# The Novel Microhotplate: A Design Featuring Ultra High Temperature, Ultra Low Thermal Stress, Low Power Consumption and Small Response Time

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***Abstract*— Microhotplate (MHP) has multiple applications, such as micro-heating elements, catalytic gas sensors, resistive gas sensing, infra-red source, non-dispersive infrared detector (NDIR) gas sensing, Fourier transform infrared (FTIR) spectroscopy, temperature sensing, flow sensing, pressure sensing, smart sensing and lab-on-chip. Low power consumption, high temperature, high thermal stability (low thermal stresses), uniform temperature distribution and fast thermal response are the most desirable features of the MHP design. This paper describes the design of the MHP that has ultra-high temperature (2000K), ultra-low thermal stress (90MPa), low power consumption (30mW) and small response time (9.13ms). All the results matched with Coventor simulation results.**

***Keywords- Microhotplate; ultra high temperature; ultra-low thermal stress; low power consumption; small thermal response time.***

## I. INTRODUCTION

One of the popular usages for the MHPs is gas sensors. Fig. 1 shows the standard MHP gas sensor with the plate structure, a Polysilicon layer, between $SiO_2$.

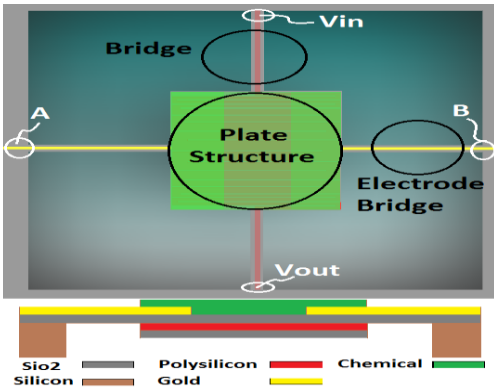

Figure 1. Microhotplate (MHP)

MHP is widely used for the catalytic and resistive gas sensing. According to Korotcenkov [1], high temperature would be desirable for selective gas sensors. It would reduce considerably the influence of air humidity and increase the sensitivity. Some metal oxide layers require high temperature for high sensitive gas sensors. For Ga2O3 sensor the operation temperature is 600-900 Celsius and it senses the O2 and CO gases. Oxygen sensors using SrTiO3 (Strontium titanate) operates at 1000 Celsius. According to [2], selectivity can be improved by operating the sensor in a temperature-modulated mode. High temperature MHP would allow a wide range of different gas sensing.

Nanomaterial processing is another one of the most important applications for high temperature MHP. It is especially important for CNT growth [3], thin film growth and characterization [4]. It requires high temperature operation with reconfigurable and controllable heating, and uniform surface deflection. All these features are well established in this paper.

Section-II concentrates on the causes of the thermal stresses and their possible solutions. Section-III demonstrates the effect of the spring structure and modulated AC signal on the low power consumption. Section-IV shows how to achieve the faster response time while keeping the uniform temperature distribution with uniform deflection. Section-V shows the novel MHP's performance by comparing it with the ones in the literature

## II. LOW THERMAL STRESS MHP DESIGN

There are two causes of high thermal stress. The first is due to having different thermal expansion constant materials in the composite structure. The second is having a structure, which cannot expand when heated. Solutions in the literature are concentrated to solve the first cause by using either the same thermal expansion constant materials or the compatible materials in the composite structure. This solves the problem partially; however, fails at a high temperature around 700 Celsius. In this work, an analytical approach is first applied to the first cause to find the optimum dimensions solution (if any); and then, the novel structure is realized and applied to the second cause to get the optimum MHP for high temperature applications.

