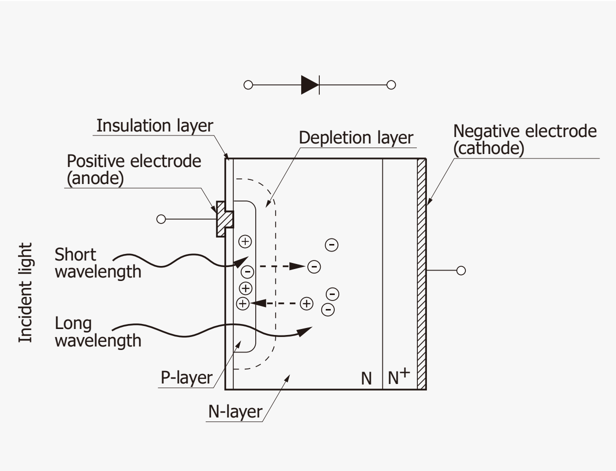
Photodiodes Exposed: Unlocking the characteristics of these crucial sensors

Photodiodes are semiconductor diodes that are sensitive to light. They generate an electric current that is proportional to the number of photons the diode is exposed to. This characteristic makes photodiodes a crucial type of sensor for various applications, such as medical and scientific measurements, analytical, fire safety, optical communications, photovoltaics, and automation.

Operating principle

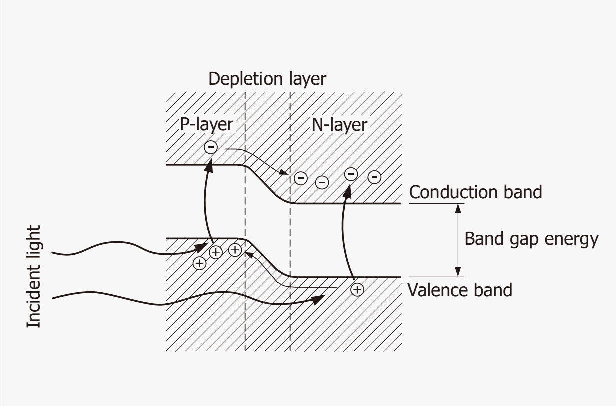
The following figure shows a cross-section example of a Si photodiode:

Figure 1: Schematic of Si photodiode cross section



When photons with light energy greater than the band gap are absorbed from the Si photodiode, electrons in the valence band are excited to the conduction band, leaving holes in the valence band.

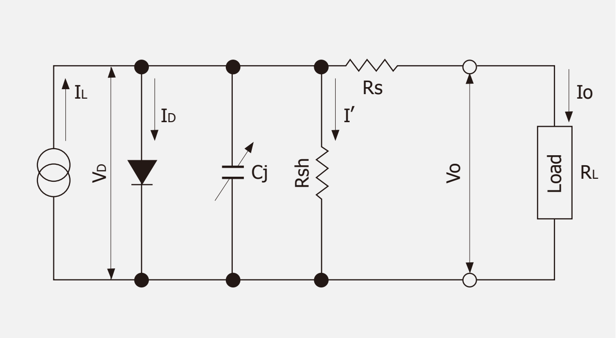
Figure 2: Silicon photodiodes operating principle



The electric field accelerates these electron-hole pairs from the depletion layer to opposite directions (electrons toward the depletion layer and the holes toward the P-layer). As shown in the figure above, when the incident light has a long wavelength, some electron-hole pairs can be generated in the N-layer. In this case, the electrons are left in the N-layer. The holes are diffused through the N-layer up to the depletion layer, accelerated, and collected in the P-layer. This means that the positive charges are in the P-layer and the negative charges are collected in the N-layer. When the P-layer and the N-layer are connected to an external circuit the electron-hole pairs will flow away and generate a current.

We can explain the behavior of the photodiode with the following circuit diagram:

Figure 3: 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
R_L : load resistance [Ω]

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

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

I_s : photodiode reverse saturation current
q : electron charge
k : Boltzma's constant
T : absolute temperature of photodiode

When **Io** = 0 we can calculate the open circuit voltage (**Voc**), expressed by the equation:

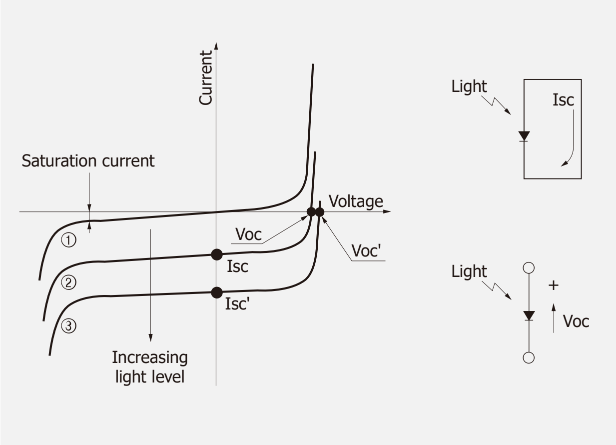
$$V_{oc} = \frac{k T}{q} \ln\left(\frac{I_L - I'}{I_s} + 1\right)$$

If **I′** is negligible, since **Is** increases exponentially with respect to ambient temperature, **Voc** is inversely proportional to the ambient temperature and proportional to the log of **IL**. Please consider that this relationship is not maintained when detecting low light levels.

