Technical note

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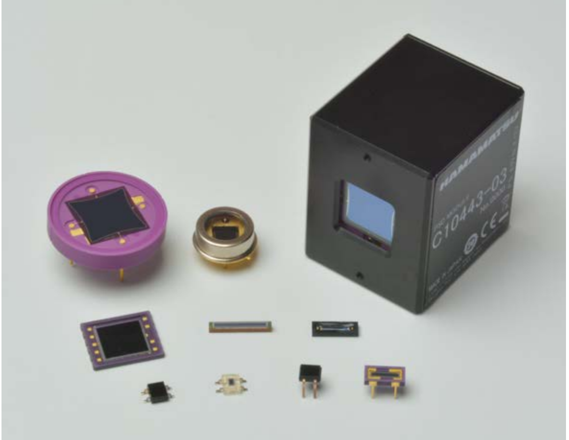
PSD
(position sensitive detectors)



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Various methods are available for detecting the position of incident light, including methods using an array of many small detectors and a multi-element detector (e.g., image sensor). In contrast to these, the PSD is a monolithic device designed to detect the position of incident light.
Since the PSD is a non-segmented photosensor that makes use of the surface resistance of the photodiode, it provides continuous electrical signals and offers excellent position resolution, fast response, and high reliability.
The PSD is used in a wide range of fields such as measurements of position, angles, distortion, vibration, and lens reflection/refraction. Applications also include precision measurement such as laser displacement meters, as well as optical remote control devices, distance sensors, and optical switches.

- Excellent position resolution
- Wide spectral response range
- High-speed response
- Simultaneous detection of light level and center-of-gravity position of light spot
- High reliability

Hamamatsu PSD

Type	Features
One-dimensional PSD	● Visible light cut type: Suitable for detecting near infrared light ● Infrared high sensitivity ● Suitable for detecting a small light spot such as laser diodes ● Long and narrow type: Photosensitive area length exceeds 20 mm
Two-dimensional PSD	● High-speed response ● Low dark current ● Excellent position detectability

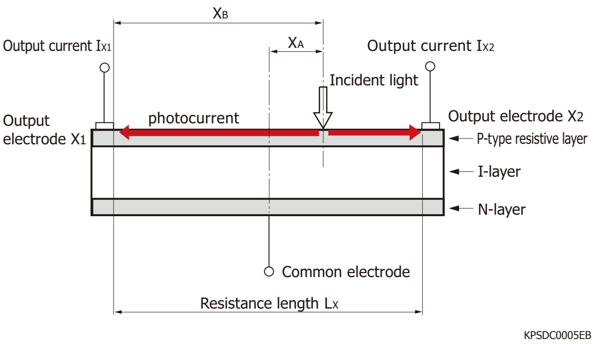
1. Structure and operating principle

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 photosensitive area, which is also a resistive layer, has a PN junction that generates photocurrent by means of the photovoltaic effect.

Figure 1-1 is a schematic view of a PSD cross section showing the operating principle. On an N-type high-resistivity silicon substrate, a P-type resistive layer is formed that serves as a photosensitive area for photoelectric conversion and a resistive layer. A pair of output electrodes is formed on both ends of the P-type resistive layer. 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 light spot strikes the PSD, an electric charge proportional to the light level is generated at the light incident position. This electric charge flows as photocurrents through the resistive layer and is extracted from the output electrodes X_1 and X_2, while being divided in inverse proportion to the distance between the light incident position and each electrode.

[Figure 1-1] Schematic of PSD cross section



In Figure 1-1, the relation between the incident light spot position and the output currents from the output electrodes X_1 and X_2 is as follows:

When the center point of the PSD is set as the origin:

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

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

When the end of the PSD is set as the origin:

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

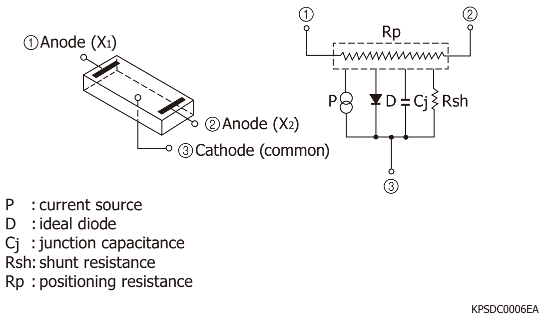
$$\frac{I_{X2} - I_{X1}}{I_{X1} + I_{X2}} = \frac{2X_B - L_X}{L_X} \cdots (1\text{-}7) \qquad \frac{I_{X1}}{I_{X2}} = \frac{L_X - X_B}{X_B} \cdots\cdots (1\text{-}8)$$

I_{X1}: output current from electrode X_1
I_{X2}: output current from electrode X_2
I_o : total photocurrent ($I_{X1} + I_{X2}$)
L_X : resistance length (length of photosensitive area)
X_A : distance from electrical center position of PSD to light incident position
X_B : distance from electrode X_1 to light incident position

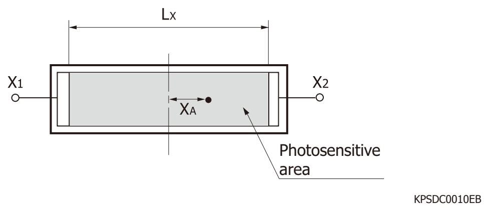
By finding the values of I_{X1} and I_{X2} from equations (1-1), (1-2) , (1-5), and (1-6) and substituting them into equations (1-3), (1-4), (1-7), and (1-8), the light incident position can be obtained irrespective of the incident light level and its changes. The light incident position obtained here corresponds to the center-of-gravity of the light spot.

