Design and Performance Analysis of MEMS Micro-Heater for Uniform Temperature Platform for Efficient Gas Sensor Application

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Abstract: *For MEMS based gas sensor, Poly-Si based spiral geometry of micro-heater is proposed. Micro-heater is placed on platform of SiO_2 having 2 µm height and 120 µm x 120 µm surface area. Micro-heater temperature characteristic is analysed for two cases: 1. Varying applied voltage for constant dimensions of micro-heater geometry. 2. Varying dimensions (height and width) of micro-heater for constant applied voltage. Also variation in resistance of micro-heater due to temperature change and transient temperature response are analysed. Power consumption for Poly-Si based geometries are compared. In presented micro-heater, temperature variations occur from 323.0° K to 645.47° K for changing applied voltage from 0 V to 3.0 V for constant dimensions of micro-heater. Also in other case, for constant applied voltage of 3.0V, there is a change in temperature from 645.47° K to 701.69° K due to height variations of micro-heater from 2 µm to 3 µm. It is also found that, better temperature uniformity can be achieved in micro-heater geometry by proper variation in width of micro-heater. These results are observed with finite element modelling of COMSOL Multiphysics 4.3. These results are helpful to find out value of applied voltage and height of micro-heater geometry for desired temperature requirement in gas sensing application. Also these results lead to transient temperature analysis of Poly-Si micro-heater and solution of temperature uniformity problem.*

Keywords: **Gas sensor, Micro-heater, COMSOL Multiphysics, Spiral geometry.**

1. Introduction

Gas sensors especially, metal oxide based gas sensors are extensively used due to having many advantages like, good sensitivity and detection capability for large number of gases, easy signal processing, fast response time, ability to detect, simple electronic interface, very low production cost, small size, and low maintenance [1, 2]. They are used to detect hazardous gases like, NO_2, NO, N_2O, H_2S, CO, NH_3, CH_4, SO_2 and CO_2. These hazardous gases are divided in two groups: reducing gases like, NH_3, CH_4, SO_2, H_2S and CO and oxidizing gases like, N_2O, CO_2, NO_2, and NO. SnO_2, ZnO, TiO_2, and WO_3 are well known materials used in metal oxide sensors. These all materials have electron depleted surface. Electron depletion on the surface occurs because adsorption of oxygen as O_2^-, O^- and O^{2-} which tie up electronic carriers [3]. Basically, metal oxide gas sensor surface is highly sensitive with oxidizing gases which cause increase in depletion region and reducing gases which cause decrease in depletion region. This minor change of depletion region changes electrical properties of material from that concentration of certain gas can be measured. This process occurs at high temperature ranging from 100° C to 500° C, depending upon the gases and gas sensor materials. Sensitivity, response time and selectivity are highly influence with temperature so temperature is crucial factor [4]. To achieve uniform high temperature, there is need of micro-heater. Micro-heaters are widely used in humidity sensors and gas sensors. They should have high temperature, good temperature uniformity and low power consumption.

There is a different temperature requirement for explained gases so it is more crucial to heat the sensing surface for desired temperature to measure proper concentration of specific gas [5]. Micro-heaters' heating can be compared with principle of joule heating which is also known as ohmic heating or resistive heating. Resistive heat generated Q is proportional to square of current density J. Electric field E is equal to negative of gradient of voltage potential V. Also there is proportional relation between current density J and electric field E and resistivity ρ is reciprocal of conductivity σ which is function of temperature. From the above discussion,

$$Q \propto |J|^2 \tag{1}$$

$$\sigma = \sigma(T) \tag{2}$$

$$\rho = \frac{1}{\sigma} \tag{3}$$

$$Q = \rho \cdot |J|^2 = \frac{1}{\sigma}|\sigma \cdot E|^2 = \sigma \cdot |\nabla V|^2 \tag{4}$$

