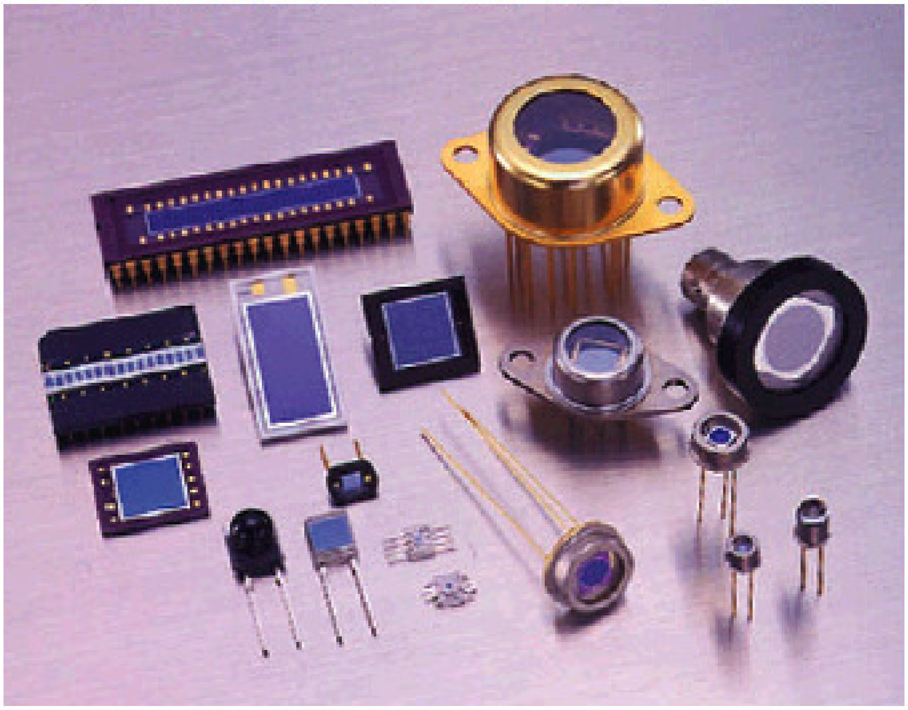
HAMAMATSU



Photodiode Technical Information

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Description of terms

1. Spectral response

The photocurrent produced by a given level of incident light varies with the wavelength. This relation between the photoelectric sensitivity and wavelength is referred to as the spectral response characteristic and is expressed in terms of photo sensitivity, quantum efficiency, etc.

2. Photo sensitivity: S

This measure of sensitivity is the ratio of radiant energy expressed in watts (W) incident on the device, to the resulting photocurrent expressed in amperes (A). It may be represented as either an absolute sensitivity (A/W) or as a relative sensitivity normalized for the sensitivity at the peak wavelength, usually expressed in percent (%) with respect to the peak value. For the purpose of this catalog, the photo sensitivity is represented as the absolute sensitivity, and the spectral response range is defined as the region in which the relative sensitivity is higher than 5 % of the peak value.

3. Quantum efficiency: QE

The quantum efficiency is the number of electrons or holes that can be detected as a photocurrent divided by the number of the incident photons. This is commonly expressed in percent (%). The quantum efficiency and photo sensitivity S have the following relationship at a given wavelength (nm):

$$QE = \frac{S \times 1240}{\lambda} \times 100\ [\%] \quad \text{............ (1)}$$

where S is the photo sensitivity in A/W at a given wavelength and λ is the wavelength in nm (nanometers).

4. Short circuit current: Isc, open circuit voltage: Voc

The short circuit current is the output current which flows when the load resistance is 0 and is nearly proportional to the device active area. This is often called “white light sensitivity” with regards to the spectral response. This value is measured with light from a tungsten lamp of 2856 K distribution temperature (color temperature), providing 100 time illuminance. The open circuit voltage is a photovoltaic voltage developed when the load resistance is infinite and exhibits a constant value independent of the device active area.

5. Infrared sensitivity ratio

This is the ratio of the output current I_R measured with a light flux (2856 K, 100 time) passing through an R-70 (t=2.5 mm) infrared filter to the short circuit current Isc measured without the filter. It is commonly expressed in percent, as follows:

$$\text{Infrared sensitivity ratio} = \frac{I_R}{Isc} \times 100\ [\%] \quad \text{............ (2)}$$

6. Dark current: I_D, shunt resistance: Rsh

The dark current is a small current which flows when a reverse voltage is applied to a photodiode even in dark state. This is a major source of noise for applications in which a reverse voltage is applied to photodiodes (PIN photodiode, etc.). In contrast, for applications where no reverse voltage is applied, noise resulting from the shunt resistance becomes predominant. This shunt resistance is the voltage-to-current ratio in the vicinity of 0 V and defined as follows:

$$Rsh = \frac{10\ [\mathrm{mV}]}{I_D}\ [\Omega] \quad \text{............ (3)}$$

where I_D is the dark current at V_R=10 mV.

7. Terminal capacitance: Ct

An effective capacitor is formed at the PN junction of a photodiode. Its capacitance is termed the junction capacitance and is the major factor in determining the response speed of the photodiode. And it probably causes a phenomenon of gain peaking in I-V conversion circuit using operational amplifier. In Hamamatsu, the terminal capacitance including this junction capacitance plus package stray capacitance is listed.

8. Rise time: tr

This is the measure of the time response of a photodiode to a stepped light input, and is defined as the time required for the output to change from 10 % to 90 % of the steady output level. The rise time depends on the incident light wavelength and load resistance. For the purpose of data sheets, it is measured with a light source of GaAsP LED (655 nm) or GaP LED (560 nm) and load resistance of 1 k Ω.

9. Cut-off frequency: fc

This is the measure used to evaluate the time response of high-speed APD (avalanche photodiodes) and PIN photodiodes to a sinewave-modulated light input. It is defined as the frequency at which the photodiode output decreases by 3 dB from the output at 100 kHz. The light source used is a laser diode (830 nm) and the load resistance is 50 Ω. The rise time tr has a relation with the cut-off frequency fc as follows:

$$tr = \frac{0.35}{fc} \quad \text{............ (4)}$$

10. NEP (Noise Equivalent Power)

The NEP is the amount of light equivalent to the noise level of a device. Stated differently, it is the light level required to obtain a signal-to-noise ratio of unity. In data sheets lists the NEP values at the peak wavelength λp. Since the noise level is proportional to the square root of the frequency bandwidth, the NEP is measured at a bandwidth of 1 Hz.

$$\mathrm{NEP}\ [\mathrm{W/Hz}^{1/2}] = \frac{\text{Noise current } [\mathrm{A/Hz}^{1/2}]}{\text{Photo sensitivity at } \lambda p\ [\mathrm{A/W}]} \quad \text{............ (5)}$$

11. Maximum reverse voltage: V_R Max.

Applying a reverse voltage to a photodiode triggers a breakdown at a certain voltage and causes severe deterioration of the device performance. Therefore the absolute maximum rating is specified for reverse voltage at the voltage somewhat lower than this breakdown voltage. The reverse voltage shall not exceed the maximum rating, even instantaneously.

Reference

● Physical constant

Constant	Symbol	Value	Unit
Electron charge	e or q	1.602×10^{-19}	c
Speed of light in vacuum	c	2.998×10^{8}	m/s
Planck's constant	h	6.626×10^{-34}	Js
Boltzmann's constant	k	1.381×10^{-23}	J/K
Room temperature thermal energy	KT (T=300 K)	0.0259	eV
1 eV energy	eV	1.602×10^{-19}	J
Wavelength in vacuum corresponding to 1 eV	-	1240	nm
Dielectric constant of vacuum	ε_o	8.854×10^{-12}	F/m
Dielectric constant of silicon	ε_{si}	Approx. 12	-
Dielectric constant of silicon oxide	ε_{ox}	Approx. 4	-
Energy gap of silicon	Eg	Approx. 1.12 (T=25 °C)	eV

12. D* (Detectivity: detection capacity)

D, which is the reciprocal of NEP, is the value used to indicate detectivity, or detection capacity. However, because the noise level is normally proportional to the square root of the sensitive area, NEP and D characteristics have improved, enabling detection of even small photo-sensitive elements. This makes it possible to observe the characteristics of materials by multiplying the square root of the sensitive area and D, with the result being used as D*. The peak wavelength is recorded in units expresseed as cm $Hz^{½}$ /W, as it is for the NEP.

