Photodiode Characteristics and Applications

Silicon photodiodes are semiconductor devices responsive to high-energy photons and particles. Photodiodes operate by absorption of photons or charged particles and generate a flow of current in an external circuit, proportional to the incident power. Photodiodes can be used to detect the presence or absence of discrete quantities of light and can be calibrated for extremely accurate measurements from intensities below 1 pW/cm² to intensities above 100 mW/cm². Silicon photodiodes are utilized in such diverse applications as spectroscopy, photography, analytical instrumentation, optical position sensors, beam alignment, surface characterization, laser range finders, optical communications, and medical imaging instruments.

**PLANAR DIFFUSED SILICON PHOTODIODE CONSTRUCTION**

Planar diffused silicon photodiodes are simply P-N junction diodes. A P-N junction can be formed by diffusing either a P-type impurity (anode), such as Boron, into a N-type bulk silicon wafer, or a N-type impurity, such as Phosphorous, into a P-type bulk silicon wafer. The diffused area defines the photodiode active area. To form an ohmic contact another impurity diffusion into the backside of the wafer is necessary. The impurity is an N-type for P-type active area and P-type for an N-type active area. The contact pads are deposited on the front active area of defined areas, and on the backside, completely covering the device. The active area is then passivated with an antireflection coating to reduce the reflection of the light for a specific predefined wavelength. The non-active area on the top is covered with a thick layer of silicon oxide. By controlling the thickness of bulk substrate, the speed and responsivity of the photodiode can be controlled. Note that the photodiodes, when biased, must be operated in the reverse bias mode, i.e. a negative voltage applied to anode and positive voltage to the cathode.

**PRINCIPLE OF OPERATION**

Silicon is a semiconductor with a band gap energy of 1.12 eV at room temperature. This is the gap between the valence band and the conduction band. At absolute zero temperature the valence band is completely filled and the conduction band is vacant. As the temperature increases, the electrons become excited and escape from the valence band to the conduction band by thermal energy. The electrons can also be accelerated to the conduction band by particles or photons with energies greater than 1.12eV, which corresponds to wavelengths shorter than 1100 nm. The resulting electrons in the conduction band are free to conduct current.

Due to concentration gradient, the diffusion of electrons from the N-type region to the P-type region and the diffusion of holes from the P-type region to the N-type region, develops a built-in voltage across the junction. The inter-diffusion of electrons and holes between the N and P regions across the junction results in a region with no free carriers. This is the depletion region. The built-in voltage across the depletion region results in an electric field with maximum at the junction and no field outside of the depletion region. Any applied reverse bias adds to the built-in voltage and results in a wider depletion region. The electron-hole pairs generated by light are swept away by drift in the depletion region and are collected by diffusion from the undepleted region. The current generated is proportional to the incident light or radiation power. The light is absorbed exponentially with distance and is proportional to the absorption coefficient. The absorption coefficient is very high for shorter wavelengths in the UV region and is small for wavelengths longer than 1200 nm. Moreover, photons with energies smaller than the band gap are not absorbed at all.

The depletion region of the photodiode is represented by a current source in parallel with a series of parallel plate capacitor (Figure 1). The junction capacitance is directly proportional to the diffused area of the photodiode and the applied reverse bias (Equation 2). The capacitance is also dependent on the reverse bias due to the reverse bias fields. The junction capacitance is directly proportional to the diffused area and inversely proportional to the width of the depletion region.

**ELECTRICAL CHARACTERISTICS**

A silicon photodiode can be represented by a current source in parallel with an ideal diode (Figure 3). The current source represents the current generated by the incident radiation, and the diode represents the P-N junction. In addition, a junction capacitance (Cj) and a shunt resistance (Rsh) are in parallel with the other components. The shunt resistance (Rs) is connected in series with all components in this model.

