

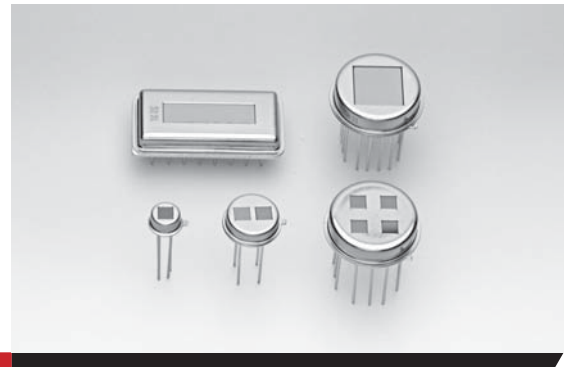
## 1 Thermopile detectors

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# Thermal detectors



Thermal detectors have an absorption layer that absorbs and converts light into heat, and provide an electric signal output that represents the change in absorption layer temperature. Because thermal detectors have no wavelength dependence, they can serve as infrared detectors when used with a window material such as Si that transmits infrared light.

Thermal detectors are mainly classified into: (1) thermopile detectors that change in electromotive force, (2) bolometers that change in resistance, (3) pyroelectric detectors that change in dielectric surface charge, and (4) diodes that change in voltage-current characteristics. Hamamatsu manufactures two types of thermal detectors: thermopile detectors and bolometers. These two types of thermal detectors are different in terms of operating principle, structure, and characteristics.

Thermopile detectors have a structure in which a large number of thermocouples are serially connected on a silicon substrate and their sensitivity increases as more thermocouples are used. This means that the larger the photosensitive area, the higher the sensitivity, because the number of thermocouples is proportional to the size of the photosensitive area.

In bolometers, the photosensitive area uses a bolometer resistance made up of thermoelectric conversion materials, so the resistance temperature coefficient is the primary cause in determining bolometer sensitivity. Since bolometer sensitivity does not depend on the size of the photosensitive area, detectors can be fabricated that have a small photosensitive area yet no drop in sensitivity.

Thermopile detectors are usually manufactured as single-element detectors with an ample photosensitive area or arrays with a small number of elements, while bolometers are manufactured as arrays with a larger number of elements than thermopile detectors.

## || Hamamatsu thermopile detectors and bolometers

Product name	Multi-element array	Sensitivity enhancement	Supply current	Package atmosphere	Rise time
Thermopile detector	Possible with larger pixel size (pixel size: 200 × 200 μm or larger)	Possible	Not required (thermal electromotive force)	Nitrogen	1 ms or more
Bolometer	Possible with smaller pixel size (pixel size: 75 × 75 μm or smaller)	Possible	Required	Vacuum	2 ms or more

# 1. Thermopile detectors

Thermopile detectors are thermal detectors that utilize the Seebeck effect in which a thermal electromotive force is generated in proportion to the incident infrared light energy. Thermopile detectors themselves have no wavelength dependence and so are used with various types of window materials for diverse applications such as temperature measurement, human body sensing, and gas analysis.

## 1 - 1 Features

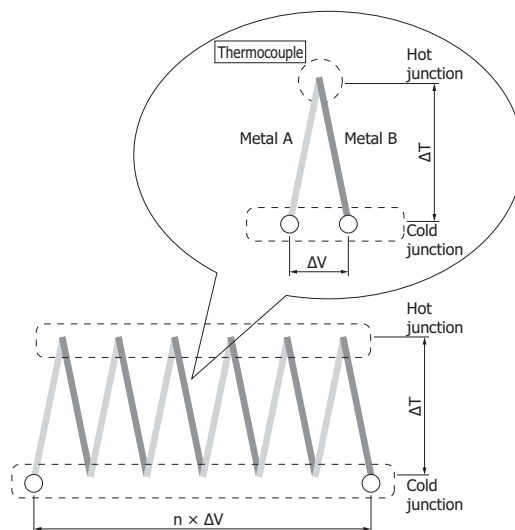
- Operates at room temperature
- Spectral response characteristics that are not dependent on wavelength
- No optical chopping is required, and voltage output can be obtained according to input energy.
- Low cost
- Long life

## 1 - 2 Structure

In order to obtain a large output voltage, Hamamatsu thermopile detectors have many thermocouples that are serially connected on a silicon substrate to magnify the temperature difference between the hot and cold junctions. The hot junction side (photosensitive area) is designed to be a thermally isolated structure on which an infrared absorption film is attached. To make the thermally isolated structure, MEMS technology is used to process the membrane (thin film) to make it float in a hollow space. Our thermopile detectors use materials that have a large Seebeck coefficient (thermal electromotive force) and are easily formed by the semiconductor process.

