Design & Electro-Thermal Analysis of Microheater for Low Temperature MEMS based Gas Sensor

Susmita Sinha
IC Design and Fabrication Center, Department of Electronics and Telecommunication Engg.
Jadavpur University
India

Sunipa Roy
IC Design and Fabrication Center, Department of Electronics and Telecommunication Engg.
Jadavpur University
India

C. K. Sarkar
IC Design and Fabrication Center, Department of Electronics and Telecommunication Engg.
Jadavpur University
India

ABSTRACT
The advent of nanocrystalline metal oxide semiconductor permits microheater to be incorporated into integrated gas sensors to heat the sensing layer to a low temperature. The low temperature sensing allows the use of a relatively thin silicon membrane instead of zero Silicon membrane resulting into temperature uniformity across the entire active area (2mmx2mm) which in turn reduces the reliability problem of suspended type microheaters (on SiO_2/ Si_3N_4 membranes) arising due to the thermal stress generated micro- cracks. So it is necessary to optimize the microheater design issues in order to achieve the temperature in the active area. The temperature distribution of the device sensing area of several heater configurations have been investigated here and optimized using a low cost nickel alloy DilverP1 (alloy of Ni, Co, Fe) having high resistivity $49x10^{-8}\Omega m$ for micromachined silicon platform. With the new release version of COMSOL multiphysics 4.0, the user is provided a dramatic new interface from which to interact, and many new features "under the hood" for solving problems more efficiently and with even greater accuracy and consistency than before. This paper will explore several of this new version4.0 features for the temperature distribution analysis of microheater. Thermal electrical analysis was done using finite element modeling of COMSOL multiphysics 4.0. A comparative study by simulating the six different geometries namely: (a) Meander shape (b) Curved Meander shape (c) Double Spiral shape (d) Curved double spiral shape (e) S-Shape (f) Fan shape have also been presented in this paper. The device size is 5mm x 5mm with a membrane size of 2mm x2mm having an active area of 2mm x2mm and a thickness of 20µm. The maximum temperature of 473K with a distribution of ± (2-3) % over the entire microheater membrane region has been achieved with 5V excitation. A comparative study has also been made by taking different microheater element using COMSOL4.0.

Keywords
Dilver P1, Microheater, MEMS, Gas sensor, Electrothermal analysis, COMSOL Multiphysics 4.0.

1. INTRODUCTION
The COMSOL application area for this paper is the low temperature MEMS based gas sensor. Conventional metal oxide gas sensors are commonly used for sensing of inflammable gases (like CO) suffer from relatively high temperature (>=573K) and high power consumption (e.g. pellistors require 350-850 mW [1] and Taguchi gas sensors require 230-760 mW [2]). So low power consumption is a crucial requirement for a sensor system with an acceptable battery lifetime in coalmine. The low power consumption is achieved by reducing the device area and confining the heat. In this paper, for the first time we present a microheater design and simulation by nickel based alloy, DilverP1 with sufficiently high resistivity using Joule-heating module of COMSOL Multiphysics4.0, particularly applicable for a relatively low temperature (423K-573K) for the micromachined nanocrystalline zinc oxide based gas sensor. As the required temperature for nanocrystalline ZnO based gas sensor is around 473K – 523K, therefore this alloy is very much suitable for this application with low power consumption(150 mW) hence increasing the efficiency of the device. This 29% nickel-iron alloy, modified by the addition of 17% cobalt mentioned in Table 1 has the lowest thermal expansion of the Fe-Ni alloys and maintains nearly constant dimensions during normal variations in atmospheric temperature [3]. Due to presence of Cobalt corrosion resistance is high. The use of thin dielectric membrane over the Si plug (50µm) which is denoted as 'active area', not only offers low thermal conductivity but also enhances the robustness and long life of the device for the continuous application in field. The power consumption can also be kept low, within100 - 150mW. This paper discusses the design and simulation of the meander shaped microheater with low power consumption and high temperature uniformity and long life robust performance and also compares its simulation results with five more different heater structures. The designs and simulations have been carried out COMSOL Multiphysics 4.0. The detail property of the alloy is given in Table 2. Comparison were made with six different heater structure.Power consumptions of microheater taking Pt and Poly-Si as heater element have also been studied.

