Description of Terms Used in This Catalog

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.

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.

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):

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

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

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 (1000 time for GaP photodiodes). 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.

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:

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

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:

$$Rsh = \frac{10\ [\text{mA}]}{I_D}\ [\Omega] \quad \dots\dots\dots\dots\dots\dots\dots\dots \ (3)$$

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

Terminal Capacitance: C_t

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 this catalog, the terminal capacitance including this junction capacitance plus package stray capacitance is listed.

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 this catalog, it is measured with a light source of GaAsP LED (655 nm) or GaP LED (560 nm) and load resistance of 1 k Ω.

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:

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

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. This catalog 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 and thus expressed in units of W/Hz$^{1/2}$.

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

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.

Characteristics and Use of Photodiodes

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 Types

1) PNN$^+$ photodiodes
2) PIN photodiodes
3) Schottky type photodiodes
4) APD (Avalanche photodiodes)

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 Photodiodes

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

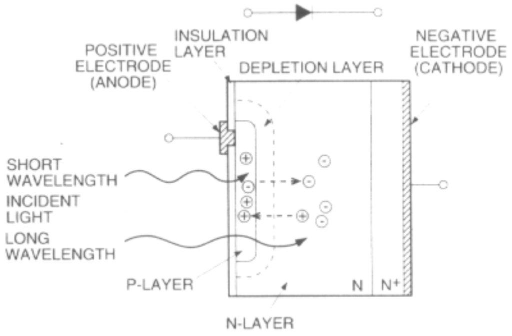
This section will serve to introduce the construction, characteristics, operation and use of photodiodes.

PRINCIPLE OF OPERATION

Figure 1 (a) 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 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 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 (b)) 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.

Figure 1 (a): Photodiode Cross Section



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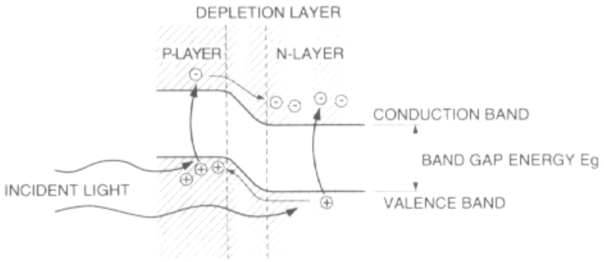
(b): Photodiode P-N Junction State



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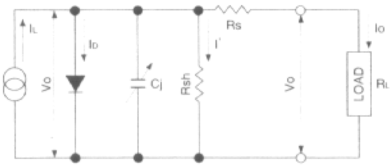
EQUIVALENT CIRCUIT

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

Figure 2: Photodiode Equivalent Circuit



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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:

$$Io = I_L - I_D - I' = I_L - Is\ (exp\ \frac{eV_D}{kT} - 1)\ - I' \ .... (6)$$

where

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

$$Voc = \frac{kT}{e} ln \left(\frac{I_L - I'}{Is} \right) + 1 \ \text{..........................} \ (7)$$

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:

$$Isc = I_L - Is \left(exp \frac{e \cdot (Isc \cdot Rs)}{kT} - 1 \right) - \frac{Isc \cdot Rs}{Rsh} \ \text{...............} \ (8)$$

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.

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 3 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:

$$Psat = \frac{V_{Bi} + V_R}{(Rs + R_L) \cdot S\lambda} \ \text{.....................} \ (9)$$

where

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

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 4 shows the result of plotting Isc and Voc as a function of incident light illuminance.

