INVESTIGATION ON THE CALIBRATION FOR THE MEMBRANE TYPE HEAT FLUX SENSOR USING MICRO HEATER

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ABSTRACT

This paper presents the calibration accuracy of the membrane type heat flux sensor using micro heater. The directional heat flow rate into the thermal sensor is simulated with FEM to estimate the heat flux from micro heater for calibration. Thin film thermopile which is fabricated on the dielectric membrane directly converts the temperature difference between hot and cold junctions of thermopile into heat flux signal created by the thermoelectric effect. However, symmetric design of thermopile is restricted to only measure x-directional heat flow rate, when heat also propagates through y direction via heat conduction and z direction with convection. Therefore, it is highly needed to investigate how amount of heat from the micro heater contributes to the calibration of heat flux sensor. In the case of the calibration using micro heater, heat conduction through the membrane dominates heat flow. Thus, 97% of heat flow from micro heater propagates through the thermopile and generates 1.038 V/W of sensitivity that was estimated by the simulated model as 1.066 V/W. On the other hand, in case of water filled micro channel, 87% of heat flow reaches to thermopile and estimated 0.392 V/W of sensitivity. This heat loss leads to the inaccurate calibration as well as the lowered sensitivity.

INTRODUCTION

Measurement of heat is involved in various research fields such as mechanics, biology, chemistry and material science, etc [1]. The thermodynamic properties of the sample can be measured by two thermal variables; temperature and heat flux. Temperature is an indication of the internal energy in control volume. So it is closely related to the heat capacity and response time is inherently slow. Heat flux is the rate of energy transfer per unit area through the boundary. So it is not related to the heat capacity and heat flux signal provides a much rapid response since it measures energy transfer. As a result, temperature is a resultant variable of heat flux. Therefore, heat flux measurement is more appropriate to quantify the heat from the sample.

Temperature can be measured by the property change of sensor itself such as thermoresistive, thermoelectric, thermomechanical and thermo-optical type. Most of the temperature sensor indicates the absolute value because the state of the sensor property is dependent on the absolute temperature. However, heat flux sensor requires the temperature difference value between two measurement points. The heat flux value is derived from the Fourier's law with known thermal conductivity and heat capacity of the sensor body. Fortunately, thermopile provides the temperature difference signal with single sensor and serial connection of junctions generate amplified signal(N) [2]. Furthermore, MEMS technology enables to fabricate the thin film thermopile on the membrane structure which has high sensitivity and fast response time.

The output voltage of the thermopile is calibrated to the heat flux across the sensor structure that is sensitivity of the heat flux sensor. There are several methods for calibration. Optical power can supply the heat power to the sensor, but the reflection and transmission efficiencies deteriorate the calibration accuracy [3]. Chemical reaction also utilized for calibration, but nonhomogeneous reaction in the micro-sized sample degrades the calibration accuracy [4]. Therefore, Joule heating of the micro heater incorporated on the membrane is widely applied to the calibration. Although the dominant heat from the micro heater flows through the thermopile by heat conduction, other directions of heat propagates to the incentive way. Therefore, directional heat flow rate from the micro heater is investigated to analyze the calibration accuracy of heat flux sensor.

MATERIALS AND METHODS

The membrane type heat flux sensor is modeled using 3D FEM simulation to identify the directional heat flow rate from the micro heater.

Theory

The membrane type heat flux sensor consists of micro heater, thermopile, membrane and silicon substrate as shown in Fig. 1. Micro heater supplies reference heat flow(q”) to the thermopile generating temperature distribution on the membrane. The temperature difference between hot(T_h) and cold(T_c) junctions is converted to the thermoelectric voltage($\Delta E_{thermopile}$) by Seebeck effect($S_{Au/Cr}$). The relationship between reference heat flow from the micro heater and output voltage from the thermopile is called as sensitivity

$$q'' = \frac{\Delta E_{thermopile}}{N \cdot S_{Au/Cr} \cdot R_{th}} \qquad (1)$$

Therefore, the amount of heat from the sample on the membrane is estimated by the output voltage of thermopile and sensitivity value.

