ISSN 1726-5479

SENSORS & TRANSDUCERS

6 vol. 129 /11

Electronic Circuits, Signal Conditioning and ASIC

International Frequency Sensor Association Publishing

IFSA

Sensors & Transducers

Volume 129, Issue 6, June 2011 | www.sensorsportal.com | ISSN 1726-5479

Sensors & Transducers Journal (ISSN 1726-5479) is a peer review international journal published monthly online by International Frequency Sensor Association (IFSA).

Sensors & Transducers Journal

Contents

Volume 129
Issue 6
June 2011

www.sensorsportal.com

ISSN 1726-5479

Research Articles

Sensors & Transducers Journal, Vol. 129, Issue 6, June 2011, pp. 135-141

www.sensorsportal.com

Sensors & Transducers

ISSN 1726-5479

http://www.sensorsportal.com

Design and Simulation of Double-spiral Shape Micro-heater for Gas Sensing Applications

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Received: 13 May 2011 /Accepted: 20 June 2011 /Published: 30 June 2011

Abstract: The paper presents the design and simulation of double spiral shape micro-heater using ANSYS 10.0 and MATLAB, which requires 12.5 mW-78.3 mW powers to create the temperature 181 °C-1002 °C for gas sensing applications. The results obtained from ANSYS simulation were verified using MATLAB Tool. A platinum-based bulk micro-machined hotplate of size 500 μm × 500 μm has been designed for fabrication as a multi-layer structure on a silicon substrate with thermal silicon dioxide as the supporting membrane, followed by LPCVD (Low pressure chemical vapor deposition) silicon nitride film. Gas sensing film (SnO_2) will be deposited on the interdigitated Pt electrodes formed on the PECVD oxide layer. The temperature uniformity of microhotplate (as it is essential for better sensing mechanism) based on double spiral heater has been reported in this paper. To estimate the resistance of the Pt heater, a 2000 Aº thick platinum film has been deposited by sputtering on silicon and its sheet resistance has been measured as 2.5 Ohm/□. We have used this value to calculate the resistance of Pt resistor, which was found 319 Ohm. *Copyright © 2011 IFSA.*

Keywords: Pt-heater, Bulk-micromachining, Microhotplate, Gas sensor, ANSYS simulation.

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1. Introduction

The semiconductor industry is moving towards sensor driven processing as more stringent environmental concern arises. The on line process control system offers significant efficiency and cost benefits, but a suitable detection system does not yet exist; the microelectronics industry has not embraced this approach. The gas sensors are becoming very important in our everyday lives. They include the area of laboratory analysis, medicine, automobiles, and industrial safety. The semiconductor based gas sensors [1-9] are widely used for both process application and life safety. These types of sensors have the advantage of small size which helps in achieving low power consumption. Such gas sensors include devices that detect unsafe levels of explosive and poisonous gases in breathing–space environments, and devices that continuously monitor humidity and contaminant levels within process gas streams. The chemical reaction between the probed environment and the active portion of the sensor produces the signal, which can be interpreted to provide the species concentrations. A limited level of selectivity can be introduced by altering the type of materials but it has been recognized that the change in temperature greatly affects the functionality of the devices by changing interaction kinetics and other properties. Therefore in the development of microhotplate based gas sensor the temperature of active area where the sensing film are deposited, should be uniform to avoid the change in characteristics of gas sensor. In addition, it has also been observed that on increasing the number of sensing elements, better flexibility and selectivity are provided. The combination of temperature and the multiple sensing elements is used to improve the selectivity and this approach has been followed by several groups. The semiconductor gas sensors are required a device, which can produce the elevated temperature (250 ^{o}C-500 ^{o}C) with small power consumption. MEMS-based microhotplate (MHP) has tremendous importance in this area. In several design of microhotplate for high temperature, resistive sensor and micro-calorimeters being the most common. In case of resistive gas sensors a gas sensing material such as doped tin oxide, heated by a microhotplate (a heater isolated on membrane formed by bulk [10-12] or surface micromachining of silicon in order to reduce the power consumption). Micro-calorimeters require a microhotplate with a catalyst such as palladium to catalyze the combustion of a flammable gas. The temperature of the hotplate rises due to combustion, because it is directly proportional to the gas concentration.