Figure 3: Current vs. Voltage

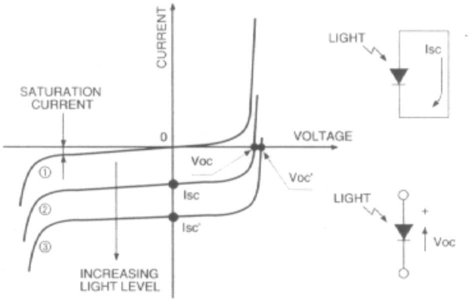

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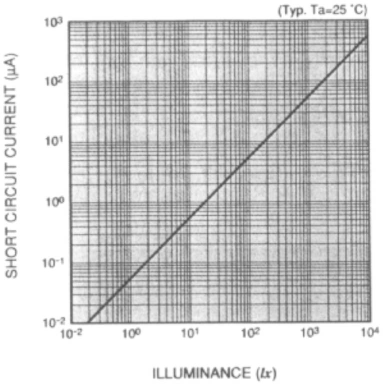
Figure 4: Output Signal vs. Incident Light Level (S2386-5K)

(a) Short Circuit Current



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(b) Open Circuit Voltage

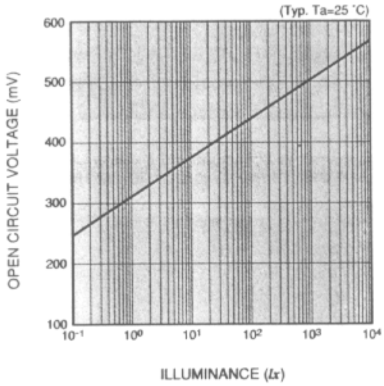

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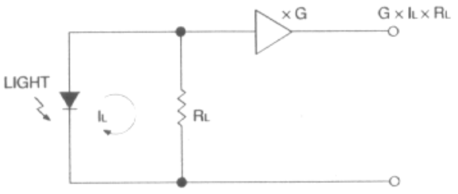
Figure 5 (a) and (b) show methods of measuring light by measuring the photocurrent I_L or Isc. In the circuit shown at (a), the voltage ($I_L \times R_L$) is amplified by an amplifier with gain G, although the circuit does have limitations on its linearity according to equation (9). This condition is shown in Figure 6. Figure 5 (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 5: Photodiode Operational Circuits

(a) LOAD RESISTANCE CIRCUIT



(b) OP-AMP CIRCUIT

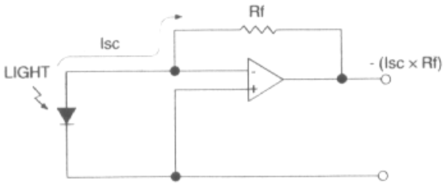


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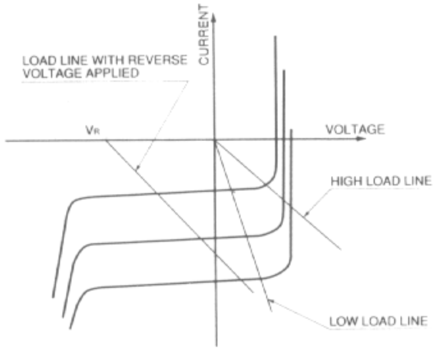
Figure 6: Current vs. Voltage Characteristics and Load Line



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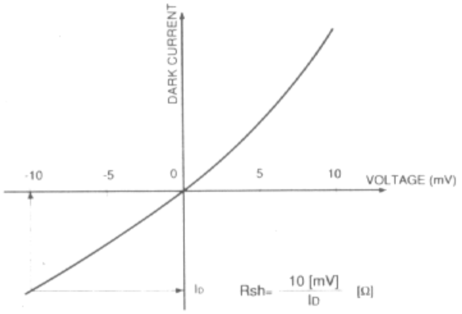
If the zero region of Figure 3 ① is magnified, we see, as shown in Figure 7, that the dark current I_D is approximately linear in a voltage range of about ±10 mV. The slope in this region indicates the shunt resistance Rsh and this resistance is the cause of the thermal noise current described later. In this catalog, values of Rsh are given using a dark current I_D measured with −10 mV applied.