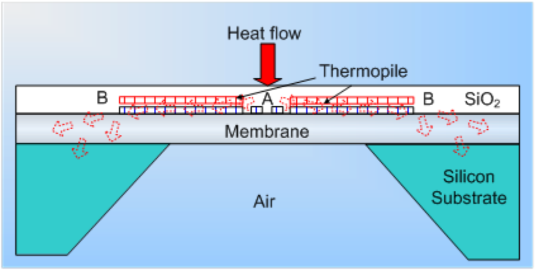


Fig. 1: Schematic design of membrane type heat flux sensor

Structure

The thermopile is composed of gold and chromium with 100 junctions on the membrane structure. The minimum width of thermopile is 10 μm for each strip. The length of each thermopile strip reaches to 1 mm considering signal-to-noise ratio. The fabrication process is shown in Fig. 2. The membrane is a stacked silicon oxide and nitride layers to minimize residual stress as well as to obtain dielectric property. Furthermore, the membrane also has high thermal resistance (R_{th}) to generate high temperature difference on the thermopile. Silicon substrate has a role of heat sink for input heat flow due to the high thermal conductivity and heat capacity of silicon property. The passivation layer finally covers the whole sensitive area to prevent the damage.

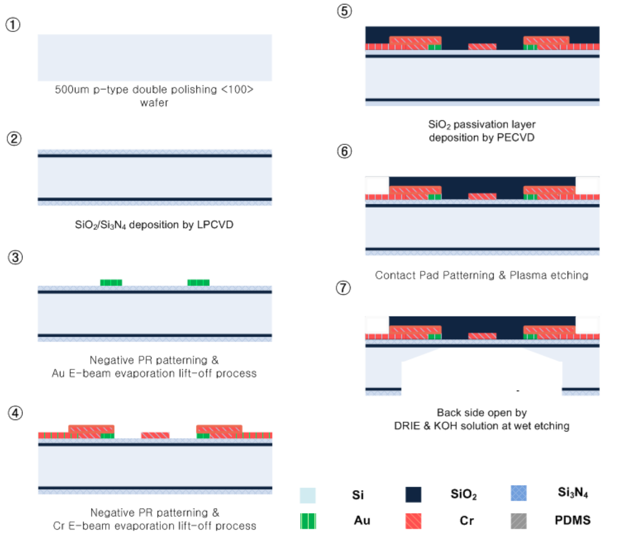


Fig. 2: Fabrication process of heat flux sensor

FEM modeling

The geometrical dimensions of heat flux sensor are shown in Fig. 3. Most of the thin film layers have under 1 μm thickness.

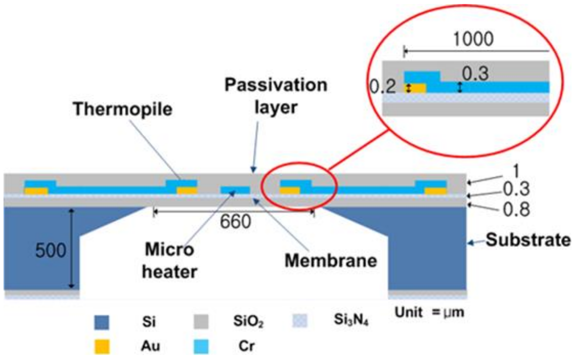
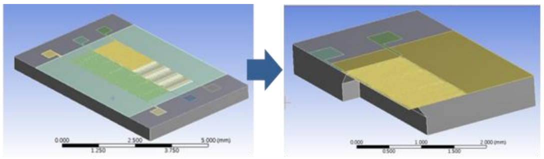


Fig. 3: Geometrical dimensions of heat flux sensor

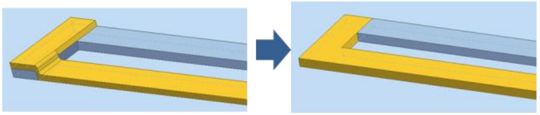
To conduct the FEM modelling with commercial software (ANSYS Workbench 14.5), several simplifications are followed.


