Characteristic and use

1. Basic principle

A PSD basically consists of a uniform resistive layer formed on one or both surfaces of a high-resistivity semiconductor substrate, and a pair of electrodes formed on both ends of the resistive layer for extracting position signals. The active area, which is also a resistive layer, has a PN junction that generates photocurrent by means of the photovoltaic effect.

Figure 1-1 PSD sectional view

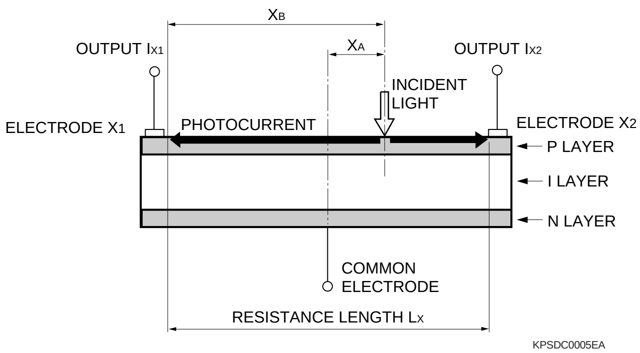


Figure 1-1 shows a sectional view of a PSD using a simple illustration to explain the operating principle. The PSD has a P-type resistive layer formed on an N-type high-resistive silicon substrate. This P-layer serves as an active area for photoelectric conversion and a pair of output electrodes are formed on the both ends of the P-layer. On the backside of the silicon substrate is an N-layer to which a common electrode is connected. Basically, this is the same structure as that of PIN photodiodes except for the P-type resistive layer on the surface.

When a spot light strikes the PSD, an electric charge proportional to the light intensity is generated at the incident position. This electric charge is driven through the resistive layer and collected by the output electrodes X_1 and X_2 as photocurrents, while being divided in inverse proportion to the distance between the incident position and each electrode.

The relation between the incident light position and the photocurrents from the output electrodes X_1, X_2 is given by the following formulas.

● **When the center point of PSD is set at the origin:**

$$I_{X1} = \frac{\frac{L_X}{2} - X_A}{L_X} \times I_o \quad \cdots\cdots\ (1\text{-}1) \qquad I_{X2} = \frac{\frac{L_X}{2} + X_A}{L_X} \times I_o \quad \cdots\cdots\ (1\text{-}2)$$

$$\frac{I_{X2} - I_{X1}}{I_{X1} + I_{X2}} = \frac{2X_A}{L_X} \quad \cdots\cdots\ (1\text{-}3) \qquad \frac{I_{X1}}{I_{X2}} = \frac{L_X - 2X_A}{L_X + 2X_A} \quad \cdots\cdots\ (1\text{-}4)$$

● **When the end of PSD is set at the origin:**

$$I_{X1} = \frac{L_X - X_B}{L_X} \cdot I_o \quad \cdots\cdots\ (1\text{-}5) \qquad I_{X2} = \frac{X_B}{L_X} \cdot I_o \quad \cdots\cdots\ (1\text{-}6)$$

$$\frac{I_{X2} - I_{X1}}{I_{X1} + I_{X2}} = \frac{2X_B - L_X}{L_X} \quad \cdots\cdots\ (1\text{-}7) \qquad \frac{I_{X1}}{I_{X2}} = \frac{L_X - X_B}{X_B} \quad \cdots\cdots\ (1\text{-}8)$$

I_o : Total photocurrent ($I_{X1} + I_{X2}$)
I_{X1}: Output current from electrode X_1
I_{X2}: Output current from electrode X_2
L_X: Resistance length (length of the active area)
X_A: Distance from the electrical center of PSD to the light input position
X_B: Distance from the electrode X_1 to the light input position

By finding the difference or ratio of I_{X1} to I_{X2}, the light input position can be obtained by the formulas (1-3), (1-4), (1-7) and (1-8) irrespective of the incident light intensity level and its changes. The light input position obtained here corresponds to the center-of-gravity of the light beam.