For particular temperature range, the electric conductivity σ is a function of temperature T according to:

$$\sigma = \frac{\sigma_0}{1+\alpha(T-T_0)} \tag{5}$$

Where α is the temperature coefficient of resistivity, which describes how the resistivity varies with temperature and σ_0 is the conductivity at the reference temperature T_0. Also, the basic resistance equation including cross sectional area A is,

$$R = \frac{\rho \cdot l}{A} = \frac{l}{\sigma \cdot A} \tag{6}$$

From above equation, there is relation between electric conductivity σ and cross sectional area A. So from the outcome of equ.(4), it is clear that resistive heating is depended on electric conductivity σ (or cross sectional area A of micro-heater) and applied voltage V across two ends of micro-heater.

Different micro-heater geometries are available as per the need of high temperature and/or good temperature uniformity. Some well-known geometries are single meander, double meander, fan shape, square shape, spiral, double spiral, honey comb, S-shape etc. But in this paper, double spiral heater geometry was found best choice after review on available options of micro-heater geometries. Many micro-heater materials like, platinum (Pt), poly-silicon (Poly-Si), Silicon Carbide (SiC), Palladium (Pd) are used. Platinum have certain advantages like, easy fabrication and high temperature stability but has major drawbacks like, high power consumption and more cost. Most common material which

widely used is Poly-Si because it has temperature limit up to 550^o C but above that temperature, its resistivity going to be unstable[6,7].
Results can be analyzed using a Finite Element Analysis (FEA) package and with the help of joule heating and thermal expansion physics under the structural mechanics module of COMSOL MULTIPHYSICS 4.3. Computer simulation has certain advantages because it provides design optimization by changing materials of the device, its properties, geometries and layer dimensions without actual fabrication .This approach can be helpful to minimize cost and time of real fabrication [8].

2. Micro-heater design

Spiral geometry of Poly-Si based micro-heater is introduced as shown in 'Figure 1'. Heating of micro-heater may damage lower layer or substrate so to avoid this problem, 120 X 120μm^2 surface area with 2 μm height platform of SiO_2 is used. The main purpose of this micro-heater is to cover vast area with more temperature uniformity. Properties of SiO_2 and Poly-Si are mentioned in Table 1 and Table 2.

Table 1. SiO_2 Properties

Sr. No.	Property	Value
1	Coefficient of thermal expansion	0.5e-6[1/K]
2	Heat capacity at constant pressure	730[J/(kg*K)]
3	Relative permittivity	4.2
4	Density	2200[kg/m^3]
5	Thermal Conductivity	1.4[W/(m*K)]
6	Young's modulus	70e9[Pa]
7	Poisson's ratio	0.17

Table 1. Poly-Si properties

Sr. No.	Property	Value
1	Coefficient of thermal expansion	2.6e6[1/K]
2	Heat capacity at constant pressure	678[J/(kg*K)]
3	Relative permittivity	4.5
4	Density	2320[kg/m^3]
5	Thermal Conductivity	34[W/(m*K)]
6	Young's modulus	160e9[Pa]
7	Poisson's ratio	0.22

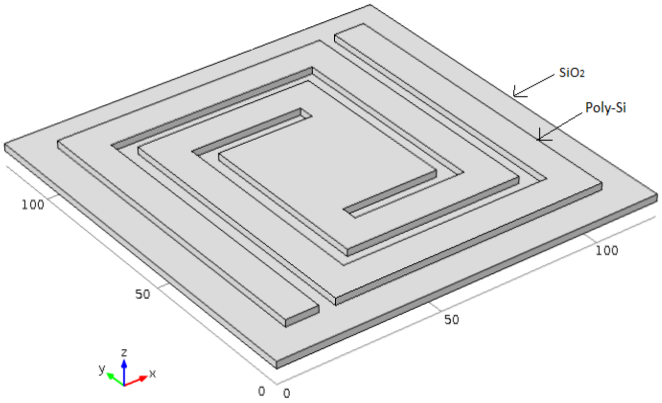

Figure 1 3D-View Of Poly-Si Based Micro-Heater Spiral Geometry On 120µm X 120µm Sio$_2$ Based Platform

3. Simulation and results

Let discuss two cases and its effect on maximum temperature of micro-heater.

