A High-Speed Thermoelectric Infrared Sensor Fabricated by CMOS Technology and Micromachining

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A High-Speed Thermoelectric Infrared Sensor Fabricated by CMOS Technology and Micromachining

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Keywords : infrared sensors, thermopiles, thermoelectric, Au-black

In recent years, much attention has been paid to uncooled or thermal infrared sensors on account of their ability to operate at room temperature and their low cost. However, the response speed of thermal sensors has not been adequate enough in many applications such as for monitoring the temperature of moving workpieces in production processes. A thermoelectric infrared sensor (thermopile) is the most promising candidate for this application in comparison with microbolometers and pyroelectric devices.

The sensitivity R and response time constant τ_{th} of the thermopiles are given by

$$R = n \bullet \alpha \bullet R_{th} \bullet \eta \quad \cdots (1)$$

$$\tau_{th} = C_{th} \bullet R_{th} \quad \cdots (2)$$

where n is the number of pairs of thermocouples, α is the Seebeck coefficient (sum of p-type and n-type polysilicon), η is infrared absorptivity, and C_{th} is the thermal capacitance of the thermopiles. Thus, a reduction of C_{th} while maintaining the sensitivity improves the response time. For improving performance, it is necessary to reduce the size of an element.

The optimization of the sensor structure and the results of a thermal equivalent circuit simulation performed with the Simulation Program with Integrated Circuit Emphasis (SPICE). The dimensions of a prototype sensor are as follows: the thickness of the Si_3N_4 films and polycrystalline silicon of the thermocouples is 300 nm and 400 nm, respectively, the total device area is 144 μm × 144 μm, the Au black absorber is 112 μm × 112 μm, and the thermopiles are 8 μm long by 1 μm wide. The internal resistance of the device is 50 kΩ. The shorter the thermopile length, the smaller the internal resistance is. As a result, the signal processing is relatively simple.

The fabrication process is based on the conventional CMOS process. The membrane structure is then formed by a micromachining technique involving anisotropic etching using hydrazine. A precisely patterned Au black infrared absorption layer black, which is deposited by an evaporation method in a nitrogen gas atmospheree, is formed by a PSG lift-off process.

The time constant of the fabricated sensor was evaluated by irradiating the device with a chopped He-Ne laser. A time constant of 270 μsec, which is smaller than any other reported value of thermopiles, was obtained from the measurement. The sensitivity of the prototype thermopile was also evaluated by irradiating the device with infrared radiation from a blackbody heated to 500 K. The measured sensitivity R and defectivity D* at atmospheric pressure were about 60 V/W and 2×10^7 cm • $(Hz)^{1/2}$/W, respectively. It is thought that the sensitivity and the time constant of the sensor can be further improved by reducing the thickness of the isolation layers.

