SOLID STATE DIVISION

TECHNICAL INFORMATION

SD-37

Characteristics and use of

Charge amplifier

HAMAMATSU

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Characteristics and use of Charge amplifier

1. General description

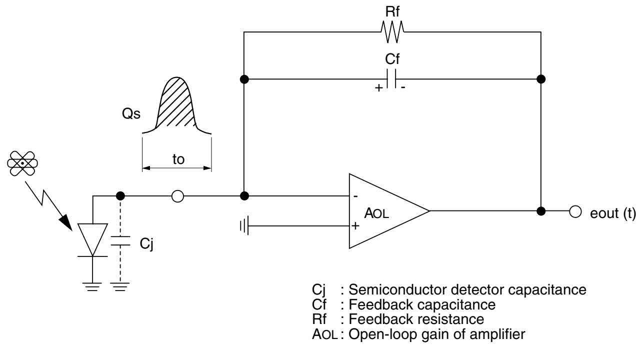
When a semiconductor detector such as Si is used for the measurement of soft X-rays and low to high-energy gamma rays, the output signal is a weak charge pulse having a pulse width of several tens of nanoseconds. As the detector element itself is a capacitive device, its impedance is very high. Therefore, the performance of the preamplifier to be connected, must be taken into consideration when amplifying this output signal.

In such applications, operational amplifier mode integrators using feedback capacitance are commonly used. As these amplifiers have high input impedance, they integrate weak charge pulses and convert them into voltage pulses for amplification then provide a low-impedance output.

Because of this operation, this type of amplifier is called a “charge amplifier”. The first stage of a charge amplifier is usually a low-noise FET and its open-loop gain is set sufficiently high so that the amplification is not influenced by the detector capacitance. The output stage is a low-impedance buffer so as to drive an external stage which is connected using a long cable.

2. Principle of operation

Figure 2-1 Principle of operation



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When soft X-rays or gamma rays strike for example a Si semiconductor detector, signal charge pulses *Qs* are generated, with an amplitude according to the particle energy. Due to this charge generation, the input-end potential of the charge amplifier rises and at the same time, a potential with reverse polarity appears at the output end. However because the amplifier's open-loop gain is sufficiently large, the output-end potential works through the feedback loop so as to make the input-end potential zero instantaneously.

As a result, the signal charge pulses *Qs* are all integrated to the feedback capacitance *Cf* and then output as voltage pulses *eout(t)*. At this point, since the feedback resistance *Rf* for direct current is connected in parallel to the feedback capacitance *Cf*, the output becomes voltage pulses that slowly discharge with the time constant determined by τ=Cf · Rf.

If a detector provides a constant charge generation over a time interval t=0 to *to*, the output signal charge *Qs* is given by the following equation using the Laplace transform.

$$\mathrm{Qs}\ (S) = \mathrm{Qs}\left(\frac{1}{S} - \frac{e^{-Sto}}{S}\right) \qquad .....\ (2\text{-}1)$$

Similarly, the transmission coefficient *T(S)* is given by

$$T\ (S) = -\frac{1}{\mathrm{Cf}} \cdot \frac{1}{S+\frac{1}{\tau}}\ (\tau = \mathrm{Cf} \cdot \mathrm{Rf}) \qquad .....\ (2\text{-}2)$$

Thus the output voltage *V(S)* is expressed using Eqs (2-1) and (2-2) as follows:

$$V\ (S) = \mathrm{Qs}\ (S) \cdot T\ (S) = \mathrm{Qs}\left(\frac{1}{S} - \frac{e^{-Sto}}{S}\right) \cdot \frac{1}{\mathrm{Cf}} \cdot \frac{1}{S+\frac{1}{\tau}}$$

$$= -\frac{\mathrm{Qs}}{\mathrm{Cf}}\left(\frac{1}{S} \cdot \frac{1}{S+\frac{1}{\tau}} - \frac{e^{-Sto}}{S} \cdot \frac{1}{S+\frac{1}{\tau}}\right)$$

$$.....\ (2\text{-}3)$$

As a result, the output voltage pulse *eout(t)* is given by

$$\mathrm{eout}\ (t) = -\frac{\mathrm{Qs}}{\mathrm{Cf}} \cdot \frac{1-e^{-t/\tau}}{to/\tau} \qquad 0 \leq t < to$$

$$= -\frac{\mathrm{Qs}}{\mathrm{Cf}} \cdot \frac{(e^{to/\tau}-1)}{to/\tau}\, e^{-t/\tau} \qquad to \leq t \qquad .....\ (2\text{-}4)$$

