Characteristics and Use of Photodiodes

INTRODUCTION

Photodiodes make use of the photovoltaic effect —the generation of a voltage across a P-N junction of a semiconductor when the junction is exposed to light. While the term photodiode can be broadly defined to include even solar batteries, it usually refers to sensors intended to detect the intensity of light. Photodiodes can be classified by function and construction as follows.

- **Photodiode Types**
  1) PN photodiodes
  2) PIN photodiodes
  3) Schottky type photodiodes
  4) Avalanche photodiodes

All of these types provide the following features and are widely used for the detection of the existence, intensity, position and color of light.

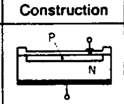
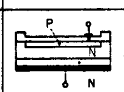
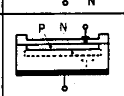
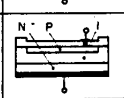
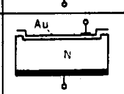
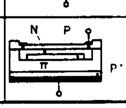
- **Features**
  1) Excellent linearity
  2) Low noise
  3) Wide spectral response
  4) Mechanical ruggedness
  5) Compact and lightweight
  6) Long life

This section will serve to introduce the construction characteristics, operation and use of photodiodes.

CONSTRUCTION

Hamamatsu photodiodes can be classified by manufacturing method and construction into five types of silicon photodiodes and two types each of GaAsP and GaP photodiodes.

Table 1: Photodiodes Types

Type	Construction	Features	Photodiode types
Planar diffusion type		Small dark current	Silicon photodiodes (eg. S2386, S2387 series, S1087, S1133 series) GaAsP photodiodes
Low C_j planar diffusion type		Small dark current Fast response High UV sensitivity High IR sensitivity	Silicon photodiodes (S1336 series, S1337 series)
PNN$^+$ type		Small dark current High UV sensitivity Suppressed IR sensitivity	Silicon photodiodes (S1226 series, S1227 series)
PIN type		Ultra-fast response	PIN silicon photodiodes
Schottky type		High ultraviolet sensitivity	GaAsP, GaP photodiodes
Avalanche type		Internal multiplying mechanism Ultra-fast response	Silicon avalanche 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 layer 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 of short wavelengths.

● PIN Type

An improved version of the low-capacitance planar diffusion device, this type makes use of an extra high-resistance I 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 bias 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

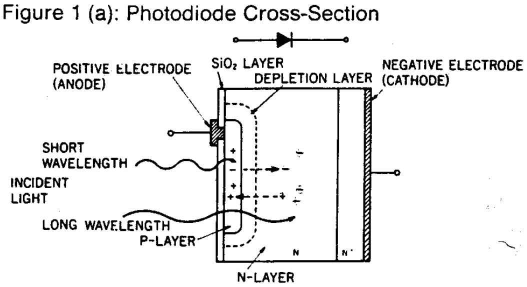
If a reverse bias is applied to a P-N junction and a high-field formed within the depletion layer, photon carriers will be accelerated by this field. They will collide with atoms in the field and secondary carriers are produced, this process occurring repeatedly. This is known as the avalanche effect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

THEORY OF OPERATION

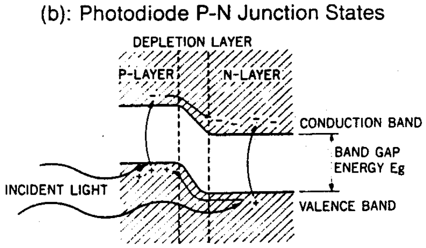
Figure 1 (a) shows a cross section of a photodiode. The P-layer material at the light sensitive surface and the N material at the substrate form a P-N junction which operates as a photoelectric converter. The usual P-layer for a silicon photodiode is formed by selective diffusion of boron to a thickness of approximately 1 μm and the neutral region at the junction between the P and N layers is known as the depletion layer. By varying and controlling the thickness of the outer P-layer, substrate N-layer and bottom N$^+$ layer as well as the doping concentration, the spectral response and frequency response can be controlled.

When light is allowed to strike a photodiode, the electrons within the crystal structure become stimulated. If the light energy is greater than the band gap energy E_g, the electrons are pulled up into the conduction band, leaving holes in their place in the valence band (see Figure 1 (b)). These electron-hole pairs occur throughout the P-layer, depletion layer and N-layer materials, and in the depletion layer the electric field accelerates the electrons towards the N-layer and the holes toward the P-layer. Of the electron-hole pairs that are generated in the N-layer, the electrons, along with electrons that have arrived from the P-layer, are left in the N-layer conduction band, while the holes diffuse through the N-layer up to the P-N junction while being accelerated, and collect in the P-layer valence band. In this manner, electron-hole pairs which are generated in proportion to the amount of incident light are collected in the N-layer and P-layer. This results in a positive charge in the P-layer and a negative charge in the N-layer. If an external circuit is connected between the P- and N-layers, electrons will flow away from the N-layer and holes from the P-layers towards the opposite electrode, respectively.

Figure 1 (a): Photodiode Cross-Section



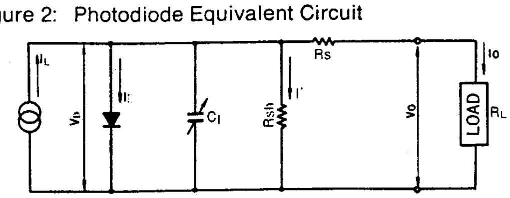
(b): Photodiode P-N Junction States



EQUIVALENT CIRCUIT

The photodiode equivalent circuit is shown in Figure 2.

Figure 2: Photodiode Equivalent Circuit



I_L: Current generated by the incident light (proportional to the amount of light)

I_D: Diode current

C_j: Junction capacitance

R_{sh}: Shunt resistance

R_s: Series resistance

I': Shunt resistance current

V_D: Voltage across the diode

I_O: Output current

V_O: Output voltage

Using the above equivalent circuit and solving for the output current, we have:

$$I_o = I_L - I_D - I' = I_L - I_s \left(exp \frac{eV_D}{kT} - 1\right) - I'$$

Where

I_s: photodiode reverse saturation current

e: Electron charge

k: Boltzmann's constant

T: Absolute temperature of the photodiode

The open circuit voltage V_{op} is the output voltage when I_o equals 0. Therefore, we have:

$$V_{op} = \frac{kT}{e} \ln\left(\frac{I_L - I'}{I_s} + 1\right)$$

If we ignore I', since I_s increases logarithmically with respect to increasing ambient temperature, V_{op} is inversely proportional to ambient temperature and inversely proportional to the log of I_L. However, this relationship does not hold for very small amounts of incident light.