Full model (3,279 contacts)

Quarter model (748 contacts) (418,117nodes, 47,916 elements)

Fig. 4: Symmetric boundary

The symmetric boundary conditions on X and Y axis provides quarter model in decreased elements contact, nodes and elements as shown in Fig. 4. The junction part is also simplified from the three different thicknesses (Au:0.2μm, Cr:0.3μm, Au/Cr:0.5μm) to the single thickness as 0.3 μm as shown in Fig. 5. The material properties of thin film are different from the bulk material. Table 1 compares the thermal conductivity in bulk and thin film materials [5, 6].


Real model : 3 different thickness layers (Au:0.2μm, Cr:0.3μm, Au/Cr:0.5μm)

Simulation model: single thickness layers (All : 0.3 μ)

Fig. 5: Junction part simplification

Table 1: Material property of heat flux sensor

Materials	FEM library (Bulk property)	Literature (Thin film property)	Reference
Au	315	317	
Cr	94	93.7	
Si	148	130	
SiO_2	1.5	0.95	K.E.Goodson (1993)
Si_3N_4	16	3.2	C.H.Mastrangelo (1990)

The meshed model is shown in Fig. 6 with minimum size as 10 μm of single layer. The boundary conditions are applied on the model as convection on the surrounded surface, constant temperature on the bottom surface as ambient temperature, and internal heat generation on the micro heater.

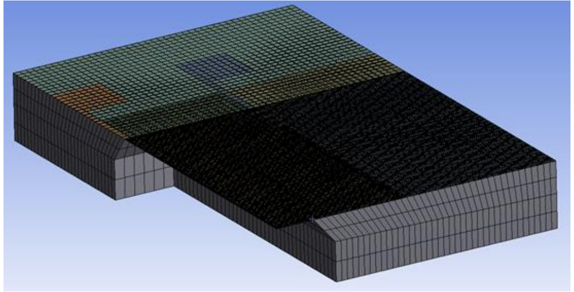


Fig. 6: Meshed model for heat flux sensor

Directional heat flow rate

The total heat flow from the micro heater propagates in three directions. To identify the directional heat flow rate on the heat flux sensor, each directional heat flux on the mesh elements is analysed as shown in Fig. 7. The directional heat flow rate is derived by equation below

$$q_x = \Sigma\,(\text{ x - direction heat flux} \times \text{area })\quad(2)$$

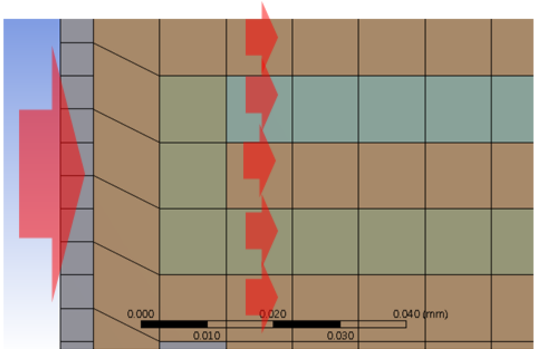
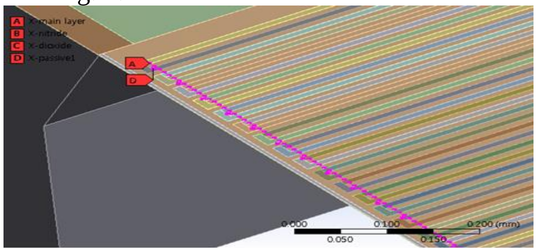
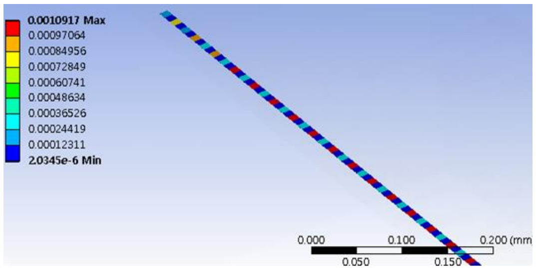


