High Temperature SOI CMOS Tungsten Micro-Heaters

S.Z.Ali, P.K.Guha, C.C.C.Lee, F.Udrea, W.I.Milne
Center for Advanced Photonics and Electronics
University of Cambridge, Cambridge, United Kingdom.
sza20@cam.ac.uk

T. Iwaki, J.Covington, J.W.Gardner
School of Engineering
University of Warwick
Coventry, United Kingdom

S.Maeng, J. Park
Electronics and Telecommunications Research Institute,
Daejeon, Korea

Abstract—**Here we present for the first time, the design, fabrication and characterization of novel high temperature SOI micro-hotplates employing tungsten resistive heaters. Tungsten has a high operating temperature, good mechanical strength, and could be used for CMOS interconnects. These devices have been fabricated using a commercial SOI-CMOS process followed by a DRIE back-etch step, offering low cost and the option of circuit integration. Here we report on micro-hotplates with two different diameters (560μm and 300μm), 3D electro-thermal simulation in ANSYS and their electro-thermal characterization. Results show that these devices can operate at a high temperature (600°C), have ultra low DC power consumption (12mW at 600°C), fast transient time (as low as 2ms to 600°C), stability in time and temperature and, more importantly, a high reproducibility both within a wafer and from wafer to wafer. The SOI micro-hotplates could be used in fully integrated micro-calorimeters or resistive gas sensors.**

I. INTRODUCTION

Silicon based gas sensors offer the possibility of low cost, low power devices for use in battery operated and wireless applications. Silicon based resistive micro gas sensors have been fabricated by various groups [1-3]. These usually consist of a gas sensing layer (such as tin oxide) heated by a micro-hotplate (a heater isolated on a membrane formed by bulk-etching in order to reduce the power consumption). At high temperatures the resistance of the sensing layer changes in the presence of the analyte gas, and this change in resistance can be used to determine the gas concentration. While these devices have shown good characteristics, they are not CMOS compatible, and hence have high manufacturing costs, and in general do not offer the possibility of circuit integration.

Micro-hotplates fabricated using commercial CMOS processes have been reported [4-6]. In [4] a polysilicon heater is used with aluminum electrodes for the gas sensing layer. The presence of aluminum reduces the maximum operating temperature of the sensors. In [5] MOSFETs are used as micro-heaters, which can operate uptil 350°C, but at high temperatures, the parasitic bipolar may be triggered and devices lose gate control.

Finally in [6] the micro-hotplates use polysilicon for the heater, however the polysilicon has stability problems at high temperatures. Extra processing steps are also required to deposit platinum sensing electrodes.

Here we present the design and analysis of novel high temperatures tungsten micro-hotplates, fabricated in a commercial SOI-CMOS process. Tungsten is used as metallization in some commercial SOI processes (for increasing the junction temperature of the CMOS), has good mechanical properties, and can operate reliably at high temperatures. The use of SOI technology allows greater flexibility in the design of micro-hotplates, and also allows the sensor interface circuitry to operate in high temperature environments (up to 250°C).

The proposed structure is shown in Fig 1. During the fabrication of the interface circuitry, the tungsten metal layers (used as interconnect in CMOS circuitry) are used to form the heater, a heat spreading plate and interdigitated electrodes for gas sensing. Back etching by Deep Reactive Ion Etching (DRIE) is then used to release the membrane, followed by the deposition of the gas sensing layer.

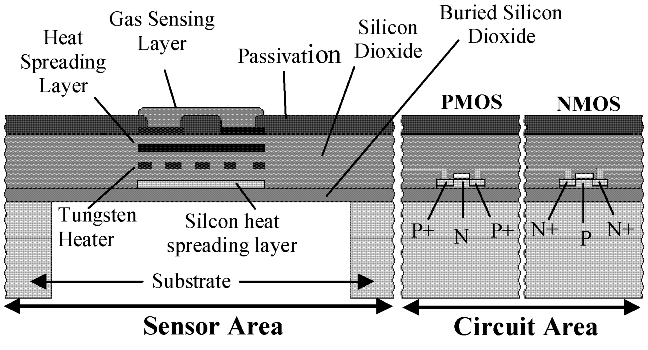

Fig 1. Design of tungsten SOI chip: gas sensor & integrated CMOS Circuitry

---

The work was partly supported by the Ministry of Information and Communication, Republic of Korea under the project no A110-0501-0073