2. DESIGN OF MEANDER SHAPED MICROHEATER
The application of Micro-heater shares some key design requirements: a) Fast thermal response time, b) Low power consumption, c)Uniform temperature distribution over the membrane, d)Mechanical stability, e)Long life. The parameter that relates the side length of the membrane to the heater size (edge length), known as the membrane to heater ratio (MHR), is critical in deciding both power consumption and mechanical robustness of the device. Poor MHR can lead to a process yield below 40% and higher power consumption. In the present work MHR has been taken to be greater than 2 for better performance of a sensor device. Before the advent of nanocrystalline ZnO, operating temperatures were very high (>=423K) for gas sensors which were impossible to attain with the thick silicon membrane. However, using nanocrystalline ZnO, as the sensing material, low temperature (373-473K) sensing is reported by several authors. The detail

dimension of the membrane structure is shown in the fig 1. As thermal conductivity of DilverP1 is quite low, therefore good temperature uniformity is obtained over the active area. The dimensions in the fig 2 have been optimized by FEM simulations.

Use of the silicon MEMS structure for hosting the active metal oxide layer permits one to design a suitable embedded microheater on the MEMS membrane so that the desired operating temperature of the active layer can be attained with much lower power dissipation. The use of this high resistivity metal enhances much smaller dimension of the microheater. The heater dimensions of length (L) = 7000 µm, width (w) =100µm, separation (s) =100 µm and thickness (t) =0.2 µm and membrane = 50 µm. Calculated heater resistance is 172Ω at room temperature**.** To setup the microheater design for gas sensor application here we have used 3D settings with stationary studies of COMSOL Multiphysics 4.0 Model Wizard. The entire geometry is designed in Model Builder. The model uses material from the Material Library of COMSOL Multiphysics 4.0.

Table 1. Chemical Composition of DilverP1(wt%)

Element	Ni	Co	Mn	Si	C	Fe
value	29	17	≤ 0.35	≤ 0.15	≤ 0.02	Bal

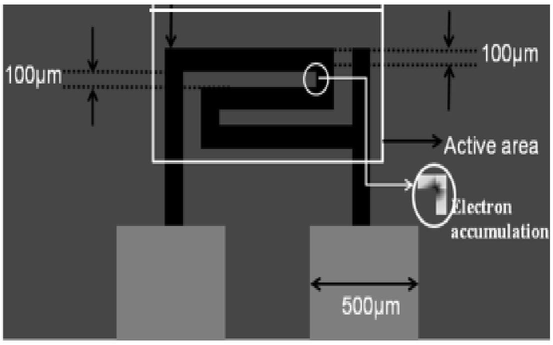


Figure 1. Detail dimensions of the structure(top view)

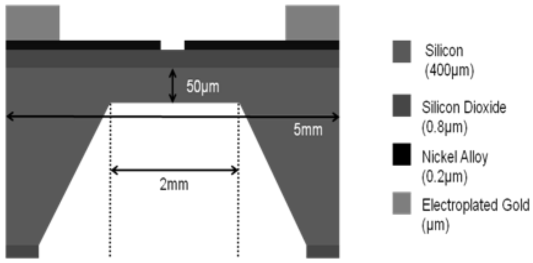


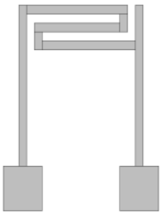
Figure2. Detail dimensions of the structure (Cross-section view

Table 2. Physical properties of DilverP1

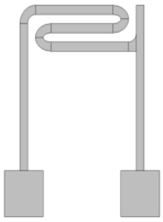
Density (g/cm^3)	Resistivity (Ωm)	Thermal conductivity (w/m/°C)	Specific heat (J/kg/°C)	CTE in (/°C)	Yield strength (MPa)	Tensile strength (MPa)	Poisson's ratio	Melting point(°C)
8.25	$49x10^{-8}$	17.5	500	4-5.2x 10^{-6}	680	700	0.3	1450

