Technical note

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Si APD

Contents

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.
Utilizing our unique technologies, we offer numerous types of Si APDs for various applications. We also offer custom-designed devices to meet special needs. Hamamatsu Si APDs have the following features.

- High sensitivity
- High-speed response
- High reliability
- Select delivery in individual specifications is possible

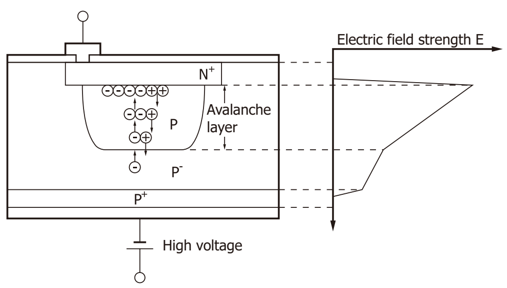
Si APD

Type		Features	Applications
Short wavelength type	Low bias operation	Enhanced sensitivity in UV to visible region	Low-light-level detection, analytical instruments
	Low terminal capacitance		
Near infrared type	Low bias operation	Low bias voltage operation	FSO (free space optics), optical fiber communications, analytical instruments
	Low temperature coefficient	Low temperature coefficient of bias voltage, easy gain adjustment	FSO , optical fiber communications
	850 nm band	High sensitivity in 850 nm band	FSO , optical fiber communications, analytical instruments
	900 nm band	High sensitivity in 900 nm band	FSO , optical fiber communications, analytical instruments
	1000 nm band	High sensitivity in 1000 nm band	FSO , analytical instruments, YAG laser light detection
	TE-cooled type	High S/N	Low-light-level detection
For LiDAR	700 nm band	Low dark current Wide operating temperature Mass production compatibility	Optical rangefinders
	800 nm band		
	900 nm band		
Gain-stabilized type	700 nm band	Temperature compensation function built into the sensor	Optical rangefinders
	800 nm band		
	900 nm band		

1. Operating principle

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)

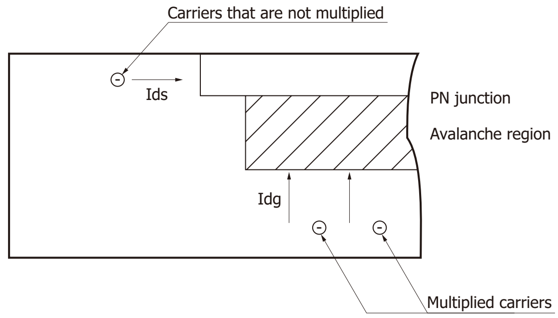


2. Characteristics

2 - 1 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 2-1].

[Figure 2-1] 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 (2-1).

$$I_D = Ids + M\ Idg \quad \cdots\cdots\cdots\cdots \text{(2-1)}$$

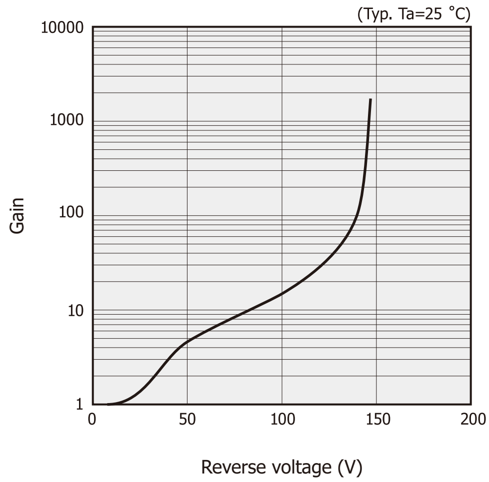
M: gain

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

2 - 2 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 2-2 shows the relation between the gain and reverse voltage for Hamamatsu Si APD S12023-05.

