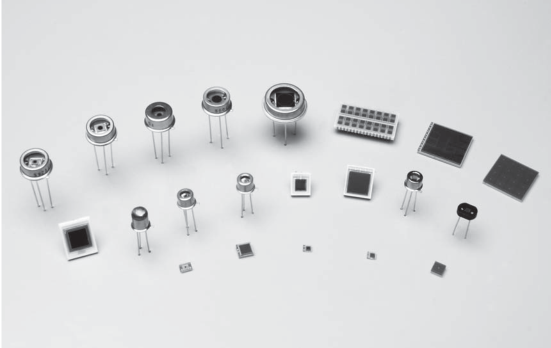
Si APD, MPPC

1 Si APD

2 MPPC

3 Applications

Si APD, MPPC



The APD (avalanche photodiode) is a high-speed, high-sensitivity photodiode that internally multiplies photocurrent when reverse voltage is applied. The internal multiplication function referred to as avalanche multiplication features high photosensitivity that enables measurement of low-level light signals. The APD's ability to multiply signals reduces the effect of noise and achieves higher S/N than the PIN photodiode. The APD also has excellent linearity.
The MPPC (multi-pixel photon counter) is an opto-semiconductor made up of multiple APD pixels operating in Geiger mode. The MPPC provides significantly higher gain than the APD and has photon-counting capability. It also features low voltage operation.
Utilizing our unique technologies, we offer numerous types of Si APDs and MPPCs for various applications. We also offer custom-designed devices to meet special needs.

Hamamatsu Si APDs

Type		Features	Applications
Short wavelength type	Low-bias operation	Enhanced sensitivity in the UV to visible region	● Low-light-level detection ● Analytical instruments
	Low terminal capacitance		
Near infrared type	Low-bias operation	High sensitivity in near infrared region and low bias voltage (reverse voltage) operation	● FSO ● Optical rangefinders ● Optical fiber communications
		Low cost and high reliability APD using surface-mount ceramic packages with the same wide operating temperature range (-20 to +85 °C) as metal package types	● Optical rangefinders ● Laser radars ● FSO
	Low temperature coefficient	Low temperature coefficient of the reverse voltage, easy gain adjustment	● FSO ● Optical rangefinders ● Optical fiber communications
	900 nm band	Enhanced sensitivity in the 900 nm band	● Optical rangefinders ● Laser radars
	1000 nm band	Enhanced sensitivity in the 1000 nm band	● YAG laser detection

Hamamatsu MPPCs

Type	Features	Applications
For general measurement	Suitable for general low-light-level detection	● Fluorescence measurement ● Flow cytometry ● DNA sequencer ● Environmental analysis ● PET ● High energy physics experiment
High-speed measurement, wide dynamic range	Features numerous pixels that are well suited to conditions where background light is present and is prone to saturation	
For very-low-light-level measurement	Cooling allows measurement with even further reduced dark count.	● Fluorescence measurement
For precision measurement	Reduced crosstalk suppresses erroneous counting during low count rate measurement	● Fluorescence measurement
Buttable type (semi custom)	Employs a structure in which the dead area in the periphery of the photosensitive area has been eliminated. Its four-side buttable structure enables elements to be arranged two-dimensionally with narrow gaps.	● PET ● High energy physics experiment
Large-area array	Monolithic array with multiple 3 × 3 mm MPPCs mounted on a single chip	● PET ● High energy physics experiment

1. Si APD

The APD is a high-speed, high-sensitivity photodiode that internally multiplies photocurrent when a specific reverse voltage is applied.
The APD, having a signal multiplication function inside its element, achieves higher S/N than the PIN photodiode and can be used in a wide range of applications such as high-accuracy rangefinders and low-level light detection that use scintillators. Though the APD can detect lower level light than the PIN photodiode, it does require special care and handling such as the need for higher reverse voltage and consideration of its temperature-dependent gain characteristics.
This describes Si APD features and characteristics so that users can extract maximum performance from Si APDs.

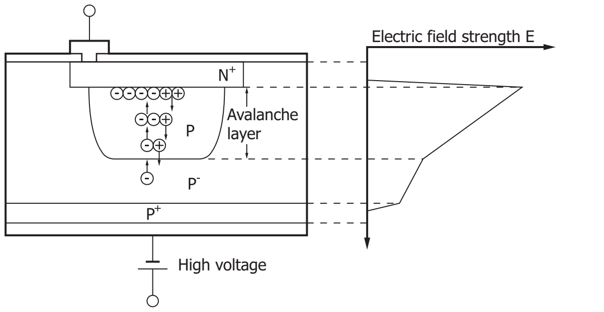
1 - 1 Features

- High sensitivity: built-in internal multiplication function
- High-speed response
- High reliability

1 - 2 Principle of avalanche multiplication

The photocurrent generation mechanism of the APD is the same as that of a normal photodiode. When light enters a photodiode, electron-hole pairs are generated if the light energy is higher than the band gap energy. The ratio of the number of generated electron-hole pairs to the number of incident photons is defined as the quantum efficiency (QE), commonly expressed in percent (%). The mechanism by which carriers are generated inside an APD is the same as in a photodiode, but the APD is different from a photodiode in that it has a function to multiply the generated carriers.
When electron-hole pairs are generated in the depletion layer of an APD with a reverse voltage applied to the PN junction, the electric field created across the PN junction causes the electrons to drift toward the N^+ side and the holes to drift toward the P^+ side. The higher the electric field strength, the higher the drift speed of these carriers. However, when the electric field reaches a certain level, the carriers are more likely to collide with the crystal lattice so that the drift speed becomes saturated at a certain speed. If the electric field is increased even further, carriers that escaped the collision with the crystal lattice will have a great deal of energy. When these carriers collide with the crystal lattice, a phenomenon takes place in which new electron-hole pairs are generated. This phenomenon is called ionization. These electron-hole pairs then create additional electron-hole pairs, which generate a chain reaction of ionization. This is a phenomenon known as avalanche multiplication.
The number of electron-hole pairs generated during the time that a carrier moves a unit distance is referred to as the ionization rate. Usually, the ionization rate of electrons is defined as "α" and that of holes as "β." These ionization rates are important factors in determining the multiplication mechanism. In the case of silicon, the ionization rate of electrons is larger than that of holes ($\alpha > \beta$), so the ratio at which electrons contribute to multiplication increases. As such, the structure of Hamamatsu APDs is designed so that electrons from electron-hole pairs generated by the incident light can easily enter the avalanche layer. The depth at which carriers are generated depends on the wavelength of the incident light. Hamamatsu provides APDs with different structures according to the wavelength to be detected.

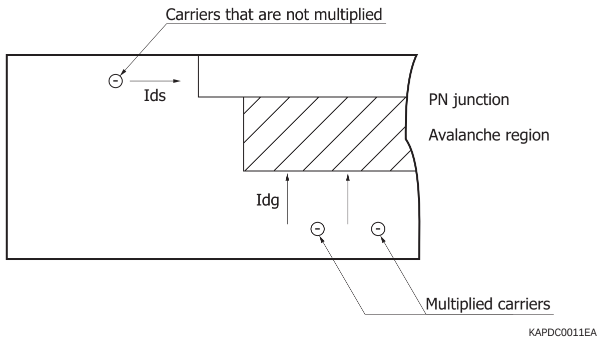
[Figure 1-1] Schematic diagram of avalanche multiplication (near infrared type)



1 - 3 Dark current

The APD dark current consists of surface leakage current (Ids) that flows through the PN junction or oxide film interface and generated current (Idg) inside the substrate [Figure 1-2].

[Figure 1-2] APD dark current



The surface leakage current is not multiplied because it does not pass through the avalanche layer, but the generated current is because it does pass through. Thus, the total dark current (I_D) is expressed by equation (1).

$$I_D = Ids + M\ Idg \quad \cdots\cdots\cdots\cdots (1)$$

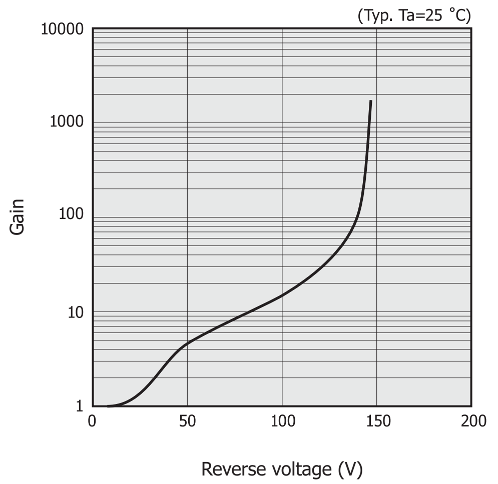
M: gain

Idg, the dark current component that is multiplied, greatly affects the noise characteristics.

1 - 4 Gain vs. reverse voltage characteristics

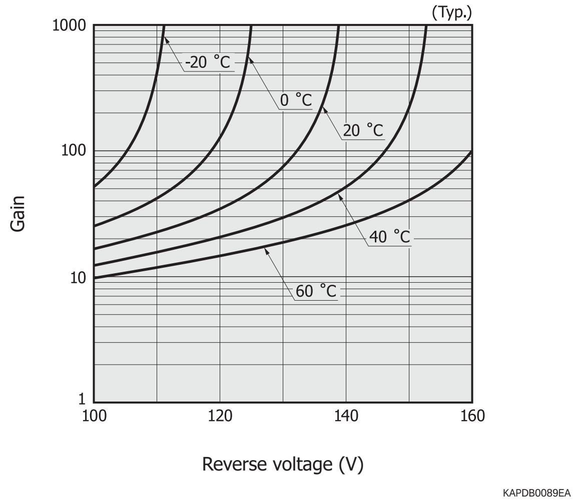
The APD gain is determined by the ionization rate, and the ionization rate depends strongly on the electric field across the depletion layer. In the normal operating range, the APD gain increases as reverse voltage increases. If the reverse voltage is increased even higher, the reverse voltage across the APD PN junction decreases due to the voltage drop caused by the series resistance component including the APD and circuit, and the gain begins to decrease.
When an appropriate reverse voltage is applied to the PN junction, the electric field in the depletion layer increases so avalanche multiplication occurs. As the reverse voltage is increased, the gain increases and the APD eventually reaches the breakdown voltage. Figure 1-3 shows the relation between the gain and reverse voltage for Hamamatsu Si APD S12023-05.

[Figure 1-3] Gain vs. reverse voltage (S12023-05)



The APD gain also has temperature-dependent characteristics. As the temperature rises, the crystal lattice vibrates more heavily, increasing the possibility that the accelerated carriers may collide with the lattice before reaching a sufficiently large energy level and making it difficult for ionization to take place. Therefore, the gain at a certain reverse voltage becomes small as the temperature rises. To obtain a constant output, the reverse voltage must be adjusted to match changes in temperature or the element temperature must be kept constant.

[Figure 1-4] Temperature characteristics of gain (S12023-05)



When an APD is used near the breakdown voltage, a phenomenon occurs in which the output photocurrent is not proportional to the incident light level. This is because as the photocurrent increases a voltage drop occurs due to current flowing through the series resistance and load resistance in the APD, reducing the voltage applied to the avalanche layer.

1 - 5 Noise characteristics

As long as the reverse voltage is constant, the APD gain is the average of each carrier's multiplication. The ionization rate of each carrier is not uniform and has statistical fluctuations. Multiplication noise known as excess noise is therefore added during the multiplication process. The APD shot noise (In) becomes larger than the PIN photodiode shot noise and is expressed by equation (2).

$$In^2 = 2q\,(I_L + Idg)\,B\,M^2\,F + 2q\,Ids\,B \quad \cdots\cdots\cdots\cdots \quad (2)$$

q : electron charge
I_L : photocurrent at M=1
Idg: current generated inside the substrate
(dark current component multiplied)
B : bandwidth
M : gain
F : excess noise factor
Ids : surface leakage current
(dark current component not multiplied)

The ratio of the ionization rate of electrons (α) to the ionization ratio of holes (β) is called the ionization rate ratio [k (=β/α)]. The excess noise factor (F) can be expressed in terms of k as in equation (3).

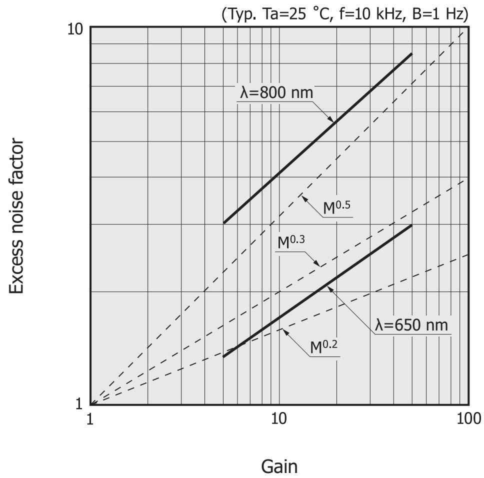
$$F = M\,k + \left(2 - \frac{1}{M}\right)(1 - k) \quad \cdots\cdots\cdots\cdots \quad (3)$$

Equation (3) shows the excess noise factor when electrons are injected into the avalanche layer. To evaluate the excess noise factor when holes are injected into the avalanche layer, k in equation (3) should be substituted by 1/k.