Case 1: Varying applied voltage for constant height of micro-heater geometry

As mentioned earlier, applied voltage always affects resistive heating. As shown in Figure 1, consider constant dimensions with equal stripe area and 2µm height of micro-heater geometry and applied voltage is varied from 0V to 3.0V. Variations in maximum temperature with applied voltage are measured and characterized as shown in 'Figure 2'.

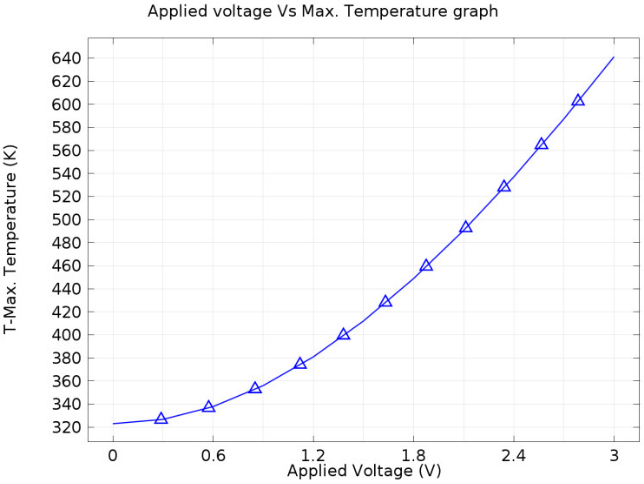

Figure 2 Maximum temperature with variations in applied voltages of micro-heater

Result shows the variations in maximum temperature start from 323°K to 645.47°K for given applied voltage from 0V to 3V. It can be observed that temperature variation occurs during the period 0V to 1.5V is from 323.0°K to 415.0°K which is quite less as compare with the period 1.5V to 3.0V which is from 415.0°K to 645.47°K.

Case 2(a): Varying height of micro-heater geometry for constant applied voltage

Cross sectional area *A* which is actually multiplication of height and width of micro-heater geometry, so height of micro-heater also affects resistive heating. Consider constant applied voltage of 3.0V and height of micro-heater geometry is varied from 2µm to 3µm for same stripe width.Same procedure is followed and variations in maximum temperature with height of micro-heater geometry are measured and characterized as shown in ‘Figure 3’.

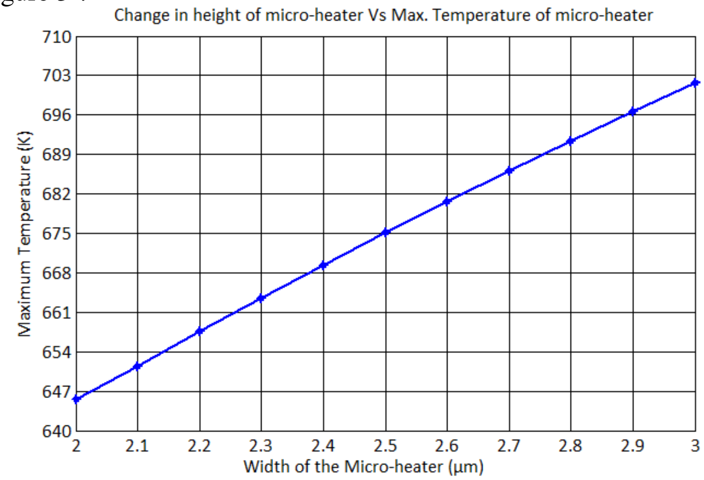

Figure 3 Maximum temperature with variations in height of micro-meter

It can be analyzed that there is almost linear relation between height variation and maximum temperature of micro-heater. As height of micro-heater varies from 2µm to 3µm, maximum temperature varies from 645.47°K to 701.69°K with almost equal change throughout the height variation.

