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Performance Analysis of a Convection-Based Tilt Sensor

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This paper presents fabrication sequence and performance improving methods for convection-based tilt sensor. Also a packaging method to minimize the effect of environmental temperature fluctuation is proposed. Both electrolytic solution-based and air convection-based tilt sensors realized using micro-electro-mechanical-system (MEMS) technology have been previously reported by our research group. Although the MEMS-based electrolytic tilt sensor shows merited characteristics, such as wider operating tilt range, lower cost and compactness, compared to commercialized conventional electrolytic tilt sensors, it still suffers from metal electrode corrosion, electrolyte deterioration, surface tension of the electrolyte, and difficulty in packaging. In order to avoid those demerits, convective tilt sensor using air medium instead of electrolytic solution has been proposed and its fundamental performances has also been demonstrated in the previous works. In this paper, the effect of air medium condition on sensitivity of proposed convective tilt sensor has been investigated. In addition, a packaging method utilizing the Peltier device is presented to minimize environmental thermal effect without additional temperature compensation circuit. It is expected that this technique can be similarly applied to improve the performance and reliability of other sensors using gas media.

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1. Introduction

Recently, tilt sensors can be found in a wide range of application fields, such as automobile, air plane, ship, construction and so on, although it had been used only for measurement of inclination in the near past.[1–8] Especially, miniaturized tilt sensors widen their application fields even into mobile electronic devices, which require a functionality of motion capture.[9,10] Micro-electro-mechanical-system (MEMS) based tilt sensors have great potential for these applications owing to the small size, low cost, possible mass production and co-integration of readout circuit.

Because proposed convective tilt sensor operates by detecting the temperature distribution profile of gas medium filled in the cavity, the cavity condition such as pressure and gas type are of most important parameters. For the same reason, the sensor is quite sensitive to external temperature fluctuation. Therefore, the performance of the sensor as a function of cavity condition must be analyzed in detail and study on minimizing undesirable performance caused by external temperature variation should be conducted. As a continuous research of previously-reported air convection-based tilt sensor by our research group,[11–13] effects of cavity pressure and gas type on sensitivity are mainly studied, and method to minimize environmental thermal effect is reported in this paper.

2. Device Structure and Functional Mechanism

Figure 1 shows structure and operating mechanism of the proposed tilt sensor. A dielectric membrane is required for thermal isolation to minimize the heat loss and environmental influence on the device. A microheater is prepared on the central area of the dielectric membrane and four temperature sensors are located with the same distance surrounding the microheater. The proposed sensor consists of two independently-fabricated and bonded wafers; top part provides a cavity filled with gas medium for free convection, and bottom one contains the microheater for heating the gas in the cavity and four temperature sensors for detecting a change of temperature distribution in the cavity.

When the sensor is balanced without tilting, a symmetric temperature profile can be deduced by reading the output signals of the temperature sensors located with the same distance from microheater. When a tilting motion is applied, an asymmetric temperature distribution occurs between sensors on the same axis due to the thermal convection.

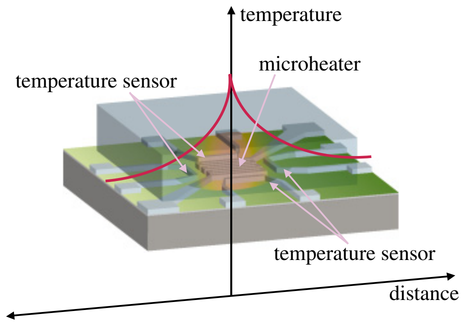

Fig. 1. (Color online) Structure and operation mechanism of proposed tilt sensor.

3. Fabrication

3.1 Top substrate

Top substrate provides a hermetic gas cavity for free convection. Figure 2 shows the fabrication process of top substrate. Silicon substrate is utilized to realize the top structure of the proposed tilt sensor, so that it is etched using tetramethylammonium hydroxide (TMAH) to provide a truncated pyramid-shape gas cavity. After forming the gas cavity, a 0.5-μm-thick oxide layer is deposited by plasma-enhanced chemical vapor deposition (PECVD) to minimize the environmental effect on operation of the proposed tilt sensor.

