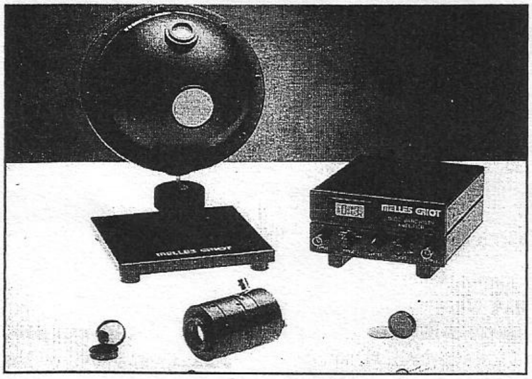


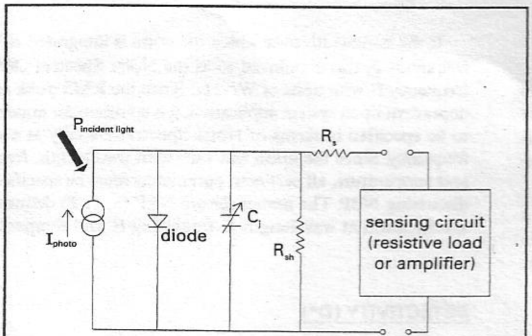
Quantifying Photodiode Performance

Melles Griot manufactures a broad range of products for sensing and measuring visible and near-infrared radiation, including silicon photodiodes, detector current amplifiers, an integrating sphere, and modular mounts for associated optical components. They not only work together but also work with our wide range of existing optical components, component holders, and positioners. In this chapter, we define and discuss the important electrical, electro-optical, and physical characteristics often specified for a photodiode.

EQUIVALENT CIRCUIT

Photodiodes have complex electrical characteristics and can best be understood using the concept of the equivalent circuit. This is a lumped-sum equivalent circuit of individual components (resistors, capacitors, etc.) whose behavior models that of the actual photodiode.

The *ideal* photodiode can be considered as a current source parallel to a semiconductor diode. The current source corresponds to the current flow caused by the light-generated drift current, while the diode represents the behavior of the junction in the absence of incident light.



LUMPED-SUM EQUIVALENT CIRCUIT MODEL OF A PHOTODIODE.

An *actual* photodiode is represented by the circuit shown in the figure. In addition to a current source in parallel with a semiconductor diode, a nonconductive layer devoid of carriers (depletion layer) is sandwiched between two conductive layers. This is a classic parallel plate capacitor, which can only support charge separation in one direction. The effective capacitance is termed the *junction capacitance* (C_j) and is represented in the equivalent circuit by a capacitor in parallel with the other components. The photodiode junction also has finite *shunt resistance* (R_{sh}). Ancillary parts of the diode (neutral layers, electrical contacts) also give rise to a resistance, usually much smaller than the shunt resistance. This resistance acts between the diode junction and the signal sensing circuit and is therefore termed the *series resistance* (R_s). The series resistance can usually be assumed to equal zero for modeling and computational purposes.

PHOTODIODE OPERATION

A photodiode behaves as a photocontrolled current source in parallel with a semiconductor diode and is governed by the standard diode equation:

$$I = I_{photo} + I_{dk}\left(e^{qV_o/kT} - 1\right)$$

where I is the total device current

I_{photo} is the photocurrent

I_{dk} is the dark current

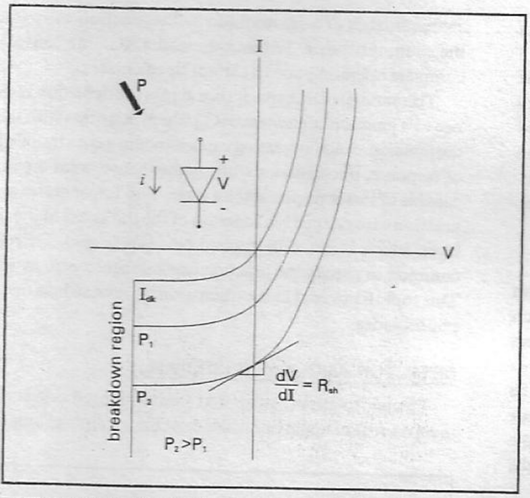
V_o is the voltage across the diode junction

q is the charge of an electron

k is Boltzmann's constant

T is the temperature in degrees Kelvin.