Case 2(b): Varying width of micro-heater geometry for constant applied voltage

Width variation in micro-heater geometry plays a vital role. Also to use metal oxide as gas sensor, crucial requirement is temperature uniformity which can be achieved with the help of proper micro-heater geometry [9]. So to analyse that width is varied and simulation results are observed. ‘Figure 4’ and ‘Figure 5’ represent 2D structure of micro-heater, where ‘Figure 4’ gives idea of dimensions and ‘Figure 5’ gives simulation result for constant applied voltage 3V and constant height of 2µm. As shown in ‘Figure 4’, micro-heater stripe area remains same throughout the geometry except central area.

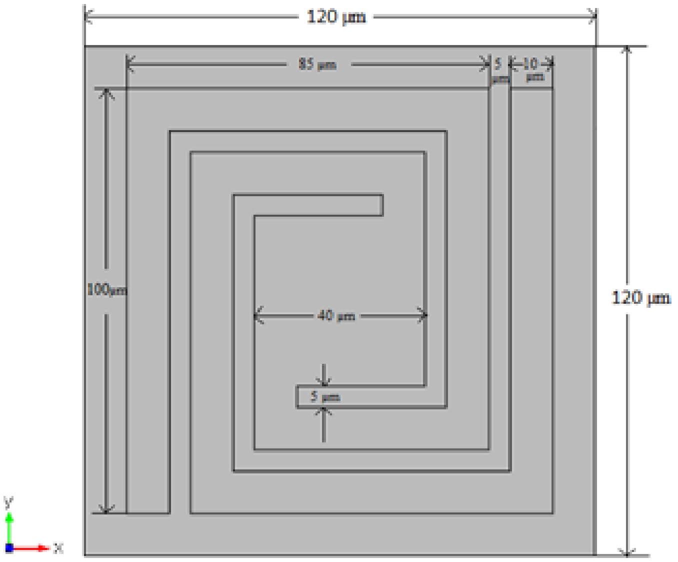

Figure 4 2D micro-heater geometry with dimensions having equal stripe size of 10µm

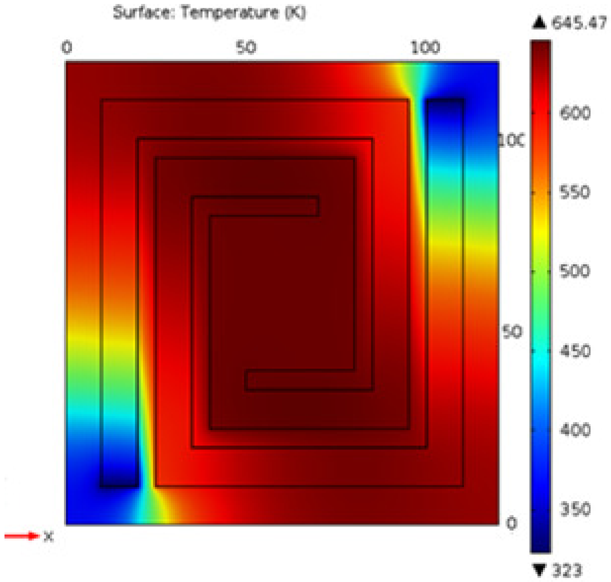

Figure 5 2D simulation result of surface temperature having equal stripe size of 10µm

From the observation, it is clear that there is less temperature (below 550°K) at two ends of micro-heater geometry. So width variation should be made in micro-heater geometry to achieve better temperature uniformity as shown in 'Figure 6' and 'Figure 7'.