3.2 Bottom substrate

Bottom substrate consists of a microheater and four temperature sensors. Figure 3 shows its fabrication process. Silicon dioxide is grown by wet oxidation and patterned on the backside for the following TMAH etch step to fabricate the silicon dioxide membrane. When the fabrication of dielectric membrane is completed, the microheater and temperature sensors are formed by lift off process on the membrane at once. The fabrication process is very simple due to the fact that both microheater and temperature sensors are deposited by e-beam evaporation using the same material, nickel. The

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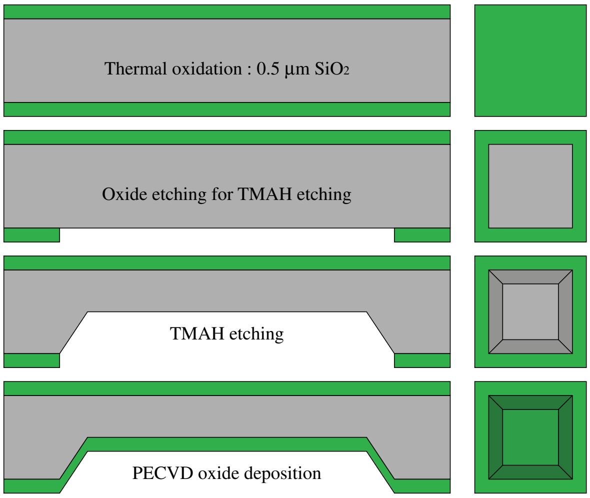

Fig. 2. (Color online) Fabrication process of the top substrate.

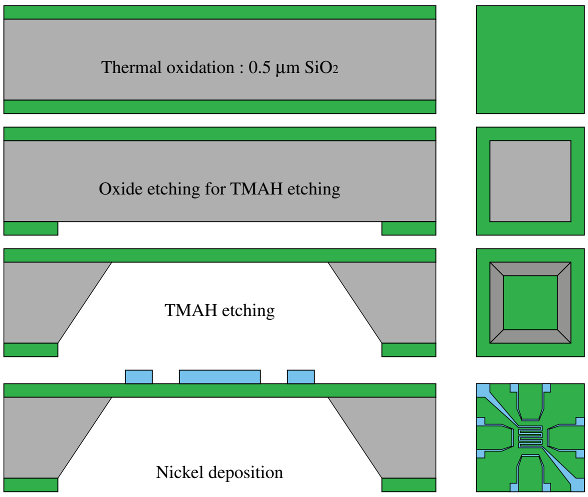

Fig. 3. (Color online) Fabrication process of the bottom substrate.

materials both for the heater and temperature sensors were replaced by nickel instead of using platinum, which was used in the previously-reported our paper,[12] because nickel has a high temperature coefficient of resistance (TCR). Even though nickel shows a narrower linear range, compared to platinum, in the resistance change as a function of temperature, the linear TCR characteristic of nickel covers the operation range of the proposed sensor. Finally, the bottom substrate is then bonded with the top substrate using epoxy. Figure 4 shows the fabricated tilt sensor.

4. Design

4.1 Material for temperature sensors

High TCR and good linearity in resistance change as a function of wide range of temperature are the basic material requirements to realize a sensitive temperature sensor. Platinum and nickel are well-known temperature-sensitive materials. Platinum has $3.8 \times 10^{-3}/°C$ of TCR and excellent linearity in a range of approximately -100 to 700 °C. In general, platinum is widely used as temperature-sensor material due to its linear TCR characteristic in wide range and distinguished chemical durability. However, it is

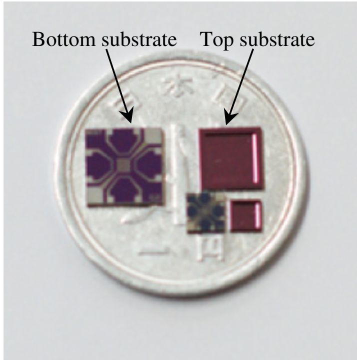

Fig. 4. (Color online) Fabricated tilt sensor.