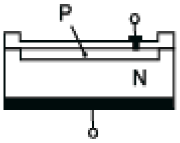
$$D^* = \frac{[\text{Effective Sensitive Area } (cm^2)]^{½}}{\text{NEP}}$$

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

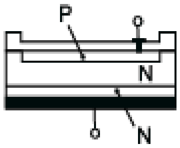
Planar Diffusion Type

An SiO2 coating is applied to the P-N junction surface, yielding a photodiode with a low level dark current.



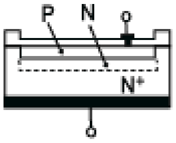
Low-Capacitance Planar Diffusion Type

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.



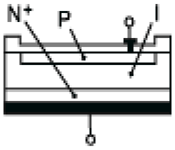
PNN+ Type

A low-resistance N+ material layer is made thick to bring the NN+ 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.



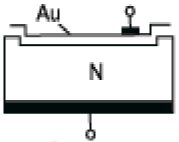
PIN Type

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.



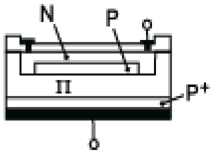
Schottky Type

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



Characteristic and use

Introduction

Photodiodes are semiconductor light sensors that generate a current or voltage when the P-N junction in the semiconductor is illuminated by light. The term photodiode can be broadly defined to include even solar batteries, but it usually refers to sensors used to detect the intensity of light. Photodiodes can be classified by function and construction as follows:

Photodiode type

1) PN photodiode
2) PIN photodiode
3) Schottky type photodiode
4) APD (Avalanche photodiode)

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

Features of photodiode

1) Excellent linearity with respect to incident light
2) Low noise
3) Wide spectral response
4) Mechanically rugged
5) Compact and lightweight
6) Long life

1. Principle of operation

Figure 1-1 shows a cross section of a photodiode. The P-layer material at the active surface and the N material at the substrate form a PN junction which operates as a photoelectric converter. The usual P-layer for a Si photodiode is formed by selective diffusion of boron, to a thickness of approximately 1 μm or less and the neutral region at the junction between the P- and N-layers is known as the depletion layer. By 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 strikes a photodiode, the electron within the crystal structure becomes stimulated. If the light energy is greater than the band gap energy Eg, the electrons are pulled up into the conduction band, leaving holes in their place in the valence band. (See Figure 1-2) These electron-hole pairs occur throughout the P-layer, depletion layer and N-layer materials. In the depletion layer the electric field accelerates these electrons toward the N-layer and the holes toward the P-layer. Of the electron-hole pairs 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. The holes at this time are being diffused through the N-layer up to the depletion layer while being accelerated, and collected 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- and P-layers. 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 will flow away from the P-layer toward the opposite respective electrodes. These electrons and holes generating a current flow in a semiconductor are called the carriers.

Figure 1-1 Photodiode cross section

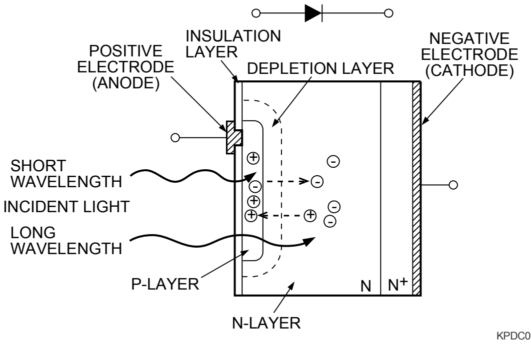


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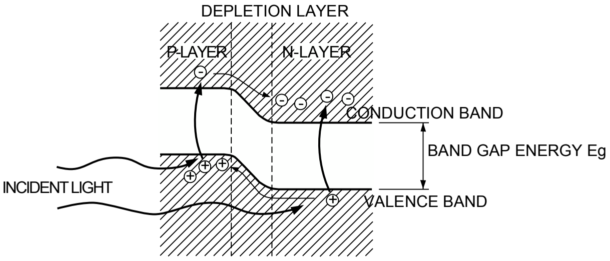
Figure 1-2 Photodiode P-N junction state



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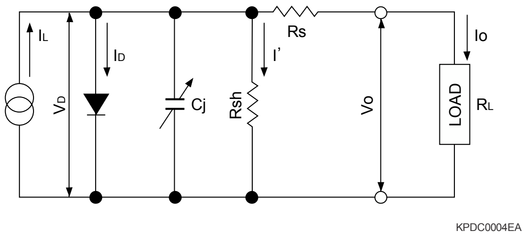
2. Si photodiode

2-1. Equivalent circuit

An equivalent circuit of a photodiode is shown in Figure 2-1.

Figure 2-1 Photodiode equivalent circuit



I_L : Current generated by the incident light (proportional to the amount of light)
I_D : Diode current
Cj : Junction capacitance
Rsh : Shunt resistance
Rs : Series resistance
I' : Shunt resistance current
V_D : Voltage across the diode
Io : Output current
Vo : Output voltage

Using the above equivalent circuit, the output current Io is given as follows:

$$Io = I_L - I_D - I' = I_L - Is\left(exp\frac{eV_D}{kT} - 1\right) - I' \ .... (2\text{-}1)$$

Is: Photodiode reverse saturation current
e : Electron charge
k : Boltzmann's constant
T : Absolute temperature of the photodiode

The open circuit voltage Voc is the output voltage when Io equals 0. Thus Voc becomes

$$Voc = \frac{kT}{e}\ ln\left(\frac{I_L - I'}{Is} + 1\right) \ .... (2\text{-}2)$$

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 I_L. However, this relationship does not hold for very low light levels.

The short circuit current Isc is the output current when the load resistance R_L equals 0 and Vo equals 0, yielding:

$$Isc = I_L - Is\left(exp\frac{e\cdot(Isc\cdot Rs)}{kT} - 1\right) - \frac{Isc\cdot Rs}{Rsh} \ ...... (2\text{-}3)$$

In the above relationship, the 2nd and 3rd terms limit the linearity of Isc. However, since Rs is several ohms and Rsh is 10^7 to 10^{11} ohms, these terms become negligible over quite a wide range.

2-2. Current vs. voltage characteristic

When a voltage is applied to a photodiode in the dark state, the current vs. voltage characteristic observed is similar to the curve of a conventional rectifier diode as shown in Figure 2-2 ①. However, when light strikes the photodiode, the curve at ① shifts to ② and, increasing the amount of incident light shifts this characteristic curve still further to position ③ in parallel, according to the incident light intensity. As for the characteristics of ② and ③, if the photodiode terminals are shorted, a photocurrent Isc or Isc 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 Voc or Voc' will be generated with the positive polarity at the anode.

The short circuit current Isc is extremely linear with respect to the incident light level. When the incident light is within a range of 10^{-12} to 10^{-2} W, the achievable range of linearity is higher than 9 orders of magnitude, depending on the type of photodiode and its operating circuit. The lower limit of this linearity is determined by the NEP, while the upper limit depends on the load resistance and reverse bias voltage, and is given by the following equation:

$$Psat = \frac{V_{Bi} + V_R}{(Rs + R_L)\cdot S\lambda} \ .... (2\text{-}4)$$

Psat : Input energy (W) at upper limit of linearity Psat ≤ 10 mW
V_{Bi} : Contact voltage (V) <0.2 to 0.3 V>
V_R : Reverse voltage (V)
R_L : Load resistance (Ω)
Sλ : Photo sensitivity at wavelength λ (A/W)
Rs : Photodiode series resistance (several Ω)

When laser light is condensed on a small spot, however, the actual series resistance element increases, and linearity deteriorates.

Voc varies logarithmically with respect to a change of the light level and is greatly affected by variations in temperature, making it unsuitable for light intensity measurements. Figure 2-3 shows the result of plotting Isc and Voc as a function of incident light illuminance.

