Design and Simulation of a Multi-Sensor System Growing a Plurality of Heater Chips on the Same Dielectric Membrane

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***Abstract*—In micro-sensors, the Micro Hotplate (MHP) is a crucial component, in particularly gas sensors. To control the temperature of the sensing layer, micro-heater is used in metal oxide gas (MOX) sensors as a hotplate. The temperature should be in the requisite temperature range over the heater area. This allows detection of the resistive changes as a function of varying concentration of different gases. Thus, their design is a very important aspect. In this paper, we presented the design and simulation results of a platinum combinative meander-spiral micro heater for a WO_3 gas sensor. The objective of this paper is also to model a multi-sensor while growing a plurality of heater chips on the same membrane to improve gas sensors selectivity performance. Four different heating voltages were applied in order to attain four maximum temperatures required to detect O_3, H_2S, CO and NO_2, by a WO_3 multi- sensor.**

***Index Terms*—Gas Sensors; Heater; Platinum; Electro-Thermal Analysis; Multi-Sensor.**

I. INTRODUCTION

Different pollutants, such as ozone O_3, hydrogen sulfide H_2S, carbon monoxide CO and nitrogen dioxide NO_2, present in the urban areas cause many health impacts. Today, gas sensors form an important subject of atmospheric and environmental research. Metal oxide thin film sensors have been extensively used for gas sensing applications by reason of their sensitivity facing a large variety of gases [1]. Gas sensors are mostly based on metal oxides. The most common and widely used are titanium dioxide TiO_2, tin oxide SnO_2, tungsten oxide WO_3 and zinc oxide ZnO [2]. Numerous researchers have proven the aptitude of thin or thick WO_3 films as sensing layers for gas monitoring applications [3]. These sensors work at high temperatures (197–447°C) [4]. Indeed, to achieve good sensing properties for a semiconductor-sensitive material, a certain operating temperature is necessary [5]. A large number of studies demonstrated that tungsten dioxide WO_3 expose a high sensitivity particularly to O_3 [6], H_2S [7], CO [8] and NO_2 [9]. To maintain the required temperature for detecting the gases, micro hotplate (MHP) is the key component. Micro hotplate consists of a thermally isolated stage with a heater structure, a temperature sensor and a set of contact electrodes for the sensitive layers. Hence, their design is a very important aspect and choosing a perfect material is a challenge for the better performance of the gas sensor. Uniform temperature distribution over the heater surface may be provided using a high thermal conductivity film [10]. A dielectric membrane is used as a high temperature electrical insulator to achieve a uniform heat distribution over the geometry [11]. MOX sensors present many advantages such as high sensitivity, small size and minimum power consumption but they suffer mostly from selectivity. The latter is the ratio of the sensitivity obtained in the presence of a gas on the sensitivity obtained in presence of another gas for a given concentration. If in the presence of another gas, the sensitivity of a sensor to a gas is little affected, then the sensor is selective. Improve gas sensors selectivity performance is the object of many researches. Previously, in gas sensors based on semiconducting metal oxides were coated with catalytic membranes to improve the selectivity of gas detection [12]. Zampollia et al. proposed a highly selective hybrid micro system based on a gas chromatographic-like (GC) approach in order to reach high selectivity for MOX gas sensors [13]. A selective multi-sensor is able to detect several gases presented at the same time.

In this work, we reported on the design and electro-thermal simulation of a combinative meander-spiral micro hotplate for ozone detection. The design is optimized for low power consumption and better temperature uniformity. Then, a new multi-sensor design was proposed in order to attain different heating temperatures required for different gases detection.

II. EXPERIMENTS

A. Combinative meander-spiral micro hotplate for gas sensors

Several heater geometries have been studied and compared in order to determine which one is the best to perform a better homogeneity in the active area with minimum power consumption, mainly from pore form [14], serpentine, spiral and fan model [15]. For our application of novel heater geometry, combinative meander-spiral has been designed. Platinum was used as the heating element with a thickness of 0.1 µm. Platinum (Pt) presents various advantages such as lower density, good specific heat capacity, high electrical conductivity etc. Thus, it is the least reactive metal. It also has a very good specific heat and heating properties. By reducing the dimensions of the geometry, higher temperature can be achieved [16]. The heating film was supported by a silicon dioxide SiO_2 membrane of size 1.4 × 1.6 mm. Membrane thickness affects the micro hotplate's performance, hence this membrane was designed to be very thin 1.4 µm to reduce the conduction losses [17].