Because generally *to* << τ, Eq (2-4) can be simplified as follows:

$$\mathrm{eout}\ (t) = -\frac{Q}{\mathrm{Cf}}\, e^{-t/\tau} \qquad .....\ (2\text{-}5)$$

As can be seen from Eq (2-5), the signal charge pulses *Qs* are converted into voltage pulses with amplitude $\mathrm{Vout} = -\frac{\mathrm{Qs}}{\mathrm{Cf}}$, which is damped with time constant τ=Cf · Rf.

3. Gain

The gain of charge amplifier is given in one of two ways: the gain for amplifier or the gain for a detector/amplifier combination.

3-1 Amplifier

The gain of amplifier *Gc*, referred to also as “charge gain”, is given by the following equation:

$$\mathrm{Gc} = \frac{\mathrm{Vout}}{\mathrm{Qs}}\left(= \frac{1}{\mathrm{Cf}}\right)\ [\mathrm{V/coulomb}]\ \text{or}\ [\mathrm{V/pico\ coulomb}]$$

$$.....\ (3\text{-}1)$$

3-2 Amplifier with detector

In this case we usually use the term called “sensitivity” rather than “gain”. Sensitivity is expressed in the output voltage (mV) per one *MeV* of particle energy irradiated onto a detector.
The amplitude of the signal charge obtained with a semiconductor detector is determined by the input particle energy such as soft X-rays and gamma rays and also by the material of the semiconductor.

$$Qs = \frac{E \cdot e^-}{\varepsilon} \text{ (coulomb) or (pico coulomb)} \qquad \text{. . . . . (3-2)}$$

E : Particle energy (MeV)
e^-: Elementary charge 1.6×10^{-19} (coulomb)
ε : Energy required to create one electron/hole pair. For example with silicon, Qs ranges from 3.62 eV (at 300 K) to 3.71 eV (at 77 K).

Thus, from Eqs (3-1) and (3-2), sensitivity is given by

$$Rs = \frac{Vout}{E} = \frac{\frac{Qs}{Cf}}{Qs \cdot \frac{\varepsilon}{e^-}}$$

$$= \frac{e^-}{Cf} \cdot \frac{1}{\varepsilon} \text{ (mV/MeV)} \qquad \text{. . . . . (3-3)}$$

For example when using a Si detector and an H4083 charge amplifier (Cf=2 pF), the sensitivity at room temperatures *Rs* becomes

$$Rs = \frac{e^-}{Cf} \cdot \frac{1}{\varepsilon}$$

$$= \frac{1.6 \times 10^{-19}}{2 \times 10^{-12}} \cdot \frac{1}{3.62}$$

$$= 2.2 \times 10^{-8} \text{ (V/eV)}$$

$$= 22 \text{ (mV/MeV)} \qquad \text{. . . . . (3-4)}$$

4. Characteristics

In general, the following characteristics are required of charge amplifier used for the detection of soft X-rays and low to high-energy gamma rays.

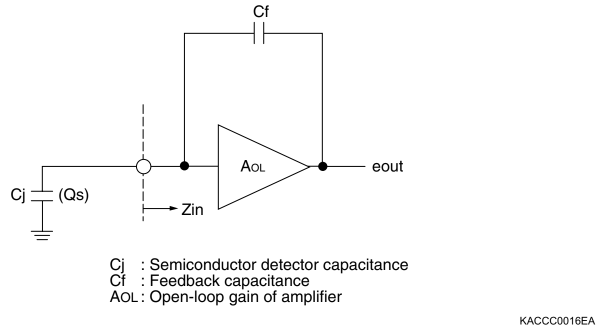
- High gain
- Low noise
- Excellent integration linearity
- High-speed rise time
- High temperature stability, etc.