As described in section 1-6, "Spectral response," the gain is wavelength dependent. Likewise, the excess noise also has wavelength dependence. Some APDs exhibit low noise at short wavelengths while others at long wavelengths. Figure 1-5 shows excess noise characteristics.

[Figure 1-5] Excess noise factor vs. gain

(a) Short wavelength type (low-bias operation)



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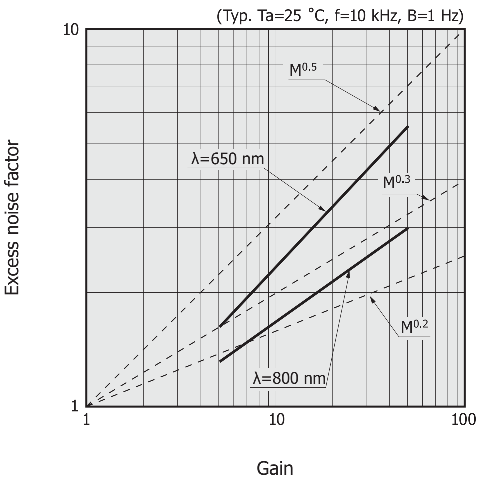
(b) Near infrared type (low-bias operation)



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The excess noise factor (F) can also be approximated as $F=M^x$ (x: excess noise index) because the equation for shot noise can be expressed in the form of $In^2=2q\, I_L\, B\, M^{2+X}$.
As explained, APDs generate noise due to the multiplication process, so excess noise increases as the gain becomes higher. On the other hand, the signal is also increased according to the gain, so there is a gain at which the S/N is maximized. The S/N for an APD can be expressed by equation (4).

$$S/N = \frac{I_L^2 M^2}{2q\,(I_L + Idg)\,B\,M^2 F + 2q\,B\,Ids + \frac{4k\,T\,B}{R_L}} \cdots\cdots (4)$$

$2q\,(I_L + Idg)\,B\,M^2 F + 2q\,B\,Ids$: shot noise
$\frac{4k\,T\,B}{R_L}$: thermal noise
k : Boltzmann's constant
T : absolute temperature
R_L : load resistance

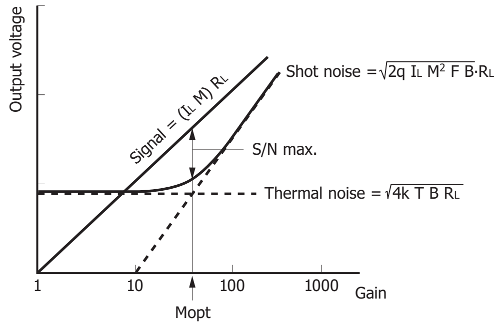
The noise equivalent power (NEP) of APDs is given by equation (5).

$$NEP = In/(M\,S) \cdots\cdots (5)$$

M: gain
S: photosensitivity [A/W]

In PIN photodiode operation, using a larger load resistance reduces thermal noise, but this also slows the response speed. Therefore, it is not practical to reduce thermal noise and, in most cases, the lower limit of light detection is determined by thermal noise. In APD operation, the signal can be multiplied without increasing the total noise until the shot noise reaches a level equal to the thermal noise, thus resulting in an improved S/N while maintaining the high-speed response. This behavior is shown in Figure 1-6.

[Figure 1-6] APD noise characteristics



R_L: load resistance
k : Boltzmann's constant
T : absolute temperature

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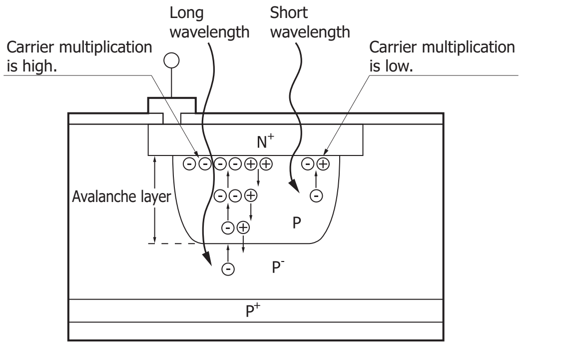
In this case, the optimum gain (Mopt) is obtained under the conditions that maximize the S/N described in equation (4). If Ids can be ignored, the optimum gain is given by equation (6).

$$Mopt = \left[\frac{4k\,T}{q\,(I_L + Idg) \times R_L}\right]^{\frac{1}{2+x}} \cdots\cdots\cdots\cdots (6)$$

1 - 6 Spectral response

Spectral response characteristics of APDs are almost the same as those of normal photodiodes if a reverse voltage is not applied. When a reverse voltage is applied, the spectral response curve will change.
The depth to which light penetrates in the silicon depends on the wavelength. The depth to which short-wavelength light can reach is shallow, so carriers are generated near the surface. In contrast, long-wavelength light generates carriers even at deeper positions. The avalanche multiplication occurs when the carriers pass through the high electric field near the PN junction. In the case of silicon, the ionization rate of electrons is high, so multiplication can be achieved efficiently when electrons are injected into the avalanche layer. For example, in the case of the APD type shown in figure 1-7, the avalanche layer is in the PN junction region on the front side. With this APD type, satisfactory gain characteristics can be obtained when long-wavelength light that reaches deeper than the avalanche layer is incident. The APD structure determines whether short- or long-wavelength light is multiplied efficiently.

[Figure 1-7] Schematic of cross section (near infrared type)



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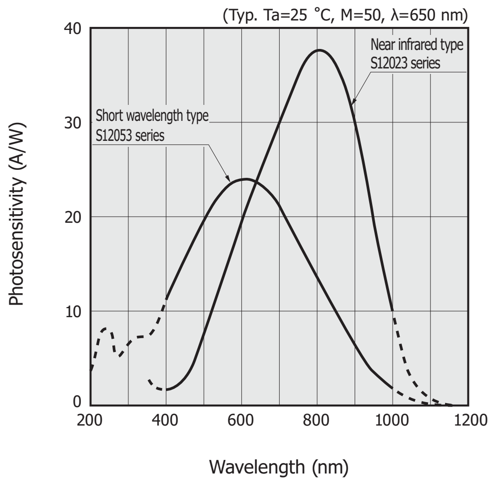
The spectral response and wavelength dependency of gain for the short wavelength type and near infrared type Si APDs are provided below.

[Figure 1-8] Spectral response



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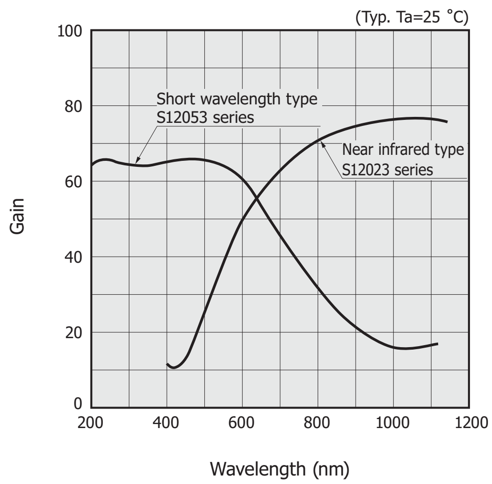
[Figure 1-9] Gain vs. wavelength



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1 - 7 Response characteristics

The factors that determine the response speed of photodiodes are the CR time constant, the carrier transit time (drift time) in the depletion layer, the time needed for multiplication (multiplication time), and the time delay which is caused by diffusion current of carriers from outside the depletion layer. The cutoff frequency fc(CR) determined by the CR time constant is given by equation (7).

$$fc(CR) = \frac{1}{2\pi \, Ct \, R_L} \cdots\cdots\cdots\cdots (7)$$

Ct: terminal capacitance
RL: load resistance

To improve photodiode response speeds, the terminal capacitance should be reduced, for example by making the photosensitive area smaller and the depletion layer thicker. The relation between the cutoff frequency fc(CR) and the rise time tr is expressed by equation (8).

$$tr = \frac{0.35}{fc(CR)} \cdots\cdots\cdots\cdots (8)$$

If the depletion layer is widened, the drift time cannot be ignored. The transit speed (drift speed) in the depletion layer begins to saturate when the electric field strength reaches the vicinity of 10^4 V/cm, and the saturated drift speed at this point will be approx. 10^7 cm/s. Ionization occurs when the carriers that have moved to the avalanche layer generate electron-hole pairs. However, since the holes move in the direction opposite to that of the electrons, the drift time in the APD becomes longer than that in PIN photodiodes. If we let the drift time be trd, the cutoff frequency fc(trd) determined by the drift time is given by equation (9).

$$fc(trd) = \frac{0.44}{trd} \cdots\cdots\cdots\cdots (9)$$

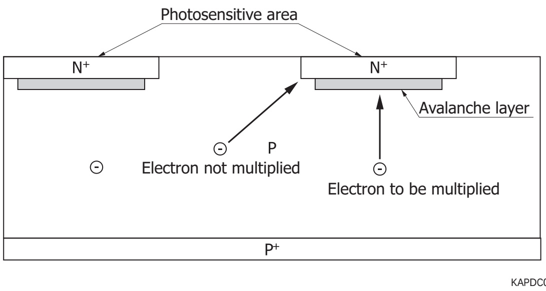
Making the depletion layer thicker to reduce the capacitance also lengthens the drift time, so it is essential to consider both cutoff frequencies, fc(CR) determined by the CR time constant and fc(trd) determined by the transit time.
The carriers passing through the avalanche layer repeatedly collide with the crystal lattice, so a longer time is required to move a unit distance in the avalanche layer than the time required to move a unit distance in areas outside the avalanche layer. The time required to pass through the avalanche layer becomes longer as the gain is increased. If an APD is used at a gain of several hundred times, the multiplication time might be a problem.
This time delay caused by the diffusion current of carriers from outside the depletion layer is sometimes as large as a few microseconds and appears more remarkably in cases where the depletion layer is not extended enough with respect to the penetration depth of the incident light into the silicon. To ensure high-speed response, it is also necessary to take the wavelength to be used into account and to apply a reverse voltage that sufficiently widens the depletion layer.

When the incident light level is high and the resulting photocurrent is large, the attractive power of electrons and holes in the depletion layer serves to cancel out the electric field, making the carrier drift speed slower and impairing the time response. This phenomenon is called the space charge effect and tends to occur especially when the incident light is interrupted.

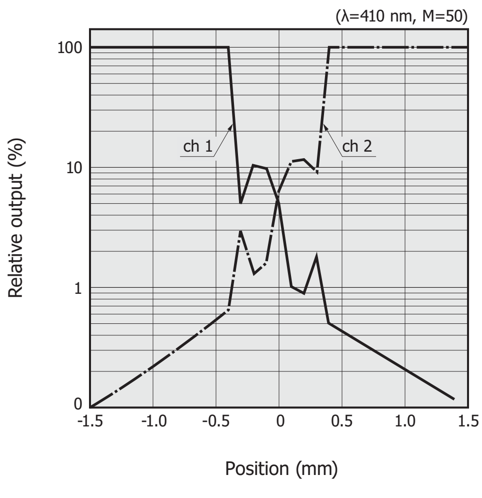
1 - 8 Multi-element type

Multi-element Si APDs have an array of photosensitive areas. The avalanche layer formed just below each photosensitive area on the APD array multiplies the light incident on the photosensitive areas. However, carriers generated outside these photosensitive areas cannot pass through the avalanche layer so their signal is small. This means that APD arrays have lower crosstalk than photodiode arrays because of their gain.

[Figure 1-10] Internal structure (multi-element type)



[Figure 1-11] Crosstalk
(S8550-02, element gap: 0.7 µm, typical example)



1 - 9 Connection to peripheral circuits

APDs can be handled in the same manner as normal photodiodes except that a high reverse voltage is required. However, the following precautions should be taken because APDs are operated at a high voltage, their gain changes depending on the ambient temperature, and so on.

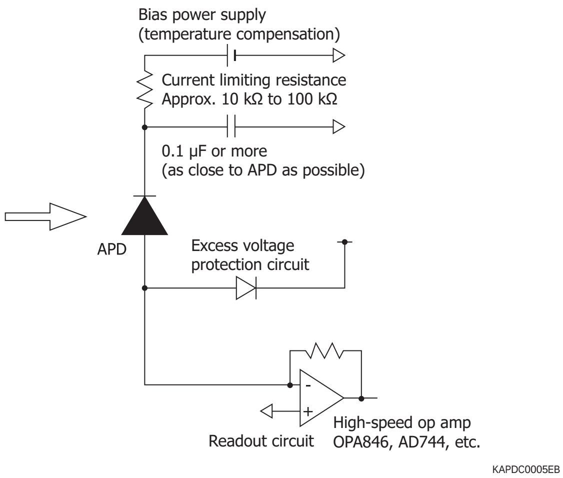
① APD power consumption is the product of the incident light level × sensitivity (M=1) × gain × reverse voltage, and it is considerably larger than that of PIN photodiodes. So there is a need to add a protective resistor between the APD and bias power supply and then install a current limiting circuit. Note that when the output current is large, the voltage drop across the protective resistor increases and the APD reverse voltage declines. In that case, the protective resistor value must be decreased.

② A low-noise readout circuit may damage the first stage in response to excess voltage. To prevent this, a protective circuit should be connected to divert any excess input voltage to the power supply voltage line.

