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Introductory Chapter: Photodetectors

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1. Introduction

Modern day electronic communications, industrial electronics, analytical equipment, medicine and healthcare, automotive and transport, etc. widely employ photodetectors, also known as photosensors, primarily as optical receivers to convert light into electrical signals. These devices may receive the transmitted optical pulses, or sense light or other electromagnetic radiation. Nevertheless, the photodetectors may be classified according to their light detection mechanisms, *viz.* the photoemission or photoelectric effect, thermal effect, polarisation effect, photochemical effect, or weak interaction effects. Photodetectors that employ semiconductors operate on the principle of electron-hole pair creation upon light irradiation. When a semiconductor material is illuminated by photons having energies greater than or equal to its bandgap, the absorbed photons promote valence band electrons into the conduction band, thus leaving behind positively charged holes in the valence band. Conduction band electrons (valence band holes) behave as free electrons (holes) that can diffuse in a concentration gradient, or drift under the influence of an intrinsic, or externally applied, electric field. The photogenerated electron-hole pairs due to optical absorption may recombine and re-emit light, unless subjected to an electric field-mediated separation to give rise to a photocurrent, which is a fraction of the photogenerated free charge carriers collected at the electrodes of the photodetector structure. The magnitude of this photocurrent at a given wavelength is directly proportional to the incident light intensity.

In this chapter, we introduce some representative photodetectors, their properties, performance and applications, as applied in the various design configurations. We also address sensing and detection in the electromagnetic spectrum spanning from the ultraviolet and visible, to infrared and terahertz.

2. Photodetection mechanisms

Heinrich Hertz discovered in 1887 that ultraviolet light illumination of electrodes generates electric sparks more easily. While studying black-body radiation in 1900, Max Planck suggested that energy carried by electromagnetic waves could only be quantised into units of discrete packets known as photons or quanta. Albert Einstein advanced the foregoing light energy packet hypothesis to explain experimental results using the notion of the photoelectric effect. The light beam photons have a characteristic energy proportional to the frequency of the light. When the light beam irradiates a material, the energy of the photon, if sufficiently high, is absorbed to liberate the electron from atomic bonding, and the remaining photon energy contributes to the free electron's kinetic energy. For photon energies too low to be absorbed, they are re-emitted. However, if the electron acquires energy surpassing the work function of the material, it is ejected as a photoelectron. Whilst the maximum kinetic energy of the emitted photoelectron depends on the frequency of the irradiance, the photoelectron ejection rate (or magnitude of the photoelectric current) is directly proportional to the intensity of the incident light.

Other than microchannel plate detectors, a range of photodetectors operate on the basis of the photoelectric or photoemission effect. Gaseous ionisation detectors detect photons having sufficient energy to ionise gas atoms or molecules, and the current flow due to the electrons and ions generated by the ionisation can be measured. Photomultiplier tubes or phototubes contain photocathodes that emit electrons when illuminated, thus conducting a current proportional to the light intensity. The thermal effect is realised when the incident photons cause electrons to transition into the mid-gap states, which then relax into the lower bands, thus leading to phonon generation and heat dissipation. The rise in temperature in turn modifies the electrical properties of the device (e.g., thermopile, pyroelectric detector, cryogenic detector, bolometer, etc.) material, such as its electrical conductivity. The polarisation effect is so called when the incident photons alter the polarisation states of appropriate materials, thereby modulating the refractive index (i.e., photorefractive effect); this is exploited in holographic data storage. Photochemical effects in photodetectors occur when chemical changes in the material are induced by the incident photons. Examples include photoreceptor cells in the retina, or photographic plates. Finally, weak interaction effects occur when secondary effects are induced by photons, such as in photon drag detectors or gas pressure changes in opto-acoustic detectors (e.g., Golay cells).