Current vs voltage characteristics

In dark conditions, the current vs voltage characteristic is the usual, rectifier diode shown as 1 in the following figure. When light strikes the photodiode, the curve at 1 shifts to 2, and the increasing incident light shifts the level to position 3 in parallel.

Figure 4: Rectifier diode behavior

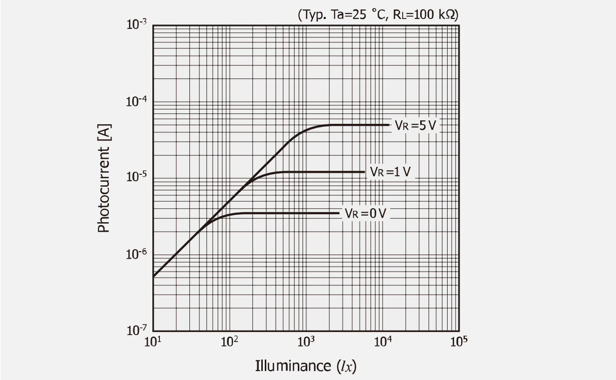


When the light is incident on the Si photodiode, a short circuit current (in this example **Isc** or **Isc′**) is generated when the terminals are shorted. This short circuit current is directly proportional to the intensity of the incident light, and it flows from the anode to the cathode. If the circuit is open, an open circuit voltage (**Voc** or **Voc′**) will be generated with the positive polarity at the anode.

Linearity characteristics

One of the most important properties of a Si Photodiode is the high level of linearity for the photocurrent with respect to the incident light level:

Figure 5: Photocurrent vs. illuminance (S1223)



Data based on Hamamatsu Photonics' S1223 SI PIN photodiode.

The lower limit of this linearity is determined by the noise equivalent power, while the upper limit depends on the load resistance and reverse voltage, and is expressed by the following equation:

$$P_{sat} = \frac{V_{Bi} + V_R}{(R_S + R_L) \times S_\lambda}$$

P_{sat} : input energy [W] at upper limit of linearity ($P_{sat} \leq 10$mW)
V_{BI} : contact voltage [V] (approx. 0.2 to 0.3V)
V_R : reverse voltage [V]
R_S : photodiode series resistance (several ohms)
R_L : load resistance [Ω]
S_λ : photosensitivity [A/W] at wavelenght λ

Please remember that as the series resistance component increases, the linearity degrades.

Noise characteristics

As outlined, the lower limits of light detection for Si photodiodes are determined by their noise characteristics. If we consider the equivalent circuit, Fig 3, the Si photodiode noise current (**in**) is the sum of the thermal noise current (or Johnson noise current, **Ij**) of a resistor which approximates the shunt resistance (**Rsh**) and the shot noise current resulting from the dark current and the photocurrent:

$$i_n = \sqrt{i_j^2 + i_{SD}^2 + i_{SL}^2} \ [A]$$

Let's see how we can describe these three contributions. Ij is viewed as the thermal noise of Rsh and is expressed by this equation:

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

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

To describe the short noise ISD we can use the dark current generated from the reverse voltage applied to Si photodiode:

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

q : electron charge
I_D : dark current

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

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

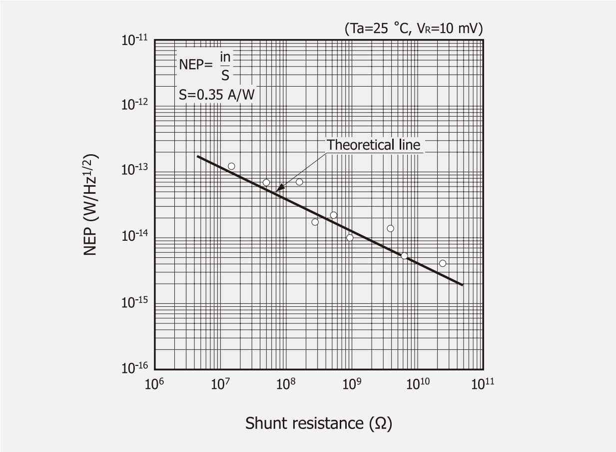
When $I_L >> 0.026/R_{sh}$ or $I_L >> I_D$, the shot noise current I_{SL} becomes predominant compared to the other two dark currents.

A very important characteristic of a Si photodiode is the noise equivalent power (**NEP**) which is the incident light level required to generate a current equal to the noise current:

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

In the following figure, we can see a very good match between the data and the theoretical line obtained when **Ij** is predominant:

Figure 6: NEP vs. shunt resistance (S1226-5BK)



Data based on Hamamatsu Photonics' S1226-5BK Si photodiode.

