ISSN: 2278 – 1323
International Journal of Advanced Research in Computer Engineering & Technology (IJARCET)
Volume 2 Issue 8, August 2013

Design and Simulation of MEMS based Microhotplate as Gas Sensor

Monika[1], Dr. Arti Arora[2]

Abstract - **MEMS based Microhotplates plays an important in gas sensing applications. In this paper, we present the simulation results of a MEMS micro-hotplate. The electro-thermo-mechanical behaviors of micro- hotplates (MHP) have been simulated using COMSOL Multiphysics. A low cost nickel alloy DilverP1 (alloy of Ni, Co, Fe) having high resistivity $49x10^{-8}\Omega m$ is used as heating element. The effect of various thicknesses of heating element on the temperature, displacement, and power consumption of the MHP is evaluated. Results show that as the thickness of the heating element is increased from 0.25 µm to 2 µm, the power consumption of the MHP increases from 4.6mW to 37mW at 0.8 V with a square cavity in silicon membrane. Two different patterns of micro-heaters which are curved spiral over the silicon membrane with and without cavity are also demonstrated. A comparison between the power consumption of different materials is also analyzed in the presented work. At the end of the paper a complete metal oxide gas sensor using sensing layer of ZNO is simulated.**

Index Terms— **DILVER P1, Gas sensor, MEMS, ZNO**

I. INTRODUCTION

The number of applications for MEMS micro-heater devices is increasing rapidly, as they are key Components in subminiature micro-sensors such as wind sensors, humidity sensors, and gas sensors [1, 2]. A micro heater generally consists of a thin film heater coil, wire, or meander which is suspended within a silicon rim for thermal isolation. The average temperature of the heater is determined from the change of the electrical resistance of the heater [1]. MEMS Microhotplates generates high temperatures at low power consumption and exhibit a fast thermal response [2]. For use them as a metal oxide gas sensors, a uniform temperature is required over a wide area of the heater [2, 3]. In metal oxide gas sensors, micro-heater is used as a hot plate which controls the temperature of the sensing layer. This type of gas sensor utilizes semiconductor properties of surface adsorption to detect changes in resistance as a function of varying concentrations of different gases. In order to detect these resistive changes, the heater temperature must be held constant and uniform over the heater area. Therefore, sensitivity, selectivity and response time of the semiconductor gas sensor are dependent on the sensing layer material and operating temperature of the micro-heater [2, 4]. The high- temperature operation with low power consumption feature of a MEMS micro heater requires high efficiency in thermal isolation so as to minimize heat conduction loss [3]. The electrical and mechanical stability of the heater structure should be considered as well because of thermal expansion effects, especially the dependence of thermal expansion coefficients on material composition [4].The Joule heating and thermal expansion model under the structural mechanics module of COMSOL MULTIPHYSICS, A Finite Element Analysis (FEA) Package is used. Computer simulation has been widely used for MEMS device design. The main advantage of computer simulation is to provide design optimization by varying geometry, layer dimension, and materials of the device without actual fabrication .This systematic approach can save time and cost of device fabrication [5]. The heat distribution in 2D design concepts is not so good due to the spreading of heat and thus quite large power consumption. This is improved by using a 3D design concept [4]. The heating electrode of curved spiral shape is used. This design gives a much more uniform heating of the sensor surface and much faster heating characteristics [6]. The semiconductor gas sensors offer low cost and a real simplicity in function, low power consumption, good mechanical stability [7]. In a semiconductor gas sensor a micro-heater is used as a hot plate which controls the temperature of the sensing layer. The semiconductor gas sensor utilizes semiconductor properties of surface adsorption to detect changes in resistance as a function of varying concentrations of different gases.

II. Joule Heating and Electro-Thermal mathematical modeling of Micro-hotplate

The Joule Heating Model node in **COMSOL** uses the following version of the heat equation as the mathematical model for heat transfer in solids:

$$\rho C_p \frac{\partial T}{\partial t} - \Delta(k\Delta T) = Q \dots\dots\dots [1]$$

With the following material properties:

- ρ is the **density**.
- C_P is the **heat capacity.**
- **k** is the **thermal conductivity** (a scalar or a tensor if the thermal conductivity is anisotropic).
- **Q** is the **heat source** (or sink)