[Figure 2-2] Gain vs. reverse voltage (S12023-05)



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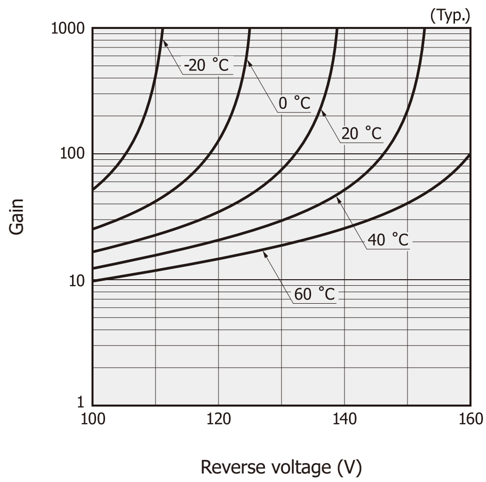
The APD gain also has temperature-dependent characteristics. As the temperature rises, the crystal lattice vibrates more heavily, increasing the possibility that the accelerated carriers may collide with the lattice before reaching a sufficiently large energy level and making it difficult for ionization 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 2-3] Temperature characteristics of gain (S12023-05)



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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.

2 - 3 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 (2-2).

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

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

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 (2-3).

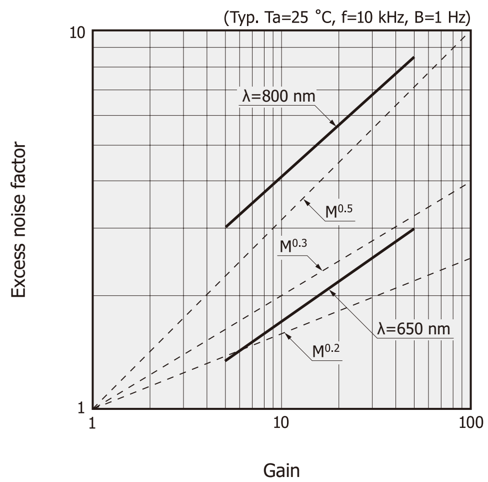
$$F = M\,k + \left(2 - \frac{1}{M}\right)(1 - k) \quad \cdots\cdots\cdots\cdots \ (2\text{-}3)$$

Equation (2-3) 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 (2-3) should be substituted by 1/k.

As described in "2-4 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 2-4 shows excess noise characteristics.

[Figure 2-4] Excess noise factor vs. gain

(a) Short wavelength type (low bias operation)



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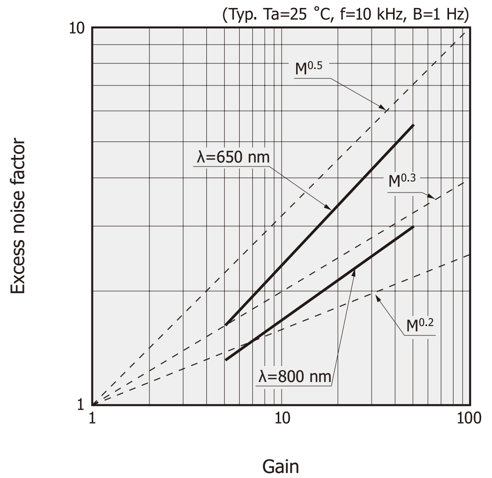
(b) Near infrared type (low bias operation)



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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 (2-4).

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

$2q\,(I_L + Idg)\, B\, M^2\, F + 2q\, B\, Ids$: shot noise squared

$\frac{4k\,T\,B}{R_L}$: thermal noise squared

k : Boltzmann's constant

T : absolute temperature

R_L : load resistance

The noise equivalent power (NEP) of APDs is given by equation (2-5).

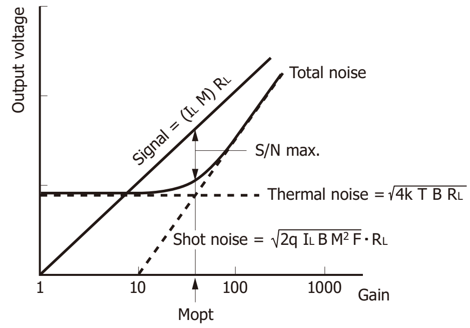
$$NEP = In/(M\,S) \cdots\cdots (2\text{-}5)$$

M: gain

S: photosensitivity [A/W]

In PIN photodiode operation, using a larger load resistance reduces thermal noise of the load resistance, but this also slows the response speed. Therefore, the thermal noise of the load resistance cannot be reduced, and the lower limit of light detection is often dominated by the thermal noise of the load resistance. 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 is shown in Figure 2-5. Idg in equation (2-4) is generally very small compared to I_L, and the Ids is not subject to multiplication, so the shot noise in Figure 2-5 is approximated by $In = \sqrt{2q\, I_L\, B\, M^2\, F}$.