3. ELECTROTHERMAL ANALYSIS

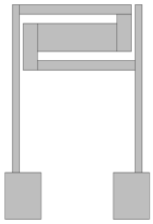
The sensor design is to achieve low power consumption and a uniform temperature distribution over the active area for a target temperature of 423K-573K. These demanding features can be best achieved by mounting the metal oxide on a thermal isolated structure, generally a dielectric membrane, obtained by means of silicon micromachining technology. Meander shaped heater geometry (shown in Fig. 1) has been incorporated first to reach the target temperature (473K). On the basis of this structure different modifications in heater structure have been made. Total six simulations were performed by considering six different heater structures (Fig. 3) and comparison is performed with respect to temperature rise and temperature uniformity along the membrane as heater keeping the input powers same as 146 mW. The commercial finite element model (FEM) programs COMSOL Multiphysics 4.0 have been employed for the thermal-electrical analysis. The simulation is done by using Joule-heating module of COMSOL Multiphysics 4.0 with tetrahedral meshing. The simulation for curved double spiral has been shown in Fig.6 for maximum temperature rise. The electro-thermal analysis of six different heater structures was done to study the temperature distribution and power consumption. We considered conduction heat losses as primary component. Convection loss depends principally upon the area of the heater and radiation loss in negligible for temperature less than 673K. Due to use of thin membrane and of low thermal conductivity material conductive heat loss is minimized. In the simulation nano crystalline ZnO has been taken as sensing material. For the better high temperature stability and the CMOS process compatibility most of the papers reported so far deal with the design of either platinum or polysilicon microheater which are particularly applied for the higher temperature range (673-973K). But the problem of high temperature sensing lies in the high power consumption and the reduced lifetime of the sensor. Most of the applications, for micromachined gas sensor, reported so far are based on a SiO_2 and Si_3N_4 composite layer on a thick (~400µm) silicon substrate with a view to reduce power consumption. However A. Gotz first proposed a thin Si plug underneath the dielectric membrane, for achieving uniform temperature distribution over the active heater area owing to the high thermal conductivity of Si. Recently several work on relatively low temperature gas sensors, using several nanotextured semiconducting oxides, have been reported. So this type of relatively low temperature (423-473K) gas sensors does not require a expensive Pt or poly-Si microheater, some low cost heating elements having high resistivity may efficiently serve in this temperature range. A comparative study has also been made by taking different microheater element using COMSOL Multiphysics 4.0.In this paper power consumption of the DilverP1 heater is compared with Pt & poly-Si heater.



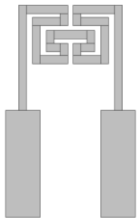
(A) Meander Shape



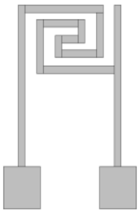
(B) Curved Meander



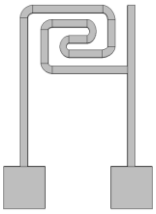
(E) S-Shape



(F) Fan Shape



(C) Meander Shape



(D) Curved Meander

Figure 3. Six different shapes of microheater

Table3. Material properties used for the electro-thermal simulation

Materials	**CTE (α) in 10^{-6}/K**	**Thermal Conductivity at 300K in W/M-K**	**Specific Heat in J/Kg-K**	**Density in $Kg\text{-}M^3$**	**Electrical resistivity in Ω-m**	**Youngs modulus GPa**	**Poisson's ratio**
Si	2.6 -3.1	150	700	2330	2300	125	0.27
Sio_2	.5	1.4	1000	2200	10^{12}-10^{14}	75	.17
ZnO	2.9	23.4	399	880	10^2	-	-
Air	-	0.0262	-	1.239	10^{18}	-	-

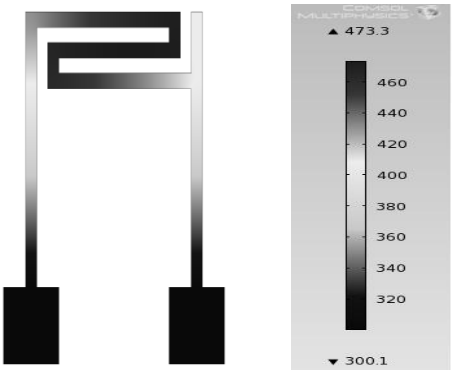


Figure 4. Simulation result(Temperature [K]) for fig(A)

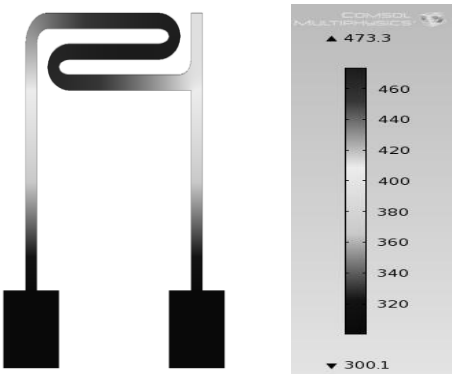


Figure 5. Simulation result(Temperature [K]) for fig(B)

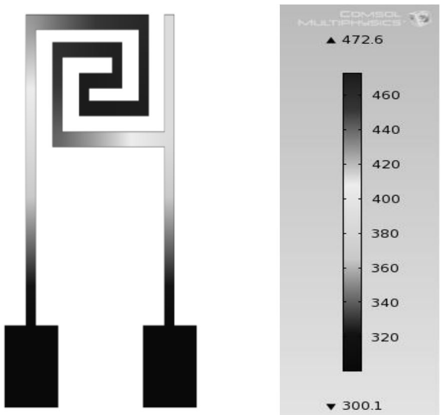


Figure 6. Simulation result(Temperature [K]) for fig(C)