In Joule heating, the temperature increases due to the resistive heating from the electric current. The electric potential **V** is the solution variable in the Conductive Media DC application mode. The generated resistive heat **Q** is proportional to the square of the magnitude of the electric current density **J**. Current density which in turn, is proportional to the electric field, which equals the negative of the gradient of the potential V, so we have

$$Q \propto |J|^2 \dots\dots\dots\dots\dots\dots [2]$$

The coefficient of proportionality is the electric resistivity **ρ= 1/σ**, which is also the reciprocal of the temperature-dependent electric conductivity **σ= σ (T)**. Combining these facts gives the fully coupled relation.

$$Q = \frac{1}{\sigma}|J^2| = \frac{1}{\sigma}|\sigma E|^2 = \sigma|\Delta V|^2 \dots\dots\dots\dots\dots\dots [3]$$

Over a range of temperatures the electric conductivity **σ** is a function of temperature T,
According to:

$$\sigma = \frac{\sigma_0}{1 + \alpha(T - T_0)} \dots\dots\dots\dots\dots [4]$$

Where σ_0 is the conductivity at the reference temperature T_0, **α** is the temperature coefficient of resistivity, which describes how the resistivity varies with temperature. Also the power consumption is described as:

$$P = \frac{V^2}{R} \dots\dots\dots\dots\dots\dots [5]$$

Where V is voltage and R stands for resistance of heating electrode. Here power consumption is directly proportional to the applied voltage and inversely proportional to the resistance of the material. The equations have been solved under Dirichlet, Neumann, and mixed boundary conditions numerically using the Finite Element Method (FEM) when the Electro-Thermal module is selected in COMSOL. Chemical Composition of DilverP1is shown in Table 1. Several material properties are required to solve the mathematical equations mentioned above are shown as below in Table 2.

Table 1. Chemical Composition of DilverP1 (wt. %) [6]

Element	N	Co	Mn	Si	C	Fe
Value	29	17	≤ 0.35	≤ 0.15	≤ 0.02	Bal

Table 2. Physical properties of DilverP1

Density (g/cm3	Resistivity (Ωm)	Thermal conductivity (w/m/°C)	Specific heat (J/kg/°C)	CTE in (/°C)	Poisson's ratio	Young's Modulus(Pa)	Yield Stress (Mpa)
8.25	$49\text{x}10^{-8}$	17.5	500	4-5.2x 10^{-6}	0.3	207e9	680

III. Electro –Thermal-Mechanical simulation of Micro-heaters

All the Micro-heater geometries simulated are curved shaped, here DILVER P1, a nickel alloy which produces the heating is taken as 100 ×100 micron with thickness of 1micron, is deposited over the silicon dioxide membrane which is taken as 2 micron thick. The simulation is carried out at a voltage of 0.8v which is applied to one end of heating electrode and other end is grounded. The inward heat flux is set at 1 Wm^{-2} k^{-1} which incorporates for heat convection. The simulated result is shown in Fig 2. Here we can see that at 0.8v supply the heater gives a temperature rise of 440.6 K with a uniform heat distribution with maximum temperature at the center of the heater.

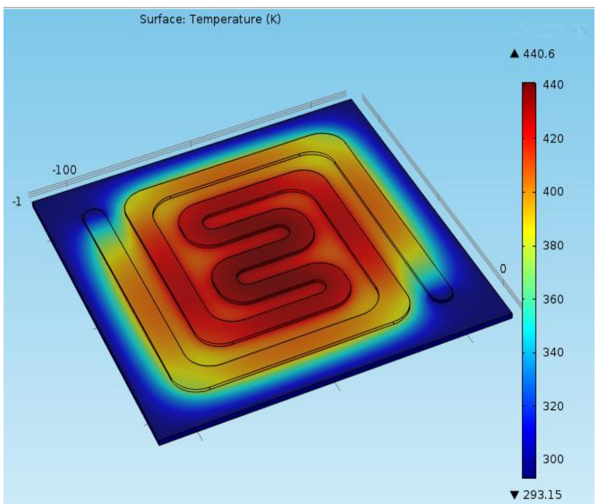

Fig1. Curved spiral heater over SiO_2 at 0.8V

The cavity can be varied in area ranging from 80×80 microns to 120×120 microns and depth around 1 micron. Here the cavity is 90×90 microns. So with an introduction of a cavity of 90×90 microns a temperature of about 723.92 K is obtained with a power consumption of 18.5 mW at the supplied voltage of 0.8V. The cavity structure provides about 277^0C higher temperature and low power consumption as compared to Structure shown in Fig 1. Also in this low power consumption geometry the deformations due to thermal expansion and stress are minimum because the membrane is not heated to the maximum temperature at the center due to a cavity underneath the heating element or due to suspended heating element. Thus the deformations in the membrane will be minimum and so will be in the heating element which is lying above the membrane.

