NOVEL DESIGN AND CHARACTERISATION OF SOI CMOS MICRO-HOTPLATES FOR GAS SENSORS

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Abstract: This paper describes the design and characterisation of a new generation of fully CMOS compatible novel micro-hotplates for gas sensors. The micro-hotplates employ advanced MOSFET heaters embedded in an SOI membrane. The heaters can operate at a ground-breaking temperature of over 400°C with ultra low power consumption (under 15 mW in continuous operation). Electronic circuits for drive and readout have also been designed and integrated with gas sensors.

Keywords: SOI micro-hotplate, gas sensor, smart sensor

INTRODUCTION

Handheld, low cost and reliable gas monitors that are able to detect poisonous gases (such as CO and NO_x) are highly desirable. However, the relatively high power consumption and the high cost of commercial devices make them impractical for portable applications and automotive units. Presently, the most widely available resistive gas sensor (Taguchi type, sold by Figaro, Japan) has an operating temperature of typically 400°C and power consumption of between 500 to 800 mW [1]. Other sensing technologies exist, one such example is the catalytic pellistor. This device is used extensively for methane detection, but again is relatively expensive and has a high power consumption of 350 to 850 mW at 500°C [2]. For these reasons many researchers have investigated silicon-based micro-hot plate designs for low power gas sensors. Predominantly these have been based on the integration of a platinum micro-heater embedded into a low stress silicon nitride membrane. Though highly successful at reducing power consumption, platinum is not CMOS compatible hence cannot benefit from the low cost CMOS fabrication. The integration of micro-hot plates into a CMOS process could well achieve the target of low cost, high reliability and low power consumption.

In the development of CMOS micro-hot designs it is critical to reduce significantly the power consumption and ensure a uniform temperature distribution over the sensing area. Such goals can be considered highly challenging as traditional materials available in CMOS technology have limitations. For example, researchers have reported micro-heaters made from polysilicon or aluminum, but polysilicon has problems associated with poor long term stability due to their highly reactive grain boundary and aluminium shows electro migration at high temperatures [3,4]. An alternative SOI CMOS heater structure was proposed by Gardner and Udrea some 10 years ago. Here a MOSFET, fabricated using a standard CMOS process in the silicon layer of SOI wafer, was used as the heater with the handle silicon removed to for a thin membrane. Although successful in reaching an operating temperature of 350°C for a power consumption of less than 100 mW, several post-processing issues limited its initial application [8-10]. At the same time other research group's such as those of Baltes (ETH, Zurich) and de Roiij (IMT, Neuchatel) were exploring non-SOI micro-heaters fabricated inside silicon plugs.

Here we report on the design and experimental characterisation of new generation of novel SOI CMOS MOSFET micro-heaters, with simpler post-processing for increased operating temperature and reduced power consumption. Furthermore, temperature sensors in the form of on-chip diodes and silicon resistors have been designed, simulated with Cadence, fabricated and experimentally characterised. Electronic circuits have also been developed and integrated with the micro-hotplates. This circuitry benefits from the advantages of SOI technology, e.g. effective isolation, reduced leakage currents, reduced parasitic capacitance.

SOI MICRO-HOTPLATE DESIGN

In our work, micro-hotplates for use in microcalorimetric and microresistive gas sensors have been developed. The device contains novel shaped MOSFET micro-hotplates fabricated using a 1.0 µm SOI CMOS process at X-Fab (6 inch process, Germany). A schematic of an SOI resistive gas sensor employing a MOSFET micro-hotplate is shown in figure 1. This is a three metal layer process. Sensing materials are added as a post-processing step to form the gas sensors. The response of devices with sensing materials to different gases will be reported elsewhere.

The MOSFET micro-heater is embedded within the SOI membrane and therefore does not require any extra fabrication steps to the standard CMOS process beyond the membrane formation (back-etch). Besides the heater the other key elements are the sensing material, the temperature sensor, the supporting structure (e.g. metal beam) and the heat spreading plate for temperature uniformity. Some of the micro-hotplates contain interdigitated electrodes made of metal3 with pad openings (for measuring the change in the resistance of the sensing material in presence of gases). In some devices refresh electrodes were designed to 'clean' the sensing material under prolonged exposure to gases. Membranes of different sizes (radii 282 μm and 150 μm) were designed, corresponding to the heater radii of 75 μm and 12 μm, respectively. The membranes were formed by high precision deep reactive ion etching (DRIE) of the silicon substrate. The buried oxide layer acts as an etch stop and thermally isolates the sensing area, hence further reduces the power losses. This type of etching produces near vertical walls, compared to wet etching using KOH or TMAH and thus leads to a significant reduction in the chip area.