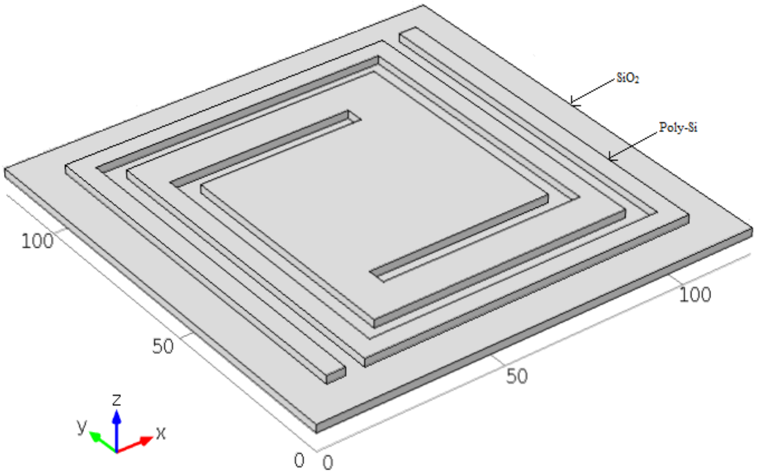

Figure 6 3D-view of Poly-Si based micro-heater spiral geometry on 120µm X 120µm SiO2 based platform with width variation

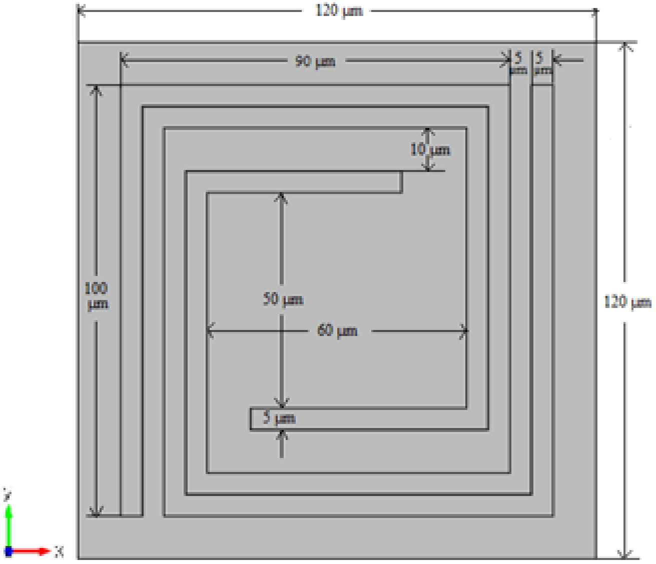

Figure 7 2D micro-heater geometry with dimensions having unequal stripe size

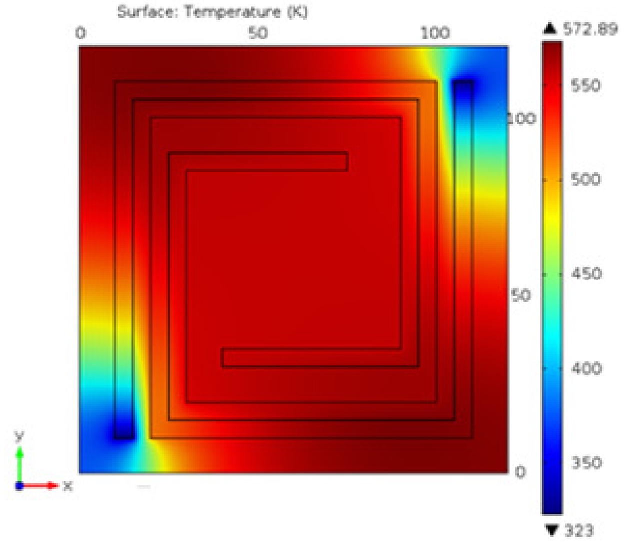

Figure 8 2D simulation result of surface temperature having unequal stripe size

Width of the micro-heater geometry should be varied such that area which is having high temperature, should be more broaden and area which has less temperature should be narrower. As shown in ‘Figure 5’, there is more temperature up to 645.47°K at central part of geometry so that area is made more broaden also ends of geometry is having less temperature so that is made more narrower in ‘Figure 7’. Simulation result is shown in ‘Figure 8’. It is observed that there is more temperature uniformity in comparison with previous simulation result (Figure 5). Maximum surface temperature of micro-heater reduces to 572.89°K but there will be more temperature uniformity. Overall surface temperature can be increased to 645.47°K by applying supply voltage up to 3.4662V.