Figure 7: Dark Current vs. Voltage (Enlarged Zero Region)



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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 λ_h can be expressed in terms of Eg as follows:

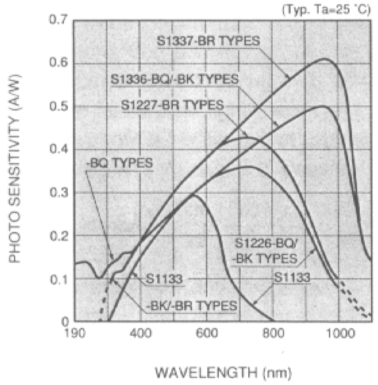
$$\lambda_h = \frac{1240}{Eg} \text{ [nm]} \ldots\ldots\ldots\ldots\ldots\ldots \text{(10)}$$

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 (a).] 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 8 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.

Figure 8: Spectral Response



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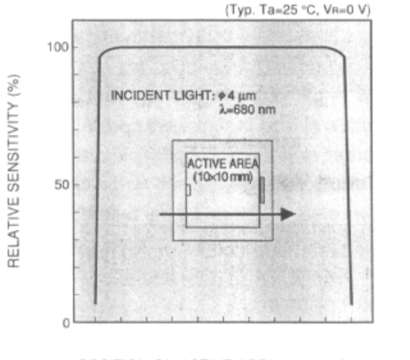
SPATIAL RESPONSE UNIFORMITY

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 9: Spatial Response Uniformity (S1227-1010BQ)



0.2 % UNIFORMITY WITHIN 80 % OF ACTIVE AREA

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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 of a resistor which approximates the shunt resistance and the shot noise i_{sD} and i_{sL} resulting from the dark current and the photocurrent.

$$i_n = \sqrt{i_j^2 + i_{sD}^2 + i_{sL}^2} \text{ [A]} \ldots\ldots \text{(11)}$$

When a photodiode is operated with no reverse voltage applied like that shown in Figure 5, i_j is given as follows:

$$i_j = \sqrt{\frac{4kTB}{Rsh}} \text{ [A]} \ldots\ldots\ldots\ldots\ldots\ldots \text{(12)}$$

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

When a bias voltage is applied as in Figure 12, there is always a dark current. The shot noise i_{sD} originating from the dark current is given by

$$i_{sD} = \sqrt{2qI_DB} \text{ [A]} \ldots\ldots\ldots\ldots\ldots\ldots \text{(13)}$$

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

With the application of incident light, a photocurrent I_L exists so i_{sL} is given by

$$i_{sL} = \sqrt{2qI_LB} \text{ [A]} \ldots\ldots\ldots\ldots\ldots\ldots \text{(14)}$$

I_L : Photocurrent

If $I_L \gg 0.026/Rsh$ or $I_L \gg I_D$, the shot noise current of equation (14) becomes predominant instead of the noise factor of eqaution (12) or (13).

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 (12) or (13). Essentially this is the noise equivalent power (NEP).

$$NEP = \frac{i_n}{S} \text{ [W/Hz}^{1/2}\text{]} \ldots\ldots\ldots\ldots \text{(15)}$$

i_n : Noise current (A)
S : Photo sensitivity (A/W)

Figure 10 shows the relationship between NEP and shunt resistance, from which can be seen the agreement with the theoretical relationship. When a photodiode is operated using a circuit like that shown in Figure 5 (a), it is necessary to take into account the noise of load resistance R_L and NF of the amplifier, as well as the above stated noise originating from the photodiode. When using a circuit like that shown in Figure 5 (b), it is necessary to take into acconnt the noise components of operational amplifier and feedback resistance Rf, moreover, in measurements at high frequencies, attention must be paid to the transfer function including the capacitive components such as the photodiode capacitance Ct and the feedback capacitance Cf. The light detection limit with this circuit 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 is 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. This technique can allow the actual measured detection limit to approach the detector's theoretical NEP.