2. One-dimensional PSD

Figure 2-1 Structure chart, equivalent circuit (one-dimensional PSD)

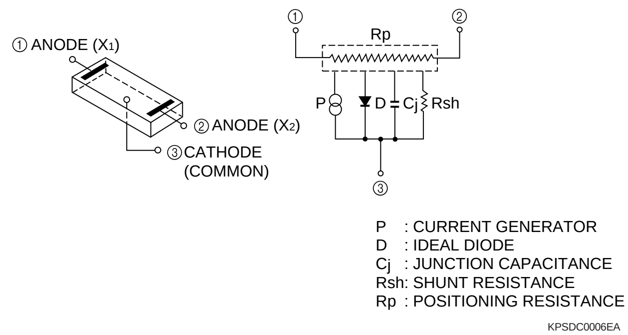
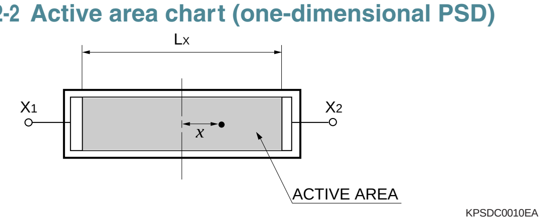


Figure 2-2 Active area chart (one-dimensional PSD)



● **Position conversion formula (See Figure 2-2.)**

$$\frac{I_{X2} - I_{X1}}{I_{X1} + I_{X2}} = \frac{2x}{L_X} \quad \cdots\cdots\ (2\text{-}1)$$

In the above formula, I_{X1} and I_{X2} are the output currents obtained from the electrodes shown in Figure 2-2.

3. Two-dimensional PSD

Two-dimensional PSDs are grouped by structure into duo-lateral and tetra-lateral types. Among the tetra-lateral type PSDs, a pin-cushion type with an improved active area and electrodes is also provided. (See “3-3”.) The position conversion formulas slightly differ according to the PSD structure. Two-dimensional PSDs have two pairs of output electrodes, X_1, X_2 and Y_1, Y_2.

3-1 Duo-lateral type PSD

On the duo-lateral type, the N-layer shown in the sectional view of Figure 1-1 is processed to form a resistive layer, and two pair of electrodes are formed on both surfaces as X and Y electrodes arranged at right angles. (See Figure 3-1.) The X position signals are extracted from the X electrodes on the upper surface, while the Y position signals are extracted from the Y electrodes on the bottom surface. As shown in Figure 3-1, a photocurrent with a polarity opposite that of the other surface is on each surface, to produce signal currents twice as large as the tetra-lateral type and achieve a higher position resolution. In addition, when compared to the tetra-lateral type, the duo-lateral type offers excellent position detection characteristics because the electrodes are not in close proximity. The light input position can be calculated from conversion formulas (3-1) and (3-2).

Figure 3-1 Structure chart, equivalent circuit (duo-lateral type PSD)

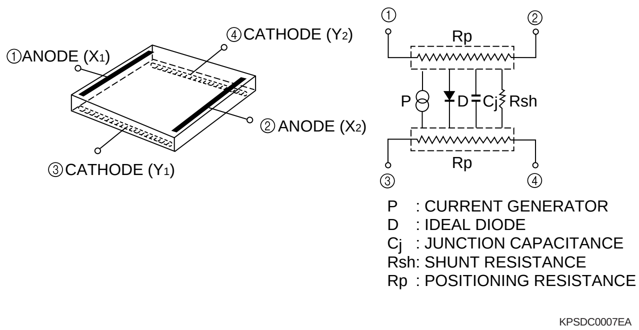
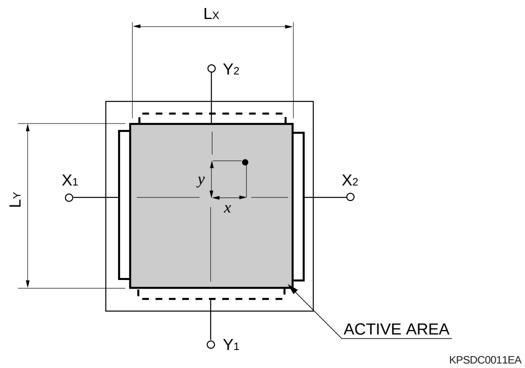


Figure 3-2 Active area chart (duo-lateral type PSD)



● **Position conversion formula (See Figure 3-2.)**

$$\frac{I_{X2} - I_{X1}}{I_{X1} + I_{X2}} = \frac{2x}{L_X} \;........\; (3\text{-}1)$$

$$\frac{I_{Y2} - I_{Y1}}{I_{Y1} + I_{Y2}} = \frac{2y}{L_Y} \;........\; (3\text{-}2)$$

3-2 Tetra-lateral type PSD

The tetra-lateral type has four electrodes on the upper surface, formed along each of the four edges. Photocurrent is divided into 4 parts through the same resistive layer and extracted as position signals from the four electrodes. Compared to the duo-lateral type, interaction between the electrodes tends to occur near the corners of the active area, making position distortion larger. But the tetra-lateral type features an easy-to-apply reverse bias voltage, small dark current and high-speed response. The light input position for the tetra-lateral type shown in Figure 3-4 is given by conversion formulas (3-3) and (3-4), which are the same as for the duo-lateral type.