The structural modeling is schematically depicted in Figure 1. The grey rectangle is the isolator SiO_2 and the blue film of 0.1µm thick is the Platinum.

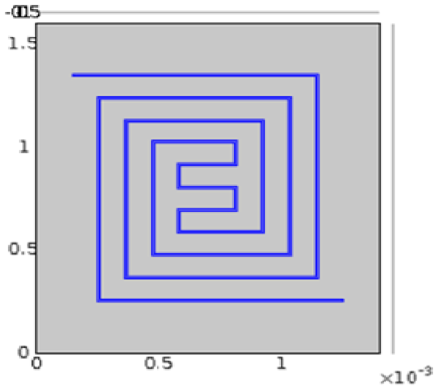

Figure 1: Heater model

The electro-thermal simulation provides coupling electrical and thermal behavior. In the framework of this simulation, electro-thermal model was used to simulate heating by Joule effect. This model includes two modes: conduction mode with the continuity equation is given by Equation (1) and heat transfer mode presented by the Equation (2) [18].

$$-\nabla.(\sigma.\nabla V) = 0 \quad (1)$$

$$\rho_v.C_p.\frac{\partial T}{\partial t} - \nabla.(k.\nabla T) = Q \quad (2)$$

These two equations are linked by the following equation of Joule heating [17]:

$$Q = \sigma|\nabla V|^2 \quad (3)$$

where ρ_v is the density of heater material, Cp is the heat capacity at constant pressure of heater material; k is the thermal conductivity of the heater material and ∇V is the potential difference across the heater material.

The simulations were carried out at a variable voltage, which was applied to one end of heating electrode and other end was grounded.

The power consumption is described by the following Equation (4):

$$P = \frac{V^2}{R} \quad (4)$$

where V is voltage and R is the resistance of heating electrode. Power consumption is directly proportional to the applied voltage and inversely proportional to the resistance of the material.

A resistance of thin micro heater can be found by using Equation (5):

$$R = \rho\frac{L}{w.e} \quad (5)$$

where ρ is the resistivity of material; L is the length; w is the width; e is the thickness.

Material properties are necessary to solve the mathematical equations of the electro-thermal simulation. In Table 1, material properties of SiO_2 and Pt are shown, respectively.

Table 1
Materials properties used in simulations [19] [20]

Material	Heat capacity at constant pressure, Cp (J.Kg^{-1} .K^{-1})	Density ρ_v (kg.m^{-3})	Thermal conductivity, k (W.m^{-1} .K^{-1})	Electric resistivity ρ (Ω.m)
SiO_2	1000	2200	1.4	$1x10^{12}$
Pt	130	21450	71.6	$10.6x10^{-8}$

B. A selective multi-Sensor

A multi-sensor was integrated on the same chip of several heating platforms matrix. Our model (Figure 2) consists of four mono-sensors supplied by different heating voltages in order to improve the selectivity of this multi-sensor.

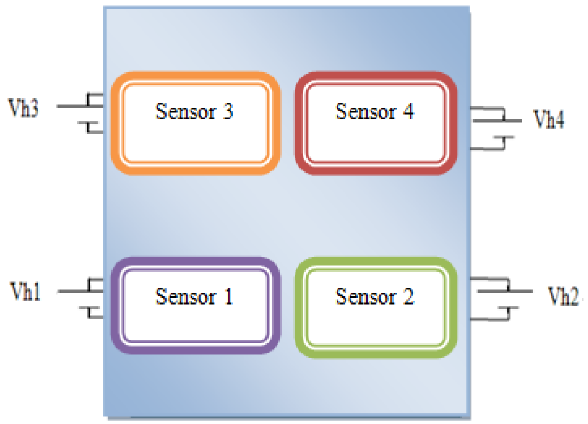

Figure 2: Block diagram of multi-sensor

For a gas sensor based on WO_3 and from [21], the optimum temperature for CO detection for a sensor was 250°C. On the other hand, studies of [22] have shown that 200°C is the optimum temperature for the detection of H_2S. Meanwhile, 225°C is an optimum temperature to detect NO_2 [23].

III. Results And Discussion

A. Combinative meander-spiral micro hotplate for ozone detection

A Finite Element Method (FEM) analysis for the designed micro hotplate was carried out using a FEM simulator. To achieve desired temperature of 300°C, optimum temperature for ozone detection as proofed in [24], a combinative meander spiral, novel heater model was designed and tested.

The result of simulation study showing the temperature distribution over the heater structure, with a power consumption of 63.14 mW, is shown in Figure 3.