Figure 10: NEP vs. Shunt Resistance (S1226-5BK)

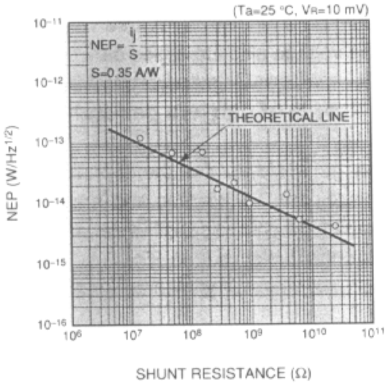

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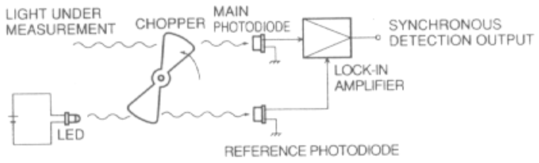
Figure 11: Synchronous Measurement Method



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Compared to normal photodiodes not having an amplification mechanism, APDs (avalanche photodiodes) exhibit additional excessive noise components caused by variations in the avalanche amplification process. Using the gain M, a photocurrent Io and the excess noise factor F, the shot noise current *in* is expressed as follows:

$$in = \sqrt{2qI_oM^2FB} \quad \text{.............................} \quad (16)$$

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

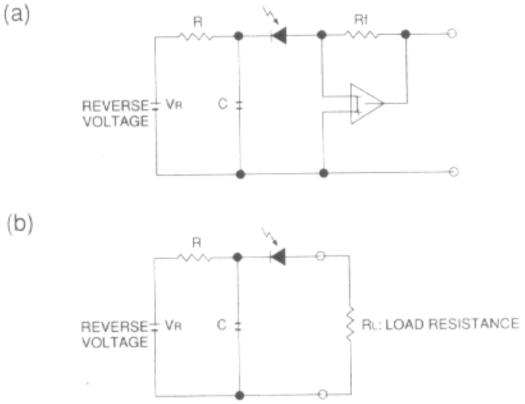
$$F = M^x \quad \text{.............................} \quad (17)$$

The exponent x is known as the excessive noise index or figure, and is in the range of approximately 0.3 to 0.5. Using APD allows the use of a smaller load resistance in comparison with normal photodiodes. This enables not only an operational speed advantage, but an improvement in S/N ratio as well, thus making it possible to detect very low light levels. For details, refer to the description on page 37.

■ 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 12 shows examples of reverse voltage connection. Figures 13 and 14 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 12: Reverse Voltage Connection



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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 this catalog are recommended values and each PIN photodiode is designed to provide optimum performance at the recommended reverse voltage. Figure 15 shows an example of the actual connection shown in Figure 12 (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 13: Cut-off Frequency vs. Reverse Voltage (S5973)

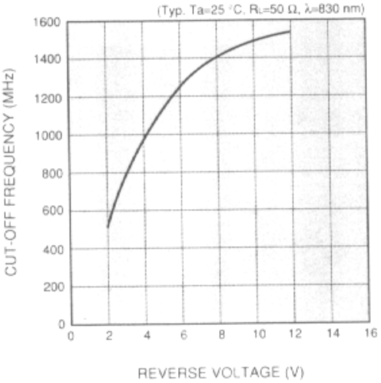

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Figure 14: Output Current vs. Illuminance (S1336-5BQ)

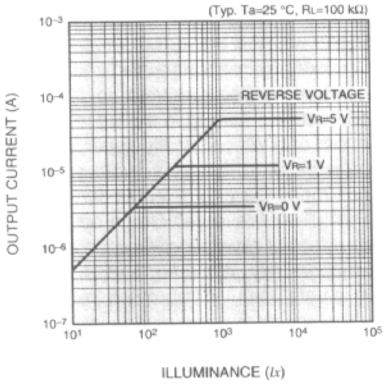

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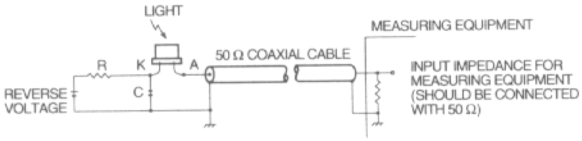
Figure 15: Connection to Coaxial Cable