The I-V (current-voltage) relationship of this equation is shown on the following page. Two significant features to note from both the curve and the equation are that the photogenerated current (I_{photo}) is additive to the diode current, and the dark current is merely the diode's reverse leakage current. Finally, the detector shunt resistance is the slope of the I-V curve (dV/dI) evaluated at V = 0.



THE I-V RELATIONSHIP OF A PHOTODIODE.

QUANTUM EFFICIENCY

Photodiodes are quantum devices. Each incoming photon will generate either one or zero units of electron charge which will contribute to the photocurrent. The probability of generating a charge is termed the quantum efficiency. Quantum efficiency mainly depends on how efficiently charge carriers are swept across the junction. The overall quantum efficiency of the photodiode is often referred to as external quantum efficiency (η).

RESPONSIVITY

Responsivity ($\Re$) quantifies the photoelectric gain of a detector. Photodiode responsivity is the ratio of the photocurrent (across an effective zero resistance) generated for each watt of incident light power, expressed as Amps/Watt (A/W). Responsivity depends directly on the quantum efficiency. The maximum theoretical achievable responsivity corresponds to detection of every incident photon (unit quantum efficiency). The energy carried by each photon depends on its frequency according to the equation $E = h\nu$, where ν is the photon frequency (inversely proportional to λ, its wavelength) and h is Planck's constant. Therefore, expressing the responsivity in A/W (as opposed to A/photon) gives this parameter an inherent wavelength dependency:

$$\Re = \frac{q\eta\lambda}{hc}$$

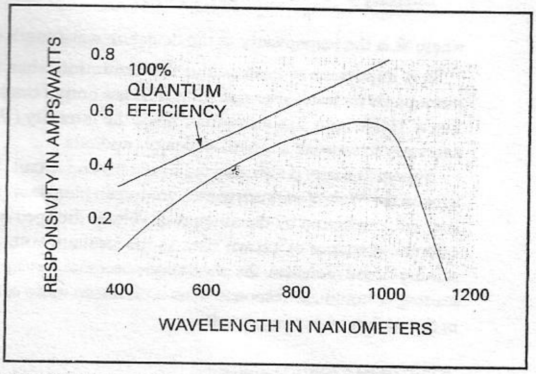
i.e., $$\Re = \frac{\eta\lambda}{1.24\times10^{-6}}\ \text{A/W}$$

where c is the speed of light

q is the charge of an electron

λ is the wavelength in meters of the photons being detected.

Responsivity has an additional wavelength dependence arising from the variation of quantum efficiency with wavelength. At wavelengths where silicon does not absorb strongly, photons may penetrate more deeply into the device (or pass through it), leading to minority carrier generation too remote from the junction to be detected, i.e., lower quantum efficiency. The typical shape of the silicon photodiode responsivity spectral curve is determined by the absorption spectrum of silicon. Photodiode responsivity is usually specified at a single wavelength unless a complete wavelength calibration is performed.



TYPICAL RESPONSIVITY OF A MELLES GRIOT SILICON PHOTODIODE.

As an example, a silicon photodiode will normally have a high quantum efficiency for light at 800 nm. Assuming a typical η of 0.8 at this wavelength, this leads to a responsivity of 0.52 A/W. At 400 nm a typical η would be only 0.15, which leads to a responsivity of 0.1 A/W.

Responsivity alone is a weak figure of merit because it specifies only the gain of a photodiode, not its associated noise. Signal-to-noise ratio represents the ultimate figure of merit, as discussed later.

LINEARITY OF RESPONSE

In many applications it is necessary for the responsivity to remain constant over a wide range of incident light power. Most P-N silicon photodiodes are linear (better than 1%) over seven or eight orders of magnitude. However, when the number of incident photons becomes comparable to the number of electron-hole locations in the active region, the device saturates, resulting in a loss of linearity.

In the case of the Melles Griot PNN+ silicon photodiodes, the photocurrent will have a linear relationship to the incident intensity, providing:

Current Density $< 5 \times 10^{-5}\ \text{A/mm}^2$.