The short-circuit I_{sh} is the output current when the load resistance R_L equals 0 and V_O equals 0, yielding:

$$I_{sh} = I_L - I_s \left(exp \frac{e(I_{sh} \cdot R_s)}{kT} - 1\right) - \frac{I_{sh} \cdot R_s}{R_{sh}}$$

In the above relationship, the 2nd and 3rd terms limit I_{sh} linearity. However, if R_s is several ohms or lower and R_{sh} is 10^7 to 10^{11} ohms, these terms become negligible over quite a wide range.

V-I CHARACTERISTICS

When a voltage is applied to a photodiode in the dark state, the V-I characteristic curve observed is similar to the curve of a conventional rectifier diode as shown in Figure 3 ①. However when light strikes the photodiode, the curve at ① shifts to ② and, increasing the amount of incident light shifts the characteristic curve still further to position ③ in parallel with respect to incident light intensity. For the characteristics for ② and ③, if the photodiode terminals are shorted, a photocurrent I_{sh} or I_{sh}' proportional to the light intensity will flow in the direction from the anode to the cathode. If the circuit is open, an open circuit voltage V_{op} or V_{op}' will be generated with the positive polarity at the anode.

Figure 3: V-I Characteristics

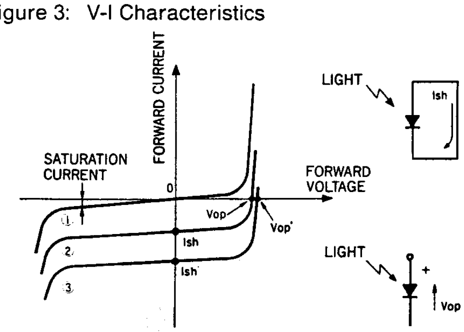
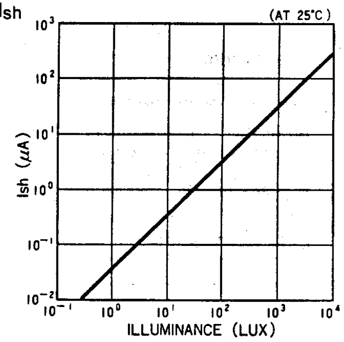
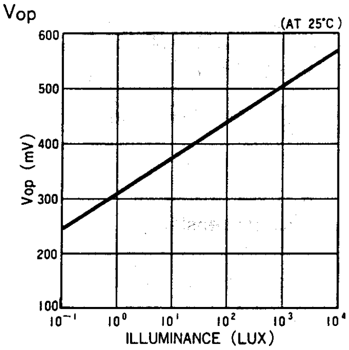


Figure 4: Output Signal vs. Incident Light Relationship (S2386-5K)

(a) Ish



(b) Vop



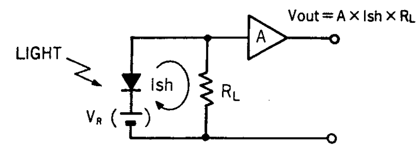
The short circuit current I_{sh} is extremely linear with respect to the amount of incident light. The achievable range of linearity is 6 to 8 orders of magnitude, depending upon the type of photodiode and circuit in which it is used. V_{op} varies logarithmically with respect to a change of amount of light and is greatly affected by variations in temperature, making it unsuitable for light intensity measurements. Figure 4 shows the result of plotting I_{sh} and V_{op} as a function of incident light illuminance.

Figure 5 (a) and (b) show methods of measuring light by measuring I_{sh}. In the circuit shown at (a), the voltage (I_{sh} x R_L) is amplified by an amplifier A and the use of the bias voltage V_R makes this circuit suitable for receiving high-speed pulse light, although the circuit has limitations with respect to linearity. This condition is shown in Figure 6. In the circuit of Figure 5 (b), an operational amplifier is used and the characteristics of the feedback circuit are such that the equivalent input resistance is several orders of magnitude smaller than R_f, enabling nearly ideal I_{sh} measurements. The value of R_f can be changed to enable I_{sh} measurements over a wide range.

If the zero region of Figure 3 ① is magnified, we see, as shown in Figure 7, that the dark current is linear over a voltage range of approximately ±10 mV. The slope in this region is termed the shunt resistance (R_{sh}) and this resistance is the cause of thermal noise currents described later. In this catalog, values of R_{sh} are given using a dark current of I_d with −10 mV applied.

Figure 5: Photodiode Operational Circuits

(a) Reverse Bias Circuit



(b) Op-Amp Circuit

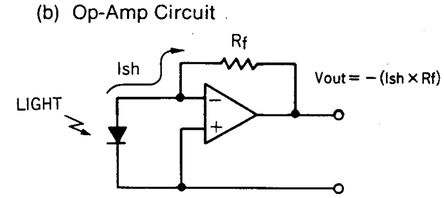


Figure 6: V-I Characteristics and Load Line

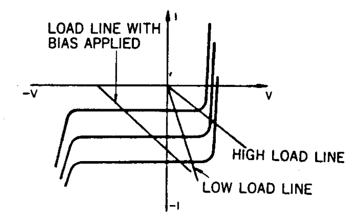
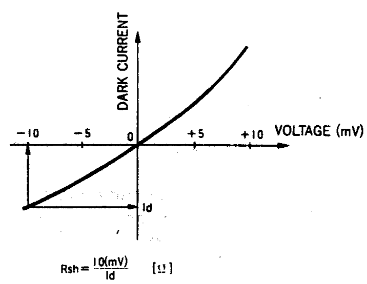


Figure 7: V-I Characteristics (Expanded Zero Region)



SPECTRAL RESPONSE CHARACTERISTICS

As explained in the section on principles of operation, when the energy of absorbed photons is lower than the band gap energy E_g, the photovoltaic effect does not occur. The limiting wavelengths λ can be expressed in terms of E_g as follows.

$$\lambda = \frac{1240}{E_g} \quad [\text{nm}] \qquad (1)$$

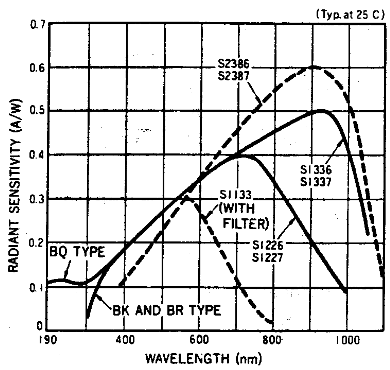
At room temperatures, E_g is 1.12eV for silicon and 1.8eV for GaAsP, so that the limiting wavelengths are 1100nm and 700nm, respectively. For short wavelengths, however, the degree of light absorption within the diffusion layer becomes very high. Therefore, the thinner the diffusion layer is and the closer the P-N junction is to the surface, the higher the sensitivity will be (see Figure 1 (a)). For normal photodiodes the cutoff wavelength is 300 to 400nm.

whereas for ultraviolet enhanced photodiodes (e.g. S1226 and S1336) it is below 190nm.