The maximum temperature (red) was in the center of the active area, the minimum temperature (blue) was in the edge, the temperature gradually increased from outside to inside as seen in Figure 3.

In this part, a time dependent study was achieved. A new time-dependent parameter was used. Therefore, a voltage step from 0 to 8.6 Volts was introduced at time t = 0 of the calculation. It is also important to define the duration and sampling the calculation. 90 ms duration of study with a step of 10 ms was chosen. Following the calculation for the model of the heater, the temperature along the cutting line on the surface of the platform was plotted, for all time values as illustrated in Figure 4.

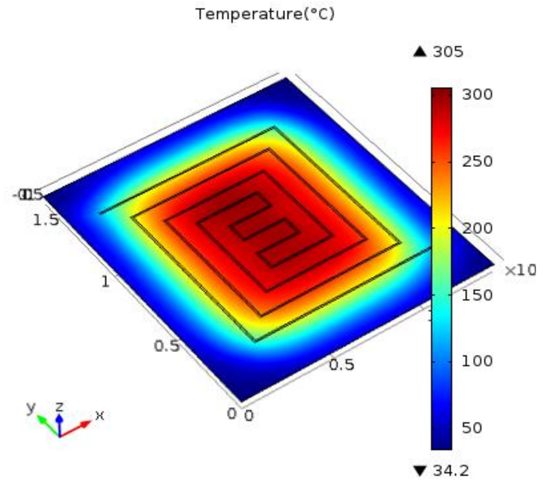

Figure 3: Temperature distribution in a combinative meander-spiral platinum heater

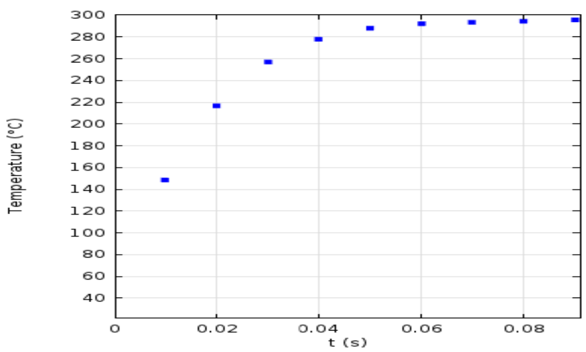

Figure 4: Temperature temporal variations along the horizontal axis to the surface of the heating platform for a combinative meander-spiral heater

After 30 ms maximum temperature sensor to the center has exceeded 250°C. Beyond 40 ms, it exceeded 280°C. It stabilized after 60 ms.

B. A selective multi-Sensor

An electro-thermal analysis was presented and a series of results on the new design of our heating platform were obtained. To verify that the behavior of the proposed multi-sensor is similar to the single-sensor, its geometry has been modified by importing metallization of two, and then four chips associated linking all masses. Figure 5 shows the model of our multi-sensor with two or four chips deposited on the same dielectric membrane.

The result of a stationary study with the same conditions and parameters is shown in Figure 6.

The temperature at the multi-sensor surface (2 chips) was about 302°C or 3°C lower compared to single-sensor. For the second multi-sensor (4 chips), the surface temperature was 300°C or 5°C less compared to single-sensor. In fact, increasing the length of the heating resistor in order to bind the masses pair wise explains this small gap. A length of 1.09 mm and 2.18 mm platinum for two and four multi-sensor chips respectively was added to make these connections. The temperature distribution and the temperature were consistent with those found in case of the single-sensor.

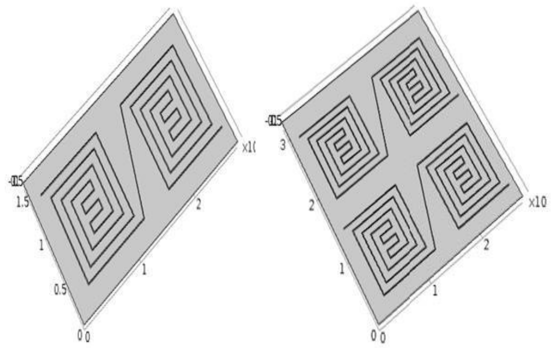

Figure 5: Multi-sensor (a) two and (b) four chips.

