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Theoretical Aspects on Photodiodes System: Mechanism, Modes and Types

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ABSTRACT

Photodiodes find extensive use in optical communication and biological imaging, among other fields. This study provides an extensive overview of recent developments in photodiode technology, emphasizing significant breakthroughs, difficulties, and potential applications. The review starts with a summary of the basic ideas that underpin photodiode function and then moves on to talk about the many kinds of photodiodes and the uses for which they are designed. After that, it explores the most recent developments in photodiode design, including as novel materials, smaller devices, and improved performance features.

Keywords: Principal Operation, Types, Characteristics, Features, Advantages, Disadvantages, Applications

INTRODUCTION

A semiconductor device known as a photodiode, or light-converting semiconductor, uses a P-N junction to transform photons into electrical current. There are a lot of holes (positive) in the P layer and a lot of electrons (negative) in the N layer. A wide range of materials, including as silicon, germanium, and indium gallium arsenide, can be used to create photodiodes. For cost savings, enhanced sensitivity, wavelength range, low noise levels, or even reaction speed, each material uses a particular set of attributes. The Fig shows the symbol of photodiode while the Fig shows the working principle of photodiode.

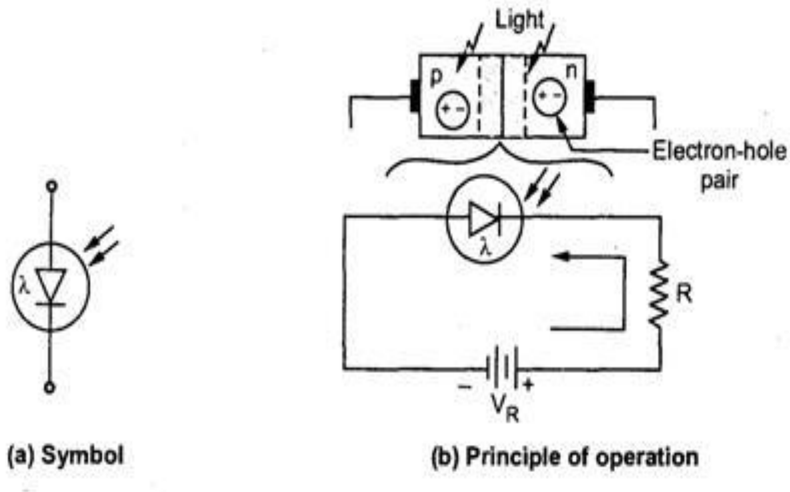

Fig1. Working Principle and Symbol of Photodiode

In reverse biased situation, the photodiode is linked. There is a significant depletion region width. Because of the minority charge carriers, it has a tiny reverse current under typical circumstances. When light enters the p-n junction through a glass window, photons from the light attack the junction, giving the valence electrons some energy. As a result, valence electrons break loose from their covalent connections and become free electrons. As a result, more electron-hole pairs are produced. As a result, there are more minority charge carriers overall, which raises the reverse current. This is the fundamental idea behind how a photodiode works.

Without light, the reverse current in the diode is in the microampere region. The light-induced variation in this current also occurs in the microampere range. Therefore, a significant change of this kind can be seen in the reverse current. The photodiode's current flow is measured in milliamperes (mA) if it is forward biased. Instead of the light, the applied forward-biased voltage controls the current. The light-induced change in forward current is very small and imperceptible. The light has no effect on the forward biased diode's resistance. Therefore, in order for light to significantly affect the current and for the photodiode to function as a variable resistance device, it must always be connected in reverse biased condition.

The photodiode's small signal model is displayed in the figure below. An ideal junction diode connected in parallel to a current source that is proportionate to light intensity serves as a representation of a photodiode.