The fabrication of microhotplate for gas sensor has been done by various research groups with heater isolate by either a membrane or micro-bridge. The membranes are fabricated by back-side etching and micro-bridges are fabricated by front side etching of silicon. This process is known as bulk-micromachining. The micro-bridge is mechanically poor stable than membrane because it suspended by four arms where as it provides the better thermal isolation than membrane. Also some micro-hotplate is fabricated by surface micromachining technique. In this technique sacrificial layer is used to provide suspended structure. The earlier technique has the high thermal isolation of hotplate in comparison to surface micromachining but provides lower mechanical strength. In the present work we have designed the Pt based microhotplate [13-14] taking the bulk micromachining into consideration. The use of platinum is preferred for MHP fabrication because it is not attacked by the etchant during bulk micromachining, thereby simplifying the process. Platinum based MHPs offer the advantages of reliability and reproducibility and stable temperature coefficient resistance (TCR). Besides gas sensing applications, they are also used in microfluidics, infrared emission and thermal flow sensing studies.

2. Design and Simulation

We have designed platinum-based microhotplate using ANSYS 10.0, as shown in Fig. 1. In this case only the membrane area of microhotplate was considered. Dimensions used in design are given in the Table 1. A platinum film of 2000 A º thickness has been deposited by sputtering technique on a 4” silicon wafer and its sheet resistance of 2.5 ohm/□ was measured. We have used this value to calculate the resistance of Pt resistor. The microhotplate is a 500×500 μm^2 membrane of thickness 1.3 micron (1 micron silicon dioxide and 0.3 micron silicon nitride) over which a Pt heater of 319 ohm will be laid out. The electro-thermal simulation of unit cell of microhotplate array has been carried out by using ANSYS 10.0, widely used finite-element based software for simulation of MEMS devices. In the present simulation work, the properties used are given in Table 2 [15]. In this simulation, the SOLID69 element has been used, which supports the basic thermoelectric analysis taking the joule heating effect into consideration. SOLID69 has 3-D thermal and electrical conduction capability. In this analysis, a Si substrate has been taken on which there is a 1.0 micron thick SiO_2 and 0.3 micron Si_3N_4 layers for supporting the membrane. Above Si_3N_4 layer there is a 0.2 micron thick Pt layer for microheater. The temperature of Si substrate surrounding the hotplate was fixed at 25 ^oC as the boundary condition. The mathematical calculation of temperature of membrane has been carried out using equation (1).

$$\text{Temperature} = \frac{\text{Heat}}{\text{Sum of multiplication of masses and specific heat of Pt, Air, } SiO_2 \text{ and } Si_3N_4} \quad (1)$$

Heat is transferred into the surface due to two phenomenon conduction and convection. We have considered only conduction in our analysis. Heat transfer by the molecules without any motion of the material is called conduction. So the heat transfer between two plane surfaces, such as heat loss through the wall of a house, the rate of conduction is given by equation (2).

$$\frac{Q}{t} = \frac{\kappa A(T_{hot} - T_{cold})}{d}, \quad (2)$$

where left hand side is rate of conduction of heat transfer, (k) is thermal conductivity *A* is the area through which heat transfer takes place, (T) is temperature (d) is the thickness of the barrier. The electro-migration limit of Pt material is 10 mA/μm^2. In our design the current density is 3.91 mA/μm^2 which is less than the electro-migration limit of Pt.

