Thermal Diode IR Sensor Technology

Author: *Daisuke Fujisawa**

1. Introduction

Uncooled infrared (IR) image sensors are typical sensors that combine Si-LSI and micromachining technologies. In recent years, the performance of these sensors has steadily improved thanks to advances in micromachining technologies. There are several types of uncooled IR image sensors. Mitsubishi Electric Corporation has proposed and developed the thermal diode type in which monocrystalline Si diodes formed on Silicon On Insulator (SOI) layers are used as thermal sensors.[(1)(2)(3)(4)(5)(6)] This type, for which diodes made from Si monocrystals are used at the thermal sensor sections, is characterized by excellent uniformity of sensitivity in the screens of image sensors. There are demands for uncooled IR image sensors with smaller pixel size to reduce cost, and more pixels to increase image resolution. Technologies to satisfy such needs have been developed. This paper describes a technology for thermal diode IR sensors, which is an expanding market (e.g., consumer goods).

2. Thermal Diode IR Sensors

2.1 Thermal diodes

Figure 1 shows a cross section of the pixel structure of a thermal diode IR sensor. In the well heat-insulated thermal sensor section, the thermal diodes are retained with support legs over cavities formed in the substrate. Based on the dose of incident infrared radiation, the temperature of the thermal diodes changes. A forward bias constant current is supplied to the diodes from the outside and the dose of incident infrared radiation is read as the change in forward voltage caused by the change in diode temperature. This uses the characteristic of thermal diodes (thermal sensors) that when their temperature increases due to incident infrared radiation, the forward voltage (V_f) decreases with a constant current behavior. In addition, the sensitivity of a thermal diode IR image sensor to the temperature of a subject is proportional to the temperature change coefficient (dV_f/dT) of the forward voltage (V_f) of the thermal diodes. Because this coefficient depends on the number of diodes connected in series, increasing the number of diodes connected in series within the drive (power source) voltage enhances the sensitivity of the sensor.

2.2 Chip-scale packaging

For an uncooled IR image sensor, pixels (thermal sensors) with a thermal insulation structure are formed on a silicon substrate and so the thermal diodes (thermal sensors) need to be kept under vacuum. Conventionally, the entire sensor was vacuum-sealed using a ceramic package or other part. However, this method increases the cost and size. Mitsubishi Electric has therefore developed a chip-scale packaging technology. In this method, as shown in Fig. 2, a seal frame is formed to surround the pixel area, a window part that lets infrared radiation through is bonded, and only the pixel area is sealed under vacuum. The chip-scale packaging technology eliminates the need for conventional ceramic packages, greatly reducing the sensor size.

2.3 Measurement of subject temperature

The output of a thermal diode IR sensor is a function of the emissivity of a subject, subject temperature, sensor temperature, and sensor module temperature.

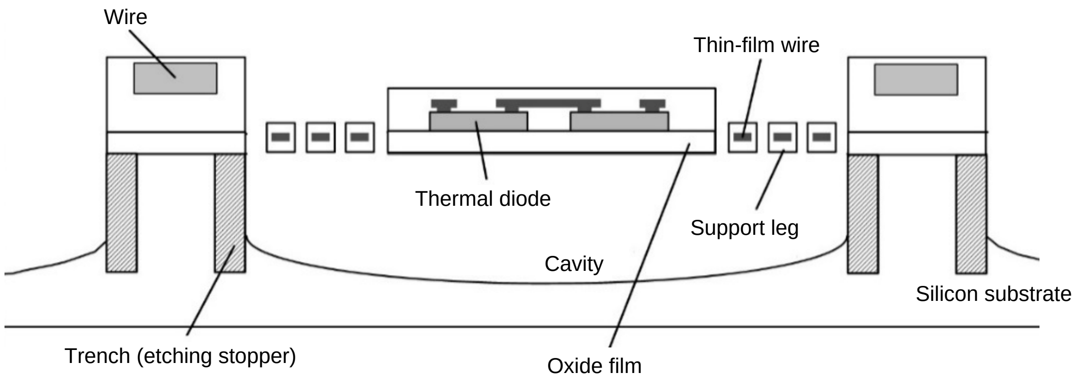

Fig. 1 Pixel structure of thermal diode IR sensor

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Therefore, the output of a thermal diode IR sensor changes depending on the offset of each pixel output, its sensitivity to radiation, and temperature characteristics. Accordingly, the shutter needs to be closed at certain intervals to enable the sensor to see a subject (shutter) of uniform temperature in order to correct the characteristics of each pixel. Figure 3 shows an example of the environmental temperature dependence of sensor output on subject temperature.