The following sections discuss major characteristics of charge amplifier.

4-1 Open-loop gain

There are various semiconductor detectors used for the detection of soft X-rays and gamma rays. Even among Si detectors for example, a variety of types are used to match the application, which have different active areas and depletion layer thicknesses. Furthermore, detectors also differ in regards to capacitance. However, when the same Si detector is used for the detection of soft X-rays and gamma rays, the amount of generated charge must be the same if the particle energy of the soft X-rays and gamma rays is equivalent. Therefore, charge amplifier must provide a constant gain regardless of the capacitance value. In fact as shown in Eq (2-5) in “Principle of operation”, the output from the detector is independent of the junction capacitance *Cj*. This is because the open-loop gain of the charge amplifier is very high.

Figure 4-1 Equivalent circuit



When a charge amplifier is connected with a Si detector, its equivalent circuit is like that shown in Figure 4-1.
In this equivalent circuit, when seen from the amplifier's input, the input impedance *Zin* is given by

$$Zin = \frac{\frac{1}{j\omega Cf}}{1 + A_{OL}(j\omega)} \qquad \text{. . . . . (4-1)}$$

If signal charge *Qs* is generated in the Si detector, the voltage *ein* at the amplifier's input becomes

$$ein = \frac{Qs}{j\omega Cj + \{1 + A_{OL}(j\omega)\} \cdot j\omega Cf} \qquad \text{. . . . . (4-2)}$$

Thus the output voltage *eout* is expressed using Eq (4-2), as follows:

$$eout = A_{OL}(j\omega) \cdot ein$$

$$= A_{OL}(j\omega) \cdot \frac{Qs}{j\omega Cj + \{1 + A_{OL}(j\omega)\}\, j\omega Cf}$$

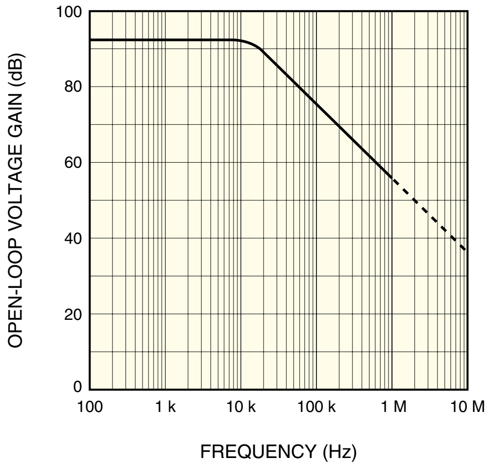
$$= \frac{Qs}{j\omega Cf + \frac{j\omega}{A_{OL}(j\omega)}(Cf + Cj)} \qquad \text{. . . . . (4-3)}$$

Here, assuming that *AOL >> 0*, in other words, the open-loop gain of the amplifier is very large, then *eout* can be simplified as follows:

$$eout = \frac{Qs}{j\omega Cf} \quad \text{.....(4-4)}$$

As discussed above, the output voltage *eout* of charge amplifier is not dependent on the capacitance of Si detectors.

Figure 4-2 Open-loop gain (H4083)



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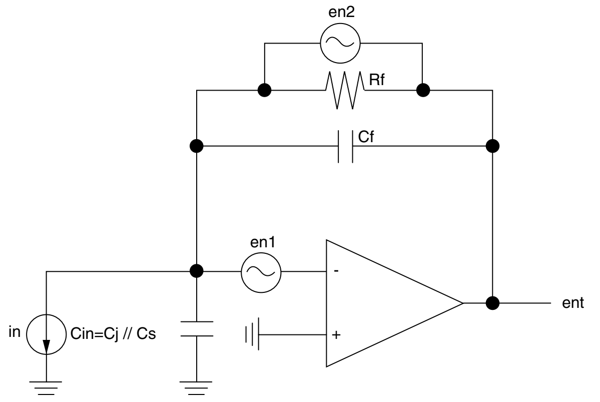
4-2 Noise

Figure 4-3 shows the noise equivalent circuit of a charge amplifier.