3. Types of photodetectors

Photodetectors may be configured in unique ways for various applications. For example, single sensors may detect overall light intensities. A 1-D array of photodetectors may be used to measure the distribution of light along a line, such as in a spectrophotometer or a line scanner. Moreover, a 2-D array of photodetectors may be used to derive images from the light intensity profile, when applied as an image sensor. Focal-plane arrays (FPAs) are devices consisting

of an array of light-sensing pixels or active pixel sensors (APS) at the focal plane of a lens, and are most commonly adopted for imaging (photos or videos) or non-imaging (spectrometry, LIDAR and wave-front sensing) purposes. In radio telescopes, the FPA usually refers to 2-D devices that are sensitive in the infrared. Other image sensors, such as charge-coupled device (CCD) or CMOS sensors, operate in the visible regime. An anti-reflective coating or a surface-plasmon antenna is sometimes used on a photodetector, to enhance the optical absorption or photogeneration of charge carriers (or photocurrent response), respectively. By embedding an ultrathin semiconductor absorption layer into a Fabry-Pérot resonant cavity, resonant cavity enhanced photodetectors can be realised, to boost the quantum efficiency or bandwidth-efficiency product, and provide superior wavelength selectivity and high speed photoresponse for wavelength division multiplexing (WDM) systems. Subwavelength microcell gratings affixed in close proximity to the optical absorber can enable near-field enhancement of optical absorption through strong electromagnetic field confinement [1].

Photovoltaic photodetectors resort to the internal electric field of a *p-n* or Schottky junction to achieve the charge separation and photocurrent generation. Solar cells are similar to photovoltaic photodetectors, which also absorb light and convert it into electrical energy, through the photovoltaic effect. The *p-n* junction photodetectors include designs consisting of a simple *p-n* junction, or *p-i-n* photodetectors incorporating a nominally undoped semiconductor layer between the *p-* and *n*-regions, or phototransistors combining a photodiode and an additional *n*-region. At equilibrium, the presence of the ionised acceptors and donors within the space charge region (SCR) sets up an internal electric field at the junction. Therefore, electron-hole pairs generated inside the SCR, or within the minority carrier diffusion length from the edges of the SCR, will be separated by the built-in electric field and contribute to the photocurrent. The width of the SCR is inversely related to the dopant concentration in the material, but its expansion may be modulated by reverse biasing, which concomitantly increases the internal electric field at the junction so as to enhance the efficiency of electron-hole pair separation. To improve the photoresponse speed, the electrical resistivity of the photodetector material may be reduced through increasing the dopant concentration, but a nominally undoped layer of a thickness largely determining the SCR width may be introduced between the *p-* and *n*-regions to form the *p-i-n* structure. With a lower resistivity and a wider SCR width (and hence lower capacitance), the *p-i-n* structure is well suited for high-speed IC applications.

Avalanche photodiodes are designed with high *p-* and *n*-type doping to intensify the junction electric field. With a reverse bias sufficiently high (100–400 V) such that the internal electric field approximates the critical breakdown field, the acceleration of the photogenerated charge carriers within the SCR is able to ionise the lattice atoms, hence resulting in an avalanche multiplication of charge carriers. The corresponding gain is typically of the order of 10–20 in these cases. Avalanche photodiodes are well suited for fibre optic systems requiring low optical power levels with quantum efficiencies eclipsing 100%.

Phototransistors are similar to photodiodes, except that an additional *n*-region is included in the photodetector design. The phototransistor comprises a photodiode with an internal gain, and it can be represented as a bipolar junction transistor enclosed in a transparent case

through which photons are allowed to irradiate the base-collector junction. The electrons generated by the absorbed photons in the base-collector junction SCR are injected into the base, and the photocurrent is amplified. Nevertheless, while a phototransistor is generally a few orders of magnitude more sensitive than the photodiode, the photoresponse speed is much slower. Polysilicon- [2], zinc oxide- [3], or organic polymer-based [4] thin film transistors (TFTs) have been adopted as photodetectors for optical interconnects, ultraviolet imaging and large area displays/flexible substrates, respectively.