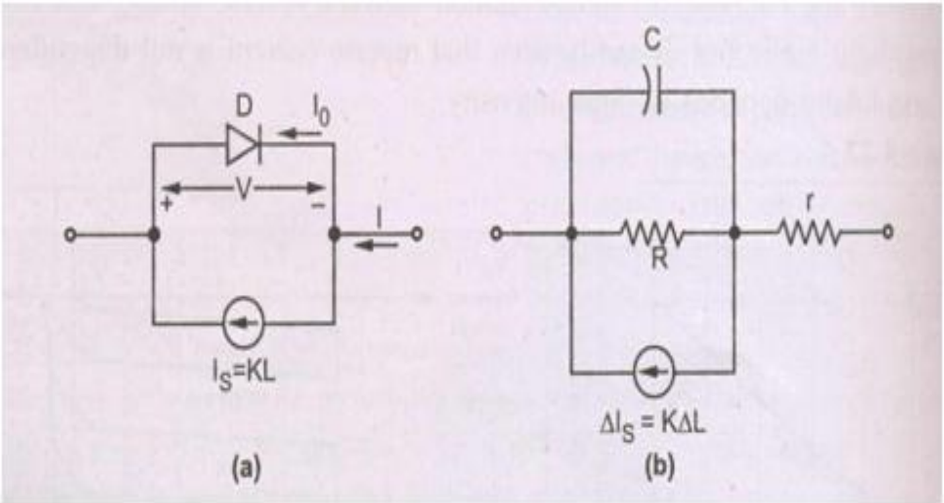

Fig 2. Small Signal Model for Photodiode

A semiconductor device called a photodiode is used to change light into electrical current. When photons are absorbed in the photodiode, electricity is produced. Photodiodes can have big or tiny surface areas, integrated lenses, and optical filters. When the surface area of a photodiode rises, its reaction time often decreases. the typical solar cell that produces an electric photodiode.

Similar to conventional solar power, photodiodes are large area semiconductors that can be packaged with a window or optical fiber connection to allow light to reach the sensitive component of the device, or exposed (to detect vacuum UV or diodes, except that they X-rays). To improve response speed, many diodes made expressly for use as photodiodes employ PIN junctions rather than p–n junctions. The reverse bias mode of operation is intended for a photodiode [1].

Overview on Photodiode

A type of diodes called photodiodes is capable of producing electricity from light energy. They operate in complete opposition to LEDs, which are diodes as well but transform electrical energy into light energy. Additionally, photodiodes can be used to measure light brightness. In this article, let's learn more about photodiodes. A photodiode is a type of PN-junction diode that generates electricity by using light radiation. They are also known as light detectors, photo-sensors, and photo-detectors.

Photodiodes are engineered to function under conditions of reverse bias. Germanium, indium gallium arsenide, and silicon are common materials used in photodiodes. A semiconductor device known as a photodiode, or light-converting semiconductor, uses a P-N junction to transform photons into electrical current. There are a lot of holes (positive) in the P layer and a lot of electrons (negative) in the N layer. A wide range of materials, including as silicon, germanium, and indium gallium arsenide, can be used to create photodiodes. For cost savings, enhanced sensitivity, wavelength range, low noise levels, or even reaction speed, each material uses a particular set of attributes.

Principle of Operation

A p-n junction, often known as a PIN structure, is a photodiode. An electron-hole pair is created in the diode when a photon with sufficient energy strikes it. Another name for this process is the inner photoelectric effect. The built-in electric field of the depletion zone sweeps these carriers away from the junction whether the absorption takes place in the depletion region of the junction or one diffusion length distant from it.

As a result, a photocurrent is created as holes go toward the anode and electrons toward the cathode. To enhance the sensitivity of the device, the dark current must be minimized. The total current flowing through the photodiode is the result of adding the photocurrent and the dark current, which is generated in the absence of light[2].