Figure 4-3 Noise equivalent circuit of the charge amplifier



Cj : Capacitance of semiconductor detector
Cs: Input capacitance of charge-sensitive amplifier
Cf : Feedback capacitance
Rf : Feedback resistance

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Noise in charge amplifier comes from the following three major sources:

◆Thermal noise of first-stage FET

Thermal noise of the first-stage FET, *en1*, is given by

$$en_1 = \sqrt{\frac{8}{3}\frac{KT}{gm}} \left(V/\sqrt{Hz}\right) \quad \text{.....(4-5)}$$

K : Boltzmann constant
T : Absolute temperature
gm: Mutual conductance of first-stage FET

◆Shot noise caused by gate current of first-stage FET and dark current of detector

The shot noise in is given by

$$in = \sqrt{2q\,(I_G + I_D)} \left(A/\sqrt{Hz}\right) \quad \text{.....(4-6)}$$

q : Elementary charge
IG : Gate leakage current of first-stage FET
ID : Dark current of detector

◆Thermal noise caused by feedback resistance

The thermal noise en2 caused by the feedback resistance *Rf* is given by

$$en_2 = \sqrt{4KTRf} \left(V/\sqrt{Hz}\right) \quad \text{.....(4-7)}$$

where *Rf* is the feedback resistance.

From Eqs (4-5), (4-6) and (4-7), the total noise *ent* (jω) becomes as follows:

$$ent^2\,(j\omega) = en_1^2 \cdot \left(1 + \frac{Cin}{Cf}\right)^2 + \left\{in^2 + \left(\frac{en_2}{Rf}\right)^2\right\} \frac{1}{(j\omega Cf)^2} \quad \text{...(4-8)}$$

In Eq (4-8) above, the first term component is constant over the entire frequency range and amplified by the noise gain (1+Cin/Cf) determined by the input capacitance *Cf*. The second term component is constant regardless of the input capacitance *Cin*, but decreases with increasing frequency. Figure 4-4 and 4-5 show noise characteristics of the H4083 charge amplifier.

Figure 4-4 Noise spectrum

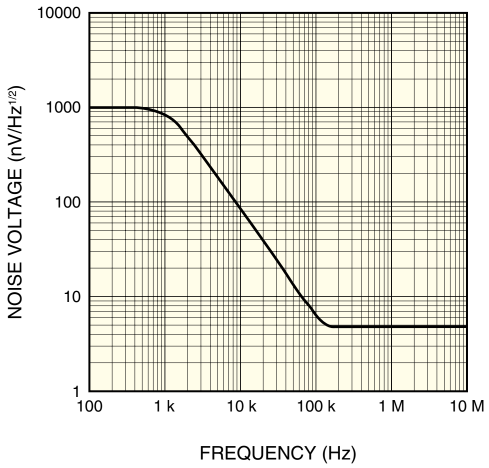

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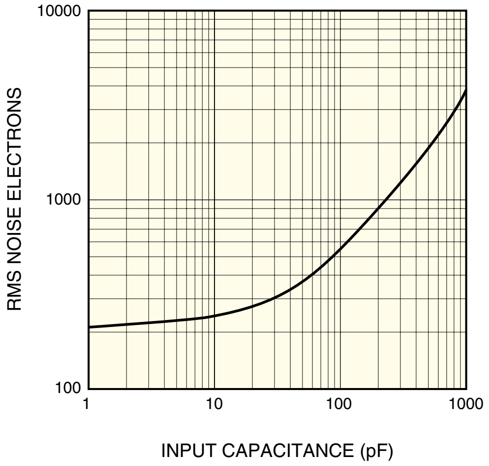
Figure 4-5 Input capacitance vs. number of noise electrons



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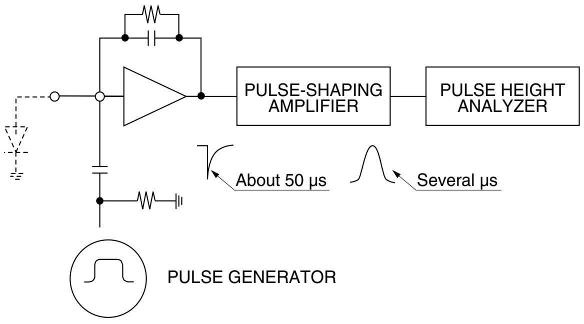
Generally, the noise measurement and evaluation for charge amplifier are carried out using a measurement system like that shown in Figure 4-6.