The cutoff wavelength is determined by the intrinsic material properties of the photodiode, but is also affected by the spectral transmittance of the window material. For borosilicate glass and plastic resin coating, wavelengths below approximately 300nm are absorbed. If these materials are used as the window, the short wavelength sensitivity will appear to be lost. For wavelengths below 300nm, photodiodes with fused silica windows are used. For measurements limited to the visible light region, a green filter is used as the light-receiving window.

Figure 8 shows the spectral response characteristics for various photodiode types. The BQ type shown uses a fused silica window, the BK type a borosilicate glass window and the BR type a resin coated window.

Figure 8: Spectral Response Characteristics



NOISE CHARACTERISTICS

Like other types of light sensors, the lower limits of light detection for photodiodes are determined by the noise characteristics of the device. The photodiode noise i_n is the sum of the thermal noise (or Johnson noise) i_j caused by the shunt resistance R_{sh} and the shot noise i_s resulting from the dark current and the photocurrent.

$$i_n = \sqrt{i_j^2 + i_s^2} \quad [A] \qquad (2)$$

When a photodiode is used in an operational amplifier circuit such as that shown in Figure 5 (b), since the applied voltage is the operational amplifier's input offset voltage only, the dark current may be ignored and i_n is given as follows.

$$i_n = i_j = \sqrt{\frac{4kTB}{R_{sh}}} \qquad (3)$$

Where
k: Boltzmann's constant
T: Absolute temperature of the photodiode
B: Noise bandwidth

When a bias voltage is applied as in Figure 5 (a), there is always a dark current. For a bias voltage of 1 to 2 V or greater, $i_s \gg i_j$, so that i_n is given as follows.

$$i_n = i_s = \sqrt{2qI_dB} \quad [A] \qquad (4)$$

Where
q: Electron charge
I_d: Dark current
B: Noise bandwidth

With the application of incident light, I_L exists and if $I_L \gg 0.026/R_{sh}$ or $I_L \gg I_d$, the above equations (3) and (4) are replaced by the following equation for shot noise.

$$i_n = i_s = \sqrt{2qI_LB} \qquad (5)$$

The amplitudes of these noise sources are each proportional to the square root of the measured bandwidth B, so that they are expressed in units of $(A/\sqrt{Hz})$.

The lower limit of light detection for a photodiode is usually expressed as the intensity of incident light required to generate a current equal to the noise current as expressed in equations (3) or (4). Essentially this is the noise equivalent power (NEP).

$$NEP = \frac{i_n}{S} \quad [W/\sqrt{Hz}] \qquad (6)$$

Where
i_n: noise
S: peak radiant sensitivity

Figure 9 shows the relationship between NEP and dark current, from which can be seen the agreement with the theoretical relationship. The light detection limit for DC coupling as shown in Figure 5(b) is influenced by the amplifier's thermal drift, low-frequency flicker noise and, as will be described later, gain peaking. Thus the limit is actually greater than the NEP.

If the incident light can be periodically switched ON and OFF by some means and detection performed in synchronization with this switching frequency, it is possible to eliminate the influence of noise outside this measurement bandwidth (refer to Figure 10). This techinique can allow the actual measured detection limit to approach the detector's theoretical NEP.

Figure 9: Relationship of NEP to Dark Current (S1226-5BK)

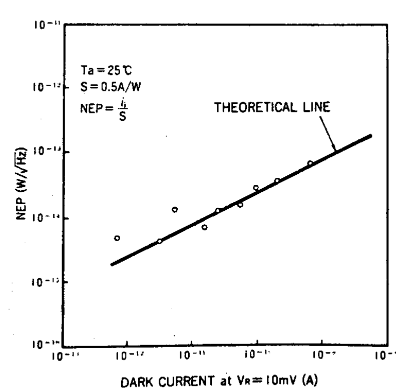
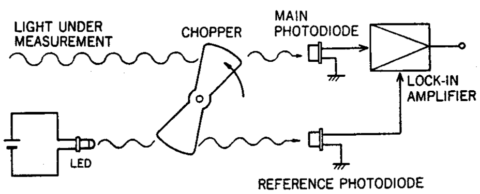


Figure 10: Synchronous Measurement Method



When compared with photodiodes not having an amplification mechanism, avalanche photodiodes exhibit additional excessive noise components caused by variations in the avalanche amplification process. Using the gain M and a light current I_L and excessive noise factor F when M = 1 in equation (4) above, we have the following expression.

$$i_n = \sqrt{2qI_LM^2FB}$$

In this expression, for M = 10 to 100, F may be approximated as follows.

$$F = M^x$$

The exponent *x* is known as the excessive noise index and is in the range of approximately 0.3 to 0.5. The advantage to using an avalanche photodiode is the ability to use a small load resistance and a small input resistance in the following stage in comparison with normal photodiodes. This enables not only an operating speed advantage, but a reduction in thermal noise generated by the noise resistance as well, thus enabling detection of extremely small signals. For details, refer to the separate data sheet.

REVERSE BIAS

Since photodiodes generate a voltage by virtue of the photovoltaic effect, they can operate without the need of an external power supply. However, speed of response and linearity can be improved by the use of such an external biasing source. It should be borne in mind that the signal current flowing in a photodiode circuit is determined by the number of photovoltaically generated electron-hole pairs and that the application of a bias voltage does not result in the loss of photoelectric conversion linearity.

Figure 11 shows an example of a reverse bias connection. Figures 12 and 13 show the effects of bias voltage on rise time and linearity limits, respectively. While application of a reverse bias to a photodiode is very useful in improving response speed and linearity, it has the accompanying disadvantage of increasing dark current and noise levels along with the danger of damaging the device by excessive applied reverse bias voltage. Thus, care is required to maintain the bias within the maximum ratings and to ensure that the cathode is maintained at a positive potential with respect to the anode.

