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DESIGN OPTIMIZATION OF A MICROHEATER USING GENETIC ALGORITHM

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Abstract— Genetic Algorithms in the design of microheaters for gas sensors has become increasingly popular in recent years. This is due to their versatility and ability to perform an extensive search in complex multimodal search places. This paper studies about utilizing a genetic algorithm (GA) based software with a complete structural design and thermoelectromechanical and transient analysis using Intellisuite v8.2 s/w to optimize the physical design parameters of a microheater of a MEMS based gas sensor and to get the desired temperature (~200°C) at minimum power consumption (~140mW) within desired physical constraints.

Keywords— Nickel alloy, Microheater, MEMS, Gas sensor, Thermoelectromechanical analysis, Transient analysis.

Introduction

The advent of nanocryatalline metal oxide semiconductors (MOS) have made it possible to lower the sensing temperature (as low as 100ºC) [1] of MOS to sense the toxic and hazardous gases therefore there is no need to use highly expensive Pt [2], polysilicon [3] or nichrome [4] microheater , instead a low cost heating element can solve the purpose. In view of that a Ni alloy based microheater integrated with the MEMS [5-9] structure has been simulated with a motive to use it in a gas sensor via nanocrystalline metal oxide semiconductors. Further, the low temperature sensing facilitates the use of a relatively thin silicon membrane instead of a composite SiO_2/Si_3N_4 membrane resulting into temperature uniformity across the entire active area. In addition to temperature uniformity it also enhances the robustness and lifetime of the device.

In this paper, we present a complete structural design and thermo electromechanical and transient analysis of a microheater for MEMS based gas sensor platform using a nickel alloy having high resistivity ~ 49×10^{-8}Ωm and high yield stress ~680MPa and on the other hand low thermal conductivity ~17.5W/m/°C which has been already reported earlier by Roy et.al.[10]. The detailed property of the alloy is given in table 1. Here the device size is 5mm x 5mm with a membrane size of 1.5mm x 1.5mm (active area) was investigated. With 50 µm silicon membrane good temperature uniformity has been achieved over the active area. Thermal electrical and mechanical analysis was done using finite element modeling of Intellisuite v8.2 software. The maximum temperature of ~200 °C with a distribution of ± (1-2) % over the entire microheater membrane region has been achieved with 4.5V excitation and with power consumption of ~144 mW, as the low power heating characteristics of a microheater are very important for the gas sensor application. Displacement study was also done using Intellisuite v8.2 software.

Table 1.Physical properties of Nickel alloy

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

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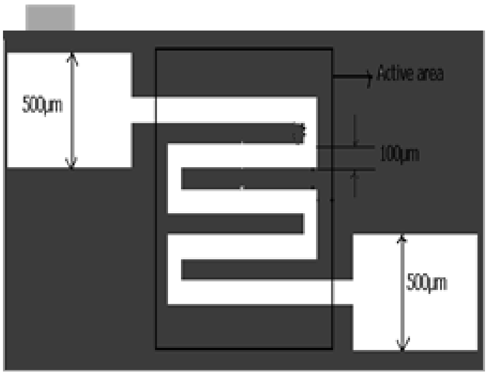
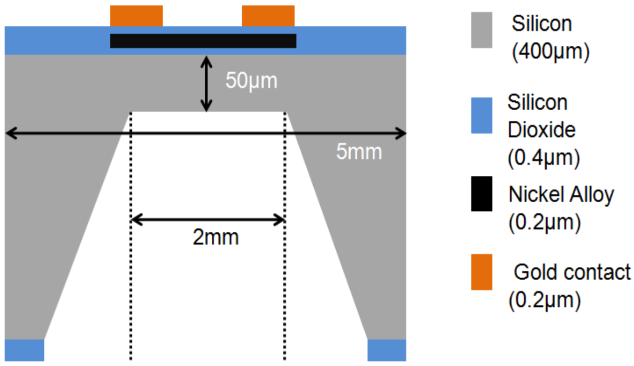
I. Design of Meander Shaped Microheater

The device is pictorially depicted in figure 1.This device structure has the following advantages: (a) Fast response time (b) Better temperature uniformity across the membrane (c) portability (d) ease of fabrication. The use of this high resistivity (~ 49x10-8Ωm) metal enhances much smaller dimension of the miroheater which could not be achieved with other materials aiming the same temperature. As thermal conductivity of this nickel alloy is quite low, therefore good temperature uniformity has been obtained over the active area. The heater dimensions of Length (l) = 7000 µm, Width (w) =100µm, Separation (s) =100 µm and thickness (t) =0.2 µm. Membrane thickness = 50 µm. Calculated heater resistance is 172.5Ω at room temperature.