### *A. Thermal Stress Analysis*

The equation for the composite structure having a different thermal expansion constant is given in [5] as shown below in (1)

$$\sigma_{xi}(y) =- \alpha_i E_i T_i(y) + E_i \frac{P_T I_{E2} - M_T I_{E1}}{I_{E0} I_{E2} - I_{E1}^2} + yE_i \frac{M_T I_{E0} - P_T I_{E1}}{I_{E0} I_{E2} - I_{E1}^2} \quad (1)$$

where

$$I_{E0} = \sum_{i=1}^{n} E_i w_i ( y_i - y_{i-1}) \;,\quad I_{E1} = \frac{1}{2} \sum_{i=1}^{n} E_i w_i (y_i^2 - y_{i-1}^2)$$

$$I_{E2} = \frac{1}{3} \sum_{i=1}^{n} E_i w_i (y_i^3 - y_{i-1}^3) \;,\; P_T = \sum_i^n \int_{y_{i-1}}^{y_i} \alpha_i E_i T_i(y) w_i dy$$

$$M_T = \sum_{i}^{n} \int_{y_{i-1}}^{y_i} \alpha_i E_i T_i(y) y \; w_i dy$$

The number of layers in a composite structure are represented in Fig. 2 and is denoted by i, where $y_i$-$y_{i-1}$=$h_i$ represents the thickness of *i-th* beam, $y_i$ represents the lower surface of *i-th* beam, $E_i$ is elastic modulus, $\alpha_i$ is thermal expansion constant for *i-th* beam, and $\sigma_{xi}(y)$ is the stress value for *i-th* beam at thickness *y* and *w* represents the width.

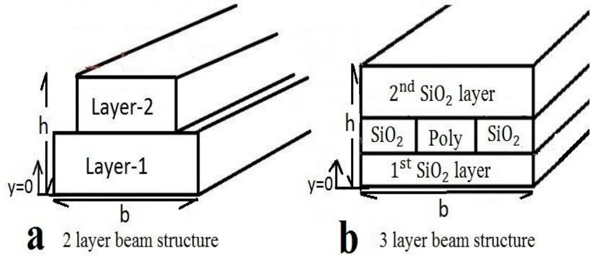

Figure 2. Cross section of the Composite structure

Conventional MHP structure is a composite structure. Fig. 3 shows the maximum thermal stress versus the temperature for the 3 layer composite structure (SiO2+Poly+SiO2). The stress value is around 240 MPa when the temperature reaches to 600 Kelvin. For the CMOS technology materials the maximum stress is around 100 MPa. Thus, at 600 Kelvin the CMOS MHP would be brittle with a conventional structure as shown in Fig. 1.

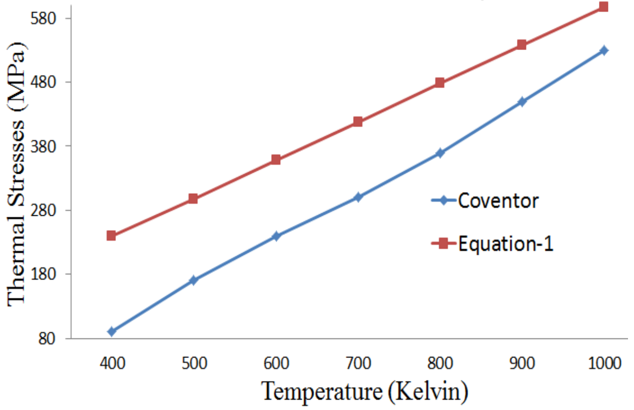

Figure 3. Stress versus Temperature for 3-layer MHP

Fig. 4a shows how the analytical results match with the Coventor simulation results for thermal stress in the middle of the polysilicon layer proving that the change in the width cannot solve the thermal stress problem. Fig. 4b shows that large thermal stress occurs in the center of the layer despite thermal stress decreasing on the sides proving changes in width cannot solve the thermal stress problem.

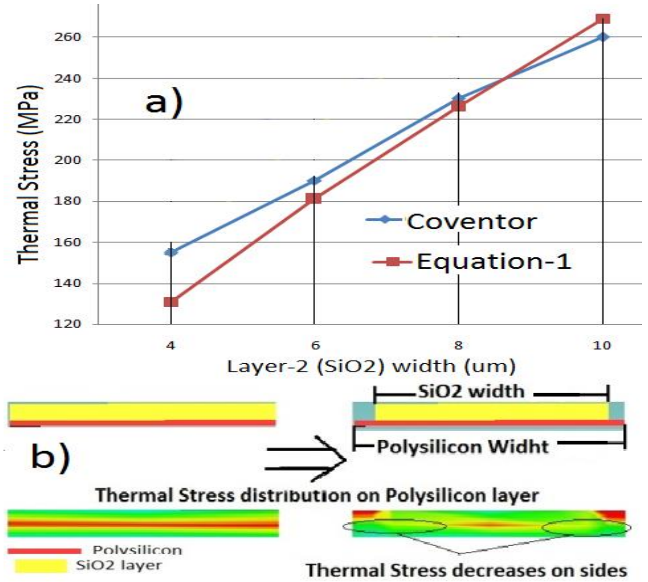

Figure 4. a) Effect of width on Thermal stress, b) cross-section view of the 2 layer composite structure