For use in applications such as optical communications and remote control which require high response speed, the PIN photodiode provides not only good response speed but excellent dark current and voltage resistance characteristics with bias applied. Figure 14 shows an example of the actual connection shown in Figure 11 (b) with a load resistance 50 Ω. The ceramic capacitor C is used to enable a reduction of the bias supply impedance, while resistor R is used to protect the photodiode. This resistor is selected such that the voltage drop caused by the average photocurrent is sufficiently smaller than the bias voltage. Note that the photodiode and capacitor leads, coaxial cable and other wires carrying high-speed pulses should be kept as short as possible.

Figure 11: Reverse Bias Connection Example

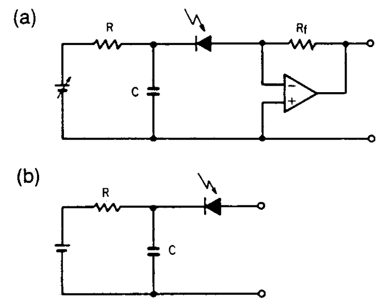


Figure 12: Risetime vs. Bias Voltage

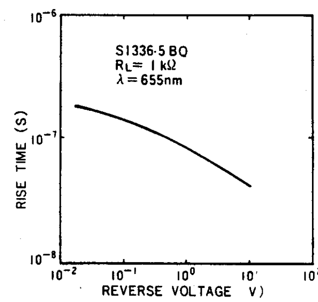


Figure 13: Linearity Limits

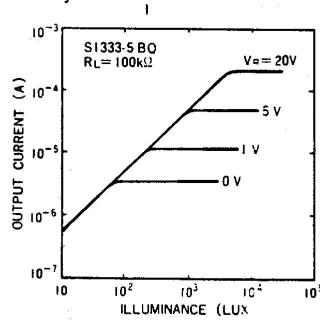
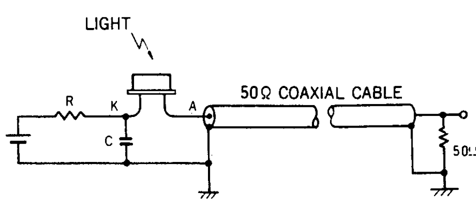


Figure 14: Connection to Coaxial Cable



RESPONSE SPEED

The response speed of a photodiode is a measure of the time required for the accumulated charge to become an external current and is generally expressed as the rise time t_r or fall time t_f. t_r is the time required to rise from 10% to 90% of the normal output value and is determined by the following factors.

1) Time constant τ_1 determined by the terminal capacitance of the photodiode C_t and the load resistance R_L.
   (C_t is the sum of the package capacitance and the photodiode junction capacitance C_j)
2) Diffusion time τ_2 of carriers generated outside the depletion layer.

If the $C_t \times R_L$ time constant τ_1 is the governing factor, t_r is given as follows.

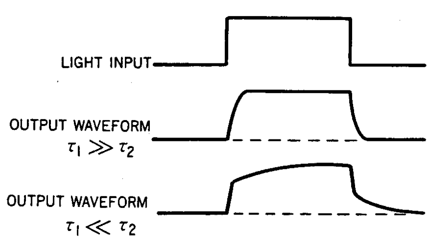
$$t_r = 2.2\tau_1 = 2.2C_t \times R_L$$

To shorten t_r, the design must be such that either C_t or R_L is made small. C_j is proportional to the light sensitive area A and inversely proportional to the second to third root of the resistivity ρ of the substrate material and reverse bias V_R.

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

Therefore, to achieve a fast response time, a photodiode with a small A and large ρ should be used with reverse bias applied. The carriers generated outside the depletion layer occur when incident light misses the P-N junction and strikes the surrounding area of the photodiode chip and when this light is absorbed by the substrate section which is below the depletion area. The time τ_2 required for these carriers to diffuse may be greater than several μs. When the $C_t \times R$ time constant is small, it is the major factor that determines the response speed. Figure 15 shows an example of the response waveform of a photodiode.

Figure 15 (a): Photodiode Response Waveform Example



In the case of a PIN or avalanche photodiode, C_t is particularly small. Also these types are designed for a low level of carrier generation outside the depletion region, thus suitable for high-speed light detection.

Figure 15 (b): S1722 Response Waveform (V_R = 100V, R_L = 50 Ω)

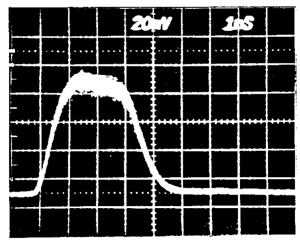
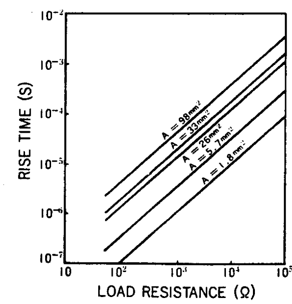


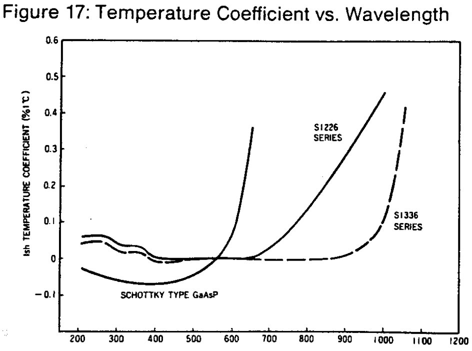
Figure 16: Rise Time vs. Load Resistance with Photosensitive Area as Parameter



TEMPERATURE CHARACTERISTICS

Ambient temperature variations greatly effect photodiode sensitivity and dark current. The cause of this is variation in the light absorption coefficient which is temperature related. For long wavelengths, sensitivity increases with increasing temperature and this increase become prominent at wavelengths longer than the peak wavelength. For short wavelengths, it decreases. Since ultraviolet enhanced photodiodes are designed to have low absorption in the short wavelength region, the temperature coefficient is extremely small at wavelengths shorter than the peak wavelength. Figure 17 shows examples of temperature coefficients of photodiodes sensitivity (I_{sh}) for a variety of photodiodes types.