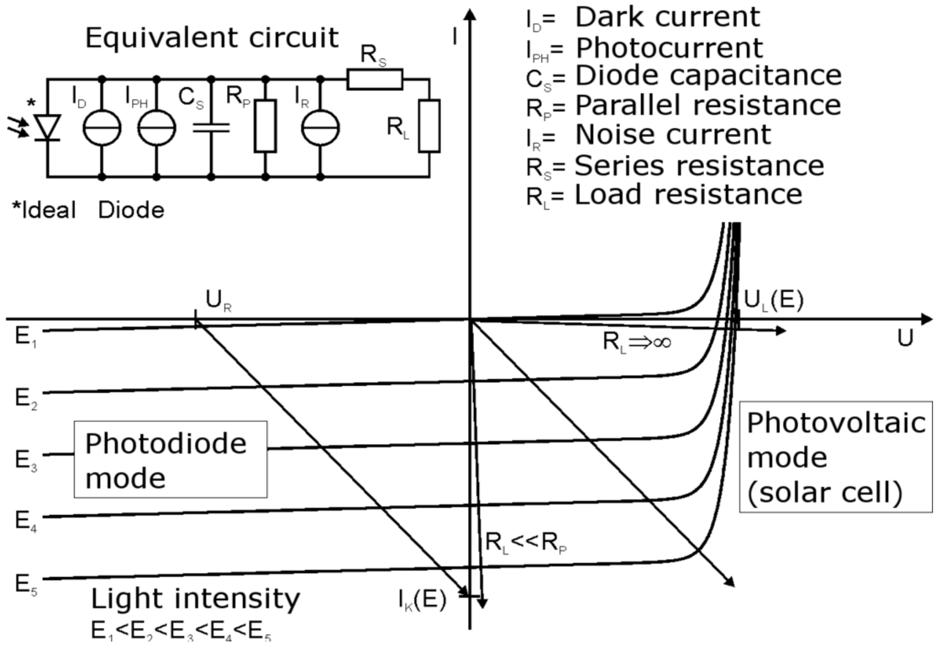

Fig3. I-V characteristic of a photodiode. The linear load lines represent the response of the external circuit: I= (Applied bias voltage-Diode voltage)/Total resistance. The points of intersection with the curves represent the actual current and voltage for a given bias, resistance and illumination [2].

Working Mechanism

Photons, which are light particles, are exposed to a photodiode and influence the creation of electron-hole pairs. In the vicinity of the diode's depletion area, electron-hole pairs are produced if the energy of the falling photons (hv) exceeds the semiconductor material's energy gap (Eg).

The junction's electric field causes the formed electron-hole pairs to split apart before recombining. The electrons in the diode are forced to travel towards the n-side by the direction of the electric field, and as a result, the holes migrate towards the p-side. An increase in the electromotive force is seen as a result of the increased quantity of holes on the p-side and electrons on the n-side. Currently, a current flow through the system can be seen when an external load is attached to it.

The current flow increases with the electromotive force generated. The intensity of the incident light directly affects the size of the electromotive force generated. By using a reverse bias, it is simple to monitor the effect of the proportionate change in photocurrent with the change in light intensity.

Photodiodes can be employed as photodetectors to detect optical signals since they immediately generate current flow based on the amount of light they receive. A photodiode's power and output can be increased by using built-in lenses and optical filters.

If a photon has enough energy, it can impact an atom inside the gadget and liberate an electron. As a result, an electron-hole pair (e- and h+) is created, where a hole is just an electron's "empty space." The electron-hole pairs in the materials will recombine as heat if photons are absorbed in either the P or N layers and are sufficiently far (at least one diffusion length) from the depletion area.

Electron hole pairs formed by photons absorbed in the depletion area (or near it) will migrate to opposite ends as a result of the electric field. The holes on the anode will travel toward the negative potential, while electrons will move toward the positive potential on the cathode. The photodiode's current, or photocurrent, is created by these moving charge carriers. A photodiode (P-N Junction) with several connection points at the top and bottom is seen in Figure 1.

The depletion region's boundaries function like the plates of a parallel plate capacitor, causing a capacitance to be created in the photodiode. The depletion region's breadth is inversely proportional to capacitance. The region's capacitance is also influenced by reverse bias voltage.

