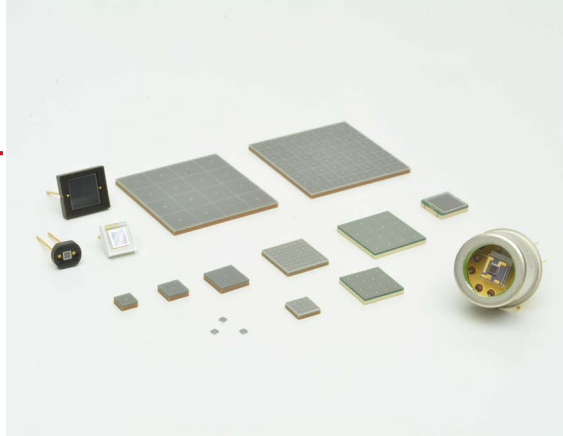


MPPC®



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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) 2)}

1. Operating principle

1 - 1 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.

1 - 2 Geiger mode and quenching resistor

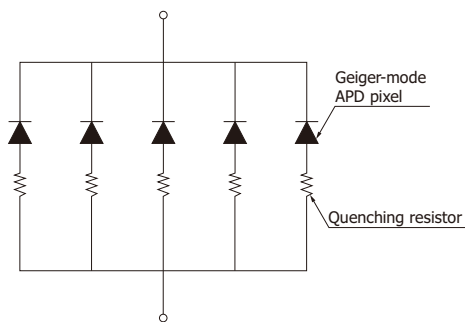
When the reverse voltage applied to an APD is set higher than the breakdown voltage, saturation output (Geiger discharge) specific to the element is produced regardless of the input light level. The condition where an APD operates at this voltage level is called Geiger mode. The Geiger mode allows obtaining 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 must be provided in the APD to 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, when the output current due to Geiger discharge flows through the quenching resistor, a voltage drop occurs and the operating voltage of the APD connected in series drops. 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 1-4].

1 - 3 Structure

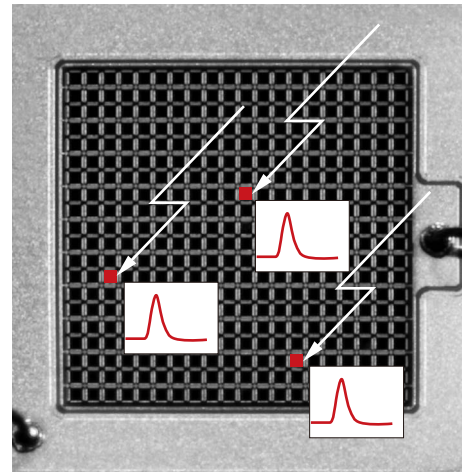
Figure 1-1 shows a structure of an MPPC. The basic element (one pixel) of an MPPC is a combination of the Geiger mode APD and quenching resistor, and a large number of these pixels are electrically connected and arranged in two dimensions.

[Figure 1-1] Structure



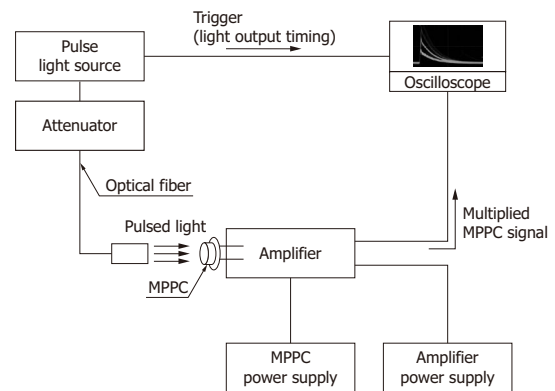
KAPDC0029EA

[Figure 1-2] Image of MPPC's photon counting



KAPDC0049EA

[Figure 1-3] Block diagram for MPPC evaluation (with an oscilloscope)



KAPDC0028EB

1 - 4 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 if the number of photons incident on the MPPC increases and two or more photons are incident on one pixel, the linearity of the MPPC output relative to the number of incident photons is degraded. This makes it essential to select an MPPC having enough pixels to match the number of incident photons.

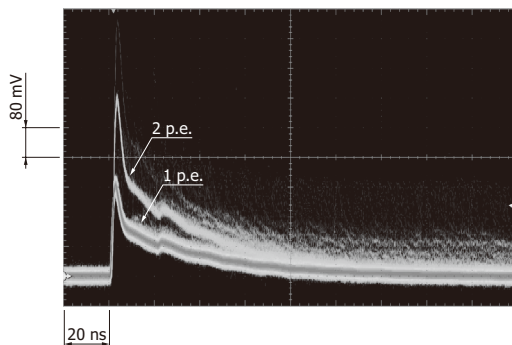
The following two methods are used to estimate the number of photons detected by the MPPC.

- 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 1-4 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 and so on. Measuring the height of each pulse allows estimating the number of detected photons.

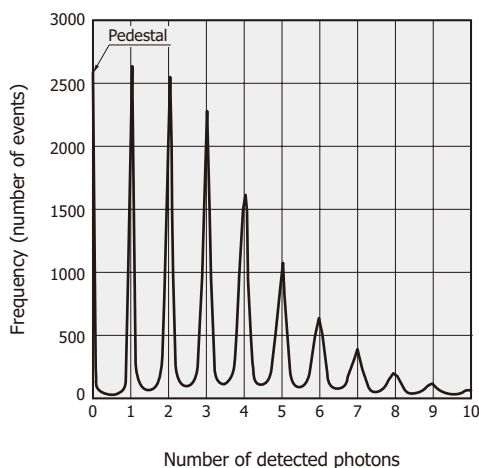
[Figure 1-4] Pulse waveforms when using a linear amplifier
(photosensitive area: 3 mm sq, pixel pitch: 50 μm)



(2) Measuring 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 1-5 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. MPPC has a large output charge due to its high gain, and shows a discrete distribution according to the number of detected photons.