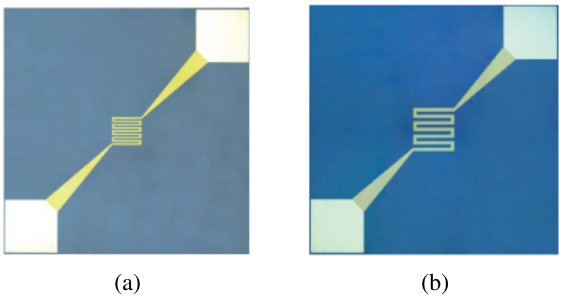

Fig. 5. (Color online) Design of the microheater. (a) 40 µm line width. (b) 80 µm line width.

expensive and the TCR value is relatively low. For a lower temperature application than 400 °C, inexpensive nickel would be a better candidate for temperature sensors, because it has high TCR value about $6.7 \times 10^{-3}/°C$ and linearity in a range of approximately -100 to 400 °C.

The tilt sensor, presented in this paper, has adopted nickel instead of platinum as the temperature sensor because the operation temperature is less than 400 °C.

4.2 Size and width of microheater

Figure 5 shows two types of fabricated microheater that have different pattern size and shape, type A shown in Fig. 5(a) has an area of $720 \times 720\,\mu m^2$ and line width of 40 µm while type B exhibited in Fig. 5(b) does $1 \times 1\,mm^2$ and 80 µm. As shown in Fig. 6, type A with thinner heating line shows better heating performance than type B with thick heating line, because the heating performance is directly proportional to the resistance of heater.

4.3 Shape of temperature sensor

Various patterns of temperature sensor are fabricated to find an optimized shape of temperature sensors for high sensitivity, as shown in Fig. 7. The sensors have been designed to have three different types, straight-line (sensor A), square-wave (sensor B) and s-like (sensor C) shapes. Figure 8 shows the sensing characteristics of fabricated temperature sensors with different pattern shape and length. All the sensors show linear sensing characteristics in the temperatures range of 30–150 °C. The temperature sensor C shows the most sensitive output characteristic due to the resistance effect. The sensing current for each temperature sensor was fixed at 10 mA.

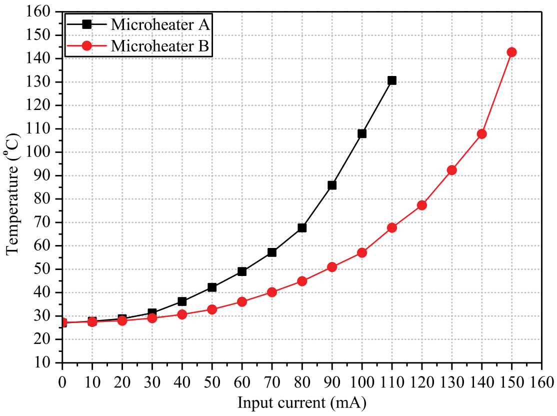

Fig. 6. (Color online) Heating performance of the fabricated microheaters.

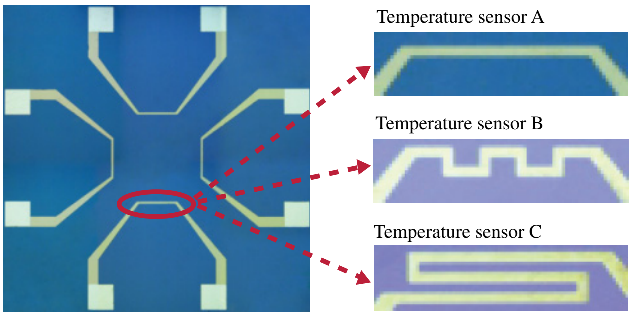

Fig. 7. (Color online) Design of temperature sensor.