Fig. 7: Mean heat flux on the element

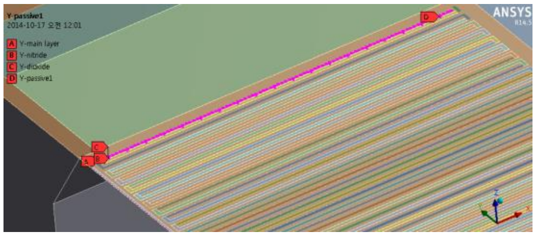
The membrane is composed of 4 layers as dioxide, nitride, main layer and passive. X and Y directional heat flux are analysed as Fig. 8.



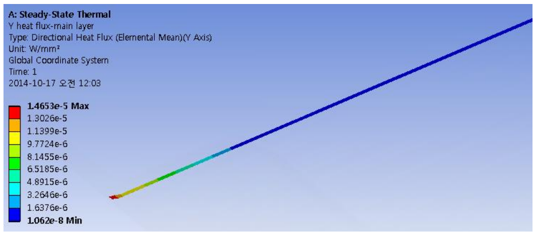
(a) Mesh selection (X-direction)



(b) Mean heat flux (X-direction)



(c) Mesh selection (Y-direction)



(d) Mean heat flux (Y-direction)

Fig. 8: Directional heat flux on the mesh elements

RESULT AND DISCUSSION

The temperature distribution on the membrane rises around mK range considering 1μW of heat generation as shown in Fig. 9.

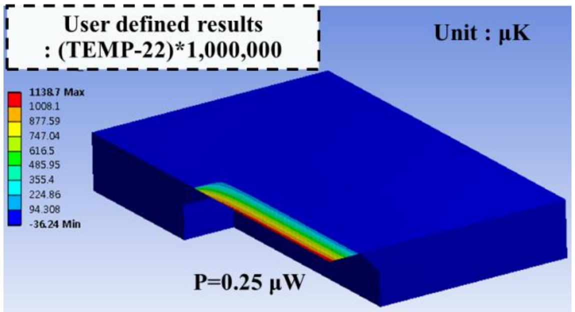


Fig. 9: Temperature distribution on the membrane

To estimate the thermoelectric voltage of the thermopile, temperature difference between hot and cold junctions is compared as shown in Fig. 10.

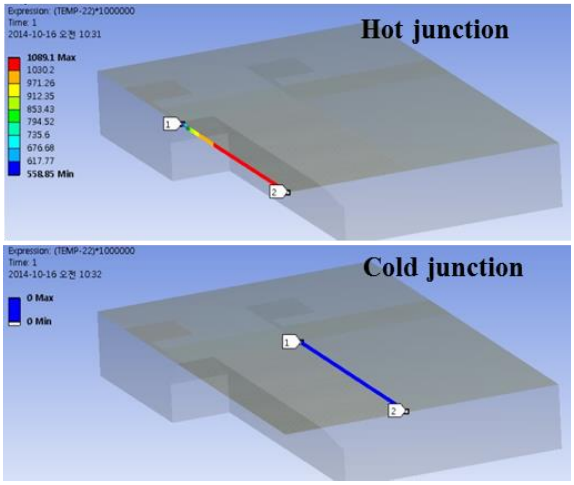


Fig. 10: Temperature rise on the hot and cold junction

As a result of simulation, sensitivity is estimated as 1.066 V/W that is similar value of experiment as 1.038 V/W. The total heat flow rate from the micro heater is 0.25 μW considering symmetric boundary conditions.