(a)



(b)

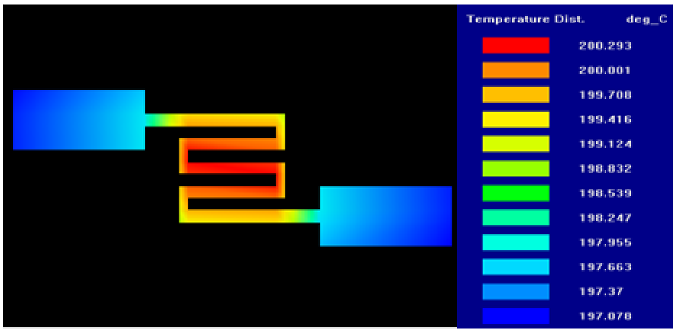
Figure. 1. (a) Detail dimensions of the microheater (top view) (b) cross sectional view of the device (not to the scale)

II. Electrothermal and Mechanical Analysis

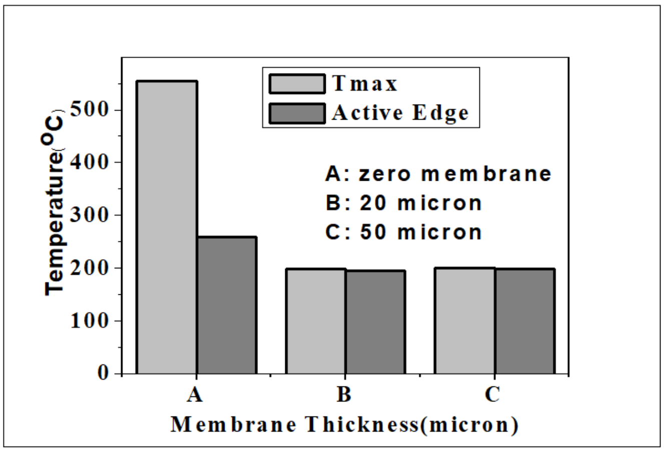
The commercial finite element model (FEM) programs INTELLISUITE 8.2 have been employed for the electro thermal and thermo electromechanical simulation.

A. *Temperature Distribution Analysis*

The temperature distribution analysis has been presented in figure 2(a). The temperature uniformity which is the difference between maximum and minimum temperature in the active region is shown in figure 2(b) (bar chart). It was observed from the bar chart that the uniformity is best for 50 µm membrane due to the high thermal conductivity of silicon.



(a)



(b)

Figure 2.(a) Simulation result for temperature distribution (b) Maximum temperature and the temperature at the edges of the active region.

B. *Displacement Analysis*

We also report the simulation result of displacement analysis in figure 3, which reveals that the compressive stress in the membrane (50 µm) causes it to bend through 0.789147 µm. The stress generated by the thermal expansion of the stacked membrane due to the heating of the membrane causes undesirable membrane deflection. At very high temperature the thermal induced stress can be high enough to produce the structural crack.

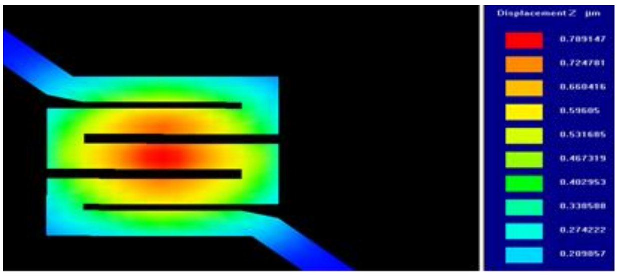


Figure 3. Simulation result for displacement

C. *Thermal Analysis*

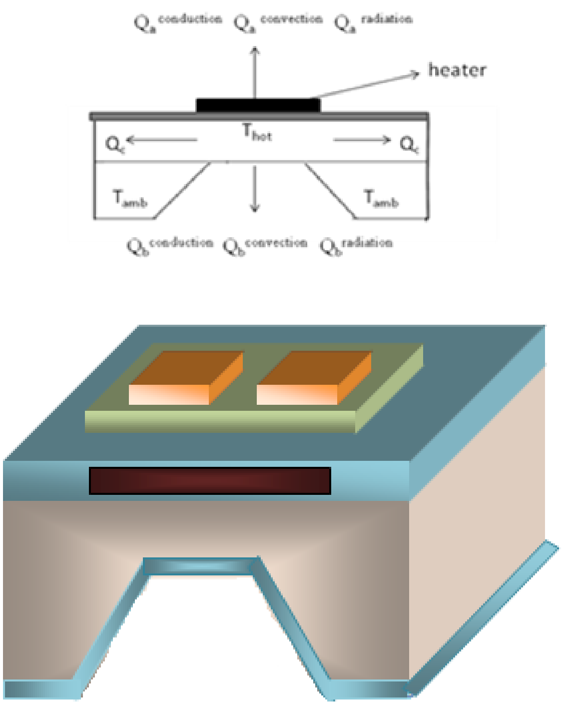


Figure 4. Pathways of Heat flow

A MATLAB program has been developed to calculate the total heat loss (in mW), which comprises of three components (figure 4). So total heat loss

$$Q_{total} = Q_a + Q_b + Q_c \qquad (1)$$

Heat loss from the surface is due to radiation, conduction through air and convection the details of which has been already reported earlier [5].