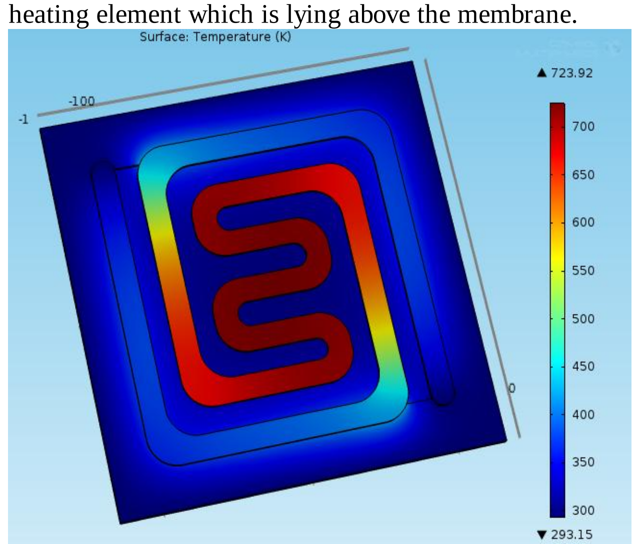

Fig 2. Curved Spiral heater with a cavity in the silicon at the center of micro-heater

Electro thermo simulation of DILVER P1 heating electrode at various thicknesses between 0.25 µm to 2µm and their corresponding power consumptions is carried out using COMSOL MULTIPHYSICS shown in table 3.and table 4.

Table 3. Electrical - Thermal Simulations for different DILVER P1 beam thickness of the Microheater for 700-750 K target temperature

Heater Material	Supply Voltage	Temperature at 0.25 μm Thickness	Temperature at 0.5 μm Thickness	Temperature at 1 μm Thickness	Temperature at 2 μm Thickness
	Volt	*K*			
DILVER P1	0	293.15	293.15	293.15	293.15
	0.2	298.34	300.81	308.21	322.06
	0.4	305.67	323.74	353.41	408.79
	0.6	346.90	361.97	428.73	553.34
	0.8	399.86	415.5	723.92	855.71
	1	430.16	484.33	835.48	1015.9

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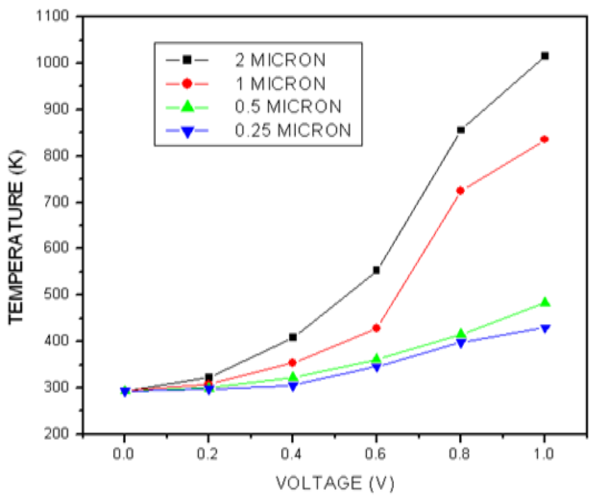


Fig.3: Heater Temperature vs. Applied voltage levels to the structure of Dilverp1 heater

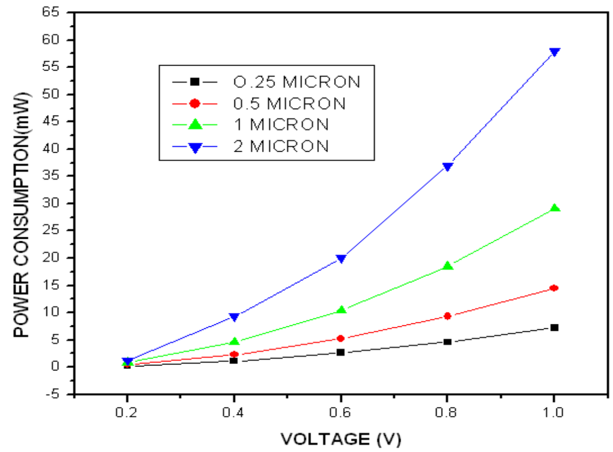


Fig.4: power consumption vs. applied voltage levels to the structure of Dilverp1 heater

Table 4. Power Consumption Calculations for the different Dilverp1 beam thickness of the Microheater for 700-750 K target temperature.

