ANALYSIS OF HIGH TEMPERATURE SOI MICROHOTPLATES

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Abstract–*The paper reports on the analysis and modelling of novel, tungsten-based SOI micro-hotplates for smart silicon-based gas sensors. Tungsten has very good physical properties for use in micro-heaters, is CMOS compatible, and can be used as an interconnect in CMOS circuits. Compared to current commercial solid state gas sensors, gas sensors based on these micro-hotplates offer low power consumption, full CMOS compatibility and low cost, achieved through smart CMOS integration of the sensing device, transducers, and MOSFET drive circuitry. Electro-thermal simulations and mathematical analysis are presented. In addition, mechanical stresses resulting from the high temperatures reached are also analysed*

1. INTRODUCTION

There is considerable research activity to develop low cost, low power gas sensors, especially for battery powered applications. Solid state sensors typically consist of a metal oxide (usually tin oxide) heated by a micro-hotplate. The heated metal oxide undergoes a change in some physical property (such as resistance) when exposed to the appropriate gas [1,2].

Micro-hotplates for gas sensors are typically based on platinum, polysilicon resistors, or MOSFET heaters [2-5]. Platinum is not CMOS compatible, and hence has the disadvantage of high fabrication cost, while polysilicon suffers from variable sheet resistance and poor longterm stability at high temperatures and MOSFET heaters cannot operate reliably above 350°C.

Tungsten based micro-hotplates, using SOI-CMOS technology can overcome these shortcomings. SOI technology is used in circuits to reduce the parasitic effects caused by the presence of the bulk silicon [1]. In MEMS the oxide can be used as a sacrificial layer, to fabricate structures easily. For micro hotplates, the oxide acts as an effective etch-stop (using Deep Reactive Ion Etching – DRIE), allowing easy fabrication of an oxide membrane.

Tungsten has very favorable properties for use in micro-hotplates. It is CMOS compatible, can operate reliably at high temperature, is not prone to electromigration, and has an optimum resistivity: high enough to be used as a heater, low enough to be used as an interconnect in CMOS circuits. It therefore facilitates the integration of the control circuitry on the same chip as the sensor to create a smart sensor.

Figure 1 shows a tungsten based micro-hotplate structure, composed of CMOS compatible layers:

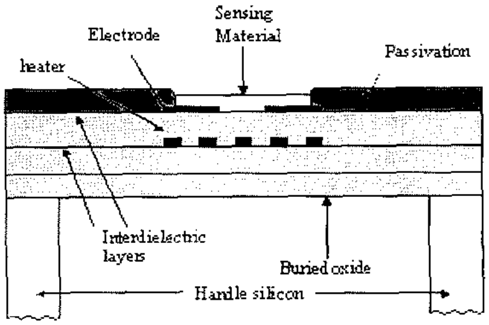

Fig. 1. Micro-Hotplate Structure.

In this paper, we present 3D electro-thermal simulations in ANSYS, on tungsten based micro-hotplates using SOI. The micro-hotplates show low power consumption (less than 50mW) and fast response time (less than 1 mS). Simulations of mechanical stresses caused due to thermal expansion are also presented.

2. HEATER DESIGN AND STRUCTURE

The structure of the micro-hotplate used for simulations is as shown in figure 2(a) and 2(b). It consists of a tungsten heater on a silicon oxide membrane, supported by a silicon substrate. Heat is generated through the self heating effect when electrical power is supplied to the heater. As a result the temperature of the membrane area increases.

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The oxide thickness is kept at 3μm, tungsten heater thickness at 0.3μm. For the first structure the heater area is 300 x 300μm, while the membrane area is 500 x 500μm.

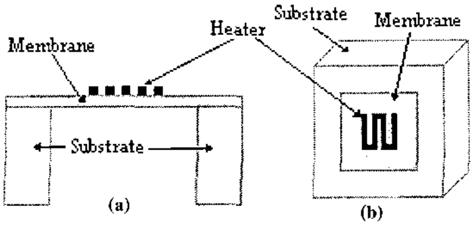

Fig. 2. Micro-Hotplate and Heater Structure

A meander shaped tungsten heater (figure 2(b)) is used. For this particular structure, the heater shape has 6 vertical lines, a width of 3.47μm, and a gap of 55.83μm. The heater is designed so as to supply appropriate power when the applied voltage is around 5V, while at the same time occupying the required area.

Circular membranes are more mechanically robust than square membranes, therefore a circular structure, with the same heater area was also considered.

In addition, a square miniature structure, with heater and membrane areas of 20x20μm and 50x50μm respectively was also considered, along with a circular version.

These simulations are preliminary, and take into account only conduction losses. Convection and radiation losses will form part of a future study.

3. SIMULATION RESULTS AND ANALYSIS

3.1. Thermal Simulations

For the large rectangular structure, an electric potential of 4.5V is applied across the heater, while the base of the silicon is assumed to be at 25^{0}C. The resulting temperature profile is shown in figure 3(a).