③ APD gain changes with temperature. To use an APD over a wide temperature range, measures must be taken such as incorporating temperature compensation, which controls the reverse voltage to match the temperature changes, or temperature control, which maintains the APD temperature at a constant level. In temperature compensation, a temperature sensor is installed near the APD to control the reverse voltage according the APD’s temperature coefficient. In temperature control, a TE-cooler is used to maintain a constant APD temperature.

④ When detecting low-level light signals, if background light enters the APD, then the S/N may decrease due to shot noise from background light. In this case, effects from the background light must be minimized by using optical filters, improving laser modulation, and/or restricting the angle of view.

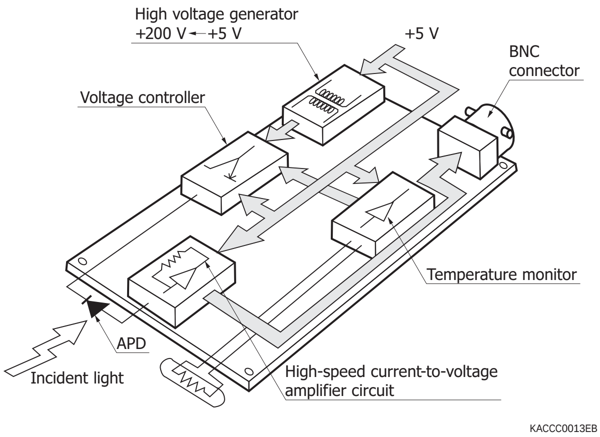
[Figure 1-12] Connection example



APD modules

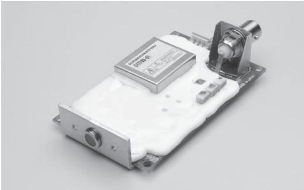
APD modules are high-speed, high-sensitivity photodetectors using an APD. APD modules consist of an APD, a low noise I/V amplifier circuit, and a bias power supply assembled in a compact configuration. By simply connecting to a low-voltage DC power supply, APD modules can detect light with a good S/N which is dozens of times higher than PIN photodiodes. APD modules help users evaluate and fabricate their high-performance system using an APD.
Figure 1-13 shows the block diagram of the C12702 series APD module. This module is designed with the precautions described in section 1-9, “Connection to peripheral circuits,” thus allowing highly accurate photometry.
For more detailed information about APD modules, refer to “3. APD modules” in Chapter 11, “Module products.”

[Figure 1-13] Block diagram (C12702 series)



[Figure 1-14] APD modules

(a) Standard type C12702 series



(b) TE-cooled type C4777-01

(c) High-speed type C5658

1 - 10 New approaches

APDs are not so easy to use because they need a high reverse voltage and their gain is temperature dependent. Hamamatsu is developing APDs that operate on a low reverse voltage and other types to make them easier to use. Hamamatsu is also working on a surface-mount chip size package (CSP) type and a type in which a filter is directly mounted on the chip to suppress effects of background light.
Moreover, since the APD gain is inconsistent within the photosensitive area, developing large-area APD arrays requires advanced technology. Hamamatsu is developing large-area APD arrays with excellent gain uniformity within the photosensitive area.

[Table 1-1] Hamamatsu APD modules

Type	Features
Standard type	Contains near infrared type or short wavelength type APD. FC/SMA fiber adapters are also available.
High sensitivity type	High gain type for low-light-level detection
High-speed type	Can be used in a wide-band frequency range (up to 1 GHz)
TE-cooled type	High-sensitivity type for low-light-level detection. Greatly improved stability through thermoelectric cooling.

2. MPPC

The MPPC (multi-pixel photon counter) is one of the devices called Si-PM (silicon photomultiplier). It is a new type of photon-counting device using multiple APD (avalanche photodiode) pixels operating in Geiger mode. Although the MPPC is essentially an opto-semiconductor device, it has an excellent photon-counting capability and can be used in various applications for detecting extremely weak light at the photon counting level.
The MPPC operates on a low voltage and features a high multiplication ratio (gain), high photon detection efficiency, fast response, excellent time resolution, and wide spectral response range, so it delivers the high-performance level needed for photon counting. The MPPC is also immune to magnetic fields, highly resistant to mechanical shocks, and will not suffer from "burn-in" by incident light saturation, which are advantages unique to solid-state devices. The MPPC therefore has a potential for replacing conventional detectors used in photon counting up to now. The MPPC is a high performance, easy-to-operate detector that is proving itself useful in a wide range of applications and fields including medical diagnosis, academic research, and measurements.[1) 3)]

2 - 1 Operating principle

Photon counting

Light has a property in both a particle and a wave. When the light level becomes extremely low, light behaves as discrete particles (photons) allowing us to count the number of photons. Photon counting is a technique for measuring the number of individual photons.
The MPPC is suitable for photon counting since it offers an excellent time resolution and a multiplication function having a high gain and low noise. Compared to ordinary light measurement techniques that measure the output current as analog signals, photon counting delivers a higher S/N and higher stability even in measurements at very low light levels.

Geiger mode and quenching resistor

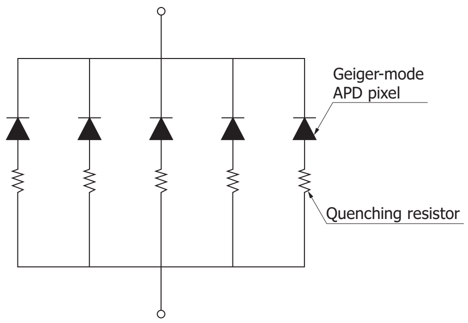
When the reverse voltage applied to an APD is set higher than the breakdown voltage, saturation output (Geiger discharge) specific to the element is produced regardless of the input light level. The condition where an APD operates at this voltage level is called Geiger mode. The Geiger mode allows obtaining a large output by way of the discharge even when detecting a single photon. Once the Geiger discharge begins, it continues as long as the electric field in the APD is maintained.

To halt the Geiger discharge and detect the next photon, an external circuit outside the APD must lower the operating voltage. One specific example for halting the Geiger discharge is a technique using a so-called quenching resistor connected in series with the APD to quickly stop avalanche multiplication in the APD. In this method, a drop in voltage occurs when the output current caused by the Geiger discharge flows in the quenching resistor, reducing the operating voltage of the APD connected in series. The output current caused by the Geiger discharge is a pulse waveform with a short rise time, while the output current when the Geiger discharge is halted by the quenching resistor is a pulse waveform with a relatively slow fall time [Figure 2-4].

Structure

Figure 2-1 shows a structure of an MPPC. The basic element (one pixel) of an MPPC is a combination of the Geiger mode APD and quenching resistor, and a large number of these pixels are electrically connected and arranged in two dimensions.

[Figure 2-1] Structure



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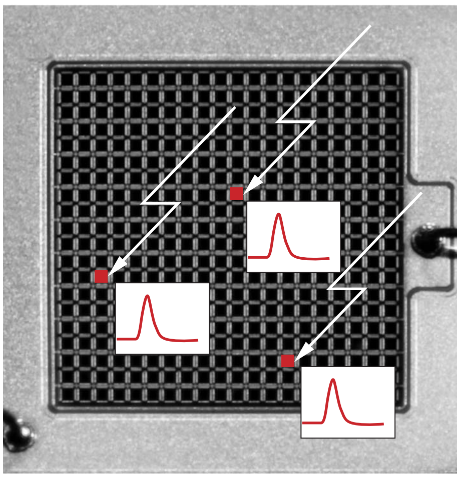
[Figure 2-2] Image of MPPC's photon counting



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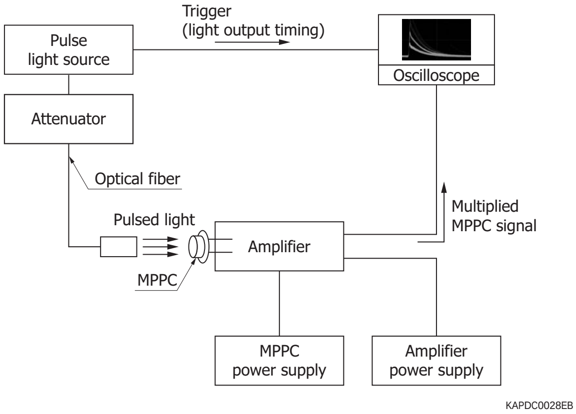
[Figure 2-3] Block diagram for MPPC evaluation (with an oscilloscope)



Basic operation

Each pixel in the MPPC outputs a pulse at the same amplitude when it detects a photon. Pulses generated by multiple pixels are output while superimposed onto each other. For example, if four photons are incident on different pixels and detected at the same time, then the MPPC outputs a signal whose amplitude equals the height of the four superimposed pulses. Each pixel outputs only one pulse and this does not vary with the number of incident photons. So the number of output pulses is always one regardless of whether one photon or two or more photons enter a pixel at the same time. This means that MPPC output linearity gets worse as more photons are incident on the MPPC such as when two or more photons enter one pixel. This makes it essential to select an MPPC having enough pixels to match the number of incident photons.

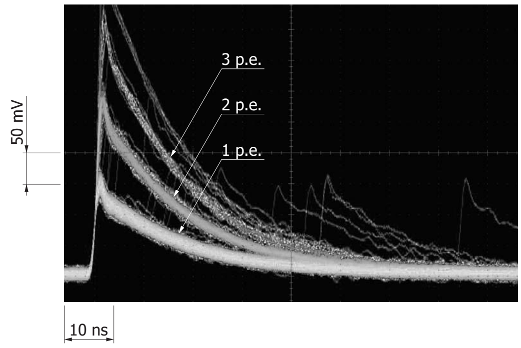
The following two methods are used to estimate the number of photons detected by the MPPC.

· Observing the pulse
· Measuring the output charge

(1) Observing pulses

When light enters an MPPC at a particular timing, its output pulse height varies depending on the number of photons detected. Figure 2-4 shows output pulses from the MPPC obtained when it was illuminated with the pulsed light at photon counting levels and then amplified with a linear amplifier and observed on an oscilloscope. As can be seen from the figure, the pulses are separated from each other according to the number of detected photons such as one, two, three photons and so on. Measuring the height of each pulse allows estimating the number of detected photons.

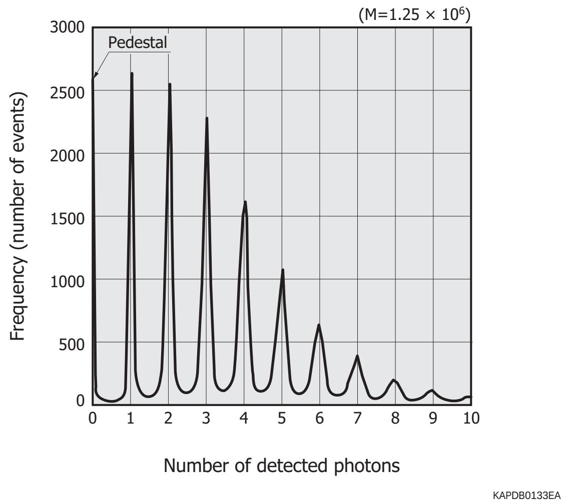
[Figure 2-4] Pulse waveforms when using a linear amplifier (120 times) (S12571-050C, M=1.25 × 10^6)



(2) Integrating the output charge

The distribution of the number of photons detected during a particular period can be estimated by measuring the MPPC output charge using a charge amplifier or similar device. Figure 2-5 shows a distribution obtained by discriminating the accumulated charge amount. Each peak from the left corresponds to the pedestal, one photon, two photons, three photons and so on. Since the MPPC gain is high enough to produce a large amount of output charge, the distribution can show discrete peaks according to the number of detected photons.

[Figure 2-5] Pulse height spectrum when using charge amplifier (S12571-050C, M=1.25 × 10^6)



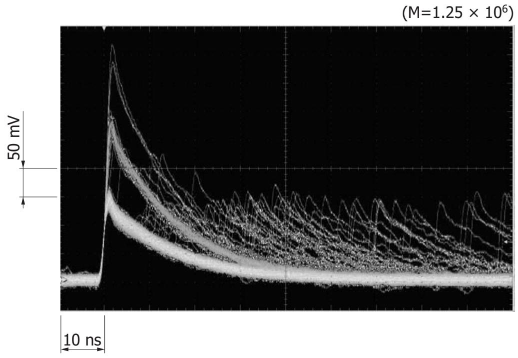
2 - 2 Features

Low afterpulses

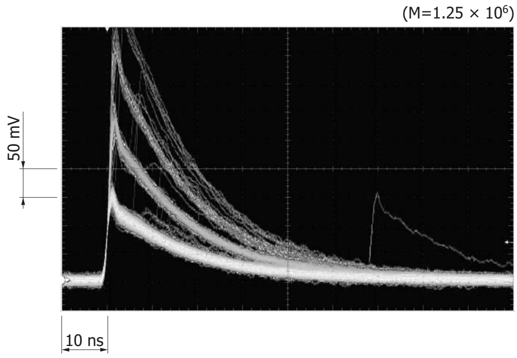
When detecting photons with an MPPC, signals delayed from the output signal may appear again. These signals are called afterpulses. Compared to our previously marketed products, new MPPCs have drastically reduced afterpulses due to use of improved materials and wafer process technologies. Reducing afterpulses brings various benefits such as a better S/N, a wider operating voltage range, and improved time resolution and photon detection efficiency in high voltage regions.