Heater Material	Supply Voltage in Volts	Power Consumption at 0.25 μm Thickness	Power Consumption at 0.5 μm Thickness	Power Consumption at 1 μm Thickness	Power Consumption at 2 μm Thickness
Dilver P1	$Volt$	mW			
	0.2	0.23	0.46	0.84	1.28
	0.4	1.1	2.3	4.6	9.3
	0.6	2.6	5.2	10.4	20
	0.8	4.6	9.3	18.5	37
	1	7.2	14.5	29.1	58

Table 5. Optimal parameters of the Dilverp1 Microheater for 700-750 K target temperature at 0.8V.

S.no.	Thickness of the Microheater	Power consumption	Maximum Temperature Over Heater	Displacement (z)	Stress(z) at the corners of heater pads
	μm	mW	K	μm	MPa
1.	0.25	4.6	399.86	0.00020	122
2.	0.5	9.3	415.5	0.00056	248
3.	1	18.5	723.92	0.00221	496
4.	2	37	855.71	0.00624	578

Table 5. Shows the Simulation observations for a 700-750 K target temperature. The selected thickness (t) of microheater are t=1µm, Supply Voltage = 0.8V, Displacement (z) =0.00221µm, Stress (z) =496MPa for the target temperature. Boundary Conditions (all external sides of the Air) are at room temperature (i.e.293.15K).

Two famous materials used for heating element i.e. Polysilicon and Platinum are compared with DILVER P1at 0.8V. As a result we found DILVER P1 material has low power consumption, stress distribution, less displacement as compared to polysilicon and platinum due to its high resistivity and low thermal expansion coefficient.

Table 6: Optimized value of different heater materials

zS.No.	Heater material	Thickness of heater material	Power consumption	Maximum temperature Over the heater	Stress at the z axis
		(µm)	(mW)	(K)	(MPa)
1.	DILVER P1	1	18.5	723.62	463
2.	POLYSILICON	1	28.3	739.29	769
3.	PLATINUM	0.5	43.1	750.08	1549

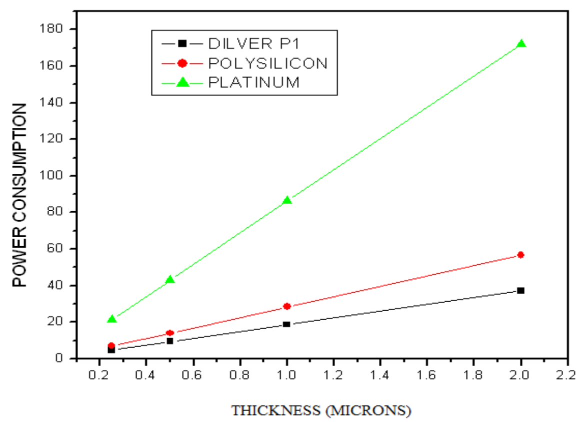


Fig.5: power consumption vs. applied thicknesses Using different materials

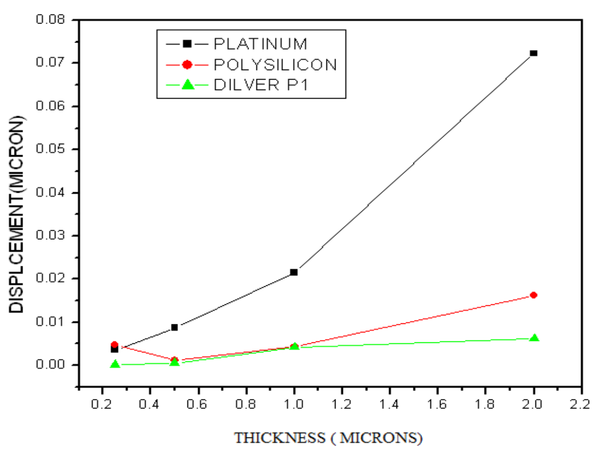
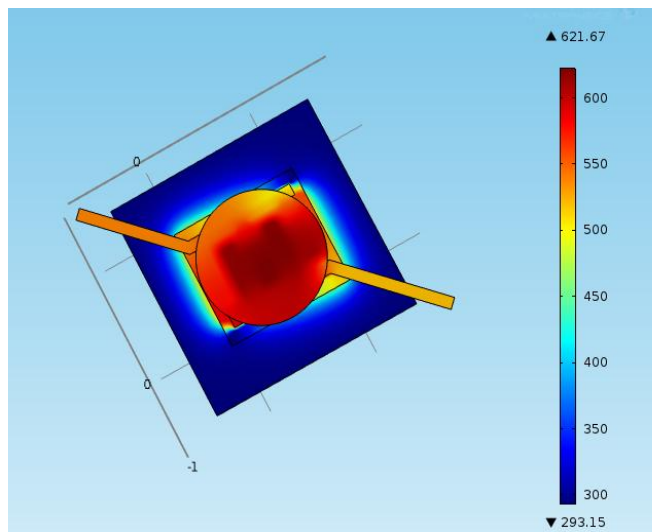