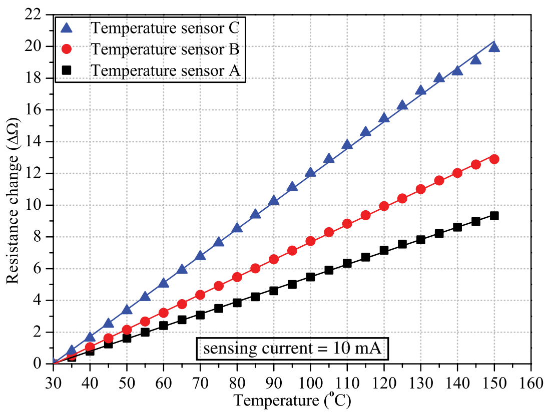

Fig. 8. (Color online) Sensing performance of fabricated temperature sensors.

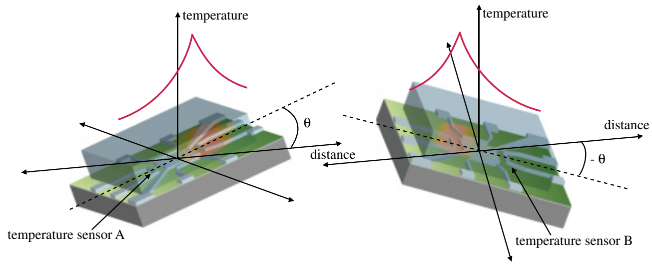

Fig. 9. (Color online) Measurement method of the proposed tilt sensor.

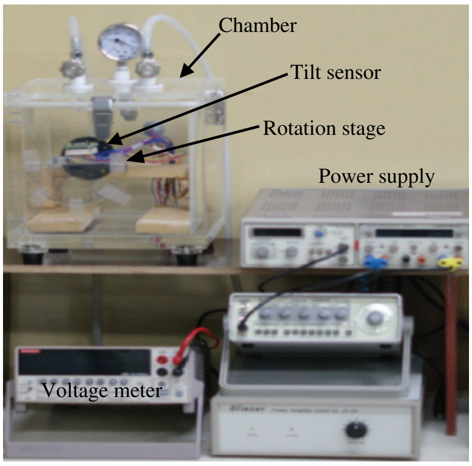

Fig. 10. (Color online) Measurement system.

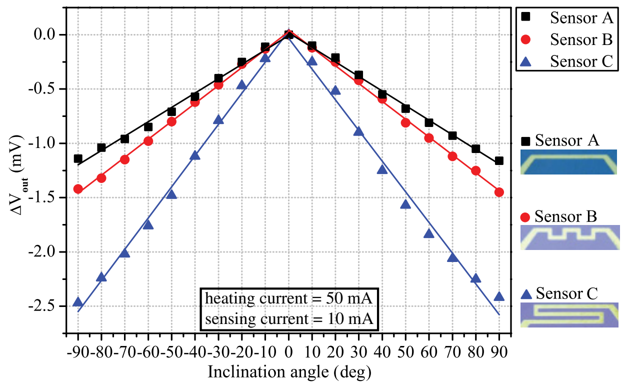

Fig. 11. (Color online) One-axis measurement result of the tilt sensor.

5. Experiments

5.1 Fundamental experiment result

Figure 9 shows a measurement method of the proposed tilt sensor. A positive angle is defined for a counterclockwise inclination. When the tilt sensor experiences a counterclockwise inclination, the measurement is performed on temperature sensor A located on the left side of the microheater, cold part, with a range of 0 to 90°. With the same principle, temperature sensor B located on the right side measures the range of 0 to −90° for clockwise tilting. Consequently, the proposed tilt sensor could measure a tilting motion in a range of −90 to +90° on two axes by combining the outputs of four temperature sensors. Figure 10 shows the measurement system. The tilt measurement result on one axis is shown in Fig. 11. For this measurement, fixed currents at 10 and 50 mA are supplied to each temperature sensor and heater, respectively. The higher sensitivity of the proposed tilt sensor can be obtained by supplying higher heating current,[12] but the proposed tilt sensor is also able to operate at slightly higher temperature than room temperature. Therefore, 10 mA sensing current and 50 mA heating current are supplied to the proposed tilt sensor considering the power consumption. With an inclination, each temperature sensor experiences a change in the resistance owing to the convection-induced temperature change. The resistance change of temperature sensor