[Figure 2-6] Pulse waveforms

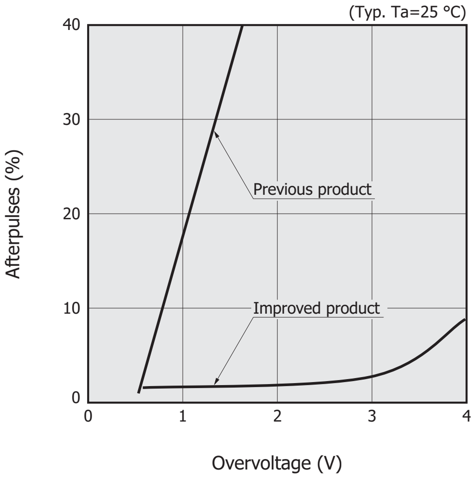
(a) S10362-11-050C (previous product)



(b) S12571-050C (improved product)



[Figure 2-7] Afterpulses vs. overvoltage



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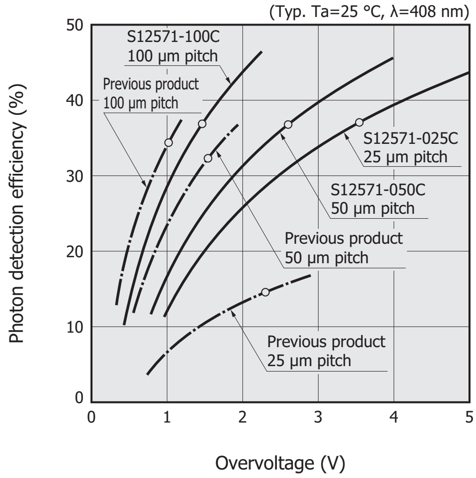
High photon detection efficiency

The MPPC has a peak sensitivity at a wavelength around 400 to 500 nm. The MPPC sensitivity is referred to as photon detection efficiency (PDE) and is calculated by the product of the quantum efficiency, fill factor, and avalanche probability. Among these, the avalanche probability is dependent on the operating voltage. Our 25 μm pitch MPPC is designed for a high fill factor that vastly improves photon detection efficiency compared to our previous types. Using this same design, we also developed 10 μm and 15 μm pitch MPPCs that deliver a high-speed response and wide dynamic range as well as high photon detection efficiency. The fill factor of 50 μm and 100 μm pitch MPPC is the same as that of previous types, but increasing the overvoltage improves photon detection efficiency.

[Figure 2-8] Photon detection efficiency vs. overvoltage



Photon detection efficiency does not include crosstalk and afterpulses.

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[Table 2-1] Recommended overvoltage

Pixel pitch (μm)	Recommended overvoltage (V)	
	Previous product	S12571 series
25	2.3	3.5
50	1.5	2.6
100	1.0	1.4

$$V_{ov} = V_{op} - V_{BR} \quad \cdots\cdots\cdots\cdots \quad (1)$$

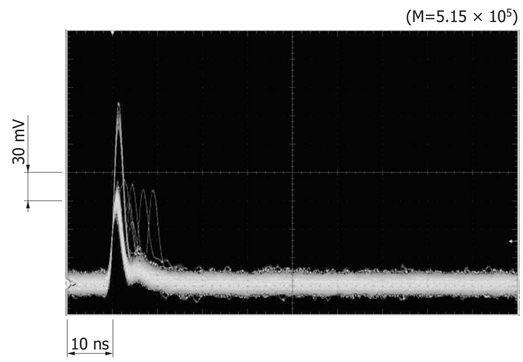
Vov: overvoltage
Vop: operating voltage
VBR : breakdown voltage

Wide dynamic range

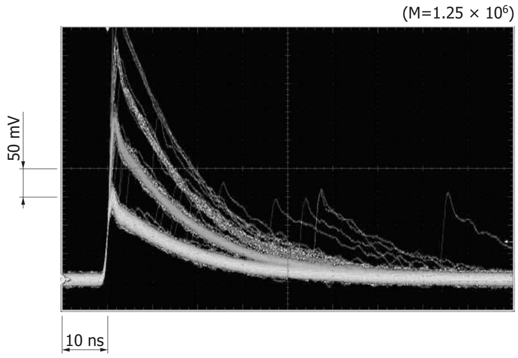
The MPPC dynamic range is determined by the number of pixels and the pixel recovery time. Hamamatsu has developed the MPPC with the smallest pixel pitch of 10 μm, which increases the number of pixels per unit area and shortens the recovery time. This drastically extends the MPPC dynamic range.

[Figure 2-9] Pulse waveforms

(a) High-speed, wide dynamic range type S12571-010C (pixel pitch: 10 μm)



(b) General measurement type S12571-050C (pixel pitch: 50 μm)

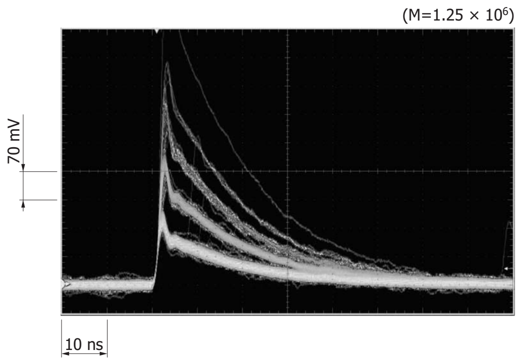


Low crosstalk

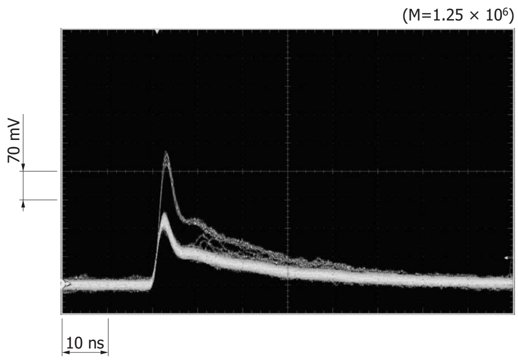
The pixel that detects photons may affect other pixels, making them produce pulses other than output pulses. This phenomenon is called crosstalk. Hamamatsu has drastically reduced the crosstalk in precision measurement MPPC by creating barriers between pixels.

[Figure 2-10] Pulse waveforms

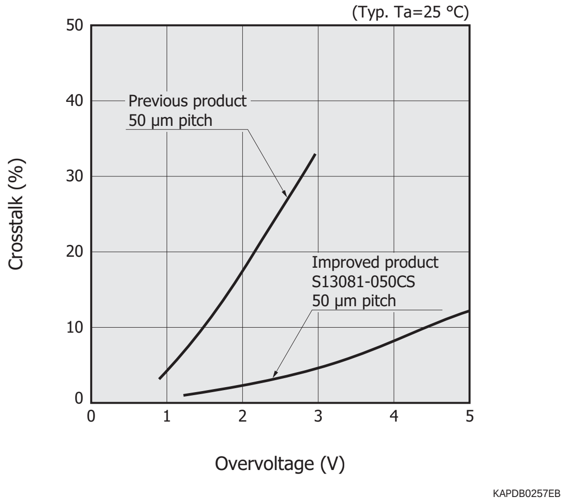
(a) Precision measurement type S12571-050C (pixel pitch: 50 μm)



(b) General measurement type S13081-050CS (pixel pitch: 50 μm)



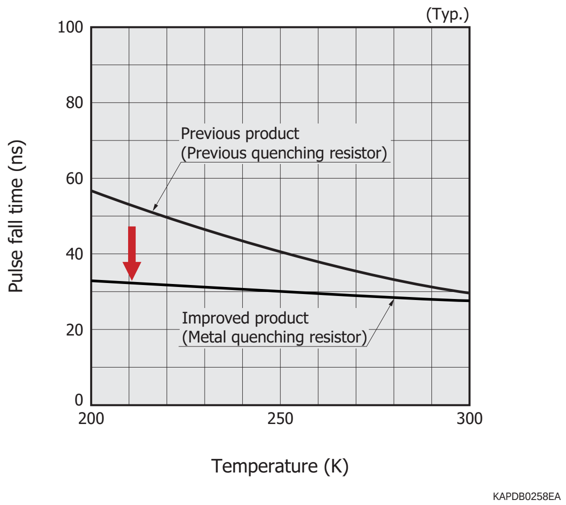
[Figure 2-11] Crosstalk vs. overvoltage



Metal quenching resistor

Due to the use of a metal quenching resistor, the temperature coefficient of the resistance is reduced to 1/5 of the previous type. This suppresses changes in the falling pulse edge especially at low temperatures and so improves the output waveform.
For information on the usable temperature range, refer to the datasheets.

[Figure 2-12] Pulse fall time vs. temperature
(photosensitive area: 1 mm sq, pixel pitch: 50 μm)



2 - 3 Characteristics

MPPC lineup and characteristics

To meet a diverse range of applications and needs, Hamamatsu provides a full lineup of MPPC types in different pixel sizes and photosensitive areas. The MPPC packages include metal, ceramic, PWB (printed wiring boards), and CSP (chip size packages). As multichannel array detectors, Hamamatsu also provides MPPC arrays having uniform characteristics on each channel and narrow dead space between the channels.

MPPC types with a larger pixel size are suitable for applications where a high gain and high photon detection efficiency are required, while types with a smaller pixel size are suitable for applications requiring high-speed response and a wide dynamic range. Types with a larger photosensitive area are suitable for a wide-dynamic-range measurement or detection of light incident on a large area, while types with smaller photosensitive area are suitable for applications where a high speed and low dark count are needed.
The MPPC characteristics vary with the operating voltage. To deal with various applications, the MPPC operating voltage can be adjusted as desired over a wide setting range. To obtain an optimum MPPC performance, the operating voltage should be set higher in applications requiring a high gain, high photon detection efficiency, and superior time resolution, while it should be set lower in applications requiring low noise (low dark, low crosstalk, and low afterpulses).

[Table 2-2] MPPC characteristics versus pixel size

Pixel size	Small ←→ Large
Gain	
Photon detection efficiency	
Dynamic range	
High-speed response	

[Table 2-3] MPPC characteristics versus photosensitive area

Photosensitive area	Small ←→ Large
Dynamic range	
Light detection over a large area	
High-speed response	
Dark	

[Table 2-4] MPPC characteristics versus operating voltage

Operating voltage	Low ←→ High
Gain	
Photon detection efficiency	
Time resolution	
Noise	

Gain

(1) Definition

The MPPC gain is defined as the charge (Q) of the pulse generated from one pixel when it detects one photon, divided by the charge per electron (q: 1.602×10^{-19} C).

$$M = \frac{Q}{q} \cdots\cdots\cdots (2)$$

M: gain

The charge Q depends on the reverse voltage (VR) and breakdown voltage (VBR) and is expressed by equation (3).

$$Q = C \times (V_R - V_{BR}) \cdots\cdots\cdots (3)$$

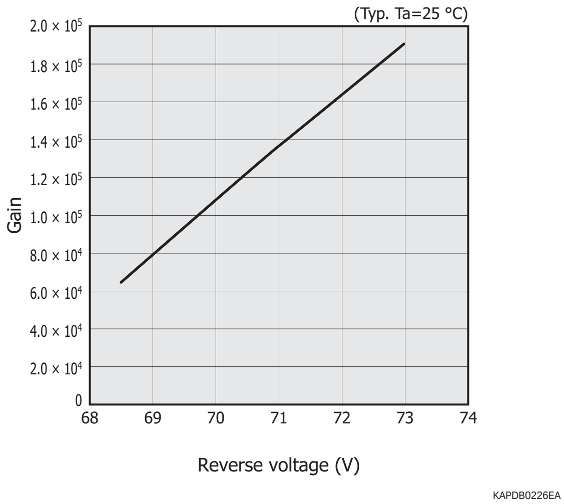
C: capacitance of one pixel

Equations (2) and (3) indicate that the larger the pixel capacitance or the higher the reverse voltage, the higher the gain will be. On the other hand, increasing the reverse voltage also increases the dark and afterpulses. So the reverse voltage must be carefully set to match the application.

(2) Linearity

As the reverse voltage is increased, the MPPC gain also increases almost linearly. Figure 2-13 shows a typical example.

[Figure 2-13] Gain vs. reverse voltage
(photosensitive area: 1 mm sq, pixel pitch: 10 μm)



(3) Temperature characteristics

As with the APD, the MPPC gain is also temperature dependent. As the temperature rises, the crystal lattice vibrations become stronger. This increases the probability that carriers may strike the crystal before the accelerated carrier energy has become large enough, making it difficult for ionization to continue. To make ionization easier to occur, the reverse voltage should be increased to enlarge the internal electric field. To keep the gain constant, the reverse voltage must be adjusted to match the ambient temperature or the element temperature must be kept constant.
Figure 2-14 shows the reverse voltage adjustment needed to keep the gain constant when the ambient temperature varies.

