Excerpt from the Proceedings of the 2011 COMSOL Conference in Bangalore

3-D Design, Electro-Thermal Simulation and Geometrical Optimization of spiral Platinum Micro-heaters for Low Power Gas sensing applications using COMSOL ™

Vineet Bansal , Anil Gurjar, Dinesh Kumar, B. Prasad
Department of Electronic Science, Kurukshetra University
vineetbansal385@gmail.com, bprasad2005@gmail.com,

Abstract: In this paper we have presented the MEMS micro-heaters for gas sensing applications. A thermal electric finite element method (FEM) analysis was used to investigate the thermal properties of individual electrically driven platinum micro-heaters. The geometric optimization for the micro-heater was performed by simulating a wide range of possible geometries using COMSOL 4.1. The simulated results of micro-heaters having an improved temperature distribution over the sensing area of gas sensor are demonstrated. These micro-heaters are designed to ensure low power consumption, low thermal mass and better temperature uniformity. Three different patterns of micro-heaters which are spiral, spiral with a square cavity in silicon membrane and suspended spiral type with their Electro- thermal simulated temperature profile are demonstrated. For the supply voltage of 2V, the uniform temperature profile and the power consumption of the heaters to obtain an operating temperature of 300C is analyzed for all the patterns and results are compared.

Keywords: Micro-heaters, COMSOL^{TM}, gas sensor, membrane, metal oxides, micron.

1. INTRODUCTION

The applications of MEMS micro heater devices are expanding rapidly particularly as key components of chemical sensing microsystems where hotplates are combined with sensitive sensing elements. 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. 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. For these reasons, heater resistors were suspended filaments like air bridge structures or generally formed onto a low heat conductive micro machined insulator membrane over the silicon cavity. In this paper, we propose a novel design of a high-temperature MEMS heater for a low power gas sensing application. We adopt suspended silicon beams for improved mechanical stability and thermal isolation of the heater resistor in place of a micro machined insulator membrane. We utilize platinum as a Joule heating resistor material for our feasibility study because it is a well-known standard material for high temperature heaters, electrically and thermally stable for high temperature operation, easily available for the deposition process. It is also highly conductive thus usable with a low drive voltage. Semiconducting Metal oxides like SnO_2, ZnO and TiO_2 have long been used for detecting poisonous (CO) and inflammable gases (CH_4) by their change in conductivity. For sensing gases the temperature of the sensing layer should be raised to a particular value (typically from 300-500˚C) thereby requiring a large amount of power (>100mW). The heating element serves the purpose by producing accurate and uniform heating of the sensor surface. 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. This design gives a much more uniform heating of the sensor surface and much faster heating characteristics.

2. Joule Heating and Electro-Thermal Mathematical modeling of Micro-heater

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

$$\rho Cp \frac{\partial T}{\partial t} - \Delta.(k.\Delta T)=Q$$

With the following material properties:

- **ρ** is the **density**.
- **Cp** 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

$$Q \propto \left|J^2\right|$$

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

$$Q = \frac{1}{\sigma}\left|J^2\right| = \frac{1}{\sigma}\left|\sigma E\right|^2 = \sigma\left|\Delta V\right|^2$$

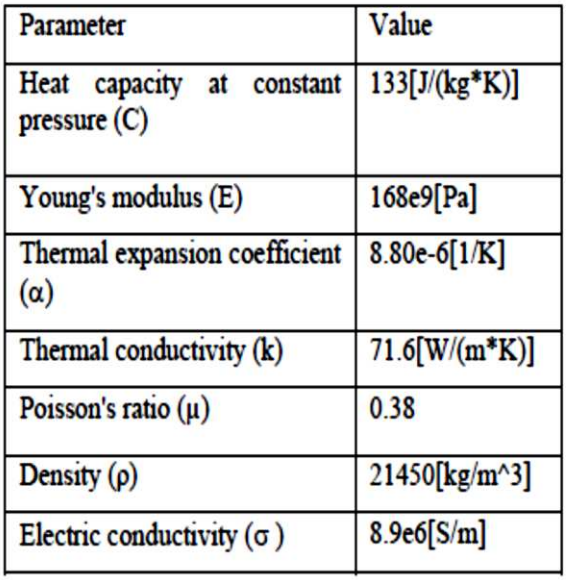
Over a range of temperatures the electric conductivity **σ** is a function of temperature **T,**
According to:

