Proposal of A New Structure Thermal Vacuum Sensor with Diode-Thermistors Combined with a Micro-Air-Bridge Heater

M. Kimura, F. Sakurai, H. Ohta, T. Terada

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PROPOSAL OF A NEW STRUCTURE THERMAL VACUUM SENSOR WITH DIODE-THERMISTORS COMBINED WITH A MICRO AIR–BRIDGE HEATER

Mitsuteru Kimura, Fumitoshi Sakurai**, Hirao Ohta** and Tomoyuki Terada***

* Dep. of Electrical Eng. & Information Tech., Tohoku-Gakuin University,
** MEMS CORE Co., Ltd

ABSTRACT

A new structure thermal vacuum sensor with two pn junction diodes, Th-A and Th-B, as a high sensitive temperature sensor working like a thermistor and a micro heater formed on a micro air–bridge is proposed. The micro air–bridge is separated into two regions of A and B. The Th-A measures the temperature of the micro-heater formed on the region A and the Th-B does that of the region B which is connected to the micro-heater with thermal resistance. The diode thermistor, Th-C, formed on the SOI substrate is provided to measure the ambient temperature Tc. Vacuum pressure is measured based on heat dissipation change from the heated micro air–bridge to ambient gas. It is demonstrated that this sensor will expand the measuring vacuum range into about two orders or more wider range (2×10^{-3}-1×10^{5} Pa) than the traditional thermal vacuum sensor, such as Pirani vacuum sensor, and has very fast response and low power consumption.

1. INTRODUCTION

Principle of the thermal vacuum sensor, such as Pirani vacuum sensor, is based on the dependence of the thermal conductivity and convection of the ambient gas on the vacuum pressure, namely based on measuring the heat loss of the hot object.

Author (M. Kimura) has proposed a micro air–bridge heater fabricated by using silicon planar technology and micromachining of silicon, and suggested that this micro air–bridge heater with a temperature sensor will be used as a flow sensor, thermal vacuum sensor, etc. to improve their sensitivity due to larger interaction area with the air and thermal isolation of the hot suspended film [1].

Efforts on improvement of the sensitivity of the thermal vacuum sensor, such as Pirani vacuum sensor, have been reported [2-6]. Especially Herwaarden et al. have first demonstrated improved sensitivity of the Pirani gauge by use of the hot floating membrane (micro air – bridge) and thermopile as a temperature sensor instead of the hot wire of Pirani gauge [2].

Berlicki et al. have analyzed the ambient temperature influence on the performance of thin-film sensor, fabricated in a thin-film process and have improved the sensitivity of the thin film vacuum sensor [3, 4]. However, the floating thin film was made of glass foil with relatively large dimensions of 10x10x0.07mm, and relatively small sensitivity temperature sensor of thermopile.

Eminoglu et al. have developed uncooled infrared microbolometer detector with a suspended pn junction diode as a temperature sensor, however, use of this diode is traditional IC temperature sensor which is based on the temperature dependence of forward voltage change on temperature at a constant current [7].

In this paper a new structure thermal vacuum sensor with three pn junction diodes as a high
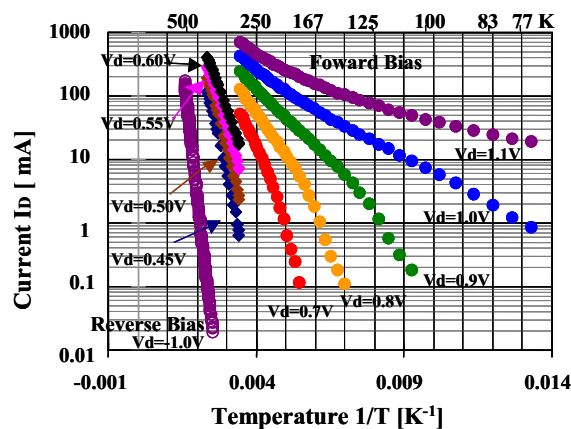

Fig.1 Temperature T dependence of the pn-diode current ID as a parameter of bias-voltage Vd.

sensitive temperature sensor working like a thermistor (we call this "diode thermistor") and a micro air−bridge heater is proposed and it is demonstrated that this sensor has about two order or more wider sensitivity (2×10^{-3}-1×10^{5} Pa) than the traditional thermal vacuum sensor, such as Pirani vacuum sensor, and has very fast response and very low power consumption.