Fig. 5 shows a nice match between the calculation results and the Coventor simulation results for the thermal stress on the interface layer between SiO2 and Poly layer. In this result, layer 2 in Fig. 2a was used. In general, it applies to any number of layers in the interface. At first glance, it looks like the change in the thickness of one material in the composite structure can decrease the thermal stress.

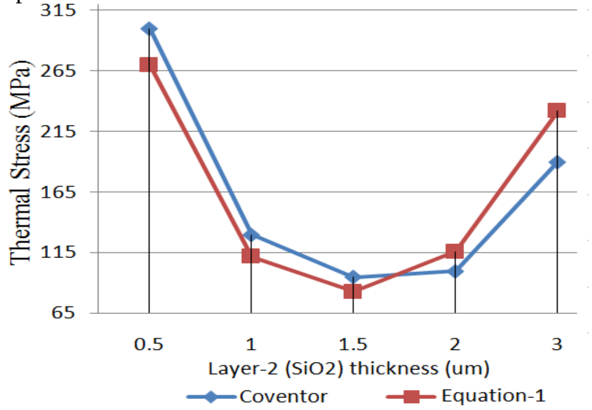

Figure 5. Effect of thickness on Thermal stress

Fig. 6 shows the distribution of the thermal stress throughout the thickness of several layers. Thermal stress is shown for the poly layer in Fig. 6a and for the SiO2 layer in Fig. 6c. Fig. 6b shows the (1)'s results. The match between the (1) and Coventor simulation results can be seen from Fig. 6. The graph in Fig. 6b shows the thermal stress versus thickness for SiO2 layer (y=0um to y=1.5um) and for the poly layer (y=1.5um to y=2um). It is proved by this example that changing the geometry (looking for the optimum dimensions) of the composite structure having a different thermal expansion constant is not a solution for low thermal stress. That is why a single layer structure or the composite structure having the same thermal expansion constant materials would be a better option to decrease the thermal stress; however, it requires further optimzations as discussed in the next section.