$$\sigma = \frac{\sigma 0}{1 + \alpha(T - T0)}$$

Where $\sigma 0$ is the conductivity at the reference temperature **T0**, **α** is the temperature coefficient of resistivity, which describes how the resistivity varies with temperature.
Also the power consumption is described as:

$$P = \frac{V^2}{R}$$

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 4.1.** Fixed temperature and potentials are assumed at ends of the heater. Several material properties are required to solve the mathematical equations mentioned above. In Figure 1 material properties of platinum are shown.



Parameter	Value
Heat capacity at constant pressure (C)	133[J/(kg*K)]
Young's modulus (E)	168e9[Pa]
Thermal expansion coefficient (α)	8.80e-6[1/K]
Thermal conductivity (k)	71.6[W/(m*K)]
Poisson's ratio (μ)	0.38
Density (ρ)	21450[kg/m^3]
Electric conductivity (σ)	8.9e6[S/m]

Fig 1. Material properties of Platinum

3. Simulation and analysis of Micro-heaters.

All the Micro-heater geometries simulated are spiral shaped, here platinum metal element which produces the heating is taken as 270 ×270 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 2v which is applied to one end of heating electrode and other end is grounded. The inward heat flux is set at 5 Wm^{-2}k^{-1} which incorporates for heat convection. The simulated result is shown in Fig 2. Here we can see that at 2v supply the heater gives a temp rise of 460 C with a uniform heat distribution with maximum temperature at the center of the heater. But the power consumption in the above mentioned spiral geometry is about 40mW. To reduce this power consumption we introduced geometry with a square cavity in the silicon membrane as shown below in fig 3.

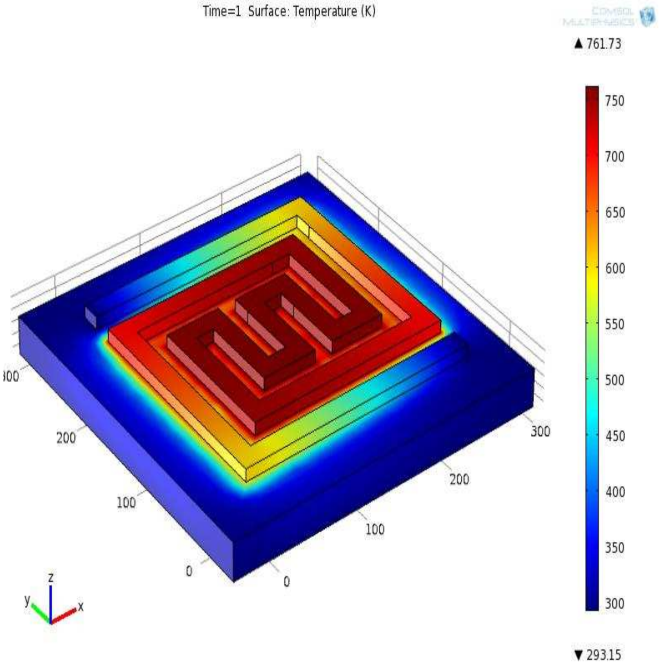


Fig 2. A spiral platinum micro-heater at 2V supply voltage.