An optical image of a fabricated SOI micro-hotplate showing the main features is presented in figure 2 and figure 3 (top view). The main micro-heaters are using p-type or n-type ring MOSFETs (in case of large membrane) and plate MOSFETs (in case of small membrane). The MOSFETs have the body-source shorted and the number of shorts was increased above that of a standard library design, so that they can sustain high temperatures and stress, hence limiting the bipolar effects within these devices.

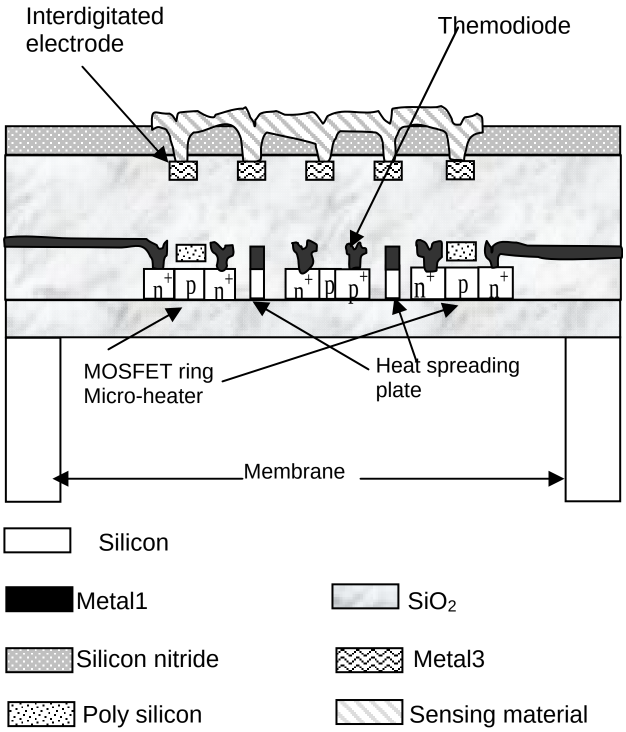

Figure 1. Cross sectional view of the designed gas sensor (drawing not to scale)

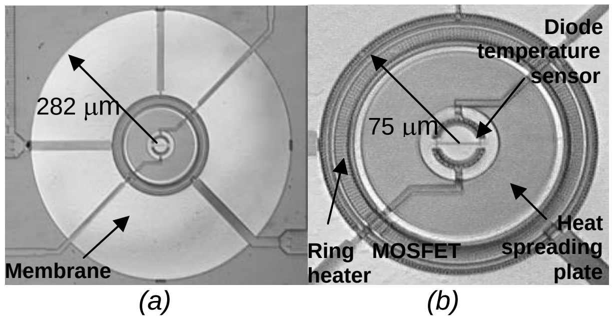

Figure 2. (a) Large MOSFET micro-hotplate (b) Enlarged view of heating element

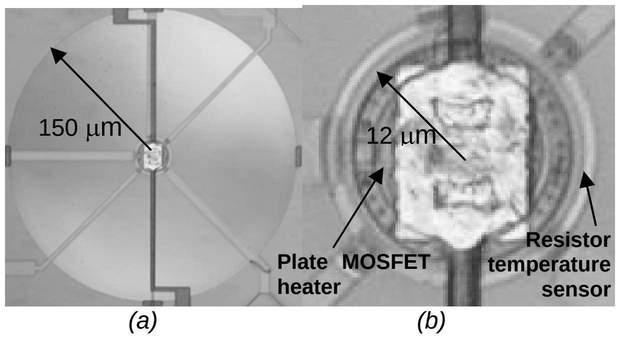

Figure 3. (a) Small MOSFET micro-hotplate (b) Enlarged view of heating element

As stated above, a further important part of the design is the integration of the temperature sensors. For the large membranes, a circular *p-i-n* diode was designed to match the shape of the ring MOSFET heater (as shown in figure 2). It was located at the centre of the membrane to enable accurate temperature sensing. For the small membranes, p^+ or n^+ silicon circular ring resistor temperature sensors were designed around the FET heater (as shown in figure 3).