1 - 1 One-dimensional PSD

[Figure 1-2] Structure and equivalent circuit (one-dimensional PSD)



[Figure 1-3] Photosensitive area (one-dimensional PSD)



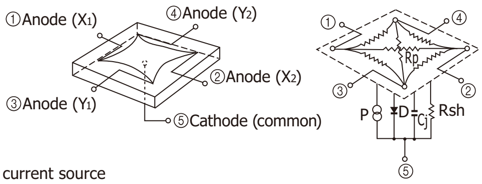
Incident position conversion formula (See also Figure 1-3.)

$$\frac{I_{X2} - I_{X1}}{I_{X1} + I_{X2}} = \frac{2X_A}{L_X} \cdots\cdots (1\text{-}9)$$

1 - 2 Two-dimensional PSD

The shapes of the photosensitive area and electrodes of two-dimensional PSDs have been improved to suppress interactions between the electrodes. Besides the advantages of small dark current, high-speed response, and easy application of reverse voltage, the peripheral distortion has been greatly suppressed. Incident position conversion formulas are shown in equations (1-10) and (1-11).

[Figure 1-4] Structure and equivalent circuit (two-dimensional PSD)



P : current source
D : ideal diode
Cj : junction capacitance
Rsh: shunt resistance
Rp : positioning resistance

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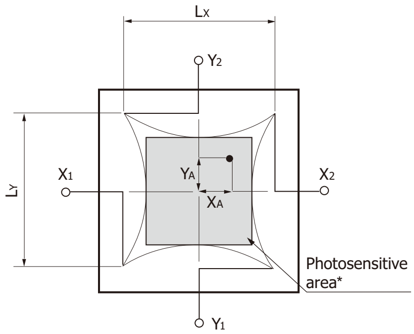
[Figure 1-5] Photosensitive area (two-dimensional PSD)



* Photosensitive area is specified as the inscribed square.

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Incident position conversion formulas (See also Figure 1-5.)

$$\frac{(I_{X2} + I_{Y1}) - (I_{X1} + I_{Y2})}{I_{X1} + I_{X2} + I_{Y1} + I_{Y2}} = \frac{2X_A}{L_X} \quad \cdots\cdots\cdots \text{(1-10)}$$

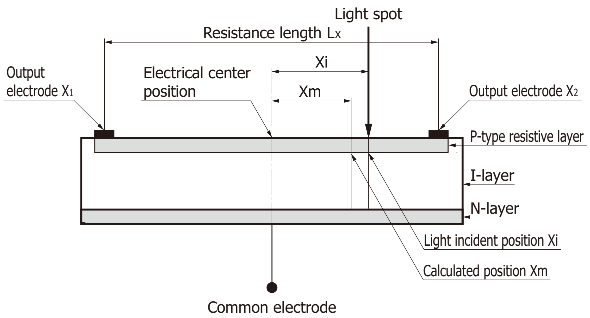
$$\frac{(I_{X2} + I_{Y2}) - (I_{X1} + I_{Y1})}{I_{X1} + I_{X2} + I_{Y1} + I_{Y2}} = \frac{2Y_A}{L_Y} \quad \cdots\cdots\cdots \text{(1-11)}$$

2. Characteristics

2 - 1 Position detection error

The position of a light spot incident on the PSD surface can be measured by making calculations based on the photocurrent extracted from each output electrode. The position obtained with the PSD is the center-of-gravity of the light spot, and it is independent of the light spot 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 one of the most important characteristics of a PSD.
If a light spot strikes the PSD surface and the photocurrents extracted from the output electrodes are equal, the position of the incident light spot on the PSD is viewed as the electrical center position. Using this electrical center position as the origin point, 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 photocurrents.

[Figure 2-1] Schematic of PSD cross section



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A position detection error is calculated as described below. In Figure 2-1, which shows the electrical center position as the reference position (origin point), if the actual position of incident light spot is Xi, the photocurrents obtained at the output electrodes are I_{X1} and I_{X2}, and the position calculated from the photocurrents is Xm, then the difference in distance between Xi and Xm is defined as the position detection error (E).

$$E = Xi - Xm\ [\mu m] \quad \cdots\cdots\cdots\cdots \text{(2-1)}$$

Xi : actual position of incident light [μm]
Xm: calculated position [μm]

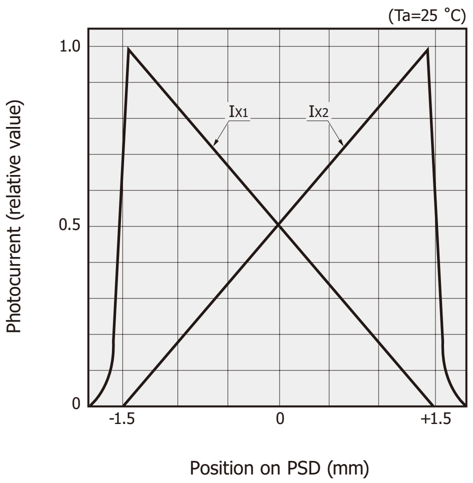
$$Xm = \frac{I_{X2} - I_{X1}}{I_{X1} + I_{X2}} \times \frac{L_X}{2} \quad \cdots\cdots\cdots \text{(2-2)}$$

The position detection error is measured under the following conditions.