Figure 17: Temperature Coefficient vs. Wavelength



The variation in dark current with respect to temperature occurs as a result of increasing temperatures causing electrons in the valence band to become excited, pulling them into the conduction band. A constant increase in dark current is shown with increasing temperature. Figure 18 indicates a two-fold increase in dark current for a temperature rise from 5°C to 10°C. This is equivalent to a reduction of the shunt resistance R_{sh} and a subsequent increase in thermal and shot noise. Figure 19 shows an example of the temperature charcteristics of open-circuit voltage V_{op}, indicating linearity with respect to temperature change.

Figure 18: Dark Current Temperature Dependence

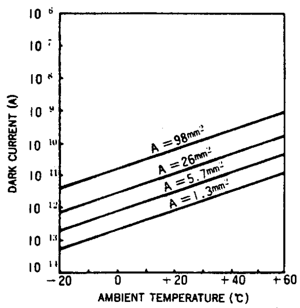
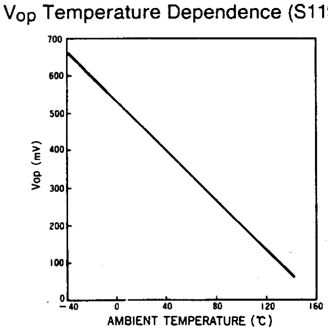


Figure 19: V_{op} Temperature Dependence (S1190)

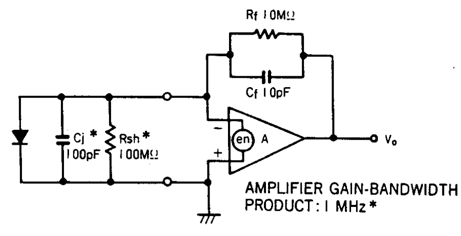


USE OF OPERATIONAL AMPLIFIERS

1) Transimpedance Circuit

Figure 20 shows a basic circuit connection of an operational amplifier and a photodiode. The output voltage V_o from DC through the low-frequency region is 180 degrees out of phase from the input short circuit current. The feedback resistance R_f is determined by I_{sh} and the required output voltage V_o. If, however, R_f is made greater than the photodiodes internal resistance R_{sh}, the operational amplifier's input noise voltage and offset voltage will be multiplied by $(R_f/R_{sh}+1)$. This is superimposed on the output voltage, and the operational amplifier's bias current error (described later) will also increase. If there is an input capacitance, the feedback capacitance C_f prevents high-frequency oscillations and also forms a lowpass filter with a time constant $C_f \times R_f$ value. It should be chosen with regard to the desired transimpedance and bandwidth. If the input light is similar to a discharge spark, and it is desired to integrate the amount of light, R_f can be removed so that the operational amplifier and C_f act as an integrating circuit.

Figure 20: Basic Photodiode Connection Example



* Values commonly available.

However, a switch is required to discharge C_f before the next integration.

2) Bias Current

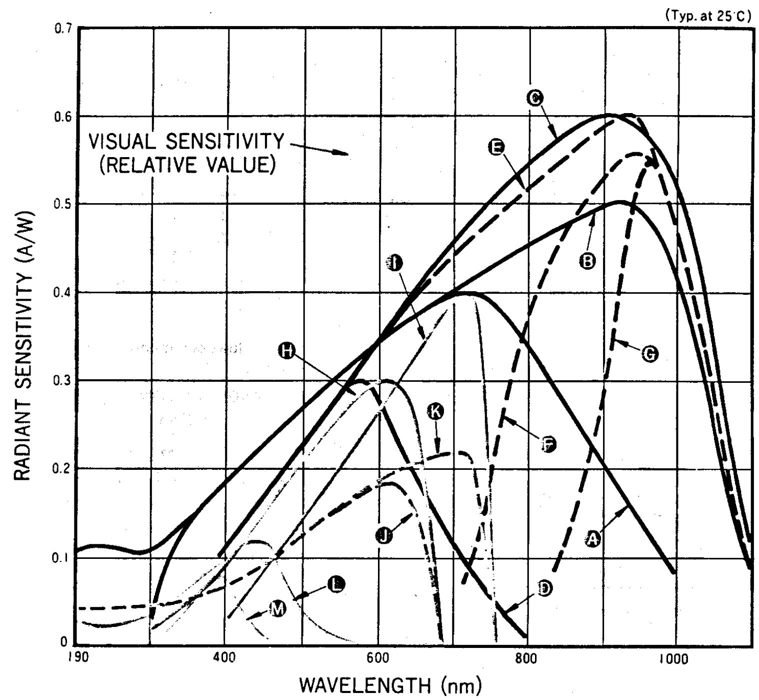
Since the actual input impedance of an operational amplifier is not infinite, there is some bias current that flows into or out of the input terminals. This may result in errors, depending upon the magnitude of the detected current. The bias current which flows in an FET input operational amplifier is sometimes lower than 0.1pA. Bipolar operational amplifiers, however, have bias currents in the order of several nA or even several hundred nA. However, the bias current of an FET operational amplifier generally increases two-fold for every increase of 10°C in temperature, whereas that of bipolar amplifiers decreases with increasing temperature. Therefore, the design of such circuits to operate at high temperatures should consider the use of bipolar amplifiers.

As is the case for offset voltage, the error voltages attributable to the bias current can be adjusted by means of a potentiometer connected to the offset adjustment terminals. Futhermore, leakage currents on the PC board used to house the circuit may be greater than the operational amplifier's bias current. Consideration must be given to the circuit pattern's design and its parts replacement. Additionally, the use of Teflon terminals and guarding may be required. However, the operational amplifier chosen is of utmost importance. A list of recommended FET and bipolar types is given on page 41.