Figure 3-3 Structure chart, equivalent circuit (tetra-lateral type PSD)

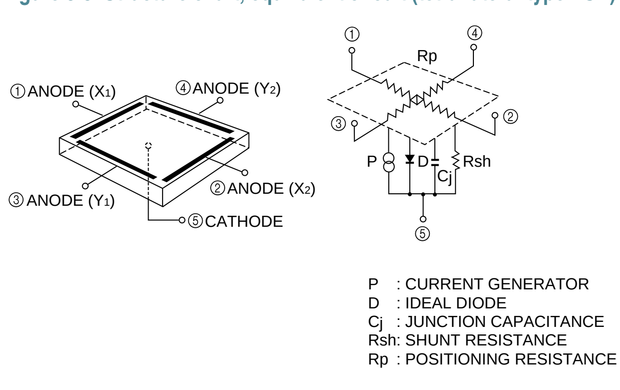
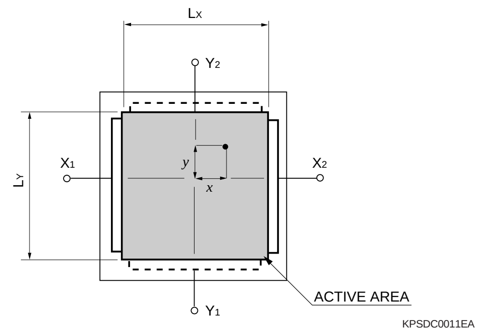


Figure 3-4 Active area chart (tetra-lateral type PSD)



● **Position conversion formula (See Figure 3-4.)**

$$\frac{I_{X2} - I_{X1}}{I_{X1} + I_{X2}} = \frac{2x}{L_X} \;........\; (3\text{-}3)$$

$$\frac{I_{Y2} - I_{Y1}}{I_{Y1} + I_{Y2}} = \frac{2y}{L_Y} \;........\; (3\text{-}4)$$

3-3 Pin-cushion type (improved tetra-lateral type) PSD

This is a variant of the tetra-lateral type PSD with an improved active area and reduced interaction between electrodes. In addition to the advantages of small dark current, high-speed response and easy application of reverse bias that the tetra-lateral type offers, the circumference distortion has been greatly reduced. The light input position of the pin-cushion type shown in Figure 3-6 is calculated from conversion formulas (3-5) and (3-6), which are different from those for the duo-lateral and tetra-lateral types.

Figure 3-5 Structure chart, equivalent circuit (pin-cushion type PSD)

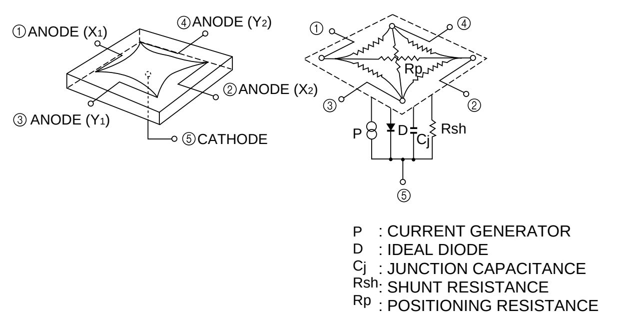
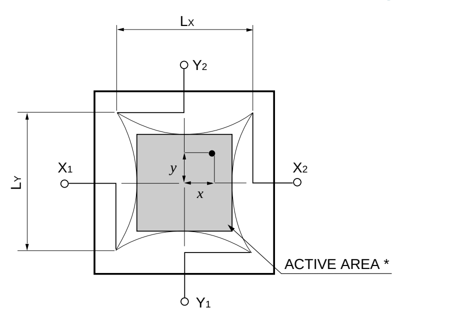


Figure 3-6 Active area chart (pin-cushion type PSD)



* Active area is specified at the inscribed square.

KPSDC0012EA

● **Position conversion formula (See Figure 3-6.)**

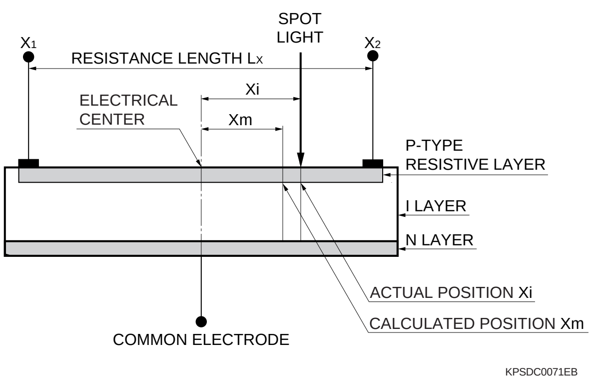
$$\frac{(I_{X2} + I_{Y1}) - (I_{X1} + I_{Y2})}{I_{X1} + I_{X2} + I_{Y1} + I_{Y2}} = \frac{2x}{L_X} \;........\; (3\text{-}5)$$

$$\frac{(I_{X2} + I_{Y2}) - (I_{X1} + I_{Y1})}{I_{X1} + I_{X2} + I_{Y1} + I_{Y2}} = \frac{2y}{L_Y} \;........\; (3\text{-}6)$$