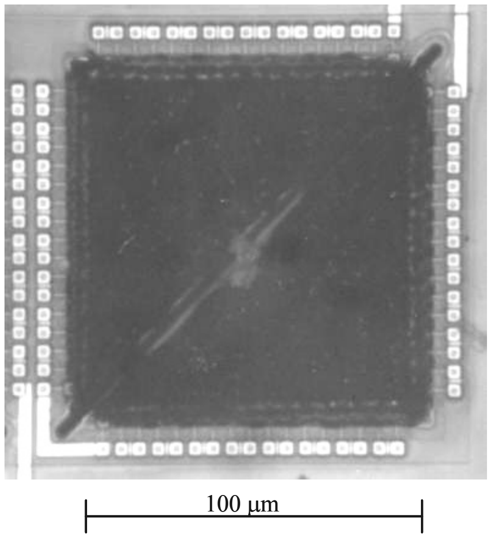

Fig. 1. A micrograph of the prototype sensor

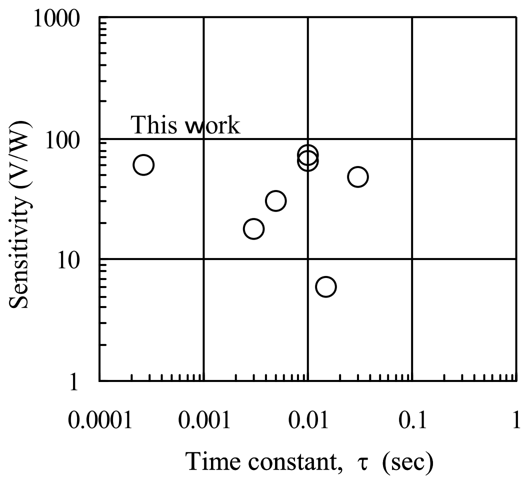

Fig. 2. Performance comparison between the prototype sensor and conventional sensors

Paper

A High-Speed Thermoelectric Infrared Sensor Fabricated by CMOS Technology and Micromachining

Masaki Hirota*, Member

A high-speed thermoelectric infrared sensor has been fabricated by the CMOS process and micromachining. The time constant of the sensor has been reduced by means of a reduction of sensor size and a thin Si_3N_4 membrane structure. The sensitivity has been improved with a precisely patterned Au black infrared absorption layer formed by a PSG lift-off process. The characteristics of the sensor have been simulated using a thermal equivalent circuit model. A time constant of 270 μsec and sensitivity of 60 V/W at atmospheric pressure have been achieved. This time constant is smaller than any other reported value of thermopiles.

Keywords : infrared sensors, thermopiles, thermoelectric, Au-black

1. Introduciton

An infrared sensor is useful for recognizing heat sources, such as living things and powered machines, against a complex background both day and night. A cooled infrared sensor has outstanding characteristics of high sensitivity and fast response speed. However, the sensor cost is very expensive due to the semiconductor material itself and the use of a cooler.

In recent years, much attention has been paid to uncooled or thermal infrared sensors on account of their ability to operate at room temperature and their low cost. An uncooled sensor does not have the mechanical parts of a cooled sensor, giving it superior reliability over the latter. However, uncooled sensors have the disadvantages of low sensitivity and a slow response speed in comparison with their cooled counterparts. The low sensitivity of thermal sensors has been improved by means of surface micro-machining and/or a marked change in characteristics at phase transformation. As a result, a high-sensitivity microbolometer and a pyroelectric device have been reported[(1)-(3)].

Nevertheless, the response speed of thermal sensors has not been adequate enough in many applications such as for monitoring the temperature of high speed moving objects such as rotaining tire, brake rotor, and workpieces in production processes. A thermoelectric infrared sensor (thermopile)[(4)-(11)], which uses a themovoltaic effect, is the most promising candidate for this application in comparison with microbolometers and pyroelectric devices. A thermopile fabricated of polycrystalline Si offers the advantages of compatibility with the complimentary metal-oxide-semiconductor (CMOS) process and a high Seebeck constant.

This paper presents the theory for the optimization of the sensor structure and the results of a thermal equivalent circuit simulation performed with the Simulation Program with Integrated Circuit Emphasis (SPICE). It also describes the sensor design and fabrication in which a Au black infrared absorber is precisely patterned in a lift-off process.

2. Sensor Structure

A thermopile detects the intensity of incident infrared radiation by using tiny thermocouples to convert the temperature rise of a Au-black absorber, resulting from infrared absorption, to a voltage signal (Fig. 1). To increase the absorptivity of incident infrared radiation, we have developed a Au-black absorber that achieves high infrared absorptivity of more than 90%. The thermocouples are fabricated of p-type and n-type polysilicon, which allows the use of low-cost ultra-fine microfabrication technology commonly employed in the conventional semiconductor manufacturing process. Thermocouple pairs are connected in series to enhance sensitivity.