[Figure 2-14] Reverse voltage vs. ambient temperature
(photosensitive area: 1 mm sq, pixel pitch: 10 μm)

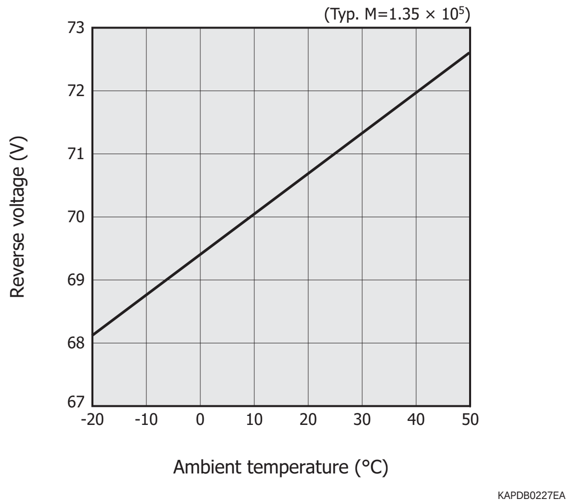
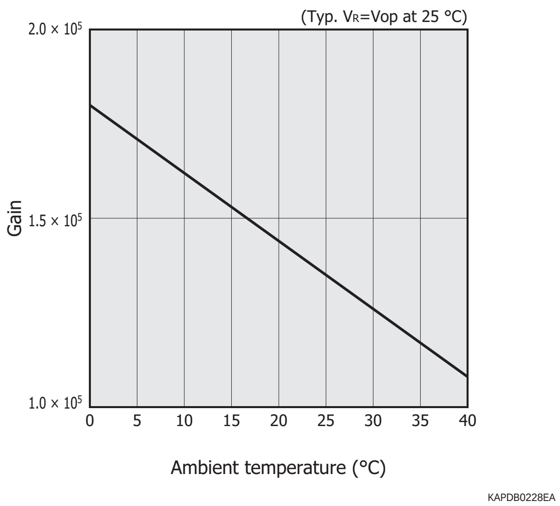


Figure 2-15 shows the relation between gain and ambient temperature when the reverse voltage is a fixed value.

[Figure 2-15] Gain vs. ambient temperature
(photosensitive area: 1 mm sq, pixel pitch: 10 μm)

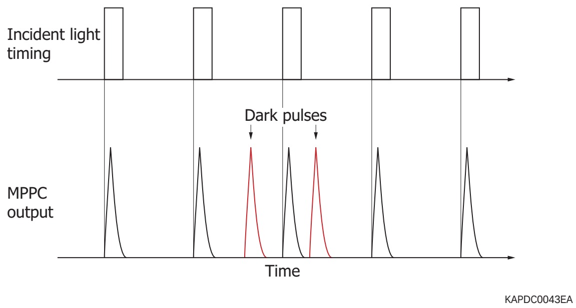


Dark count

(1) Definition

In the MPPC operation just the same as with APD, pulses are produced not only by photon-generated carriers but also by thermally-generated carriers. The pulses produced by the latter are called the dark pulses. The dark pulses are observed along with the signal pulses and so cause detection errors. Thermally-generated carriers are also multiplied to a constant signal level (1 p.e.). These dark pulses are not distinguishable by the shape from photon-generated pulses [Figure 2-16].

[Figure 2-16] Dark pulses



The number of dark pulses observed is referred to as the dark count, and the number of dark pulses per second is termed as the dark count rate [unit: cps (counts per second)]. The dark count rate of Hamamatsu MPPC is defined as the number of pulses that are generated in a dark state and exceed a threshold of 0.5 p.e. This is expressed as $N_{0.5\ p.e.}$.

(2) Temperature characteristics

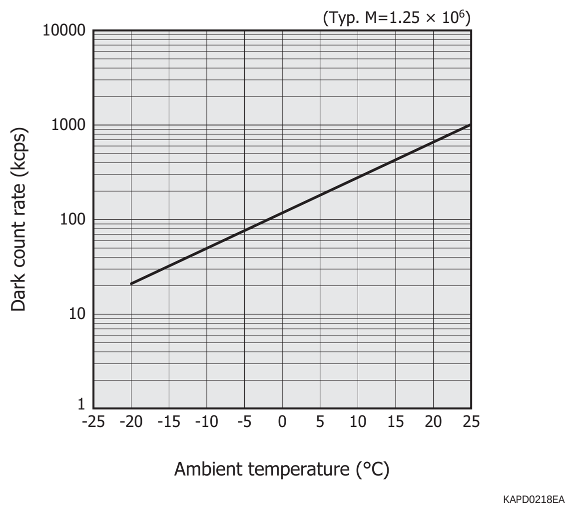
Since dark pulses are produced by thermally-generated carriers, the dark count rate varies with the ambient temperature. The dark count rate is given by equation (4) within the operating temperature range.

$$N_{0.5\ p.e.}(T) \approx AT^{\frac{3}{2}} \exp\left[\frac{Eg}{2k\,T}\right] \cdots\cdots\cdots (4)$$

T : absolute temperature [K]
A : arbitrary constant
Eg: band gap energy [eV]
k : Boltzmann's constant [eV/K]

Figure 2-17 shows a relation between the dark count rate and the ambient temperature when the gain is set to a constant value.

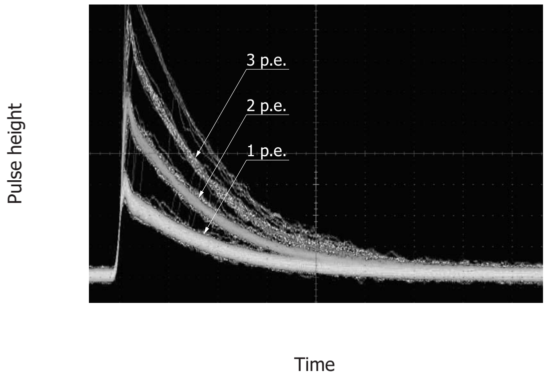
[Figure 2-17] Dark count rate vs. ambient temperature
(photosensitive area: 3 mm sq, pixel pitch: 50 μm)



Crosstalk

When light enters one MPPC pixel, there may be cases where a pulse of 2 p.e. or higher is observed. This is because secondary photons are generated in the avalanche multiplication process of the MPPC pixel and those photons are detected by other pixels. This phenomenon is called the optical crosstalk.

[Figure 2-18] Crosstalk example

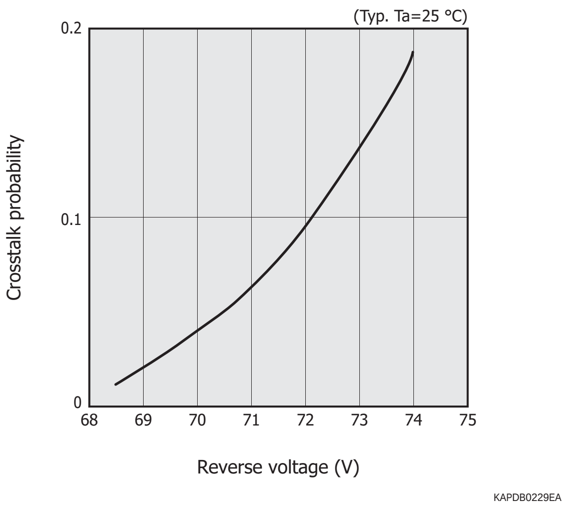


We define the crosstalk probability (Pcrosstalk) as equation (5).

$$\text{Pcrosstalk} = \frac{N_{1.5\text{ p.e.}}}{N_{0.5\text{ p.e.}}} \cdots\cdots\cdots (5)$$

The crosstalk probability has almost no dependence on the temperature within the rated operating temperature range. The probability that the crosstalk will occur increases as the reverse voltage is increased [Figure 2-19].

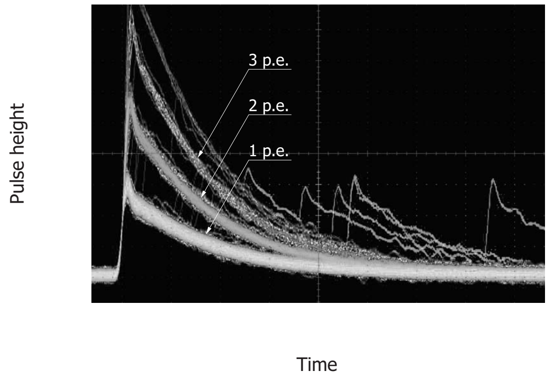
[Figure 2-19] Crosstalk probability vs. reverse voltage (photosensitive area: 1 mm sq, pixel pitch: 50 μm)



Afterpulses

During the avalanche multiplication process in MPPC pixels, the generated carriers may be trapped by lattice defects. When these carriers are released, they are multiplied by the avalanche process along with photon-generated carriers and are then observed as afterpulses. The afterpulses are not distinguishable by shape from photon-generated pulses.

[Figure 2-20] Afterpulse observed



Dark current

Output current produced even when operated in a dark state is called the dark current. The MPPC dark current (I_D) is expressed by equation (6).

$$I_D = I_s + I_j + I_b \cdots\cdots\cdots (6)$$

Is: surface leakage current
Ij: recombination current
Ib: bulk current

When the MPPC is operated in Geiger mode, the bulk current is expressed by equation (7), assuming that the number of pixels in which avalanche multiplication occurs per unit time is Nfired.

$$I_b = q\ M\ \text{Nfired} \cdots\cdots\cdots (7)$$

q: electron charge
M: gain

Since the MPPC gain is usually 10^5 to 10^6, the bulk current Ib is dominant in equation (6) and equation (7) can then be approximated to equation (8).

$$I_D \approx I_b = q\ M\ \text{Nfired} \cdots\cdots\cdots (8)$$

In a dark state, the number of pixels where avalanche multiplication occurred equals the dark count rate, so the dark current I_D can be approximated to equation (9) using $N_{0.5\text{ p.e.}}$ and Pcrosstalk. If the gain and crosstalk probability at a particular reverse voltage are known, then the dark current can be roughly estimated from the dark count rate and vice versa.

$$I_D \approx q\ M\ N_{0.5\text{ p.e.}} \frac{1}{1 - \text{Pcrosstalk}} \cdots\cdots\cdots (9)$$

Photosensitivity and photon detection efficiency

The photosensitivity and the photon detection efficiency are used to express the MPPC light detection sensitivity. The photosensitivity is expressed as the ratio of the MPPC output current (analog value) to the amount of continuous light incident on the MPPC. The photon detection efficiency is a ratio of the number of detected photons to the number of incident photons during photon counting where the pulsed light enters the MPPC. Both photosensitivity and photon detection efficiency relate to parameters such as fill factor, quantum efficiency, and avalanche probability.

The fill factor is the ratio of the light detectable area to the entire pixel area of an MPPC. Unlike photodiodes and APD, the MPPC photosensitive area contains sections such as the inter-pixel wiring that cannot detect light, so some photons incident on the photosensitive area are not detected. Generally, the smaller the pixel size, the lower the fill factor.

The quantum efficiency is defined as probability that carriers will be generated by light incident on a pixel. As in other types of opto-semiconductors, the MPPC quantum efficiency is dependent on the incident light wavelength.

The avalanche probability is the probability that the carriers generated in a pixel may cause avalanche multiplication. The higher reverse voltage applied to the MPPC, the higher avalanche probability.

(1) Photosensitivity

Photosensitivity (S; unit: A/W) is a ratio of the MPPC photocurrent to the light level (unit: W) incident on the MPPC, as expressed by equation (10).

$$S = \frac{I_{MPPC}}{\text{Incident light level}} \cdots\cdots\cdots (10)$$

I_{MPPC}: photocurrent [A]

The photosensitivity is proportional to the gain, so the higher the reverse voltage applied to the MPPC, the higher the photosensitivity. Note that the photosensitivity includes a crosstalk and afterpulses.

(2) Photon detection efficiency

The photon detection efficiency (PDE) is an indication of what percent of the incident photons is detected, and is given by equation (11).

$$PDE = \frac{\text{Number of detected photons}}{\text{Number of incident photons}} \cdots\cdots\cdots (11)$$

The PDE can be expressed by the product of a fill factor, quantum efficiency, and avalanche probability.

$$PDE = Fg \times QE \times Pa \cdots\cdots\cdots (12)$$

Fg : fill factor
QE: quantum efficiency
Pa : avalanche probability

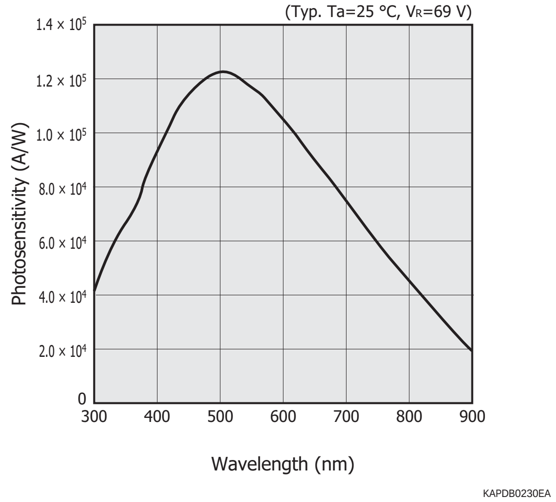
The PDEcurrent, which is determined from photosensitivity, is expressed by equation (13).

$$PDEcurrent = \frac{1240}{\lambda} \times \frac{S}{M} \cdots\cdots\cdots (13)$$

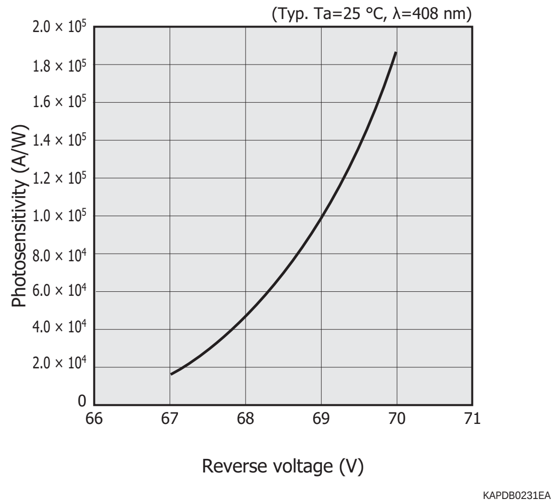
λ: incident light wavelength [nm]

PDEcurrent includes crosstalk and afterpulses, and so PDEcurrent becomes higher than the PDE.