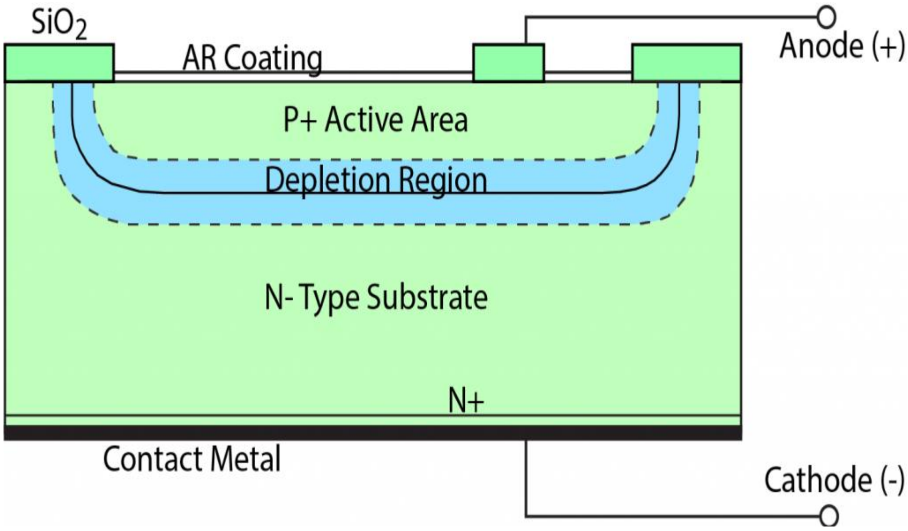

Fig4. shows a cross section of a typical photodiode. A Depletion Region is formed from diffusion of electrons from the N layer to the P layer and the diffusion of holes from the P layer to the N layer. This creates a region between the two layers where no free carriers exist. This develops a built-in voltage to create an electric field across the depletion region. This allows for current to flow only in one direction (Anode to Cathode). The photodiode can be forward biased, but current generated will flow in the opposite direction. This is why most photodiodes are reversed biased or not biased at all. Some photodiodes cannot be forward biased without damage.

Photovoltaic Mode

When operating in the zero bias or photovoltaic mode, the device's ability to release photocurrent is limited, resulting in the accumulation of voltage. The foundation of solar cells is the photovoltaic effect, which is exploited in this mode. A conventional solar cell is just a large area photodiode.

Photoconductive Mode

The diode is frequently reverse biased in this mode, meaning that the cathode is driven positively relative to the anode. Because the added reverse bias widens the depletion layer and lowers the capacitance of the junction, the response time is shortened. Without significantly altering the photocurrent, the reverse bias likewise raises the dark current. The photocurrent is linearly proportional to the illumination (and to the irradiance) for a given spectral distribution [3].

The photoconductive mode tends to show more electronic noise even though it is faster [4]. In a typical circuit, the Johnson–Nyquist noise of the load resistance generally takes center stage since the leakage current of a decent PIN diode is so low (<1 nA).

Other Modes of Operation

The structure of avalanche photodiodes is designed to allow for high reverse bias operation, which is close to the reverse breakdown voltage. This makes it possible to multiply each photo-generated carrier via avalanche breakdown, creating internal gain in the photodiode and raising the device's effective responsiveness.

A light-sensitive transistor is called a phototransistor. A typical kind of phototransistor is known as a photobipolar transistor, which is essentially a transparent bipolar transistor with a base-collector that allows light to reach the junction. It was created at Bell Laboratories in 1948 by Dr. John N. Shive (the more well-known wave machine),[5]:205, but it wasn't made public until 1950 [6]. The photodiode current is amplified by the transistor's current gain β (or hfe), and the electrons produced by photons in the base–collector junction are injected into the base.

The phototransistor turns become a photodiode if the emitter is left disconnected and the base and collector leads are utilized. Despite having a greater sensitivity to light than photodiodes, phototransistors are not any more sensitive to low light levels. Additionally, phototransistors have noticeably longer response times. PhotoFETs, or field-effect phototransistors, are a type of field-effect transistor that is sensitive to light. In contrast to photobipolar transistors, PhotoFETs use a gate voltage to regulate the drain-source current.