Fig. 2 shows a cross-sectional view of a prototype sensor. The device consists of a thin Si_3N_4 membrane, thirty-four pairs of thermocouples on the membrane, an isolation layer on the thermocouples, and an infrared absorber fabricated of precisely patterned Au-black on that layer. The hot junctions of the thermocouples are on the membrane near the edge of the infrared absorber and the cold junctions are on the silicon frame. Each thermocouple is composed of p-type and n-type polycrystalline silicon, and the thermocouples are interconnected by an Al layer.

The dimensions of the device are as follows: the thickness of the Si_3N_4 films and polycrystalline silicon of the thermocouples is 300 nm and 400 nm, respectively, the total device area is 144 μm × 144 μm, the Au black absorber is 112 μm × 112 μm, and the thermopiles are 8 μm long by 1 μm wide. The internal resistance of the device is 50 kΩ. The shorter the thermopile length, the smaller the internal resistance is. As a result, the signal processing

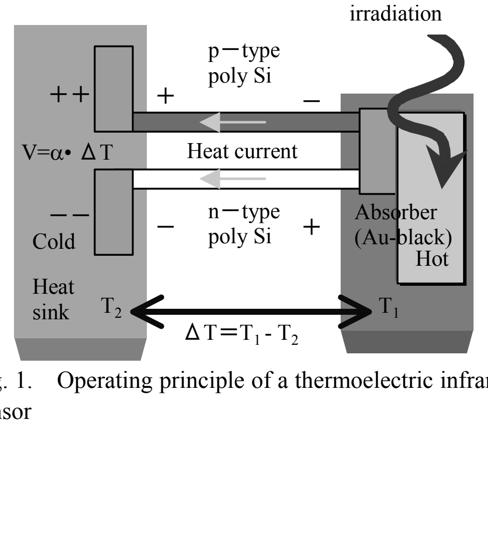

Fig. 1. Operating principle of a thermoelectric infrared sensor

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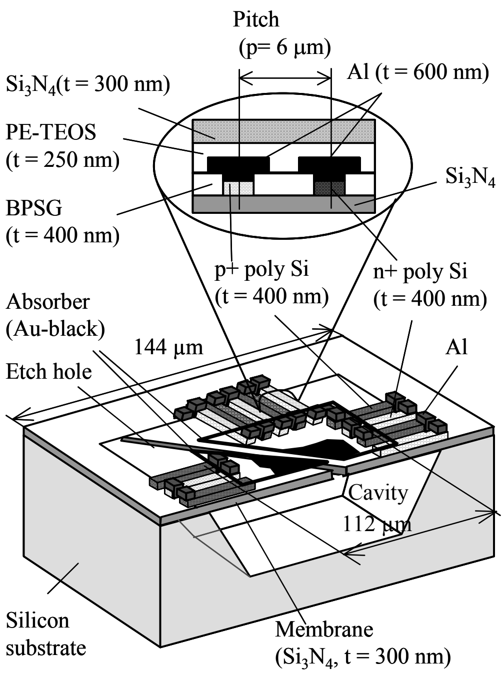

Fig. 2. A cross-sectional view of a prototype sensor

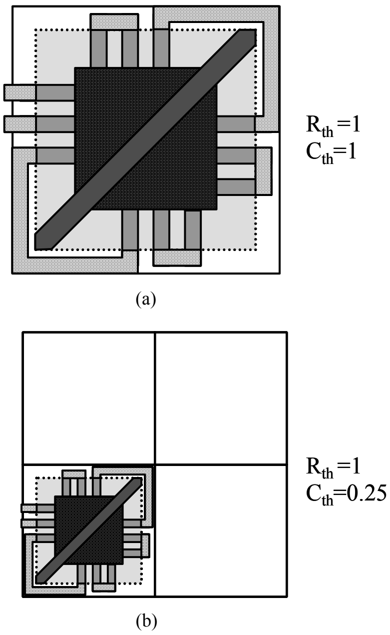

Fig. 3. Technique for improving response time constant; (a) a conventional sensor and (b) a high-speed device