Figure 4-6 Noise measurement system



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In this system, a charge *Q* is supplied from the pulse generator via the capacitance connected to the input end of a charge amplifier.

The output from the charge amplifier is amplified once with the pulse-shaping amplifier and input to the pulse height analyzer. Then the pulse height distribution is measured to obtain the noise based on the half width.

The pulse-shaping amplifier improves the S/N of the charge amplifier and also serves as a filter. As various types of pulse-shaping amplifiers are available depending on the circuit configurations, choose the best amplifier for your application. One of the more popular pulse-shaping amplifiers is a Gaussian

shaping circuit. Its typical frequency characteristic and output waveform are shown in Figure 4-7 and 4-8, respectively.

Figure 4-7 Frequency characteristic

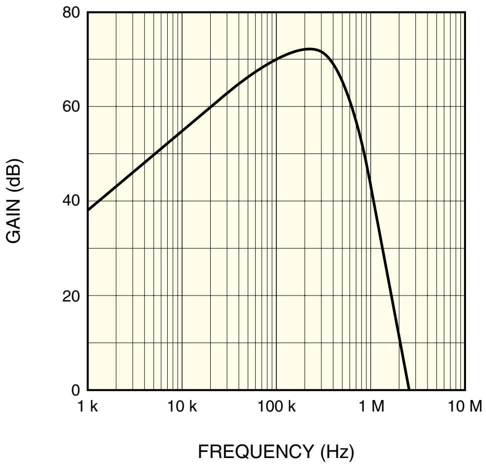

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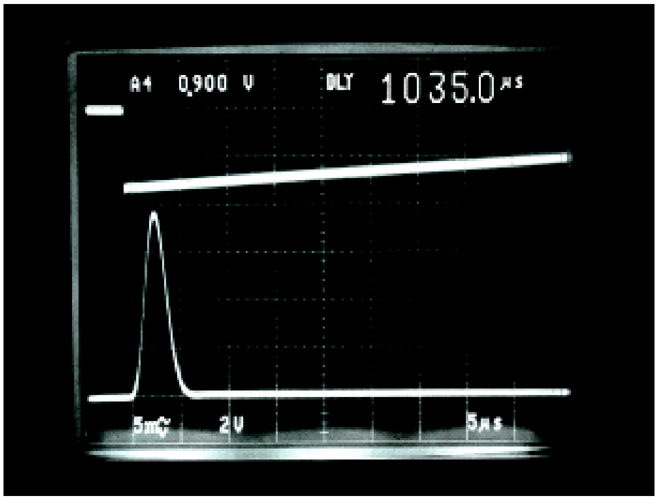
Figure 4-8 Output waveform



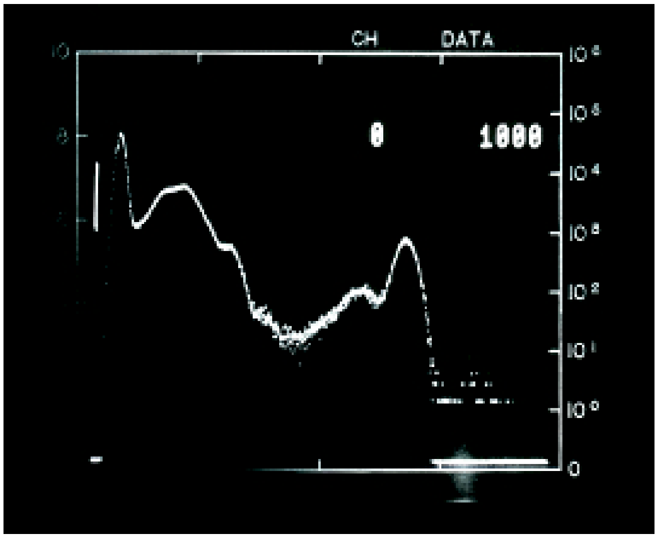
Since the output signal from a charge amplifier is as small as several tens of millivolts even after being integrated. The pulse-shaping amplifier is also used to amplify this signal to a level that matches the input range (0 to 10 V) of the pulse height analyzer.