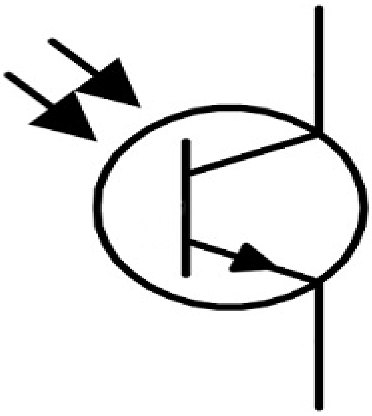

Fig 5. Electronic Symbol for a Phototransistor

Materials

Because only enough energy to activate electrons across the material's photons with a large enough bandgap can result in appreciable photocurrents, the material utilized to create a photodiode is essential to determining its characteristics. Compared to germanium-based photodiodes, silicon-based photodiodes produce less noise due to their larger bandgap.

The following materials are frequently used to make photodiodes [7]:

Material	Electromagnetic Spectrum Wavelength Range (nm)
Silicon	190-1100
Germanium	400-1700
Indium Gallium Arsenide	800-2600
Lead Sulphide	<1000-3500
Mercury Cadmium Telluride	400-14000

Key Performance Specifications

When selecting the appropriate photodiode and determining whether to reverse bias the photodiode, four key factors are taken into consideration.

- The photodiode's response (speed/time) is dictated by the P-N junction's capacitance. It is the amount of time charge carriers require to pass through the P-N junction.
- The depletion region's width has a direct impact on this.
- The ratio of photocurrent produced by incident light to incident light power is known as responsiveness. Usually, this is stated in A/W (current over power) units. A photodiode's typical responsivity curve will display A/W as a function of wavelength. We refer to this as quantum efficiency.
- When there is no incident light, the current in the photodiode is known as the dark current. This could be one of the photodiode system's primary sources of noise. This measurement can also take background radiation's photocurrent into account. To measure dark current, photodiodes are often placed in an enclosure that blocks light from reaching them. Dark current levels can mask the current produced by incident light at low light levels because the photodiode can create very little current. Temperature causes an increase in dark current. Diminished dark current can occur in the absence of biasing. A photodiode without any dark current would be perfect.

Types of Photodiodes

Planar Diffusion Type

An SiO_2 coating is applied to the P-N junction surface, yielding a photodiode with a low level dark current.

Low-Capacitance Planar Diffusion Type

A high-speed version of the planar diffusion type photodiode. This type makes use of a highly pure, high-resistance N-type material to enlarge the depletion layer, and thereby decrease the junction capacitance, thus lowering the response time to 1/10 the normal value. The P layer is made extra thin for high ultraviolet response.

PNN + Type

A low-resistance N + material is made thick to bring the N-N+ boundary close to the depletion layer. This somewhat lowers the sensitivity to infrared radiation, making this type of device useful for measurements short wavelengths.

PIN Type

An improved version of the low-capacitance planar diffusion device, this type makes use of an extra-high resistance layer between the P- and N- layers to improve response time. This type of device exhibits even further improved response time when used with reversed biased and so is designed with high resistance to breakdown and low leakage for such applications.

Schottky Type

A thin gold coating is sputtered onto the N material layer to form a Schottky Effect p-n junction. Since the distance from the outer surface to the junction is small, ultraviolet sensitivity is high.

Avalanche Type

If a reverse is applied to a p-n junction and a high-field formed within the depletion layer, photon carriers will be accelerated by this field. They will collide with atoms in the field and secondary carriers are produced, this process occurring repeatedly. This is known as the avalanche effect, and since it results in the signal being amplified, this type of device is ideal for detecting extremely low-level light.

Electrical Characteristics of Photodiode

A current source connected in parallel to an ideal diode can be used to imitate a silicon photodiode (Figure 3). The diode symbolizes the p-n junction, and the current source represents the current produced by the incident radiation. Furthermore, a shunt resistance (RSH) and a junction capacitance (Cj) are connected in parallel to the other parts. All of the parts in this model are connected in series using series resistance (RS).