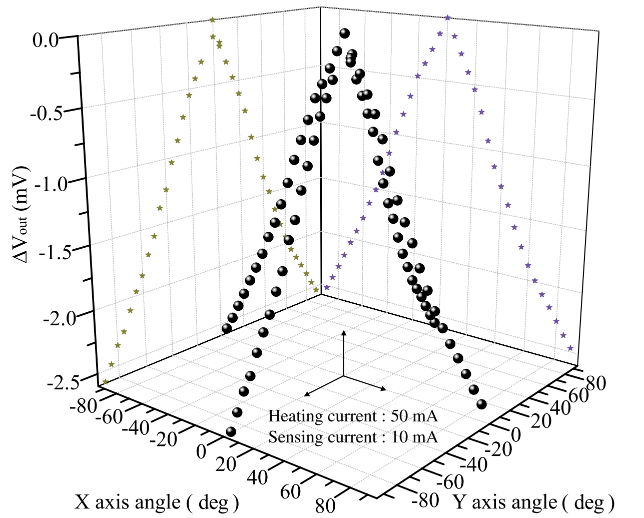

Fig. 12. (Color online) Two-axis measurement result of the proposed tilt sensor.

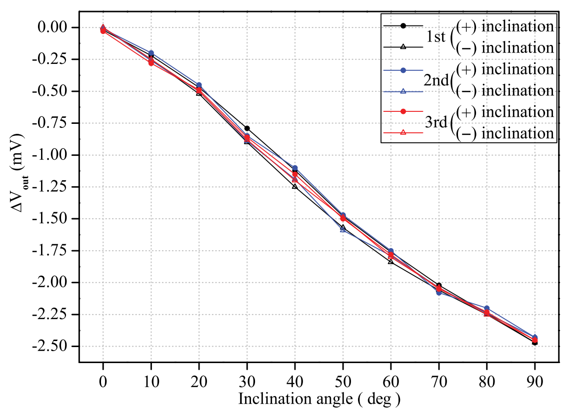

Fig. 13. (Color online) Measurement hysteresis result of the proposed tilt sensor.

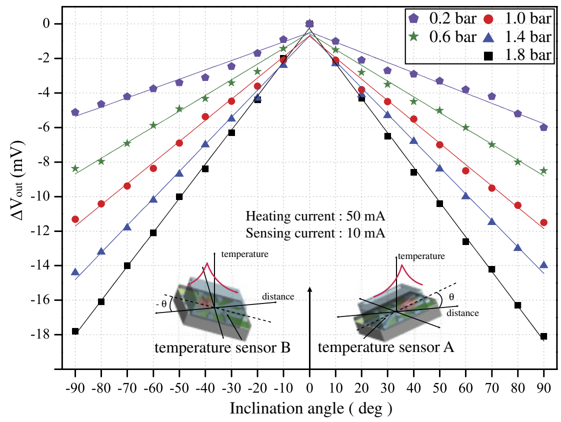

Fig. 14. (Color online) Measurement result of the proposed tilt sensor as a function of gas pressure.

corresponding to a given inclination angle is measured as the output voltage by the Ohm's law. The fabricated tilt sensor gives quite linear and symmetric characteristics with respect to three different types of temperature sensors in the whole range of $\pm 90°$, as shown in Fig. 11.

Figure 12 shows the output characteristic of proposed sensor on two axes using four temperature sensors, formed around the central microheater. This result reveals that proposed sensor operates well and shows quite linear characteristics even on two axes.

Experiments were conducted to evaluate the actual hysteresis characteristic of the proposed tilt sensor in operating range of 0 to 90°. For the experiment, inclinations have been applied with positive increment to the maximum operating range, +90°, and then with decrement to 0° as a single cycle. The experimental results during three cycles are summarized in Fig. 13. A minor hysteresis has been observed but this can be further improved by minimizing external temperature fluctuation as discussed in §5.5.