· Light source: λ=830 nm
· Light spot size: ϕ200 µm
· Total photocurrent: 10 µA
· Reverse voltage: specified value listed in our datasheets

Figures 2-2 shows the photocurrent measurement example using a one-dimensional PSD with a resistance length of 3 mm (e.g., S4583-04). The position detection error determined from the data is also shown in Figure 2-3.

[Figure 2-2] Photocurrent measurement example of one-dimensional PSD (e.g., S4583-04)



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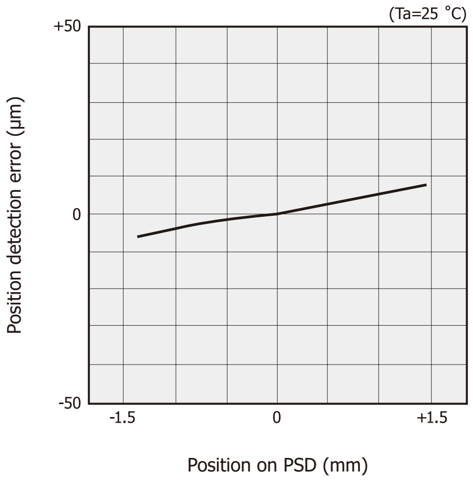
[Figure 2-3] Position detection error example of one-dimensional PSD (e.g., S4583-04)



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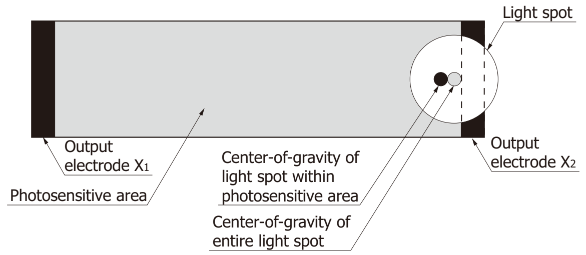
Specified area for position detection error

The light spot position can be detected over the entire photosensitive area of a PSD. However, if part of the light spot strikes outside the PSD photosensitive area as shown in Figure 2-4, a positional shift in the center-of-gravity occurs between the entire light spot and the light spot falling within the photosensitive area, making the position measurement unreliable. It is therefore necessary to select a PSD whose photosensitive area matches the incident light spot.

[Figure 2-4] Center-of-gravity of incident light spot



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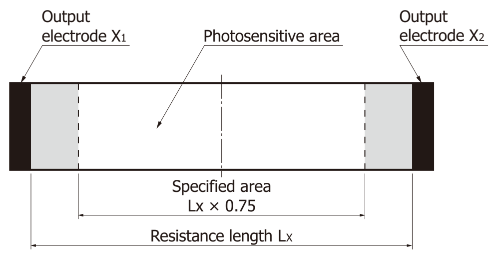
The areas used to measure position detection errors are specified as shown in Figure 2-5.

[Figure 2-5] Specified area for position detection error

(a) One-dimensional PSD (resistance length ≤ 12 mm)



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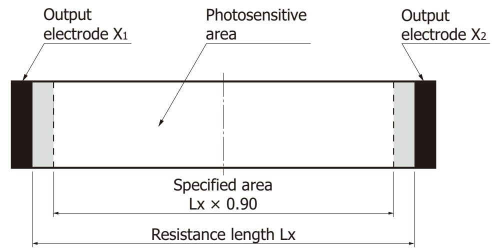
(b) One-dimensional PSD (resistance length > 12 mm)



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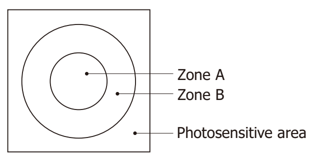
(c) Two-dimensional PSD



Zone A: within a circle with a diameter equal to 40% of one side length of the photosensitive area
Zone B: within a circle with a diameter equal to 80% of one side length of the photosensitive area

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On two-dimensional PSDs, the position detection error along the circumference is larger than that in the center of the photosensitive area, so the error is specified separately in Zone A and Zone B.

2 - 2 Position resolution

Position resolution is defined as the minimum detectable displacement of a light spot incident on a PSD, and it is expressed as a distance on the PSD photosensitive area. Position resolution is determined by the PSD resistance length and the S/N. Using equation (1-6) for position calculation as an example, equation (2-3) can be established.

$$I_{X2} + \Delta I = \frac{X_B + \Delta x}{L_X} \times Io \cdots\cdots\cdots (2\text{-}3)$$

ΔI: change in output current
Δx: small displacement of light spot

Then, Δx can be expressed by equation (2-4).

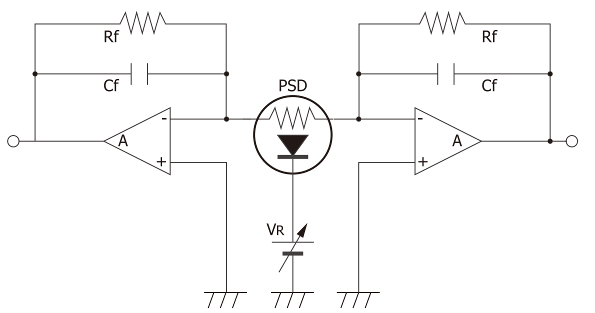
$$\Delta x = L_X \times \frac{\Delta I}{Io} \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots (2\text{-}4)$$

When the positional change is infinitely small, the noise component contained in the output current I_{X2} determines the position resolution. If the PSD noise current is In, then the position resolution (ΔR) is generally expressed by equation (2-5).

$$\Delta R = L_X \times \frac{In}{Io} \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots (2\text{-}5)$$

Figure 2-6 shows the connection example when using a one-dimensional PSD with current-to-voltage conversion op amps. The noise model for this circuit is shown in Figure 2-7.