Q_a: heat loss from the top surface of the ZnO layer by radiation and through air.

$$Q_a = Q_r + Q_{air} = A_h \varepsilon_{ZnO} \sigma (T_h^4 - T_a^4) + 4\pi r_o k_{air} (T_h - T_a) \qquad (2)$$

Here A_h is the area of the heater surface, εZnO is the emissivity constant of ZnO , σ is Stefan-Boltzmann constant (5.67 x 10-8); Th is the heater temperature and Ta is the ambient temperature (300K).

Q_b: heat loss from the etched surface of the Si bulk by radiation and through air.

$$Q_b = Q_r + Q_{air} = A_m \varepsilon_{ZnO} \sigma (T_m 4 - T_a 4) + 4\pi r_o k_{air} (T_m - T_a) \qquad (3)$$

Here, A_m = area of the lower surface (i.e. membrane area) 4 x 10^{-6} m^2, Tm = temperature of the lower surface.

For all practical values of T_h we can assume $T_m = T_h = 473K$.

Q_c: heat coming out from the lateral surface of the cylindrical source.

$$Qc = k_{SiO2}\ x\ d_{SiO2}[dT/dx]_{ro}\ x\ 2\pi_{ro} \qquad (4)$$

k_{SiO2} =thermal conductivity of SiO_2 layer 1.4 $Wm^{-1}K^{-1}$ at 300K, d_{SiO2}= thickness of SiO_2 layer

Thus calculating all these equations we get

Q_a = 0.0625W(approx.) ,
Q_b = 0.0625W(approx.),
Q_c = 0.0075W(approx.)

Therefore from equations (1) we get,

$$Q_{total} = (62.5 + 62.5 + 7.5)mW = 130.5mW$$

III. Result and Discussion

A. Genetic Algorithm based Optimization

This part reflect the utilization of the genetic algorithm (GA) as a design tool to optimize the physical design parameters of the MEMS gas sensor to get the desired temperature with minimum power consumption. GA was first presented systematically by Holland et.al.[6], and its applications by Goldberg et.al.[7]. At each generation, a new set of approximations is created by the process of selecting individuals according to their level of fitness and breeding them together using operators borrowed from natural genetics such as selection, recombination, and mutation. These processes lead to the evolution of populations of individuals that are better suited to their environment than the individuals that they were created from, just as in natural adaptation. Our goal is to minimize the objective function i.e. to minimize the power consumption of the microheater by sprouting individual members of several populations that represents the candidates of physical design parameters. The basic construction of a GA can be simply described as follows:

Define the String of a Chromosome:

The string of searching parameters for the optimization problem will consist of (p_opt, q_opt, r_opt and s_opt). Where p is the side of the membrane. q is the target temperature of the microheater. R is the applied voltage and S is the thickness of the microheater element. These parameters are real coded genes in a chromosome. The parameter constraints will be given as follow: p_opt [mm]: (1-3), q_opt [K]: (423-473), r_opt [V]:(2-5) and s_opt [micron]: (0.1-0.2).

Generate Initial Sub-population:

Two sets of sub-populations are generated randomly initially. Each sub-population consists of 200 individuals.

Generate the next generation or stop:

GA uses the operations of reproduction, crossover, and mutation to generate the next generation. From generation to generation, the minimum value of the fitness value is achieved for each generation.

a) Reproduction:

Reproduction is the operator carrying old strings through into a new population, depending on the fitness value. Strings with high fitness values obtain a larger number of copies in the next generation.

b) Crossover:

Crossover is a recombination operator operated with reproduction. It is an effective way of exchanging information and recombining segments from high-fitness individuals. The crossover procedure is to randomly select a pair of strings from a mating pool, and then randomly determine the crossover position.

c) Mutation:

The mutation operator is used to avoid the possibility of mistaking a local optimum for a global one. It is an occasional random change at some string position based on the mutation probability. Table II presents the result of optimization.

TABLE II : RESULT OF THE GA BASED OPTIMIZED VALUES OF THE BEST CANDIDATE INDIVIDUAL (PERFORMANCE OF THE VARIABLES OF THE MICROHEATER.