3) Gain Peaking

The frequency response of a photodiode operational amplifier is determined by the time constant $R_f \times C_f$. However, for large values of junction capacitance (i.e., input capacitance) a phenomenon known as gain peaking will occur. Figure 21 shows an example of such a frequency response, from which it can be seen that the output voltage increases sharply in the high frequency region, causing significant ringing in the output voltage response to pulsed light input. This gain operates in the same manner with respect to operational amplifier input noise and may result in abnormally high noise levels (see Photograph (c)). This occurs by virtue of the fact that the reactance of the input capacitance and that of the feedback capacitance on the

• Photodiode Spectral Response Characteristics (Representative Example)



Type	Features	Spectral Response Characteristics			Type No.	Listed Page
		Range	Peak Wavelength	Mark		
Silicon Photodiodes	Ultraviolet to visible light, for precision photometry	190~1000	720	A	S1226, S1227 Series	14·15
	Ultraviolet to infrared, for precision photometry	190~1100	920	B	S1336, S1337 Series	16·17
	Visible light to infrared, for precision photometry	400~1100	900	C	S2386, S2387 Series	18·19
	Visible light, for general-purpose photometry	320~730	560	D	S1087, S1133, etc.	20·21
	Visible light to infrared, for general-purpose photometry	300~1100	900	–	S1087-01, S1133-01, etc.	
PIN Silicon Photodiodes	High-speed response	400~1060	900	–	S1188, S2216, S1721, etc.	22~25
		400~1100	920	E	S1190, S1223, etc.	
	For optical disk players (multi-element type)	400~1060	900	–	S2336, S2337	
	Visible light cutoff type	700~1100	950	F	S2506	
		840~1100	980	G	S2506-01	
	Large sensitive area, high ultraviolet sensitivity	190~1060	920	–	S1723-05, etc.	
GaAsP Photodiodes (Diffusion Type)	For visible light	300~680	610	H	G1115, G1116, G1117, etc.	26·27
	Extended red sensitivity	400~760	710	I	G1735, G1736, G1737, etc.	
GaAsP Photodiodes (Schottky Type)	Ultraviolet to visible light	190~680	610	J	G1125-02, G1126-02, etc.	28·29
	Extended red sensitivity	190~760	710	K	G1745, G1746, G1747 etc.	
GaP Photodiodes	Ultraviolet to green light	190~520	440	L	G1961, G1962, G1963	30·31
	Ultraviolet only	280~410	380	M	G1961-01, G1962-01	
Silicon Avalanche Photodiodes	High-speed response and high gain	350~1050	830	–	S2381, S2382, S2383, S2384, S2385	32·33

Spectral Response

The photocurrent produced by a given level of incident light varies with wavelength. This wavelength/response relationship is known as the spectral response characteristic and is expressed numerically in terms of radiant sensitivity, quantum efficiency, NEP, detectivity, etc.

Radiant Sensitivity

This measure of sensitivity is the ratio of radiant energy expressed in watts incident on the device to the photocurrent output expressed in amperes. It may be expressed as either an absolute sensitivity, i.e., the A/W ratio, or as a relative sensitivity, normalized with respect to the sensitivity at the wavelength of peak sensitivity, with the peak value usually taken as 100. For the purposes of this catalog, the spectral response range is taken to be the region within which the radiant sensitivity is within 5% of the peak value.

Quantum Efficiency (Q.E.)

This is the ratio of number of incident photons to resulting photoelectrons in the output current, without consideration given to the individual photon energy levels, resulting in a slightly different spectral response characteristic curve from that of the radiant sensitivity.

NEP (Noise Equivalent Power)

This is the amount of light equivalent to the intrinsic noise level of the device. Stated differently, it is the light level required to obtain an S/N ratio of 1. The NEP is one means of expressing the spectral response. In this brochure, the NEP value at the wavelength of maximum response is used. Since the noise level is proportional to the square root of the bandwidth, the NEP is expressed in units of $W/Hz^{1/2}$.

$$NEP = \frac{\text{Noise Current } (A/Hz^{1/2})}{\text{Radiant Sensitivity at Peak } (A/W)}$$

D* (D-Star)

Detectivity, D, is the inverse of the NEP and is used as a measure of the detection sensitivity of a device. Since noise is normally proportional to the square root of the photosensitive area, the smaller the photosensitive area, the better the apparent NEP and detectivity. To take into consideration material properties, the detectivity D is multiplied by the square root of this area to obtain D*, expressed in units of $cm \cdot Hz^{1/2}/W$. As with NEP, the values used herein are those at the wavelength of the peak sensitivity.

$$D^* \text{ (D-star)} = \frac{[\text{Effective Sensitive Area } (cm^2)]^{1/2}}{NEP}$$

Short Circuit Current (I_{sh})

This value is measured using white light of 2856K distribution temperature from a standard tungsten lamp of 100 lux illuminance (100 lux for GaP photodiodes). The short circuit current is that current which flows when the load resistance is 0 and is proportional to the device photosensitive area.

Dark Current (I_d) and Shunt Resistance (R_{sh})

The dark current is the small current which flows when reverse voltage is applied to a photodiode under dark conditions. It is a source of noise for applications in which a reverse bias is applied to photodiodes as is typically the case with PIN photodiodes. To observe the dark current there are two methods—observation of the V/I ratio (termed shunt resistance) in the 0 V region (−10 mV for the data herein), or observation of the current at actual applied reverse bias conditions.

$$R_{sh} = \frac{10 \text{ (mV)}}{\text{Dark Current at } V_R = 10 \text{ mV (A)}}$$

Junction Capacitance (C_j)

An effective capacitor is formed at the P-N junction of a photodiode. Its capacitance is termed the junction capacitance and is the major factor in determining the response speed of the photodiode. This is measured at 1 MHz for PIN types and 10 kHz for other types.

Rise Time (t_r)

This is the measure of the photodiode response to a stepped light input. It is the time required for transition from 10% to 90% of the stationary output level. Since the rise time is a function of the wavelength of the incident light and of the load resistance.
A light source matching the photodiode's spectral response and a specified load resistance is used.

Cutoff Frequency (f_c)

This is the measure of the photodiode response to sinewave incident light and frequently used for PIN photodiodes. It is defined as the frequency at which the output current decreases by 3dB from the low frequency response. The load resistance used is 50Ω.

Maximum Reverse Voltage (V_R max)

Applying reverse voltages to photodides can cause breakdown and severe deterioration of device performance. Therefore reverse voltage should be kept somewhat lower than the maximum rated value, $V_{R\ max}$, even for instantaneously applied reverse bias voltages.

UNITED DETECTOR TECHNOLOGY INC.

PLANAR DIFFUSED SILICON PIN PHOTODIODES

DESCRIPTION

These devices represent the state of the art in planar diffused silicon photodiode light sensors. They are all low leakage, low noise, high impedance, wide spectral range devices of a quality suitable for instrument use.

The "D" series is comprised of the following: PIN-3D, PIN-5D, PIN-6D, PIN-10D. This series is optimized for a voltage biased mode of operation (photoconductive), which is required for fast response (less than 750ns). These devices are particularly suited for AC light signals.