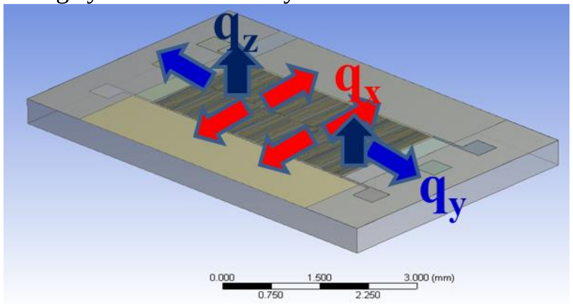


Fig. 11: Directional heat flow rate

Table 2: Directional heat flow rate of each layers

Direction	Elements	Heat flow rate (nW)	Total heat flow rate (nW)	%
X	main layer	199.00	208.66	97.2
	nitride	0.17		
	dioxide	5.06		
	passive1	4.43		
Y	main layer	0.57	4.50	2.1
	nitride	1.58		
	dioxide	1.25		
	passive1	1.10		
Z	passive1	1.60	1.60	0.7

The heat flow from the micro heater is devided into three directional heat flow rate as shown in Fig. 11. The results of directional heat flow rate for each membrane layer are summarized in Table 2. One more considerable situation is the effect of micro channel containing liquid sample on the directional heat flow rate. The PDMS micro channel has 800 μm of width and 50 μm of height to load the sample on the membrane as shown in Fig. 12.

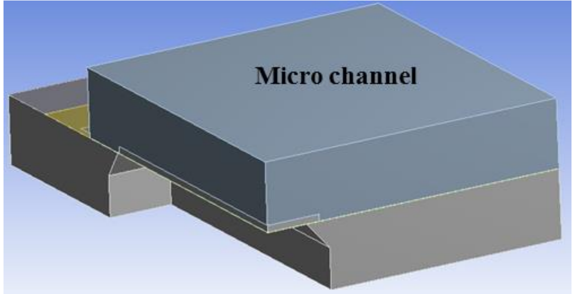


Fig. 12: Heat flux sensor with micro channel

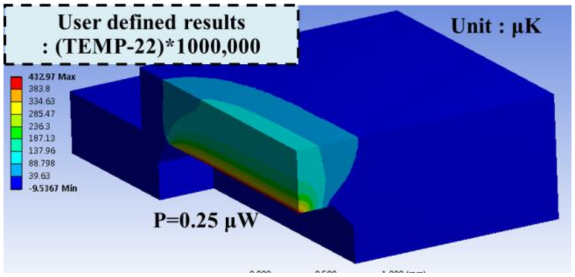


Fig. 13: Temperature distribution on the micro channel

The simulation result shows that heat from the micro heater propagates not only through the membrane, but also through the liquid sample inside the micro channel as shown in Fig. 13. The directional heat flow rate of heat flux sensor with the cmiro channel is listed on Table 3.

Table 3: Directional heat flow rate of heat flux sensor with micro channel

Direction	Heat flow rate with channel (nW)	%
X	133.0	87.2
Y	4.3	2.8
Z	15.3	10.0

The Z directional heat flow rate is increased to 10%. So, the calibration accuracy of heat flux sensor containing the liquid sample becomes to around 87%.

CONCLUSION

Membrane type heat flux sensor has high sensitivity and fast response time. To calibrate the heat flow to the output signal of thermopile, reference heat is generated with micro heater inside the membrane. But propagating heat is three dimensions. The sensitive direction of heat flux sensor is one direction and the other direction's heat flux becomes calibration error. To investigate the calibration accuracy, FEM simulation is conducted. As a result, the heat flux sensor has just under 3% of error and 97% of heat flows through the sensor. However, the heat flux sensor with liquid sample has 13% of error and 87% of accuracy. It is because heat conduction through the liquid has lower thermal resistance than convection through the air. In conclusion, the calibration should be conducted according to the different sample on the heat flux sensor due to the different calibration accuracy.

ACKNOWLEDGEMENTS

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