The maximum allowable radiant intensity is therefore given by:

$$\text{Intensity} < \frac{5\times10^{-5}}{\Re}\ \text{W/mm}^2$$

where $\Re$ is the responsivity at the detection wavelength in A/W.

It is important to understand this limitation when using a photodiode to detect laser radiation. The raw output beam from a 1 mW HeNe laser has more than twice the intensity (W/mm^2) necessary to saturate a typical silicon photodiode.

System linearity is also affected by the sensing circuit. Incident light on the photodiode's active area produces a photocurrent which is usually measured by the amount of voltage dropped across an external resistance of known size. As the resultant voltage in the sensing circuit increases, the photodiode becomes forward biased, leading to nonlinear response. This is discussed more completely in the section on sensing circuits.

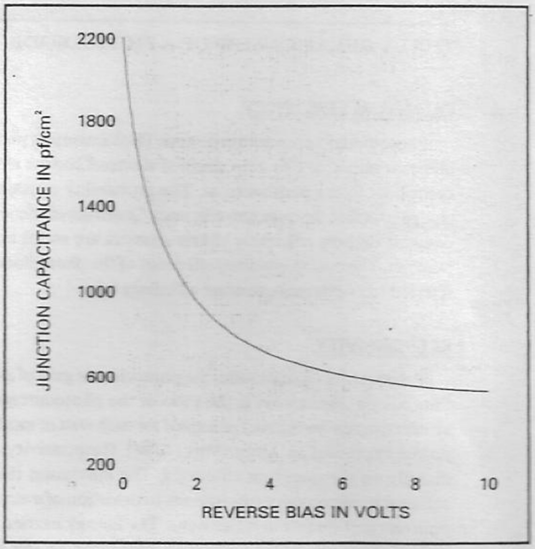
JUNCTION CAPACITANCE

When designing a sensing circuit to maximize the speed or linearity of response, one must know two important electrical characteristics of a photodiode — the junction capacitance and the shunt resistance. Without these, the RC time constant of the complete operating circuit cannot be calculated.

The parallel plate capacitance across the depletion region gives rise to a junction capacitance (C_j) which increases with the area of the junction. Since increasing capacitance in a circuit slows its speed of response, photodiodes with smaller active areas are inherently capable of faster response than those with larger active areas. The junction capacitance is a function of the thickness of the depletion layer, which varies with applied bias (*see graph*). Therefore, it is common to specify the junction capacitance at zero external bias. This topic is covered in the discussion on reverse bias operation of photodiodes.

DETECTOR ANGULAR RESPONSE

The photocurrent generated from a photodiode is essentially independent of angle of incidence of the incoming radiation when



TYPICAL RELATIONSHIP OF A SILICON PHOTODIODE'S JUNCTION CAPACITANCE AND APPLIED BIAS.

the angle of incidence is less than 30°. Typically, a variation in photocurrent of 1 to 2% can be expected, provided the detector's active area is underfilled, i.e., the incoming radiation does not completely cover the device's entire active area. (This condition assumes the photodiode's absorption layer thickness approximately equals the depletion layer thickness in the photodiode junction.)

In circumstances where the photodiode is immersed in a collimated beam of incident light, the device's responsivity will fall off with the cosine of the angle of incidence as follows:

$$\Re_\theta = \Re \cos \theta$$

where $\Re$ is the photodiode responsivity at normal incidence.

PHOTODIODE SPEED OF RESPONSE

Inherent limitations of photodiode response are due to structure and specific junction design, the presence of an externally applied bias, and the wavelength of incoming radiation. The inherent time constant of a photodiode causes a delay in generated photo current (τ). For Melles Griot silicon photodiodes, this time constant is typically 7 to 15 nsec. The photodiode speed of response for various load conditions is discussed in the section on sensing circuits for photodiodes.

DARK CURRENT

The P-N junction of a photodiode does not present an infinite resistance to reverse current flow. Consequently, when a reverse bias is applied to a photodiode, a small current (I_{dk}) flows even in the absence of incident light, as shown in the I-V curve. This dark current increases slowly with increasing reverse bias.

A large dark current is undesirable since it may represent a significant background above which the actual photocurrent is measured. Furthermore, shot noise associated with the dark current may be significant.