[Figure 2-5] APD noise characteristics



R_L: load resistance

k : Boltzmann's constant

T : absolute temperature

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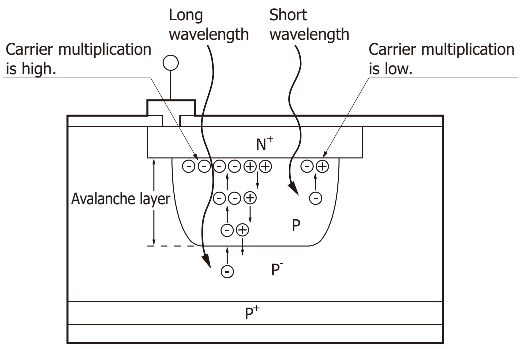
In this case, the optimum gain (Mopt) is obtained under the conditions that maximize the S/N described in equation (2-4). If Ids can be ignored, the optimum gain is given by equation (2-6).

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

2 - 4 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 2-6, 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 2-6] Schematic of cross section (near infrared type)



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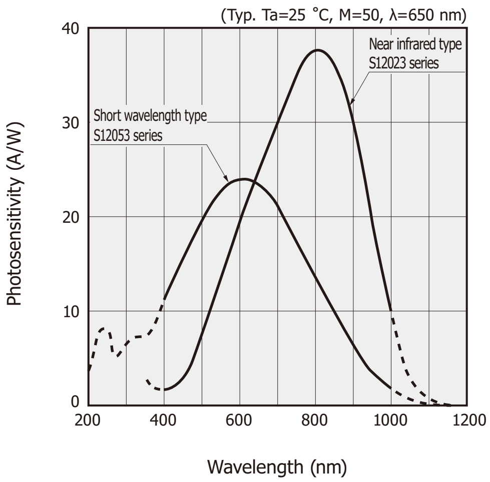
The spectral response and wavelength dependency of gain for the short wavelength type and near infrared type Si APDs are provided below.

[Figure 2-7] Spectral response



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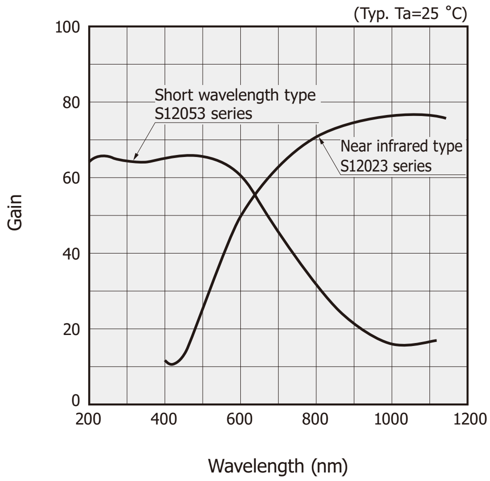
[Figure 2-8] Gain vs. wavelength



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2 - 5 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 (2-7).

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

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 (2-8).

$$tr = \frac{0.35}{fc(CR)} \quad \cdots\cdots\cdots\cdots \ (2\text{-}8)$$

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 (2-9).

$$fc(trd) = \frac{0.44}{trd} \quad \cdots\cdots\cdots\cdots \ (2\text{-}9)$$

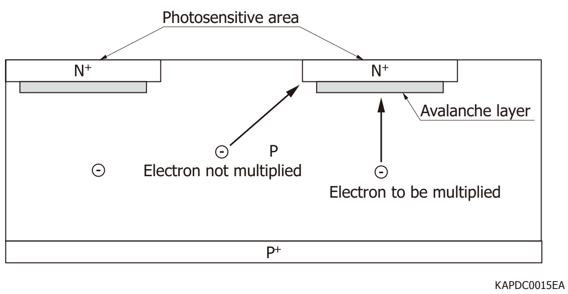
Making the depletion layer thicker to reduce the capacitance also lengthens the drift time, so it is essential to consider both cutoff frequencies, fc(CR) determined by the CR time constant and fc(trd) determined by the transit time.
The carriers passing through the avalanche layer repeatedly collide 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.