Figure 2-2 Current vs. voltage characteristic

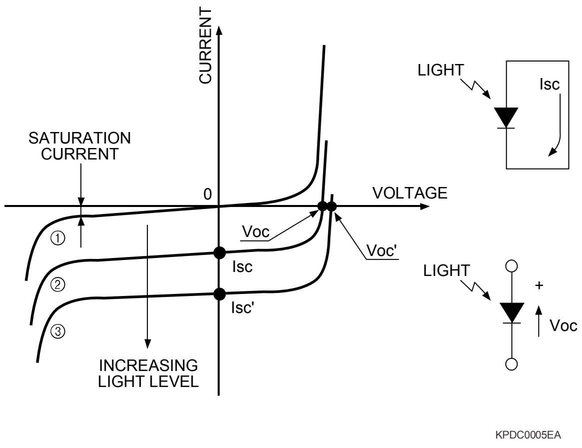
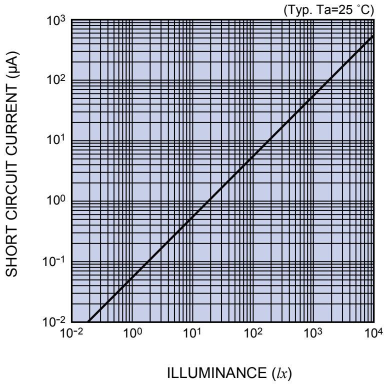


Figure 2-3 Output signal vs. incident light level (S2386-5K)

(a) Short circuit current



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(b) Open circuit voltage

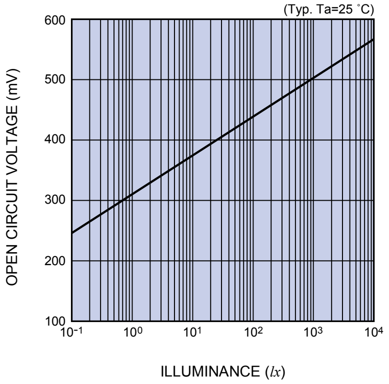

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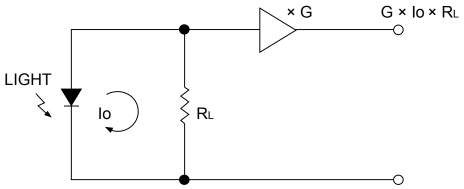
Figure 2-4 (a) and (b) show methods of measuring light by measuring the photocurrent I_L or Isc. In the circuit shown at (a), the voltage (Io × R_L) is amplified by an amplifier with gain G, although the circuit does have limitations on its linearity according to equation (2-4). This condition is shown in Figure 2-5. Figure 2-4 (b) is a circuit using an operational amplifier. If we set the open loop gain of the operational amplifier as A, the characteristics of the feedback circuit allows the equivalent input resistance (equivalent to load resistance R_L) to be $\frac{Rf}{A}$ which is several orders of magnitude smaller than Rf. Thus this circuit enables ideal Isc measurement over a wide range. For measuring a wide range, R_L and Rf must be adjusted as needed.

Figure 2-4 Photodiode operational circuits

(a) Load resistance circuit



(b) Op-amp circuit

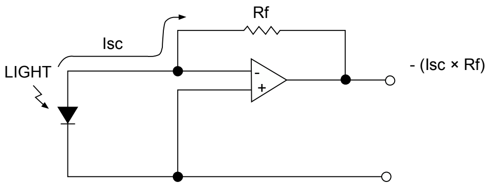


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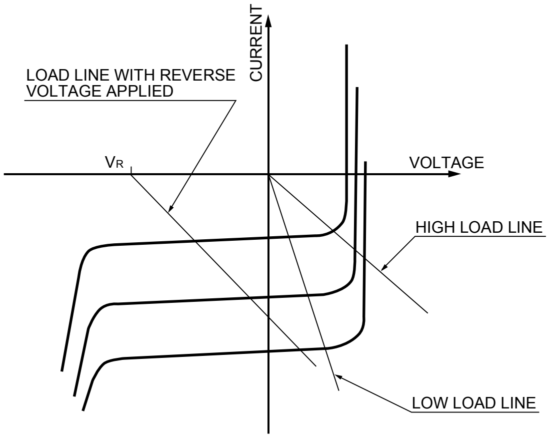
Figure 2-5 Current vs. voltage characteristic and load line



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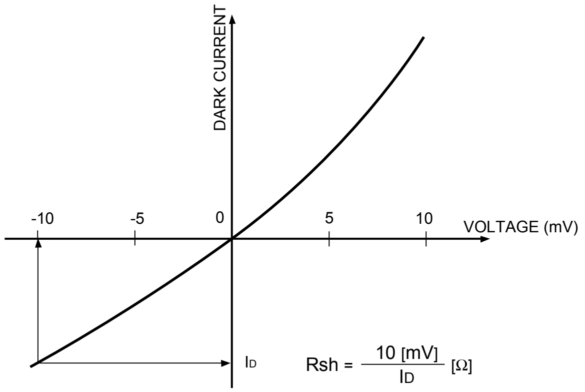
If the zero region of Figure 2-2 ① is magnified, we see, as shown in Figure 2-6, that the dark current I_D is approximately linear in a voltage range of about ±10 mV. The slope in this region indicates the shunt resistance Rsh and this resistance is the cause of the thermal noise current described later. In data sheets, values of Rsh are given using a dark current I_D measured with -10 mV applied.

Figure 2-6 Dark current vs. voltage (Enlarged zero region)



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2-3. Spectral response

As explained in the section on principle of operation, when the energy of absorbed photons is lower than the band gap energy Eg, the photovoltaic effect does not occur. The limiting wavelength λh can be expressed in terms of Eg as follows:

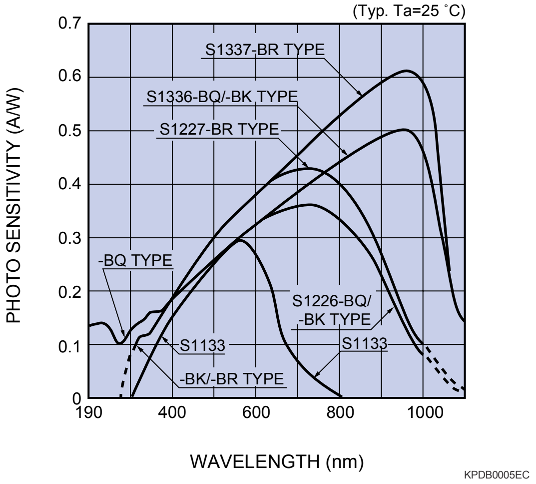
$$\lambda h = \frac{1240}{Eg} \text{ [nm]} \quad .... \text{(2-5)}$$

At room temperatures, Eg is 1.12 eV for Si and 1.8 eV for GaAsP, so that the limiting wavelength will be 1100 nm and 700 nm, respectively. For short wavelengths, however, the degree of light absorption within the surface diffusion layer becomes very large. 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 1-1.) For normal photodiodes the cut-off wavelength is 320 nm, whereas for UV-enhanced photodiodes (e.g. S1226/S1336 series) it is 190 nm.

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

Figure 2-7 shows the spectral response characteristics for various photodiode types. The BQ type shown uses a quartz window, the BK type a borosilicate glass window and the BR type a resin-coated window. S1133 is a visible photodiode with a visual-compensated filter.

Figure 2-7 Spectral response example



2-4. Noise characteristic

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 in is the sum of the thermal noise (or Johnson noise) ij of a resistor which approximates the shunt resistance and the shot noise isD and isL resulting from the dark current and the photocurrent.

$$in = \sqrt{ij^2 + isD^2 + isL^2} \quad [A] \quad .... (2\text{-}6)$$

ij is viewed as the thermal noise of Rsh and is given as follows:

$$ij = \sqrt{\frac{4kTB}{Rsh}} \quad [A] \quad .... (2\text{-}7)$$

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

When a bias voltage is applied as in Figure 3-1, there is always a dark current. The shot noise isD originating from the dark current is given by

$$isD = \sqrt{2qI_DB} \quad [A] \quad .... (2\text{-}8)$$

q : Electron charge
I_D: Dark current
B : Noise bandwidth

With the application of incident light, a photocurrent I_L exists so isL is given by

$$isL = \sqrt{2qI_LB} \quad [A] \quad .... (2\text{-}9)$$

If I_L >> 0.026/Rsh or I_L >> I_D, the shot noise current of equation (2-9) becomes predominant instead of the noise factor of eqaution (2-7) or (2-8).