BREAKDOWN REGION

There is a maximum reverse bias voltage that can be applied to a photodiode, called the reverse breakdown voltage. At this point, the device is no longer useful as a photodetector and can sustain permanent damage. Care should be taken to limit the current through the diode in the reverse bias region so that the resultant power dissipated does not exceed 200 mW.

NOISE EQUIVALENT POWER AND SIGNAL-TO-NOISE RATIO

Noise Equivalent Power (NEP) is the incident light level impinging on a photodiode, which produces a photocurrent equal to the noise level. It is usually regarded as the most significant figure of merit for a photodetector. The NEP is a function of the photodiode's responsivity, the noise of the photodiode and the associated sensing circuit, and the frequency bandwidth over which the noise is measured. In systems applications, the Signal-to-Noise Ratio (SNR) may be computed by taking the ratio of the incident optical power to the photodiode NEP.

In general terms, NEP is defined as follows:

$$\mathrm{NEP}_{\mathrm{rms}} = \frac{i_{\mathrm{rms}}}{\Re}$$

where $\Re$ is in A/W.

The RMS noise current (i_{rms}) is the total integrated noise over the frequencies of interest (f_1 to f_2), defined as follows:

$$i_{\mathrm{rms}} = \sqrt{\int_{f_1}^{f_2} \left(i_1^2(f) + i_2^2(f) + \ldots i_N^2(f) \right) df}\,.$$

If the bandwidth over which the noise is integrated is 1 Hz at frequency F, this is referred to as the Noise Spectral Density at frequency F, with units of W/$\sqrt{\mathrm{Hz}}$. Since the RMS noise is highly dependent upon system application, it is common for noise sources to be specified in terms of Noise Spectral Density at a specific frequency. Since the noise will vary with wavelength, frequency, and temperature, all pertinent parameters must be specified when discussing NEP. The nomenclature NEP (λ, F, T) delineates the specification at wavelength λ, frequency F, and temperature T.

DETECTIVITY (D*)

Detectivity (D*) is often used to describe the sensitivity for a class of photodetectors. It is inversely proportional to the NEP and is normalized to the area of the detector. A high detectivity value indicates a low-noise photodiode or detection system:

$$D^*(\lambda,\ 1\ \mathrm{Hz},\ T) = \frac{\sqrt{\mathrm{area}}}{\mathrm{NEP}(\lambda,\ 1\ \mathrm{Hz},\ T)} \quad \frac{\mathrm{cm}\sqrt{\mathrm{Hz}}}{\mathrm{W}}.$$

NOISE SOURCES

The lower detection limit for any photodetector is ultimately determined by the device's noise characteristics. There are three main contributions to photodiode noise.

Johnson Noise

The statistical fluctuation in the thermal electron-hole pair generation is called thermal noise or Johnson noise ($I_{R_{sh}}$). Johnson noise is broadband "white" noise and is expressed as noise per unit bandwidth. The expression for Johnson noise of the photodiode shunt resistance is:

$$I_{R_{sh}} = \sqrt{\frac{4kT}{R_{sh}}} \quad \mathrm{A}/\sqrt{\mathrm{Hz}}$$

where k is Boltzmann's constant

T is the absolute temperature in degrees Kelvin

R_{sh} is the shunt resistance in ohms.

As seen from the above formula, Johnson noise increases in proportion to the square root of the temperature.

Shot Noise

Shot noise (I_{sh}) is the statistical noise associated with the photocurrent and dark current (if present). Since shot noise is also broadband, it is expressed as noise per unit bandwidth:

$$I = \sqrt{2q\left(I_{photo} + I_{dk}\right)} \quad \mathrm{A}/\sqrt{\mathrm{Hz}}$$