[Figure 2-6] Connection example of one-dimensional PSD and current-to-voltage conversion op amps



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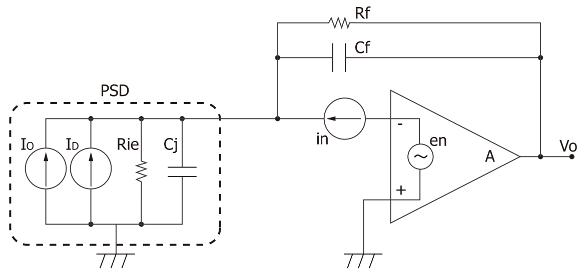
[Figure 2-7] Noise model



Io : photocurrent
ID : dark current
Rie: interelectrode resistance
Cj : junction capacitance
Rf : feedback resistance
Cf : feedback capacitance
in : equivalent input current noise of op amp
en : equivalent input voltage noise of op amp
Vo : output voltage

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Noise current

Noise currents that determine the position resolution are described below.

(1) When Rf >> Rie

If the feedback resistance (Rf) of the current-to-voltage converter circuit is sufficiently greater than the PSD interelectrode resistance (Rie), the noise current is calculated using equation (2-8). In this case, 1/Rf can be ignored since it is sufficiently smaller than 1/Rie.

- Shot noise current Is originating from photocurrent and dark current

$$Is = \sqrt{2q \times (Io + I_D) \times B} \ [A] \cdots\cdots\cdots\cdots (2\text{-}6)$$

q : electron charge [C]
Io : photocurrent [A]
ID : dark current [A]
B : bandwidth [Hz]

- Thermal noise current (Johnson noise current) Ij generated from interelectrode resistance

$$Ij = \sqrt{\frac{4kTB}{Rie}} \ [A] \cdots\cdots\cdots\cdots (2\text{-}7)$$

k : Boltzmann's constant [J/K]
T : absolute temperature [K]
Rie: interelectrode resistance [Ω]

Note: Rsh can be usually ignored as Rsh >> Rie.

- Noise current Ien by op amp equivalent input voltage noise

$$Ien = \frac{en}{Rie}\sqrt{B} \ [A] \cdots\cdots\cdots\cdots (2\text{-}8)$$

en: equivalent input voltage noise of op amp [V/Hz$^{1/2}$]

By taking the sum of equations (2-6), (2-7), and (2-8), the PSD noise current (In) can be expressed as an effective value (rms) by equation (2-9).

$$In = \sqrt{Is^2 + Ij^2 + Ien^2}\ [A] \cdots\cdots\cdots\cdots (2\text{-}9)$$

(2) If the effect of Rf cannot be ignored with respect to Rie (when $\frac{Rie}{Rf}$ > approx. 0.1)

The noise current is calculated by converting it to an output noise voltage. In this case, equations (2-6), (2-7), and (2-8) are respectively converted into output voltages as follows:

$$Vs = Rf \times \sqrt{2q \times (Io + I_D) \times B}\ [V] \cdots\cdots\cdots\cdots (2\text{-}10)$$

$$Vj = Rf \times \sqrt{\frac{4kTB}{Rie}}\ [V] \cdots\cdots\cdots\cdots (2\text{-}11)$$

$$Ven = \left(1 + \frac{Rf}{Rie}\right) \times en \times \sqrt{B}\ [V] \cdots\cdots\cdots\cdots (2\text{-}12)$$

The thermal noise from the feedback resistance and the op amp equivalent input current noise are also added as follows:

- Thermal noise voltage V_{Rf} generated by feedback resistance

$$V_{Rf} = Rf \times \sqrt{\frac{4kTB}{Rf}}\ [V] \cdots\cdots\cdots\cdots (2\text{-}13)$$

- Noise voltage Vin due to op amp equivalent input current

$$Vin = Rf \times in \times \sqrt{B}\ [V] \cdots\cdots\cdots\cdots (2\text{-}14)$$

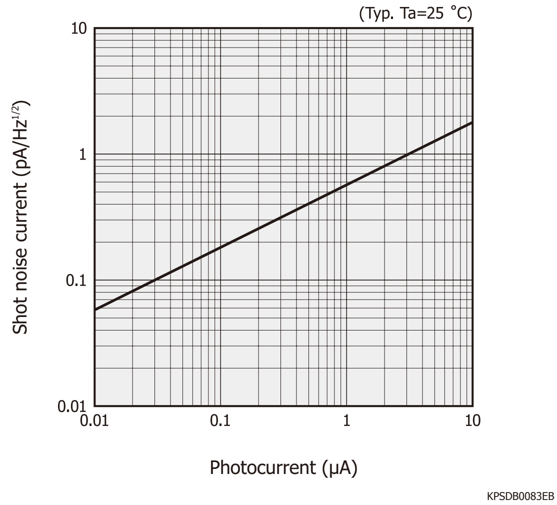
in: op amp equivalent input current noise [A/Hz$^{1/2}$]

The op amp output noise voltage (Vn) is then expressed as an effective value (rms) by equation (2-15).