[Figure 1-5] Pulse height spectrum when using charge amplifier
(pixel pitch: 50 μm)

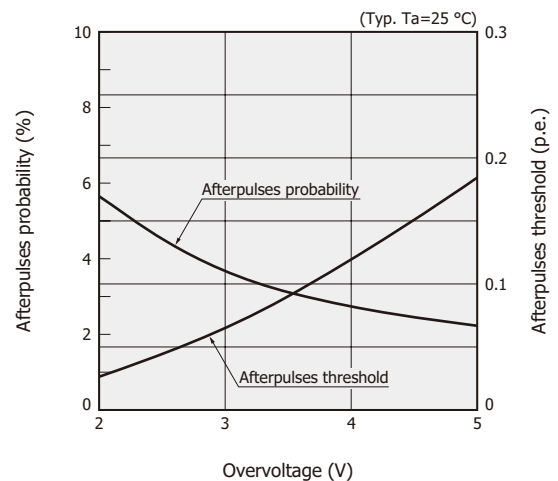


2. Features

2 - 1 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 2-1] Afterpulses vs. overvoltage
(photosensitive area: 3 mm sq, pixel pitch: 50 μm)



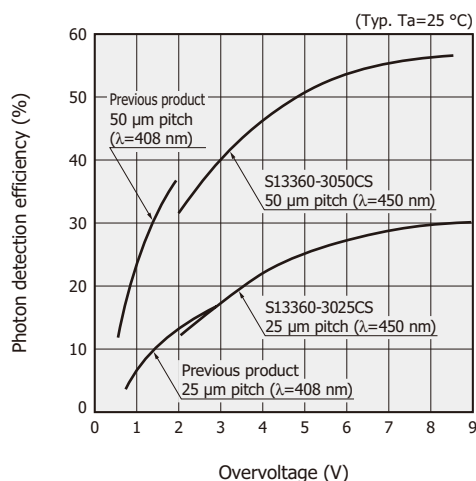
KAPDB0256EB

2 - 2 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.

KAPDB0133EB

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



Photon detection efficiency does not include crosstalk and afterpulses.

KAPD080217EC

[Table 2-1] Recommended overvoltage

Pixel pitch (μm)	Recommended overvoltage (V)		
	Previous products S12571/S12572/ S12576 series	S13360 series	S14160 series
10	4.5	-	5
15	4	-	4
25	3.5	5	-
50	2.6	3	-
75	-	3	-

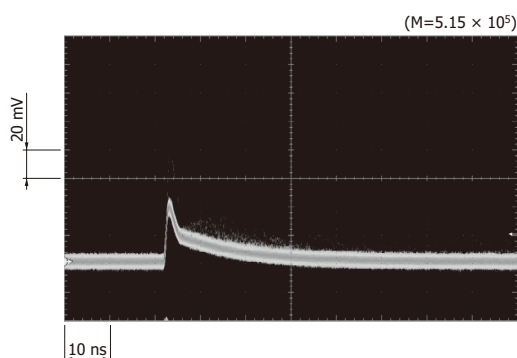
$$V_{ov} = V_{op} - V_{BR} \dots\dots\dots (2-1)$$

V_{ov} : overvoltage
 V_{op} : operating voltage
 V_{BR} : breakdown voltage

2 - 3 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 2-3] Pulse waveform
(S14160-1310PS, pixel pitch: 10 μm)

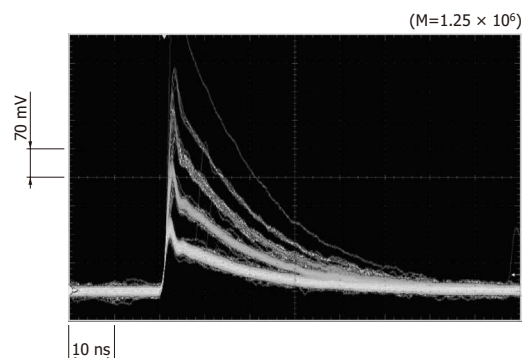


2 - 4 Low crosstalk

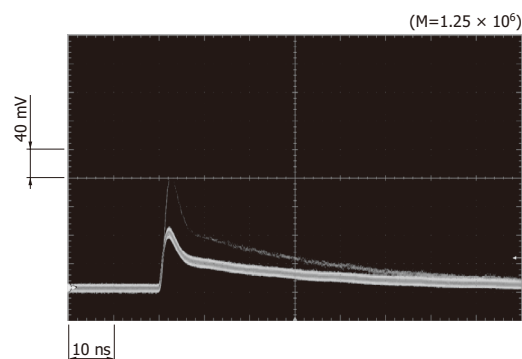
The pixel that detects photons may affect other pixels, making them produce pulses other than output pulses. This phenomenon is called crosstalk. Hamamatsu has drastically reduced the crosstalk in precision measurement MPPC by creating barriers between pixels.

[Figure 2-4] Pulse waveforms

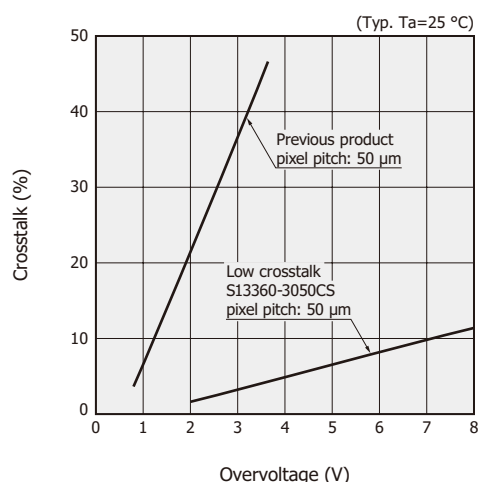
(a) General measurement type S12571-050C (pixel pitch: 50 μm)



(b) Low crosstalk type S13360-3050CS (pixel pitch: 50 μm)



[Figure 2-5] Crosstalk vs. overvoltage



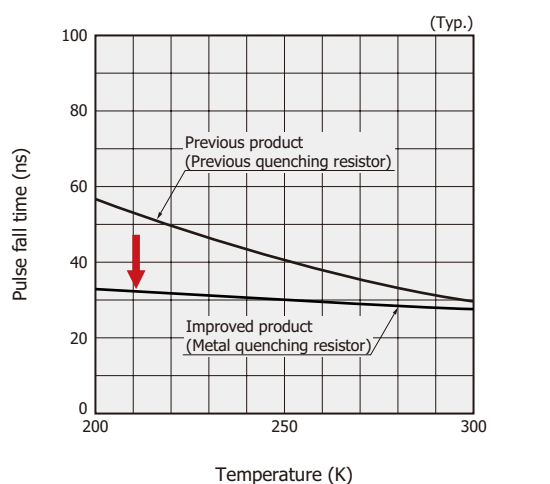
KAPD0613EA

2 - 5 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 2-6] Pulse fall time vs. temperature
(photosensitive area: 1 mm sq, pixel pitch: 50 μm)



3. Characteristics

3 - 1 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 [Table 3-1]. 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 [Table 3-2]. The MPPC characteristics vary with the operating voltage [Table 3-3]. 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 3-1] MPPC characteristics versus pixel size

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

[Table 3-2] MPPC characteristics versus photosensitive area

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

[Table 3-3] MPPC characteristics versus operating voltage

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

3 - 2 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).

$$M = \frac{Q}{q} \dots\dots\dots (3-1)$$

M: gain

The charge Q depends on the reverse voltage (V_R) and breakdown voltage (V_{BR}) and is expressed by equation (3-2).

$$Q = C \times (V_R - V_{BR}) \dots\dots\dots (3-2)$$

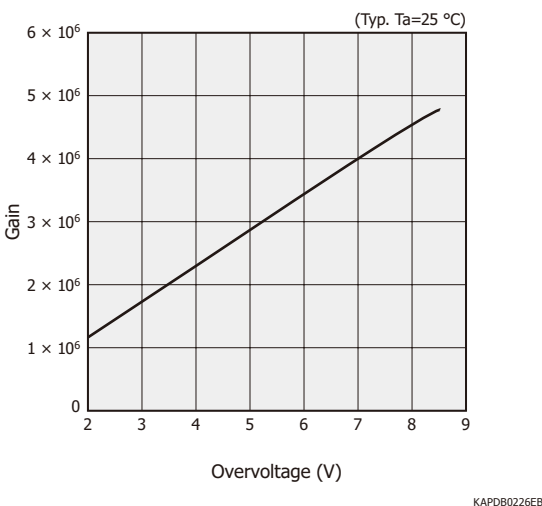
C: capacitance of one pixel

Equations (3-1) and (3-2) 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 3-1 shows a typical example.