5. Applications

5-1 Gamma ray measurement (Direct detection using Si PIN photodiode)

Figure 5-1 shows a typical pulse height distribution when the H4083 charge amplifier combined with S3590-05 Si PIN photodiode is irradiated with gamma rays from an ^{241}Am radiation source.

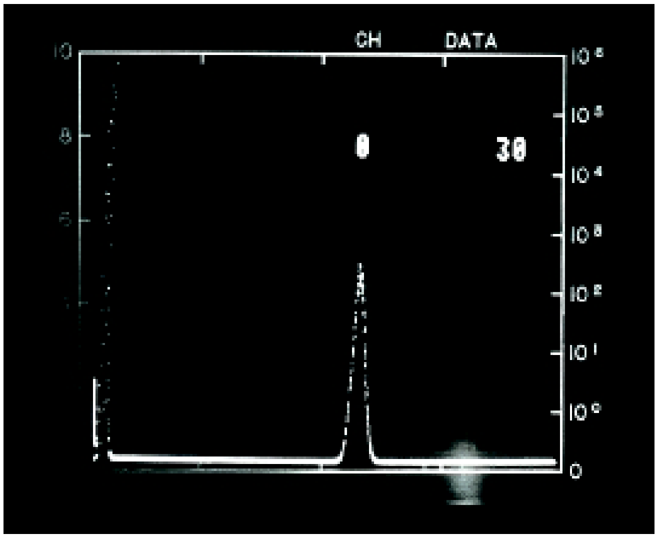
Figure 5-1



5-2 Power and stability measurements from lasers

Figure 5-2 shows a typical pulse height distribution when the H4083 charge amplifier combined with S3590-01 Si PIN photodiode is irradiated from a laser having a pulse width of about 100 ns and a wavelength at 830 nm. The peak channel of the pulse height distribution indicates the average laser power and the half width represents the fluctuation in the power level.

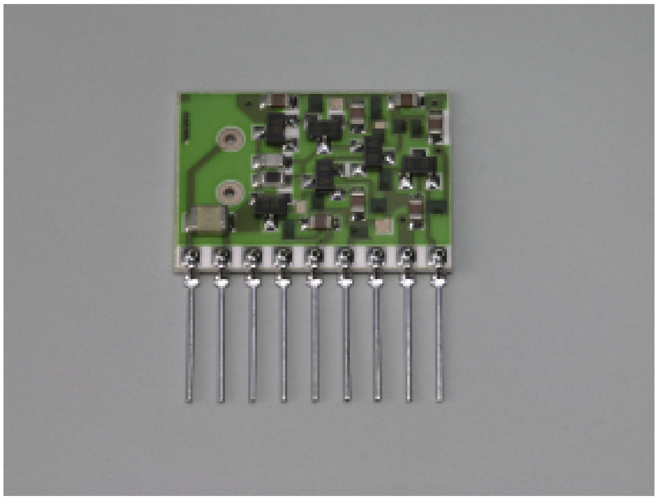
Figure 5-2



6. Specifications (H4083)

Charge amplifier H4083 is a hybrid low-noise amplifier that can be used in a wide range of application, including soft X-ray and low to high energy gamma-ray spectrometers. H4083 is used in conjunction with semiconductor detectors such as Si detectors. Even when combined with a detector having a relatively large terminal capacitance, H4083 can make measurements with good energy resolution.

For optimum operation it is recommended that H4083 be used with Hamamatsu Si PIN photodiodes (S3590/S3204 series, etc.). In particular, S3590 series eliminates the risk of trouble from increased capacitance because it solders directly onto the rear side of H4083 thus reducing wire length. The increased compactness and light weight offered by this configuration make it easy to incorporate in with other test equipment, etc.