Shunt Resistance, Rsh

Shunt resistance is the slope of the current-voltage curve of the photodiode at the origin, i.e. V=0. Although an ideal photodiode should have an infinite shunt resistance, actual values range from 10's to 1000's of Mega ohms. Experimentally it is obtained by applying a 10 mV, measuring the current and calculating the resistance. Shunt resistance is used to determine the noise current in the photodiode with no bias (photovoltaic mode). For best photodiode performance the highest shunt resistance is desired.

Series Resistance, Rs

Series resistance of a photodiode arises from the resistance of the contacts and the resistance of the undepleted silicon (Figure 1). It is given by:

\[
R_s = \frac{(W - W_a) \rho}{A} \quad (1)
\]

Where W is the thickness of the substrate, W_a is the width of the depletion area, A is the diffused area of the junction, and \( \rho \) is the resistivity of the substrate and R_s 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 are measured.

Junction Capacitance, Cj

The boundaries of the depletion region act as the plates of a parallel plate capacitor (Figure 1). The junction capacitance is directly proportional to the diffused area and inversely proportional to the width of the depletion region. In addition, higher resistivity substrates and a higher reverse bias results in a lower junction capacitance. Furthermore, the capacitance is dependent on the reverse bias as follows:

\[
C_j = \frac{\varepsilon_r \varepsilon_0 A}{2 \varepsilon_d \mu_p (V+V_a)} \quad (2)
\]

Series resistance adds to the built-in voltage and results in a wider depletion region. The resulting smaller area of the depletion region results from the decrease in voltage of silicon and \( V+V_a \) 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, t_r / t_f

The rise and fall time of a photodiode is defined as the time for the signal to rise or fall from 10% to 90% or 90% to 10% of the final value respectively. This parameter can be also expressed as frequency response, which is the frequency at which the photodiode output decreases by 3dB. It is roughly approximated by:

\[
t_{f/d} = \frac{0.35}{f_{3dB}} \quad (3)
\]

There are three factors defining the response time of a photodiode:

1. \( t_{diffusion} \), the charge collection time of the carriers in the undepleted region of the photodiode.
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3. \( t_{RC} \), the RC time constant of the diode-circuit combination.

\( t_{diffusion} \) is determined by \( t_{diffusion} = t_{diffusion} + t_{diffusion} + t_{RC} \), where \( W_a \) is the sum of the diode series resistance and the RC time constant of the photodiode (RC), and \( Cj \) is the sum of the photodiode capacitance and the stray capacitance. Since the photodiode capacitance is proportional to the diffused area of the photodiode and the applied reverse bias (Equation 2), faster rise times are obtained for larger diffused areas and larger applied reverse biases. In addition, stray capacitance can be minimized by using short leads, and careful layout of the electronic components. The total rise time is determined by:

\[
t_{r/d} = \sqrt{t_{diffusion}^2 + t_{diffusion}^2 + t_{RC}^2} \quad (4)
\]

Generally, in photovoltaic mode of operation (no bias), rise time is dominated by the diffusion time for diffused areas less than 5 mm² and by RC time constant for larger diffused areas for all wavelengths. When operated in photovoltaic mode (applied reverse bias), if the photodiode is fully depleted, such as high speed areas, the dominant factor is the drift time. In non-depleted photodiodes, however, all three factors contribute to the response time.

**Typical Capacitance vs. Reverse Bias**

Where \( \kappa = 8.854 \times 10^{-12} \) F/cm², is the permittivity of free space, \( \kappa_n = 11.9 \) is the silicon dielectric constant, \( \mu = 1400 \) cm²/Vs is the mobility of the electrons at 300 K, \( \kappa_r = \kappa - \kappa_r \) is the resistivity of the silicon, \( V_a \) is the built-in voltage in silicon and \( V+V_a \) 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.