[Figure 3-1] Gain vs. overvoltage (pixel pitch: 50 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 3-2 shows the reverse voltage adjustment needed to keep the gain constant when the ambient temperature varies.

[Figure 3-2] Reverse voltage vs. ambient temperature (photosensitive area: 3 mm sq, pixel pitch: 50 μm)

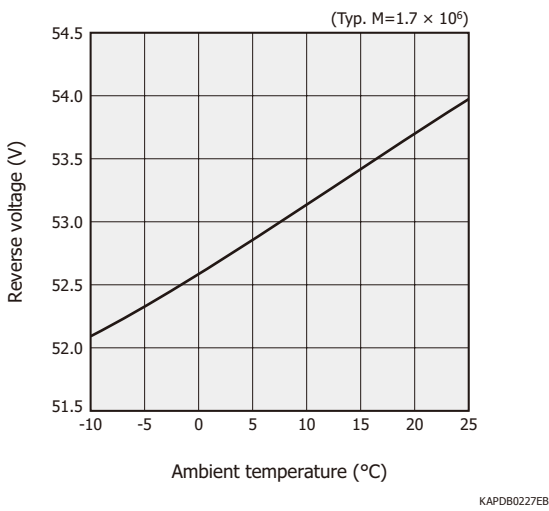
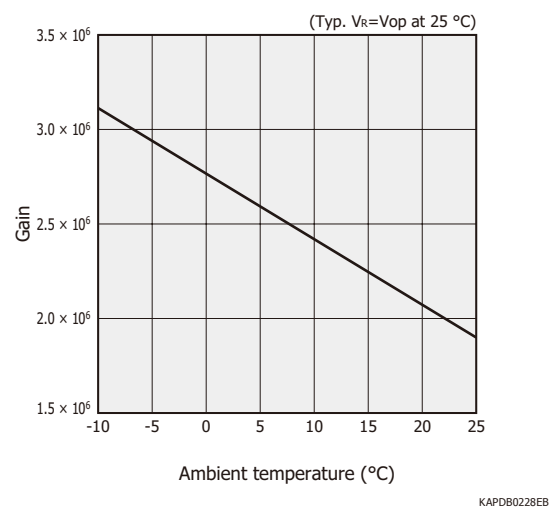


Figure 3-3 shows the relation between gain and ambient temperature when the reverse voltage is a fixed value.

[Figure 3-3] Gain vs. ambient temperature (photosensitive area: 3 mm sq, pixel pitch: 50 μm)

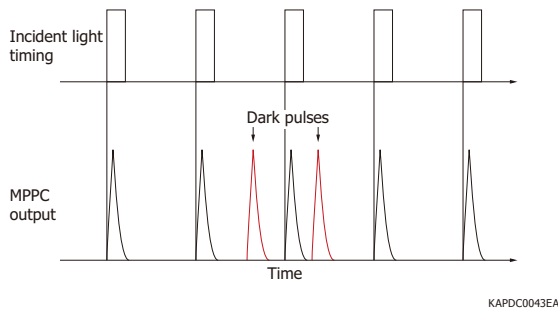


3 - 3 Dark count rate

(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 3-4].

[Figure 3-4] 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 $N_{0.5 \text{ p.e.}}$.

(2) Temperature characteristics

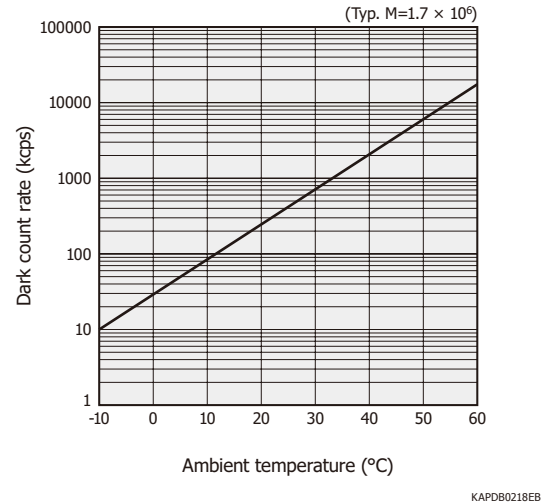
Since dark pulses are produced by thermally-generated carriers, the dark count rate varies with the ambient temperature. The dark count rate is given by equation (3-3) within the operating temperature range.

$$N_{0.5 \text{ p.e.}}(T) \approx AT^{\frac{3}{2}} \exp\left[\frac{-E_g}{2kT}\right] \dots\dots\dots (3-3)$$

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

Figure 3-5 shows a relation between the dark count rate and the ambient temperature when the gain is set to a constant value.

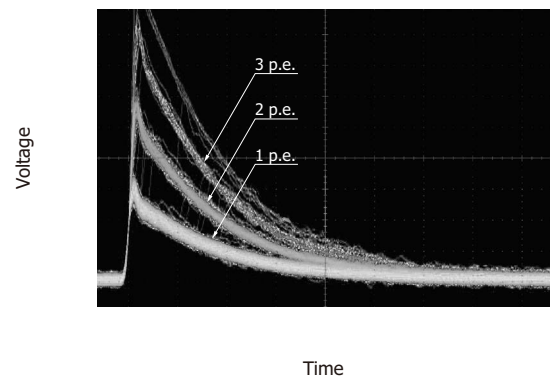
[Figure 3-5] Dark count rate vs. ambient temperature
(photosensitive area: 3 mm sq, pixel pitch: 50 μm)



3 - 4 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 3-6] Crosstalk observation example

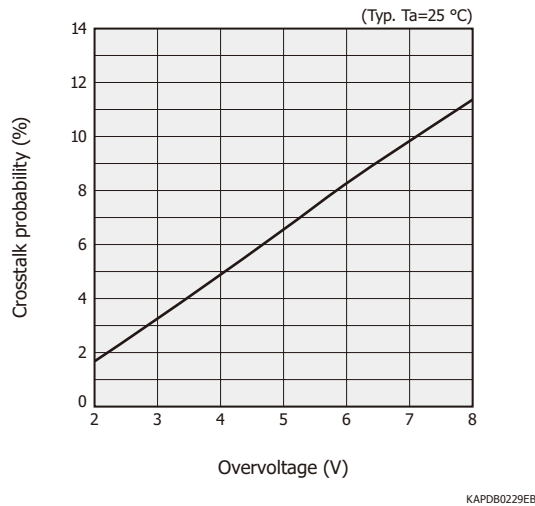


We define the crosstalk probability ($P_{\text{crosstalk}}$) as equation (3-4).

$$P_{\text{crosstalk}} = \frac{N_{1.5 \text{ p.e.}}}{N_{0.5 \text{ p.e.}}} \dots\dots\dots (3-4)$$

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 overvoltage is increased [Figure 3-7].