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 $A/Hz^{1/2}$.

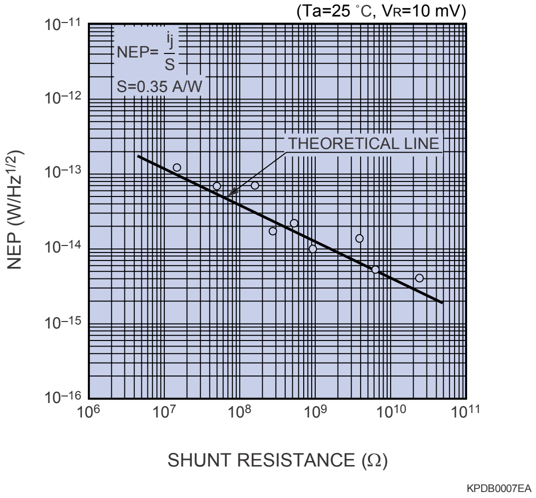
The lower limit of light detection for a photodiode is usually expressed as the intensity of incident light required to generate a current equal to the noise current as expressed in equation (2-7) or (2-8). Essentially this is the noise equivalent power (NEP).

$$NEP = \frac{in}{S} \quad [W/Hz^{1/2}] \quad .... (2\text{-}10)$$

in: Noise current ($A/Hz^{1/2}$)
S : Photo sensitivity (A/W)

Figure 2-8 shows the relationship between NEP and shunt resistance, from which a photodiode is agreement with the theoretical relationship.

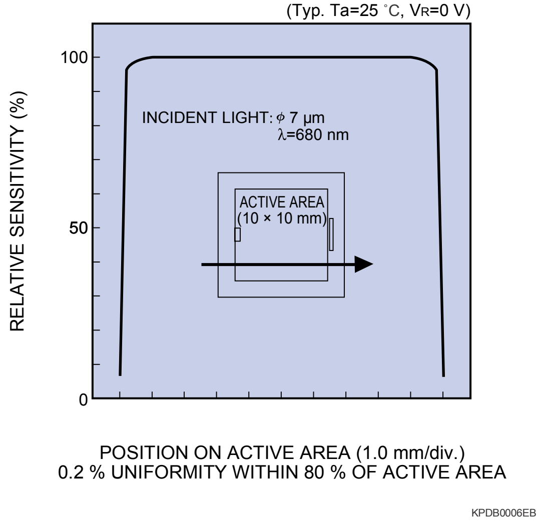
Figure 2-8 NEP vs. shunt resistance (S1226-5BK)



2-5. Spatial response uniformity

This is the measure of the variation in sensitivity with the position of the active area. Photodiodes offer excellent uniformity, usually less than 1 %. This uniformity is measured with light from a laser diode (680 nm) condensed to a small spot from several microns to several dozen microns in diameter.

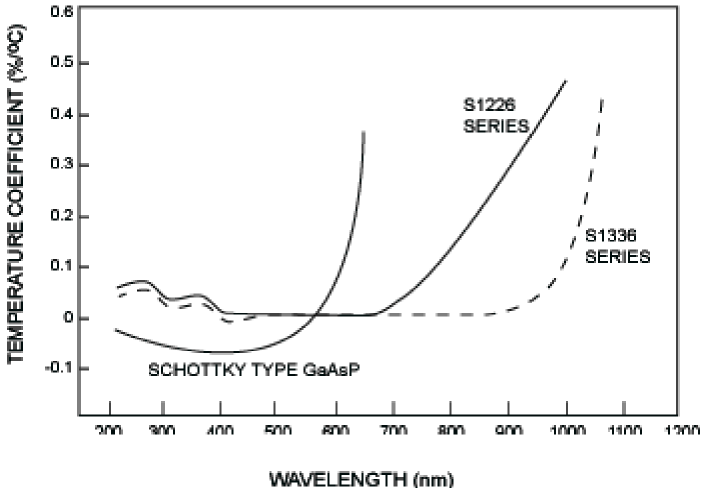
Figure 2-9 Spatial response uniformity (S1227-1010BQ)



2-6 Temperature Characteristics

Ambient temperature variations greatly affect 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 2-10 shows examples of temperature coefficients of photodiodes sensitivity for a variety of photodiodes types.

Figure 2-10 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 2-11 indicates a twofold increase in dark current for a temperature rise from 5°C to 10°C. This is equivalent to a reduction of the shunt resistance Rsh and a subsequent increase in thermal and shot noise. Figure 2-12 shows an example of the temperature characteristics of open-circuit voltage Vop, indicating linearity with respect to temperature change.

Figure 2-11: Dark Current Temperature Dependence (S2387)

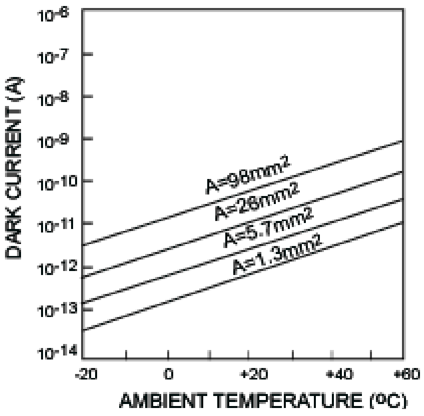
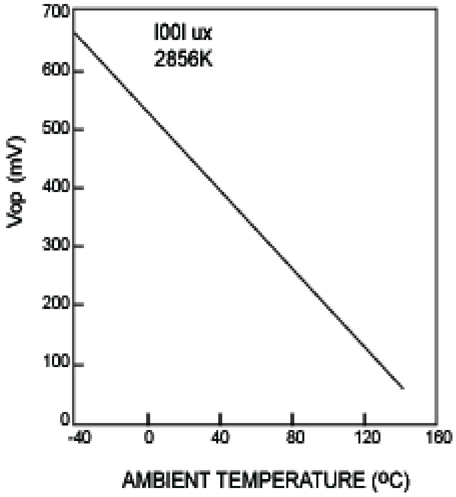


Figure 2-12 : Vop Temperature Dependence (S2387)

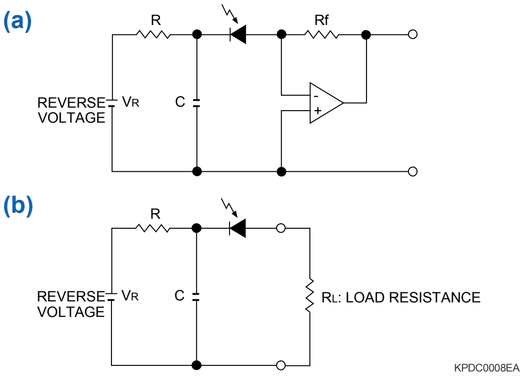


3. Si PIN photodiode

3-1. Reverse voltage

Because photodiodes generate a power due to the photovoltaic effect, they can operate without the need for an external power source. However, frequency response and linearity can be improved by using an external reverse voltage V_R. 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 reverse voltage does not affect the signal current nor impair the photoelectric conversion linearity. Figure 3-1 shows examples of reverse voltage connection. Figures 3-2 and 3-3 show the effect of reverse voltage on cut-off frequency and linearity limits, respectively. While application of a reverse voltage to a photodiode is very useful in improving frequency response 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 voltage. Thus, care is required to maintain the reverse voltage within the maximum ratings and to ensure that the cathode is maintained at a positive potential with respect to the anode.

Figure 3-1 Reverse voltage connection



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 reverse voltage applied. Note that the reverse voltages listed in data sheets are recommended values and each PIN photodiode is designed to provide optimum performance at the recommended reverse voltage.