1-4244-0376-6/06/$20.00 ©2006 IEEE

II. DESIGN AND FABRICATION

A. *Design and Simulation*

Circular micro-hotplates of two different sizes were designed. The large micro-hotplate has a heater radius of 75µm and a membrane radius of 280µm. The small micro-hotplate has a heater radius of 12µm, and membrane radius of 150µm. A circular shape was chosen for better mechanical stability. Etch rates in DRIE, unlike KOH etching, are not dependent on crystal orientation, and hence allow the fabrication of circular membrane structures.

Extensive 3D electro-thermal simulations of the structures were carried out in ANSYS. Fig 2 shows the power vs temperature curves for the micro-hotplates. There are two main sources of heat loss: conduction losses through the membrane to the base of the chip, and convection losses to the air surrounding the membrane. The effects of both of these heat losses were simulated. Our initial simulations showed extremely low power consumption, needing 34mW for the large heater, and 14mW for the small heater for a temperature of 300°C.

B. *Fabrication*

The micro-hotplates were fabricated using the XFAB SOI-CMOS process using tungsten metallization and back etched to the buried oxide at Silex (Sweden), by DRIE. In collaboration with the foundry, we developed a very accurate back to front alignment and minimized the under cut effect of the DRIE. This is shown in Figs 3 and 4 where the edge of the membrane is right below the top metal alignment marks.

A multi-ringed heater design was used as simulations showed that this has a much better uniformity than a meander or spiral design. For the small heater, the small size and process constraints do not allow for much variation in heater design, so a design with evenly sized rings was used for a high resistance compared to the heater tracks.

The large heater consists of two outer rings of high resistance and one inner ring with a smaller resistance. The inner ring compensates for heat loss due to convection from the heater, while the outer rings compensates for the heat loss due to convection outside the heater area and conduction. A low resistance for the inner ring was used as simulations showed that convection loss within the heater region was much lower than the other heat losses. This arrangement provides good temperature uniformity within the heater region. Floating metal plates between the gaps in the rings also improve the temperature uniformity.

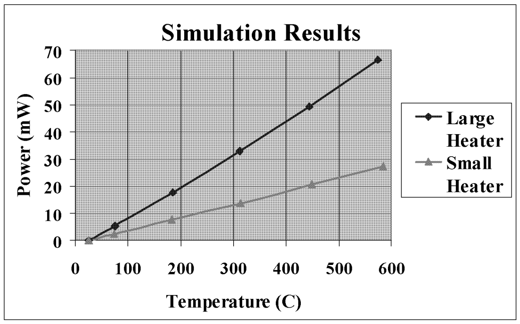

Fig 2. Initial simulation results in ANSYS

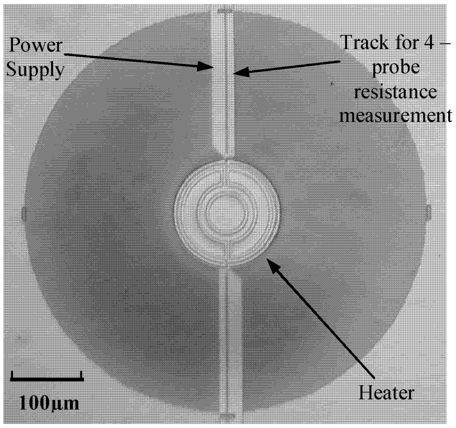

Fig 3. Fabricated Large Micro-hotplate

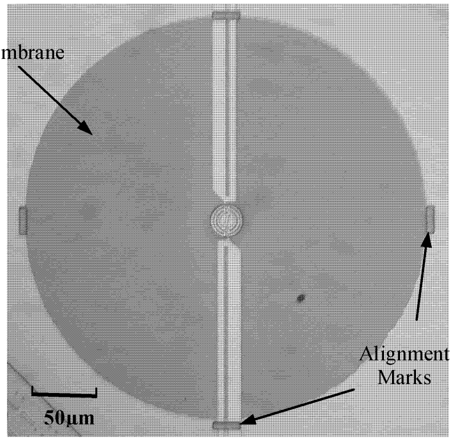

Fig 4. Fabricated Small Micro-hotplate

The heater itself is used as a temperature sensor. Two thick tracks to the heater can be used to supply a constant current. The voltage is measured using the two thinner tracks for an accurate, 4 point resistance measurement of the heater. The change in resistance due to the high temperature can be used to determine the temperature.