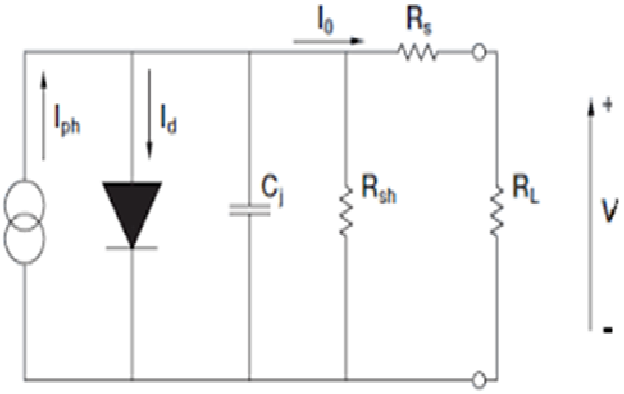

Fig. 6. Equivalent Circuit for the Silicon Photodiode

Shunt Resistance

The slope of the photodiode's current-voltage curve at the origin, or V=0, is known as the shunt resistance. The shunt resistance of an ideal photodiode should be infinite, but real values vary from tens to thousands of megaohms. Through experimentation, the resistance is calculated, the current is measured, and ±10 mV is applied. The noise current in the photodiode without bias (photovoltaic mode) is measured using shunt resistance. The maximum shunt resistance is required for optimal photodiode performance.

Series Resistance

The resistance of a photodiode's contacts and its undepleted silicon are the sources of its series resistance. It is provided by:

$R_s = (W_s - W_d)\,\varrho / A + R_c$-------(1)

Where,
WS is the thickness of the substrate,
Wd is the width of the
depleted region,
A is the diffused area of the junction,
ϱ is the resistivity
of the substrate and,
RC is the contact resistance.

Series resistance is used to determine the linearity of the photodiode in photovoltaic mode (no bias, V=0). Although an ideal photodiode should have no series resistance, typical values ranging from 10 to 1000 Ω's are measured.

Junction Capacitance

The depletion region's borders function as a parallel plate capacitor's plate. The diffused area and the depletion region width are inversely and directly related to the junction capacitance, respectively. Furthermore, substrates with higher resistivity have lower junction capacitance.

$C(J) = \epsilon_{Si}\,\epsilon_0\,A / \sqrt{2\epsilon_{Si}\,\epsilon_0\,\mu\,\varrho\,[V(A) + V(bi)]}$ -------(2)

$= A\sqrt{\epsilon_{Si}\,\epsilon_0 / 2\mu\varrho\,[V(A) + V(bi)]}$

$= \epsilon_{Si}\,\epsilon_0\,A / W(d)$

$W(d) = \sqrt{2\,\epsilon_{Si}\,\epsilon_0\,A\,\mu\,\varrho\,[V(A) + V(bi)]}$

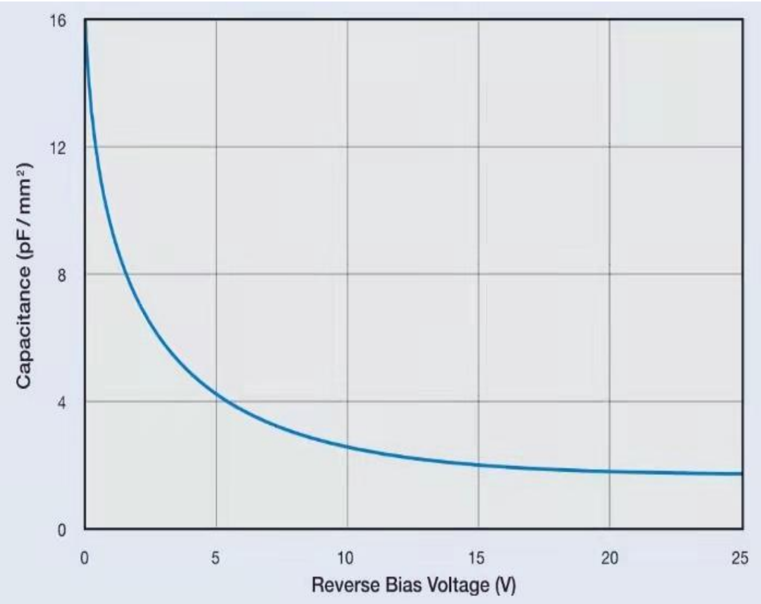

Fig7. Capacitance of Photoconductive Devices versus Reverse Bias Voltage

where ϵ_0 = 8.854x10-14 F/cm, is the permittivity of free space, ϵ_{Si} =11.9 is the silicon dielectric constant, μ = 1400 cm2/Vs is the mobility of the electrons at 300 K, ϱ is the resistivity of the silicon, Vbi is the built-in voltage of silicon and VA is the applied bias.