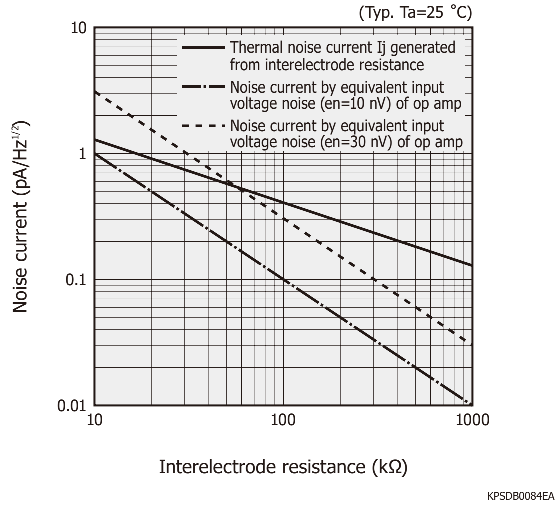
$$Vn = \sqrt{Vs^2 + Vj^2 + Ven^2 + V_{Rf}^2 + Vin^2}\ [V] \cdots\cdots\cdots (2\text{-}15)$$

Figure 2-8 shows the shot noise current plotted versus the photocurrent value when Rf>>Rie. Figure 2-9 shows the thermal noise and the noise current by the op amp equivalent input voltage noise plotted versus the interelectrode resistance value. When using a PSD with an interelectrode resistance of about 10 kΩ, the op amp characteristics become a crucial factor in determining the noise current, so a low-noise current op amp 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.

[Figure 2-8] Shot noise current vs. photocurrent



[Figure 2-9] Noise current vs. interelectrode resistance



As explained, the position resolution of a PSD is determined by the interelectrode resistance and photocurrent. This is the point in which the PSD greatly differs from segmented type position detectors. The PSD with high interelectrode resistance or short resistance length has excellent position resolution.

The following methods are effective for improving the PSD position resolution when using the PSD.

· Increase the incident light level.
· Use an op amp with appropriate noise characteristics.

Hamamatsu measures and calculates the position resolution under the conditions that the photocurrent is 1 μA, the circuit input noise is 1 μV (31.6 nV/Hz$^{1/2}$), and the frequency bandwidth is 1 kHz.

2 - 3 Response speed

As with photodiodes, the response speed of a PSD is the time required for the generated carriers to be extracted as current to an external circuit. This is generally expressed as the rise time and is an important parameter when detecting a light spot moving on the photosensitive area at high speeds or when using a signal light source driven by pulse for background light subtraction. The rise time is defined as the time needed for the output signal to rise from 10% to 90% of its peak and is mainly 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 a PSD basically acts as load resistance (R_L), so the time constant t_1 determined by the interelectrode resistance and terminal capacitance (Ct) is expressed as in equation (2-16).

$$t_1 = 2.2 \times Ct \times (Rie + R_L) \cdots\cdots\cdots (2\text{-}16)$$

The interelectrode resistance of a PSD is distributed between the electrodes. Hamamatsu measures the response speed with a light spot incident on the center of the photosensitive area, so equation (2-16) roughly becomes equation (2-17).

$$t_1 = 0.5 \times Ct \times (Rie + R_L) \cdots\cdots\cdots (2\text{-}17)$$

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

Carriers are also generated outside the depletion layer when light enters the PSD chip peripheral areas outside the photosensitive area or when light is absorbed 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.
Equation (2-18) gives the approximate rise time (tr) of a PSD, and Figure 2-10 shows output waveform examples.

$$tr \approx \sqrt{t_1^2 + t_2^2} \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots (2\text{-}18)$$

[Figure 2-10] Examples of PSD response waveforms

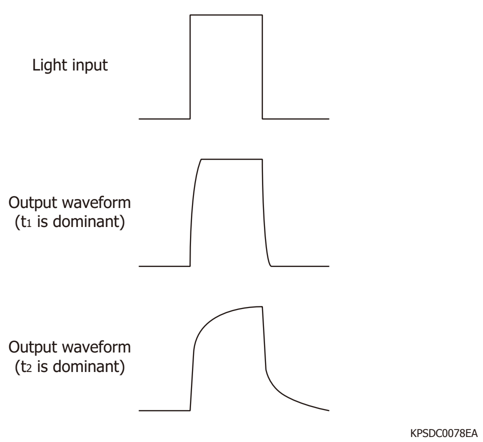
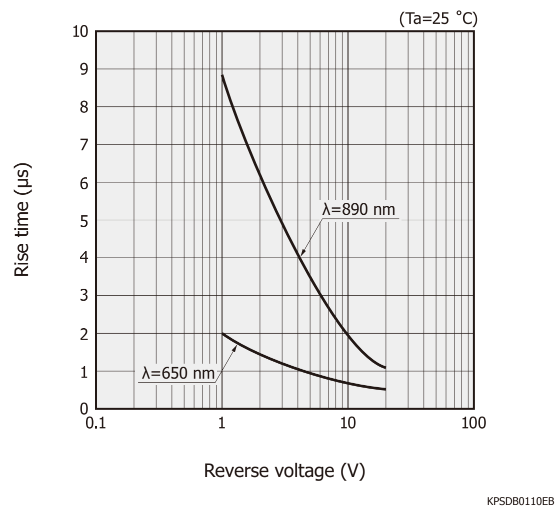


Figure 2-11 shows the relation between the rise time and reverse voltage for incident light at different wavelengths. As seen from the figure, the rise time can be shortened by using light of shorter wavelengths and increasing the reverse voltage. Selecting a PSD with a small interelectrode resistance is also effective in improving the rise time.