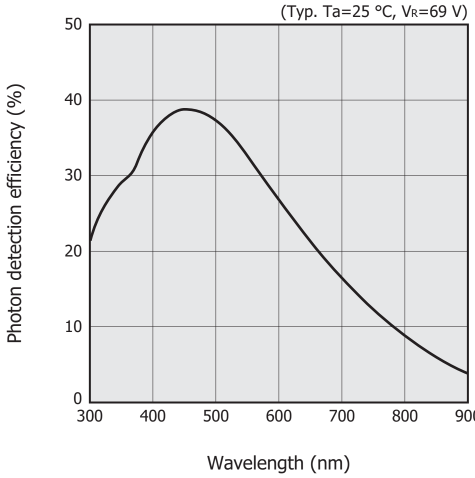
[Figure 2-21] Spectral response (pixel pitch: 25 μm)



[Figure 2-22] Photosensitivity vs. reverse voltage (pixel pitch: 25 μm)



[Figure 2-23] Photon detection efficiency vs. wavelength (pixel pitch: 25 μm)



Photon detection efficiency does not include crosstalk and afterpulses.

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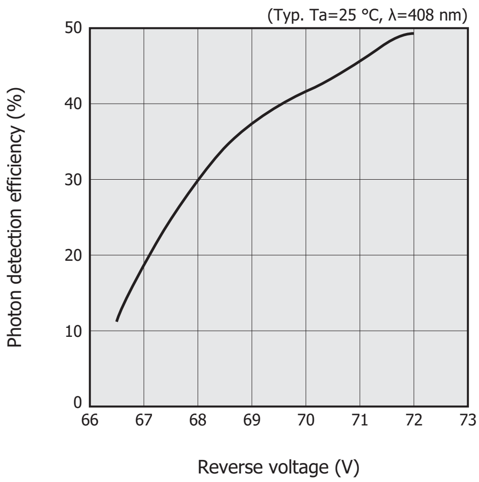
[Figure 2-24] Photon detection efficiency vs. reverse voltage (pixel pitch: 25 μm)



Photon detection efficiency does not include crosstalk and afterpulses.

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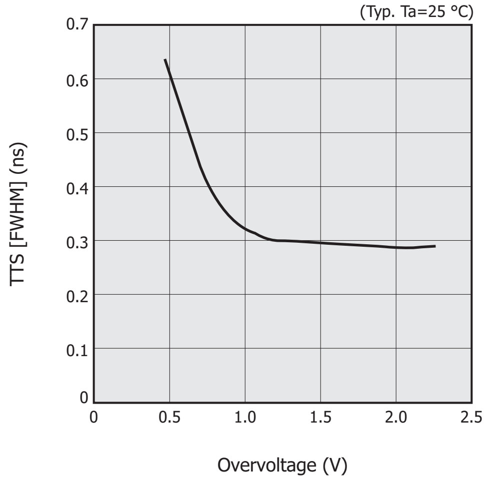
■ Time resolution

The time required for each pixel of the MPPC to output a signal after the incidence of light varies depending on the wiring length, etc. This variation is called TTS (transit time spread). Increasing the reverse voltage applied to the MPPC reduces and improves the TTS.

[Figure 2-25] TTS vs. overvoltage (photosensitive area: 1 mm sq, pixel pitch: 50 μm)



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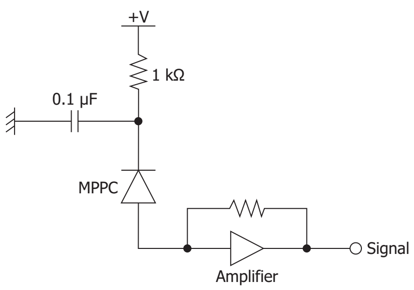
2 - 4 How to use

The MPPC characteristics greatly vary depending on the operating voltage and ambient temperature. In general, raising the operating voltage increases the electric field inside the MPPC and so improves the gain, photon detection efficiency, and time resolution. On the other hand, this also increases unwanted components such as dark count, afterpulses, and crosstalk which lower the S/N. The operating voltage must be carefully set in order to obtain the desired characteristics.

The MPPC can be used by various methods according to the application. Here we introduce a typical method for observing light pulses. Using a wide-band amplifier and oscilloscope makes this measurement easy. Figure 2-26 shows one example of a connection to a wide-band amplifier. The 1 kΩ resistor and 0.1 μF capacitor on the power supply portion serve as a low-pass filter that eliminates high-frequency noise of the power supply. The 1 kΩ resistor is also a protective resistor against excessive current. The MPPC itself is a low-light-level detector, however, in cases where a large amount of light enters the MPPC, for example, when it is coupled to a scintillator to detect radiation, a large current flows into the MPPC. This may cause a significant voltage drop across the protective resistor, so the protective resistor value must be carefully selected according to the application. The amplifier should be connected as close to the MPPC as possible.

[Figure 2-26] Connection example



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In measurements utilizing the MPPC output pulse having a sharp rising edge, an appropriate wide-band amplifier and oscilloscope must be selected. Since the MPPC output pulses usually rise within a few nanoseconds, it is strongly recommended to use an amplifier and oscilloscope capable of sampling at about 1 GHz. Using a narrow-band amplifier and oscilloscope might dull or blunt the output pulse making it impossible to obtain accurate values.

2 - 5 Measurement examples

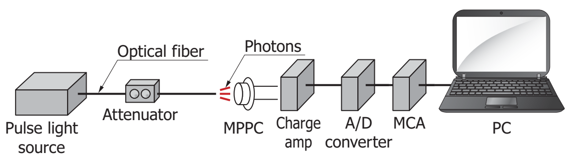
Examples of measuring MPPC characteristics are described below.

Gain

(1) Measurement using a charge amplifier

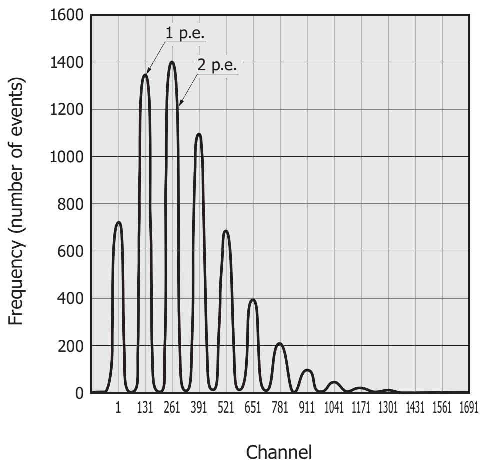
The gain can be estimated from the output charge of the MPPC that detected photons. Figure 2-27 shows a connection setup example for the gain measurement using a charge amplifier.

[Figure 2-27] Gain measurement connection example (using charge amplifier)



When the MPPC is illuminated with pulsed light whose light level is sufficiently reduced by an attenuator and the number of the output charges is plotted, a frequency distribution like that shown in Figure 2-28 is obtained.

[Figure 2-28] Frequency distribution example of output charge



In Figure 2-28, each peak on the curve from the left indicates the pedestal, one photon, two photons and so forth. The pedestal is a basis of the output. This example shows that the MPPC has mainly detected one photon and two photons. The interval between adjacent peaks corresponds to the amount of the charge produced by detecting one photon. The gain (M) is given by equation (14).

$$M = \frac{\text{Charge difference between adjacent peaks}}{q} \quad \cdots\cdots\cdots (14)$$

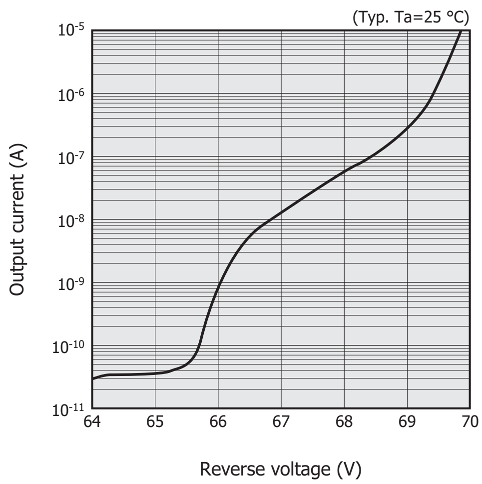
q: electron charge

Furthermore, equation (14) can be used to create and extrapolate a gain vs. reverse voltage graph as shown in Figure 2-13 to determine the reverse voltage for gain of 1, or namely the breakdown voltage V_{BR}.

(2) dI/dV measurement

Figure 2-29 shows the output current vs. reverse voltage characteristics of the MPPC. If the voltage of Vpeak maximizes the value to the function [equation (15)] obtained by differentiating the output current by the reverse voltage, Vpeak - V_{BR} is approximately constant for each type no., but the individual values Vpeak and V_{BR} are different between elements even with the same type no. By determining Vpeak - V_{BR} for a given type no. in advance, you will be able to estimate V_{BR} for a particular element by measuring Vpeak.

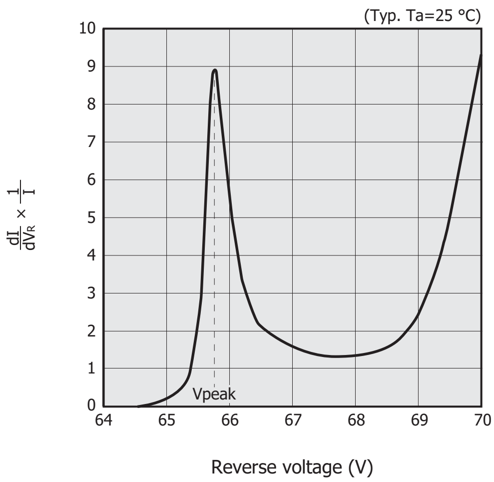
[Figure 2-29] Output current vs. reverse voltage (photosensitive area: 1 mm sq, pixel pitch: 50 μm)



$$\frac{d}{dV_R}\log(I) = \frac{dI}{dV_R} \times \frac{1}{I} \quad \cdots\cdots\cdots (15)$$

I : output current [A]
V_R: reverse voltage [V]

[Figure 2-30] Reverse voltage characteristics of $\frac{dI}{dV_R} \times \frac{1}{I}$



The gain (M) is given by equation (16).

$$M = \frac{C \times (V_R - V_{BR})}{q} \quad \cdots\cdots\cdots (16)$$

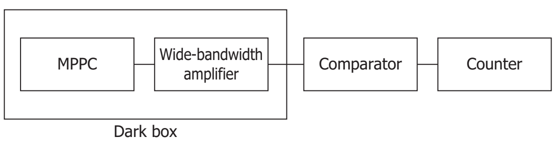
C : pixel capacitance [F]
V_{BR} : breakdown voltage [V]
q : electron charge [C]

Since the pixel capacitance is constant, the gain can be obtained from the breakdown voltage and reverse voltage that are obtained by dI/dV measurement. However, if the operating voltage applied to the MPPC is significantly higher than the recommended operating voltage, noise components such as afterpulses and crosstalk will increase and make accurate measurement impossible.

Dark

The MPPC is installed and operated in a dark box and the output pulse is input to a pulse counter. The number of events where the output pulse exceeds the predetermined threshold (0.5 p.e., etc.) is counted to determine the dark count rate. In this case, a wide-band amplifier must be used because the MPPC output pulse width is very short, down to a few dozen nanoseconds.

[Figure 2-31] Block diagram of dark measurement

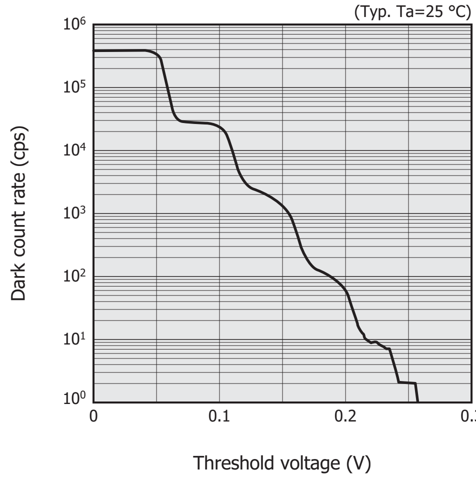


Crosstalk

When the threshold is set, for example, to 0.5 p.e. and 1.5 p.e., to measure the count rate of dark pulses exceeding the threshold, the dark count rates $N_{0.5\,p.e.}$ and $N_{1.5\,p.e.}$ at each threshold can be measured. The crosstalk probability Pcrosstalk is calculated by equation (5).