III. EXPERIMENTAL RESULTS

A. *Thermal Characterization*

The tungsten heaters were first calibrated up to 300°C using a high temperature chuck (Signatone S-1060R-6TG), having an accuracy of 1°C. The calibration was performed on unetched wafers, because etched wafers were difficult to measure at high temperatures, due to larger bowing. The calibration curve is shown in Fig 5. The Temperature Coefficient of Resistance (TCR) extracted from the measurements matched very well with the value given by the foundry (X-FAB).

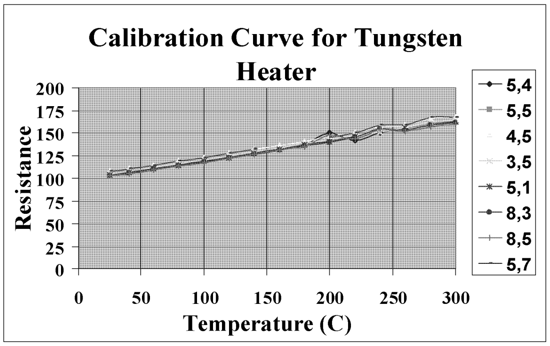

Fig 5. Calibration of 8 different tungsten heaters on a single wafer

The micro-hotplates were subsequently characterized by heating with a constant current source, and measuring the voltage across the heater. The change in resistance was used to determine the temperature using the TCR determined during calibration. Fig 6 shows the power vs temperature curves for different devices across the wafer. The power consumption was observed to be much lower than predicted by the initial simulations(6mW and 14 mW for small and large heaters at 300°C). The results are remarkably uniform all over the wafer (within 2%).

Transient measurements were made by applying a constant voltage pulse to the heaters for a very short time.

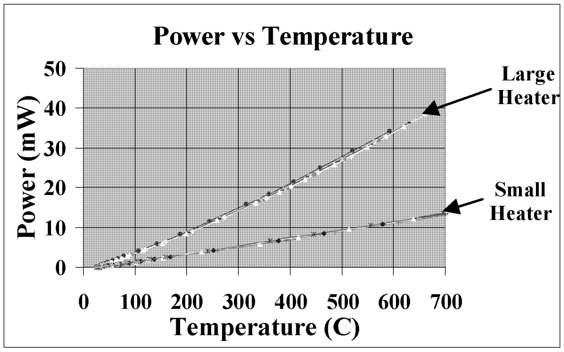

Fig 6. Measured Thermal Characteristics

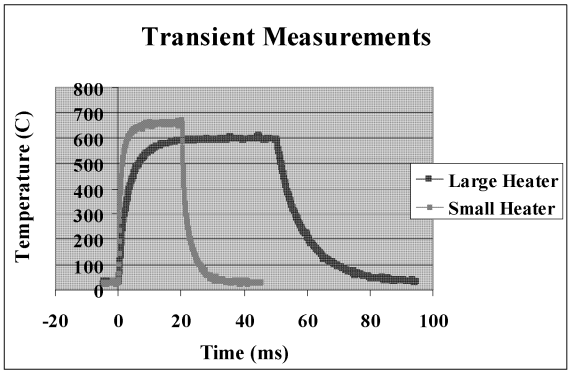

Fig 7. Transient time for large micro-hotplate (Square wave voltage input, 50ms pulse width for large heater, and 20ms pulse width for small heater)

Fig 7 shows rise and fall times needed for a temperature of 600°C. The large heater has a 10-90% rise time of 10ms and a fall time of 20ms, while for the small heater, the rise and fall times are 2ms and 6 ms respectively.