Figure 3-2 Cut-off frequency vs. reverse voltage (S5973 series, S7911, S7912)

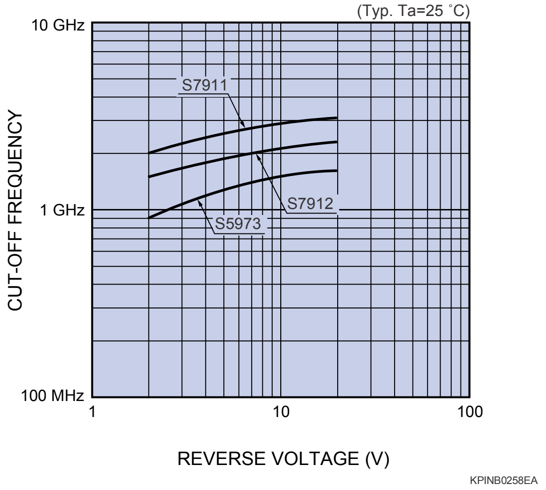


Figure 3-3 Output current vs. illuminance (S1223)

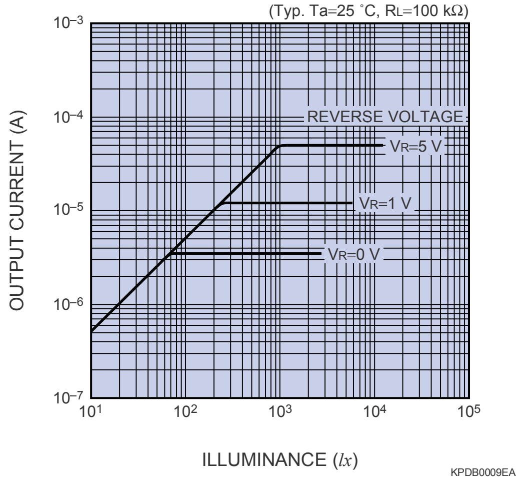
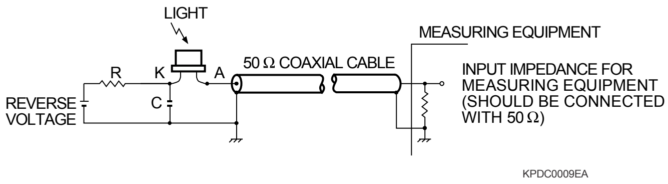


Figure 3-4 shows an example of the actual connection shown in Figure 3-1 (b) with a load resistance 50 Ω. The ceramic capacitor C is used to enable a reduction of the bias supply impedance, while resistor R is used to protect the photodiode. The resistor value is selected such that the voltage drop caused by the maximum photocurrent is sufficiently smaller than the reverse voltage. The photodiode and capacitor leads, coaxial cable and other wire carrying high-speed pulses should be kept as short as possible.

Figure 3-4 Connection to coaxial cable



3-2. Response speed and frequency response

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 or cut-off frequency. The rise time is the time required for the output signal to change from 10 % to 90 % of the peak output value and is determined by the following factors:

1) Terminal capacitance Ct and time constant t_1 of load resistance R_L

Time constant t_1 determined by the terminal capacitance Ct of the photodiode and the load resistance R_L.
Ct is the sum of the package capacitance and the photodiode junction capacitance. t_1 is given by

$$t_1 = 2.2 \times Ct \times R_L \text{ .... } (3\text{-}1)$$

To shorten t_1, the design must be such that either Ct or R_L is made smaller. Cj is nearly proportional to the active area A and inversely proportional to the second to third root of the depletion layer width d. Since the depletion layer width is proportional to the product of the resistivity ρ of the substrate material and reverse voltage V_R, the following equation is established as:

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

Accordingly, to shorten t_1, a photodiode with a small A and large ρ should be used with a reverse voltage applied. However, reverse voltage also increases dark current so caution is necessary for use in low-light-level detection.

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

Carriers may generate outside the depletion layer when incident light misses the P-N junction and is absorbed by the surrounding area of the photodiode chip and the substrate section which is below the depletion area. The time t_2 required for these carriers to diffuse may sometimes be greater than several microseconds.

3) Carrier transit time t_3 in the depletion layer

The transit speed vd at which the carriers travel in the depletion layer is expressed using the traveling rate μ and the electric field E developed in the depletion layer, as in $vd = \mu E$. If we let the depletion layer width be d and the applied voltage be V_R, the average electric field $E = V_R/d$, and thus t_3 can be approximated as follows:

$$t_3 = d / vd = d^2 / (\mu V_R) \quad \text{............ (3-3)}$$

To achieve a fast response time for t_3, the moving distance of carriers should be short and the reverse voltage larger.

The above three factors determine the rise time tr of a photodiode and rise time tr is approximated by the following equation:

$$tr = \sqrt{t_1{}^2 + t_2{}^2 + t_3{}^2} \quad \text{............. (3-4)}$$

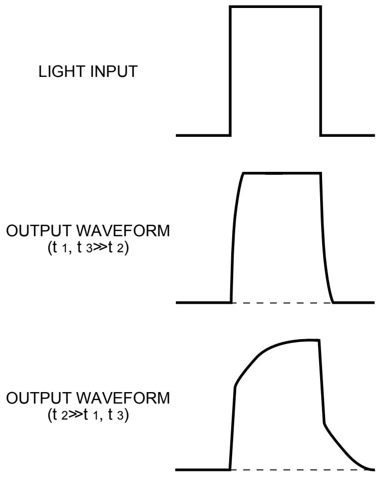
PIN photodiodes and avalanche photodiodes are designed such that less carriers are generated outside the depletion layer, Ct is small and the carrier transit time in the depletion layer is short. Therefore, these types are ideally suited for high-speed light detection.

The cut-off frequency fc is the frequency at which the photodiode output decreases by 3 dB from the output at 100 kHz when the photodiode receives sinewave-modulated light from a laser diode. The rise time tr roughly approximates this fc in the formula:

$$tr = \frac{0.35}{fc} \quad \text{............ (3-5)}$$

Figures 3-5 (a), (b) and (c) show examples of the response waveform and frequency response characteristics for typical photodiodes.

Figure 3-5 (a) Photodiode response waveform example



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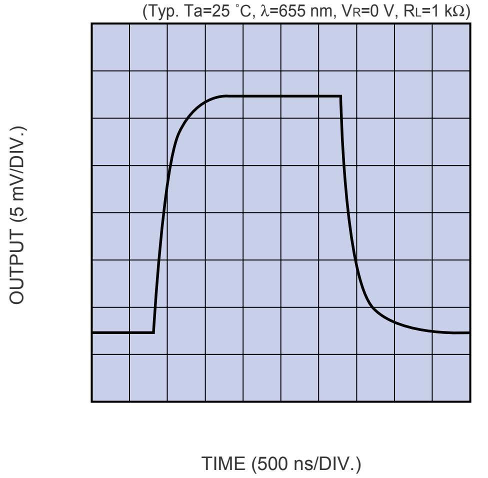
(b) Response waveform (S2386-18K)



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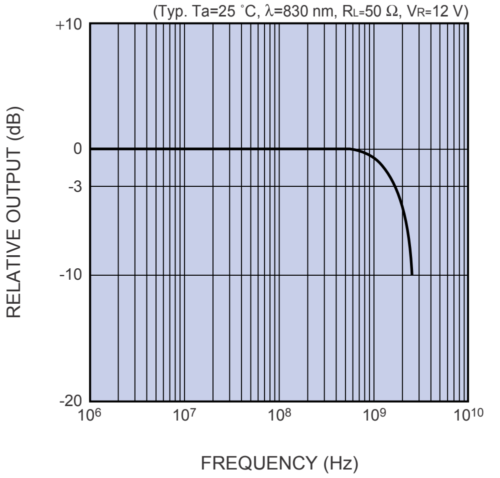
(c) Frequency response (S5973)



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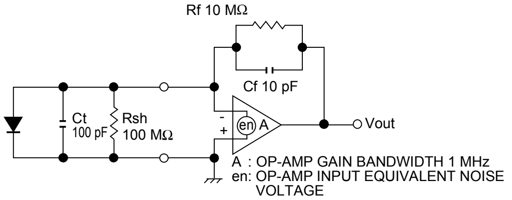
4. Si photodiode with preamp

4-1. Feedback circuit

Figure 4-1 shows a basic circuit connection of an operational amplifier and photodiode. The output voltage Vout from DC through the low-frequency region is 180 degrees out of phase with the input current Isc. The feedback resistance Rf is determined by Isc and the required output voltage Vout. If, however, Rf is made greater than the photodiode internal resistance Rsh, the operational amplifier's input noise voltage en and offset voltage will be multiplied by $\left(1+\frac{\mathrm{Rf}}{\mathrm{Rsh}}\right)$. This is superimposed on the output voltage Vout, and the operational amplifier's bias current error (described later) will also increase. It is therefore not practical to use an infinitely large Rf. If there is an input capacitance Ct, the feedback capacitance Ct prevents high-frequency oscillations and also forms a lowpass filter with a time constant Cf × Rf value. The value of Cf should be chosen according to the application. If the input light is similar to a discharge spark, and it is desired to integrate the amount of light, Rf can be removed so that the operational amplifier and Cf act as an integrating circuit. However, a switch is required to discharge Cf before the next integration.