The temperature in the heater region is above 600^{0}C, with the highest temperature obtained almost 700^{0}C. The power required is 48.2mW.

Figures 3(b)-3(d) show the temperature profiles of the other micro-hotplate structures, while figure 4 shows a graph of the highest temperature reached against the power required.

In addition, transient analysis was also performed on the small circular structure to determine the time required to heat up. The graph is shown in Figure 5.

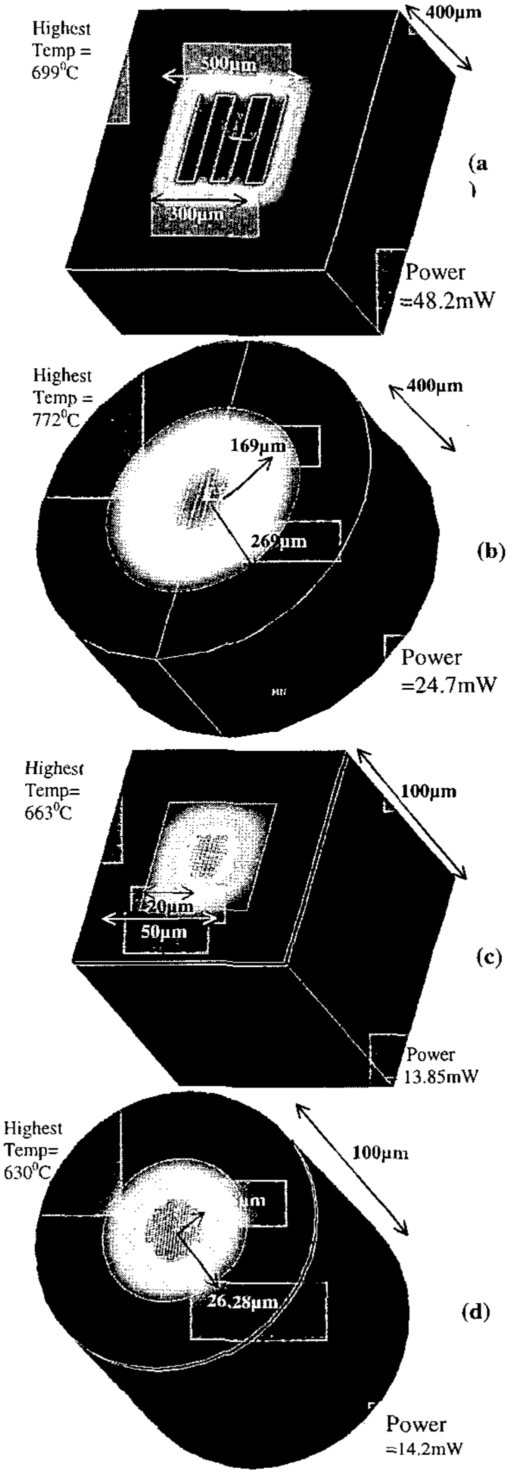

Fig. 3. Temperature profiles for various heater structures.

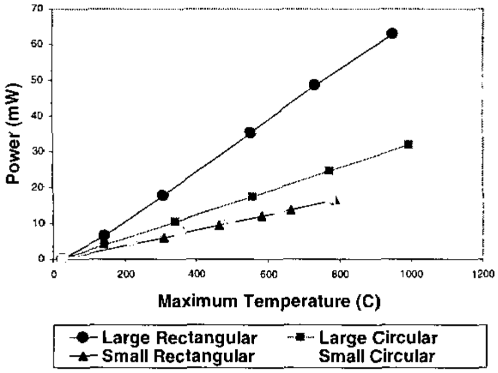

Fig.4. Power Vs Maximum Temperature

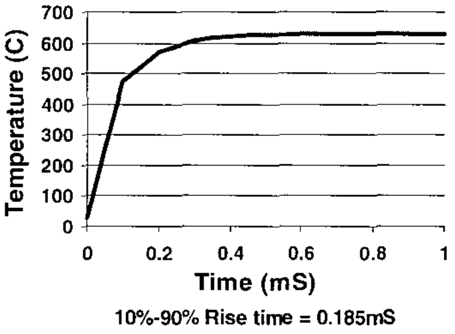

Fig. 5. Temperature vs time at centre of small circular heater.

3.2. Mathematical Analysis

Mathematical analysis of thermal conduction was performed on the circular structure to verify the results of simulations, as well as to gain a better understanding of the heat conduction process to aid in better heater design. The concept of thermal resistance is used [6].

Consider a circular membrane, and let r1 be the radius of the heater area, while r2 is the radius of the membrane. Heat flows from the inner circle to the outer one. Consider a small ring between these two radii, of thickness dr.