In our thermal diode method, monocrystalline Si diodes are used and so, in the temperature range of normal sensor environments, the relationship is almost linear. Therefore, even when two-point signal correction based on data under two environmental temperature conditions (20°C, 40°C) is applied, FPN is 0.1°C or lower, which provides sufficient performance for temperature analysis in units of 0.1°C. The value of FPN is obtained by converting the standard deviation of each pixel output of a thermal diode IR image sensor when a subject of uniform temperature is pictured into the subject temperature. A smaller value of FPN is better.

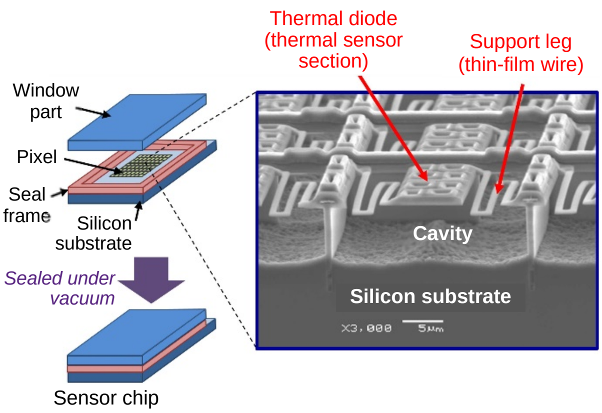

Fig. 2 Chip-scale vacuum package

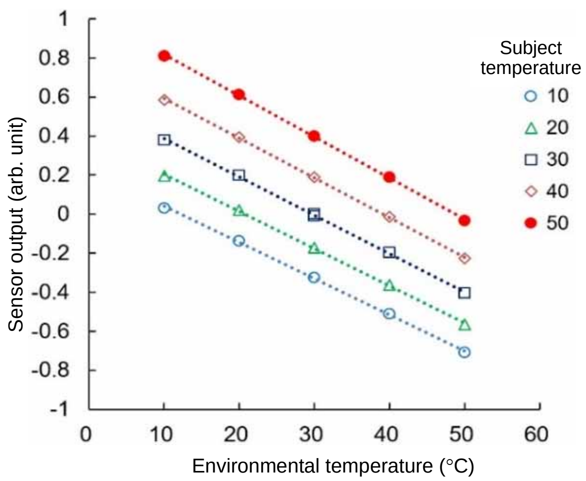

Fig. 3 Environmental temperature dependence of sensor

3. Development of Higher-Performance IR Sensors

3.1 Technology for downsizing thermal diodes

The downsizing of each pixel in 2-dimensional pixel arrays of thermal diode IR sensors reduces the sensor chip size, which can reduce the cost and also the size of sensor modules including the optical systems. Consequently, downsizing of pixels is an important trend in the development of uncooled IR sensors. For example, if the pixel pitch is reduced from 25 µm to 17 µm, the pixel area is reduced by half, greatly reducing the area of the thermal sensor section. Therefore, to maintain the sensitivity, some measures are required: (1) higher sensitivity of thermal sensors and (2) higher heat insulation of support legs. The thermal diode method has a characteristic that the greater the number of diodes connected in series, the higher the sensitivity. Therefore, it is important to reduce the area of a single diode. In the conventional structure, PN diodes are connected in series by dividing them with isolation regions of oxide films. Mitsubishi Electric has developed a 2-in-1 diode structure in which a PN diode and NP diode are paired and connected without an isolation region. This structure can reduce the area of diodes by over 15%.

3.2 High-sensitivity readout circuit technology

It is also important to improve the sensitivity of thermal diode IR sensors to enhance the accuracy of measurement of subject temperature. As described above, one way to enhance the sensitivity is to increase the number of diodes connected in series at a thermal sensor section, but this requires a higher source voltage. If there is a limitation on the source voltage, the higher-sensitivity readout circuit shown in Fig. 4 can be used to increase the sensitivity without changing the number of diodes connected in series.