4. Position detection error

Position detection capability is the most important characteristic of a PSD. The position of a spot light incident on the PSD surface can be measured by making calculations based on the photocurrent extracted from each electrode. The position obtained here with the PSD is the center-of-gravity of the spot light, and is independent of the spot light size, shape and intensity.
However, the calculated position usually varies slightly in each PSD from the actual position of the incident light. This difference is referred to as the "position detection error" and is explained below.
If a light beam strikes the electrical center of a PSD, the signal currents extracted from the output electrodes are equal. When this electrical center is viewed as the origin, the position detection error is defined as the difference between the position at which the light is actually incident on the PSD and the position calculated from the PSD outputs.

Figure 4-1 Cross section of PSD



In Figure 4-1 above, if the actual position of incident light is Xi and the position calculated by the photocurrents (I_{X1} and I_{X2}) from electrodes X_1 and X_2 is Xm, then the difference in distance between Xi and Xm is defined as the position detection error as calculated below.

Position detection error E = Xi - Xm [µm] .... (4-1)
Xi : Actual position of incident light (µm)
Xm: Calculated position of incident light (µm)

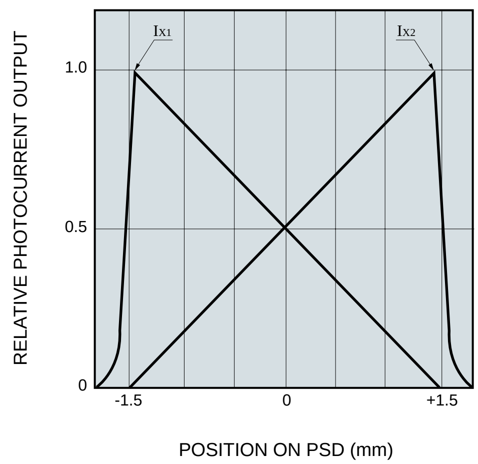
$$X_m = \frac{I_{X2} - I_{X1}}{I_{X1} + I_{X2}} \cdot \frac{L_X}{2} \quad \text{........ (4-2)}$$

The position detection error is measured under the following conditions.

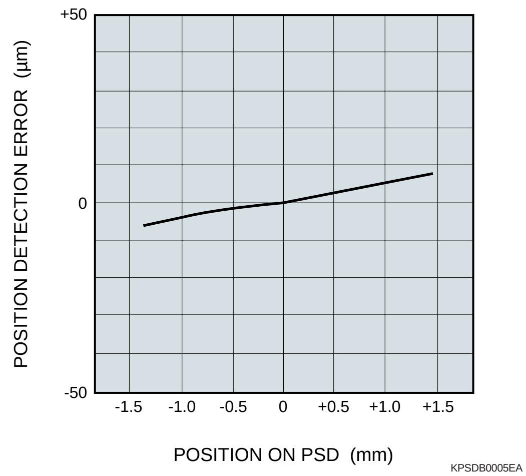
- Light source : λ=890 nm
- Spot light size : ϕ200 µm
- Total photocurrent: 10 µA
- Reverse voltage : Specified value (listed in data sheets)

Figure 4-2 shows the photocurrent output example from electrodes of a one-dimensional PSD with a resistance length of 3 mm (S4583-04, etc.), measured when a light beam is scanned over the active surface. The position detection error estimated from the obtained data is also shown in the lower graph.

Figure 4-2 Photocurrent output example of one-dimensional PSD (S4583-04, etc.)



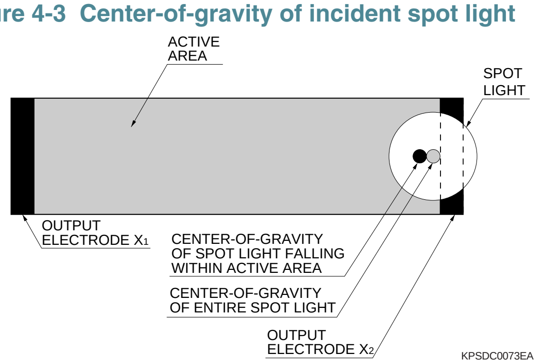
Position detection error example of one-dimensional PSD (S4583-04, etc)



Specific area for position detection error

The light beam position can be detected over the entire active area of PSD. However, if part of the light beam strikes outside the active area, a positional shift in the center-of-gravity occurs between the entire light beam and the light spot falling within the active area, making the position measurement unreliable. It is therefore necessary to select a PSD whose active area matches the incident spot light.