2. EXPERIMENTAL

2.1. Diode-thermistor and its characteristics

Author (M. Kimura) has proposed the very high sensitive diode-thermistor acting as a variable sensitivity NTC thermistor [8-10]. The temperature sensitivity of this pn junction diode sensor can be adjusted by the forward bias-voltage, since the diode current I of this sensor has an exponential factor with respect to the reciprocal absolute temperature T at a constant bias-voltage V. This diode-thermistor is more sensitive and different from the usual diode temperature sensor based on the temperature dependence of the forward voltage change at the constant forward current.

Characteristics of this diode-thermistor are shown in Fig.1.

For a given bias-voltage V of the pn-diode, the diode current I can be expressed by next equations.

$$log \quad I = -B \ \frac{1}{T} + C \qquad (1)$$

$$B = q \ \frac{(V_d - V)}{nk} \qquad (2)$$

, where q is electronic charge, Vd diffusion potential, n the ideal factor of about 1, k Boltzmann constant, C a constant determined by properties of Si material. B is the same as thermistor constant.

2.2. Structure and working principle of the sensor

Author (M. Kimura) has proposed a new thermal conduction type gas sensor using the three temperature sensors and microheater formed together on the micro-air-bridge, and this sensor is applied to the humidity sensor [10].

In this paper this sensor is applied to the thermal vacuum sensor. Two temperature sensors as a diode thermistor, Th-A (A diode) and Th-B (B diode), are formed on separated region A and B, respectively, of a micro air−bridge (floating membrane). These region A and B are thermally and weakly connected
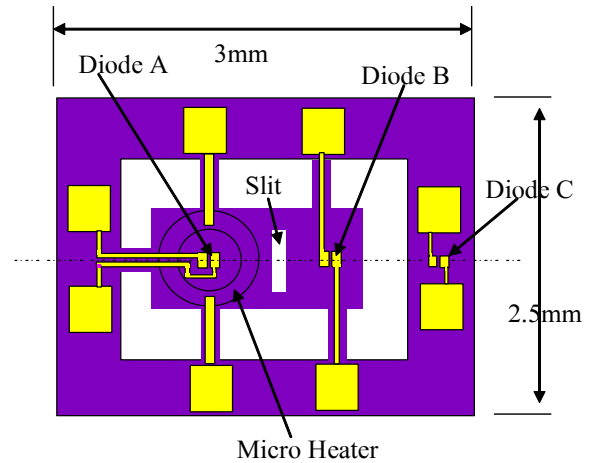

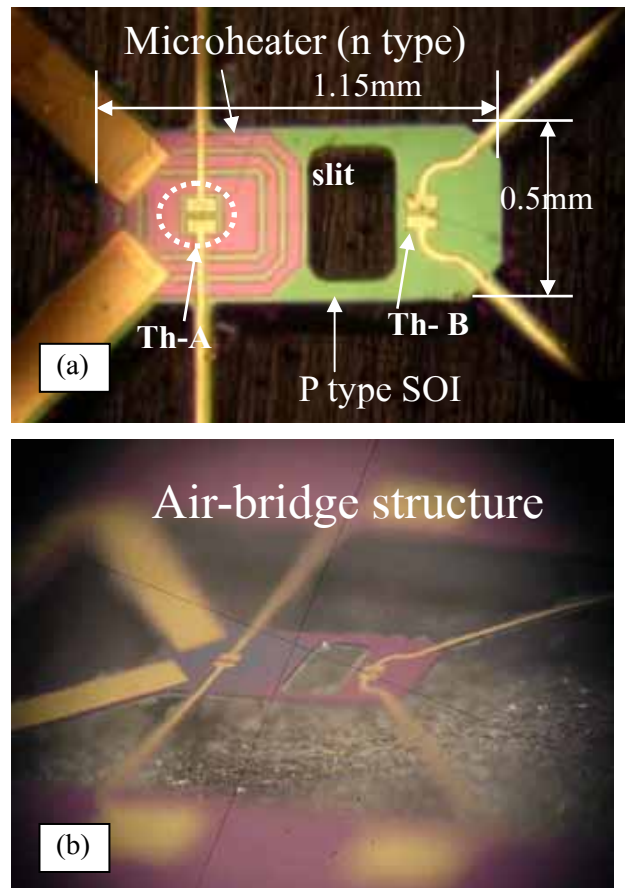Fig.2 Sketch of the proposed vacuum.