As the diode temperature increases (decreases), the forward voltage (V_f) decreases (increases). The gate voltage at Md, which is obtained by subtracting V_f from the source voltage, increases (decreases) and the current at Md decreases. This decrease (increase) in the current reduces (increases) the diode current (I_f) by the current mirror circuit. This further reduces (increases) the diode forward voltage. Therefore, because the circuit configuration illustrated in Fig. 4 has a positive feedback loop for the change in diode forward voltage (V_f) and the change in diode current (I_f), the obtained change in output voltage is more than the change in pixel output voltage obtained by a single diode, which increases the sensitivity for a single diode. Figure 5 shows the output characteristics of a sensor using this higher-sensitivity readout circuit.

As a result of using the higher-sensitivity readout circuit, the diode temperature change coefficient (dV_f/dT)

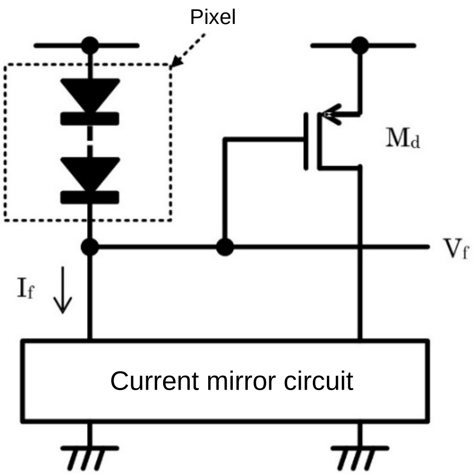

Fig. 4 Circuit diagram

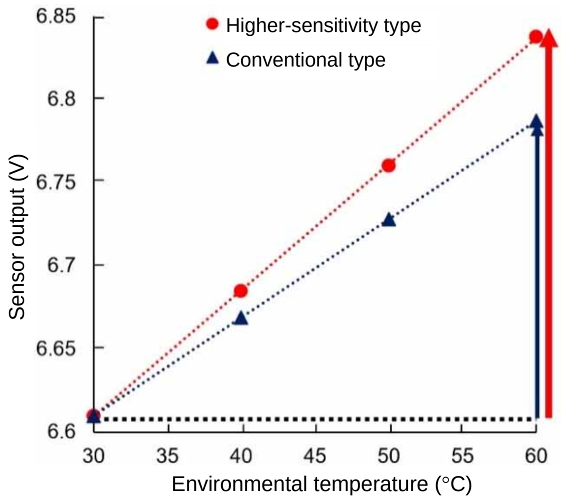

Fig. 5 Temperature dependence of output (V_f)

is 1.9 mV/K (per piece), which is approximately 1.3 times (per piece) that of the conventional readout circuit. When circuits in this configuration are arrayed, a positive loop circuit, current source, and integration circuit are provided for each row of the array of multiple pixels.

4. Conclusion

This paper introduced the thermal diode IR sensor technology. For thermal diode IR sensors, the thermal sensors can be manufactured by Si-LSI technology and so the method is suitable for cost reduction and mass production. These sensors can be applied to various purposes, such as crime prevention, monitoring, air conditioning, lighting, equipment control, counting numbers of people, and measurement and monitoring of body temperature. Low-priced IR sensors are expected to become increasingly important in the consumer goods sector and thermal diode IR sensors are likely to be key devices for developing new IR sensor applications.

References

(1) D. Takamuro., et al.: Proc. SPIE, Vol. 8012, 80121E (2011)
(2) D. Fujisawa., et al.: Proc. SPIE, Vol. 8353, 83531G (2012)
(3) D. Fujisawa., et al.: Proc. MEMS 2015, 905–908 (2015)
(4) D. Fujisawa., et al.: Proc. SPIE, Vol. 10624, 1062421 (2018)
(5) D. Fujisawa., et al.: Proc. SPIE, Vol. 11002, 110022C (2019)
(6) D. Fujisawa., et al.: Proc. SPIE, Vol. 11407, 114071A (2020)