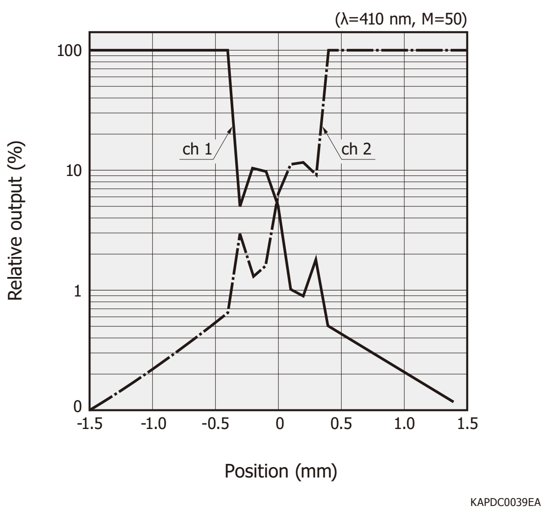
2 - 6 Crosstalk

Crosstalk occurs in multi-element Si APDs. The APD has an avalanche layer under the photosensitive area, so it has a good multiplication function for the light incident on the photosensitive area, but the carrier generated outside the photosensitive area does not pass through the avalanche layer, so the signal is not multiplied and is small. Therefore, the APD array has less crosstalk than the photodiode array.

[Figure 2-9] Internal structure (multi-element type)



[Figure 2-10] Crosstalk (S8550-02, element gap: 0.7 mm, typical example)



3. How to use

3 - 1 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.

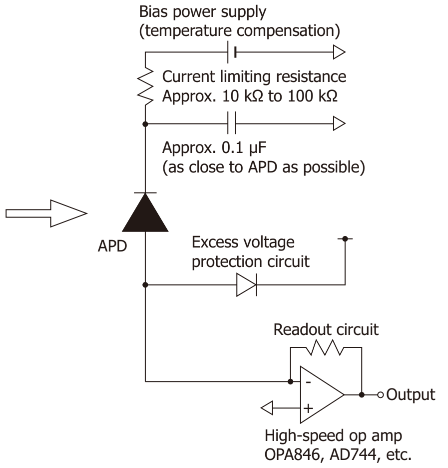
① APD power consumption is the product of the incident light level × sensitivity (M=1) × gain × reverse voltage, and it is considerably larger than that of PIN photodiodes. So there is a need to add a protective resistor between the APD and bias power supply and then install a current limiting circuit. 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 3-1] Connection example



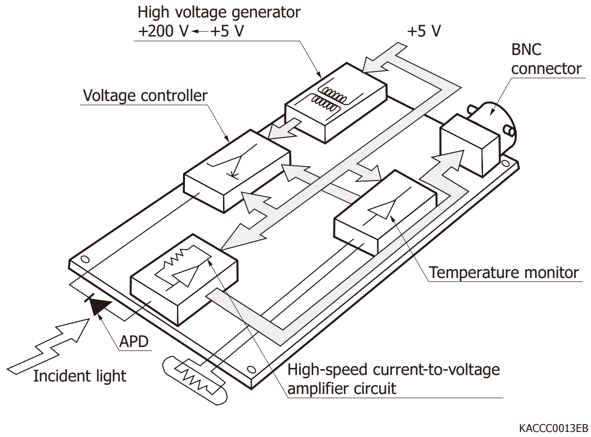
3 - 2 APD modules

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 3-2 shows the block diagram of the C12702 series APD module. This module is designed with the precautions described in “3-1 Connection to peripheral circuits,” thus allowing highly accurate photometry.