where q is the charge carried by an electron

I_{photo} is the photocurrent

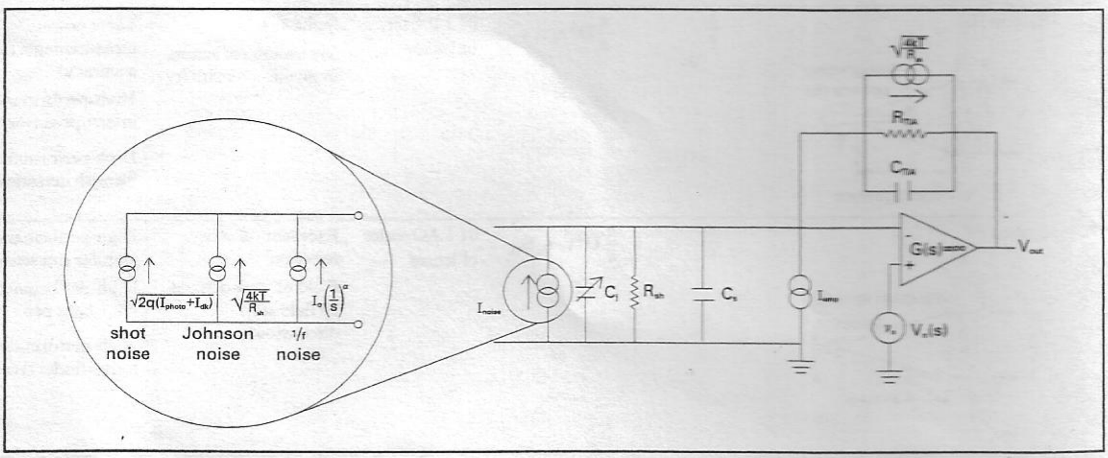
I_{dk} is the dark current

1/f Noise

The mechanism for 1/f noise is not particularly well understood. Often the characteristics are empirically determined for individual families of photodetectors. The 1/f noise is governed by the following characteristics:

$$I_{1/f}\left(s\right) = I_o\left(\frac{1}{s}\right)^{\alpha} \quad \mathrm{A}/\sqrt{\mathrm{Hz}}$$

where I_o is typically an inverse function of the active area



SYSTEM NOISE MODEL OF A DETECTOR AND TRANSIMPEDANCE AMPLIFIER SENSING DETECTOR.

α is an empirically derived constant that will vary from 0.25 to 1.0 depending upon the specific construction of the detector

s is the Laplace operator and = $j\omega$.

1/f noise is of concern at frequencies below 100 Hz. For higher frequency applications, photodiode performance is limited by other noise sources.

TEMPERATURE EFFECTS

Like all semiconductor devices, photodiodes are temperature sensitive. The relative population inversion of electrons and holes in the P- and N-layers of the photodiode is directly influenced by temperature, which changes the conductivity and shifts the absorption spectrum. The major photodiode parameters that are sensitive to temperature are shunt resistance, dark current, and, to a lesser extent, responsivity.

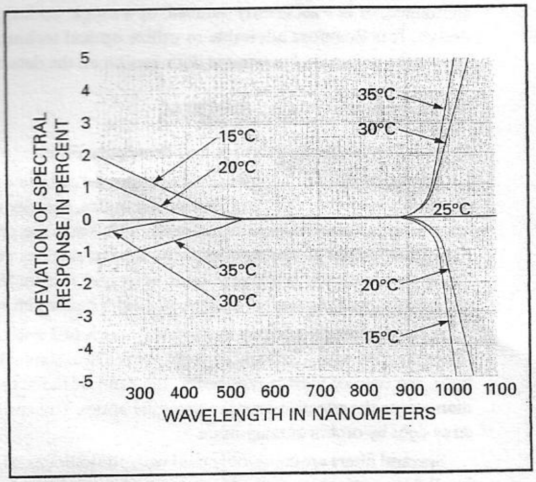
Typically, the dark current of a PNN+ silicon photodiode approximately doubles for each 10°C increase or decrease in the device temperature. The shunt resistance approximately doubles for each 6°C change:

$$I_{dk}(T_2) = I_{dk}(T_1)\,2^{\frac{(T_2-T_1)}{10}}$$

$$R_{sh}(T_2) = R_{sh}(T_1)\,2^{\frac{(T_2-T_1)}{6}}$$

These formulas can be used to calculate the shunt resistance and dark current for any temperature from the specified values, which are usually specified at 25°C.

Increasing the temperature of a semiconductor shifts its absorption spectrum to longer wavelengths by reducing the effective band gap. Fortunately, the absorption spectrum of silicon is quite broad. Consequently, the small temperature-induced shifts in the absorption spectrum only affect the responsivity significantly at the edges of the spectral responsivity curve, as shown in the figure below.



TEMPERATURE DEPENDENCE OF SILICON PHOTODIODE RESPONSIVITY.