Schottky junction photodetectors include Schottky barrier photodiodes and metal-semiconductor-metal (MSM) photodiodes. In the former, the Schottky junction is formed between a metal and a doped semiconductor. Analogous to that formed at the *p-n* junction, the SCR is comparable, and its width can be modulated in tandem with the built-in electric field proportional to the reverse bias to the Schottky junction photodetector. Typically, an ultrathin, semitransparent metal layer, for example, Au of about 10-nm thick, is used as the Schottky contact, which allows transmissivity up to 95% and around 30% for infrared and ultraviolet, respectively. MSM photodiodes are designed with two Schottky contacts, with one Schottky junction reversed-biased to support an elongated SCR width, and the other, forward biased. Typically, the semiconductor material is nominally undoped, and hence, the SCRs are spatially extended into the device. The reversed-biased Schottky junction generates the photocurrent, whereas the forward-biased Schottky junction acts as a highly efficient charge carrier collector.

In photoconductors, an electric field is applied across a layer of a semiconductor through electrically biased ohmic contacts on either side, leading to the collection of charge carriers. Photoresistors, light-dependent resistors (LDRs) or photoconductive cells change electrical resistivity according to the light intensity, hence exhibiting photoconductivity. Such devices have a higher gain, as the response of photoconductors is typically several orders of magnitude greater than that of the photovoltaic detector counterpart, based on a given material. However, for photoconductors, the bandwidth, infrared sensitivity, ultraviolet-visible contrast and a range of other key performance parameters are inferior to that of other types of photodetectors. Hence, the scope of potential applications is significantly limited.

Rewritable nanoscale photodetectors have been demonstrated based on insulating oxide ($LaAlO_3/SrTiO_3$) interfaces [5], exhibiting electric field-tunable photoconductive response within the electromagnetic spectrum ranging from the visible to near-infrared. The integration of nanoscale photodetectors based on nanodots and nanowires has also benefited from recent innovations in subwavelength imaging beyond the diffraction limit, by adapting (plasmonic) metamaterials for superlenses suitable for superresolution, near-field light focussing [6].

4. Performance figures of merit

High sensitivity at the operating wavelength, short response times, linear response over a wide range of light intensities, minimum noise contribution, stability of performance characteristics, reliability, low bias voltage and low cost are amongst the photodetector requirements

for technology adoption. State-of-the-art graphene-on-diamond photodetectors have been demonstrated to exhibit superior responsivity and photocurrent, as well as open circuit voltage [7]. Particularly, in high-speed optical data communications, photodetectors must also be highly responsive to photoexcitation, yet immediately/rapidly relax to the ground state after the light source is switched off. However, the excited non-equilibrium state is usually maintained for a finite amount of time through an effect known as persistent photoconductivity, owing to long recombination times that originate from charge carrier trapping by bulk defects (vacancies or impurities) and surface states. The photodetector may be characterised by various figures of merit such as the spectral response, quantum efficiency, responsivity, bandwidth, gain, noise equivalent power (NEP), dark current, response time and detectivity. The spectral response characterises the photodetector response with respect to the photon frequency. The quantum efficiency is the measure of the number of charge carriers generated per photon. The responsivity is the ratio of the output electrical current to the input optical power to the photodetector. The NEP is the minimum amount of optical power required to generate a signal in the presence of noise in the photodetector. The specific detectivity is the reciprocal of NEP normalised to the square root of the photodetector active area-bandwidth product. The gain is the ratio of the output electrical current to the photogenerated current directly generated by the incident photons. The dark current is a measure of charge carrier flow through a photodetector in the absence of an optical input. The response time is the time needed for a photodetector to rise from 10 to 90% of the final output. The noise spectrum is the intrinsic noise voltage/current as a function of frequency, which can be represented as a noise spectral density. The RF output is constrained by the nonlinearity of the photodetector. All in all, having a large angular acceptance, high temporal resolution, as well as high spectral and energy resolution, may also be crucial design considerations for a high-performance photodetector.

5. Conclusion

For a comparison of the viability and performance of photodetectors, an in-depth understanding of their figures of merit is essential. The insights underpinning the physics and technology of various photodetector designs and configurations must be conscientiously examined for successful implementation and integration of high-performance photodetection and optoelectronic sensing within the relevant wavelength ranges, on low-cost substrates or CMOS-compatible substrates. New device concepts and techniques to develop monolithic integration of optoelectronic materials on a single substrate may permit revolutionary ultrafast and ultrasensitive near-field photodetection at high spatial, temporal and spectral resolution.

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