When infrared light enters a thermopile detector having the above mentioned structure, the hot junction on the membrane heats up and produces a temperature difference ( $\Delta T$ ) between the hot and cold junctions accompanied by generation of a thermal electromotive force ( $\Delta V$ ).

[Figure 1-1] Thermally isolated structure (thermopile detector)



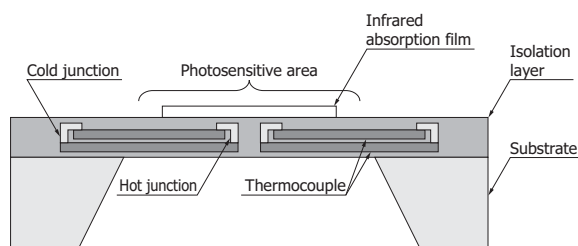
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Our thermopile detector structures differ according to the type of device, namely, single/dual/quad element types and linear/area arrays.

### Single/dual/quad element types

Single/dual/quad element types have large photosensitive areas and are manufactured by bulk processing technology with high workability. Etching is performed from the backside of the substrate to form the photosensitive area in a membrane state so that the hot and cold junctions are thermally isolated from each other to achieve high sensitivity.

[Figure 1-2] Cross-sectional view (single/dual/quad element types)



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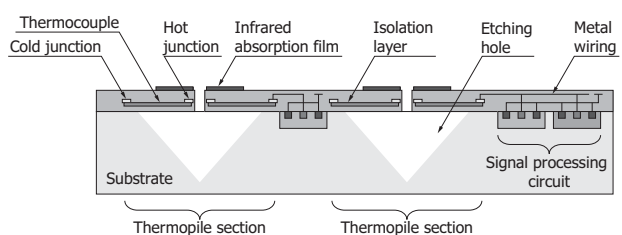
[Table 1-1] Hamamatsu thermopile detectors

Type	Number of elements	Window material	Spectral response range	Package	Main applications
Single element	1	Anti-reflection coated Si	3 to 5 $\mu\text{m}$	TO-18	Gas analysis, temperature measurement
Dual element	2	Band-pass filter	3.9 $\mu\text{m}$ , 4.3 $\mu\text{m}$	TO-5	Gas analysis
Quad element	4		3 to 5 $\mu\text{m}$	TO-8	
Linear array	16, 32	5 $\mu\text{m}$ long-pass filter	5 to 14 $\mu\text{m}$	Flat package	Temperature measurement
Area array	8 $\times$ 8			TO-8	Temperature measurement, human body sensing

## Linear and area arrays

To manufacture linear and area arrays, the gap between each element must be made narrow in order to reduce non-sensitive areas. To do this, the portion directly under each photosensitive area is selectively bored by surface processing technology so that the photosensitive area becomes a thin membrane-like structure. CMOS process technology is utilized to lay out the signal processing circuits on the same chip where the thermopile section is formed.

[Figure 1-3] Cross-sectional view (linear and area arrays)



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## 1 - 3 Characteristics

### Sensitivity

Thermopile sensitivity ( $R_v$ ) is determined by the number of thermocouples as expressed by equation (1).

$$R_v = \frac{\eta n \alpha}{G \sqrt{1 + \omega^2 \tau^2}} \text{ [V/W]} \dots\dots\dots (1)$$

$\eta$  : emissivity  
 $n$  : number of thermocouples  
 $\alpha$  : Seebeck coefficient  
 $G$  : thermal conductivity  
 $\omega$  : angular frequency  
 $\tau$  : thermal time constant

### Noise

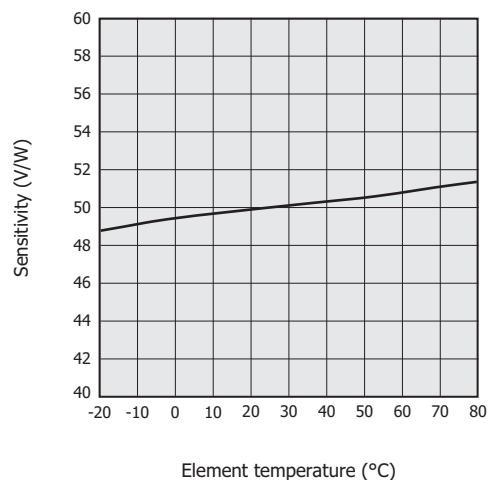
Thermal noise called Johnson noise in the element resistance is predominant in thermopile detector noise. Noise ( $V_N$ ) is expressed by equation (2).