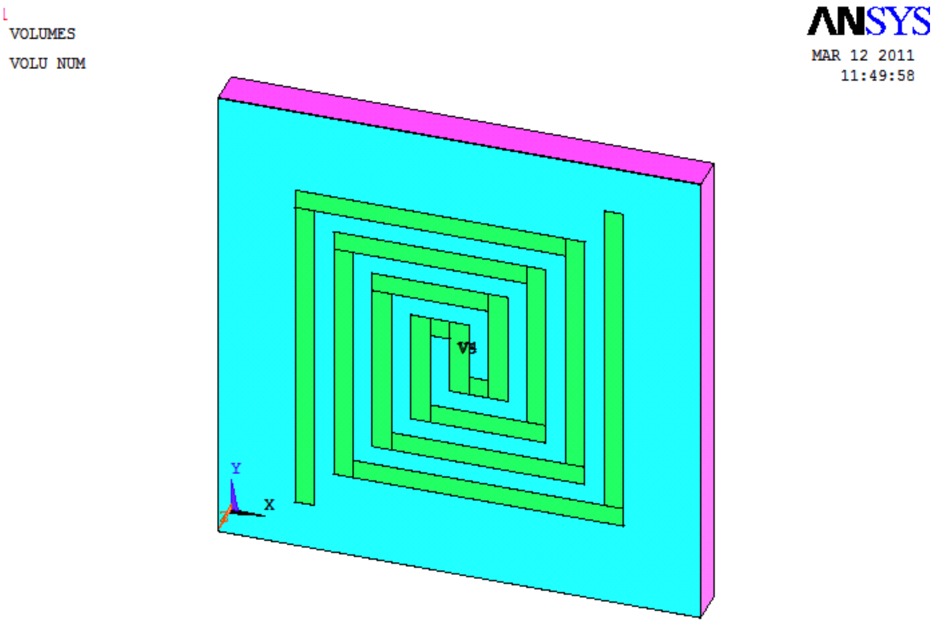


Fig. 1. Structure of platinum-based microhotpltae.

Table 1. Dimensions used in the design.

Heater finger width	20 μm
Gap between fingers:	20 μm
Hotplate size:	500 × 500 μm^2
Pt heater size	340 × 340 μm^2

Table 2. Properties used in simulation.

Material Properties (in MKS)	Si	SiO_2	Pt	Si_3N_4
Thermal Conductivity (W/m/K)	157	1.4	72	0.027
Resistivity (ohm-m)	1.0×10^{-1}	5.05×10^{13}	0.5×10^{-6}	-
Specific Heat (J/kg/K)	0.7×10^{3}	710	133	3100
Density (kg/m^3)	2.33×10^{3}	2200	21400	1.205

3. Results and Discussion

The typical ANSYS plots of temperature distribution at 5 V, 4 V, 3 V and 2 V Fig. 2 (a), (b) (c) and (d) respectively. It is seen from Fig. 2 that a temperature of 1002 °C was achieved at 5V where as 181 °C was achieved at 2 V. Thus by varying the supply voltage to the heater terminals, the required temperature of the platform is reachable. The red color showing the maximum temperature at the centre and it is going downward towards edge of the membrane. The temperature versus distance from the center of the membrane at a fixed applied voltage are shown in Fig. 3. The double spiral shape heater has the better temperature uniformity in comparison to meander shape [15] type heater. It is clear from this Fig. that when we move towards the edge of the membrane, the temperature is non-uniform after a certain distance. Therefore by using this result we can define the active area of MHP for gas sensing films where the microhotplate temperature is uniform. In the present case it is 200 µm for 1.3 µm thick SiO_2 + $Si3N_4$ membrane. Fig. 3. also shows that at bias voltage 2 V, 3 V, 4 V and 5 V the temperature of hotplate membrane is uniform from -100 µm to 100 µm. To verify the results obtained from ANSYS simulation, mathematical calculation of temperature of MHP has been carried out using equation (1) by MATLAB Tool. Fig. 4. shows the variation of temperature with applied voltage.

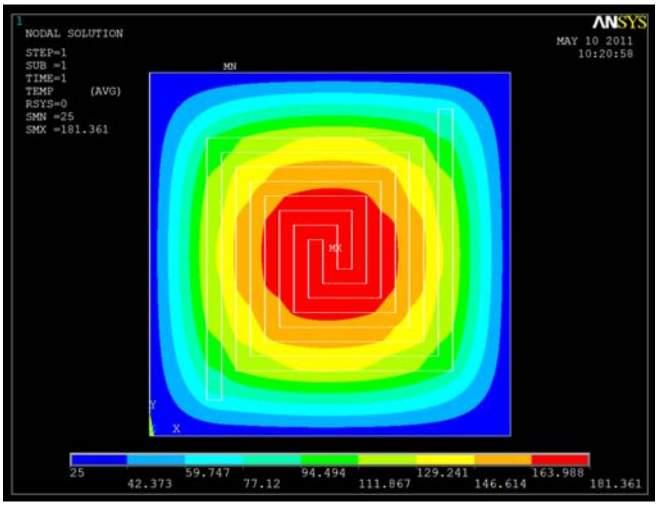
Finally the combined results obtained from both mathematical and simulated work are plotted in Fig. 5. The similar results were obtained from both ANSYS and MATLAB Tool.