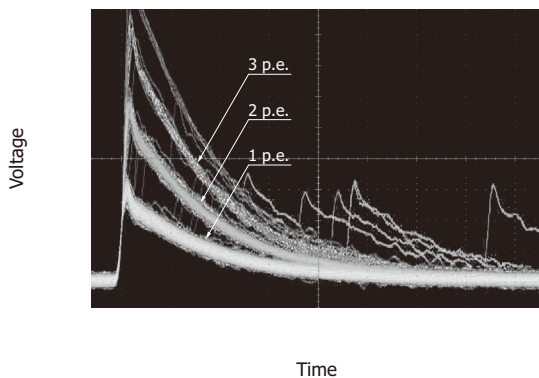
[Figure 3-7] Crosstalk probability vs. overvoltage
(pixel pitch: 50 μm)



3 - 5 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 3-8] Afterpulse observation example



3 - 6 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 (3-5).

$$I_D = I_s + I_j + I_b \quad \text{..... (3-5)}$$

I_s : surface leakage current
 I_j : recombination current
 I_b : bulk current

When the MPPC is operated in Geiger mode, the bulk current is expressed by equation (3-6), assuming that the number of pixels in which avalanche multiplication occurs per unit time is N_{fired} .

$$I_b = q M N_{\text{fired}} \quad \text{..... (3-6)}$$

q : electron charge
 M : gain

Since the MPPC gain is usually 10^5 to 10^6 , the bulk current I_b is dominant in equation (3-5) and equation (3-6) can then be approximated to equation (3-7).

$$I_D \approx I_b = q M N_{\text{fired}} \quad \text{..... (3-7)}$$

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 (3-8) using $N_{0.5 \text{ p.e.}}$ and $P_{\text{crosstalk}}$. 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.

$$I_D \approx q M N_{0.5 \text{ p.e.}} \frac{1}{1 - P_{\text{crosstalk}}} \quad \text{..... (3-8)}$$

3 - 7 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 (3-9).

$$S = \frac{I_{MPPC}}{\text{Incident light level}} \dots\dots\dots (3-9)$$

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 (3-10).

$$PDE = \frac{\text{Number of detected photons}}{\text{Number of incident photons}} \dots\dots\dots (3-10)$$

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

$$PDE = Fg \times QE \times Pa \dots\dots\dots (3-11)$$

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

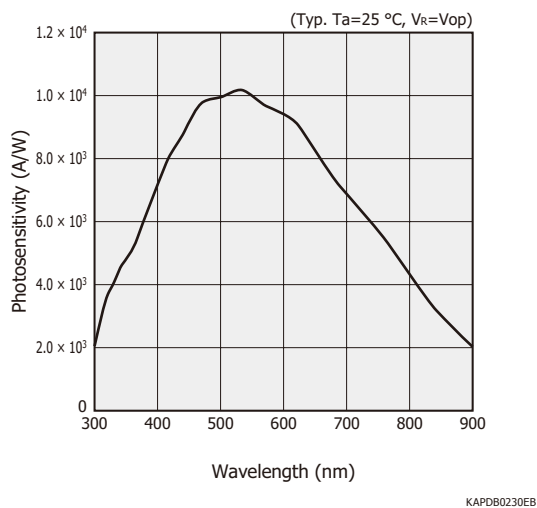
The PDEcurrent, which is determined from photosensitivity, is expressed by equation (3-12).

$$PDE_{\text{current}} = \frac{1240}{\lambda} \times \frac{S}{M} \dots\dots\dots (3-12)$$

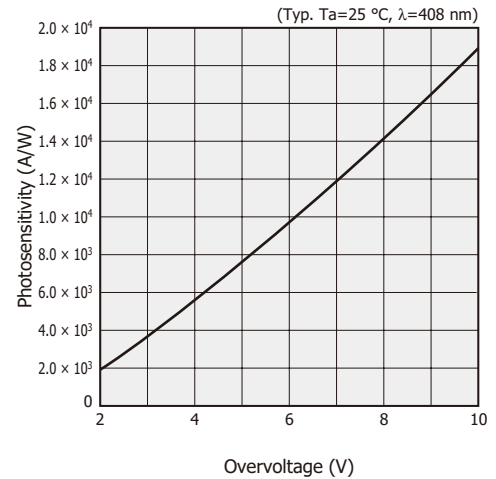
λ : incident light wavelength [nm]

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

[Figure 3-9] Spectral response (pixel pitch: 25 μm)

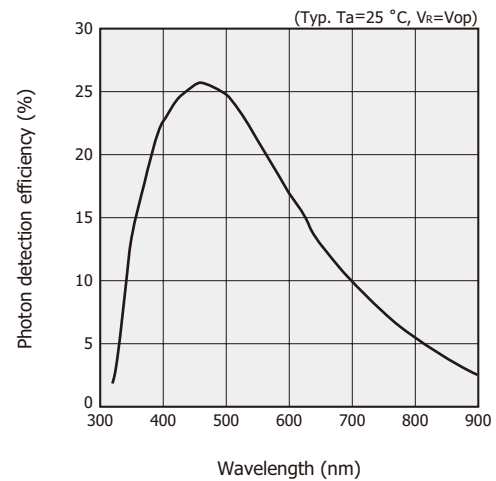


[Figure 3-10] Photosensitivity vs. overvoltage (pixel pitch: 25 μm)



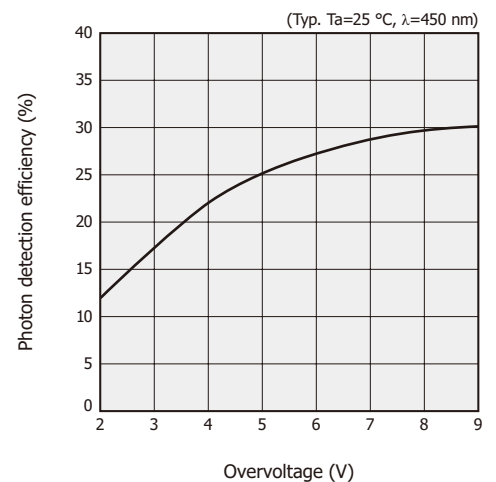
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[Figure 3-11] Photon detection efficiency vs. wavelength (pixel pitch: 25 μm)