For more detailed information about APD modules, refer to “APD modules” technical note.

[Figure 3-2] Block diagram (C12702 series)



[Figure 3-3] APD modules

(a) Standard type C12702 series

(b) High sensitivity type C12703 series

(c) High stability type C10508-01

(d) High-speed type C5658

[Table 3-1] 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 stability type	Digital temperature compensation type high stability APD Module.
High-speed type	Can be used in a wide-band frequency range (up to 1 GHz)

4. Gain-stabilized APD (GS APD)

4 - 1 Features

Si APD is used for distance measurement, medical and scientific measurement, etc., due to its high-speed, high-sensitivity and high S/N characteristics owing to its internal multiplication function. However, due to the variation in individual operating voltages and the fluctuation in gain caused by temperature changes, when using conventional Si APDs, it was necessary to design a circuit to adjust these factors. The newly developed gain-stabilized APD has a built-in temperature compensation function that can keep the gain constant for temperature fluctuations. This eliminates the need to adjust the operating voltage and makes it easier to use.

4 - 2 How to use

Figure 4-1 shows a GS APD connection example. Connection to a bias power supply and a current limiting circuit are essential. Please connect four terminals of the element as follows. It is recommended to connect a capacitor near the anode in order to stabilize the bias voltage.

· Anode: Apply operating voltage + current limiting circuit
· Guard: Grounding
· Gain control: Grounding
· Output: Readout circuit

[Figure 4-1] Connection example (when gain M=50)

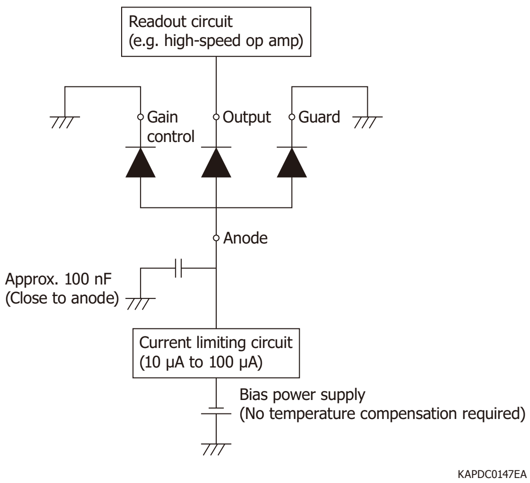
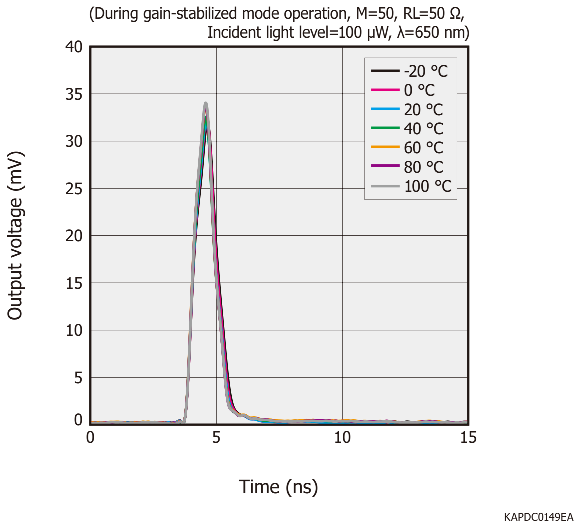


Figure 4-2 shows an output example of the gain-stabilized mode operation* when there is a incoming light pulse with a wavelength = 650 nm and a light level = 100 μW. It provides a stable output to temperature.