B. *Mechanical Characterisation*

The profile of the membranes was measured using an optical interferometer (Fogale Nanotech Zoomsurf 3D). The membranes show very little deflection; the large membrane deflected downwards by only 8.5µm (max deflection is 2% of membrane diameter)(Fig 8), and the small membrane deflected upwards by only 2.5µm (Max deflection is 1% of membrane diameter) (Fig9). These measurements were taken at room temperature, without supplying power to the heater. The different directions of deflection are possibly because although the small membrane deflects upwards, the different stresses in the nitride and oxide layers tend to cause a downward deflection, and have a greater effect in the larger membrane as the area is larger.

Fig 10 shows the maximum deflection in the small heater when the membrane is heated up to 400°C using its own heater. The figure shows that operating the micro-hotplates up to a high temperature does not cause any significant deflection (<0.5µm), thus showing that the membranes are mechanically stable, and can operate at high temperatures.

IV. ANALYSIS

As is evident from figs 3 and 6, the observed power consumption of the micro-hotplates is about half that predicted by the initial simulations. The main reason is the value of the thermal conductivity of silicon nitride.

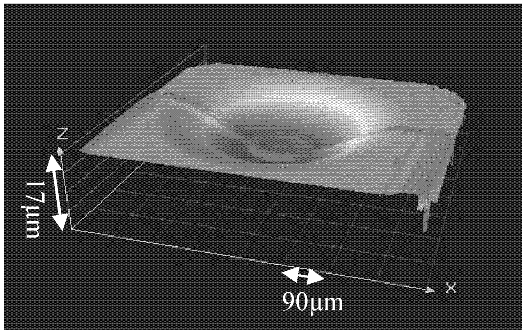

Fig 8. Mechanical Profile of Large Heater (Max Deflection = - 8.5µm)

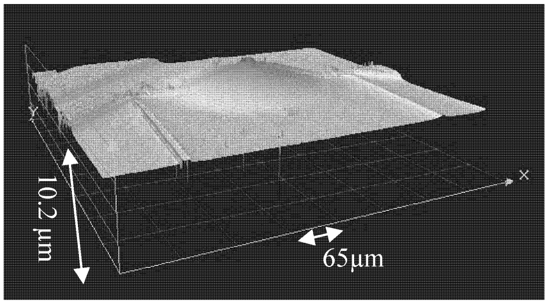

Fig 9. Mechanical Profile of small Heater (Max Deflection = + 2.5µm)

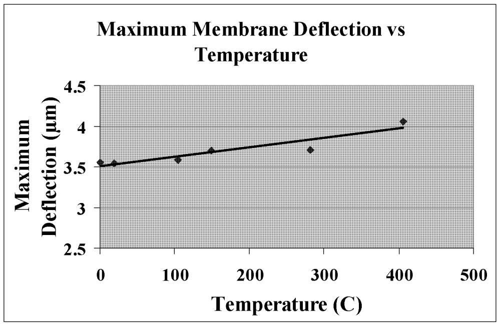

Fig 10. Effect of Heating on Membrane Deflection

Depending on the deposition conditions, the thermal conductivity of silicon nitride can vary considerably and values between 9W/mK and 30W/mK are used in sensor literature[1], so a value of 20W/mK was used in our simulations. However many commercial foundries, including XFAB deposit PECVD nitrides which can have a thermal conductivity of less than 3W/mK [7].

This was verified by etching away the silicon nitride from some of the micro-hotplates using RIE with SF_6 (about 10min with 40sccm of SF_6 at 100mT and RF power 100W). The difference in thermal characteristics was used to determine the thermal conductivity of nitride, which was found to be about 2.2 W/mK.

Simulations with this value gave a much better agreement with the experimental results (~10%). The comparison is shown in Fig 11. Transient simulations (Fig 12 & 13) also match very well with the measured values.