5.2 Effect of gas pressure on sensitivity

Convection is the heat transfer induced by the motion within a fluid which may arise from temperature differences in the fluid. Free convection occurs in any fluid that expands or contracts in response to a temperature change, resulting in a local change of fluidic medium in density. This local change in density then results in buoyancy forces that cause currents in the fluid. Because the proposed tilt sensor operates based on the free convection, the sensitivity is directly related to the condition of gas medium. The convection depends heavily on the Grashof number, which approximates the ratio of buoyancy force to the viscous force acting on a fluid and is linearly proportional to the medium pressure.[14–16] The Grashof number is expressed as

$$Gr = \frac{\rho^2 g \beta \Delta T l^3}{\mu^2} \tag{1}$$

with ρ, the gas density, g, the earth gravity, β, gas coefficient of expansion, ΔT, the differential temperature between hot and cold sides, l, the distance between regions of high temperature and low temperature and μ, gas viscosity. Two factors, g and β, are constant, and both ΔT and l are also assumed to be constant, because the heating power and the structure of the proposed tilt sensor are fixed.

The condition of gas medium in the cavity gives a significant impact on the sensitivity of the proposed tilt sensor; a lager Grashof number is preferable for a sensitive tilt sensor. As known in eq. (1), gas density and viscosity are the only variables. If the type of gas medium is determined, viscosity is known and gas density is the only parameter to be concerned. The gas density ρ is proportional to the pressure so a higher gas pressure in the cavity brings a larger Grashof number, resulting in an enhanced performance. Superior sensitivities have been observed at higher gas pressures, as shown in Fig. 14. It seems that the velocity of thermal convection increases at higher pressure compared to the lower one when medium volume remains the same. It is worthy to notify the facts that the power consumption would be saved and the sensitivity could be further improved without changing the structure by packaging the device at higher gas pressure.

5.3 Effect of gas medium on sensitivity

When gas density is constant, the kinematic viscosity of gas can be changed by adopting different gas to the proposed tilt sensor. In order to compare the performances of tilt sensor as a function of cavity medium, three different samples of

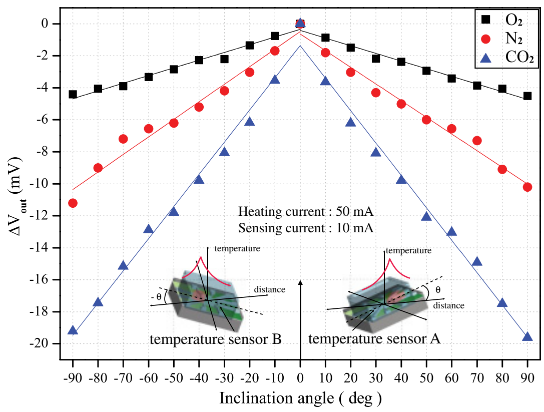

Fig. 15. (Color online) Measurement result of the proposed tilt sensor as a function of gas medium.

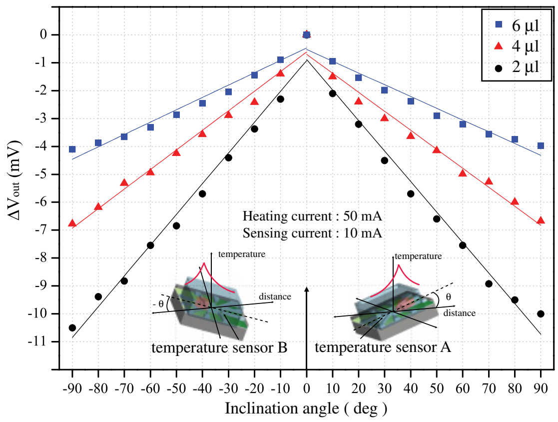

Fig. 17. (Color online) Output characteristics of the tilt sensor as a function of cavity volume.