Response speed characteristics

The response speed of a photodiode is a 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 the cutoff frequency which is the time required for the output signal to charge from 10% to 90% of the peak output value.

To calculate the rise time we need to consider:

1. Time constant t_1 related to terminal capacitance C_t and load resistance R_L

$$t_1 = 2.2 \times C_t \times R_L$$

To have a short t_1, we need to consider in the design that C_t and R_L are made smaller. C_t is proportional to the photosensitive area (A) and inversely proportional to the depletion layer width (d), and in turn proportional to the electrical resistivity (ρ) of the substrate material:

$$C_j \propto A \{(V_R + 0.5) \times \rho\}^{-1/2 \text{ to } -1/3}$$

It is important to note that applying a reverse voltage also increases dark current. Therefore, it is necessary to be careful, particularly for low-light-level detection.

2. Diffusion time t_2 of carriers generated outside the depletion layer

Usually, this time is greater than several microseconds and, in many cases, can be considered negligible.

3. Carrier transit time t_3 in the depletion layer

We can describe the transit time in the depletion layer as the ratio between the depletion layer width and the transit speed (vd). The transit speed (vd) is the product between the carrier travelling rate (μ) and the electric field (E) that expresses using the reverse voltage (VR) became (E = VR/D).

We can describe this transit time as:

$$t_3 = \frac{d}{vd} = \frac{d^2}{\mu V_R}$$

The total response time will be:

$$tr = \sqrt{t_1^2 + t_2^2 + t_3^2}$$

Therefore, the slowest factor becomes predominant. Please consider that t1 and t3 contain factors in conflict, so if we decrease for example t1 we increase t3. During the design phase it is very important to find the right balance between these three factors.

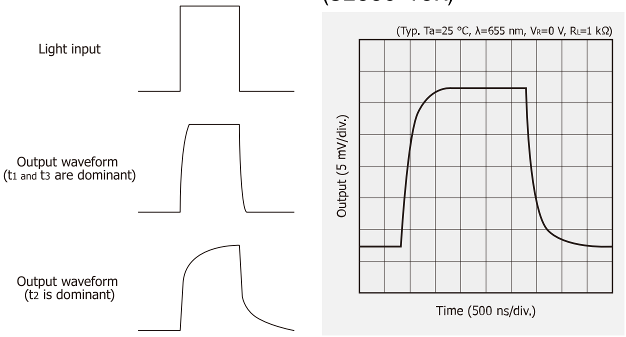
The cutoff frequency (fc) is defined as the frequency at which the photodiode output drops by 3 dB relative to 100% output level, which is maintained while the sine wave frequency is increased. This is roughly approximated from rise time (tr) as:

$$fc = \frac{0.35}{tr}$$

For applications that require a high-speed response such as optical communications, usually PIN photodiodes are designed such that fewer carriers are generated outside the depletion layer, the terminal capacitance is small and the carrier transit time in the depletion layer is short.

An example of our Si PD:

Figure 7: Examples of response waveforms and frequency characteristics



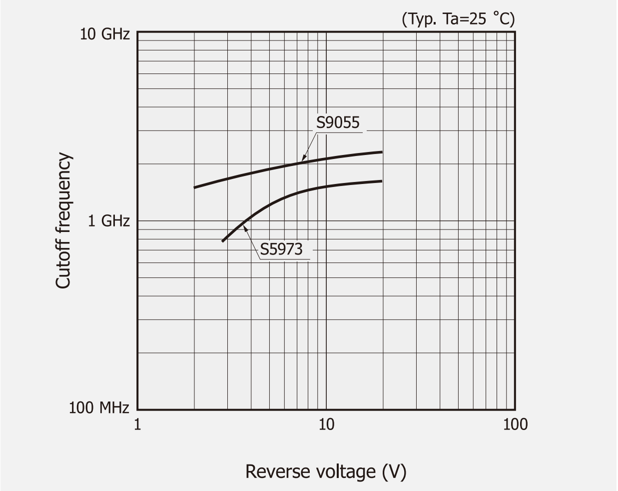
(a) Response waveforms

(b) Response waveform (S2386-18K)

Data based on Hamamatsu Photonics' S2386-18K Si photodiode.

Hamamatsu Si photodiodes exhibit relatively low dark current when reverse voltage is applied, and have excellent voltage resistance:

Figure 8: Cutoff frequency vs. reverse voltage (S5973, S9055)



Data based on Hamamatsu Photonics' S5973 and S9055 Si PIN photodiodes.

Reference

Si Photodiodes, Technical Notes, Hamamatsu Photonics, Oct. 2023: https://www.hamamatsu.com/content/dam/hamamatsu-photonics/sites/documents/99_SALES_LIBRARY/ssd/si_pd_kspd9001e.pdf