The thermal resistance of this region is given by:

$$dR = 1/(2\pi r\alpha t)dr$$

where dR is the resistance of the infinitesimal element, r is the radius, α is the conductivity (1.4 W $m^{-1}K^{-1}$) and t is the thickness. The total resistance is given by integrating with the inner and outer radii as the limits:

$$R = \int_{r1}^{r2} 1/(2\pi r\alpha t)dr$$

$$R = \frac{1}{2\pi\alpha \cdot t}\ln\left(\frac{r2}{r1}\right)$$

The resistance of the small circular structure is calculated using this formula, and comes out to be 32 $\times 10^3$ K/W. The power generated by the heater was 14.2mW. Therefore the temperature difference in the membrane area should be around 455°C. In the simulation, the temperature at the edge of the heater (which is different from the maximum temperature) was approximately 500°C, meaning a difference of about 475°C, which is close to the calculated value. Similarly for the large circular structure, the resistance is17614 K/W, and for 24.7mW of power, the temperature at edge of heater should be 460°C.

It is also interesting to determine, for a given membrane radius, the optimum heater radius in terms of power required per heated area.

For a heater of radius **r**, the power required for a temperature T is:

$$P = \frac{T}{K\ln\left(\frac{r2}{\mathbf{r}}\right)}, \text{ where } K = \frac{1}{2\pi\alpha \cdot t}$$

Power per unit area is:

$$p = \frac{T}{\pi \cdot \mathbf{r}^2 \cdot K\ln\left(\frac{r2}{\mathbf{r}}\right)}$$

Therefore for minimum value,

$$\frac{dp}{d\mathbf{r}} = \frac{T}{k\pi}(-1)\left[\mathbf{r}^2\ln\left(\frac{r_2}{\mathbf{r}}\right)\right]^{-2}\left[2\mathbf{r}\ln\left(\frac{r_2}{\mathbf{r}}\right) - \mathbf{r}\right] = 0$$

$$\mathbf{r} = \frac{r_2}{e^{0.5}}$$

This is therefore the optimum heater radius for a given membrane radius in terms of power per heated area.

3.3. Mechanical Simulations

The difference between the thermal expansion coefficients in the materials, together with the thermal gradient in the membrane produces induced-thermal strain and stress that causes structure deflections.

This stress was simulated using the previous temperature distributions as a load for the mechanical model in order to ensure the convergence and to avoid numerical instabilities related with the membrane buckling. Two cases are considered:

1) No passivation layer on top of the membrane (Fig. 6a).

2) Structures with a thin Silicon Nitride passivation layer (0.25 μm) on top of the membrane (Fig. 6b).

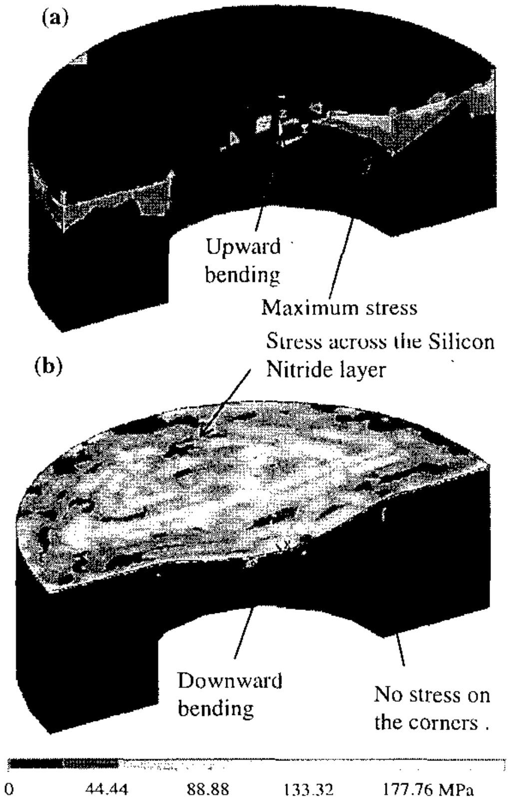

Fig. 6. Induced-thermal stress.

As can be seen in Fig. 6a, the structure without passivation layer, presents a considerable amount of stress, which in time, can lead to film delamination or micro-crack. This stress is more pronounced in rectangular membranes. Also, an upward bending can be observed due to the thermal expansion against the fixed walls.

On the other hand, Fig. 6b shows a significantly less amount of stress across the silicon rim and the membrane. This is because the nitride acts to compensate the stress given by the oxide. The change of the bending direction is related with the layers configuration and the fact that the active area is hotter than the rest of the membrane. This temperature difference induces the expansion of the active area from the Silicon Nitride, and thus it bends relatively to the remainder material. In this situation, there coexist in the membrane an upwards deflection and a bimetallic downwards deflections at the membrane centre [7], but the second effect is more pronounced.

4. CONCLUSIONS

In this paper we have presented 3D electro-thermal simulations on tungsten based micro-hotplates. The micro-hotplates have very low power consumption, and a fast response time, which means they can be used in pulsed-mode, to reduce the average power consumption even more, making them suitable for battery powered or wireless applications. Simulations of mechanical stress due to thermal expansion have also been presented. Further work will involve studies on heat losses due to convection, as well as better heater design for more uniform temperature distribution. Extensive mechanical simulations, as well as calculations of the maximum deflection before the thermal-induced stress produces a fracture in the membrane in different structures will also be considered.

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