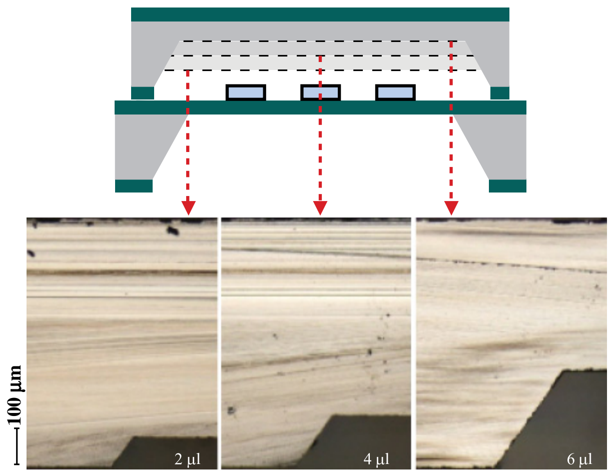

Fig. 16. (Color online) Structures with different volumes.

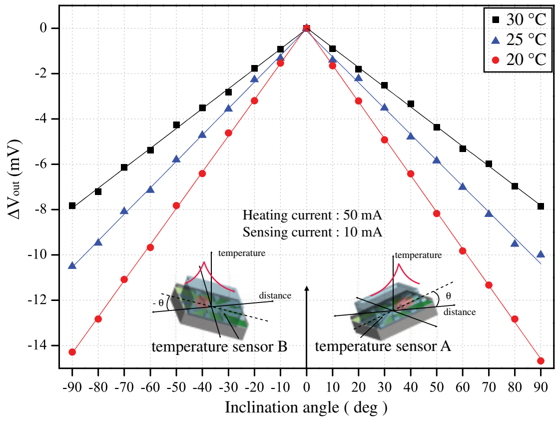

Fig. 18. (Color online) Measurement result of the proposed tilt sensor as a function of environmental temperature.

device with cavities filled with oxygen, nitrogen and carbon dioxide are examined, and the results are shown in Fig. 15. The viscosity of oxygen, nitrogen and carbon dioxide are 0.02075, 0.01787, and 0.01501 mPa·s, respectively.

The tilt sensor filled with carbon dioxide medium shows a superior sensitivity than that filled with other gas media due to its low gas viscosity.

5.4 Effect of cavity volume on sensitivity

The Grashof number is a dimensionless quantity used in fluid dynamics for free convection systems. Therefore, cavity-volume-related factors concerned with the sensitivity of the proposed tilt sensor can be found either by simulation or experimental results on material- and structure-based thermal losses.

Three gas cavities with different volumes, 2, 4, and 6 µl, were made by controlling TMAH etching time, as shown in Fig. 16. Figure 17 shows the tilt measurement result of the proposed sensor as a function of cavity volume. The experiment has been performed at room temperature and under atmospheric pressure filled with nitrogen gas. Heating current of 50 mA and sensing current of 10 mA were applied to the heater and temperature sensors, respectively.

A superior sensitivity has been observed with smaller volume when the heating power remains the same at 50 mA. However, the sensitivity of the proposed tilt sensor with excessively small cavity is expected to decrease by conduction-induced thermal loss through the top substrate. In this case, the differential temperature between hot and cold sides, ΔT related to Grashof number, would be decreased. The effect of cavity volume to sensitivity is contingent also on the heating power so that the optimization process on cavity volume should be concerned with meticulous care considering the heating power as well. More details on this will be discussed in §6.

5.5 Effect of external temperature on sensitivity

The output characteristics of the proposed tilt sensor could be fluctuated by variation in environmental temperature because the operation is based on the heat transfer. Because the convection is proportionally generated by temperature difference, a change of external temperature will lead a variation of the sensitivity of the proposed tilt sensor.

Figure 18 shows the output result as a function of environmental temperature. The experiment performed with 1 bar of nitrogen gas and 2 µl of cavity volume. The proposed tilt sensor shows a superior sensitivity at low environmental temperatures.