Figure 4-3 Center-of-gravity of incident spot light



The position detection error is usually measured with a light beam of ϕ200 µm, so the specified areas shown in Figures 4-4 to 4-6 are used for position detection error.

Figure 4-4 Specific area for one-dimensional PSD position detection error (resistance length ≤ 12 mm)

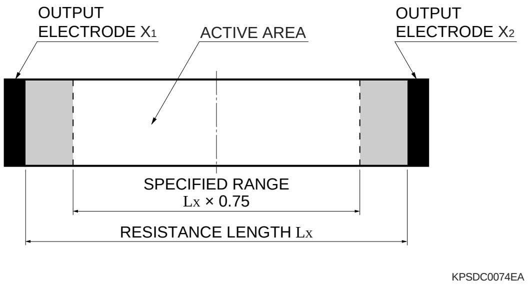


Figure 4-5 Specific area for one-dimensional PSD position detection error (resistance length > 12 mm)

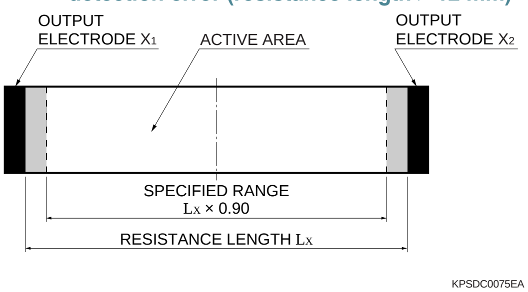
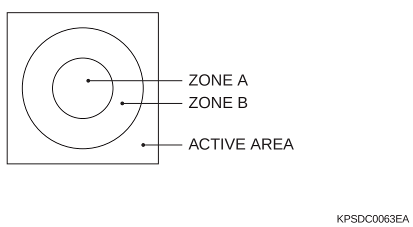


Figure 4-6 Specific area for two-dimensional PSD position detection error



Position detection error for two-dimensional PSDs is separately measured in two areas: Zone A and Zone B. Two zones are used because position detection error in the circumference is larger than that in the center of the active area,

· Zone A: Within a circle with a diameter equal to 40 % of one side length of the active area.
· Zone B: Within a circle with a diameter equal to 80 % of one side length of the active area.

5. Position resolution

Position resolution is the minimum detectable displacement of a spot light incident on PSD, expressed as a distance on the PSD surface. Resolution is determined by the PSD resistance length and the S/N. Using formula (1-6) as an example, the following equation can be established.

$$I_{X2} + \Delta I = \frac{X_B + \Delta x}{L_X} \cdot Io \text{ .... } (5\text{-}1)$$

Δx: Small displacement
ΔI: Change in output current

Then, Δx can be expressed by the following equation.

$$\Delta x = L_X \cdot \frac{\Delta I}{Io} \text{ .... } (5\text{-}2)$$

In cases where the positional displacement is infinitely small, the noise component contained in the output current I_{X2} clearly determines the position resolution. Generally, if the PSD noise current is In, then the position resolution ΔR is given as follows:

$$\Delta R = L_X \cdot \frac{In}{Io} \text{ .... } (5\text{-}3)$$

Figure 5-1 shows the basic connection example when using a PSD in conjunction with current-to-voltage amplifiers. The noise model for this circuit is shown in Figure 5-2.

Figure 5-1 Basic connection example of one-dimensional PSD and current-to-voltage conversion type operational amplifier

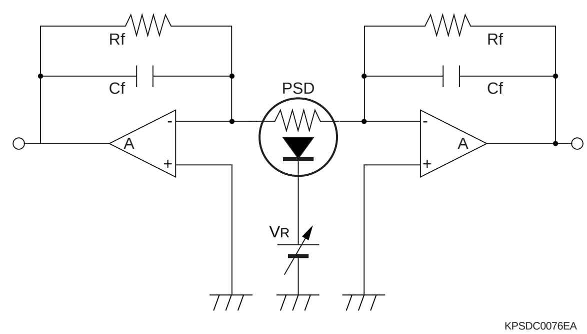
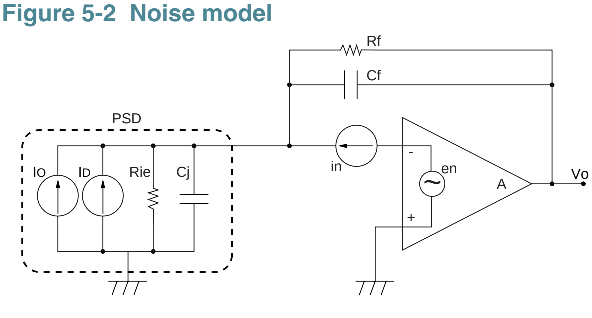