Fig.6: Displacement vs. applied thicknesses using



different materials

Fig. 7: Simulated metal oxide gas sensor

Fig 7. Shows a complete gas sensor with a sensing layer of zinc oxide (ZnO). Here the curved spiral microheater of Fig 2 is used. On the heater surface an insulating layer of silicon oxide of thickness 0.2 to 0.3 microns is deposited and above it inter-digital electrodes made of gold is deposited. These electrodes detect the change in the resistance when a gas reacts with the sensing layer of metal oxide which is deposited on the inter- digital electrodes [8]. For a gas sensor to operate at maximum potential the temperature distribution on the sensing layer must be uniform. This uniform distribution is achieved and the maximum temperature at the sensing layer is at the center where most of the adsorption takes place.

IV. Conclusion

In the present work, the design, modeling and simulation of a MEMS based micro-heater device has been studied for gas sensor system operating in the temperature range of 600 K. COMSOL MULTIPHYSICS (A MEMS design and simulation software) has been used for electro-thermal-mechanical analysis of microhotplate. In the simulation process, the effects of thickness, design and Electro-Thermal-mechanical Analysis of MEMS Based Micro-hotplate for Gas Sensor of the DilverP1 heater layer temperature, power consumption are evaluated. The sensor's operating temperature is achieved with low applied voltage of 0.8v with thickness of 1 micron. At a sensor temperature, the power consumption is reduced as the thickness of heating element decreases. Here we can see that if the thickness of the heating electrode is increased to 2 microns then power consumption also increases. So the power consumption depends upon the geometry and type of material used for heating purpose. Therefore DilverP1 micro-heater is more desirable for the gas sensor application**.**

References

[1]. J.F. Creemer, D. Briand, H.W. Zandbergen, W. vander Vlist , C.R. de Boer, N.F. de Rooij, P.M. Sarro "Microhotplates with TiN heaters", Sensors and Actuators A: Physical 148, issue 2, 416-421, 2008.

[2]. Woo-Jin Hwang, Kyu-Sik Shin, Ji-Hyoung Roh, Dae-Sung Lee, and Sung-Hoon Choa, "Development of Micro-Heaters with Optimized Temperature Compensation Design for Gas Sensors". Sensors 2011, 11, 2580-2591; doi: 10.3390/s110302580

[3]. Cerdà Belmonte J, Puigcorbe J, Arbiol J,Vila A, Morante JR, Sabate N, Gracia I, Cane C " High-temperature low-power performing micro machined suspended micro-hotplate for gas sensing applications". Sensors and Actuators B 114:826–835, 2006.

[4]. Vineet Bansal, Anil Gurjar, Dinesh Kumar, B. Prasad " 3-D Design, Electro-Thermal Simulation and Geometrical Optimization of spiral Platinum Micro-heaters for Low Power Gas sensing applications using COMSOL" Proceedings COMSOL conference, 2011

[5]. Bijoy kantha, Pallavi kar, Saral saha, and Subir Kumar sarkar "Design and Electro-Thermal Analysis of MEMS based Micro-hotplate for Gas Sensor". Chennai and Dr. MGR University Second International Conference on Sustainable Energy and Intelligent System (SEISCON 2011).

[6]. A. Wisitsoraat, A. Tuantranont, T. Lomas, "Design and Simulation of Electro-fabricated MEMS Micro-hotplate for Gas Sensor Applications". International MEMS Conference, 2006.

[7].L.Sujatha, V.S.Selvakumar, S.Aravind, R.Padamapriya, B.Preethi "Design and Analysis of Micro-Heaters using COMSOL Multiphysics for MEMS Based Gas Sensor", Proceedings COMSOL conference, 2012.

[8]. V.k Khanna et .al. "Electro thermal simulation of a polysilicon micro heater on a suspended membrane for gas using" Indian journal of pure and applied physics
Indian journal of pure and applied physics, vol.45, pp-332-335, 2007.