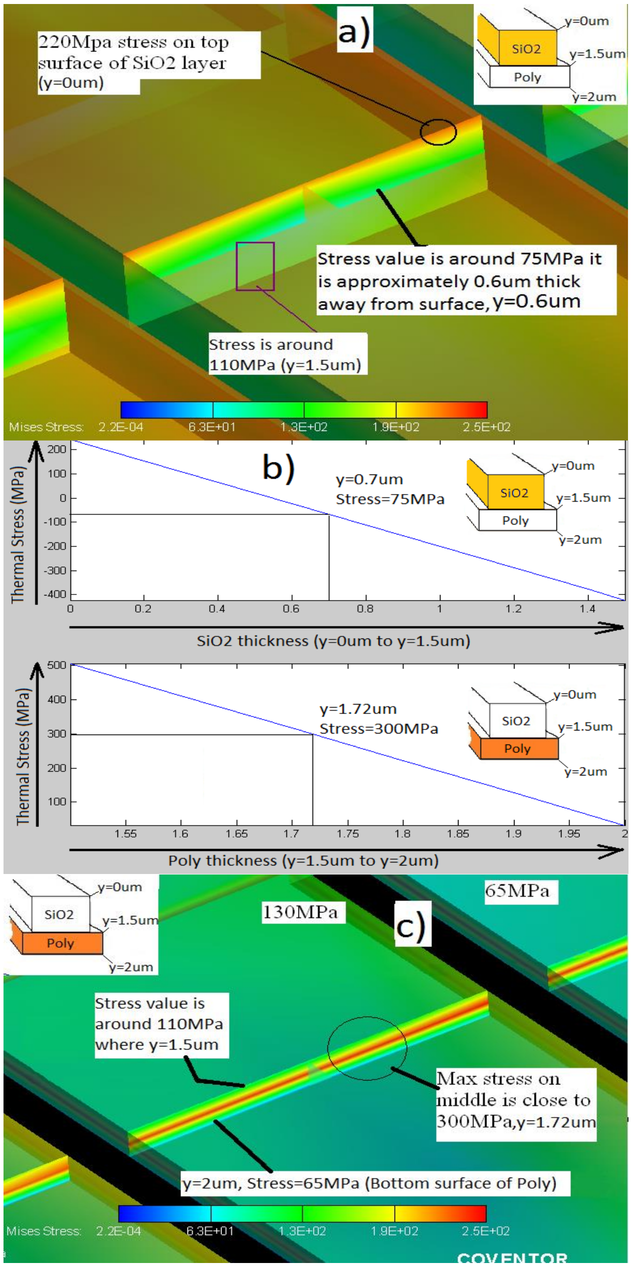

Figure 6. a)Thermal stresses versus thickness of SiO2, b)Thermal stress versus thickness from (1), c)Thermal stress versus thickness of Poly layer

### B. *Designing a structure that can expand*

From the above discussion, a second cause for thermal stress is the restriction of expansion in the original MHP design shown in Fig. 1. A single layer and the composite structure with the same thermal expansion constant are described here. Spring structure allows the MHP to expand freely, and decreases the stress values, as shown in Fig. 7. Stress on the electrode bridge is around 370 MPa in Fig. 7a; however, it is around 230 MPa in Fig. 7b. Further design optimizations on the spring structure can be accomplished by varying the width, length, or thickness. If the width increases, then stress decreases according to equation $\sigma_{allowable} = \frac{M_{max}c}{(1/12)bh^3}$ and it increases the safety factor. In our design the maximum stress at 2000 Kelvin is less than 90 MPa as shown in Fig. 8. Fig. 11 shows the temperature effect on the thermal stress. The thermal stress increases while the thickness increases due to the increase in volume and thermal expansion. The safety factor is realized around 1.5.

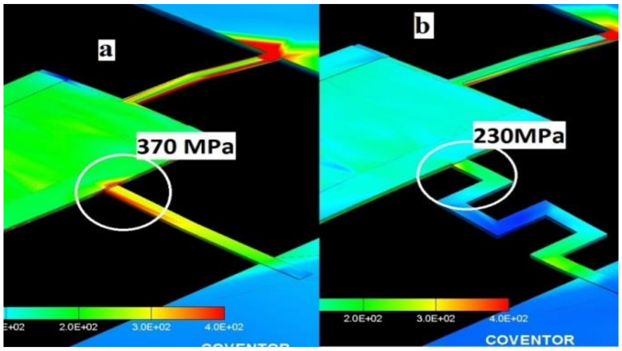

Figure 7. Spring design for low thermal stress

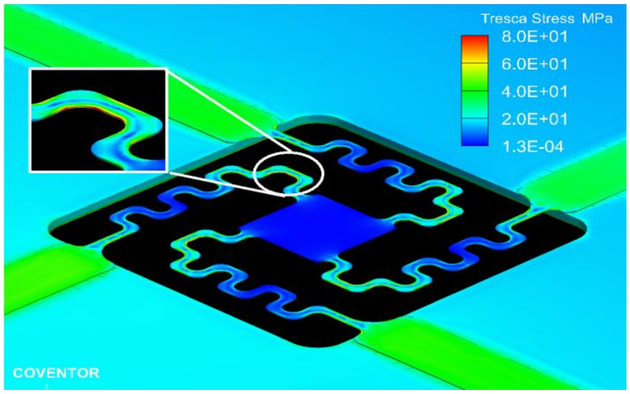

Figure 8. Maximum Thermal Stresses at 2020K

## III. LOW POWER CONSUMPTION MHP

The spring structure decreases the heat flux to the substrate and keeps most of the heat on the MHP as shown in Fig. 9. $R_o$ is the resistance of the heater plate, *R1* is for the heater bridge and *R2* is for the connection between the substrate and the heater bridge. $T_o$ is the center temperature on the plate, *T1* is at the connection of the bridge and plate, *T2* is at the connection of the heater and substrate and *T3* is the substrate temperature. The temperature at each node can be found via thermal conduction and heat generation equations as shown below.