The "DP" series is comprised of the following: PIN-3DP, PIN-5DP, PIN-6DP, and PIN-10DP. This series is optimized for an unbiased mode of operation (photovoltaic). Because of their high zero bias impedance, these devices are ideally suited for coupling to an op amp in the current mode.† In this photodiode/op amp mode, dc light level changes of up to ten decades can be linearly detected and converted to an output voltage. These devices are particularly suited for DC light signals.

The PIN-3D and PIN-3DP have .03 cm^2 active areas and are hermetically sealed in a TO-18 housing. The PIN-5D and PIN-5DP have .05 cm^2 active areas and are hermetically sealed in a TO-5 housing. The PIN-6D and PIN-6DP have .20 cm^2 active areas and are hermetically sealed in a TO-8 can. The PIN-10D and PIN-10DP have 1 cm^2 active areas and are sealed in a 1" O. D. metal housing with BNC output connectors.

† P. H. Wendland, "Solid State Combo Vies With Tubes", Electronics, P. 50, 5/24/71.

PIN-3D and PIN-3DP (.03 cm^2 active area)

PIN-5D and PIN-5DP (.05 cm^2 active area)

PIN-6D and PIN-6DP (.2 cm^2 active area)

PIN-10D and PIN-10DP (1.0 cm^2 active area)

FEATURES

"D" Series

- Voltage Biased Operation (photoconductive)
- Fast Response Time
- Low Capacity
- Low Noise
- Low Dark Current

"DP" Series

- Zero Voltage Bias Operation (photovoltaic)
- Optimized for op amp hook-up
- Ultra High Impedance
- Ultra Low 1/f noise
- Ten Decade Output Linearity with DC light inputs

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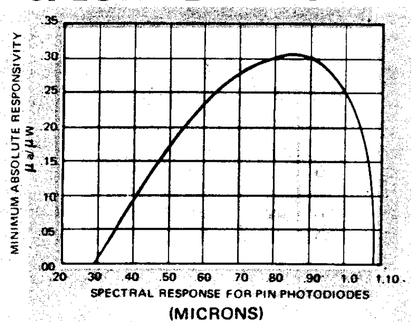
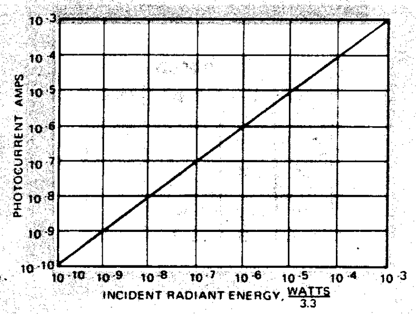
PLANAR DIFFUSED SILICON PIN PHOTODIODES (all models)

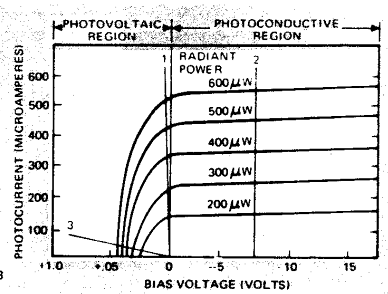
SPECTRAL RESPONSE



LINEARITY

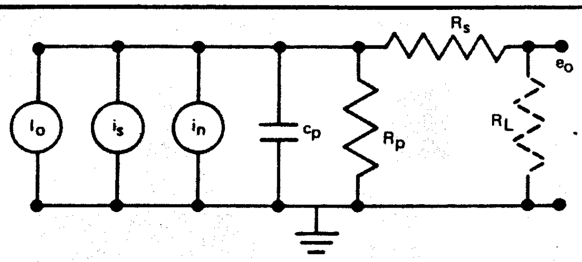


I-V CHARACTERISTICS



1 LOAD LINE WITH ZERO APPLIED BIAS AND NEAR ZERO LOAD RESISTOR
2 LOAD LINE WITH 7 V APPLIED BIAS AND NEAR ZERO LOAD RESISTOR
3 LOAD LINE WITH ZERO APPLIED BIAS AND LARGE LOAD RESISTOR

EQUIVALENT CIRCUIT (all models)



$e_o = (i_s + i_n + I_o) R_L$

i_s = signal current = $I_L R$

I_L = input light (watts)

R = responsivity (amps/watt)

i_n = noise current = $(2eI_oB)^{1/2}$

I_o = dark current (dc)

C_p = barrier capacitance

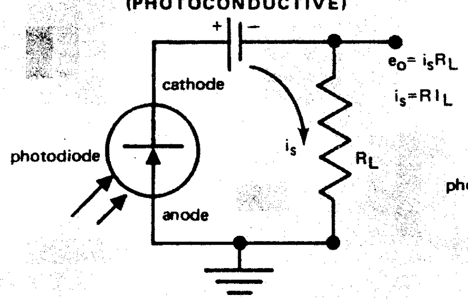
R_p = barrier resistance

R_s = series resistance

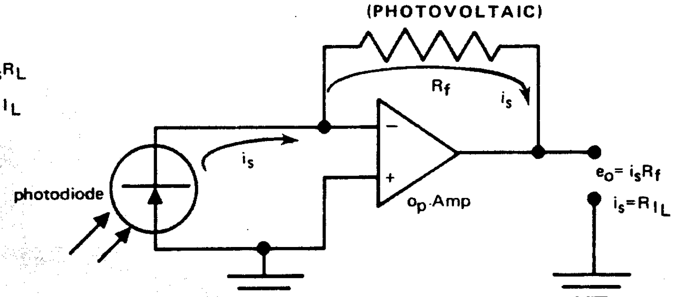
R_L = load resistor (user supplied)

TYPICAL HOOKUPS

"D" Series (PHOTOCONDUCTIVE)



"DP" Series (PHOTOVOLTAIC)



- R=photodiode responsivity (amps/watt)
- I_L= input light (watts)
- R_L=load resistance
- R_f=feedback resistance

SPECIALS

UDT's unique capability in both planar diffused and Schottky junction technology offers the customer the flexibility of having a custom detector optimized for the intended application. Multiple array geometries can be fabricated with elements as small as .001" x .005" or as large as ½" x 10". Custom hybridization of photodiode/op amp combinations, either single element or array, is available from UDT. Send us your requirement, we will send our recommendations and quote.