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■ 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

$$t_1 = 2.2 \times Ct \times R_L \quad \text{.........} \quad (18)$$

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:

$$Cj \propto A \{(V_R + 0.5) \times \rho\}^{-1/2 \text{ to } -1/3} \quad \text{.........} \quad (19)$$

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:

$$t_3 = d/vd = d^2/(\mu V_R) \quad \text{.........} \quad (20)$$

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:

$$tr = \sqrt{t_1^2 + t_2^2 + t_3^2} \quad \text{.........} \quad (21)$$

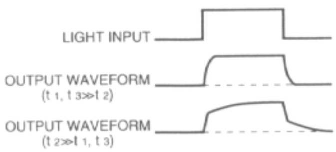
PIN photodiodes and avalanche photodiodes are designed such that less carriers are generated outside the depletion layer, Ct is small and the carrier transit time in the depletion layer is short. Therefore, these types are ideally suited for high-speed light detection.

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:

$$tr = 0.35/fc \quad \text{.........} \quad (22)$$

Figures 16 (a), (b) and (c) show examples of the response waveform and frequency response characteristics for typical photodiodes.

Figure 16 (a): Photodiode Response Waveform Example



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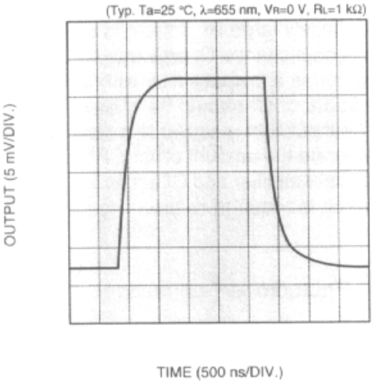
(b): S2386-18K Response Waveform



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(c): S5973 Frequency Response

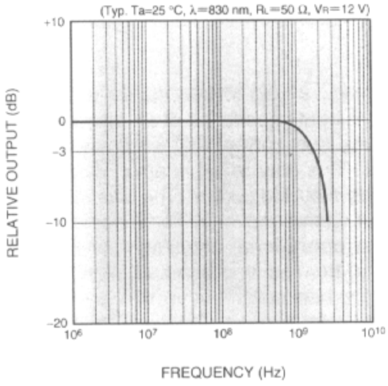

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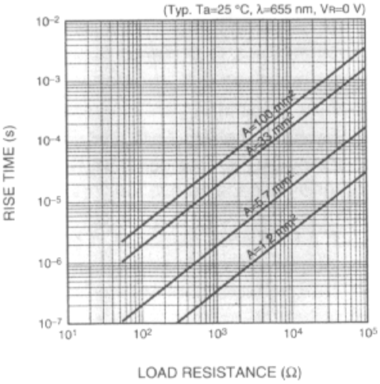
Figure 17: Rise Time vs. Load Resistance with Active Area as Parameter (S2387 Series)



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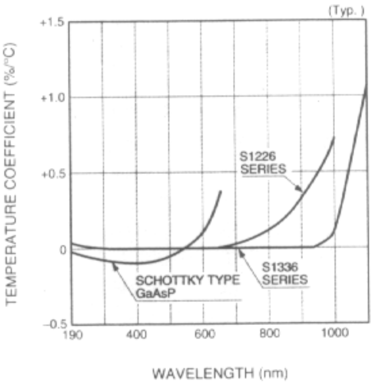
TEMPERATURE CHARACTERISTICS

Ambient temperature variations greatly affect photodiode sensitivity and dark current. The sensitivity variation is mainly caused by an increase in the light absorption coefficient which is temperature related. For long wavelengths, sensitivity increases with increasing temperature, and this increase becomes prominent at wavelengths longer than the peak wavelength. Since Hamamatsu photodiodes are designed to have low absorption loss in the short wavelength region, the temperature coefficient is extremely small at wavelengths shorter than the peak wavelength. Figure 18 shows examples of temperature coefficients of sensitivity for a variety of photodiode types.