$$T_a - T_b = \frac{q'L^2}{2k}, \text{ where } q' = \frac{E_g'}{V},\ E_g' = I_{eq}^2 R,\ R = \rho\frac{L}{A} \quad (2)$$

$$T_a - T_b = q''R'', \text{ where } R'' = L/k \quad (3)$$

where $q'$ is the heat generation per volume, V is the volume, R is the resistance, $I_{eq}$ is the current flow, $\rho$ is the density, L is the length, A is the area, $q''$ is the heat flux, k is the thermal conduction constant and $R''$ is the resistance for a unit surface area.

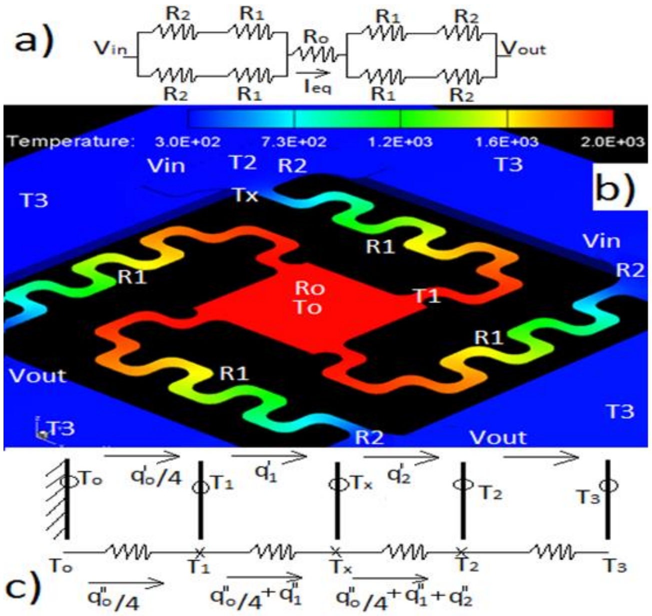

Figure 9. a) Electrical equivalent circuit of MHP, b) Temperature Distribution on MHP at 0.4Volt, c) Thermal Conduction equivalent circuit of MHP

Coventor simulation results matched with (2) and (3). Equation-2 is used in the section between $T_o$ and T2. Equation-3 is used in the section between T2 and T3 as shown in Fig. 9c. This procedure allows us to find the optimum design in terms having low power consumption, high uniform temperature distribution and uniform deflection on the surface. The design in this paper has 37mW power consumption with a 0.46 Volt voltage at 2000 Kelvin.

Using AC voltage (frequency modulated signal) rather than DC voltage decreases the power consumption further for low-voltage design. Ta in Fig. 10 is the time period when the voltage is high; Tb is the time period when there is no voltage applied to the MHP. Tb depends on the cooling time of the system. In this way the system can be kept at 2000K with much more less power consumption.

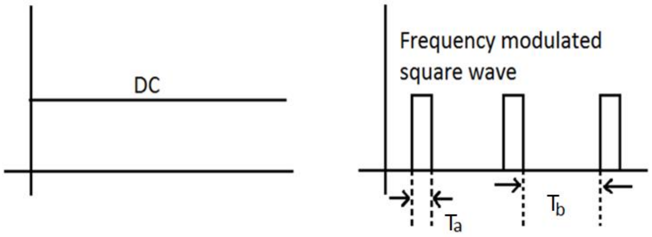

Figure 10. DC voltage versus modulated square wave

Fig. 11 shows an example for thickness effect on power consumption. A decrease in thickness also results in a decrease in power consumption because the resistance increases and drops the current flow.