KAPD80259EB

[Figure 3-12] Photon detection efficiency vs. overvoltage (pixel pitch: 25 μm)

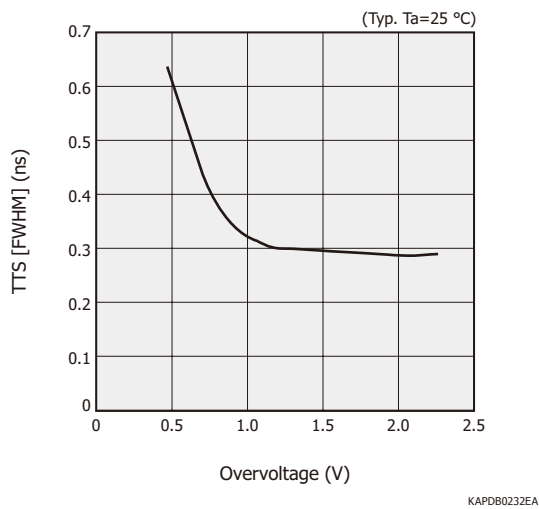


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3 - 8 Time resolution

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 3-13] TTS vs. overvoltage
(photosensitive area: 1 mm sq, pixel pitch: 50 μ m)



4. Measurement examples

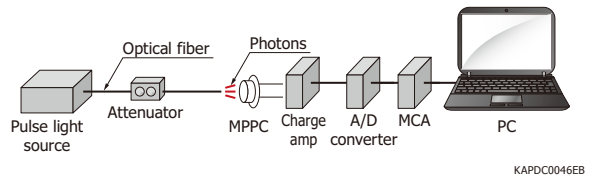
Examples of measuring MPPC characteristics are described below.

4 - 1 Gain

(1) Measurement using a charge amplifier

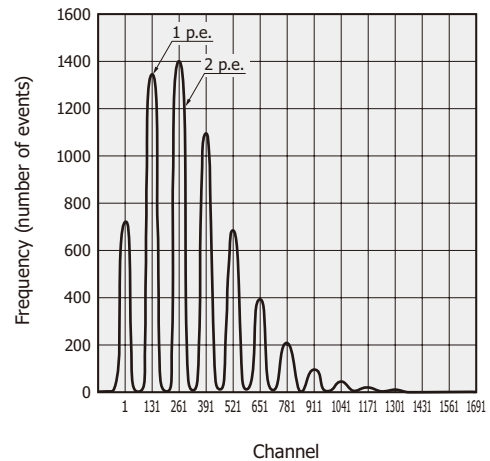
The gain can be estimated from the output charge of the MPPC that detected photons. Figure 4-1 shows a connection setup example for the gain measurement using a charge amplifier.

[Figure 4-1] 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 4-2 is obtained.

[Figure 4-2] Frequency distribution example of output charge



In Figure 4-2, 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 (4-1).

$$M = \frac{\text{Charge difference between adjacent peaks}}{q} \dots\dots\dots (4-1)$$

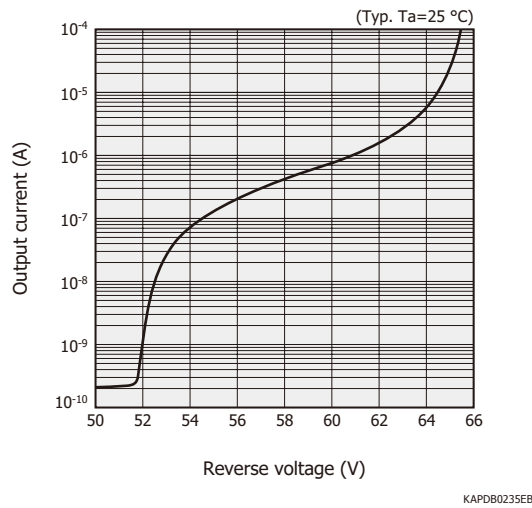
q: electron charge

Furthermore, equation (4-1) can be used to create and extrapolate a gain vs. reverse voltage graph to determine the reverse voltage for gain of 1, or namely the breakdown voltage V_{BR} .

(2) Measurement by dI/dV method

Figure 4-3 shows the output current vs. reverse voltage characteristics of the MPPC. If the voltage of V_{peak} maximizes the value to the function [equation (4-2)] obtained by differentiating the output current by the reverse voltage, $V_{peak} - V_{BR}$ is approximately constant for each type no., but the individual values V_{peak} and V_{BR} are different between elements even with the same type no. By determining $V_{peak} - V_{BR}$ for a given type no. in advance, you will be able to estimate V_{BR} for a particular element by measuring V_{peak} .

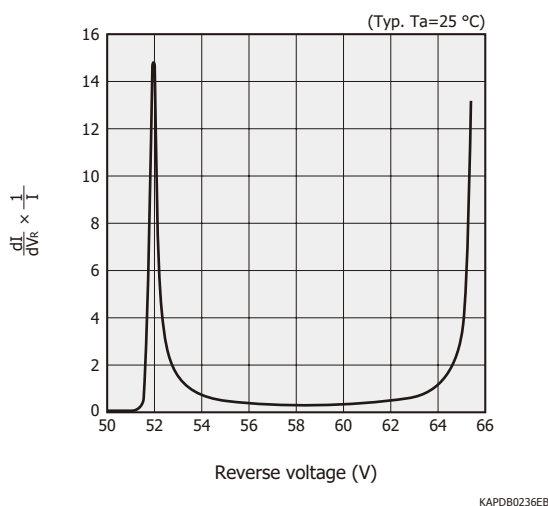
[Figure 4-3] Output current vs. reverse voltage (S13360-3050CS, photosensitive area: 3 mm sq, pixel pitch: 50 μ m)



$$\frac{d}{dV_R} \log(I) = \frac{dI}{dV_R} \times \frac{1}{I} \quad \dots\dots\dots (4-2)$$

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

[Figure 4-4] Reverse voltage characteristics of $\frac{dI}{dV_R} \times \frac{1}{I}$



The gain (M) is given by equation (4-3).

$$M = \frac{C \times (V_R - V_{BR})}{q} \quad \dots\dots\dots (4-3)$$

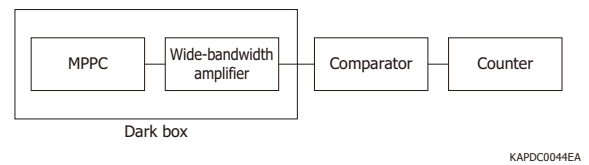
C : pixel capacitance [F]
 V_{BR} : breakdown voltage [V]
 q : electron charge [C]

Since the pixel capacitance is constant, the gain can be obtained from the breakdown voltage obtained by dI/dV method and reverse voltage. 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.