$$V_N = \sqrt{4k T R_d \Delta f} \text{ [V rms]} \dots\dots\dots (2)$$

$k$  : Boltzmann's constant  
 $T$  : absolute temperature  
 $R_d$  : element resistance  
 $\Delta f$  : bandwidth

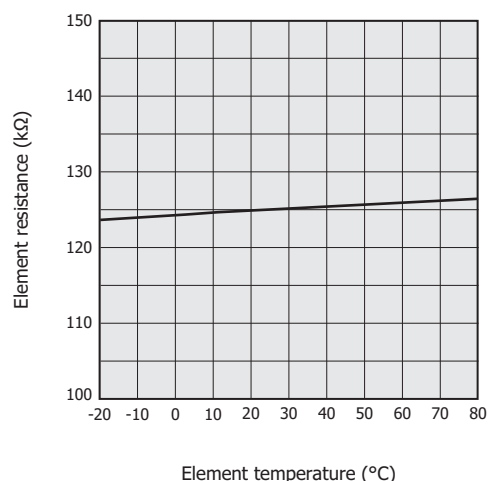
## Temperature characteristics

[Figure 1-4] Temperature characteristics of sensitivity (single element type T11262-01, typical example)



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[Figure 1-5] Temperature characteristics of element resistance (T11262-01, typical example)

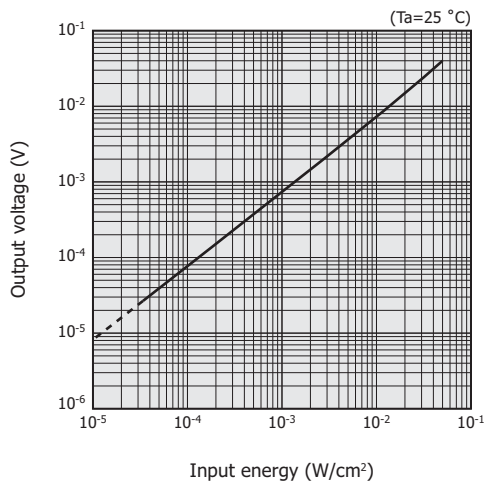


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### Linearity

Figure 1-6 shows an example of the relation between the input energy and output voltage. Thermopile detector output voltage is proportional to the input energy.

[Figure 1-6] Output voltage vs. input energy (T11262-01, typical example)

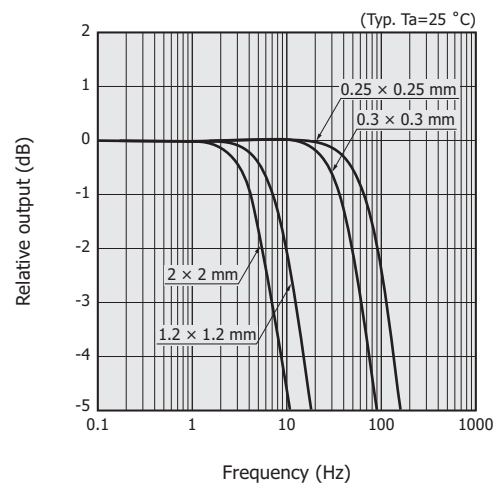


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## Frequency characteristics

Figure 1-7 shows the frequency characteristics of thermopile detectors each having a different photosensitive area. Frequency response tends to decrease as the photosensitive area becomes larger.

[Figure 1-7] Frequency characteristics



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## Spectral response

Since thermopile detectors have no wavelength dependence, their spectral response is determined by the transmittance characteristics of window materials. Spectral transmittance characteristics of typical window materials are shown in Figure 1-8.