If the threshold is swept, the dark count rate will be plotted as shown in Figure 2-32. The threshold voltages at which the dark count rate abruptly decreases correspond to the levels of one photon, two photons, and so on from left. The dark count rates $N_{0.5\,p.e.}$, $N_{1.5\,p.e.}$, $N_{2.5\,p.e.}$ and so on can be obtained from this graph.

[Figure 2-32] Dark count rate vs. threshold voltage



Afterpulses

The dark pulses are generated randomly and the time interval of the dark pulse generation follows an exponential distribution. The dark pulse generation time interval Δt_{dark} (unit: seconds) is expressed by equation (17).

$$\Delta t_{dark} \propto \exp\left(\frac{\Delta t}{\tau_{dark}}\right) \quad \cdots\cdots\cdots (17)$$

τ_{dark}: time constant of dark pulse generation [s]

The time interval during afterpulse generation is expressed by the sum of several exponential distributions. The afterpulse generation time interval Δt_{AP} (unit: seconds) is given by equation (18).

$$\Delta t_{AP} \propto \sum_k A_k \times \exp\left(\frac{\Delta t}{\tau_k}\right) \quad \cdots\cdots\cdots (18)$$

k : number of time constants for Δt_{AP}
A_k: constant
τ_k : time constant of afterpulse generation [s]

Here, τ_{dark} differs greatly from τ_k ($\tau_{dark} >> \tau_k$), so it is necessary to create a histogram of the elapsed time Δt after the generation of a given pulse until the next pulse is observed and then estimate dark pulse components in the time region that does not include afterpulses. Then, subtracting the fitted components from the entire histogram gives the afterpulse components.
During measurement, a discriminator, TAC, and MCA are used to create the above mentioned histogram. The photons enter the MPPC and the detected signals are amplified by the amplifier and sent to the discriminator. When the discriminator receives a signal with an amplitude exceeding the threshold for photon detection, it sends the signal to

the TAC. When the next signal is output from the MPPC, that signal is also sent to the TAC. The TAC then outputs a pulse whose amplitude is proportional to the time interval between the first MPPC signal and the next MPPC signal. The MCA sorts the pulses received from the TAC into different channels according to pulse height. The data stored in the MCA displays a histogram of Δt.

[Figure 2-33] Connection example of afterpulse measurement

TAC : time-to-amplitude converter
MCA: multichannel analyzer

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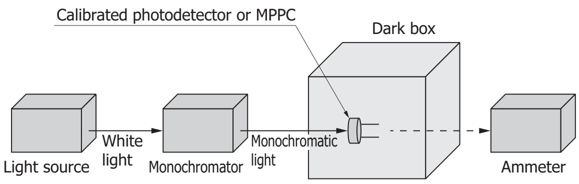
Photosensitivity

To measure the photosensitivity of an MPPC, the incident light from a monochromatic light source is first detected by a calibrated photodetector in a dark box and the light level (unit: W) incident on the photodetector is found from the output. Then, the MPPC is set in the dark box in place of the photodetector to make the same measurement and the MPPC photocurrent (unit: A) is measured. Based on these measurement results, the photosensitivity (S) of the MPPC is calculated as in equation (19).

$$S = \frac{I_{MPPC}}{\text{Incident light level}} \cdots\cdots\cdots (19)$$

I_{MPPC}: photocurrent [A]

[Figure 2-34] Connection example of photosensitivity measurement



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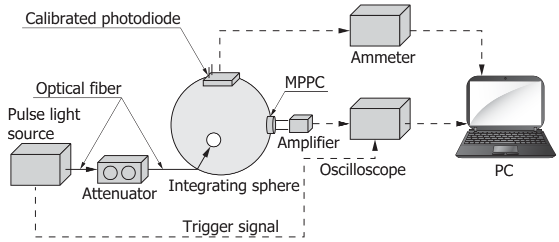
Photon detection efficiency

To measure the photon detection efficiency of an MPPC, a pulsed light source is used as shown in Figure 2-35. The monochromatic pulsed light emitted from the pulsed light source is passed through an attenuator to reduce the light level and is guided into an integrating sphere where the light is scattered and distributed equally in all directions. And then it enters a calibrated photodiode and the MPPC. The output current from the calibrated photodiode is measured with an ammeter and, based on that value, the number of photons incident on the MPPC is found.[2)]

[Figure 2-35] Connection example of photon detection efficiency measurement



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The MPPC output signal is fed to an oscilloscope in synchronization with the trigger signal from the pulsed light source to measure the MPPC output waveform in response to the pulsed light. The MPPC output charge is then obtained from the response waveform. This output charge is obtained for many events to create a frequency distribution of the output charge like that shown in Figure 2-28. In an ideal case, when the pulsed light is so weak that only a few photons are emitted per pulse, this frequency distribution follows a Poisson distribution with a mean value of the number of photons detected by the MPPC. However, part of the events contains dark pulses and the events at 1 p.e. or higher are affected by crosstalk and afterpulses, distorting the actually measured distribution from the Poisson distribution. On the other hand, since the event at pedestal is not affected by crosstalk and afterpulses, the effects of dark pulses can be corrected on the basis of the number of these events and so the mean value of the Poisson distribution can be found.
The Poisson distribution is defined by equation (20).

$$P(n, x) = \frac{n^x e^{-n}}{x!} \cdots\cdots\cdots (20)$$

n: average number of photons detected by MPPC
x: number of photons detected by MPPC

If x=0 in equation (20), then the Poisson distribution is expressed by equation (21).

$$P(n, 0) = e^{-n} \cdots\cdots\cdots (21)$$

The left side of equation (21) is expressed by equation (22) when the correction of dark pulses is included.

$$P(n, 0) = \frac{\left(\frac{N_{ped}}{N_{tot}}\right)}{\left(\frac{N_{ped}^{dark}}{N_{tot}^{dark}}\right)} \cdots\cdots\cdots (22)$$

N_{ped} : number of events at 0 p.e. during pulsed light measurement
N_{tot} : number of all events during pulsed light measurement
N_{ped}^{dark} : number of events at 0 p.e. in dark state
N_{tot}^{dark} : number of all events in dark state

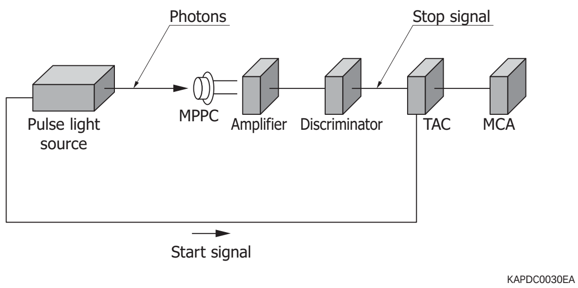
The average number of photons detected by MPPC, n, is given by equation (23). Photon detection efficiency can then be found by dividing n by the number of incident photons.

$$n = -\ln\left(\frac{\frac{N_{ped}}{N_{tot}}}{\frac{N_{ped}^{dark}}{N_{tot}^{dark}}}\right) = -\ln\left(\frac{N_{ped}}{N_{tot}}\right) + \ln\left(\frac{N_{ped}^{dark}}{N_{tot}^{dark}}\right) \cdots\cdots\cdots (23)$$

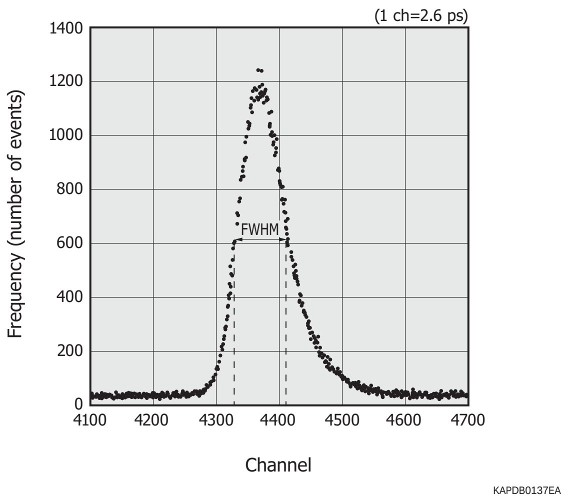
Time resolution

Figure 2-36 is an example of connection for time resolution measurement using the TTS method. The pulse light source emits photons and simultaneously sends a start signal to the TAC. The TAC starts measuring the time upon receiving the start signal. Meanwhile, the photons enter the MPPC and the detected signals are amplified by the amplifier and sent to the discriminator. When the discriminator receives a signal with an amplitude exceeding the threshold for photon detection, it sends the signal to the TAC. The TAC receives the signal from the discriminator as a stop signal for time measurement. At this point, the TAC also provides a pulse output proportional to the time from when photons entered the MPPC until the signal is output. The MCA sorts the pulses received from the TAC into different channels according to pulse height. The data stored in the MCA is a histogram of MPPC responses, and the time resolution is expressed as the full width at half maximum (FWHM) of this histogram.

[Figure 2-36] Connection example of time resolution measurement



[Figure 2-37] TTS (typical example)



Dynamic range

(1) Dynamic range for simultaneously incident photons

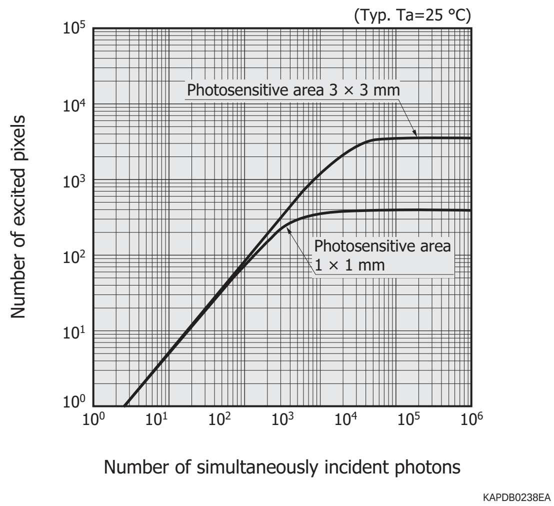
The dynamic range for simultaneously incident photons is determined by the number of pixels and photon detection efficiency of the MPPC. As the number of incident photons increases, two or more photons begin to enter one pixel. Even when two or more photons enter one pixel, each pixel can only detect whether or not the photons entered the MPPC. This means that the output linearity degrades as the number of incident photons increases.

$$N_{fired} = N_{total} \times \left\{1 - \exp\left(\frac{-N_{photon} \times PDE}{N_{total}}\right)\right\} \cdots\cdots (24)$$

Nfired : number of excited pixels
Ntotal : total number of pixels
Nphoton: number of incident photons
PDE : photon detection efficiency

Widening the dynamic range requires using an MPPC having a sufficiently large number of pixels compared to the number of simultaneously incident photons (namely, an MPPC with a large photosensitive area or a narrow pixel pitch).

[Figure 2-38] Dynamic range for simultaneously incident photons (pixel pitch: 50 μm)



(2) Dynamic range in photon counting

The number of MPPC excited pixels is given by equation (25).

$$N_{fired} = N_{photon} \times PDE \cdots\cdots\cdots (25)$$

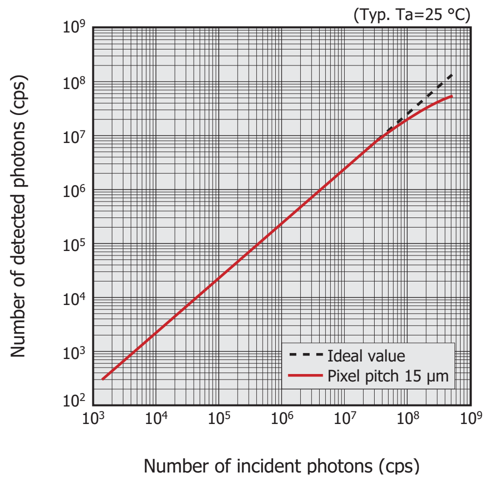
As the number of incident photons becomes larger, two or more output pulses overlap each other causing counting errors and degrading the output linearity. This linearity is determined by a parameter called the pulse-pair resolution. The pulse-pair resolution is determined by the MPPC recovery time (refer to “Recovery time” in section 2-5, “Measurement examples”) and the readout circuit characteristics. Equation (26) expresses the number of MPPC excited pixels that takes into account the pulse-pair resolution.

$$N_{fired} = \frac{N_{photon} \times PDE}{1 + N_{photon} \times PDE \times T_{resolution}} \quad \cdots\cdots\cdots (26)$$

Tresolution: pulse-pair resolution

To widen the dynamic range, an MPPC with a short recovery time should be selected.

