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PHOTON IS OUR BUSINESS

Meeting optical communication demands by revealing the potential of InGaAs photodiodes

The conversion of light into electrical current is made possible by a crucial component – the photodiode. Initially developed using Silicon, these photodiodes facilitated the detection of ultraviolet and visible light. Recent technological advancements have expanded their capabilities to include the detection of infrared light, utilizing materials like Indium Gallium Arsenide for longer wavelengths.

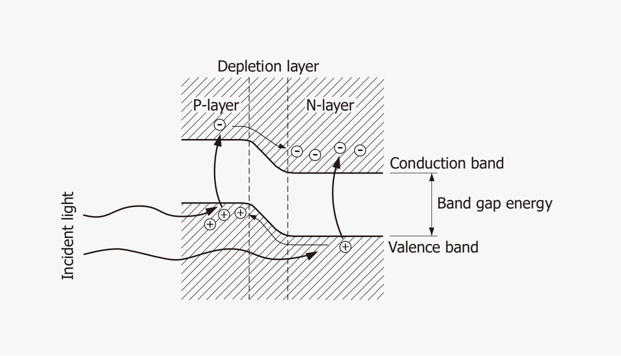
In the rapidly evolving field of telecommunications, the demand for high-data throughput has driven engineers to explore efficient emitters and detectors. This has led to the increased use of light in telecommunications, known as Optical Communication. The benefits include minimal interference, crucial in dense urban areas, and the ability to penetrate physical barriers. Moreover, light enables wireless data transmission over long distances, offering the potential to reduce infrastructure in remote areas. Near-infrared light, with its high frequency, allows faster data transmission and contributes to lower energy consumption in data centers. In this context, we delve into the functionalities of Indium Gallium Arsenide Photodiodes (InGaAs PD), exploring their role in advancing these technological frontiers.

Operating principle

The technical behavior closely resembles that of Silicon photodiodes, with the primary distinction lying in the variance of band gap energy attributable to the different materials employed.

The PN junction, constituted by the sensitive surface P-layer and the N-layer, functions as a photoelectric converter. When an InGaAs photodiode (PD) is illuminated with light energy surpassing the band gap energy, electrons in the valence band get elevated to the conduction band, creating holes in the valence band (as illustrated in Figure 1 below).

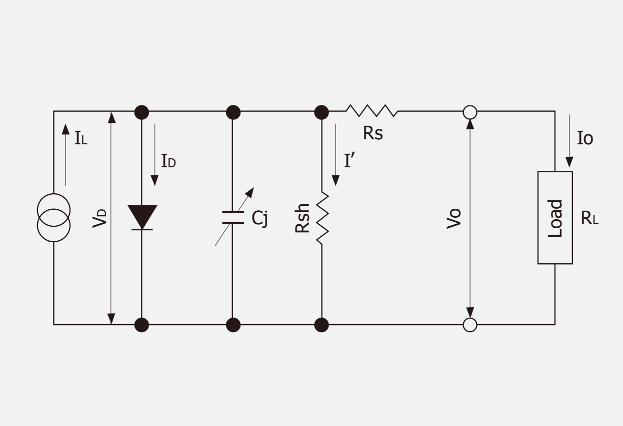
Figure 1: Silicon photodiodes operating principle



Subsequently, the electric field propels these electron-hole pairs in opposite directions — electrons toward the depletion layer and holes toward the P-layer. Notably, as shown in Figure 1, when incident light has a long wavelength, some electron-hole pairs are generated in the N-layer, resulting in electrons being retained in the N-layer. These holes diffuse through the N-layer to the depletion layer, undergo acceleration, and aggregate in the P-layer. This configuration positions positive charges in the P-layer and negative charges in the N-layer. Connecting the P-layer and N-layer to an external circuit allows the flow of electron-holes, generating a current.

We can summarize the behavior of an InGaAs PD with the following equivalent circuit in Figure 2 below.