![Figure 4. Capacitance of Photocathode Devices versus Reverse Bias Voltage](image-url)
Photodiode Characteristics

Quantum Efficiency, Q.E.
Quantum efficiency is defined as the fraction of the incident photons that contribute to photocurrent. It is related to responsivity by:

\[ Q.E. = \frac{R_p \text{ Observed}}{R_p \text{ Ideal}} \quad (6) \]

where \( h = 6.63 \times 10^{-34} \text{Js} \), \( c = 3 \times 10^8 \text{m/s} \), \( q = 1.6 \times 10^{-19} \text{C} \), and \( \lambda \) is the wavelength in nm.

Non-Linearity
A silicon photodiode is considered linear if the generated photocurrent increases linearly with the incident light power. Photocurrent linearity is determined by measuring the small change in photocurrent as a result of a small change in the incident light power as a function of total photocurrent or incident light power. Non-Linearity is the variation of the ratio of the change in photocurrent to the same change in light power, i.e. \( \Delta I_p / \Delta I_p \).

Noise Equivalent Power (NEP)
Noise Equivalent Power is the amount of incident light power on a photodetector that results in a specified amount of noise power. NEP is defined as:

\[ \text{NEP} = \sqrt{2q(I_d + I_p)\Delta f} \quad (9) \]

where \( I_d \) is the photodiode dark current, \( I_p \) is the reverse saturation current, \( q \) is the electron charge, \( V \) is the voltage applied, \( k_B = 1.38 \times 10^{-23} \text{J/K} \) is the Boltzmann constant, and \( T \) is the absolute temperature (273 K = 0°C).

Total Noise
The total noise current generated in a photodetector is determined by:

\[ I_n = \sqrt{\frac{4k_B T \Delta f}{R_S}} \quad (10) \]

where \( k_B = 1.38 \times 10^{-23} \text{J/K} \) is the Boltzmann constant, \( T \) is the absolute temperature in degrees Kelvin (273 K = 0°C), \( R_S \) is the shunt resistance of the photodiode. This type of noise is known as Johnson noise.

Noise Equivalent Power (NEP)
Noise Equivalent Power is the amount of incident light power on a photodetector, which generates a photocurrent equal to the noise current. NEP is defined as:

\[ \text{NEP} = \frac{I_n}{I_p} \quad (11) \]

where \( I_n \) is the total noise of the photodetector, \( I_p \) is the photocurrent, and \( I_p \) is the photogenerated current. NEP values can vary from 10^{-11} W/Hz for large area photodiodes down to 10^{-15} W/Hz for small active area photodiodes.
Photodiode Characteristics

TEMPERATURE EFFECTS

All photodiode characteristics are affected by changes in temperature. They include shunt resistance, dark current, breakdown voltage, responsivity and to a lesser extent other parameters such as junction capacitance.

Shunt Resistance and Dark Current:

There are two major currents in a photodiode contributing to dark current and shunt resistance. Diffusion current is the dominating factor in a photovoltaic (unbiased) mode of operation, which determines the shunt resistance. It varies as the square of the temperature. In photoconductive mode (reverse biased), however, the drift current becomes the dominant current (dark current) and varies directly with temperature. Thus change in temperature affects the photodetector more in photoconductive mode than in photovoltaic mode of operation.

In photoconductive mode the dark current may approximately double for every 10°C increase in temperature. And in photovoltaic mode, shunt resistance may approximately double for every 6°C decrease in temperature. The exact change is dependent on additional parameters such as the applied reverse bias, resistivity of the substrate as well as the thickness of the substrate.

Breakdown Voltage:

For small active area devices, by definition breakdown voltage is defined as the voltage at which the dark current becomes 10µA. Since dark current increases with temperature, therefore, breakdown voltage decreases similarly with increase in temperature.

Responsivity:

Effects of temperature on responsivity is discussed in the "Responsivity" section of these notes.

BIASING

A photodiode signal can be measured as a voltage or a current. Current measurement demonstrates far better linearity, offset, and bandwidth performance. The generated photocurrent is proportional to the incident light power and it must be converted to voltage using a transimpedance configuration. The photodiode can be operated with or without an applied reverse bias depending on the application specific requirements. They are referred to as “Photoconductive” (biased) and “Photovoltaic” (unbiased) modes.