4 - 2 Dark count rate

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 4-5] Block diagram of dark count rate measurement

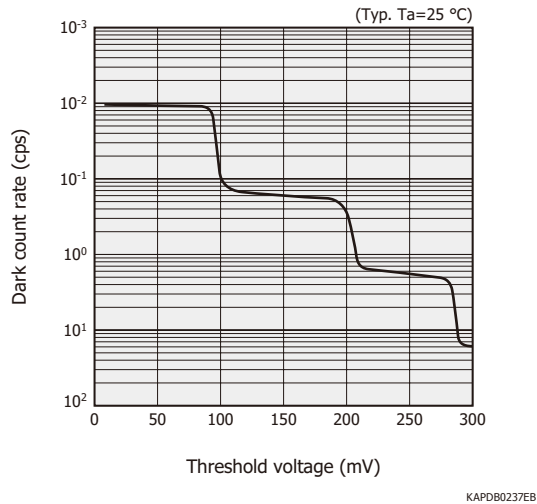


4 - 3 Crosstalk

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 $N_{0.5 \text{ p.e.}}$ and $N_{1.5 \text{ p.e.}}$ at each threshold can be measured. The crosstalk probability ($P_{\text{crosstalk}}$) is calculated by equation (3-4).

If the threshold is swept, the dark count rate will be plotted as shown in Figure 4-6. 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 $N_{0.5 \text{ p.e.}}$, $N_{1.5 \text{ p.e.}}$, $N_{2.5 \text{ p.e.}}$ and so on can be obtained from this graph.

[Figure 4-6] Dark count rate vs. threshold voltage



4 - 4 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 (4-4).

$$\Delta t_{\text{dark}} \propto \exp\left(-\frac{\Delta t}{\tau_{\text{dark}}}\right) \dots\dots\dots (4-4)$$

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 (4-5).

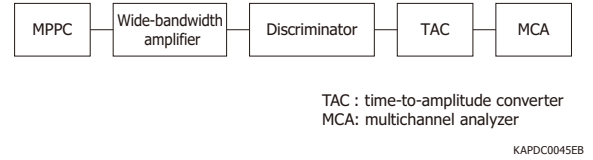
$$\Delta t_{\text{AP}} \propto \sum_k A_k \times \exp\left(-\frac{\Delta t}{\tau_k}\right) \dots\dots\dots (4-5)$$

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 ($\tau_{\text{dark}} \gg \tau_k$), 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 output signals obtained by photon incidence to the MPPC are multiplied 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 4-7] Connection example of afterpulse measurement



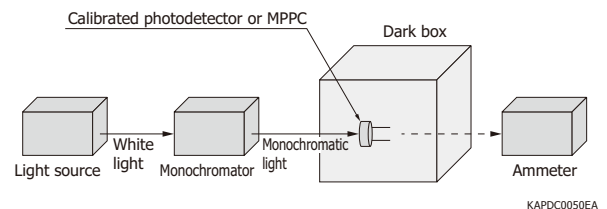
4 - 5 Photosensitivity

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 (4-6).

$$S = \frac{I_{\text{MPPC}}}{\text{Incident light level}} \dots\dots\dots (4-6)$$

I_{MPPC} : photocurrent [A]

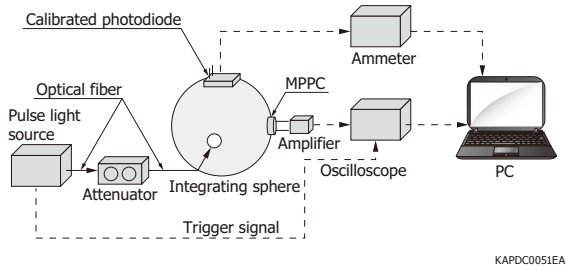
[Figure 4-8] Connection example of photosensitivity measurement



4 - 6 Photon detection efficiency

To measure the photon detection efficiency of an MPPC, a pulsed light source is used as shown in Figure 4-9. 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.³⁾

[Figure 4-9] Connection example of photon detection efficiency measurement



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 4-2. 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 (4-7).

$$P(n, x) = \frac{n^x e^{-n}}{x!} \quad \text{..... (4-7)}$$

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

If $x=0$ in equation (4-7), then the Poisson distribution is expressed by equation (4-8).

$$P(n, 0) = e^{-n} \quad \text{..... (4-8)}$$

The left side of equation (4-8) is expressed by equation (4-9) when the correction of dark pulses is included.

$$P(n, 0) = \frac{\left(\frac{N_{ped}}{N_{tot}}\right)}{\left(\frac{N_{ped}^{dark}}{N_{tot}^{dark}}\right)} \quad \text{..... (4-9)}$$

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 (4-10). Photon detection

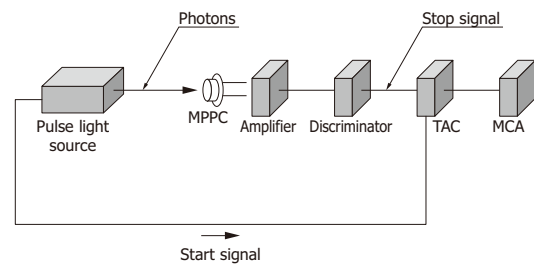
efficiency can then be found by dividing n by the number of incident photons.

$$n = -\ln \left(\frac{N_{ped}}{N_{tot}} \right) = -\ln \left(\frac{N_{ped}}{N_{tot}} \right) + \ln \left(\frac{N_{ped}^{dark}}{N_{tot}^{dark}} \right) \quad \text{..... (4-10)}$$

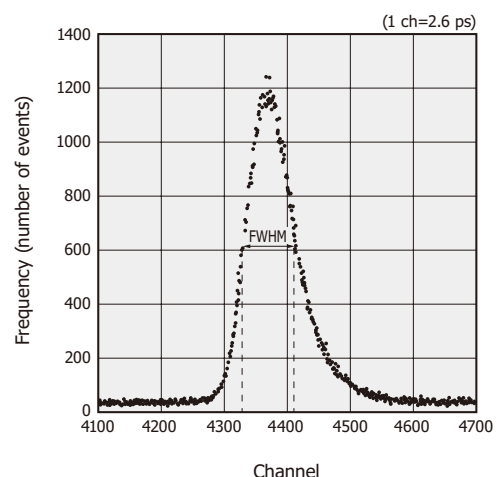
4 - 7 Time resolution

Figure 4-10 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 4-10] Connection example of time resolution measurement



[Figure 4-11] TTS (typical example)