Figure 4 shows the dependence of the capacitance on the applied reverse bias voltage. Junction capacitance is used to determine the speed of the response of the photodiode.

Rise/Fall Time and Frequency Response

A photodiode's rise and fall times are measured in terms of how long it takes the signal to increase or decrease from 10% to 90% or 90% to 10% of its ultimate value, respectively. The frequency response, or the frequency at which the photodiode output drops by 3dB, is another way to express this characteristic. It can be loosely represented by:

Tr = 0.35/f (3 dB) ------- (3)

The response time of a photodiode is determined by three factors:

1. T(DRIFT), the carriers' charge collection time in the photodiode's depletion area.
2. T(DIFFUSED), the carriers' charge collecting time in the photodiode's undepleted area.
3. The diode-circuit combination's RC time constant, or t(RC).

With R representing the sum of the diode series resistance and the load resistance (RS+ RL) and C representing the sum of the photodiode junction and the stray capacitances (Cj+CS), t(RC) is found by formulating t(RC)=2.2 RC. Faster rise times are achieved with smaller diffused area photodiodes and bigger applied reverse biases since the junction capacitance (Cj) depends on both the applied reverse bias and the photodiode's diffused area (Equation 2). Additionally, by employing short leads and carefully arranging the electronic components, stray capacitance can be reduced. What determines the overall increase time is:
$T(R) = \sqrt{t\,DRIFT^2 + T\,DIFFUSED^2 + t\,RC^2}$ ------- (4)

Advantages

1. Suitable for use as a variable resistance gadget.
2. Very susceptible to light.
3. The operation is moving at a very fast pace. It happens very quickly when the current switches, changing the resistance value from high to low or vice versa.

Disadvantages

1. Temperature affects the dark current.
2. Because the general characteristics of photodiodes rely on temperature, they have weak
3. Stability of temperature.
4. The current and its variation fall within the range of 1, which might not be adequate to power additional circuits. Therefore, clarification is required.

Applications

1. Similar to other photodetectors, P-n photodiodes are employed in charge-coupled devices, photomultiplier tubes, and photoconductors. They can be used to modify the state of circuitry (digital; either for control and switching, or digital signal processing) or to produce an output that is reliant on illumination (analog; for measurement and the like).
2. Compact disc players, smoke detectors, and the receivers for infrared remote-control devices—which are used to operate everything from air conditioners to televisions—all contain photodiodes. In numerous applications, one can utilize either photodiodes or photoconductors. Both kinds of photosensors can be used to detect light levels and act upon them, such as turning on street lighting after dark or measuring light, as in the case of camera light meters.
3. In research and industry, photodiodes are frequently employed to measure light intensity accurately. Compared to photoconductors, their response is typically more linear.
4. Additionally, they are widely utilized in many different medical applications, including pulse oximeters, immunoassay equipment, and detectors for computed tomography that are connected with scintillators.
5. Alarm systems and counting systems are the two most popular photodiode-based systems.

CONCLUSION

In many domains, including optical communication systems, remote sensing, medical imaging, and telecommunications, photodiodes are essential components. A thorough grasp of photodiodes is necessary to maximize their performance and create novel applications. Going forward, additional research endeavours are necessary to tackle various obstacles and investigate unexplored possibilities. Subsequent research endeavours may concentrate on refining the quantum efficiency and noise characteristics of photodiodes, creating new materials with customized attributes, and investigating innovative device architectures to augment performance. Furthermore, photodiode-based systems with artificial intelligence and machine learning algorithms integrated into them have potential for intelligent imaging and autonomous sensing applications. Photodiodes remain an essential element in a multitude of technological applications, and current research endeavours are well-positioned to unleash their complete potential, resulting in revolutionary breakthroughs across multiple domains.

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