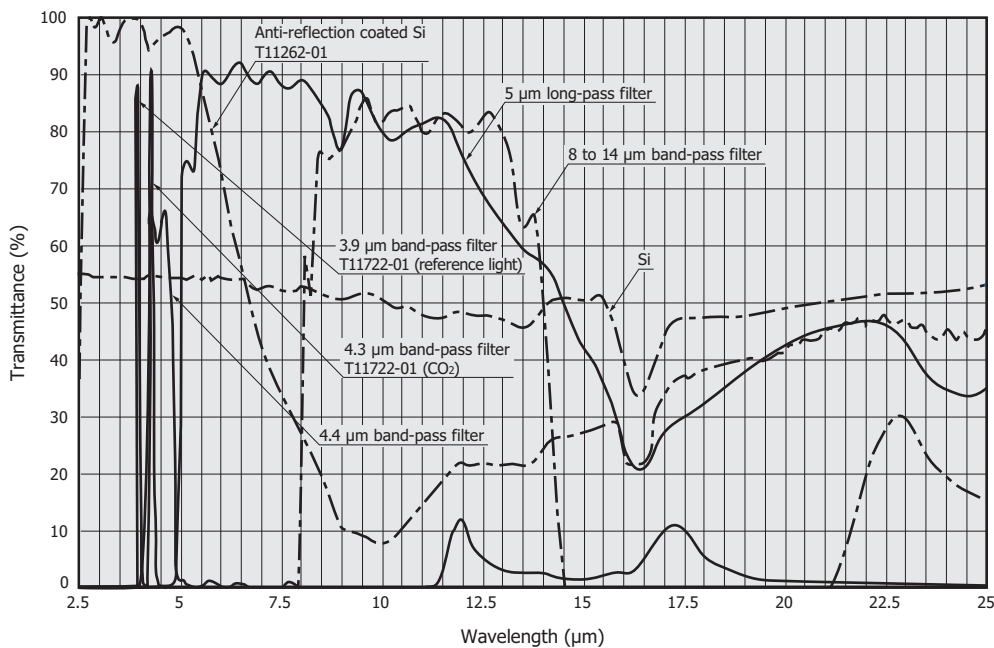
## 1 - 4 How to use

### Single/dual/quad element types

(1) Circuit not using thermistor

In cases where the ambient temperature is constant or high precision measurement is not required, thermopile detectors can be used with a circuit that does not include a thermistor.

[Figure 1-8] Spectral transmittance characteristics of window materials

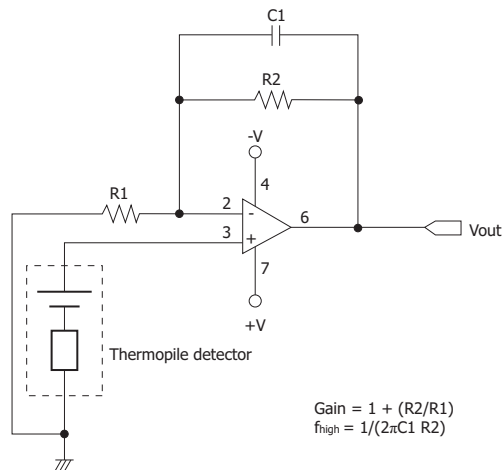


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- Dual-polarity power supply type

**[Figure 1-9] Amplifier circuit (dual-polarity power supply type)**

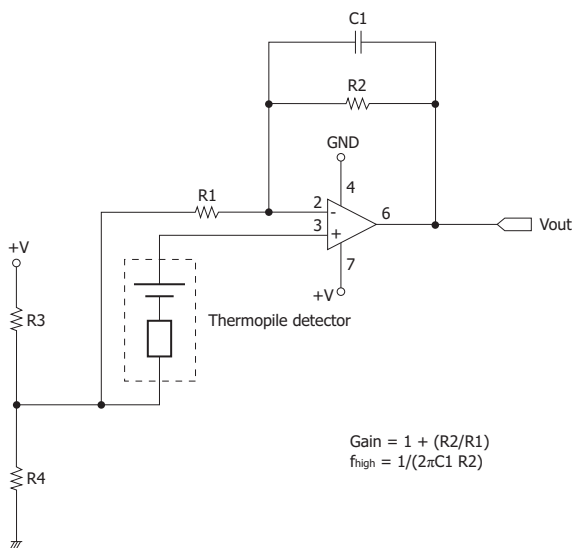


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- Single power supply type

When using an op amp that operates from a single power supply, an error occurs near ground potential which is caused by the op amp's offset voltage and nonlinearity. To cope with this, the thermopile detector is operated with one terminal biased. In the circuit shown in Figure 1-10, the op amp supply voltage is biased with dividing resistors R3 and R4.

**[Figure 1-10] Amplifier circuit (single power supply type)**



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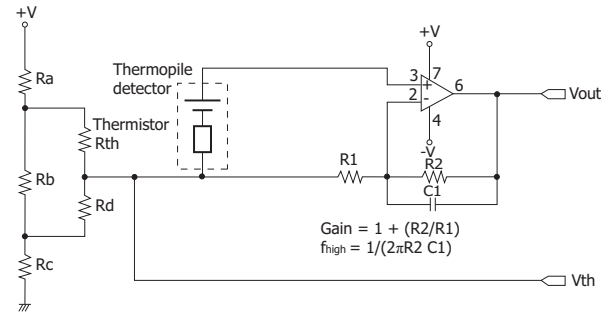
## (2) Circuit using thermistor

Output signals of a thermopile detector are temperature dependent. When detecting the temperature of an object in locations where the thermopile element temperature may drastically fluctuate, some means of making the output signals constant is required to ensure stable temperature detection. There are two methods to compensate for the temperature: one is to directly input the thermopile detector and thermistor signals into a microcontroller, and the other is to feed the thermistor output signal into the amplifier circuit. If high accuracy is necessary, the

method using a microcontroller is more common.