Fig.3 Micrographs of the proposed thermal vacuum sensor. (a) Top view, (b) Angle view.

each other by slit formed in the same micro air−bridge as shown in Fig.2. The Th-A can measure the temperature T_A of the region A, in where the microheater is also formed, and control the temperature of the microheater, and the Th-B formed in the region B can measure temperature T_B,
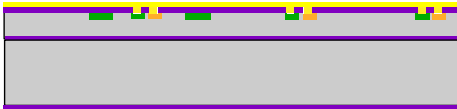
which is sensitive to the vacuum pressure P. The

1. n+ diffusion   Th-SiO2 200nm

Micro heater area
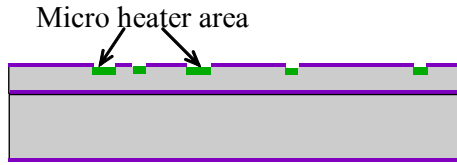
2. p+ diffusion Th-SiO2 300nm
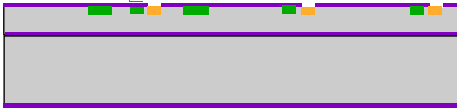
3. Electrode metal CVD : Al-Si

4. Photolitho. Air bridge ; DRIE

Fig.4 Fabrication process of the vacuum sensor.

ambient temperature T_C (correspondent to the room temperature) of the surrounding gas can be measured by the third diode-thermistor, Th-C, formed on the rim of the SOI substrate. The temperature T_A of the microheater is maintained to be constant such as $T_A = T_A1$ (such as 100 ℃) by feedback control combined with the Th-A.

The thermal conductance λ of a gas can be expressed as,

$$\lambda = \frac{1}{3} mnlvc \qquad . \qquad (3)$$

,where m is the molecular mass, n the molecular density, l the mean free path, v the average molecular velocity and c the specific heat of the gas at constant volume.

In the higher vacuum pressure range , such as 1 atm., the vacuum pressure P dependence of n and l will cancel each other [6] and λ will be saturated. So in this range this thermal vacuum sensor will be insensitive to the vacuum pressure P. However, in the pressure range below the point of mean free path l being on the order of the spacing between the microheater and heat sink, the l will be limited,
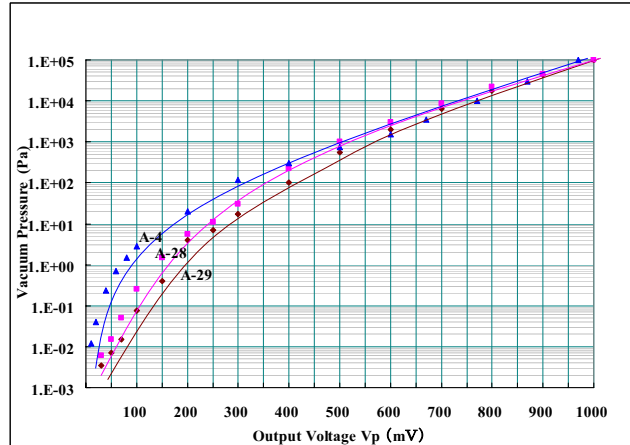
Fig.5 Relationship between vacuum pressure P and output voltage difference Vp for various structures of micro air−bridge.

therefore the thermal conductance λ of a gas will depend on the molecular density n, namely, will proportional to the vacuum pressure P. Furthermore in the extremely low vacuum pressure range this thermal sensor becomes insensitive to P, since the molecular density n itself becomes extremely low and the heat loss to the vacuum due to thermal conductance is extremely decreased.

2.3. Fabrication process

The micro air − bridge heater made of Phosphorous impurity diffused resistor and two diode-thermistors, Th-A and Th-B, of pn junction diode are formed on SOI layer of 0.5 Ωcm and 10 μm thick, and the micro air−bridge can be formed by use of Si-MEMS, in which deep RIE is used to fabricate the back-side cavity, and Si-IC technologies compatible with CMOS technologies.

The micro air−bridge in this case has an area of 1150x500x10 μm. In Fig.3 micrographs of the proposed vacuum sensor are shown.

