CMOS technology platform for ubiquitous microsensors

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Abstract— In this paper we review a range of microsensors based on a common CMOS platform technology. The technology features a CMOS core which includes high temperature tungsten metallization and a post-CMOS deep reactive ion etching step of the substrate to release membranes, where the sensing elements are embedded. In one single process we were able to accommodate a variety of sensors such as gas, humidity, pressure, flow, temperature and infra-red detectors and emitters. The benefits of this platform are: (i) ultra-low power consumption, (ii) small form factor, (iii) high reliability and yield (iv) possibility of on-chip electronics and last but not least (v) low unit price.

Keywords— CMOS sensing platform; gas sensors, Infra-Red devices, humidity sensors, pressure sensors, flow sensors, temperature sensors.

1. Introduction - CMOS technology platform

Our research group in Cambridge University in collaboration with Warwick University has worked for over 20 years in the development of a CMOS MEMS platform technology [1-4]. The platform incorporates temperature, gas, humidity, pressure and flow sensors and comprises two major steps: the first (i) being based on standard bulk CMOS or SOI CMOS process, which ensures compatibility with IC processing and on-chip drive and read-out circuits, followed by the second (ii) the membrane formation using DRIE etching. Both steps have been integrated in a single commercial foundry. Additional intellectual property and know how have been built around this platform, which led to two Cambridge Spin-offs, Cambridge CMOS Sensors and Flusso. The platform includes now materials and proprietary designs such as Tungsten for the microheater or the thermal wire, Gold for the top interdigitated electrodes, plasmonic structures for IR emission/absorption enhancement and filtering, ultra-high temperature SOI (Silicon On Insulator) diodes for temperature sensing. The processing is done on 6” wafers with 0.6 to 1 micron linewidth. A three-metal process is used with the option of using Al or W (tungsten) metallization for high temperature applications. The employment of tungsten as metal layer is favorable in terms of its physical properties such as, high melting point and resistance against electromigration and high and reproducible TCR (temperature coefficient of resistance). However its most important asset is its CMOS compatibility, which sets it apart against other contenders such as Platinum.

The CMOS process is followed by Deep Reactive Ion Etching (DRIE). When used in large quantities, DRIE is cheaper than anisotropic etching. The result is vertical sidewalls (instead of the slanting ones obtained by anisotropic etching), meaning that less chip area is required. Furthermore, DRIE allows complete freedom in the choice of the membrane shape, since, in contrast to wet etching techniques, it is not constrained by the silicon lattice orientation. It is thus possible to design circular membranes, which have a more uniform stress distribution at the membrane/substrate edge in comparison to square membranes. This ultimately results in higher thermo-mechanical robustness. Finally, DRIE allows multi-cells or array of sensors to be placed together on the same chip without a penalty in the dead area between the membranes. A schematic cross-section of the CMOS sensing technology developed at Cambridge platform is depicted in Fig. 1, where the example of gas-sensor is shown.

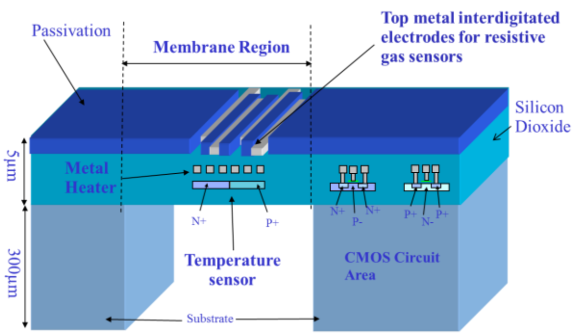

Fig. 1. Schematic drawing of an SOI CMOS microhotplate with an integrated thermodiode and CMOS cells outside the membrane. In this schematic drawing the micro-hotplate features top electrodes and a sensitive layer for gas-sensing or humidity detection.

The CMOS sensing platform technology developed at Cambridge University resulted in two University spin-offs: Cambridge CMOS Sensors (2008) and Flusso (2016)[1].