Figure 1-11 shows a circuit example where the thermistor output signal is fed into the amplifier circuit. This type of circuit is used when high measurement accuracy is not required. The circuit shown in Figure 1-11 applies to both cases where the thermistor is externally connected to the thermopile detector or the thermistor is built into the thermopile detector.

**[Figure 1-11] Amplifier circuit with thermistor**



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- Finding the resistance values (Ra, Rb, Rc, Rd) for the circuit with a thermistor

- ① To find the resistance value of Rd at which the thermistor output Vth is linear in the operating temperature range

- 1) Determine the operating temperature range (Tmin to Tmax).
- 2) Find the resistance value (Rh) of the thermistor Rth at Tmax.
- 3) Find the resistance value (Rl) of the thermistor Rth at Tmin.
- 4) Find the resistance value (Rm) of the thermistor Rth at an intermediate temperature between Tmin and Tmax.
- 5) Find the resistance value of Rd from equation (3).

$$Rd = \frac{Rh Rm + Rl Rm - 2Rh Rl}{Rh + Rl - 2Rm} \dots\dots\dots (3)$$

- ② To measure the thermopile output voltage Vout and check the voltage range where the thermistor output voltage (Vth) varies in the operating temperature range (when the measurement object's temperature is 25 °C)

- 1) Measure the thermopile detector output voltage (Voutmin) at Tmax.
- 2) Measure the thermopile detector output voltage (Voutmax) at Tmin.

- ③ To find the resistance values of Ra, Rb and Rc

- 1) Find the voltage drop (Vb) of Rb and the voltage drop (Vc) of Rc, from the simultaneous equations (4) and (5).

$$Voutmin = \frac{Vb Rd}{Rh + Rd} + Vc \dots\dots\dots (4)$$

$$Voutmax = \frac{Vb Rd}{Rl + Rd} + Vc \dots\dots\dots (5)$$

2) Find the voltage drop ( $V_a$ ) of  $R_a$ .

$$V_a = V - V_b - V_c \dots\dots\dots (6)$$

$V$ : supply voltage

3) Determine the  $R_b$  value which should be smaller than  $R_{th} + R_d$  by at least two orders of magnitude.

4) Find the  $R_a$  and  $R_c$  values from the simultaneous equations (7) and (8).

$$V_a = \frac{V R_a}{R_a + R_b + R_c} \dots\dots\dots (7)$$

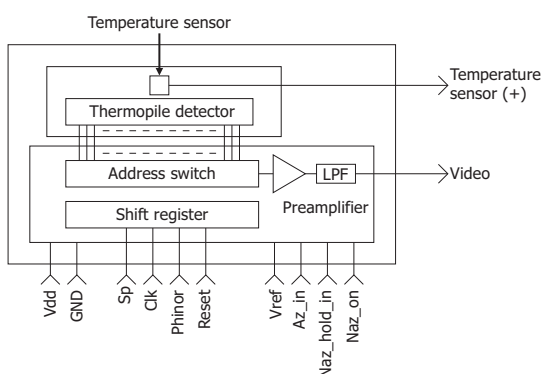
$$V_c = \frac{V R_c}{R_a + R_b + R_c} \dots\dots\dots (8)$$

## Linear and area arrays

Linear and area arrays consist of a one- or two-dimensional thermopile array, shift registers and temperature sensor, and to which a preamplifier is hybrid-connected to amplify the output signal. Since the preamplifier is built into the same package, this reduces external noise and also simplifies the circuit configuration connected subsequent to the sensor.