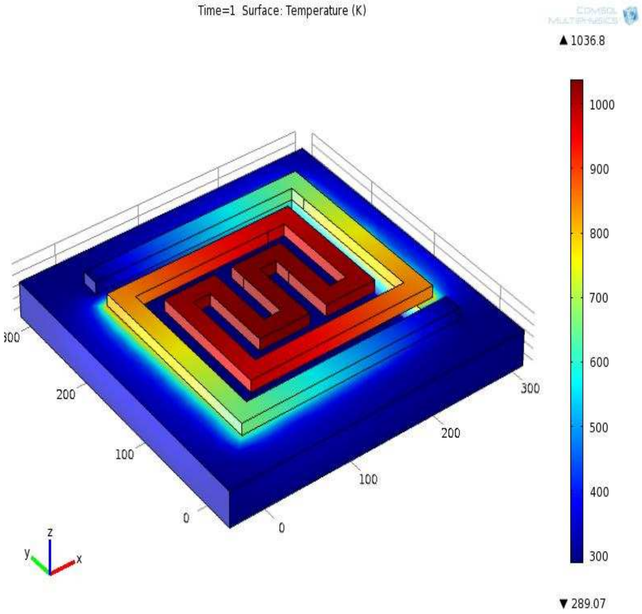


Fig 3. Spiral heater with a cavity in the silicon at the center of micro-heater.

The cavity can be varied in area ranging from 100×100 microns to 250×250 microns and depth around 1 micron. Here the cavity is 240×240 microns. So with an introduction of a cavity a temperature of about 750 C is obtained and typical power consumption is reduced to around 25mW to obtain a temperature of 450 C

In the third microheater structure in fig 4 four supporting bridges made of silicon dioxide are placed at the four corners of the microheater element to elevate the microheater above the membrane at a gap of about 0.5 to 1 micron so that the heat dissipation loss into the membrane can be reduced. The resulting structure is shown in Fig 4. We can also note that temperature distribution is unifrom acros the heater and maximum temperature is at the center. So by lifting up the microheater element to a certain amount of gap we can minimize the power consumption and also able to overcome the thermal expansion induced by the underlying membrane of silicon dioxide.

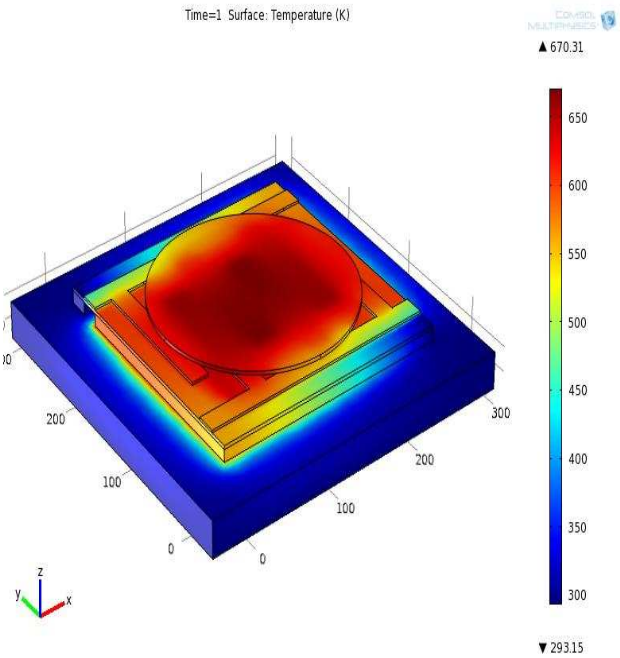


Fig 5. A complete gas sensor at operating temperature of about 377 C

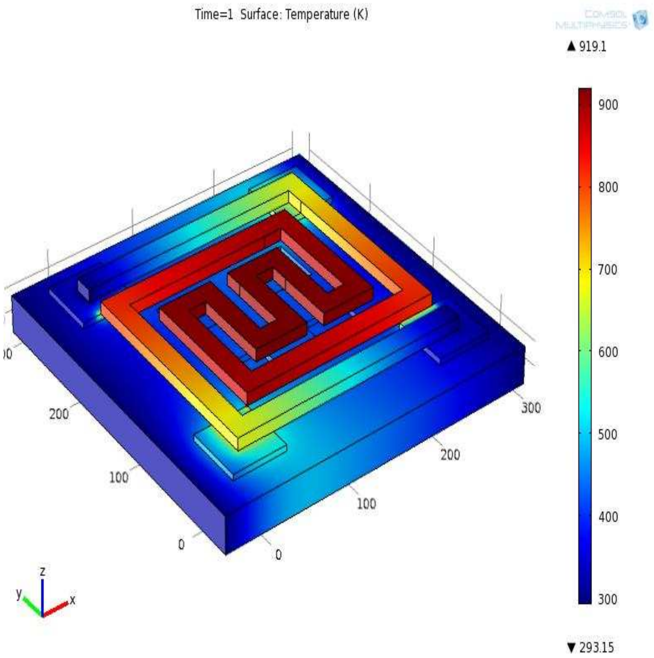


Fig 4. A suspended micro-heater on four bridges.