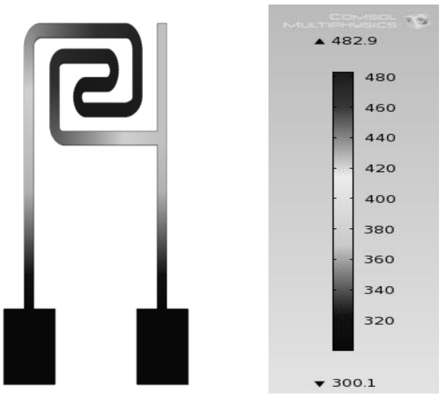


Figure 7. Simulation result(Temperature [K]) for fig(D)

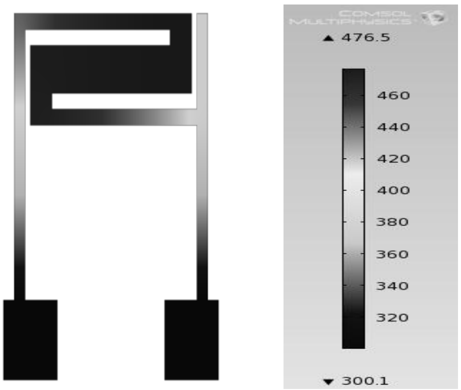


Figure 8. Simulation result(Temperature [K]) for fig(F)

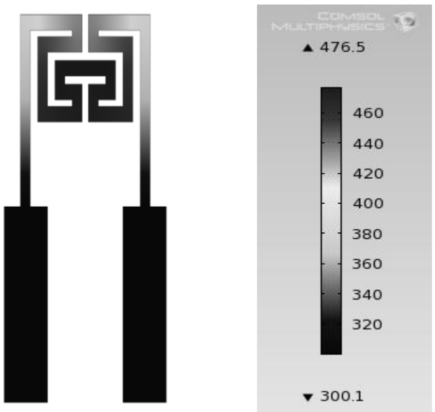


Figure 9. Simulation result(Temperature [K]) for fig(E)

Table4. Power consumption using different heater materials

Materials	**Thermal Expansion Coeff α in 10-6/K**	**Thermal Conductivity at 300K in W/M-K**	**Electrical resistivity in Ω-m**	**Resistance in Ω**	**Voltage in V**	**Temperature in K**	**Power Consumption in mW**
Pt	8.8	70	10.6×10^{-8}	37.1	2.6	473.397	182
Poly silicon	2.8	29-34	32.2×10^{-8}	112	4.7	473.065	189
DilverP1	4 – 5.2	17.5	49×10^{-8}	171.5	5	473.3	145

4. TRANSIENT ANALYSIS

Transient analysis was also done on gas sensor having DilverP1 microheater on micromachined silicon membrane. Temperature distribution over the membrane rises from 27°C at t = 0s to 200 °C at time t = 1.7×10^{-3}s after that temperature distribution over the membrane remains constant. So rise time = 0.7×10^{-3}s and boundary conditions are all external sides of air are vat room temperature.It has been observed that it is taking much less time to rise the temperature.