4. Conclusions

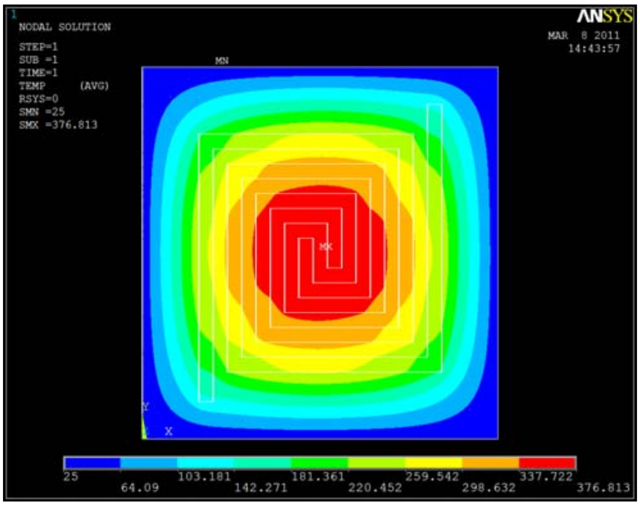
A double-spiral Pt heater based microhotplate has been designed and characterized by electro-thermal simulation using ANSYS. The results obtained from ANSYS simulation were verified using MATLAB tool. A good agreement is found between the simulated and mathematical results. The simulation results also shows the temperature uniformity (active area) of microhotplate which is essential for better sensing mechanism.

Acknowledgements

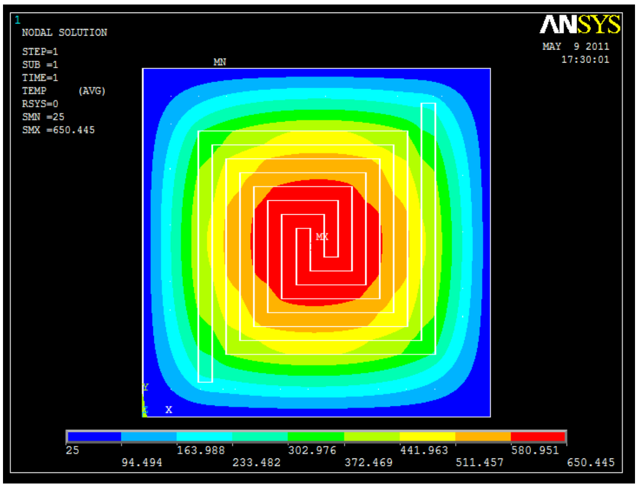
The authors are thankful to the Director, CEERI for encouragement and guidance.



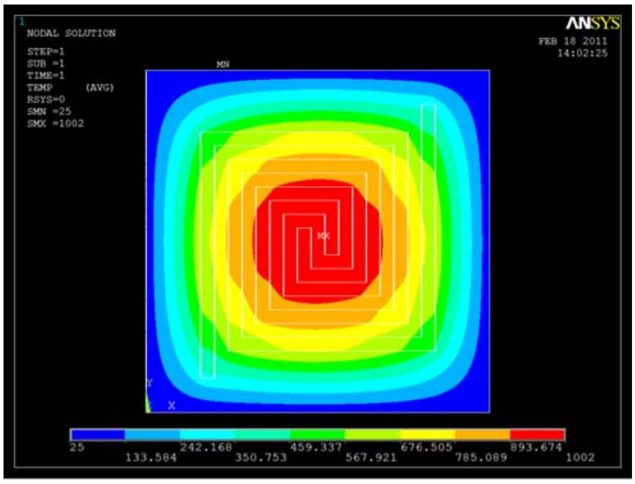
(a) at 2 V.



(b) at 3 V.



(c) at 4 V.



(d) at 5V.

Fig. 2. Temperature distribution of micro-hotplate membrane at (a) 2V; (b) 3V; (c) 4V; (d) 5V.