2. Micro-hotplate based gas sensors

Gas sensors are widely used for a variety of applications which include air quality monitoring, flammable/toxic gas detection, food processing, medical diagnostics and security. Traditionally, electrochemical sensors have dominated the market in spite of their relatively high unit cost (~$10-15), their reduce lifetime and their large form factor. In the last few years there has been an increased demand for miniaturised gas sensors for devices in 'smart homes', wearables and mobile accessories. There is also an emerging market in smart phones, tables and smart watches which in the next five years could see an exponential increase in the volume of gas sensors needed. The solution to all these demands cannot be met by electrochemical solutions or anything that is bulky and has reduced lifetime. Instead, gas sensors based on a CMOS platform would be ideal because of their reduced cost ~$1, high reproducibility, and the possibility of on-chip read out and drive electronics. Recent market analysis estimate that the gas sensors market, driven by Heating, Ventilation Air Conditioning (HVAC) and future consumer applications, will reach almost $920M in 2021, at a 7.3% CAGR. This is however a very conservative estimate as it does not take into account volume applications in smart phones and tablets. This is still an emerging market and to some extent difficult to predict when it would take off.

The past and current R&D activities within our group at Cambridge and within the spin-off company from our group, Cambridge CMOS Sensors, now acquired by ams (see footnote 1), thus aimed and aim to satisfy this commercial demand by investigating novel approaches based on the described CMOS micro-hotplate technology platform. The sensing layer could be a metal oxide such as tin oxide, tungsten oxide or zinc oxide or a nano based material such as Carbon Nanotubes (CNTs), graphene, nanowires, nanorods, *etc.*) or indeed a combination of those. In [5] we demonstrated a CNT based smart micro-hotplate. Good sensitivity to NO_2 was observed at room temperature and the embedded micro-heater was used to greatly improve the sensor recovery time. In [6] we have used simple ink-jet printed graphene as a gas sensitive layer. The graphene was functionalized with metallic nanoparticles, however this did not yield higher gas sensitivity. The graphene sensors show high sensitivity of approximately 0.1% per ppb to NO_2. In [7] zinc oxide nanorods were integrated with the SOI CMOS MEMS platform using dip pen nanolithography. The ethanol sensing performance was investigated in the temperature range 250–450 °C and the optimum operating temperature was found to be at 350 °C. Ethanol sensitivity was found to be 5.8–0.39% ppm for the concentration range 25–1000 ppm. The response and recovery times were found to be 9 s and 480 s at 750 ppm of ethanol, respectively. The CMOS sensors were tested in presence of ethanol, toluene and acetone in humid air. The sensor showed good selectivity to ethanol. The response was however found to decrease in humid air as compared to dry air environment, and this could be compensated for by employing alongside a humidity sensor. Similarly, in [8] Gold tin oxide nanocomposites were investigated and the response to ethanol is shown in Fig. 2.

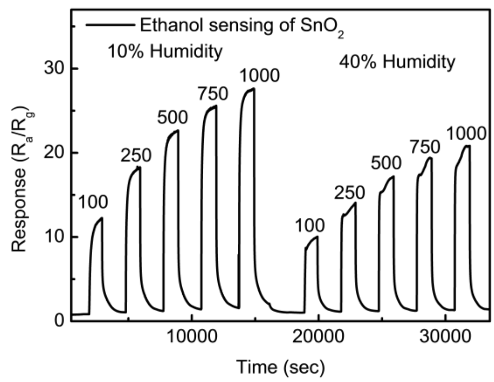

Fig. 2. Ethanol sensing at 400 °C of Au–SnO_2 nanocomposites at two different humidity levels. Taken from [8].

Our micro-hotplates are characterized by very fast thermal transient times (< 20 ms); this opens

[1] Cambridge CMOS Sensors was founded by Prof. Florin Udrea, Prof. Julian Gardner and Prof. Bill Milne. Its aim was to develop ultra-low power consumption metal oxide gas-Sensors and IR devices (emitters and thermopiles). Cambridge CMOS Sesnors was acquired by ams in 2016 and it is considered one of the most successful trade exits in physical sciences from Cambridge University. Flusso was founded by Prof. Florin Udrea and Dr. Andrea De Luca to commercialise work on flow and pressure sensors. The company had the first investment from Cambridge Enterprise, the venture arm of Cambridge University.

up opportunities for pulsed mode sensing operation, where the sensing layer is not kept at a constant temperature but pulsed between at least two different temperature levels. Such temperature modulation techniques are extremely beneficial in terms of selectivity, sensitivity, drift, response time, and very importantly, power consumption. For instance, in [9] we proved that ZnO-based chemoresistors working in pulsed mode, can achieve a significant enhancement in the NH_3 sensing performance, while having reduced power consumption. It was proposed that this phenomenon is not only related to the presence of high temperature surface oxygen species but also to the modulation of H_2O (-OH) and N_2O on the surface.