Figure 4-1 Basic photodiode connection



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4-2. Bias current

Since the actual input impedance of an operational amplifier is not infinite, some bias current that will flows into or out of the input terminals. This may result in error, depending upon the magnitude of the detected current. The bias current which flows in an FET input operational amplifier is sometimes lower than 0.1 pA. Bipolar operational amplifiers, however, have bias currents ranging from several hundred pA to several hundred nA. However, the bias current of an FET operational amplifier increases two-fold for every increase of 5 to 10 ˚C in temperature, whereas that of bipolar amplifiers decreases with increasing temperature. The use of bipolar amplifiers should be considered when designing circuits for high temperature operation.

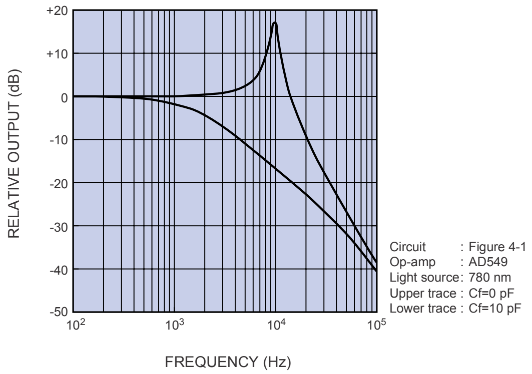
As is the case with offset voltage, the error voltage attributable to the bias current can be adjusted by means of a potentiometer connected to the offset adjustment terminals. Furthermore, leakage currents on the PC board used to house the circuit may be greater than the operational amplifier's bias current. Consideration must be given to the circuit pattern design and parts layout, as well as the use of Teflon terminals and guard rings.

4-3. Gain peaking

The frequency response of a photodiode and operational amplifier circuit is determined by the time constant Rf × Cf. However, for large values of terminal capacitance (i.e. input capacitance) a phenomenon known as gain peaking will occur. Figure 4-2 shows an example of such a frequency response. It can be seen from the figure that the output voltage increases sharply in the high frequency region, causing significant ringing [See the upper trace in (a).] in the output voltage waveform in response to the 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 the upper trace in (c).] This occurs at the high frequency region when the reactance of the input capacitance and the feedback capacitance of the operational amplifier circuit jointly form an unstable amplifier with respect to input amplifier noise. In such a case, loss of measurement accuracy may result.

Figure 4-2 Gain peaking

(a) Frequency response



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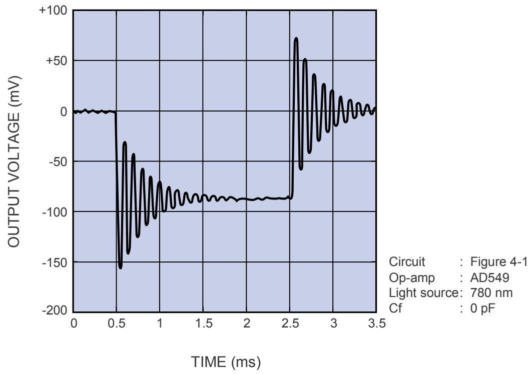
(b) Light pulse response



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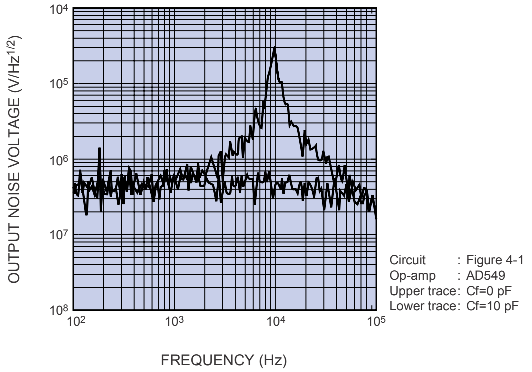
(c) Frequency response of noise output



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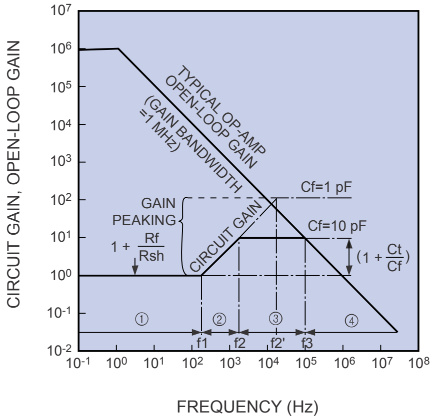
4-4. Gain peaking elimination

To achieve a wide frequency characteristic without gain peaking and ringing phenomena, it is necessary to select the optimum relationship between the photodiode, operational amplifier and feedback element. It will prove effective in the case of photodiodes to reduce the terminal capacitance Ct, as was previously explained in the section on Response speed and frequency response. In the operational amplifier, the higher the speed and the wider the bandwidth, the less the gain peaking that occurs. However, if adequate internal phase compensation is not provided, oscillation may be generated as a result. A feedback element, not only the resistance but also the feedback capacitance should be connected in parallel, as explained previously, in order to avoid gain peaking. The gain peaking phenomena can be explained as follows, using the circuit shown in Figure 4-1. As shown in Figure 4-3, the circuit gain of the operational amplifier is determined for the low-frequency region ① simply by the resistance ratio of Rsh to Rf. From the frequency $f1 = \frac{Rsh + Rf}{2\pi\, RshRf\, (Cf + Ct)}$ gain begins to increase with frequency as shown in region ②.

Next, at the frequency $f2 = \frac{1}{2\pi\, CfRf}$ and above, the circuit gain of the operational amplifier enters a flat region (region ③) which is determined by the ratio of Ct and Cf. At the point where frequency f3 intersects the open-loop gain frequency response at rolloff (6 dB/octave) of the operational amplifier, region ④ is entered. In this example, f1 and f2 correspond to 160 Hz and 1.6 kHz respectively under the conditions of Figure 4-1. If Cf is made 1 pF, f2 shifts to f2’ and circuit gain increases further. What should be noted here is that, since the setting of increasing circuit gain in region ③ exceeds the open-loop gain curve, region ③ actually does not exist. As a result, ringing occurs in the pulsed light response of the operational amplifier circuit, and the gain peaking occurs in the frequency, then instability results. (See Figure 4-2.)

Figure 4-3 Graphical representation of gain peaking



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To summarize the above points:

a) When designing Rf and Cf, f2 should be set to a value such that region ③ in Figure 4-3 exists.

b) When f2 is positioned to the right of the open-loop gain line of the operational amplifier, use the operational amplifier which has a high frequency at which the gain becomes 1 (unity gain bandwidth), and set region ③.

The above measures should reduce or prevent ringing. However, in the high-frequency region ③, circuit gain is present, and the input noise of the operational amplifier and feedback resistance noise are not reduced, but rather, depending on the circumstances, may even be amplified and appear in the output. The following method can be used to prevent this situation.

c) Replace a photodiode with a low Ct value. In the example shown in the figure, $\left(1 + \frac{Ct}{Cf}\right)$ should be close to 1.

Using the above procedures, the S/N deterioration caused by ringing and gain peaking can usually be solved. However, regardless of the above measures, if load capacitance from several hundred pF to several nF or more, for example, a coaxial cable of several meters or more and a capacitor is connected to the operational amplifier output, oscillation may occur in some types of operational amplifiers. Thus the capacitance load must be set as small as possible.

5. Si APD

5-1. Advantage of APD

When using a opto-semiconductor for low-light-level measurement, it is necessary to take overall performance into account, including not only the opto-semiconductor characteristics but also the readout circuit (operational amplifier, etc.) noise.

When a Si photodiode is used as a photodetector, the lowest detection limit is usually determined by the readout circuit noise because photodiode noise level is very low. This tendency becomes more obvious when the higher frequency of signal to be detected.

This is because the high-speed readout circuit usually exhibits larger noise, resulting in a predominant source of noise in the entire circuit system.