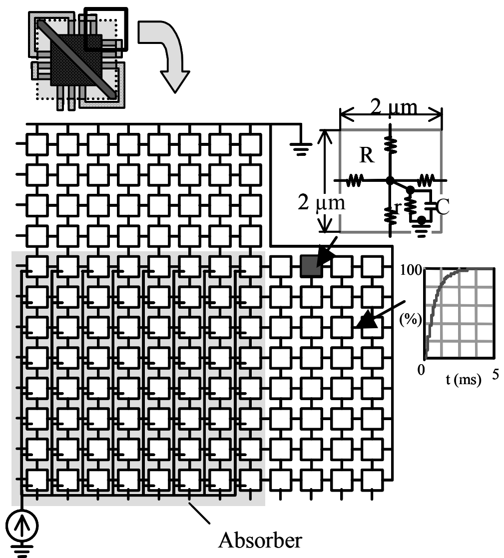

Fig. 4. Schematic view of the thermal equivalent circuit of the sensor used in the performance simulation

is relatively simple.

3. Simulation Aiming for High-Speed Response

The sensitivity R of the thermopiles is given by

$$R = n \cdot \alpha \cdot R_{th} \cdot \eta \quad \cdots\cdots (1)$$

where n is the number of pairs of thermocouples, α is the Seebeck coefficient (sum of p-type and n-type polysilicon), R_{th} is the thermal resistance between the hot and cold junctions and η is infrared absorptivity. The time constant τ_{th} is given by

$$\tau_{th} = C_{th} \cdot R_{th} \quad \cdots\cdots (2)$$

where C_{th} is the thermal capacitance of the thermopiles. Thus, a reduction of C_{th} while maintaining the sensitivity improves the response time. The thermal resistance R_{th} is a ratio of the thermal propagation length and the cross-sectional area of the thermopiles and membrane. The cross-sectional area of the thermopiles depends on the size of the sensor and the thickness of the materials of which the device is constructed. For improving sensitivity, it is necessary to reduce the size of an element as shown in Fig. 3.

A suitable configuration for the thermopile device was determined on the basis of a thermal equivalent circuit simulation. In the simulation, a calculation was made of the dependence of responsivity R on the thermopile length, defined as the distance between the hot and cold junctions. A part of the circuit model used is shown in Fig. 4. An area of 2 μm × 2 μm was used as a unit cell. The potentials in the circuit were calculated by SPICE. Mathematically approximated equations, related to the sensitivity and the time constant, were formulated from the results of the SPICE simulation. The thermopile length and the thickness of each layer were used as easily changeable parameters in order to vary the design and fabrication conditions.

Fig. 5 shows typical simulation results for the sensitivity and time constant as a function of the thermopile length. Results like these were used in fabricating the prototype thermopile sensor. When the thermopile length is shorter than a few times the thickness of the membrane, or a few microns, the time constant of the device mainly depends on the delay due to the thermal capacitance under the infrared absorber. However, in the longer region, the time constant is related to the delay due to the thermal conductance and the thermal capacitance in the thermopile length, in addition to the delay due to the thermal capacitance under the infrared absorber. This suggests that if the thermopile size and structure are constant, the time constant has a limit. In this case, a time constant of about 0.2 msec is the limit. The sensitivity of the thermopiles as given in Eq. 1 shows nearly a linear dependence on the thermopile length, so the time constant and sensitivity have to be adapted in order to determine the best thermopile length. With the aim of striking a balance between a small time constant and high sensitivity, the thermopile length was set at 8 μm as shown in Fig. 5.