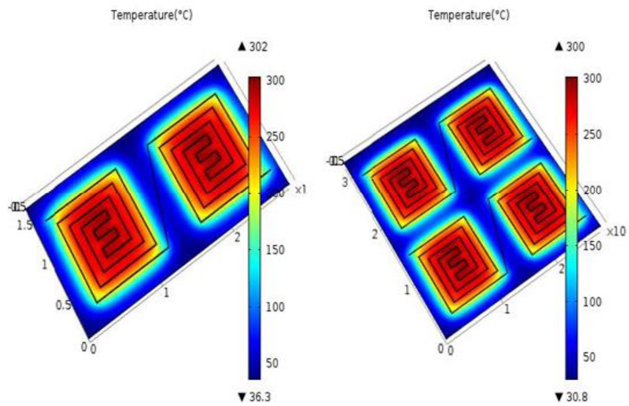

Figure 6: Thermal distribution for platinum multi-sensor.

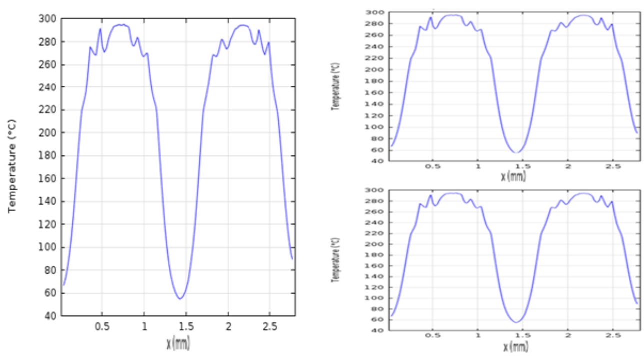

Figure 7: Temperature profile for (a) two and (b) four chips.

A cutting line on the surface of the multi-sensor model was used to check if the temperature is the same for all chips.

It is clear from the curves of Figure 7 that thermal distributions are identical for different chips of the multi-sensor. This similarity was verified for 4 chips.

To improve the selectivity of this multi-sensor, different heating voltages were applied to reach different maximum temperatures required for the detection of four polluting gases. The result is shown in Figure 8.

The temperature reached by the first chip to the left was about 200°C. It was this chip that was dedicated to H_2S. The temperature of the chip to its side was about 225°C (NO_2 detector temperature). The third sensor at the top left, dedicated to CO, reached a temperature close to 250°C. The maximum temperature of the fourth sensor was almost 300°C (temperature detection of O_3). The temporal evolution of the temperature of the multi-sensor is shown in Figure 9.

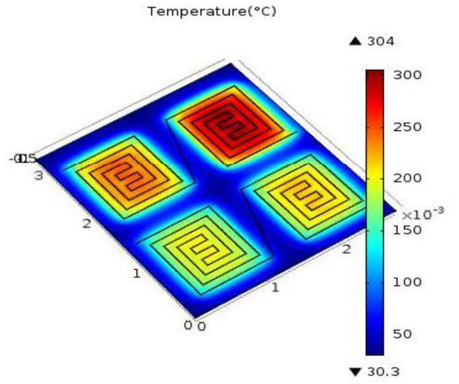

Figure 8: Different detection temperatures for the multi-sensor.

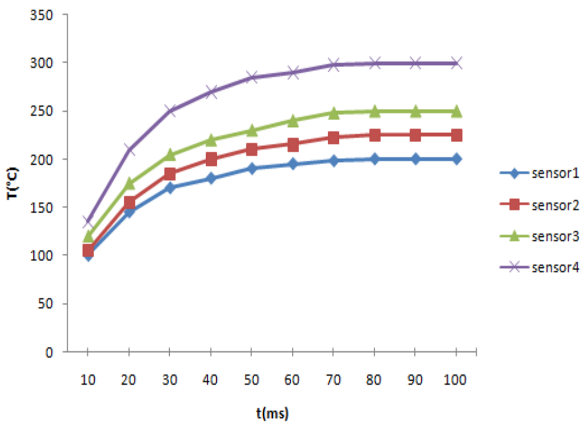

Figure 9: Time evolution of temperature for the multi-sensor.

We noted from Figure 9 that after 80 ms the maximum temperature stabilized at the desired temperature of detection for each sensor.

IV. CONCLUSION

This paper was devoted firstly to the modeling of a single-sensor for ozone detection. A combinative spiral-meander micro heater was simulated in order to achieve desired temperature, for ozone detection, on the active surface. The heater attained 300°C with a power consumption of 63.14 mW. This temperature stabilized after 60 ms. Furthermore, the purpose of this work was to model a multi-sensor while growing a plurality of heater chips on the same membrane. The results obtained confirm the good behavior of our design and proper symmetry localized heating systems. Different heating voltages were applied to achieve various maximum temperatures required for the multi-sensor. It attains the required temperatures after 80 ms.

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