Figure 2: InGaAs PD circuit example



I_L : current generated by incident light
(proportional to light level)
V_D : voltage across diode
I_D : diode current
C_j : junction capacitance
R_{sh} : shunt resistance
I' : shunt resistance current
R_s : series resistance
V_o : output voltage
I_o : output current

Using the above equivalent circuit, the output current (I_O) is given by the equation:

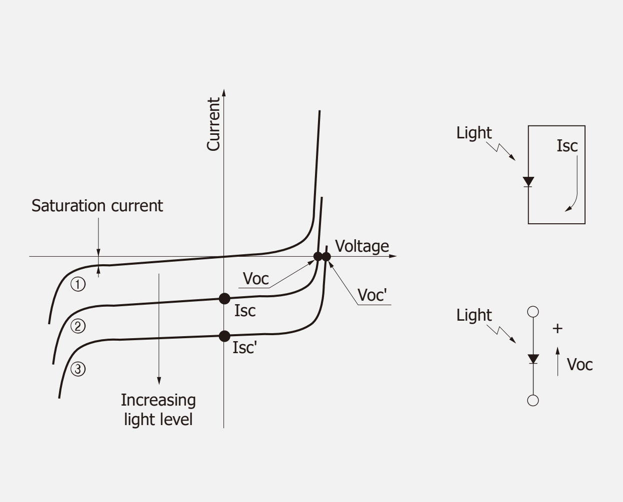
$$I_o = I_L - I_D - I' = I_L - I_S (\exp \frac{q\,V_D}{k\,T} - 1) - I'$$

I_s : current generated by incident light
(proportional to light level)
q : voltage across diode
k : diode current
T : junction capacitance

Current vs voltage characteristics

In low-light conditions, the current vs voltage characteristics exhibit the typical rectifier diode behavior, as depicted by curve 1 in Figure 3 below. However, when illuminated, the curve shifts to 2, reflecting an increase in incident light. This shift occurs in parallel with position 3.

Figure 3: Rectifier diode behavior



Upon illumination, a short circuit current (I_{SC} or $I_{SC'}$) proportional to the light level is generated when the InGaAs PD terminals are shorted. Conversely, in an open circuit, an open circuit voltage (V_{OC} or $V_{OC'}$) is produced, with positive polarity at the anode.

Noise characteristics

The detection sensitivity of InGaAs PDs is constrained by their noise characteristics. Referring back to the equivalent circuit in Figure 3, the InGaAs PD noise current (in) comprises the sum of the thermal noise current (or Johnson noise current, ij) from a resistor approximating the shunt resistance (R_{sh}), and the shot noise current arising from both dark current and photocurrent as shown in this equation:

$$in = \sqrt{ij^2 + i_{SD}^2 + i_{SL}^2}\ \ [A]$$

Now, let's delve into the descriptions of the three contributions which make up this sum.

1. ij equation

The first is viewed as the thermal noise of R_{sh} and is given by the following equation:

$$ij = \sqrt{\frac{4k\,T\,B}{R_{sh}}}\ [A]$$

k : Boltzmann's constant
T : absolute temperature of photodiode
B : noise bandwidth

2. i_{SD} equation

To describe the shot noise i_{SD} we can use the dark current generated from the reverse voltage applied to the Si photodiode:

$$i_{SD} = \sqrt{2q\,I_D B}[A]$$

q : electron charge
I_D : dark current

3. i_{SL} equation

The shot noise i_{SL} is generated by the photocurrent (I_L) due to the incident light expressed by the equation:

$$i_{SL} = \sqrt{2q\,I_L\,B}[A]$$

When I_L is >> $0.026/R_{sh}$ or $I_L >> I_D$, the shot noise current i_{SL} becomes predominant compared to the other two dark currents.