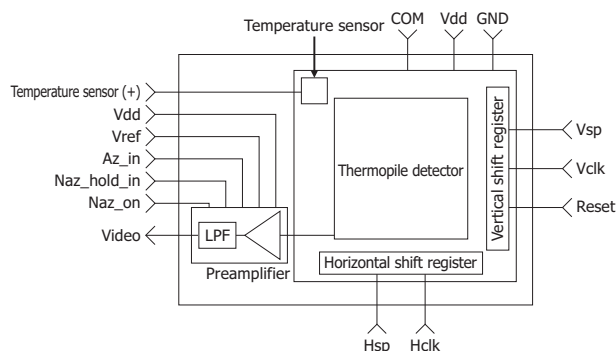
[Figure 1-12] Block diagram

### (a) T11263 series



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### (b) T11264 series

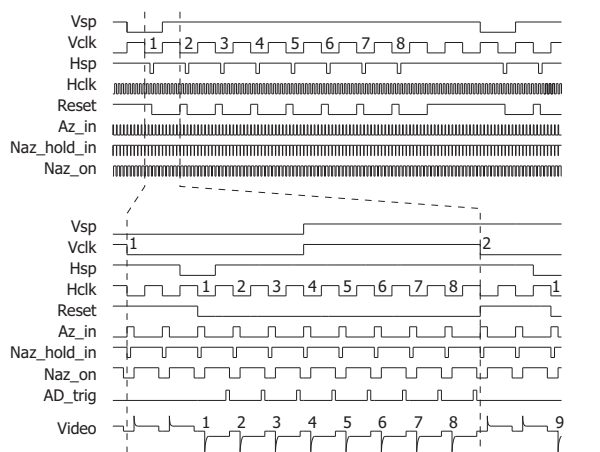


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### (1) Driving method

The voltage to linear and area arrays is supplied from a 5 V single power supply. The timing pulse to each terminal is input as shown in the timing chart below so that the signal (Video signal) from each element of the thermopile array is output in a time series.

[Figure 1-13] Timing chart (T11264 series)



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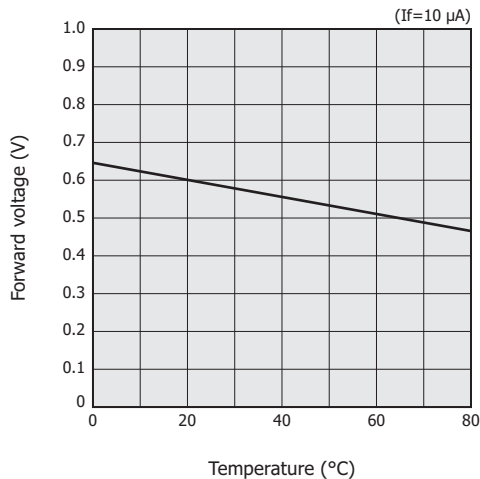
### (2) Temperature sensor

In linear and area arrays, a temperature sensor is mounted on the same chip where the thermopile is formed. When a constant current flows in this temperature sensor, a voltage signal can be obtained that is inversely proportional to the temperature. A Si diode is used in the temperature sensor, which typically has a temperature coefficient of approximately  $-2.2 \text{ mV}/^\circ\text{C}$ .

[Table 1-2] Digital input description (linear and area arrays)

Digital input	Description
Vsp, Hsp	Input logic signals needed to start the vertical/horizontal shift register scans. These inputs are required to scan the shift registers.
Vclk, Hclk	Input logic signals needed to switch the vertical/horizontal shift register channels. The shift register scan speed can be adjusted by changing the clock rate.
Reset	Input logic signal for setting the video output to a fixed potential while the pixel output signals are not read out
Video	This outputs the thermopile detector signals in synchronization with the vertical/horizontal shift register scan timing.
Az_in	Logic signals for driving the internal amplifier
Naz_hold_in	
Naz_on	
AD_trig	Timing signal for acquiring the video signal into an external A/D converter, etc. This is used in synchronization with the logic signals to the input terminals.

[Figure 1-14] Temperature sensor forward current vs. temperature (T11264 series, typical example)



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## 1 - 5 New approaches

We are further enhancing our in-house CMOS and MEMS technologies to develop thermopile detectors with higher performance and more sophisticated functions yet at a lower cost. We also plan to offer small thermopile detectors with a lens, which come in a wafer level package.

## 1 - 6 Applications

### CO<sub>2</sub> sensors

Thermopile detectors are used for non-dispersive infrared (NDIR) detection type CO<sub>2</sub> sensors. These CO<sub>2</sub> sensors allow precision measurements with high accuracy (minimal error deviation from the true value).

### Temperature and human body sensing in specific areas

Thermopile linear and area arrays are used for temperature and human body sensing in specific areas such as for air conditioner operation control. These can detect locations where persons are present and the direction that a person moves.

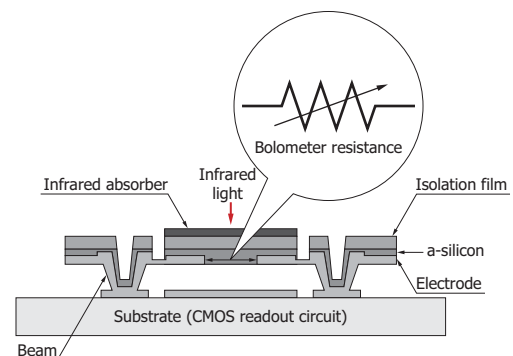
## 2. Bolometers

Bolometers are small infrared sensors that do not require cooling. When infrared light enters a bolometer, the bolometer resistance heats up, causing a change in its resistance. This change is converted into a voltage for readout. Bolometers include a readout circuit to minimize intrusion of external noise.