Figure 18: Temperature Coefficient of Photo Sensitivity vs. Wavelength



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The variation in dark current with temperature is caused by probability from increasing temperatures causing electrons in the valence band to become excited, pulling them into the conduction band. A constant increase in dark current is evident with the increasing temperature. Figure 19 indicates a two-fold increase in dark current for a temperature rise from 5 to 10 °C. The dark current I_D of a photodiode and its temperature characteristics are expressed in the following relation:

$$I_{D2} = I_{D1} \times T_{CID}^{(T2 - T1)} \quad \text{......................} \quad (23)$$

T_{CID} : Temperature coefficient of photodiode dark current
I_{D1} : Dark current at T1 (°C)
I_{D2} : Dark current at T2 (°C)

Stated differently, this is equivalent to a reduction in the shunt resistance and a subsequent increase in thermal and shot noise. Figure 20 shows an example of the temperature characteristics of open-circuit voltage, indicating linearity with respect to temperature change. However, since the temperature dependence of Voc is large compared to that of sensitivity (Isc), Voc is not suited for light intensity measurement.

Figure 19: Dark Current vs. Ambient Temperature (S2387 Series)

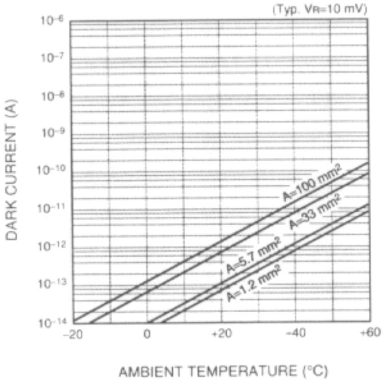

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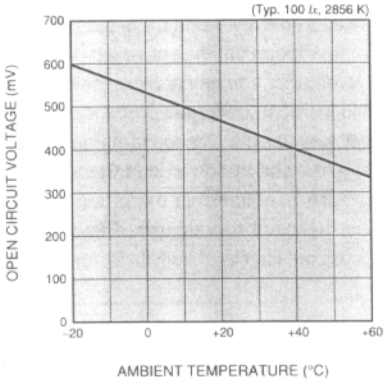
Figure 20: Temperature Dependence of Open Circuit Voltage (S2387 Series)



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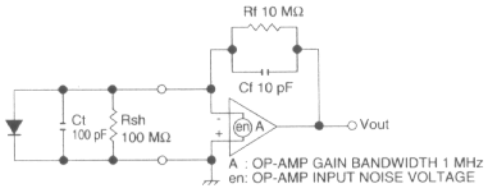
■ USE OF OPERATIONAL AMPLIFIERS

1) Feedback Circuit

Figure 21 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 $\left(1 + \frac{Rf}{Rsh}\right)$. 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 21: Basic Photodiode Connection



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2) Bias Circuit

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.

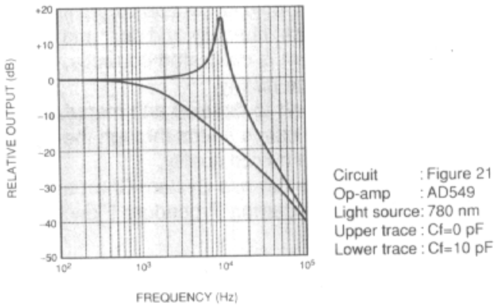
As is the case with offset voltage, the error voltage attributable to the bias current can be adjusted by means of a potentiometer connected to the offset adjustment terminals. Furthermore, leakage currents on the PC board used to house the circuit may be greater than the operational amplifier's bias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

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 22 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 [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 (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 22: Gain Peaking

(a) Frequency Response



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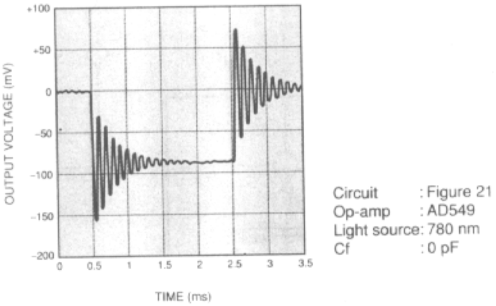
(b) Light Pulse Response