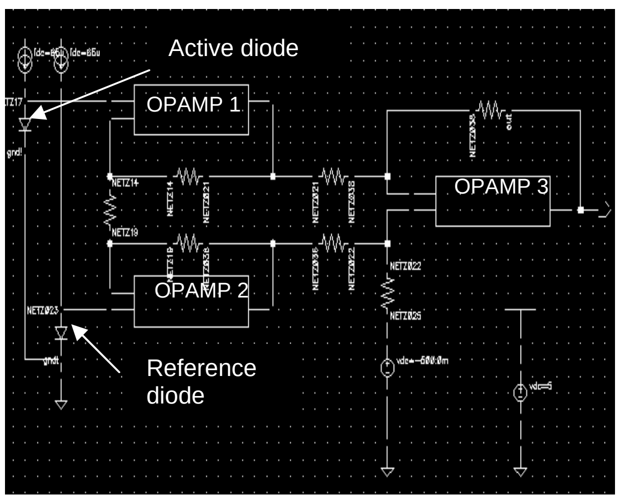

Figure 4. Instrumentation amplifier circuit for temperature measurement

Lastly, the designs also had integrated electronic circuits to condition signals form the integrated temperature sensors. A cascode current mirror circuit was designed to drive the temperature sensor. An instrumentation amplifier (IA) was designed to measure the peak temperature in the membrane. The concept here is to have one temperature sensor on the membrane and a reference sensor off the membrane; the instrumentation amplifier will therefore amplify the difference in the signals coming from the two temperature sensors (as shown in figure 4). The instrumentation amplifiers can be accessed from outside to control the voltage gain. The instrumentation amplifier was designed with three op-amps. The op-amps are of single supply two stage designs and have *p*-channel MOSFETs at the input. The gain of the amplifier was designed to be 60 dB with a phase margin of 60 degrees. An active second order low pass filter was also integrated for the microcalorimetric gas sensor to reduce the effect of noise.

MEASUREMENTS

Power measurements were carried out on the same device at different locations on the 6 inch wafer and it was found that the results were almost identical (figure 5). This shows the excellent reproducibility and reliability of our fabricated design. Results show that the large heaters can operate above 400°C with a power consumption of around 26 mW. For small heaters, a temperature rise of 400°C can be reached for a power consumption of below 15 mW. To our knowledge is the smallest DC power consumption reported in the literature.

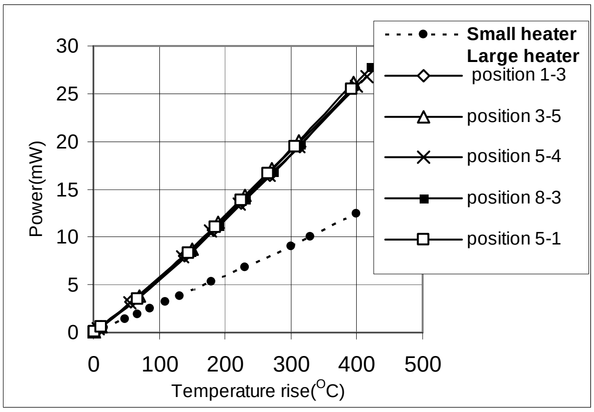

Figure 5. Power vs Temperature rise of large and small MOSFET heater

Theoretical calculations on different sized micro-heaters on the same membrane area suggest that the power consumption depends mainly on heater size (as shown in the figure 6). Thus, in order to minimize the power consumption, the heater area should be reduced to an absolute minimum. However this leads to a reduced sensing area and therefore could lower sensitivity.

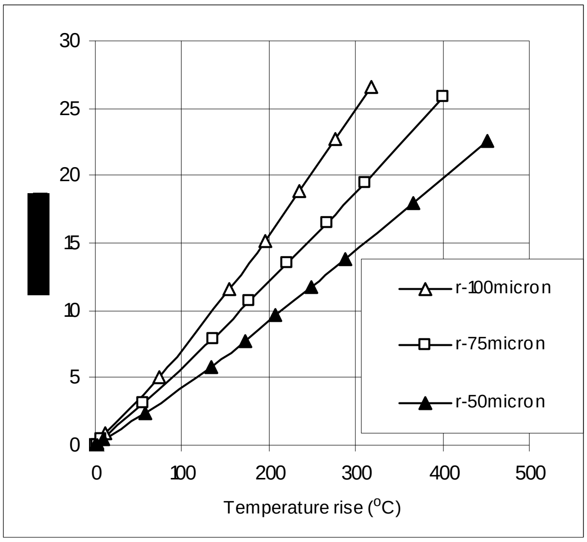

Figure 6. Estimated power vs. temperature rise of MOSFET heaters of different radii

Thermal calibration of temperature sensors was also carried out so that the membrane peak temperature could be measured accurately. A computer controlled hot chuck (Make, model?) with 1°C resolution was used for this purpose. The corresponding voltage drop was measured with a 20°C temperature interval up to 260°C (the upper limit of the hot chuck is 300°C). The voltage vs. temperature curve of the temperature sensor is shown in figure 7. These results was compared with the simulated ones obtained from Cadence SPECTRE, also shown in figure 7. The simulation has been carried out through direct extraction of the components (including parasitic elements) from the layout design and therefore they are quite close to what we have observed experimentally. The temperature co-efficient of diode was measured to be ~ –1.2mV/°C.