Power consumption(Watt)	**p_opt(mm)**	**Q_opt(K)**	**R_opt(V)**	**S_opt(micro n)**
0.1301	2.2716	430.7647	3.3340	0.1827
0.0882	1.9734	441.8235	4.4902	0.1786
0.0725	1.9000	426.7255	3.7451	0.1533

0.1302	1.3120	453.0000	3.3882	0.1373
0.1313	**1.3100**	**473.0392**	**4.3275**	**0.1734**
0.0310	1.3500	423.0000	3.3529	0.1332
0.0310	1.3687	423.0000	4.1718	0.1718
0.0504	1.6324	440.8431	4.7735	0.1914
0.1260	3.0000	423.0000	2.0000	0.1300
0.1261	2.4500	423.0000	3.5000	0.1400
0.1062	2.1450	423.1961	4.8835	0.1963
0.1016	2.1227	435.9412	4.7529	0.1938
0.1226	2.2353	426.1373	4.5588	0.1831
0.1267	2.3608	444.5686	2.3000	0.1990
0.1052	2.0720	437.9020	4.6235	0.1792
0.1076	2.0800	433.3922	4.3098	0.1643
0.1075	2.1800	423.0000	4.8431	0.1999
0.1226	2.2583	435.3529	3.9725	0.1583
0.1043	2.2600	423.0000	3.9961	0.1825
0.1239	2.1561	448.0980	3.2902	0.1278
0.1121	2.2675	431.0392	3.0000	0.1200

The method of heat analysis employed in this paper is simple enough and MATLAB programs on the basis of this theory have been written which calculate the heat loss (i.e. power consumption) at different temperatures. We have also found the function for P(x) from which Best fitting curve has been plotted (as shown in figure 5 where x is the running horizontal distance from the center of the sensing layer. The equation for this plot is,

Total heat power consumed,

*P(x) = (x(1)^2*10^-6*0.65*5.70*10^-8)*(x(2)^4-300^4)+(4*3.14*0.5412*x(1)*10^-3)*0.044(x(2)-300)+(x(1)^2*10^-6*0.2*5.7*10^-8)*(x(2)^4-300^4)+(4*3.14*0.5412*x(1)*10^-3*0.044)*(x(2)-300)+(1.4*1.5*10^-6*1.93*10^6*2*3.14*0.5412*x(1)*10^-3)*

Where,

P(x) = power consumption of the microheater

x(1) = heater area = 2mm x 2mm

x(2) = heater temperature = 200 ºC

Thus, Total heat power consumed, P(x) = 136 mW which is in compliance with Previous MATLAB based result. Optimized one in the table marked bold. The results of GA simulation are shown in figure. 5.

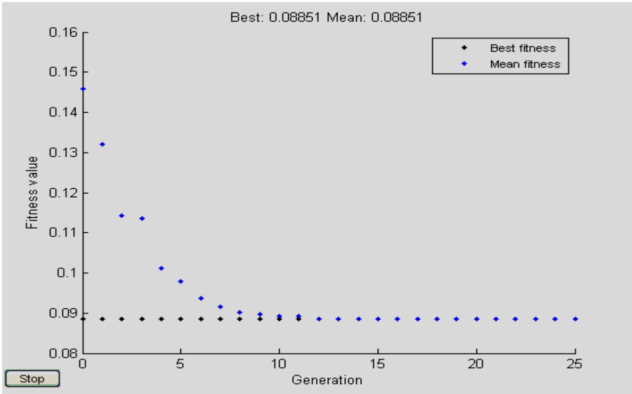


Figure 5. Best fitting curve of Power consumption.

The fitness value of an individual is the value of the power for that individual. Because the toolbox finds the minimum of the value power, the best fitness value for a population is the smallest fitness value for any individual in the population. At each generation, a new set of approximations is created by the process of selecting individuals.

IV.CONCLUSION

In the first part a MEMS based microheater using a nickel alloy on top of the micromachined Si substrate was proposed for gas sensor system, operating in the temperature range of 423K-473K with sufficiently high resistivity, have been simulated here for the using Intellisuite 8.2 simulation s/w. The developed microheaters was found to be cheap compared to that of Pt or poly-Si, very much suitable for the temperature range of 150ºC -250ºC with good mechanical stability for long life, faster response (0.7x10-3 s). Emphasis is given on the low input power consumption which should be around 140 mW. Detailed electrothermal & transient analysis was carried out using Intellisuite 8.2. In the second part the physical design parameters of a MEMS based microheater have been optimized using genetic algorithm (GA). The results of GA simulation certify the design of MEMS based microheater by revealing the accomplishment of desired operating temperature at low power consumption and fast response time. Future work will involve assessment of optimized results with experimental data**.**

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