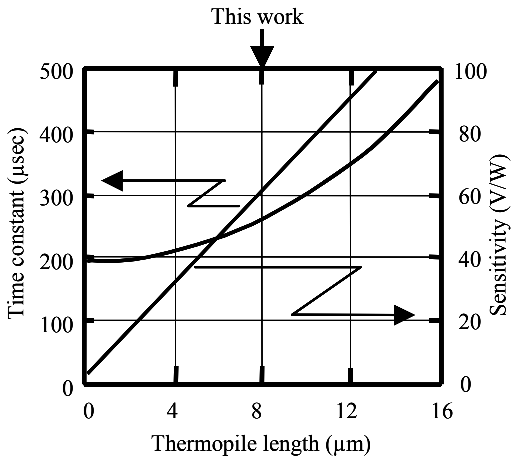

Fig. 5. Simulation results for the time constant and sensitivity as a function of the thermopile length

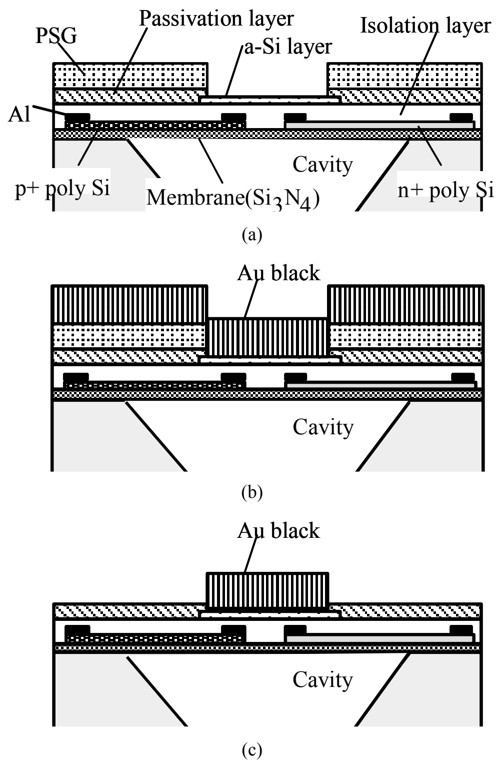

Fig. 6. Flow chart of the fabrication process of the Au-black absorber; (a)PSG sacrificial layer formation, (b)Au-black deposition (P=266 Pa) and (c)Lift-off process

4. Fabrication

The fabrication process is based on the conventional CMOS process[12]. Fig. 6 shows the fabrication process of the absorber. After the CMOS process, amorphous Si (a-Si) is deposited to a thickness of 100 nm on the isolation layer by a rf sputtering deposition method. A PSG sacrificial layer is then formed by atmospheric CVD. The PSG sacrificial layer is precisely patterned by a dry etching method in the region of the infrared absorber. The membrane structure is then formed by a micromachining technique involving anisotropic etching using hydrazine. The process to this point is shown in Fig. 6(a). After that, the Au black