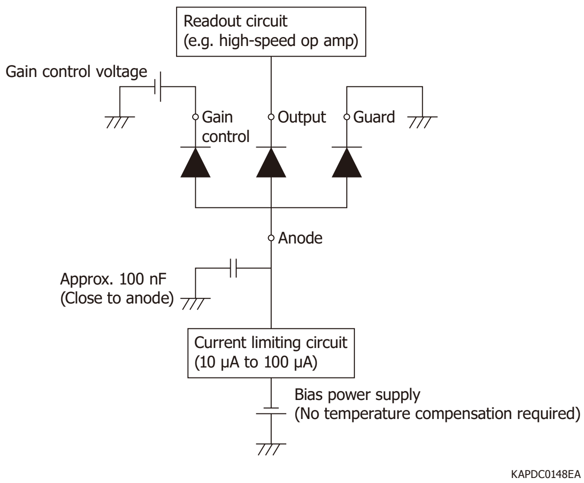
* Bias voltage is applied to anode
I_R anode limit=10 μA, guard pin=GND

[Figure 4-2] Temperature dependence of output voltage when a light pulse is input (S15415-05, measurement example)

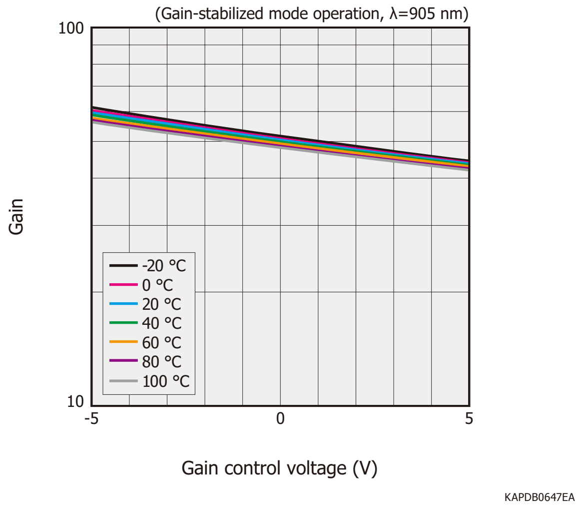


The GS APD is designed with a gain of M=50, but the gain can be controlled by applying a voltage to the gain control terminal. Figure 4-3 shows a connection example when controlling the gain. Figure 4-4 shows an example of the gain vs. gain control voltage. Even if the gain is changed, the fluctuation of the gain due to temperature change is kept very small.

[Figure 4-3] Connection example (when controlling the gain)



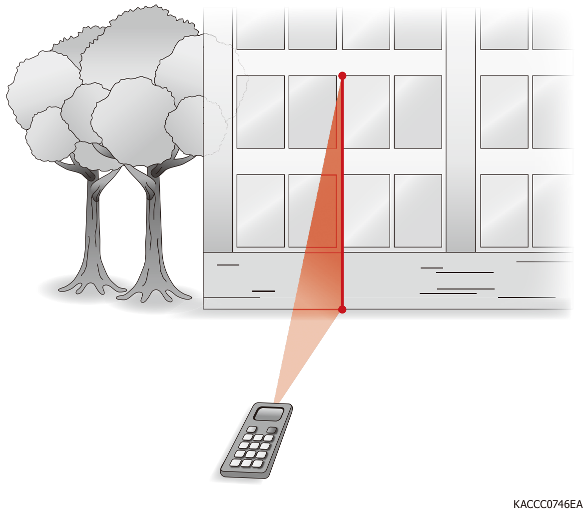
[Figure 4-4] Gain vs. gain control voltage (S15415-05, typical example)



5. Applications

5 - 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.



5 - 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.

5 - 3 Remote sensing

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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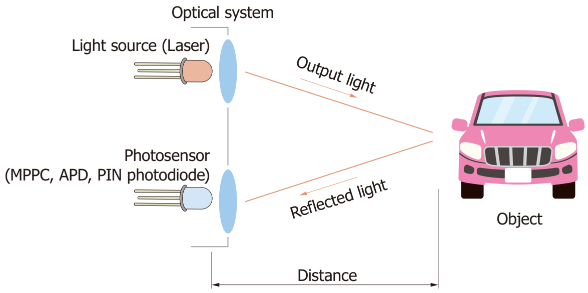
5 - 4 LiDAR (light detection and ranging)

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 is used in ADAS (advanced driver assistance systems) and AGV (automatic guided vehicles).



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