Figure 5-2 Noise model



Io : Photocurrent
ID : Dark current
Rie: Interelectrode resistance
Cj : Junction capacitance
Rf : Feedback resistance
Cf : Feedback capacitance
en : Equivalent noise input voltage of operational amplifier
in : Equivalent noise input current of operational amplifier
Vo : Output voltage

Noise currents are calculated below, assuming that the feedback resistance Rf of the current-to-voltage conversion circuit is sufficiently greater than the PSD interelectrode resistance Rie. In this case, 1/Rf can be ignored since it is sufficiently small compared to 1/Rie. Position resolution as listed in our PSD data sheets is calculated by this method.

1) Shot noise current Is originating from photocurrent and dark current

$$I_s = \sqrt{2q \cdot (I_o + I_D) \cdot B} \; [A] \quad \text{............ (5-4)}$$

q : Electron charge (1.60×10^{-19} C)
Io: Signal photocurrent (A)
ID: Dark current (A)
B : Bandwidth (Hz)

2) Thermal noise current (Johnson noise current) Ij generated from interelectrode resistance (This can be ignored as Rsh >> Rie.)

$$I_j = \sqrt{\frac{4kTB}{Rie}} \; [A] \quad \text{............ (5-5)}$$

k : Boltzmann constant (1.38×10^{-23} J/K)
T : Absolute temperature (K)
Rie: Interelectrode resistance (Ω)

3) Noise current Ien by equivalent noise input voltage of operational amplifier

$$I_{en} = \frac{e_n}{Rie}\sqrt{B} \; [A] \quad \text{............ (5-6)}$$

en: Equivalent noise input voltage of operational amplifier ($V/Hz^{1/2}$)

By taking the sum of equations (5-4), (5-5) and (5-6), the PSD noise current can be expressed as an RMS value as follows:

$$I_n = \sqrt{I_s^2 + I_j^2 + I_{en}^2} \; [A] \quad \text{............ (5-7)}$$

If Rf cannot be ignored versus Rie (as a guide, Rie/Rf > 0.1), then the equivalent noise output voltage must be taken into account. In this case, equations (5-4), (5-5) and (5-6) are converted into output voltages as follows:

$$V_s = R_f \cdot \sqrt{2q \cdot (I_o + I_D) \cdot B} \; [V] \quad \text{............ (5-8)}$$

$$V_j = R_f \cdot \sqrt{\frac{4kTB}{Rie}} \; [V] \quad \text{............ (5-9)}$$

$$V_{en} = \left(1 + \frac{R_f}{Rie}\right) \cdot e_n \cdot \sqrt{B} \; [V] \quad \text{............ (5-10)}$$

The thermal noise from the feedback resistance and the equivalent noise input current of the operational amplifier are also added as follows:

$$V_{Rf} = R_f \cdot \sqrt{\frac{4kTB}{R_f}} \; [V] \quad \text{............ (5-11)}$$

$$V_{in} = R_f \cdot i_n \cdot \sqrt{B} \; [V] \quad \text{............ (5-12)}$$

The equivalent noise input voltage of the operational amplifier is then expressed as an RMS value by the following equation.

$$V_n = \sqrt{V_s^2 + V_j^2 + V_{en}^2 + V_{Rf}^2 + V_{in}^2} \; [V] \quad \text{............ (5-13)}$$

Figure 5-3 shows the shot noise current plotted along the signal photocurrent value when Rf >>Rie. Figure 5-4 shows the thermal noise current and the noise current by the equivalent noise input voltage of the operational amplifier, plotted along the interelectrode resistance value. When using a PSD with an interelectrode resistance of about 10 kΩ, the operational amplifier becomes a crucial factor in determining the noise current, so a low-noise-current operational amplifier must be used. When using a PSD with an interelectrode resistance exceeding 100 kΩ, the thermal noise generated from the interelectrode resistance of the PSD itself will be predominant.
As explained above, PSD position resolution is determined by interelectrode resistance and light intensity. This is the point in which the PSD greatly differs from discrete type position detectors.
The following methods are effective for increasing the PSD position resolution.

- Increase the signal photocurrent Io.
- Increase the interelectrode resistance Rie.
- Shorten the resistance length L.
- Use a low noise operational amplifier.