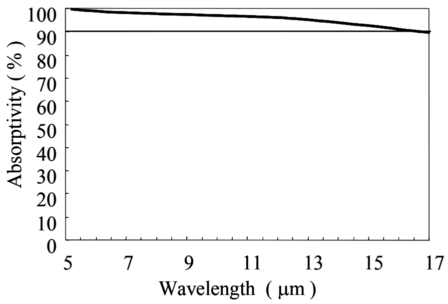

Fig. 7. Absorptivity of the deposited Au-black layer

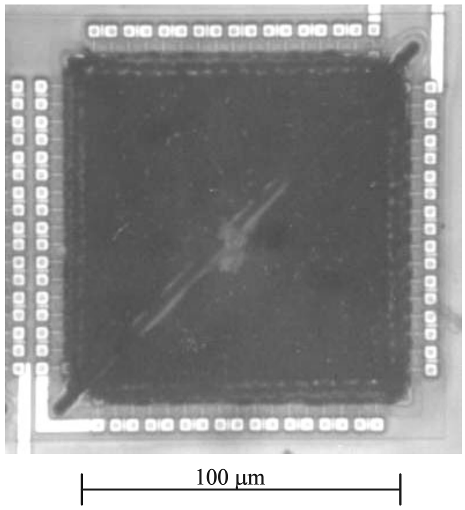

Fig. 8. A micrograph of the prototype sensor

is deposited by an evaporation method in a nitrogen gas atmosphere. The pressure during deposition is kept at 266 Pa as shown in Fig. 6(b). The spectral distribution of Au-black absorptivity is shown in Fig. 7. The reflectivity and transparency of the Au-black layer deposited on FZ-Si were measured with a Fourier Transform Infrared (FT-IR) device, and absorptivity was then calculated with Eq. (3). The deposited Au-black layer had high absorptivity of more than 90% in a wavelength range of 8-13 μm. This absortivity was much higher than that of the memberane and isolation layers of about 50%.

(absorptivity) = 1− (reflectivity＋transparency)··········(3)

Then, the sacrificial PSG layer is etched off by NH_4F:CH_3COOH:H_2O (1:1:1), and simultaneously the Au black layers on the PSG are removed. Only the Au black layer at the center of the membrane remains. The formation accuracy of this process is about 1,000 times greater than that of conventional partial evaporation deposition and the dripping method. This makes it possible to form the Au-black absorber, which has been difficult to pattern precisely, with the same patterning accuracy as that of the conventional CMOS IC process. Finally, the wafer is thoroughly rinsed in deionized water. The result obtained is shown in Fig. 6(c). Fig. 8 shows a micrograph of the prototype sensor. The black part located in the center is the precisely patterned Au-black absorber.

5. Results

The time constant of the fabricated sensor was evaluated by irradiating the device with a chopped He-Ne laser. The

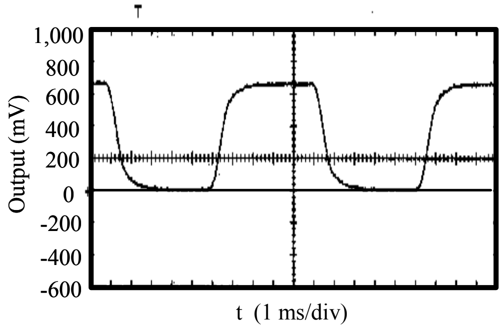

Fig. 9. Measured output waveform of the prototype sensor

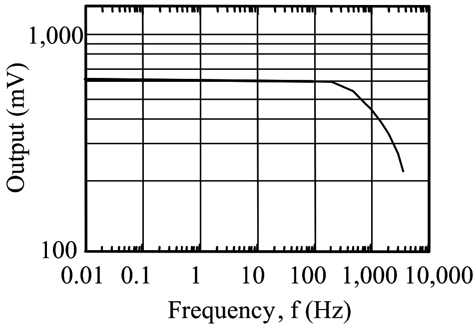

Fig. 10. Frequency characteristics of the prototype sensor

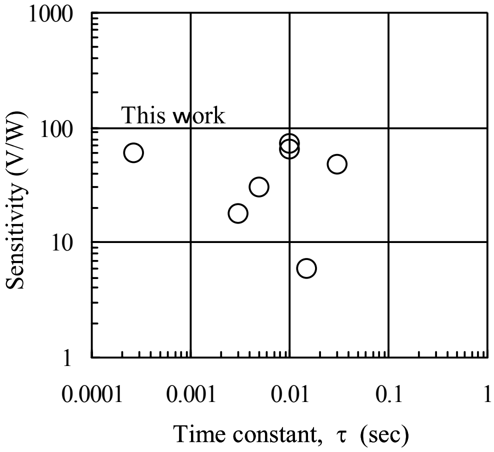

Fig. 11. Performance comparison between the prototype sensor and conventional sensors