Fig 5 Shows a gas sensor with a sensing layer of zinc oxide (ZnO). Here the spiral microheater of Fig 2 is used. On the heater surface an insulating layer of silicon oxide of thickness 0.2 to 0.4 microns is deposited and above it inter-digital electrodes made of gold or aluminum 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. 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.

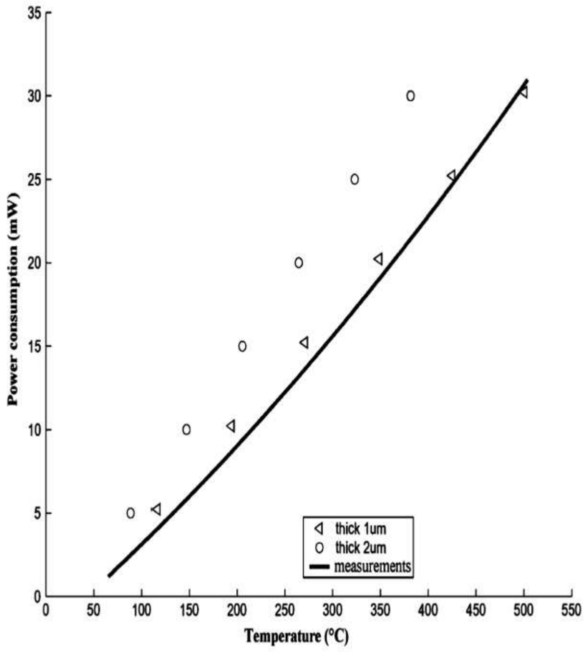


Fig 6. Power consumption versus temperature along with the thickness of the heating material.

In fig 6 above power consumption versus temperature is plotted for the optimized geometries of micro-heaters shown in fig 3 and fig 4. 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.

Conclusion

The purpose of the work was to establish new designs for obtaining micro-heaters for use in gas sensors requiring a uniform heating. In this study a spiral micro-heater is optimized for low power consumption applications resulting into two new geometries. These optimized micro heaters have uniform temperature distribution profiles at low power consumption. Also by further modifying the substrate thickness and more optimization into the heating material parameters better Micro-heaters can be obtained.

Acknowledgements

The authors are thankful to NPMASS for funding this activity and setting up a Design Center for research in MEMS at Electronic Science Department, Kurukshetra University.

REFRENCES

[1] Moldovan O. Nedelcu, U. Kaufmann, HJRitzhaupt-Kleissl, S. Dimov, P. Petkov, R.Dorey, K. Persson, D. Gomez, P. Johander “Mixed technologies for gas sensors microfabrication”, Proceedings 4M Conference on Multi Material Micro Manufacture 29 june-1 July 2005 Karlsruhe pp 211-z1217.

[2] D. Briand, S. Colin, A. Gangadharaiah, E.Vela, P. Dubois, L. Thiery,N.F. de Rooij, Sens. Actuat. A: Phys., **132**, 317–324 (2006)

[4] S. Semancik, R.E Cavicchi, M.C Wheeler, J.ETiffany, G.E Poirier, R.M Walton, J.S Suehle, B. Panchapakesan and D.L DeVoe, “Microhotplateplatforms for Chemical Sensor Research” Sensorand Actuators p 579-591 B77 (2001)

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

[6] Spannhake J, Schulz O, Helwig A, Krenkow A, Muller Gand Doll T 2006 High-temperature MEMS heater platforms: long-term performance of metal and semiconductor heater materials Sensors

[7] Cengel Y A 2003 Heat Transfer: A Practical Approach (New York: McGraw-Hill)