■ Specifications

Parameter	Specification
Amplification method	Charge-sensitive type
Input/output polarity	Inverted
Charge gain	0.5 V/pC
	22 mV/MeV (Si)
Noise characteristic	550 electrons/FWHM
Negative feedback constant	50 MΩ//2 pF
Power supply	±12 V
Power consumption	150 mW
Configuration	9-pin, single line type
Dimensional outline	24 (W) × 19 (H) × 4 (T) mm

■ Pin connections

Pin No.	Symbol	Content
①	IN	Input terminal
②	GAIN	Feedback constant adjustment terminal
③	GND *	Input ground terminal
④	CAL	Last pulse input terminal
⑤	GND *	Power and output ground terminal
⑥	-12 V	Power terminal
⑦	+12 V	Power terminal
⑧	GND *	Output ground terminal
⑨	OUT	Output terminal
Through-hole A	P	Anode connection terminal
Through-hole B	N	Cathode connection terminal

* GND is internally connected.

The left end pin is designated No. 1 when viewed from the component side with the pins facing downwards.

● Using pin No. 2

Use pin No. 2 when changing the feedback constant which is typically 50 MΩ/2 pF. Connect feedback resistance and capacitance between pin No. 2 and No. 9. Note that this connection is made parallel to the internal feedback resistance and capacitance.

● Changing the feedback resistance and capacitance

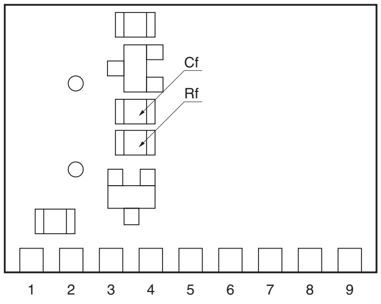
If you want to change the feedback constant without making parallel connections, directly replace the resistor (Rf) and capacitor (Cf) shown at the right, which serve as feedback resistance and capacitance.

Replacement components shoud be 2012 size.

● Using through-holes A and B

When H4083 is not covered with protective coating, a photodiode (such as S3590 series) can be directly soldered on the board. In this case, insert the photodiode leads into the through-holes from the solder side.

■ Component side diagram



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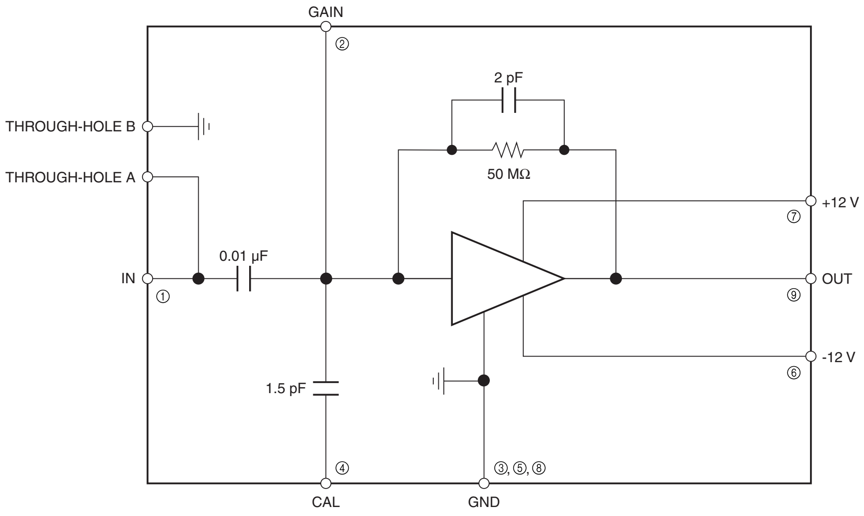
■ Equivalent circuit



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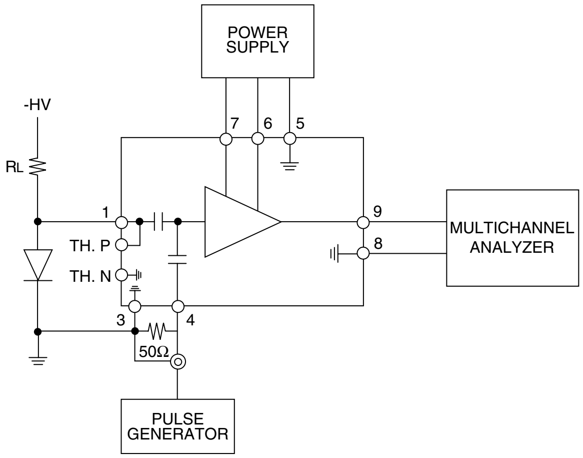
■ Circuit example 1 (external connection to photodiode)