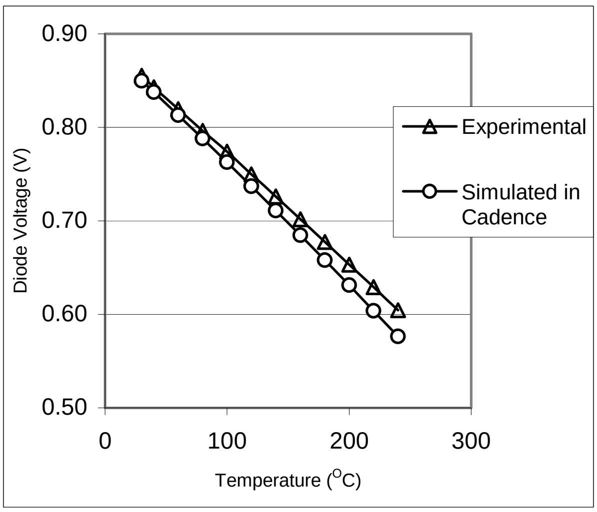

Figure 7: Calibration of diode temperature sensor

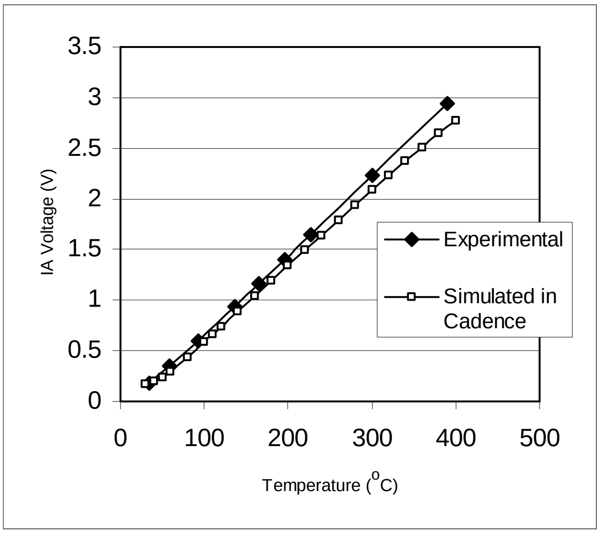

Figure 8. Instrumentation amplifier output voltage vs temperature

The peak temperature in the membrane was measured with the aid of the on-chip instrumentation amplifier. Figure 8 shows the variation of measured instrumentation amplifier voltage with temperature; the ramp is approximately 8 mV/ ºC. The simulated graph in Cadence SPECTRE is close to that of the experimental result obtained.

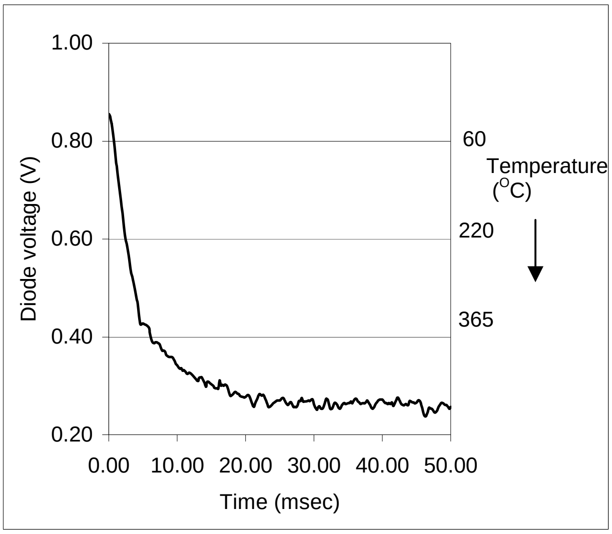

Figure 9. Transient temperature response of large micro-heater as indicated by diode temperature sensor

Dynamic electro-thermal measurements were carried out to estimate the thermal rise and fall times of the MOSFET micro-hotplates. This was determined by monitoring the voltage response of the thermodiode against time. Figure 9 shows the diode voltage vs. time characteristics of the heater. The transient rise time was calculated by considering the time needed for the temperature to rise from 10% to 90% of the final stabilized voltage (temperature). The transient thermal response is very fast – maximum rise time is ~10 ms.

CONCLUSIONS

Here a new class of novel MOSFET SOI micro-heaters is reported. The design is based on a SOI CMOS process with a deep RIE backetch, and hence permits the integration of control and signal conditioning circuits on the same chip. We have shown operation at a temperature in excess of 400°C with nominal power consumption of 26 mW for large heaters and 12.4 mW for small heaters, and thermal time constants of below 10 ms. To the best of our knowledge this is the first report in the literature where MOSFETs are working (in this case as a heater) beyond 400°C and with such lower power consumption. We believe that the development of such low power CMOS sensors will lead to the development of low cost, portable gas sensors.

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