The reverse bias to the p-n diode helps to increase both the absorption efficiency and the collection efficiency. Photons absorbed in the neutral regions also generate photocarriers that partially contribute to the photocurrent. In fact, the absence of the electric field allows the generated carriers to recombine without affecting the charge neutrality. Only the photocarriers generated in the proximity of the space charge region (about one diffusion length) can contribute to the photocurrent. This current represents the diffusion contribution to the photocurrent, and as it is not affected by the electric field, it is constant with the reverse bias.

Although drift and diffusion currents contribute to the photocurrent, it is important to minimize the diffusion current for a high performance photodetector. This is a relatively slow process in comparison with the drift mechanism. The transit time of the carriers drifting across to the contacts play an important role in the response time of the detectors. However, since the response time of photodiodes is determined by the transit time of the carriers and not their lifetime, photodiodes are often slower than photodetectors.

Heterojunction photodetectors are photodiodes with different materials in the junction, i.e., with unequal bandgap energies ($E_g$). The heterojunctions allow more design flexibility and better performance. For example, consider a normal incidence p-n detector in which the top layer has $E_{g1} > E_{g2}$. Photons with energy $E_{g1} > h\nu > E_{g2}$ can pass through the top layer without absorption while they are absorbed in the bottom material minimizing the diffusion photocurrent from the top region while improving the temporal response. Another important advantage is the possibility to realize photodetectors at certain wavelengths, with the substrate being transparent in that spectrum.
Figures of Merit

The main figures of merit of a photodetector are responsivity (R), quantum efficiency (η) response time, signal to noise ratio (SNR), noise equivalent power (NEP), and detectivity (D*). Quantum efficiency is an important parameter representing the capability of the photodetector to convert a photon in an electron-hole pair; when η is 1, every single photon generates a carrier pair. Typically, quantum efficiency takes into account reflectance, absorbance, and scattering. Considering a photoactive layer of thickness d, neglecting reflections at the interface, the quantum efficiency can be expressed as a function of the absorption coefficient (α) as:

\[ \eta = \eta_c (1 - e^{-\alpha d}), \]  

(1)

where, \( \eta_c \) is the collection efficiency, i.e. the percentage of carriers generated and contributing to the photocurrent, and generally can be considered close to 1. The quantum efficiency is a function of wavelength, principally because the absorption coefficient (α) depends on wavelength.

The responsivity of a photodetector indicates how efficiently light is converted into photocurrent, and is given by the ratio between the photocurrent \( I_{ph} \) flowing in the photodetector and the incident optical power \( P_{in} \):

\[ R = \frac{I_{ph}}{P_{in}}. \]  

(2)

Responsivity decreases with large optical power. This condition, called detector saturation, limits the detector’s linear dynamic range, i.e., the range over which it responds linearly with the incident optical power.

The sensitivity of the detector can be quantified by taking together the responsivity and the noise performance of the detector. The minimum optical power a detector can distinguish from noise depends on the responsivity and the noise level. The signal current
produced by the light must be greater than the noise level in order to be detected. Noise Equivalent Power ($NEP$) of the photodetector is the minimum optical power required for an output signal-to-noise ratio ($SNR$) of 1.

$$SNR = RP/i_n,$$
$$NEP = i_n/R,$$

where $R$ is responsivity, $P$ is the incident optical power, and $i_n$ is the noise current.

Detectivity is the most important parameter for characterizing a photodetector and can be described as the reciprocal of the noise equivalent power, measuring the sensitivity of the detector taking into account various noise contributions.

The detectivity ($D^*$) is the most important parameter for characterizing a photodetector and can be described as the reciprocal of the noise equivalent power ($NEP$), measuring the sensitivity of the detector taking into account various noise contributions. The expression for $D^*$ is,

$$D^* = \sqrt{A_dB/NEP},$$

where $A_d$ is the photosensitive area, and $B$ is electrical bandwidth. The detectivity $D^*$ is a function of many parameters such as applied bias, temperature, noise current, and wavelength. Therefore, measurement conditions should be carefully optimized to avoid measurement errors.