In order to minimize the effect of environmental temperature, the proposed sensor was packaged with an additional

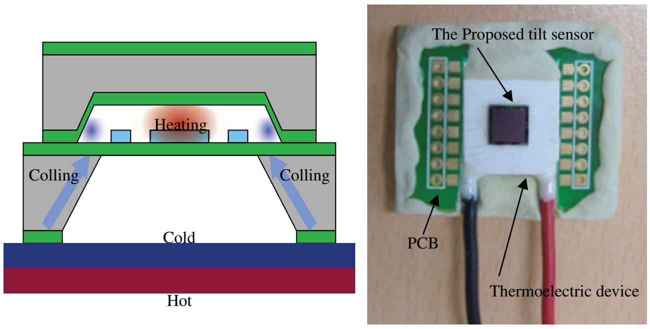

Fig. 19. (Color online) Packaging concept and packed tilt sensor.

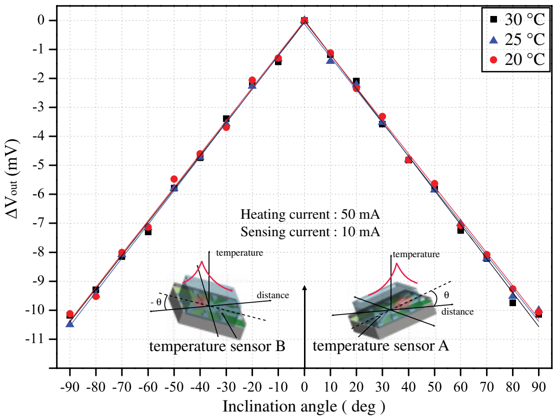

Fig. 20. (Color online) Measurement result of the packaged tilt sensor as a function of environmental temperature.

Peltier device in a way that the external temperature is kept at a constant value. The packaging concept and packaged tilt sensor with the Peltier device are shown in Fig. 19. With the proposed packaging, consistent output results were measured even at different external temperatures, as shown in Fig. 20.

6. Discussion

A convection-based tilt sensor operates at a steady state where both forced heating power to warm up the gas medium and natural cooling power by capping material—if the heat loss through the thin membrane is ignored—remain constant. As previously reported,[12] the sensitivity of convection-based tilt sensor has been improved by increasing heating current. By reducing the volume cavity with a fixed heating current, the heating power gets dominant compared to the cooling power due to the smaller heat capacity of reduced cavity volume, resulting in an improved sensitivity. However, excessively reduced cavity volume with the fixed heating power at relatively high current produces an increased thermal loss and slight temperature difference in the cavity owing to immoderate heating power. So the process to find an optimal cavity volume should be performed considering the heating current as well. This fact merits both the fabrication cost and power consumption by exploiting an optimized design, because much smaller convective tilt sensor can be realized at a low cost without performance loss.

The study of cavity pressure effect on sensitivity brings the possibility to enhance the performance without changing the structure. However, limits in reducing the cavity volume and in increasing cavity pressure might be considered, because a very small cavity size and extremely high pressure could restrain the flow pattern of the convection. By keeping the environmental temperature constant using a conventional thermoelectric device, the proposed sensor showed a stable output results. Thin film-type thermoelectric device presented in literatures[17–19] might be integrated into the proposed tilt sensor to enhance the reliability.

7. Conclusions

A simple convection-based tilt sensor has been developed and characterized in various experimental conditions. The proposed convective tilt sensor shows quite linear characteristics within the tilt range of -90 to $+90°$ even on two axes. Experiments have been carried out with different cavity volumes and gas pressures in order to find optimized operation conditions. The measurement results revealed that the convective tilt sensor with small cavity volume and high gas pressure gives a higher sensitivity, and the constant output result was detected even for various external temperature conditions by packaging with thermoelectric device. The mass production of the proposed tilt sensor is feasible at a low cost and the performance of the sensor can be further improved by replacing the gas pressure and type of gas medium, and by optimizing its structure and material.

Acknowledgements

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