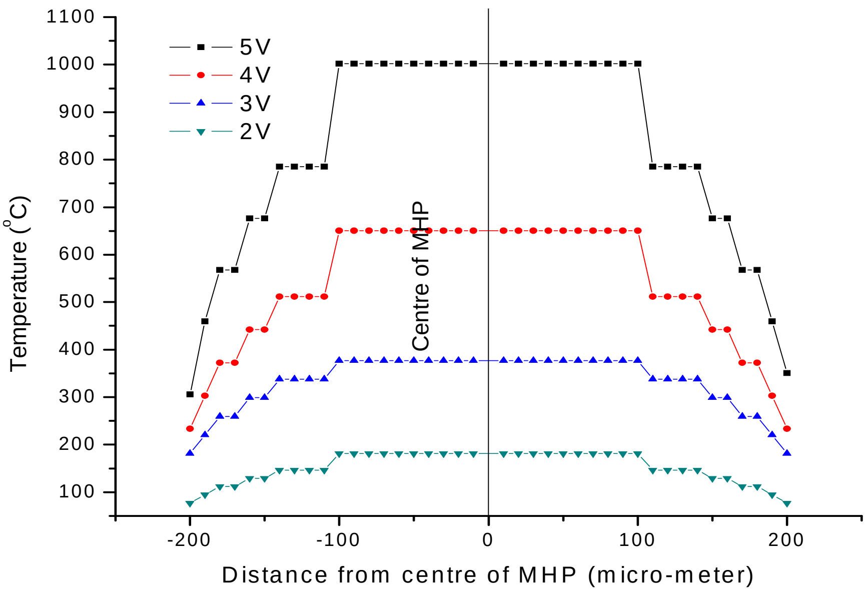


Fig. 3. Variation of temperature with distance from centre of micro-hotplate.

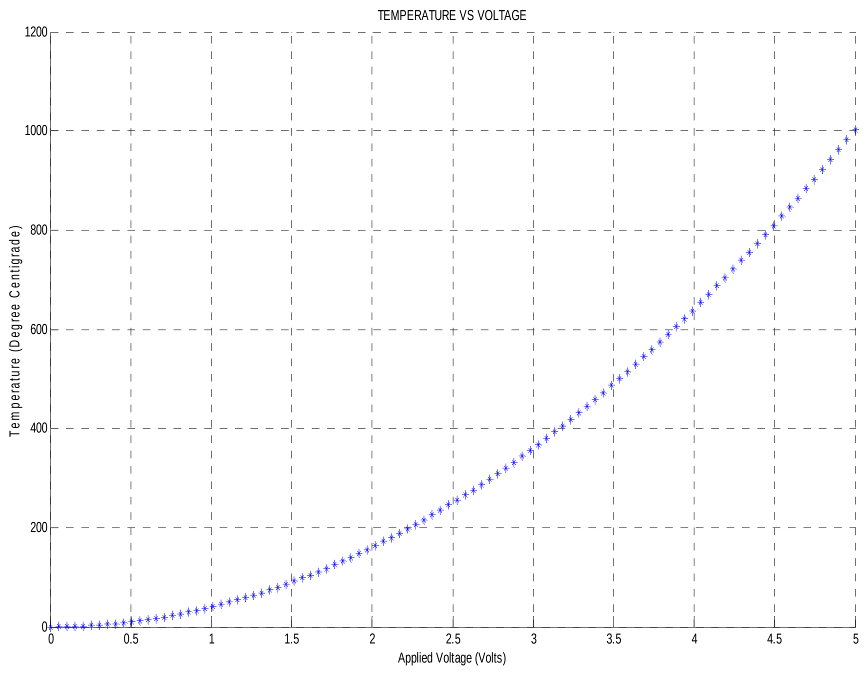


Fig. 4. Mathematical calculation of temperature with applied voltage using MATLAB.

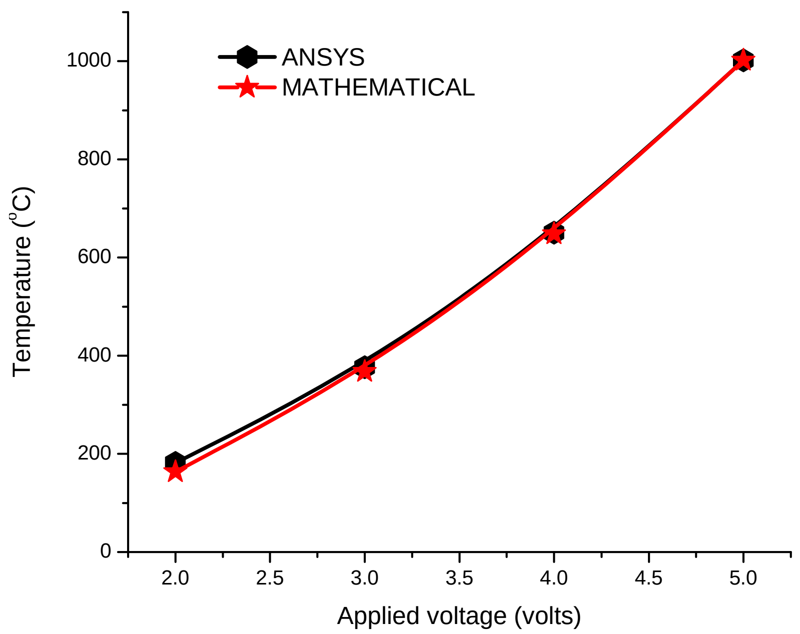


Fig. 5. Variation temperature with applied voltage.

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