The position resolution listed in our PSD data sheets is measured under the following conditions.

- Photocurrent: 1 μA
- Circuit input noise: 1 μV (31.6 $nV/Hz^{1/2}$)
- Frequency bandwidth: 1 kHz

Figure 5-3 Shot noise vs. signal photocurrent

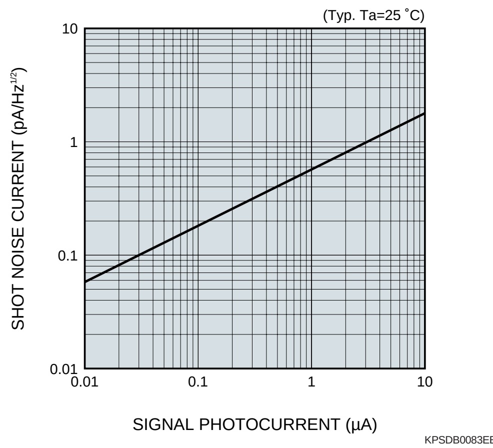
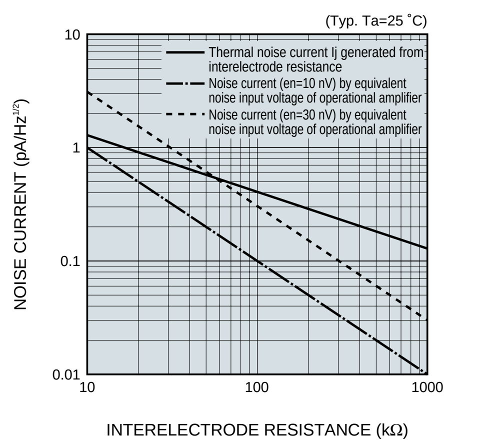


Figure 5-4 Noise current vs. interelectrode resistance



6. Response speed

As with photodiodes, the response speed of PSD is the time required for the generated carriers to be extracted as current by an external circuit. This is generally expressed as the rise time tr and is an important parameter when detecting a spot light traveling over the active surface at high speeds or using pulse-modulated light for subtracting the background light. The rise time is defined as the time needed for the output signal to rise from 10 to 90 % of its peak value and is chiefly determined by the following two factors.

1) Time constant t_1 determined by the interelectrode resistance, load resistance and terminal capacitance

The interelectrode resistance Rie of PSD basically acts as load resistance R_L, so the time constant t_1 is given by the interelectrode resistance Rie and terminal capacitance Ct, as follows:

$$t_1 = 2.2 \cdot Ct \cdot (Rie + R_L) \quad \text{......... (6-1)}$$

The rise time listed in our PSD datasheets is measured with a spot light striking the center of the active area with the interelectrode resistance Rie distributed between the electrodes. So the time constant t_1 is as follows:

$$t_1 = 0.5 \cdot Ct \cdot (Rie + R_L) \quad \text{......... (6-2)}$$

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

Carriers are also generated outside the depletion layer when light is absorbed in the PSD chip surrounding areas outside the active area or at locations deeper than the depletion layer in the substrate. These carriers diffuse through the substrate and are extracted as an output. The time t_2 required for these carriers to diffuse may be more than several microseconds.

The equation below gives the approximate rise time tr of a PSD. Figure 6-1 shows typical output waveforms in response to stepped light input.

$$tr \fallingdotseq \sqrt{t_1^2 + t_2^2} \quad \text{.................... (6-3)}$$

Figure 6-1 Response wavelength example of PSD

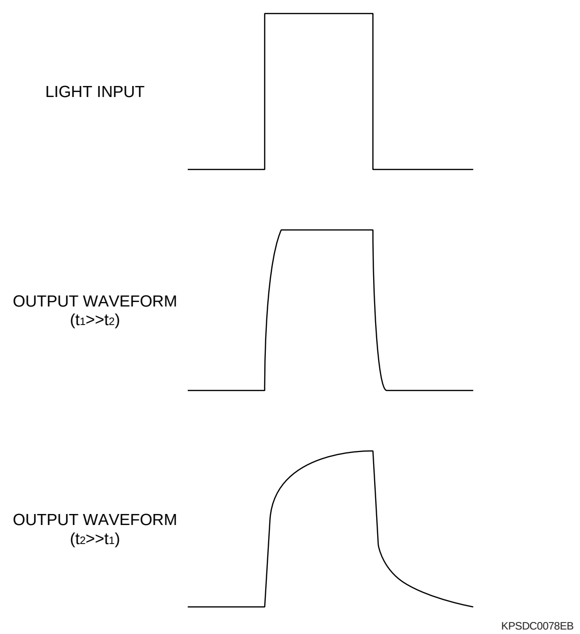
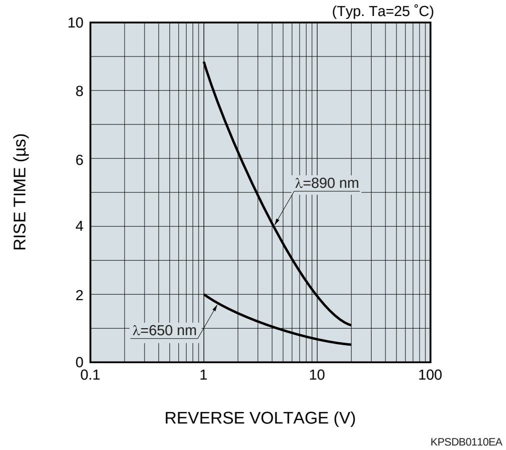