4 - 8 Dynamic range

(1) Dynamic range for simultaneously incident photons

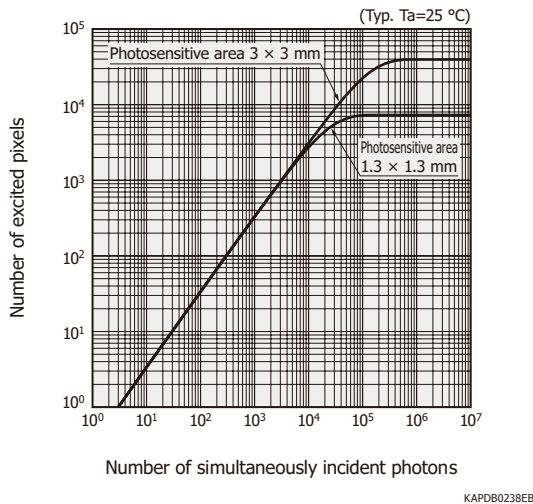
The dynamic range for simultaneously incident photons is determined by the number of pixels and photon detection efficiency of the MPPC. As the number of incident photons increases, two or more photons begin to enter one pixel. Even when two or more photons enter one pixel, each pixel can only detect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

$$N_{\text{fired}} = N_{\text{total}} \times \left\{ 1 - \exp\left(\frac{-N_{\text{photon}} \times \text{PDE}}{N_{\text{total}}}\right) \right\} \dots (4-11)$$

N_{fired} : number of excited pixels
 N_{total} : total number of pixels
 N_{photon} : 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 4-12] 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 (4-12).

$$N_{\text{fired}} = N_{\text{photon}} \times \text{PDE} \dots (4-12)$$

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 “4-9 Recovery time”)

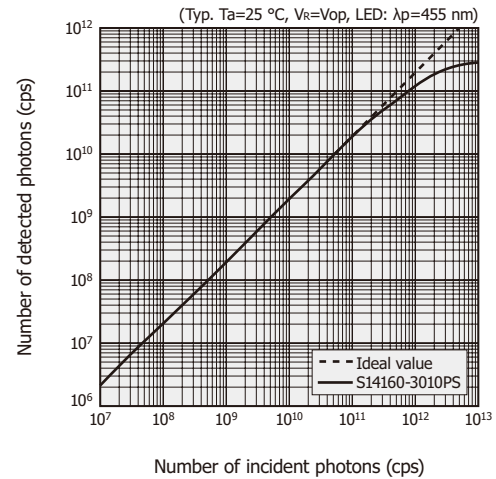
and the readout circuit characteristics. Equation (4-13) expresses the number of MPPC excited pixels that takes into account the pulse-pair resolution.

$$N_{\text{fired}} = \frac{N_{\text{photon}} \times \text{PDE}}{1 + N_{\text{photon}} \times \text{PDE} \times T_{\text{resolution}}} \dots (4-13)$$

$T_{\text{resolution}}$: pulse-pair resolution

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

[Figure 4-13] Dynamic range in photon counting (S14160-3010PS, photosensitive area: 3 mm sq, pixel pitch: 10 μm)



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(3) Dynamic range in current measurement

The MPPC photocurrent (I_{MPPC}) is expressed by equation (4-14).

$$I_{\text{MPPC}} = N_{\text{photon}} \times \text{PDE}_{\text{current}} \times M \times q \dots (4-14)$$

$\text{PDE}_{\text{current}}$: PDE determined from photosensitivity
 M : gain
 q : electron charge

The number of incident photons is expressed by equation (4-15) using the incident light level (unit: W).

$$N_{\text{photon}} = \frac{\text{Incident light level} \times \lambda}{h \times c} \dots (4-15)$$

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

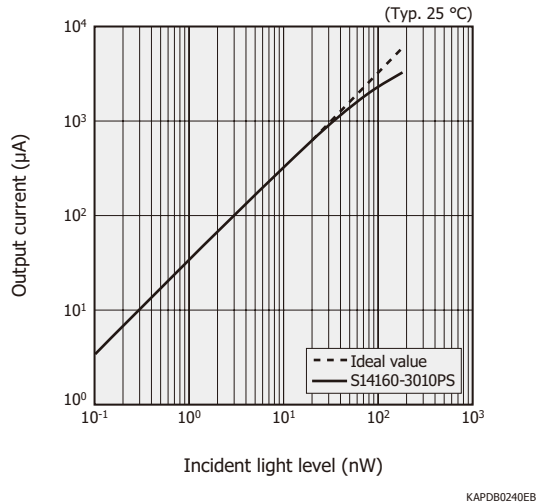
As the incident light level increases, two or more photons tend to enter one pixel, also the next photon tends to enter the same pixel within its recovery time. These actions degrades the linearity. Equation (4-16) expresses the MPPC output current I_{MPPC} while taking these actions into account.

$$I_{\text{MPPC}} = \frac{N_{\text{photon}} \times \text{PDE}_{\text{current}}}{1 + \frac{N_{\text{photon}} \times \text{PDE}_{\text{current}} \times T_{\text{r}}}{N_{\text{total}}}} \times M \times q \dots (4-16)$$

T_{r} : recovery time [s]

When a large amount of light is incident, the element generates heat and the gain lowers, which may cause the linearity to deteriorate. Since a large amount of output current flows, the reverse voltage applied to the MPPC may decrease depending on the protective resistor used. So a protective resistor having the right value must be selected to prevent this problem.

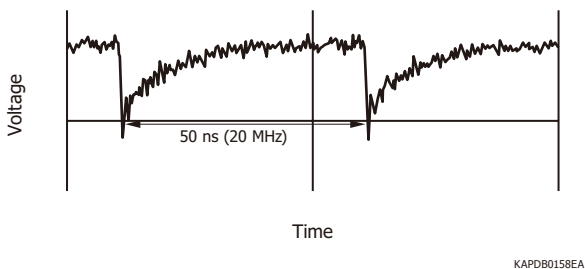
[Figure 4-14] Output current vs. incident light level (S14160-3010PS, photosensitive area: 3 mm sq, pixel pitch: 10 μ m)



4 - 9 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 μ m pixel pitch, 50 ns for 50 μ m pixel pitch, and 100 to 200 ns for 100 μ m pixel pitch. Figure 4-15 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 μ m, 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 4-15] Pulse level recovery (photosensitive area: 1 mm sq, pixel pitch: 50 μ m)

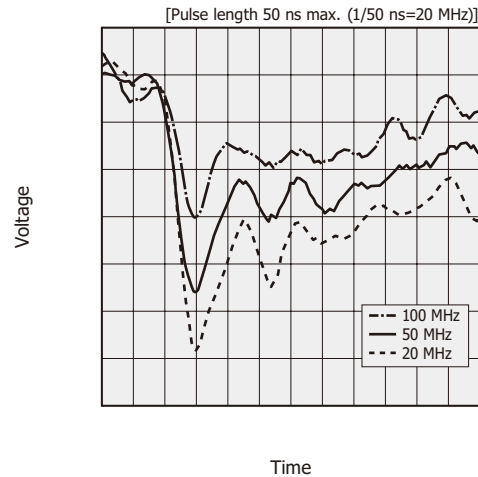


If the next input pulse enters before the output pulse is completely restored, then a small pulse is output, which does not reach the gain set by the operating voltage. In Figure 4-15, the rising region of the pulse indicates the process for charging the pixel. When

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 4-16 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 4-16] Output pulses obtained when light at different frequencies was input (photosensitive area: 1 mm sq, pixel pitch: 50 μ m, typical example)



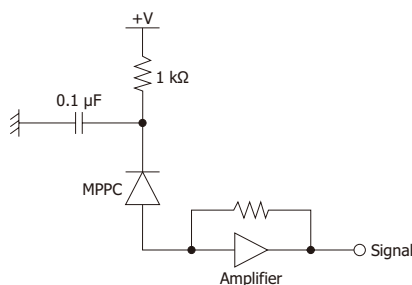
5. How to use

5 - 1 Connection example

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 5-1 shows one example of a connection to a wide-band amplifier. The 1 k Ω resistor and 0.1 μ F capacitor on the power supply portion serve as a low-pass filter that eliminates high-frequency noise of the power supply. The 1 k Ω 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 5-1] Connection example



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.