It is common observation that there is proportional relation between gas sensor response time and transient temperature response time of its micro-heater. So transient temperature responses for equal stripe size geometry and unequal stripe size geometry are compared for same surface temperature of 645.47°K and they are shown in ‘Figure 9’ and ‘Figure 10’. As width of geometry changes and structure gives more uniformity but transient temperature response time also increases. In first spiral geometry (Figure 1), transient response time is 13ms while in second spiral geometry which has width variation (Figure 6), is about 23ms.

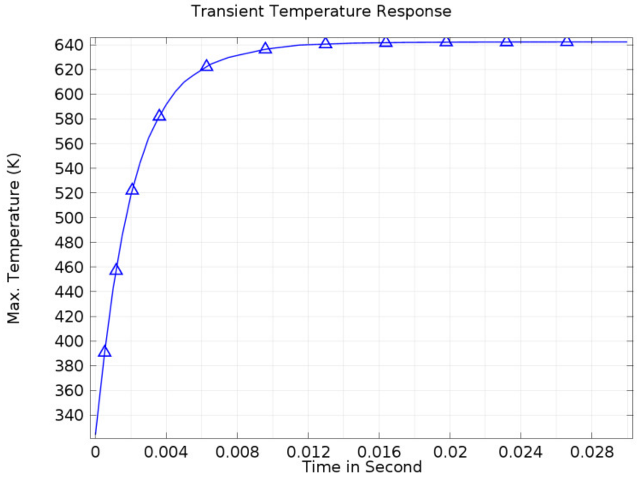

Figure 9 Transient Temperature Response for geometry having equal stripe size of 10µm for Max. Temperature of 645.47°K

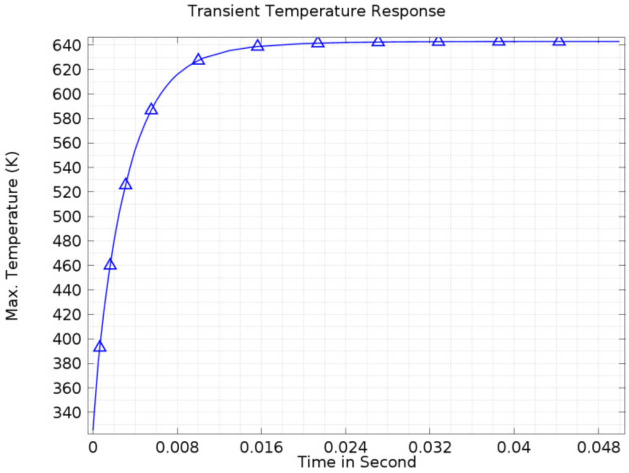

Figure 10 Transient Temperature Response for geometry having unequal stripe size for Max. Temperature of 645.47°K

On the basis of resistive heating principle, resistance of micro-heater changes with time till surface temperature reaches to its maximum value. For both the geometry, micro-heater resistance is measured for equal surface temperature of 645.47°K and responses are analyzed. Transient response of micro-heater resistance of first spiral geometry (Figure 1) is shown in 'Figure 11' which resistance varies from 600.51 Ω to 712.54 Ω for applied voltage of 3.0V and transient response of micro-heater resistance of second geometry (Figure 6) is shown in 'Figure 12' which resistance varies from 1210.6 Ω to 1433.8 Ω for applied voltage 3.4662V.