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OPTICAL/ELECTRICAL CHARACTERISTICS "D" SERIES

23°C Ambient	PIN-3D			PIN-5D			PIN-6D			PIN-10D			Units
	Min	Typ	Max	Min	Typ	Max	Min	Typ	Max	Min	Typ	Max	
Responsivity (10 Volt, 850nm)	.3	.4	.5	.3	.4	.5	.3	.4	.5	.3	.4	.5	A/W
Capacity (10 Volts)	9	10	12	10	15	20	40	60	80	300	350	400	pf
(50 Volts)	4	6	8	5	7	10	20	30	40	150	190	250	pf
Dark Current (10 Volts)		.02	.05		.1	.25		.3	.4		.5	1.5	μa
N. E. P. (AC, 1KHz, .85μ)		$2x10^{-13}$			$5x10^{-13}$			$8x10^{-13}$			10^{-12}		Watt/√HZ
Response Time (to 67%) (50Ω, 50v, 900nm)		15	25		15	25		15	25		25	50	ns
Breakdown Volts (10μa)	50			100			50			100			Volt
Active Area		.032			.051			.203			1.00		cm^2
Active Size		.050 x.100			.100 Dia			.200 Dia			.444 Dia		in.
Maximum Light Power Density			50			50			50			50	mw/cm^2
Temp. Range (operate)	-55		125	-55		125	-55		125	0		70	°C
(storage)	-55		150	-55		150	-55		150	0		70	°C

"DP" SERIES

23°C Ambient	PIN-3DP			PIN-5DP			PIN-6DP			PIN-10DP			Units
	Min	Typ	Max	Min	Typ	Max	Min	Typ	Max	Min	Typ	Max	
Responsivity, 850nm (PV op amp)	.3	.35	.45	.3	.35	.45	.3	.35	.45	.3	.35	.45	A/W
Capacity (PV, op amp)	250	300	350	450	500	575	1700	1800	2000	2200	2400	2800	pf
Source Resistance (PV, op amp)	100	300		40	50		20	40		.5	2		megohm
N. E. P. (DC, PV, 850nm)		$2x10^{-13}$			$5x10^{-13}$			$8x10^{-13}$			10^{-12}		Watt/√HZ
Response Time (to 67%) (PV, op amp, 900nm)		1000			1000			1000			1000		ns
Breakdown Volts (10μa)	5			5			5			5			Volt
Active Area		.032			.051			.203			1.00		cm^2
Active Size		.050 x.100			.100 Dia			.200 Dia			.444 Dia		in. in.
Maximum Light Power Density			10			10			10			10	mw/cm^2
Temp. Range (operate)	-55		125	-55		125	-55		125	0		70	°C
(storage)	-55		150	-55						0		70	

Note 1: (PV, op amp) - refers to zero voltage bias with coupling to a current mode op amp.

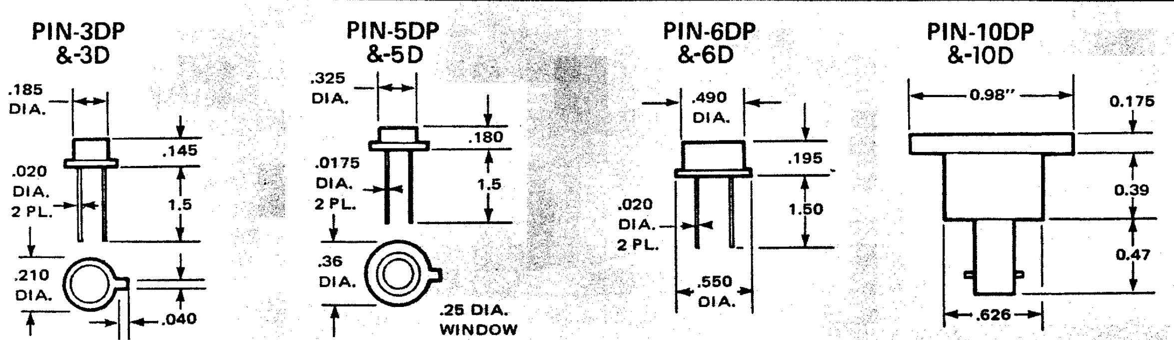
Note 2: See Typical Hookups on data sheet back side for measurement setup.

Note 3: For a complete relative spectral response see back side of data sheet.

Note 4: Typical characteristics represent approximately 50% of the total yield. Detectors can be source selected for a particular spec. at an increase in price.

UNITED DETECTOR TECHNOLOGY INC.

MECHANICAL CHARACTERISTICS "D" AND "DP" SERIES



Distance from Detector Active Surface to Front Window Surface (±.005 in):

PIN-3D PIN-3DP .090 in.	PIN-5D PIN-5DP .110 in.	PIN-6D PIN-6DP .125 in.	PIN-10D PIN-10DP .085 in.

the pin nearest the tab is the anode (–bias)

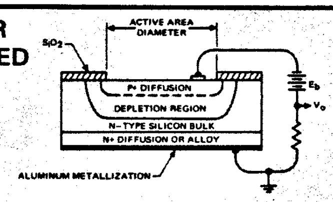
the photodiode anode is connected to outer BNC shield (–bias)

CONSTRUCTION

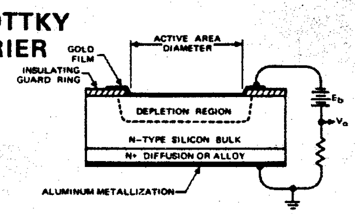
A PIN photodiode is one in which a heavily doped p region and a heavily doped n region are separated by a lightly doped "i" region. This "i" region resistivity can range from 10 ohm cm to 100,000 ohm cm, the p and n region resistivities being less than 1 ohm cm. The output from this two terminal sensor is a current whose value is proportional to the input light power. There are different ways to optimize the performance of PIN photodiodes. The "D" series is optimized for voltage biased operation, featuring high breakdown voltage and low capacitance. The "DP" series is optimized for unbiased operation (photovoltaic) into a current mode op amp, featuring high detector resistance and, thereby, linear light sensing over ten decades.

UDT also manufactures a complete line of SCHOTTKY Silicon photodiodes. These devices are recommended when high blue response (less than 500nm), fast response time (less than 25 ns) or large areas (greater than 1cm^2) are required. They are not recommended for high temperature operation (greater than 160°F) or high light level operation (greater than 2 mw).

PLANAR DIFFUSED



SCHOTTKY BARRIER



APPLICATIONS

"D" Series
- **Laser Rangers**
- **OCR Scanners**
- **GaAs Pulse Detector**
- **Production Line Sorting**

"DP" Series
- **Colorimeters**
- **Photometers**
- **Densitometers**
- **Radiometers**

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