thermovoltaic signal was first amplified 100 times, and the ouput response waveform was memorized and plotted. A typical example is shown in Fig. 9. The vertical axis indicates the output voltage which was amplified 100 times, and the horizontal axis indicates time in milliseconds. The chopping frequency was 100 Hz. The waveform suggests that the prototype thermopile has sufficiently fast response. The peak-to-peak value of the thermoelectric electromotive force is plotted as the chopping frequency in Fig. 10. A time constant of 270 µsec was obtained from the measurement. This value includes both the thermal and electrical time constants. However, it is almost the same as the thermal time constant, because the electrical time constant is sufficiently small in comparison with the thermal time constant. This value of 270 µsec almost coincides with the simulated value in Fig. 4. It is very close to the limit of 200 µsec for the given size and structure. This time constant is the smallest value reported to date for thermal infrared sensors[(6)-(11)] as shown in Fig. 11.

The sensitivity of the prototype thermopile was also evaluated by irradiating the device with infrared radiation from a blackbody heated to 500 K. The measured sensitivity R and defectivity D* at atmospheric pressure were about 60 V/W and 2×10^7 cm • $(Hz)^{1/2}$/W, respectively.

6. Conclusion

This paper has presented a thermoelectric infrared sensor characterized by high response speed. A time constant of 270 µsec has been obtained, which is smaller than any other reported value of thermopiles. The sensor was fabricated with the standard CMOS process and a micromachining technique. In addition, PSG lift-off technology was employed. It is thought that the sensitivity and the time constant of the sensor can be further improved by reducing the thickness of the isolation layers.

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References

(1) R. A. Wood, C. J. Han, and P. W. Kruze : "Integrated uncooled IR detector imaging arrays", Proc. of the IEEE Solid State Sensor and Actuator Workshop, pp.132-135 (1992)
(2) C. Hanson : "Uncooled thermal imaging at Texas Instruments", *SPIE*, Vol.1689, pp .330-339 (1993)
(3) A. Tanaka, S. Matsumoto, N. Tsukamoto, S. Itoh, T. Endo, A. Nakazato, Y. Kumazawa, M. Hijikawa, H. Gotoh, T. Tanaka, and N. Teranishi : "Silicon IC Process Compatible Bolometer Infrared Focal Plane Array", Trans. '95, pp.632-635 (1995)
(4) A. W. Herwaarden and P. M. Sarro : "Thermal sensors based on the Seebeck effect", *Sensors and Actuators A*, Vol.10, pp.321-346 (1986)
(5) T. Kanno and M. Saga : "Uncooled infrared focal plane array having 128 × 128 thermopile detector elements", *SPIE*, Vol.2269, pp.450-459 (1994)
(6) W. G. Baer, K. Najafi, K. D. Wise, and R. S. Toth : "A 32-element micromachined thermal imager with on-chip multiplexing", *Sensors and Actuators A* 48, pp.47-54 (1995)
(7) G. R. Lahiji and K. D. Wise : "A batch-fabricated silicon thermopile infrared detector", *IEEE Trans. on Electron Device*, Vol.ED-29, No.1, pp.14-22 (1982-1)
(8) R. Lenggenhanger, H. Baltes, and T. Elbel : "Thermoelectric infrared sensors in CMOS technology", *Sensors and Actuators A*, Vol.37-38, pp.216-220 (1993)
(9) A. D. Oliver, W. G. Baer, and K. D. Wise : "A bulk-micromachined 1024-element uncooled infrared imager", Trans. '95, pp.636-639 (1995)
(10) M. Mueller, R. Gottfried- Gottfried, H. Kueck, and W. Mokwa : "A fully CMOS-compatible infrared sensor fabricated on SIMOX substrates", Sensors and Actuators A 41-42, pp.538-541 (1995)
(11) J. Schieferedecker, R. Quad, E. Holzenkaempfer, and M. Schulze : "Infrared thermopile sensors with high sensitivity and very low temperature coefficient", Sensors and Actuators, A 46-47, pp.422-427 (1995)
(12) M. Hirota and S. Morita : "Infrared sensor with precisely patterned Au-black absorption layer", *SPIE*, Vol.3436, pp.623-634 (1998)

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