5 - 2 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.

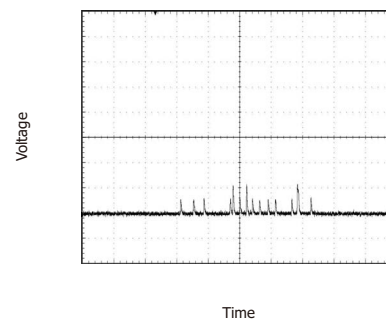
Figures 5-2 (a), (b), and (c) show the MPPC output waveforms measured at different incident light levels and observed on an oscilloscope. The incident light level was increased in the order of (a), (b), and (c), starting from (a) at very low light levels. The output signal of (a) as seen here consists 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.

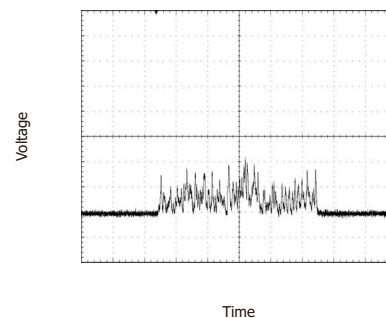
Figure 5-3 shows the incident light levels suitable for the digital mode and analog mode (MPPC photosensitive area: 3 mm sq, pixel pitch: 50 μ m).

[Figure 5-2] Output waveforms

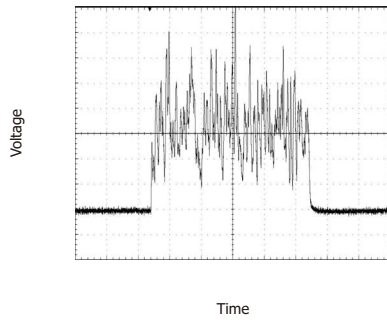
(a) Light level is low (very low light level)



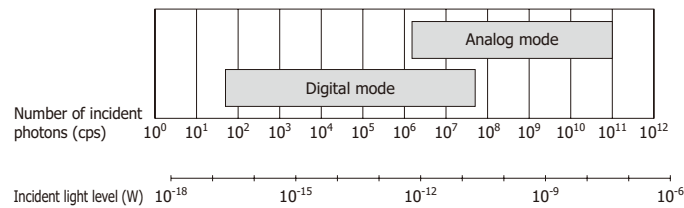
(b) Light level is moderate



(c) Light level is high



[Figure 5-3] Incident light levels suitable for the digital mode and analog mode (photosensitive area: 3 mm sq, pixel pitch: 50 μ m)



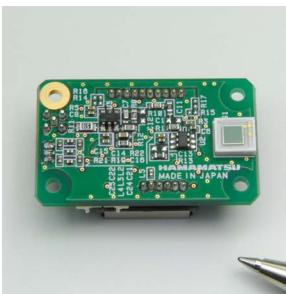
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5 - 3 MPPC module

The MPPC modules are low-light-level detection modules with a built-in MPPC. We have a lineup that can measure a wide range of light levels, from photon counting level to nW (nanowatt) level. They come equipped with an amplifier and a high-voltage power supply circuit required for MPPC operation, so measurement can be performed by simply providing a power supply (± 5 V, etc.). We offer an analog output type non-cooled model equipped with a temperature compensation function, which enables stable measurement for applications with a relatively high incident light level. Also, our options include a digital output type TE-cooled model that realizes a low dark count for photon counting. We also support customization according to requested specifications. For details, refer to “MPPC modules” technical note.

[Figure 5-4] MPPC modules

(a) Analog output type
Non-cooled type C13365 series



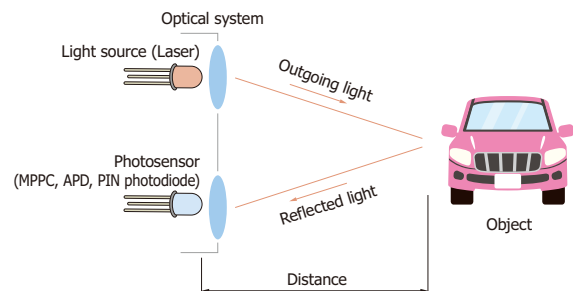
(b) Digital output type
TE-cooled type C13366-GD series



6. Applications

6 - 1 LiDAR (Light Detection and Ranging)

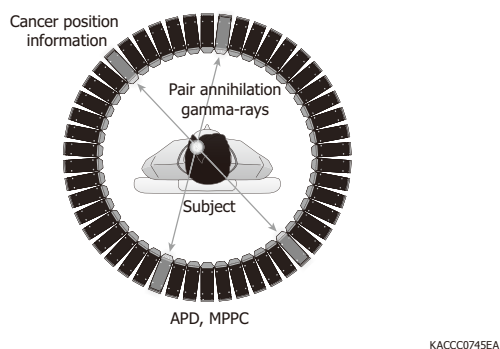
An object is irradiated with laser light, and the reflected light is captured by an optical sensor to measure distance. In recent years, there has been progress toward realizing fully autonomous vehicles, and LiDAR has been used in ADAS (advanced driver assistance systems), AGV (automatic guided vehicles), and other such applications.



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6 - 2 Scintillation measurement

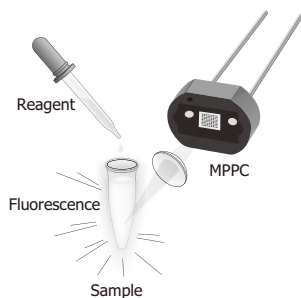
APDs or MPPCs arranged around 360° detect pair annihilation gamma-rays to capture the target position such as cancer tissue. APDs and MPPCs can be used with MRI because they are not affected by magnetic fields.



KACCC0745EA

6 - 3 Fluorescence measurement

The MPPC can detect minute fluorescence emission of reagents.



KACCC0749EB

6 - 4 High energy physics experiment

MPPCs are used in 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) 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)
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