4. Noise equivalent power

Another important characteristic of photodiodes is their noise equivalent power (NEP) which is the incident light level required to generate a current equal to the noise current:

$$NEP = \frac{in}{S}\ [W/Hz^{1/2}]$$

in : noise current $[A/Hz^{1/2}]$
S : photosentitivity [A/W]

Spectral response

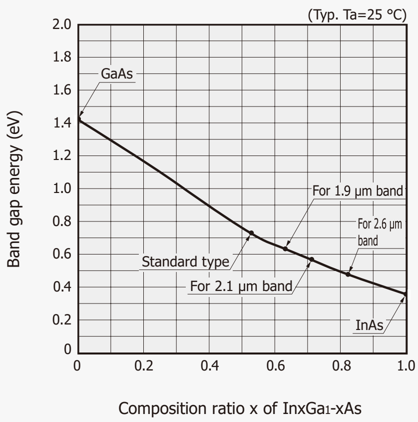
The cutoff wavelength of photodiodes is expressed by the following equation:

$$\lambda c = \frac{1.24}{Eg}\ [nm]$$

Eg : band gap energy [eV]

For InGaAs PD the band gap energy depends on the composition ratio of In and Ga:

Figure 4: Band gap energy vs composition ratio x of InxGa1-xAs



Hamamatsu provides standard types having a cutoff wavelength of 1.7 µm, short-wavelength enhanced types, and long-wavelength types having a cutoff wavelength extending to 1.9 µm, 2.1 µm or up to 2.6 µm.

Response characteristics

The response speed of a photodiode is the measure of how fast the generated carriers are extracted to an external circuit as output current. The conventional definition for the sensors is the rise time of cutoff frequency which is the time required for the output signal to charge from 10% to 90% of the peak output value. We can express the rise time by the following equation:

$$tr = 2.2Ct\,(R_L + R_s)$$

C_t : terminal capacitance
R_L : load resistance
R_S : series resistance

Generally, R_s can be disregarded because $R_L >> R_s$. To reduce the rise time, C_t and R_L should be lowered, but R_L is determined by an external factor and so cannot freely be charged. C_t is proportional to the photosensitive area (A) and is inversely proportional to the square root of the reverse voltage (V_R):

$$C_t \propto \frac{A}{\sqrt{V_R}}$$

Higher response speeds can be obtained by applying a reverse voltage to a photodiode with a small photosensitive area.

Navigating optical advancements with new InGaAs PIN Photodiodes

Hamamatsu Photonics has made speed its priority for the success of optical communication, leading to the development of an ultra-high-speed InGaAs PIN photodiode. This innovation complements their existing 25 Gbps and 50 Gbps photodiodes. Leveraging their optical design and manufacturing expertise, Hamamatsu has incorporated advanced techniques to maximize light guidance into a compact photosensitive area. This approach ensures an equivalent signal-to-noise ratio (S/N ratio) compared to standard products.

The resulting InGaAs PIN photodiode operates effectively at low reverse voltage and demonstrates reliable performance in transmission bands up to 64 Gbps at V_R = 2V when paired with an optimized preamp. The culmination of their efforts is exemplified in their latest device, which can be explored further at www.hamamatsu.com/eu/en/product/optical-sensors/infrared-detector/ingaas-photodiode/G12183-210KA-03.html

While this represents their most recent achievement, Hamamatsu is committed to pushing boundaries and is actively working towards achieving even higher speeds in their future sensor developments.

Hamamatsu's ongoing commitment to optical innovation

In the realm of optical communication, harnessing the potential of near-infrared light stands out as one of the most pivotal challenges in the coming years. Despite the manifold advantages presented by this light spectrum, it is not without its complexities. Concurrently, engineers worldwide are delving into the exploration of Quantum communications, heralding a new era in secure and efficient data transfer.

With a rich history in the design and production of optical components, Hamamatsu emerges as a reliable partner for those navigating the intricacies of advancing optical communication technologies. Offering a comprehensive suite of products, Hamamatsu is dedicated to supporting customer developments across a diverse array of applications.

Hamamatsu consistently refines products to meet evolving optical communication challenges. Explore their InGaAs photodiodes, positioning Hamamatsu as a collaborative force in addressing corporate advancements: www.hamamatsu.com/eu/en/product/optical-sensors/photodiodes/ingaas-photodiode.html