[Figure 2-11] Rise time vs. reverse voltage (typical example)

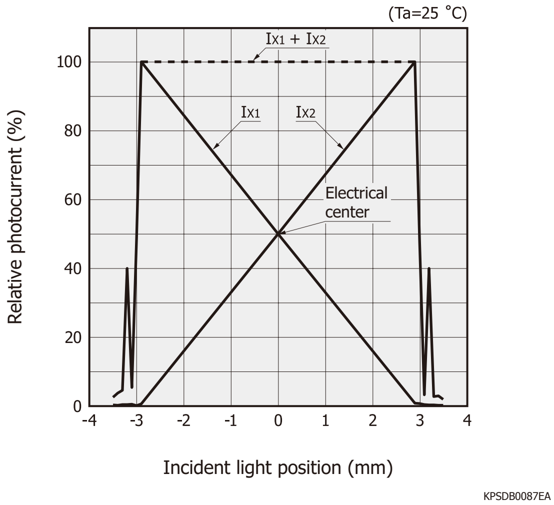


2 - 4 Saturation photocurrent

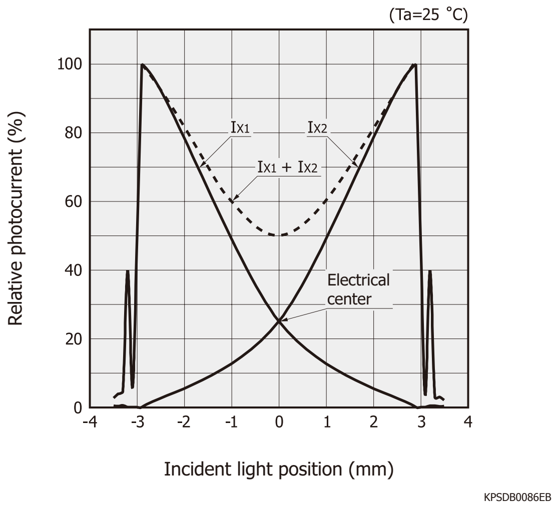
Photocurrent saturation must be taken into account when a PSD is used in locations such as outdoors where the background light level is high, or when the signal light level is extremely large. Figure 2-12 shows an output example of a non-saturated PSD. This PSD is operating normally with good output linearity over the entire photosensitive area.
Figure 2-13 shows an output example of a saturated PSD. This PSD does not function correctly since the output linearity is lost.
Photocurrent saturation of a PSD depends on the interelectrode resistance and reverse voltage [Figure 2-14]. The saturation photocurrent is specified as the total photocurrent measurable when the entire photosensitive area is illuminated. If a small light spot is focused on the photosensitive area, the photocurrent will be concentrated only on a localized portion, so saturation will occur at a lower level than specified.
A PSD with a small photosensitive area or a low interelectrode resistance hardly causes the saturation effect. The following methods are effective to avoid the saturation effect when using the PSD.

· Reduce the background light level by using an optical filter.
· Increase the reverse voltage.
· Make the light spot larger.

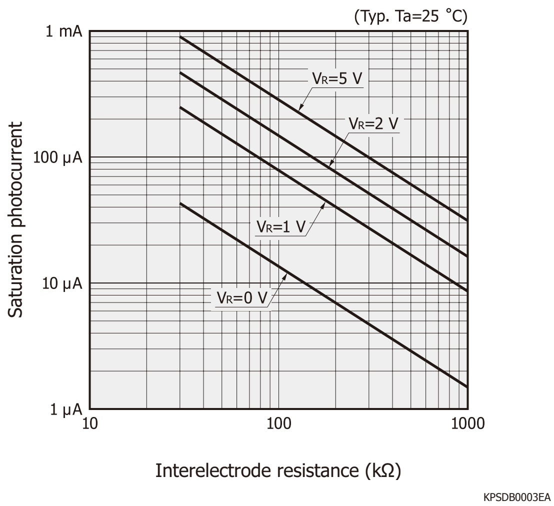
[Figure 2-12] Photocurrent output example of PSD in normal operation (S15430-02CT)



[Figure 2-13] Photocurrent output example of saturated PSD (S15430-02CT)



[Figure 2-14] Saturation photocurrent vs. interelectrode resistance (entire photosensitive area fully illuminated)



3. How to use

3 - 1 Operating circuit examples

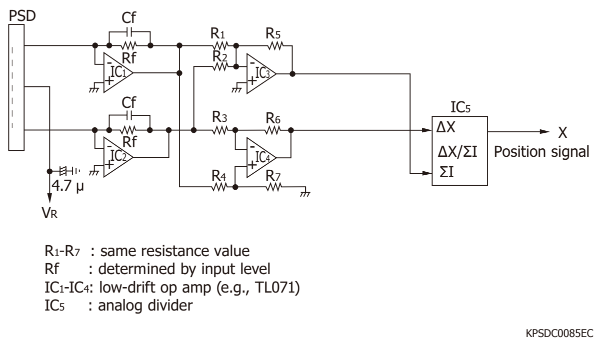
The output of a PSD is current, which is usually converted to a voltage signal using an op amp and then arithmetically processed with a dedicated IC. Typical circuits are shown in Figures 3-1 and 3-2. If a light spot is incident on the photosensitive area of the PSD, the calculated position output does not change even if the incident light level fluctuates due to changes in the distance between the PSD and the light source or in the light source brightness.