Figure 6-2 shows the relation between the rise time and reverse voltage measured at different wavelengths. The rise time can be reduced by increasing the reverse voltage and using a light beam of shorter wavelengths. Selecting a PSD with a small Rie is also effective in improving the rise time.

Figure 6-2 Rise time vs. reverse voltage (S4583-06)



A method for integrating position signals can be used when detecting pulsed light having a pulse width shorter than the PSD rise time.

7. Saturation photocurrent

Photocurrent saturation must be taken into account when a PSD is used outdoors, in locations where the background light level is high, or the signal light amount is extremely large. Figure 7-1 shows typical photocurrent output of a PSD in a non-saturated state. This PSD is operating normally with good output linearity over the entire active area.
If the background light level is excessively high or the signal light amount is extremely large, the PSD photocurrent will saturate. A typical output from a saturated PSD is shown in Figure 7-2. The output linearity of the PSD is impaired so the correct position cannot be detected in this case.
Photocurrent saturation of a PSD depends on the interelectrode resistance and reverse voltage, as shown in Figure 7-3. The saturated photocurrent is measured as the total photocurrent of a PSD when the entire active area is illuminated. If a small spot light is focused on the active area, the photocurrent that is generated is concentrated only on a localized portion, so saturation occurs at a lower level.

To avoid the saturation effect, use the following methods.
- · Reduce the background light level by using an optical filter.
- · Use a PSD with a small active area.
- · Increase the reverse voltage.
- · Decrease the interelectrode resistance.
- · Avoid concentrating the light beam on a small area.

Figure 7-1 Photocurrent output example of PSD in normal operation (S5629)

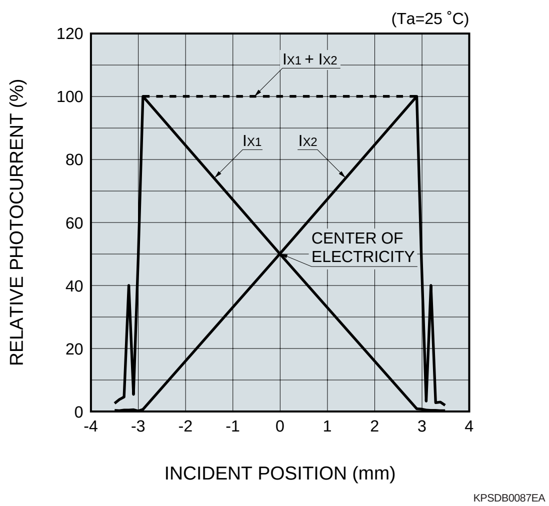


Figure 7-2 Photocurrent output example of saturated PSD (S5629)

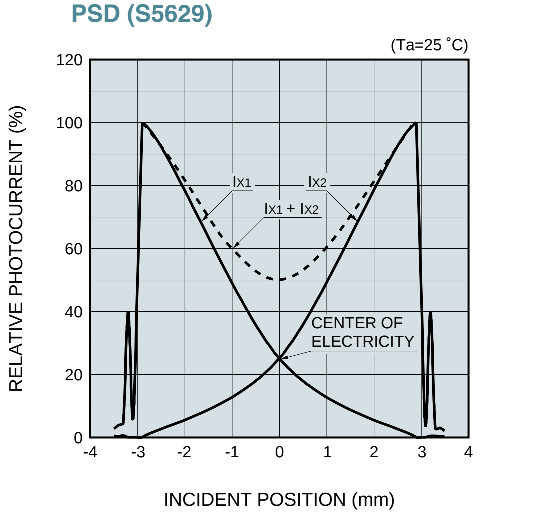


Figure 7-3 Saturation photocurrent vs. interelectrode resistance (entire active area fully illuminated)