In Fig.4 fabrication process of the micro vacuum sensor is shown. DRIE process is used to form the back-side cavity and the micro air−bridge thermally isolated from the SOI substrate, because surface protection for the alkali-etchant is free and many chips can be produced from one wafer because of straight and vertical etching. Au/Ti sputtering layer is used as a metallization film.
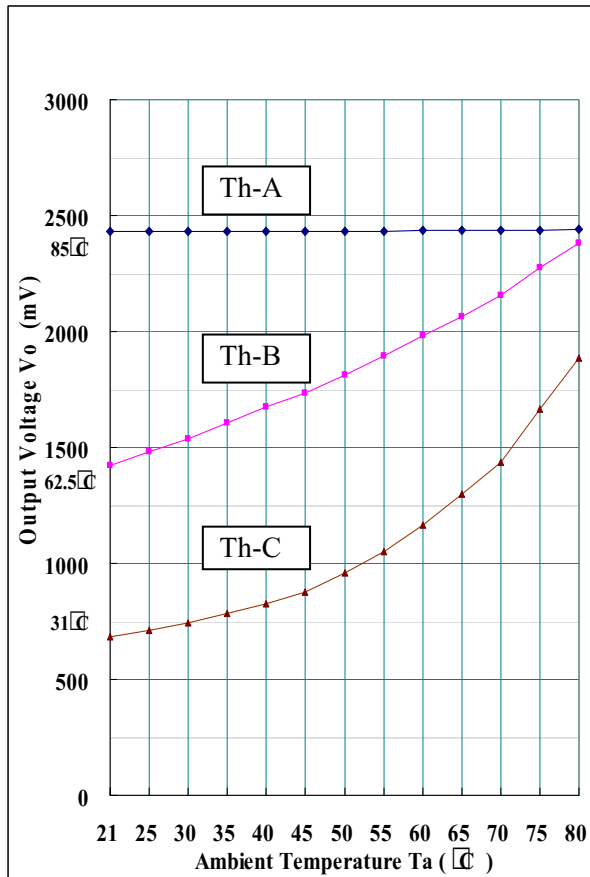
2.4. Experimental results

Fig.6 Ambient temperature Tc dependence of output voltage Vo of each diode of Th-A, Th-B, Th-C for maintaining the microheater temperature T_A at 85 ⁰C constant and at 1 atm.

In Fig. 5 relationship between vacuum pressure P and output voltage Vp for various structures of micro air－bridge. Output voltage Vp means a output voltage difference between output voltage of the diode thermistor Th-A and that of the Th-B at the constant ambient temperature of 25 ⁰C. In this case the temperature of the microheater T_A is maintained at 85 ⁰C. In the lower pressure range (higher vacuum range) the temperature of the Th-B will close to that of the Th-B, since heat dissipation from the Th-B to the ambient gas will decreased. On the other hand in the higher vacuum pressure range near 1 atm.($1.03x10^5$ Pa) the temperature of the Th-B will decreased and the temperature difference between the Th-A and the Th-B will increase since heat dissipation from the Th-B to the ambient gas is increased.   We can see that this new structure thermal vacuum sensor can clearly measure over very wide vacuum pressure range of about $2x10^{-3}-1x10^5$ Pa. This high performance of this sensor will come from adoptions of the new
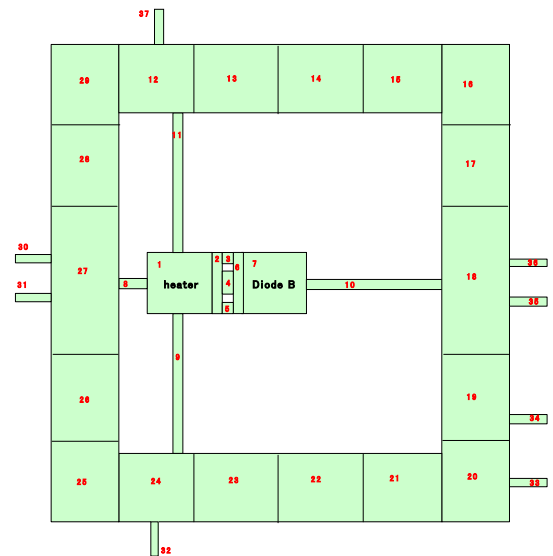

Fig.7 Model structure for thermal simulation using finite element method for the vacuum sensor.

micro air－bridge structure with spatially and thermally separated regions of A and B, and of very high temperature sensors, in where the hot thin film of region A due to the microheater has thermally semi-insulating connection to the thin film of region B being sensitive to the vacuum pressure P.