### 2 - 1 Operating principle and structure

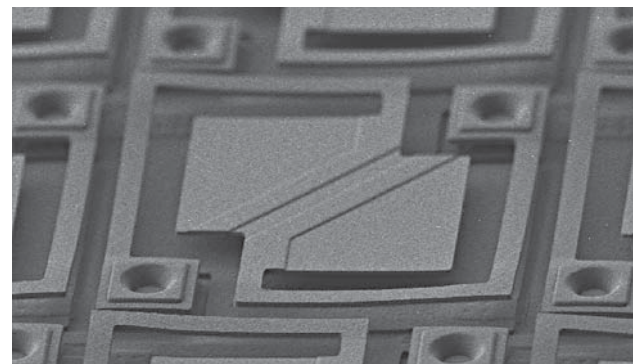
Since bolometers are thermal detectors, the membrane (thin film) that absorbs infrared light must be thermally isolated from the substrate, so the structure has two long, thin legs called “beams” to support the membrane. The membrane is formed by sacrificial layer etching and floats about 2 μm from the substrate. Infrared light radiated from an object is absorbed by the infrared absorber on the membrane, causing the membrane temperature to increase and the bolometer resistance to decrease. The incident light level can be read out as a voltage signal by applying an electric current to the bolometer resistance. As the bolometer resistance material, we use a-Si (amorphous silicon) whose resistance greatly varies with temperature. A CMOS readout circuit (ROIC: readout integrated circuit) is fabricated on the substrate.

[Figure 2-1] Cross-sectional view (one pixel)



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[Figure 2-2] Enlarged photograph of photosensitive area (bolometer)

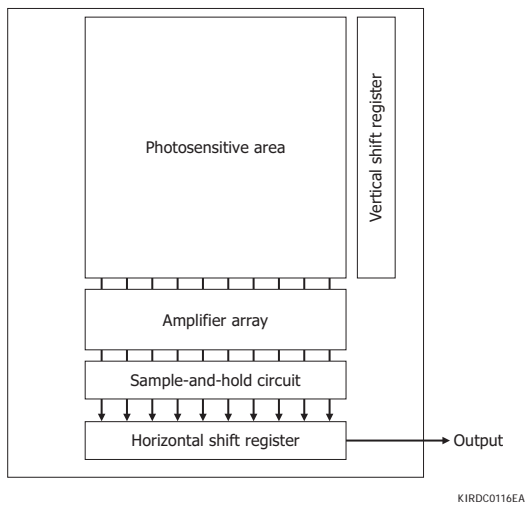




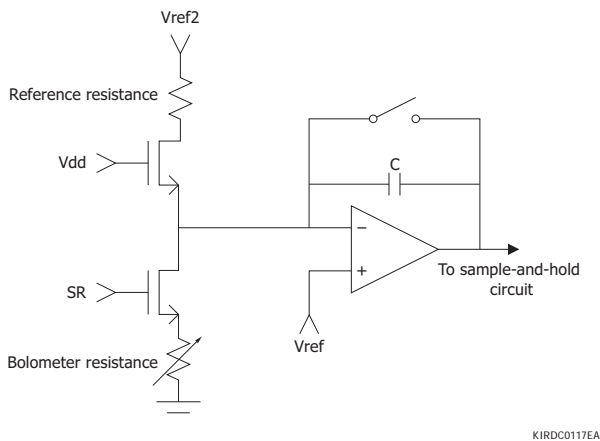
If there are gas molecules such as air around the membrane, the heat absorbed by the membrane is conducted to the gas molecules, causing the bolometer sensitivity to drop. To prevent this, bolometers are sealed inside a vacuum package.

Figure 2-3 shows a block diagram of a bolometer. The vertical shift register selects each pixel, and the amplifier array converts current changes to voltage changes, which are sampled and held, and are finally output from one line of the horizontal shift register. Figure 2-4 shows the readout circuit (one pixel) from the photosensitive area to the amplifier. This circuit has a reference resistance that is equivalent to the bolometer resistance, and both are connected in series so that changes in current equivalent to changes in the bolometer resistance are converted to voltage signals by a later stage amplifier.