If background light exists, use a pulse-driven light source to eliminate the photocurrent caused by background light, and only AC signal components should be extracted by AC-coupling the PSD to current-to-voltage converters like the circuit shown in Figure 3-2.

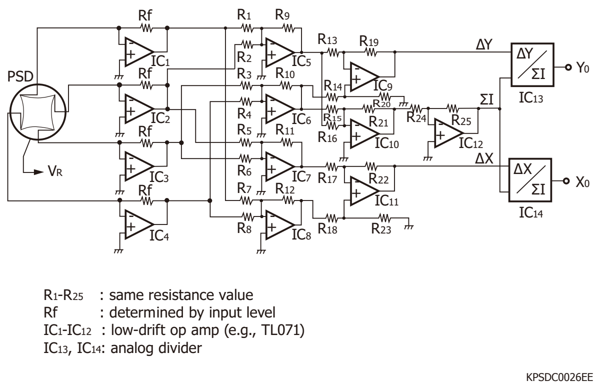
Figure 3-3 shows the block diagram of an operating circuit with a digital output that allows data transfer to a PC. This circuit arithmetically processes the PSD output current with the microcontroller after performing current-to-voltage conversion and A/D conversion.

[Figure 3-1] DC-operating circuit examples

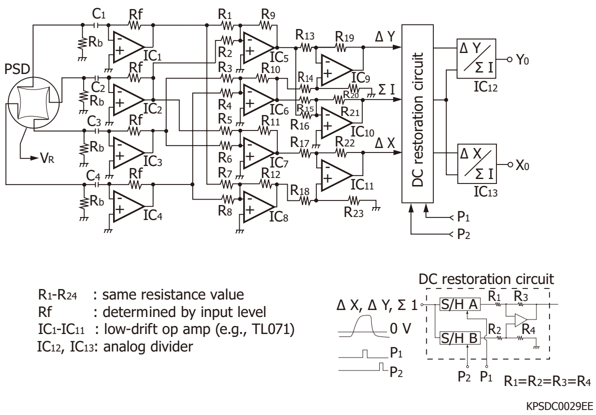
(a) For one-dimensional PSD



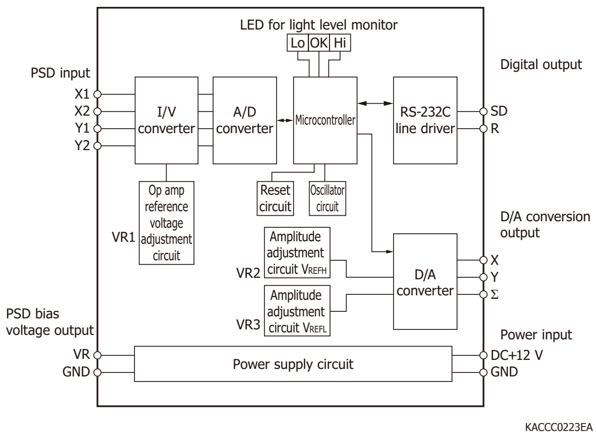
(b) For two-dimensional PSD



[Figure 3-2] AC-operating circuit example (for two-dimensional PSD)

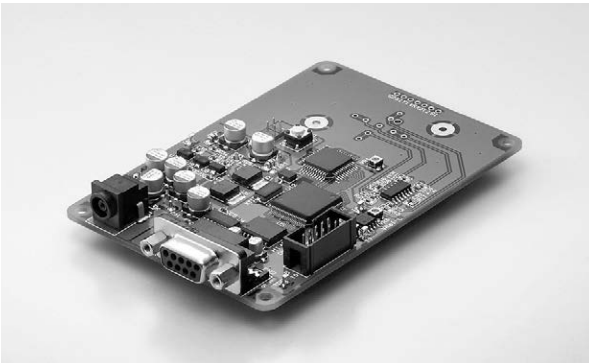


[Figure 3-3] Block diagram of DC-operating circuit with digital output (C9069)



3 - 2 PSD signal processing circuits

[Figure 3-4] Two-dimensional PSD signal processing circuit C9069



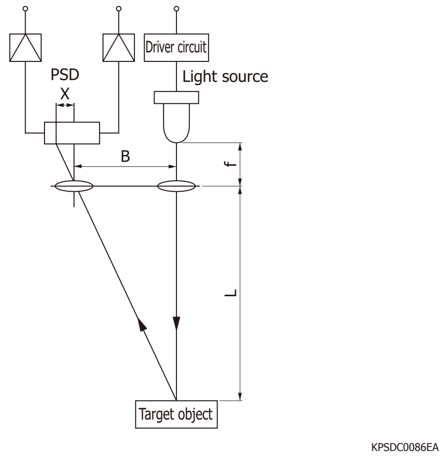
Hamamatsu provides various types of PSD signal processing circuits to help users easily evaluate one-dimensional and two-dimensional PSDs. These include a DC signal processing circuit assembled on a compact board that contains a current-to-voltage converter, addition/subtraction circuit, and analog divider circuit similar to the DC-operating circuit examples described above. Also available is an AC signal processing circuit that contains a sync circuit and LED driver circuit in addition to the AC-operating circuit example described above, so measurement can be started by simply connecting to a power supply (±15 V) and an LED. Hamamatsu also offers a digital-output signal processing circuit that uses a microcontroller to perform all position calculations such as addition/subtraction and division. Stable position output can be obtained in measurements where the incident light level is high but brightness changes are small. This processing circuit is easy to handle as it operates on an AC power adapter.