[Figure 2-39] Dynamic range in photon counting (pixel pitch: 15 µm)



(3) Dynamic range in current measurement

The MPPC photocurrent (I_{MPPC}) is expressed by equation (27).

$$I_{MPPC} = N_{photon} \times PDE_{current} \times M \times q \quad \cdots\cdots\cdots (27)$$

PDEcurrent: PDE determined from photosensitivity
M : gain
q : electron charge

The number of incident photons is expressed by equation (28) using the incident light level (unit: W).

$$N_{photon} = \frac{\text{Incident light level} \times \lambda}{h \times c} \quad \cdots\cdots\cdots (28)$$

λ: wavelength [m]
h: Planck's constant
c: speed of light

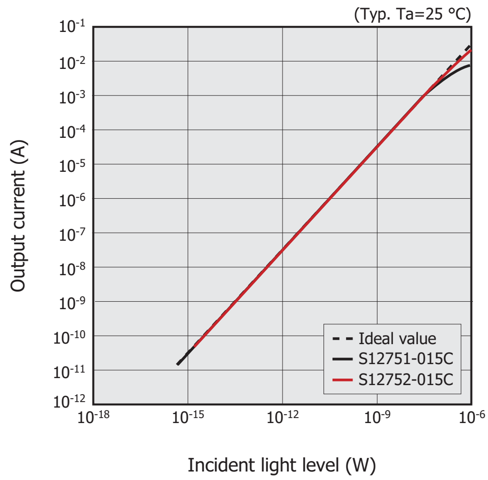
As the incident light level increases, two or more photons tend to enter one pixel, also the next photon tends to enter the same pixel within its recovery time. These actions degrades the linearity. Equation (29) expresses the MPPC output current I_{MPPC} while taking these actions into account.

$$I_{MPPC} = \frac{N_{photon} \times PDE_{current}}{1 + \dfrac{N_{photon} \times PDE_{current} \times T_R}{N_{total}}} \times M \times q \quad \cdots\cdots (29)$$

TR: recovery time [s]

When a large amount of light enters an MPPC, the output linearity may deteriorate because the MPPC element heats up and the gain lowers. A large output current then flows which might lower the reverse voltage applied to the MPPC depending on the value of the protective resistor used. So a protective resistor having the right value must be selected to prevent this problem.

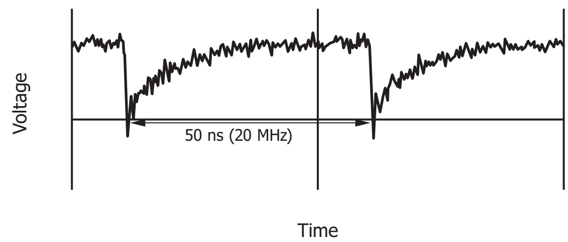
[Figure 2-40] Output current vs. incident light level (pixel pitch: 15 µm)



Recovery time

The time (recovery time) required for pixels to restore 100% of the gain depends on the photosensitive area and pixel size. In the case of the MPPC having a photosensitive area of 1 mm sq, the recovery time will be approximately 20 ns for 25 µm pixel pitch, 50 ns for 50 µm pixel pitch, and 100 to 200 ns for 100 µm pixel pitch. Figure 2-41 shows an output measured when light enters a pixel of the MPPC with a photosensitive area of 1 mm sq, and a pixel pitch of 50 µm, at a period equal to the pulse recovery time. It can be seen that the pulse is restored to a height equal to 100% of output.

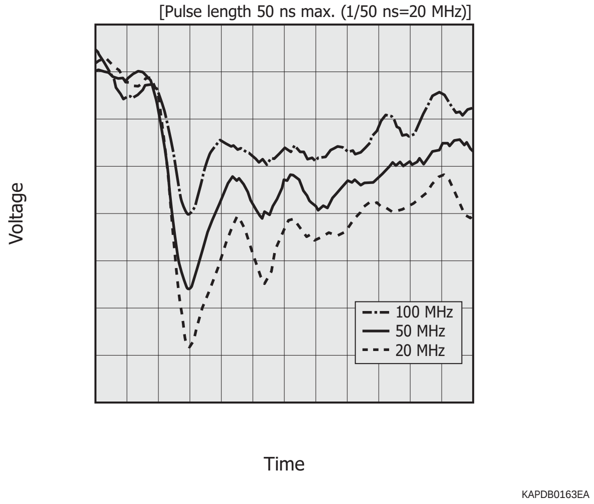
[Figure 2-41] Pulse level recovery (photosensitive area: 1 mm sq, pixel pitch: 50 µm)



If the next input pulse enters before the output pulse is completely restored, then a small pulse is output, which does not reach the gain set by the operating voltage. In Figure 2-41, the rising region of the pulse indicates the process for charging the pixel. When the next photon is detected before the pixel is fully charged, the output pulse will have an amplitude that varies according to the charged level.

Figure 2-42 shows output pulse shapes obtained when light at different frequencies was input to a pixel. It can be seen that as the frequency of the incident light increases, the pulse height decreases because the pixel is not fully charged.

[Figure 2-42] Output pulses obtained when light at different frequencies was input (photosensitive area: 1 mm sq, pixel pitch: 50 µm)



2 - 6 Selecting digital mode or analog mode

The readout mode (digital mode or analog mode) should be selected according to the light level incident on the MPPC.

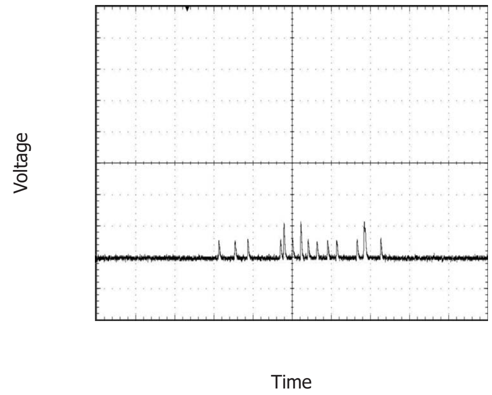
Figures 2-43 (a), (b), and (c) show the MPPC output waveforms measured at different incident light levels and observed on an oscilloscope. The incident light level was increased in the order of (a), (b), and (c), starting from (a) at very low light levels. The output signal of (a) as seen here consists of discrete pulses. In this state, selecting the digital mode allows measuring at a higher S/N, where the signals are binarized and the number of pulses is digitally counted. Since the digital mode can subtract the dark count from the signal, the detection limit is determined by dark count fluctuations.

As the light level increases, the output waveform consists of pulses overlapping each other [(b), (c)]. In this state, the number of pulses cannot be counted and the analog mode should be selected to measure the analog output and find the average value. The detection limit in the analog mode is determined by the dark current shot noise and the cutoff frequency of the readout circuit.

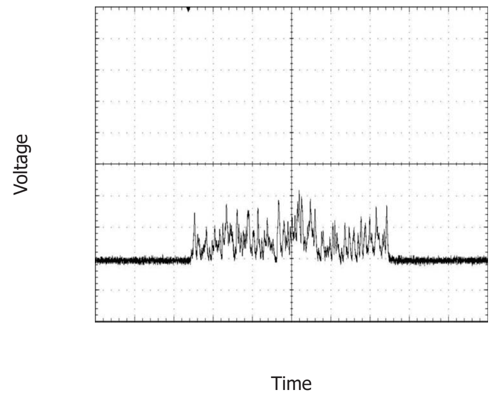
Figure 2-44 shows the incident light levels suitable for the digital mode and analog mode (MPPC photosensitive area: 3 × 3 mm, pixel pitch: 50 µm).

[Figure 2-43] Output waveforms

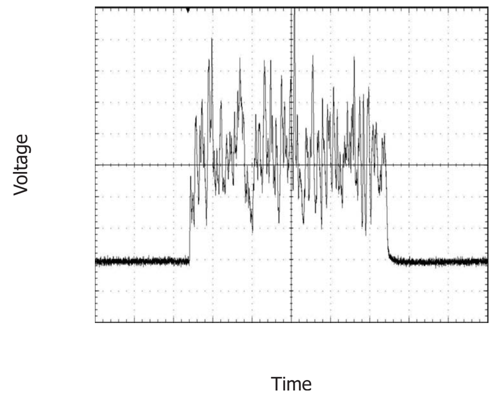
(a) Light level is low (very low light level)



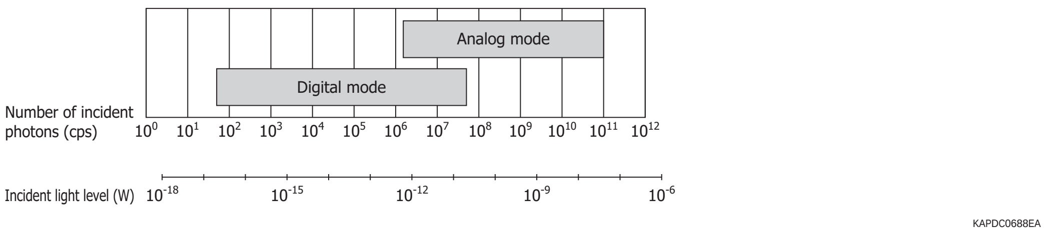
(b) Light level is moderate



(c) Light level is high



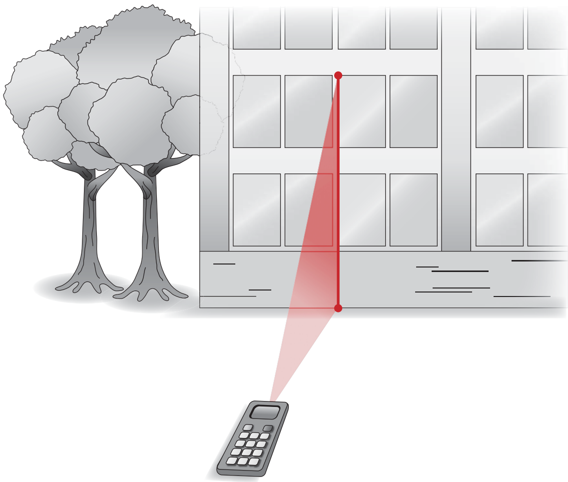
[Figure 2-44] Incident light levels suitable for the digital mode and analog mode (photosensitive area: 3 × 3 mm, pixel pitch: 50 µm)



3. Applications

3 - 1 Optical rangefinders

The distance to an object can be determined by directing laser light onto an object and then the APD measuring the time required for the reflected light to return or the phase difference of the light.



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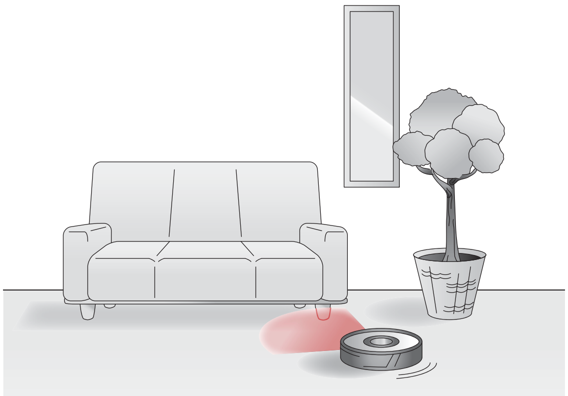
3 - 2 Obstacle detection

The APD can be used in unmanned robots and the like to detect obstacles. It can also be used to detect movement of people in a particular area.



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3 - 3 LIDAR (light detection and ranging)

The condition of the earth's surface, particles in the air, and cloud can be measured by directing laser onto an object and then the APD detecting the reflected or scattered light.

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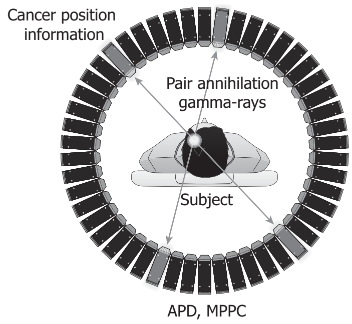
3 - 4 Scintillation measurement

APDs or MPPCs arranged around 360° detect pair annihilation gamma-rays to capture the target position such as cancer tissue. APDs and MPPCs can be used with MRI because they are not affected by magnetic fields.



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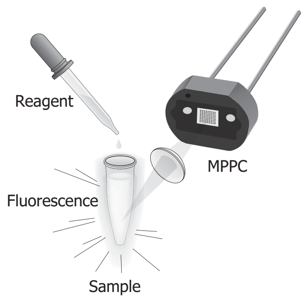
3 - 5 Fluorescence measurement

The MPPC can detect minute fluorescence emission of reagents.



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3 - 6 High energy physics experiment

The MPPC is a promising candidate for high-energy accelerator experiments to discover the ultimate constituents of matter. The European Organization for Nuclear Research (called CERN) is presently assessing the MPPC for use in calorimeter units needed to detect particle energy in its next-generation International Linear Collider (ILC). Moreover, in Japan, the High Energy Accelerator Research Organization (KEK) and the Japan Atomic Energy Agency (JAEA) are conducting a joint experiment at the Japan Proton Accelerator Research Complex (called J-PARC) being built in Tokai-mura (Ibaraki Prefecture). This experiment called "T2K" (Tokai to Kamioka) will verify whether or not the neutrino has mass, by sending neutrino beams to Super-Kamiokande (Gifu Prefecture, about 300 km away from Tokai-mura). A large number of MPPCs (62000 pieces) are used in monitoring the neutrino beams in this experiment.

■ Reference

1) K. Sato, K. Yamamoto, K. Yamamura, S. Kamakura, S. Ohsuka et al., Application Oriented Development of Multi-Pixel Photon Counter (MPPC), 2010 IEEE Nuclear Science Symposium Conference Record (2010)

2) Patrick Eckert, Hans-Christian Schultz-Coulon, Wei Shen, Rainer Stamen, Alexander Tadday et al., Characterisation Studies of Silicon Photomultipliers, http://arxiv.org/abs/1003.6071v2

3) T. Nagano, K. Yamamoto, K. Sato, N. Hosokawa, A. Ishida, T. Baba et al., Improvement of Multi-Pixel Photon Counter (MPPC), 2011 IEEE Nuclear Science Symposium Conference Record (2011)