[Figure 2-3] Block diagram (bolometer)



[Figure 2-4] Readout circuit (one element)



## 2 - 2 Characteristics

### Voltage sensitivity

The voltage sensitivity of a bolometer is defined as the output voltage divided by the infrared light level incident on the photosensitive area. The voltage sensitivity ( $R_v$ ) is expressed by equation (1).

$$R_v = \frac{\alpha \eta V_b}{G} \left[ 1 - \exp\left(-\frac{t}{\tau}\right) \right] \dots\dots\dots (1)$$

$\alpha$  : temperature coefficient of resistance  
 $\eta$  : infrared absorptance  
 $V_b$ : supply voltage  
 $G$  : thermal conductance  
 $t$  : readout time  
 $\tau$  : thermal time constant

If  $t \gg \tau$  in equation (1), the voltage sensitivity is expressed by equation (2).

$$R_v = \frac{\alpha \eta V_b}{G} \dots\dots\dots (2)$$

### Noise

Bolometer noise comes from several sources including thermal noise caused by temperature fluctuations in the bolometer resistance,  $1/f$  noise resulting from factors such as bolometer materials and electrical conductivity of contact, temperature fluctuation noise caused by temperature changes in the membrane, photon noise caused by photons in the environment, and readout circuit noise caused by the amplifier and other devices. Temperature fluctuation noise and photon noise are low compared to other sources of noise, so thermal noise and  $1/f$  noise are usually predominant.

The total noise ( $V_N$ ) of a bolometer is given by equation (3).

$$V_N = \sqrt{V_J^2 + V_{1/f}^2 + V_{TH}^2 + V_{PN}^2 + V_{ROIC}^2} \dots\dots\dots (3)$$

$V_J$  : thermal noise  
 $V_{1/f}$  :  $1/f$  noise  
 $V_{TH}$  : temperature fluctuation noise  
 $V_{PN}$  : photon noise  
 $V_{ROIC}$ : readout circuit noise

#### (1) Thermal noise

$$V_J = \sqrt{4k T R_{bol} (f_2 - f_1)} \dots\dots\dots (4)$$

$k$  : Boltzmann's constant  
 $T$  : membrane temperature  
 $R_{bol}$ : bolometer resistance  
 $f_1$  : lower limit of frequency bandwidth  
 $f_2$  : upper limit of frequency bandwidth

#### (2) $1/f$ noise

$$V_{1/f} = \sqrt{K V_b^2 \ln\left(\frac{f_2}{f_1}\right)} \dots\dots\dots (5)$$

$K$ :  $1/f$  coefficient

$f_1$  and  $f_2$  are respectively defined by equations (6) and (7).

$$f_1 \approx \frac{1}{4t_{stare}} \dots\dots\dots (6)$$

$t_{stare}$ : correction period of reference output

$$f_2 = \frac{1}{2t} \dots\dots\dots (7)$$

(3) Temperature fluctuation noise

$$V_{TH} = \frac{R_V}{\eta} \sqrt{4k T^2 G f_{TF}} \dots\dots\dots (8)$$

$f_{TF}$ : thermal equivalent noise bandwidth

$f_{TF}$  is defined by equation (9).

$$f_{TF} = \frac{1}{4\tau} \dots\dots\dots (9)$$

(4) Photon noise

$$V_{PN} = R_V \sqrt{\frac{8A \sigma k (T^5 + T_{BKG}^5) f_{TF}}{\eta}} \dots\dots\dots (10)$$

A : photosensitive area  
 $\sigma$  : Stefan-Boltzmann constant ( $5.67 \times 10^{-8} \text{ W/m}^2 \text{ K}^4$ )  
 $T_{BKG}$  : background temperature

### □ Noise equivalent power

Noise equivalent power (NEP), which corresponds to the S/N, is used to indicate the relation between the bolometer signal output and noise. The NEP signifies the incident light level required to obtain a signal output equivalent to the total noise level and is given by equation (11).

$$NEP = \frac{V_N}{R_V} \dots\dots\dots (11)$$

### □ Noise equivalent temperature difference

Noise equivalent temperature difference (NETD) is used to express the bolometer performance including the readout circuit. NETD indicates the temperature change that occurs when infrared light with a power equivalent to NEP enters the bolometer, and is given by equation (12).

$$NETD = \frac{4Fno^2 V_N}{R_V A \phi_{\lambda 1-\lambda 2} \pi L_{\lambda 1-\lambda 2}} \dots\dots\dots (12)$$

Fno : F number of optical system  
 $\phi_{\lambda 1-\lambda 2}$  : transmittance of optical system  
 $L_{\lambda 1-\lambda 2}$  : temperature contrast in wavelength interval  
 $\lambda$  : wavelength