In such cases, if the detector itself has an internal gain mechanism and if the output signal from the detector is thus adequately amplified, the readout circuit can be operated so that its noise contribution is minimized to levels equal to one divided by gain (1/10 th to 1/100 th).

In this way, when the lowest detection limit is determined by the readout circuit, use of an APD offers the advantage that the lowest detection limit can be improved by the APD gain factor to a level 1/10 th to 1/100 th of the lowest detection limit obtained with normal photodiodes.

5-2. Noise characteristic of APD

When the signal is amplified, the inherent excess noise resulting from statistical current fluctuation current fluctuation in the avalanche multiplication process is also generated. This noise current can be expressed by the following equation:

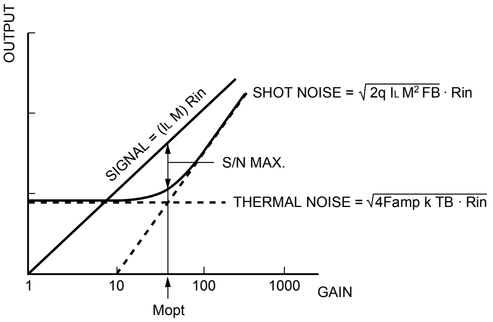
$$in = \sqrt{2\, qI_L M^2 FB} \quad \text{............} \quad (5\text{-}1)$$

In the range of M=10 to 100, F is approximated M^x.

$\left(\begin{array}{l} \text{F: Excess noise factor, M: Gain, } I_L\text{: Photocurrent at M=1,} \\ \text{q: Electron charge, B: Bandwidth, x: Excess noise index} \end{array}\right)$

In PIN photodiodes, using a large load resistance is not practical since it limits the response speed, so the circuit noise is usually dominated by the thermal noise of the photodiode. In contrast, the gain of an APD, which is internally amplified, can be increased until the shot noise reaches the same level as the thermal noise. The APD can therefore offer an improved S/N without impairing the response speed.

Figure 5-1 Noise characteristic of APD



Famp: Noise figure of next-stage amplifier
Rin : Input resistance of next-stage amplifier
k : Boltzmann’s constant
T : Absolute temperature

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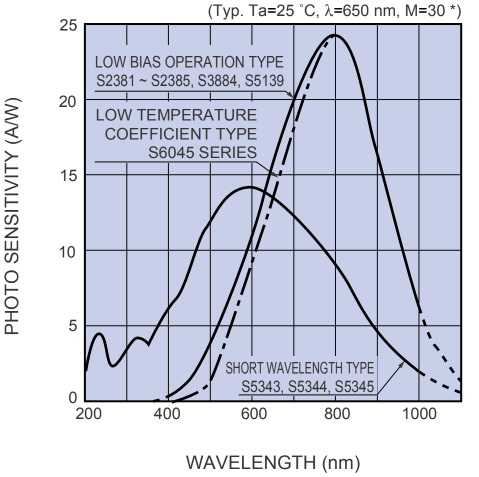
5-3. Spectral response of APD

The spectral response characteristics of the APD are almost the same as those of normal photodiodes if a bias voltage is not applied. When a bias voltage is applied, the spectral response curve will change. This means that the gain changes depending on the incident light wavelength. This is because the penetration depth of light into the silicon substrate depends on the wavelength so that the wavelength absorption efficiency in the light absorption region differs depending on the APD structure. It is therefore important to select a suitable APD.
To allow selection of spectral response characteristics, Hamamatsu provides two types of Si APDs: S2381 series and S6045 series for near infrared detection and S5343 series for light detection at shorter wavelengths.
Figure 5-2 shows typical spectral response characteristics measured with a gain of 30 at 650 nm wavelength.

Figure 5-2 Spectral response



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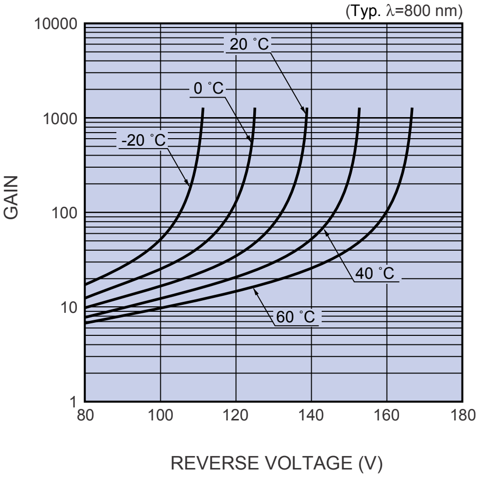
5-4. Temperature characteristic of gain

APD gain varies with temperature. For example, when an APD is operated at a constant bias voltage, the gain decreases with increasing temperature. Therefore, in order to obtain a constant output, it is necessary to vary the bias voltage according to the APD temperature or to keep the APD at a constant temperature. In S2381 series, the temperature coefficient of the bias voltage is nearly equal to that of the breakdown voltage which is 0.65 V/˚C Typ. at a gain of 100.
Hamamatsu also provides S6045 series APDs which are designed to have an improved temperature coefficient (0.4 V/˚C Typ.).

Figure 5-3 Gain temperature characteristics (S2381 to S2385, S3884, S5139)



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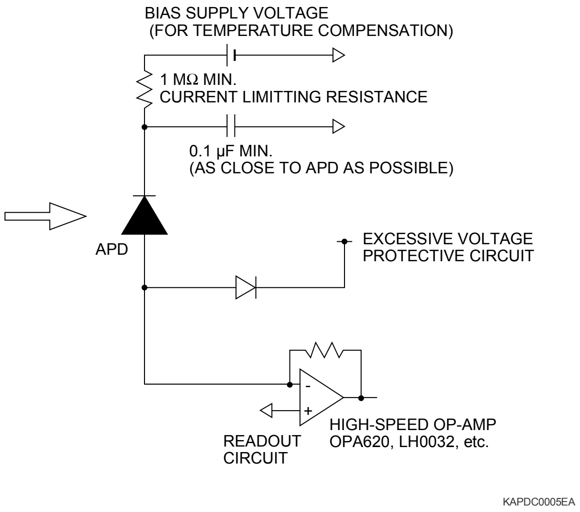
5-5. Connection to peripheral circuits

APDs can be handled in the same manner as normal photodiodes except that a high bias voltage is required. However the following precautions should be taken because APDs have an internal gain mechanism and are operated at a high voltage.

1) APDs consume a considerably large amount of power during operation, which is given by the product of the signal power × sensitivity (e.g. 0.5 A/W at 800 nm) × gain × bias voltage. To deal with this, a protective resistor should be added to the bias circuit or a current limiting circuit should be used.
2) A low-noise readout circuit usually has a high impedance, so if an excessive voltage higher than the supply voltage for the readout circuit flows into the readout circuit, the first stage tends to be damaged. To prevent this, a protective circuit (diode) should be connected so that excessive voltage is diverted to the power supply voltage line.
3) As stated above, APD gain depends on temperature. The S2381 series has a typical temperature coefficient of 0.65 V/˚C, but there is no problem with using the APD at a gain of around M=30 and 25 ˚C±3 ˚C. However, when used at a higher gain or wider temperature range, it is necessary to use some kind of temperature offset (to control the bias voltage according to temperature) or temperature control (to maintain the APD at a constant temperature).
4) When detecting low-level light signals, the detection limit can be determined by the shot noise of background light. If background light enters the APD, then the S/N may deteriorate due to the shot noise. As a countermeasure for minimizing background light, use of an optical filter, improving laser modulation or restricting the field of view is necessary.

Figure 5-4 Peripheral circuit example of APD



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Reliability

If used within the specified operating ratings, chips of photodiodes will exhibit virtually no deterioration of characteristics. Deterioration can often be attributed to package, lead or filter failure. Package leakage at high temperatures and humidity, in particular, often causes the dark current to increase. Therefore, plastic and ceramic package photodiodes have a somewhat limited temperature and humidity range. In contrast, metal package types feature excellent resistance to ambient humidity. Photodiodes with filters are greatly affected by endurance of the filter to environmental conditions. These factors must be taken into consideration when using and storing photodiodes.