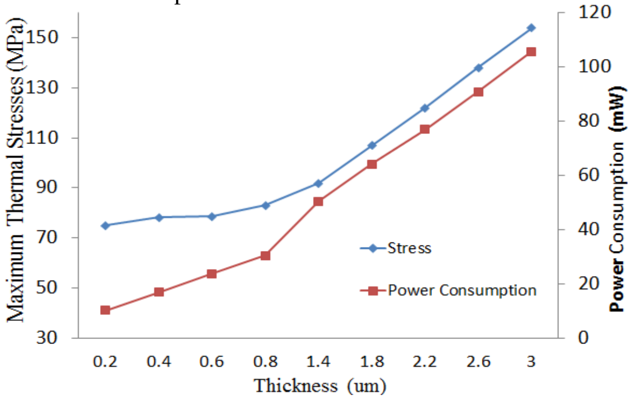

Figure 11. Power Consumption and Thermal stress versus thickness at 2000K

## IV. SOLUTION TO FAST RESPONSE TIME WITH UNIFORM TEMPERATURE DISTRIBUTION AND DEFLECTION

The response time can be decreased by increasing the current because heat is proportional to the rate of current flowing through the heater. If the voltage increases more than the required value to reach the target temperature, then the heating rate will increase. This results in high temperature in a short time due to an increase in the current density. Fig. 12 shows how the voltage affects the temperature increase in a shorter time period. By combining the frequency modulated square wave solution from Fig. 10 with the high voltage solution from Fig. 12, we can get a reconfigurable heating rate on MHP. This feature is very important especially for high quality CNT growth. Having a single layer structure not only enables the uniform temperature distribution on the MHP as shown in Fig. 8b, but also enables a very small response time as 9.1ms to reach 2000K with 0.46V.

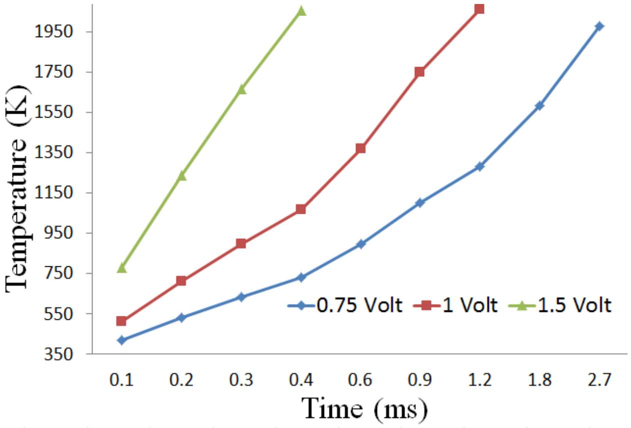

Figure 12. Transient Responses Temperature from Coventor simulation results when different voltages applied to the MHP

## V. CONCLUSON

Previous results in the literature to the best of our knowledge show the smallest thermal stress is 210MPa at 650 Celsius in [6], the highest temperature is up to 1000 Celsius in [7], the lowest power consumption is 16mW at 550 Celsius in [8], and the smallest response time is 5ms for 400 Celsius in [9] and 10ms for 550 Celsius in [8]. We succeeded to design the MHP with less than 90MPa stress at 2000 Kelvin with 9.13ms response time, 37mW power consumption and 0.7um uniform deflection. Detailed results can be seen from Fig. 13. The MHP structure shown in this paper is currently being fabricated for measurements. MHP will be tested to sense the gases that require high temperature. The temperature modulated mode will also be tested by using the advantage of a wide range of temperature (0-2000K) capability to sense the different gases

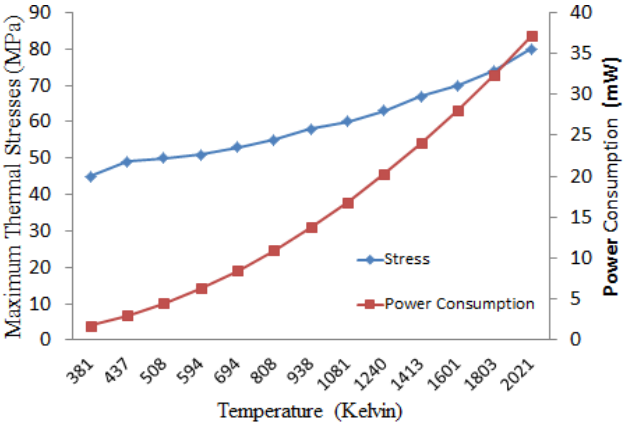

Figure 13. Power Consumption and Thermal stress versus temperature

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