Photoconductive Mode (PC)

Application of a reverse bias (i.e. cathode positive, anode negative) can greatly improve the speed of response and linearity of the device. This is due to increase in the depletion region width and consequently decrease in junction capacitance. Applying a reverse bias, however, will increase the dark and noise currents. An example of low light level / high speed response operated in photoconductive mode is shown in figure 8.

In this configuration the detector is biased to reduce junction capacitance thus reducing noise and rise time (t_r). A two stage amplification is used in this example since a high gain with a wide bandwidth is required. The two stages include a transimpedance pre-amplifier for current- to-voltage conversion and a non-inverting amplifier for voltage amplification. Gain and bandwidth (f_3dB) are directly determined by R_L, per equations (13) and (14). The gain of the second stage is approximated by 1 + R_1 / R_2. A feedback capacitor (C_L) will limit the frequency response and avoid gain peaking.

Photovoltaic Mode (PV)

The photovoltaic mode of operation (unbiased) is preferred when a photodiode is used in low frequency applications (up to 350 kHz) as well as ultra low level light level applications. In addition to offering a simple operational configuration, the photodiodes in this mode have less variations in responsivity with temperature. An example of an ultra low light level / high speed is shown in figure 10.

In high speed, high light level measurements, however, a different approach is preferred. The most common example is pulse width measurements of short pulse gas lasers, solid state laser diodes, or any other similar short pulse light source. The photodiode output can be either directly connected to an oscilloscope (Figure 8) or fed to a fast response amplifier. When using an oscilloscope, the bandwidth of the scope can be adjusted to the pulse width of the light source for maximum signal to noise ratio. In this application the bias voltage is large. Two opposing protection diodes should be connected to the input of the oscilloscope across the input and ground.

In low speed applications, a large gain, e.g. >10^6 can be achieved by introducing a large value (R_L) without the need for the second stage.

Typical components used in this configuration are:

- Amplifier: OPA-671, OPA-468, OPA-487, or similar
- R_L: 1 to 10 KΩ Typical, depending on C_L
- R_1: 10 to 50 KΩ
- R_2: 0.5 to 10 KΩ
- C_L: 0.2 to 2 pF
- C_P: 100 pF

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To avoid ringing in the output signal, the cable between the detector and the oscilloscope should be short (< 20cm) and terminated with a 50 ohm load resistor (R_L). The photodiode should be enclosed in a metallic box, if possible, with short leads between the detector and the capacitor, and between the detector and the coaxial cable. The metallic box should be tied through a capacitor (C1), with lead length (L) less than 2 cm, where R_L, C1 > 10 * I_r where I_r is the DC photocurrent. Bandwidth is defined as 0.35 / T. A minimum of 100V reverse bias is necessary for this application. Note that a bias larger than the photodiode maximum reverse voltage should not be applied.

Photovoltaic Mode of Operation Circuit Example:

Ultra low level light / low speed

In this example, a FET input operational amplifier as well as a large reverse bias resistor (R_L) are required. The generated photocurrent is amplified by an operational amplifier. In this example, the photocurrents in this mode have less variations in responsivity with temperature.

For stability, select C_L such that

\[
\frac{1}{2 \pi R_L (C_L + C_P + C_s)} > \frac{1}{2 \pi R_L C_s}
\]

Operating bandwidth, after gain peaking compensation is:

\[
f_{op} [Hz] = \frac{1}{2 \pi R_L C_s}
\]

Some recommended components for this configuration are:

- Amplifier: OPA-117 or similar
- R_L: 500 MΩ

These examples or any other configurations for single photodiodes can be applied to any of OSI Optoelectronics’ monolithic, common substrate linear array photodiodes. The output of the first stage amplifiers can be connected to a sample and hold circuit and a multiplexer. Figure 11 shows the block diagram for such configuration.

Figure 8. Photodiode Characteristics

Figure 9. Photodiode Characteristics

Figure 10. Photodiode Characteristics