Hamamatsu photodiodes are subjected to reliable test based on JEITA (Japan Electronic Information and Technology Association). Reliable tests are also performed in compliance with MIL (US Military) standards and IEC (International Electrotechnical Commission) standards according to the product applications. The major reliability test standards used by Hamamatsu are summarized below in major reliability test standards.

Major reliability test standards

Test item	Condition	ED-4701	Criteria
Terminal strength	Pulling 10 seconds, bending 90˚ two times	A-111	Damage to terminal, etc.
Vibration	100 to 2000 Hz, 200 m/s^2 XYZ directions, 4 minutes, 4 times each (total 48 minutes)	A-121	Appearance and electrical characteristics
Shock	1000 m/s^2, 6 ms XYZ directions, 3 times each	A-122	
Solderability	235 ± 5 ˚C, 5 or 2 seconds, 1 to 1.5 mm	A-131	Solderability
Resistance to soldering heat (except surface mount type)	260 ± 5 ˚C, 10 seconds, 1 to 1.5 mm	A-132	Appearance and electrical characteristics
Resistance to soldering heat (surface mount type)	Reflow 235 ˚C, 10 seconds	A-133	
High temperature storage	Tstg (Max.) : 1000 hours	B-111	
Low temperature storage	Tstg (Min.) : 1000 hours	B-112	
High temperature, high humidity storage	60 ˚C, 90 %: 1000 hours	B-121	
Temperature cycle	Tstg Min. to Tstg Max., in air, 30 minutes each, 10 cycles	B-131	
Electrostatic discharge	R=1.5 kΩ, C=100 pF, E=±1000 V, 3 times	C-111	
Resistance to solvent	Isopropyl alchohol, 23 ± 5 ˚C, 5 minutes	C-121	Marking legibility, paint peeling
High temperature reverse bias	Topr Max., V_R Max.: 1000 hours	D-212	Appearance and electrical characteristics

Note 1) Reference standards
Test method: JEITA-ED-4701 “Environmental and endurance test methods for semiconductor devices”
Note 2) Breakdown criteria standards
Test conditions and breakdown criteria standards table for collecting reliability test data
(National Institute of Advanced Industrial Science and Technology)

Precaution for use

● Window

Care should be taken not to touch the window with bare hands, especially in the case of ultraviolet detection since foreign materials on the window can seriously affect transmittance in the ultraviolet range. (There have been occasions where contamination of the window by oil from hands reduced sensitivity at 250 nm by as much as 30 %.)

If the window needs to be cleaned, use ethyl alcohol and wipe off the window gently. Avoid using any other organic solvents than ethyl alcohol as they may cause deterioration of the device's resin coating or filter.

When using tweezers or other hard tools, be careful not to allow the tip or any sharp objects to touch the window surface. If the window is scratched or damaged, accurate measurement cannot be expected when detecting a small light spot. In particular, use sufficient care when handling resin-coated or resin-molded devices.

Lightly wipe dirt of the window using ethyl alcohol.

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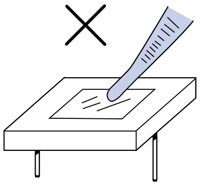

Avoid scratching the light input window with pointed objects (tweezers tip, etc.) or rubbing it with a hard flat surface.

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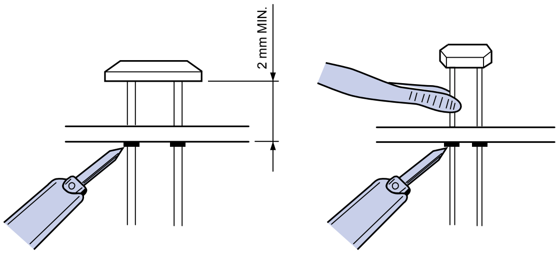
● Lead forming

When forming leads, care should be taken to keep the recommended mechanical stress limits: 5 N pull for 5 seconds maximum, two 90 degrees bends and two twists of the leads at 6 mm minimum away from the package base.

To form the leads of plastic-molded package devices, use long-nose pliers to hold near by the root of the leads securely.

● Soldering

Since photodiodes are subject to damage by excessive heat, sufficient care must be given to soldering temperature and dwell time. As a guide, metal package devices should be soldered at 260 ˚C or below within 10 seconds, ceramic package devices at 260 ˚C within 5 seconds at 2 mm minimum away from the package base, and plastic package devices at 230 ˚C or below within 5 seconds at 1 mm minimum away from the package base.



Mount ceramic package types 2 mm minimum away from any surface and solder at 260 ˚C maximum for 5 seconds maximum time.

Use tweezers, etc. as a heatsink when soldering small photodiodes.

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● Recommended soldering condition

Package	Soldering temperature Max. (˚C)	Soldering time Max. (s)	Remark
Metal	260	10	
Ceramic	260	5	2 mm or more away from package
Ceramic chip carrier	260	5	S5106, S5107 non moisture absorption
Plastic	230	5	1 mm or more away from package

● Cleaning

Use alcohol to remove solder flux. Never use other type of solvent because, in particular, plastic packages may be damaged. It is recommended that the device be dipped into alcohol for cleaning. Ultrasonic cleaning and vapor cleaning may cause fatal damage to some types of devices (especially, hollow packages and devices with filters). Confirm in advance that there is no problem with such cleaning methods, then perform cleaning.

Some caution may be needed when using the photodiode according to the particular structure. Cautions needed when using various products are listed on the next page.

Bare chip Si photodiode (S3590-19, S6337-01)

S3590-19 and S6337-01 have a windowless package and does not incorporate measures to protect the photodiode chip.

- Never touch the photodiode chip surface or wiring.
- Wear dust-proof gloves and a dust-proof mask.
- Use air-blow to remove foreign objects or objects attached to the surface.
- Do not attempt to wash.

Si photodiode with preamp

The Si photodiode with preamp is prone to damage or deterioration from static electricity in the human body, surge voltages from test equipment, leakage voltage from soldering irons, and packing materials, etc.
To eliminate the risk of damage from static electricity, the device, worker, work location, and tool jig must all be at the same electrical potential. Take the following precautions during use.

- Use items such as a wrist strap to get a high resistance (1 MΩ) between the human body and ground to prevent damage to the device from static electricity that accumulates on the worker and the worker's clothes.
- Lay a semi-conductive sheet (1 MΩ to 100 MΩ) on the floor and also on the workbench, and then connect them to ground.
- Use a soldering iron having an insulation resistance of 10 MΩ or more and connect it to ground.
- Conductive material or aluminum foil is recommended for use as a container for shipping or packing. To prevent accumulation of static charges, use material with a resistance of 0.1 MΩ/cm^2 to 1 GΩ/cm^2.

Surface mount type Si photodiode

Surface mount Si photodiodes come in ceramic or plastic package types. Sealing resin used for photodiodes was designed with light transmittance in mind and so has low resistance to moisture and heat compared to sealing resin for general-purpose IC. This means that special care is required during handling. Unexpected troubles can occur if the IC temperature profile is used in reflow soldering. Therefore keep the following points in mind.

1) Ceramic type (silicone resin coating type)
- The resin protecting the photodiode surface is soft so that applying an external force may damage the resin surface, warp the bonding wires, or break wires, so avoid touching the surface as much as possible.
- If stored for 3 months while unpacked or if more than 24 hours have elapsed after unpacking, bake for 3 to 5 hours at 150 ˚C in a nitrogen atmosphere, or for 12 to 15 hours at 120 ˚C in a nitrogen atmosphere.
  Note) Stick type shipping container material is vulnerable to heat, so do not try baking while the photodiodes are still in a stick.

2) Plastic type (epoxy resin mold type)
- Trouble during reflow is due to moisture absorption in the epoxy resin forming the package material. During soldering, the amount of moisture increases suddenly due to the heat and trouble such as peeling on the chip surface and package cracks is prone to occur.
- The packing is not usually moisture-proof so baking for 3 to 5 hours at 150 ˚C or for 12 to 15 hours at 120 ˚C in a nitrogen atmosphere is necessary before reflow soldering.
  Note) Stick type shipping container material is vulnerable to heat, so do not try baking while the photodiodes are still in a stick.
- When required, it is possible to bake photodiodes prior to shipping and pack them in a moisture-proof case.

3) Reflow soldering
- Reflow soldering conditions depend on factors such as the PC board, reflow oven and product being used. Please ask in advance, about recommended reflow conditions for a particular product.