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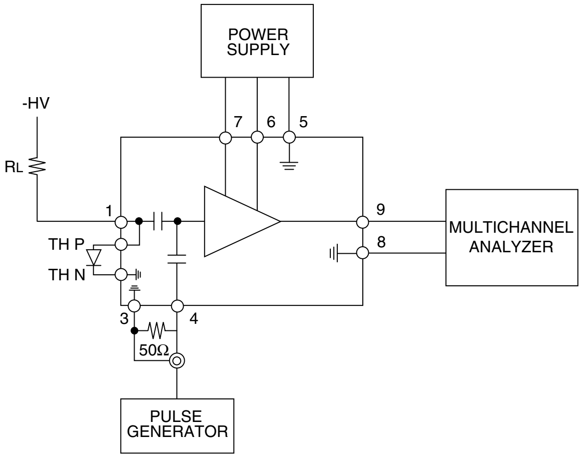
■ Circuit example 2 (direct connection to photodiode)



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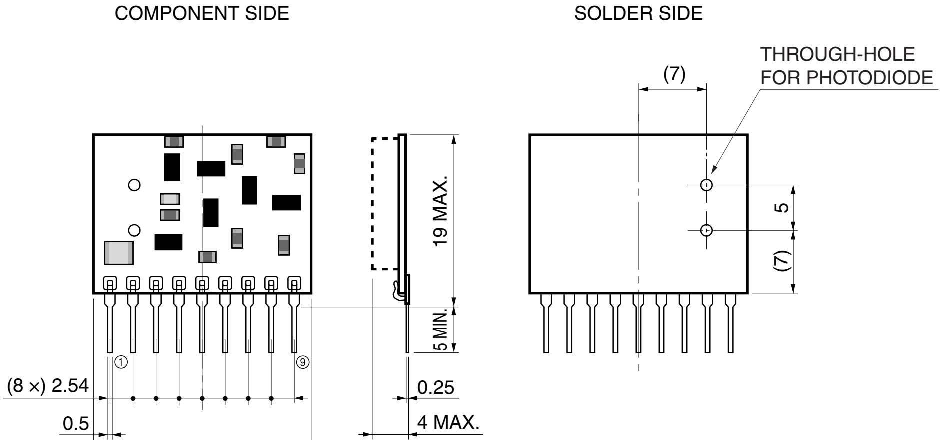
■ Dimensional outline (unit: mm)



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7. Precautions for handling charge amplifier

- Because charge amplifier H4083 is designed so that Si PIN photodiode of S3590 series can be directly soldered on it, no protective coating is provided. Avoid touching any part with bare hands when handling H4083.

- For proper storage of the charge amplifier, insert its leads into a non-conductive sponge material or wrap it with aluminum foil to protect it against static electricity because the impedance at the input end is very high.

- When soldering Si PIN photodiode S3590 series onto a charge amplifier or the amplifier onto a PC board, carry out the soldering as quickly as possible to prevent the amplifier and other components from being damaged by excessive heat.

- When configuring a measurement system using Si PIN photodiode and a charge amplifier, the following points should be observed.
  - When mounting Si PIN photodiode on a charge amplifier, take care to minimize stray cpacitance.
  - The output end of the amplifier should be kept away from the input end as much as possible.
  - In the power supply line connect a ceramic capacitor of about 0.1 μF between the amplifier and the ground.
  - In the bias line for the photodiode, use a bias resistor and capacitor which can adequately withstand the bias voltage applied.
  - Si PIN photodiodes are capacitive elements with high impedance. Provide appropriate shielding to prevent external noise from interfering with the signal.
  - As a power supply for the system, we recommend using a series power supply with minimum noise characteristics.

- The following points must also be observed during operation:
  - To increase the bias voltage applied to Si PIN photodiode, slowly increase it while monitoring the output so that the output amplitude does not swing past the optimum level.
  - Because Si PIN photodiodes also have high sensitivity in the visible range, provide sufficient light-shielding against visible light when measuring soft X-rays or gamma rays.

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