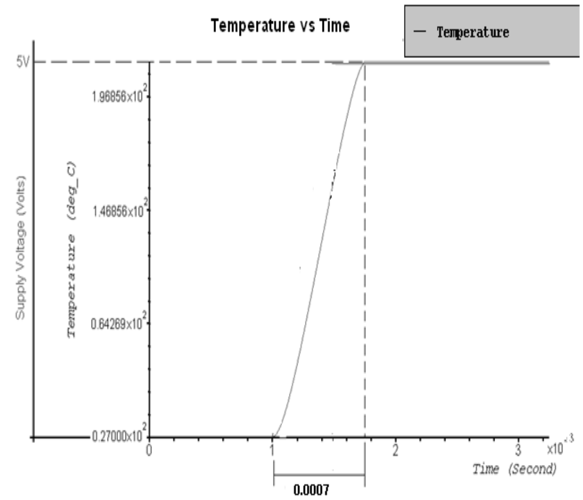


Figure10. Graph of Transient response

5. RESULT AND DISCUSSION

The simulated result of microheater shows that for the rise of 473K temperature the power consumption is 145mW. The temperature distribution profile along the membrane with an input power of 145 mW is shown in fig11. Fig.12 shows the maximum temperature and the temperature distribution over the active region for 6 different types of heater structure. It is evident from the graph that though structure 4 gives the highest maximum temperature and uniform distribution is achieved. From the plot it is evident that the temperature uniformity has been obtained over the entire active area with a tolerance of +- 1-2% which is very much within the limit. Fig.12 shows comparative study of simulated temperature distribution along the membrane for six different heater structures for a constant input power of 146 mW. Heater structure (D) and (E) have offered better performance with respect to temperature uniformity and temperature rise. Due to electron accumulation at the concave corners of the heater coil marked in Fig 1, the effective resistance of the heater coil increases whereas in the curved pattern(Fig.7) electron accumulation at the corners reduces resulting much more temperature rise. For same input power maximum active area temperature of 483K and 476K was found with structure (D) and (E) respectively. The temperature uniformity which is the difference between maximum and minimum temperature in the active region is shown in fig13 (bar chart). It was observed from the bar chart of fig.13 that uniformity is best for structure (E) due to more effective heater area.Fig.14 is showing that compared to Pt & poly-Si, power consumption is low in case of DilverP1 heater for same temperature (473K).It is evident that DilverP1 heater power consumption is 145mW. Microheater performance parameters like the power consumption, and the temperature distribution along the membrane was studied.

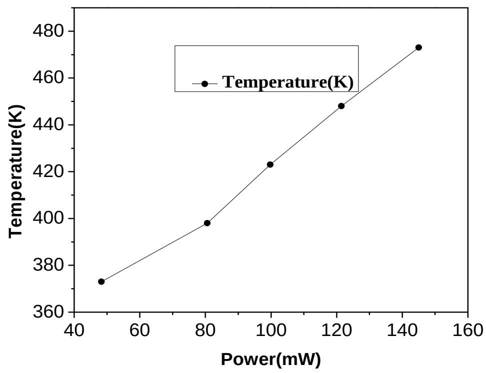


Figure 11. Simulated graph of Power Vs Temperature

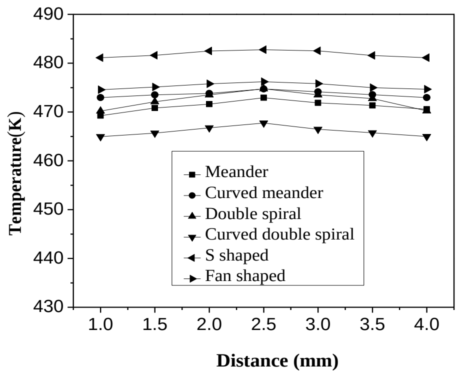


Figure 12. Simulation result for 6 different heater structures

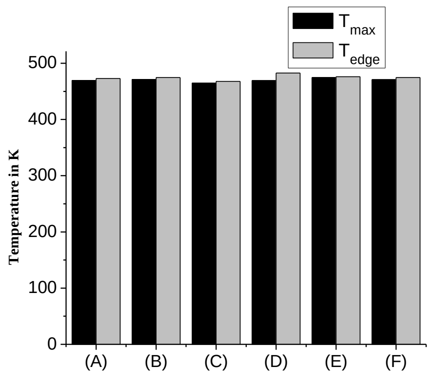


Figure 13. Temperature uniformity comparative study.

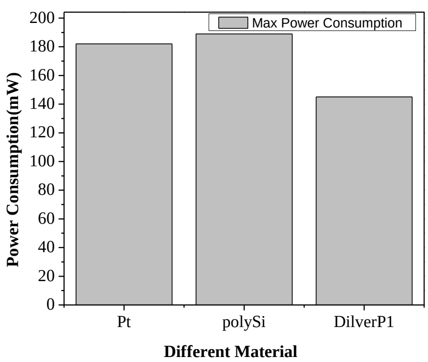


Figure 14. Comparative study of power consumption using

different material.

6. CONCLUSION

A novel microheater design using a novel material- nickel alloy (DilverP1) on top of the micromachined Si substrate was proposed for gas sensor system, operating in the temperature range of 373K-473K with sufficiently high resistivity, have been simulated here for the first time using COMSOL Multiphysics 4.0 to explore the features of a new version of COMSOL Multiphysics simulation S/W. Emphasis is given on the low input power consumption which should be around 150 mW. Detail design and electro-thermal analysis was carried out using COMSOL Multiphysics 4.0. The developed microheater was found to be cheap compared to that of Pt or poly-Si and very much suitable for the temperature range of 423K - 573K. We have found many powerful improvements thus far in our upgrade path while learning the new features of COMSOL Multiphysics 4.0.Work in progress for Stress analysis of the device with different shapes of microheater.As our work is in basic level,it is our future concerned to fabricate a microheater on the basis of these simulations.

7. ACKNOWLEDGEMENT

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8. REFERENCES

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