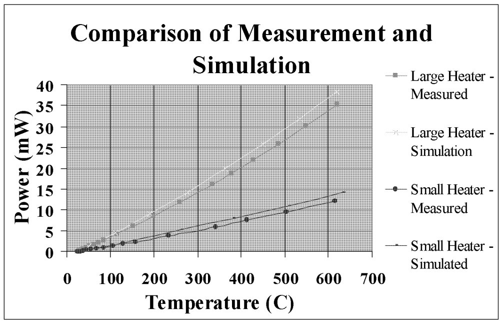

Fig 11. Comparison of Simulation and Measurement after adjusting the value of the thermal conductivity of Silicon Nitride

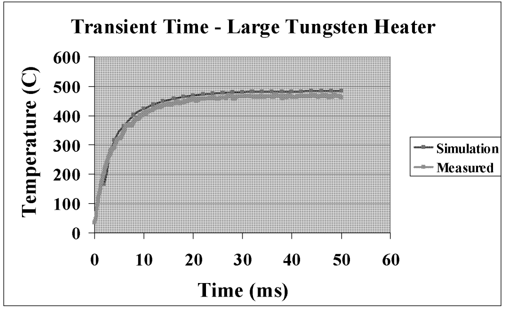

Fig 12. Transient Simulation and Measurements for Large Heater

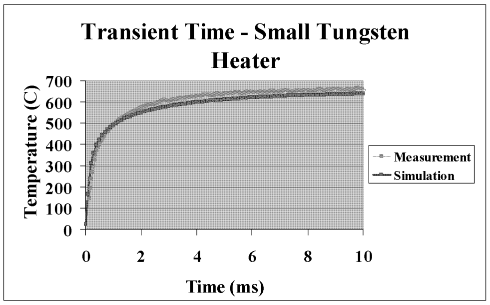

Fig 13. Transient Simulation and Measurements for small Heater

V. CONCLUSIONS

Novel tungsten based SOI-CMOS micro-hotplates have been presented. The devices have been fabricated using commercial batch processes, resulting in low cost and allowing monolithic circuit integration. The DC power consumption (12mW for a temperature of 600°C for the small heater,) to our knowledge, is the lowest for micro-hotplates reported. The fast transient time (2ms rise time to 600°C) allows operation in pulsed mode – this can further lower the average power consumption making them suitable for battery operated, handheld sensors. The heaters have very uniform characteristics, the power consumption curves being almost identical for devices on different parts of the wafer. Finally, the membranes are mechanically stable, with very low deflection even at high temperatures (up to 400°C). The micro-hotplates are therefore ideal to use as a platform for silicon based gas sensors.

ACKNOWLEDGMENT

Dr. Udrea acknowledges the award of the Philip Leverhulme Prize. S.Z. Ali would like to thank the Cambridge Commonwealth Trust for bursary awarded.

REFERENCES

[1] I. Simon, N. Barsan, M. Bauer, and U. Weimar, "Micromachined metal oxide gas sensors: opportunities to improve sensor performance," Sensors and Actuators B, vol. 73, pp. 1–26, 2001

[2] U. Dibbern, "A substrate for thin-film gas sensors in microelectronic technology," Sensors and Actuators B, vol 2, pp. 63-70, 1990

[3] J.W. Gardner, A. Pike, N.F. de Rooij, M. Koudelka-khep, P.A. Clerc, A. Hierlemann, W. Goepel, "Integrated array sensor for detecting organic solvents," Sens and Acts B, Vol 26/27, pp. 135-139, (1995)

[4] J. Suehle, R.Cavicchi, M.Gaitan, S. Semancik, "Tin oxide gas sensor fabricated using CMOS micro-hotplates and in situ processing," IEEE Electron Device Letters, Vol 14 (3), pp.118-120, (1995)

[5] F. Udrea, J.W. Gardner, D. Setiadi, J.A. Covingtom, T. Dogaru, C.C. Lu, W.I. Milne, "Design and simulations of SOI CMOS micro-hotplate gas sensors," Sens and Act B, Vol 78, pp. 180-190, (2001)

[6] M. Graf, D. Barrettino, K. Kirstein, and A. Hierlemann, "CMOS microhotplate sensor system for operating temperatures up to 500°C," Sensors and Actuators B, Vol 117, pp. 346-352, (2006)

[7] M. Arx, O. Paul, and H. Baltes, "Process-dependent thin-film thermal conductivities for thermal CMOS MEMS," Journal of micro-electro-mechanical systems, Vol 9 No 1, pp. 136-145, March 2000