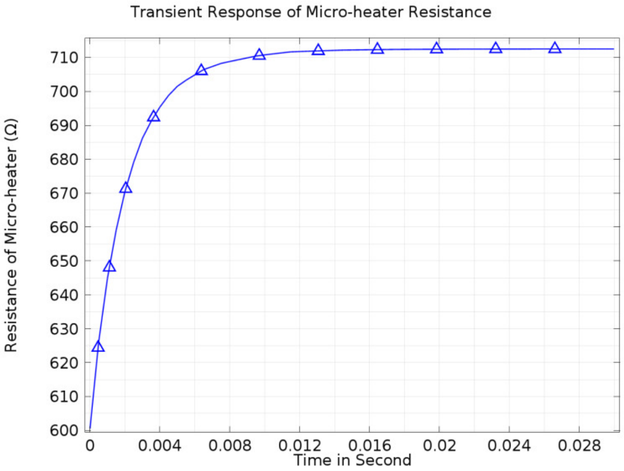

Figure 11 Transient Response for micro-heater resistance for geometry having equal stripe size of 10µm and Max. Temperature of 645.47°K

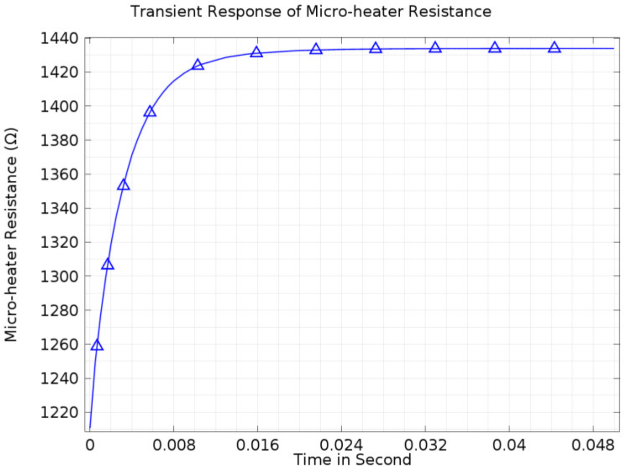

Figure 12 Transient Response for micro-heater resistance for geometry having unequal stripe size and Max. Temperature of 645.47°K

Micro-heaters are always made such that its power consumption should be low. Both the geometries (Figure 1 and Figure 6) are experienced different power consumption values, 12.63mW and 8.3791mW respectively to achieve equal surface temperature of 645.47°K. All the analytical results are mentioned in Table 3:

Table 3. Comparison of two micro-heater geometries

	Spiral Geometry with equal width of 10µm	Spiral Geometry with unequal width
Max. Surface Temperature	645.47 °K at 3.0V	572.89 °K at 3.0V 645.47 °K at 3.4662V
Transient Temperature response time	13 ms	23 ms
Resistance Variation	600.51 Ω to 712.54 Ω (till temperature reaches 323 °K to 645.47 °K)	1210.6 Ω to 1433.8 Ω (till temperature reaches 323 °K to 645.47 °K)

Power Consumption	**12.63mW**	**8.3791mW**

3. Conclusion

This letter presents the relationship of maximum heating temperature of micro-hater with applied voltage across the two ends of micro-heater geometry and height of micro-heater geometry. In case: 1, as voltage gradient is increased across the two ends of micro-heater, maximum temperature changes exponentially (during the period 1.5V to 3.0V). That leads to simple conclusion that more the voltage gradient, more the heating temperature. In case: 2(a), change in height of micro-heater leads to almost linear change in heating temperature. Also in case: 2(b), if proper width variation of micro-heater geometry can be made, one can get better temperature uniformity at low power consumption. That brings on to some drawbacks like, low transient temperature response, high resistance of micro-heater geometry and need of more applied voltage to increase surface temperature. These results may helpful for sensing different gases as each gas needs certain temperature for proper detection. This letter is also helpful to find height of micro-heater and value of applied voltage to attain certain temperature for detection of desired gas.

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