4. Applications

4 - 1 Triangulation distance measurement

The principle of triangulation distance measurement is shown in Figure 4-1. Light emitted from a light source (LED or LD) is focused by a light projection lens to strike the target object, and light reflecting from that object is input via a light receiving lens onto the PSD photosensitive surface. If we let the distance between the PSD and light source (baseline length) be B, the lens focal distance be f, and the amount of movement of the light spot from the center on the PSD be X, then the distance L to the target object is expressed as $L = (1/X) \times f \times B$. This method offers a great advantage: the distance can be found regardless of the reflectance of the target object and variations in the light source power. This principle is also applied in laser displacement meters.

[Figure 4-1] Principle of triangulation distance measurement

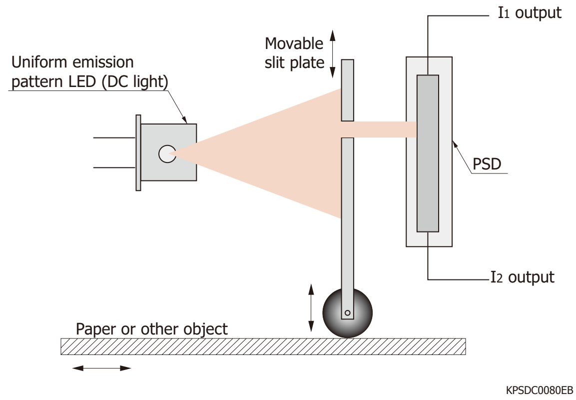


4 - 2 Direct position detection

Figure 4-2 shows the direct position detection principle. The light source (LED or LD, etc.) emits light which passes through a slit and irradiates onto the photosensitive area of the PSD. The position where the light strikes the PSD surface shifts according to the slit movement. Calculating that position information allows finding the amount of slit displacement.

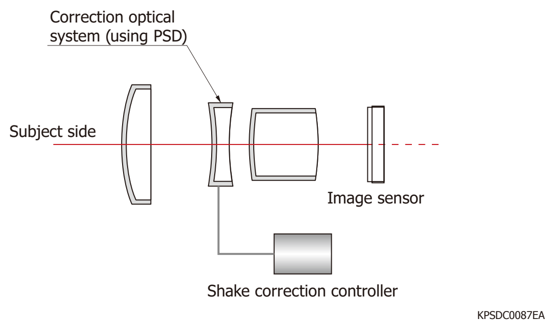
Figure 4-3 shows how this is applied to optical camera-shake correction. When a camera lens shake occurs due to shaky hands, the correction optical system (using a PSD) causes a horizontal movement in the direction of the shake so that the center of the image returns to a position at the center of the image sensor photosensitive area. The PSD is utilized to detect and control movement (position information) of the slit which is built into the correction optical system.

[Figure 4-2] Example of direct position detection

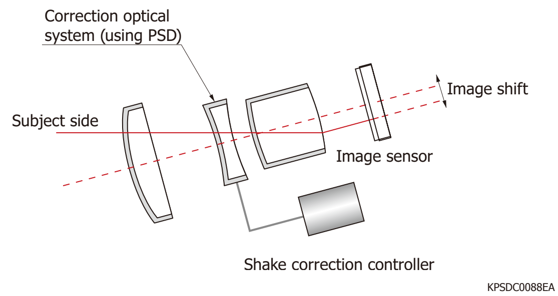


[Figure 4-3] Optical camera-shake correction

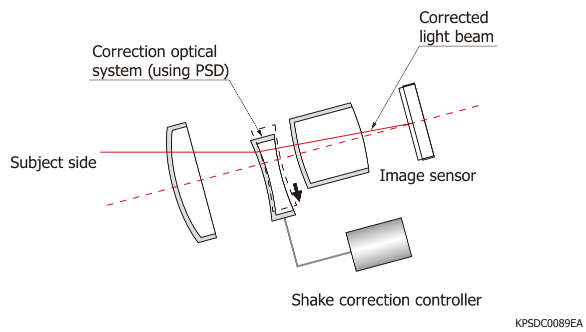
(a) State with no camera shake



(b) State when camera shake occurred



(c) State when camera shake was corrected (by moving the correction optical system)



Information described in this material is current as of June 2021.
Product specifications are subject to change without prior notice due to improvements or other reasons. This document has been carefully prepared and the information contained is believed to be accurate. In rare cases, however, there may be inaccuracies such as text errors. Before using these products, always contact us for the delivery specification sheet to check the latest specifications.
The product warranty is valid for one year after delivery and is limited to product repair or replacement for defects discovered and reported to us within that one year period. However, even if within the warranty period we accept absolutely no liability for any loss caused by natural disasters or improper product use.

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