In Fig.6 ambient temperature Tc dependence of each diode temperature of Th-A, Th-B and Th-C at the controlled constant microheater temperature T_A of 85 ⁰C and at 1 atm. is shown. In this case the output voltage Vo represents merely the amplified voltage proportional to the temperature dependent each diode current I at constant forward voltage. From this figure we can see that it is very important to take account of the ambient temperature effects.
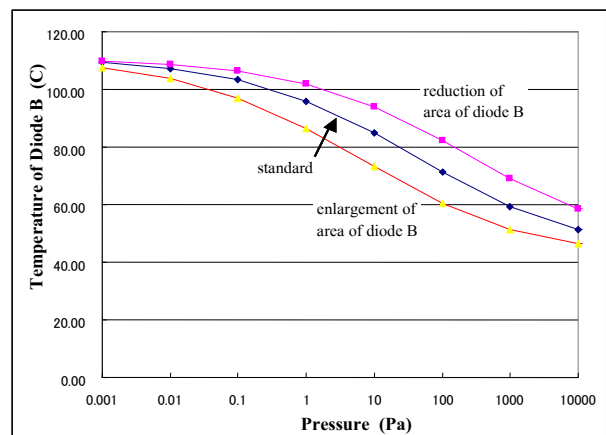
The power consumption of the microheater of

Fig.8 Thermal simulations of pressure dependence of the temperature of the Th-B for various area of Th-B.

this sensor at 1 atm. and at Ta =21 °C for maintaining T_A=85 °C was about 90 mW.

3. THERMAL SIMULATION

This vacuum sensor shown in Fig.2 is modeled for thermal simulations by finite element method divided as shown in Fig.7. In Fig. 8 one of thermal simulation results is shown for various film area of the region B, on where Th-B is formed.

We can see that larger area of Th-B will be relatively more sensitive than the smaller area.

The sensitivity of this thermal vacuum sensor will be improved especially in the higher vacuum by adoption of the optimized shape for thermal design.

4. CONCLUSIONS

A new structure thermal vacuum sensor with three pn junction diodes as a temperature sensor and a micro air−bridge heater is proposed and demonstrated that this has about two order wider measurable vacuum pressure range of about 2×10^{-3}-1×10^5 Pa than the traditional one of thermal vacuum sensor, such as Pirani vacuum sensor, and has very fast response and low power consumption. Since this sensor can be fabricated by use of full-grown silicon IC technologies and micromachining technologies, this can be mass production. Therefore this has a potential to be high sensitive and low cost vacuum sensor in near future.

ACKNOWLEDGMENT

REFERENCES

[1] M. Kimura, ́Microheater and microbolometer using microbridge of SiO_2 film on silicoń Electron. Letters, Vol.17, No.2, pp.80-82, 1981.

[2] A. W. Van Herwaarden, P. M. Sarro and H. C. Meijer, ́Integrated vacuum sensoŕ Sensors and Actuators,Vol. 8, No. 3 , pp.187-196, 1985.

[3] T. M. Berlicki, and K. J. Urbanski, "Ambient temperature effect in thin film vacuum sensoŕ Vacuum, Vol. 68, No. 4, pp. 303-309, 2002.

[4] T. M. Berlicki, "Thermal vacuum sensor with compensation of heat transfeŕ Sensors and Actuators A: Physical, Vol. 93, No. 1 , pp. 27-32, 2001.

[5] R. Puers, S. Reyntjens and D. De Bruyker, "The Nano Pirani—an extremely miniaturized pressure sensor fabricated by focused ion beam rapid prototypinǵ Sensors and Actuators A: Physical, Vol. 97-98 , pp.208-214, 2002

[6] Erno H. Klaassen and Gregory T. A. Kovacs, "Integrated thermal-conductivity vacuum sensoŕ Sensors and Actuators A: Physical, Vol. 58, No. 1, pp.37-42, 1997.

[7] Selim Eminoglu, Deniz Sabuncuoglu Tezcan, M. Yusuf Tanrikulu and Tayfun Akin, "Low-cost uncooled infrared detectors in CMOS procesś , Sensors and Actuators A: Physical Vol.109, pp.102-113, 2003.

[8] M. Kimura, "Thermal Microsensorś Sensors, Wiley-Vch, Vol. 6, pp. 257-275, 2000.

[9] M. Kimura and K. Toshima, Ó Thermistor-like pn junction temperature-Sensor with variable sensitivity and its combination with a micro air–bridge heateŕ Sensors and Actuators, A108, pp.239-243, 2003.

[10] M. Kimura and K. Kikuch, ́New Operation of Diode Temperature sensor and its Application to Gas Sensing Combined with a Micro air–bridge Heateŕ Proc. of 9th THERMINIC Workshop, pp.325-329, 2003.