**Filter Free Narrowband Optical Detection via Quantum Confinement**

A promising filter-free spectral discrimination approach is the modification of the energy occupation level by quantum confinement (density of states — DOS). When the spatial dimension of a semiconductor is reduced in the order of the de Broglie wavelength of the carriers, quantum confinement effects come into play. Due to the reduction in the size, the energy levels and density of states follow the quantum size effect and behave accordingly (see *Figure 2*). When all three spatial dimensions are in the order of the...
de Broglie wavelength of the carriers (in case of QDs), the energy band shows discrete energy levels. Due to these descrete energy levels, QDs are also known as ‘artificial atoms’. The spatial dimensions of semiconductor QDs are in the range of 2–20 nm. Generally, QDs are embedded in a semiconductor or dielectric matrix with a higher bandgap to study their optical and electrical properties. Bandgap increases with decrease in the size of QDs, providing the ability to tune the bandgap, which results in spectral selective response. Several methods such as Stranski–Krastanov epitaxy growth, electron beam lithography, ion implantation, solvothermal process, thermal evaporation, and laser ablation have been reported for the synthesis of quantum dots, nanostructures and nanoparticles.\(^9\)

Ion implantation is a versatile process compatible with current silicon-based electronics. The formation of size-controlled quantum dots in a dielectric matrix (SiO\(_2\), Al\(_2\)O\(_3\)) provides several advantages like encapsulation and passivation. Dielectric matrix with a large bandgap does not contribute to photocurrent as it is transparent to all the wavelengths. Sequential implantation of elements creates a near-surface supersaturated solid solution of individual elements and their compounds. Thermal annealing then causes precipitation, chemical bonding, and the formation of nanocrystals or nanoclusters. The size and distribution of the nanoparticles or quantum dots can be controlled by varying

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\(^9\) A material that possesses insulating properties and can be polarized by an applied electric field.

\(^9\) The term epitaxy comes from the Greek language, *epi* meaning ‘above’, and *axis* meaning ‘in ordered manner’. It can be translated as ‘to arrange upon’.

\(^{10}\) Small dimension (1–10 nm) materials.
Figure 3. Schematic representation of the formation of size controlled nanocrystals in a dielectric matrix using ion implantation.

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Unlike macroscopic particles or bulk semiconductors, the energy levels of QDs can have only certain quantized values (see Figure 4), and the transition between these energy levels occurs only when the incident photon energy is exactly equal to the energy separation of the participating pair of quantum energy states. Photons with energy levels not equal to the energy gap are not absorbed in QDs, whereas the larger nanoparticles absorb shorter wavelengths. Figure 4(b) shows the schematic representation of the modification of the energy levels of QDs with decreasing their size.

The responsivity of the photodetector as a function of incident optical wavelength provides the spectral response of the device. The photoresponse (responsivity) of a typical narrowband photodetector based on QDs is shown in Figure 5. The wavelengths with energy lower than the bandgap of QDs do not generate electron-hole pairs and result in cut-off at a longer wavelength. The cut-off at a shorter wavelength can be accredited to the size-dependent quan-
tum confinement effect where the energy levels of the photons are not equal to the energy separation between the states. The broadening of the spectral response is due to the size inhomogeneity of the QDs in the ensemble. Currently, these quantum dots based narrowband detectors are not commercially available. However, high-performance photodetectors based on quantum dots have been demonstrated in a wide spectral range spanning from the visible to the mid-infrared. The cost-effective solution may be

**Figure 4.** (a) Energy states of bulk material and, (b) Energy band structure and spectrum-selective detection mechanism in QDs with decreasing QD size.

**Figure 5.** Spectral response of a narrow band photodetector with a small FWHM (FWHM refers to full-width half-maximum and it is the width of a line shape at half of its maximum amplitude).
provided by mass production or using some low-cost synthesis methods.

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