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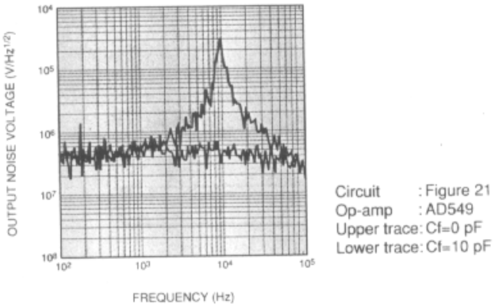
(c) Frequency Response of Noise Current



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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. 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 21. As shown in Figure 23, 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 21. 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 22.)

To summarize the above points:

a) When designing Rf and Cf, f2 should be set to a value such that region ③ in Figure 23 exists.

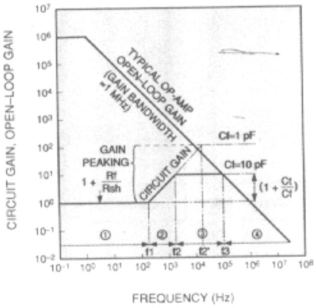
b) When f2 is positioned to the right of the open-loop gain line of the operational amplifier, use the operational amplifier which has a high frequency at which the gain becomes 1 (unity gain bandwidth), and set region ③.

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 ratio 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.

Figure 23: Graphical Representation of Gain Peaking



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Handling Precautions

● 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 off the window using ethyl alcohol.

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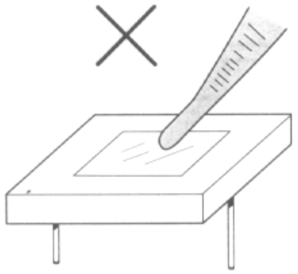

Don't allow the tip or any sharp objects to touch the window suface.

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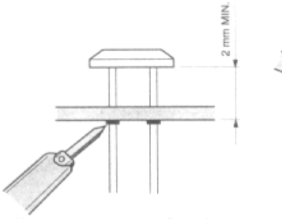
● Lead Forming

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

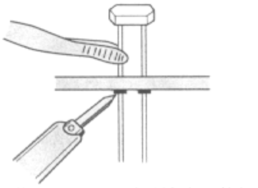
To form the leads of plastic-molded package devices, use long-nose pliers to hold near by the root of the leads securely.

● 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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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.

References

● Physical Constants

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	εo	8.854×10^{-12}	F/m
Dielectric Constant of Silicon	εsi	approx. 12	–
Dielectric Constant of Silicon Oxide	εox	approx. 4	–
Energy Gap of Silicon	Eg	approx. 1.12 (T=25 °C)	eV

● Unit Conversion Table for Illuminance

lux	Photo	Foot-candle	Watt per Square Centimeter *1	Watt per Square Centimeter *2
lx (lm/m²)	ph (lm/cm²)	fc (lm/ft²)	W/cm²	W/cm²
1	1.000×10^{-4}	9.290×10^{-2}	5.0×10^{-6}	9.1×10^{-7}
1.000×10^{4}	1	9.290×10^{2}	5.0×10^{-2}	9.1×10^{-3}
1.076×10^{1}	1.076×10^{-3}	1	5.4×10^{-5}	9.8×10^{-6}
2.0×10^{5}	2.0×10^{1}	1.9×10^{4}	1	–
1.1×10^{6}	1.1×10^{2}	1.03×10^{5}	–	1

*1: Total irradiance (measured value) by a CIE standard light source "A" (color temperature: 2856 K).

*2: Surface irradiance of sunlight on the earth at meridian transit in fine weather. (measured value; direct sunlight rays in summer approx. 10^5 *lx*)

Illuminance: Luminous flux incident per unit area of a surface. measured with a sensor having spectral response characteristics limited to the sensitivity of the human eyes (conforms to CIE standards).