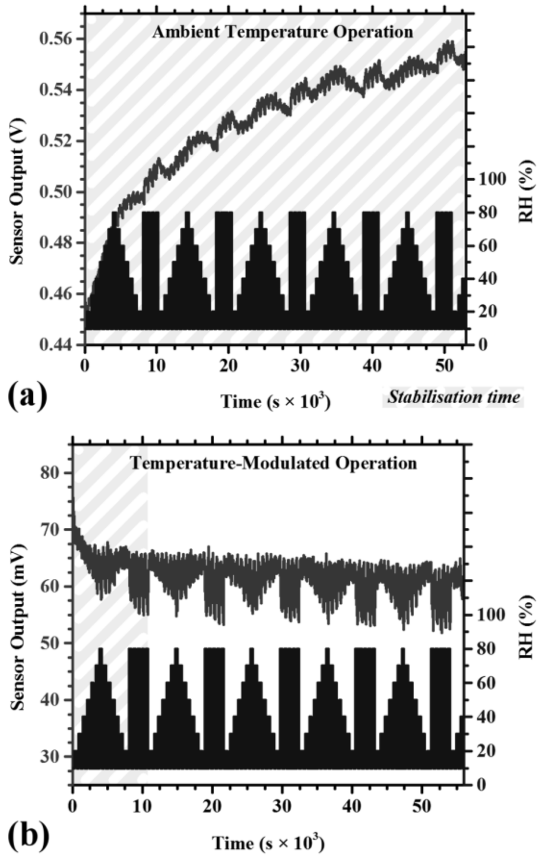

Fig. 3. (a) Ambient temperature operation: humidity sensor output as a function of time for different RH levels. (b) Temperature-modulated operation: humidity sensor output as a function of time for different RH levels. Taken from [10].

In [10], a temperature modulation technique, applied to a graphene oxide resistive humidity sensor, coupled with a differential readout methodology resulted in a significant reduction in the sensor drift (Fig. 3), improved linear response with a sensitivity of 0.14 mV per %, resolution below 5%, and a maximum hysteresis of ±5%; response and recovery times equal to 189 ± 49 s and 89 ± 5 s, respectively. These performance parameters satisfy current humidity indoor air quality (IAQ) monitoring requirements.

3. IR emitters and detectors

There is a growing need for miniature Infra Red (IR) emitters for Non-Dispersive Infra-Red (NDIR) sensing and spectroscopy applications [11]. A micro-bulb is typically used as the IR source in such applications. Micro-bulbs have the advantage of being extremely cheap, but they suffer from several significant disadvantages. Firstly, they have high power consumption (typically hundreds of mW), secondly they are bulky compared to a silicon die and thirdly, most importantly their emission is completely cut at mid to high IR wavelengths above 5 – 6 µm due to optical absorption by the outer glass. Mid- and Long-IR wavelengths are needed for certain gases (*e.g.* ethanol). Finally, micro-bulbs have typically large tolerances on the exact heater position, and the heating element can vibrate during operation, further enhancing the noise.

Our group has put a lot of effort in the development of CMOS IR emitters based on tungsten metallization [12]. Tungsten is an interconnect metal found in high temperature CMOS processes, and/or used as vias in CMOS processes. By employing a tungsten heater, a stable IR emitter can made while having all the advantages of CMOS – very low cost in high volume, excellent device reproducibility and the possibility of a wide range of on-chip circuitry.

IR emitters can be as small as 1 mm × 1 mm. with a heater diameter of 250 µm and a membrane diameter of 600 µm. The device has a DC power consumption of only 70 mW, 50% frequency modulation depth of 70 Hz, and optical output power of 0.8 mW, when operated at 550 °C. We have also shown the stability of the device over 5000 hours, and a basic setup has been used to demonstrate the use of the device for a carbon dioxide NDIR sensor, which shows a resolution of 0.5% in 6-14% CO2 concentration range (suitable for boiler applications). Furthermore, the emitter shows very good emission at wavelengths above 8 µm, and makes it ideal for applications requiring mid- to long-IR wavelengths. Larger devices (*e.g.* the one in Fig. 4) can also be fabricated. They offer higher emissions for applications requiring improved gas sensitivity at the expenses of slower frequency modulation, higher power consumption and larger chip area.

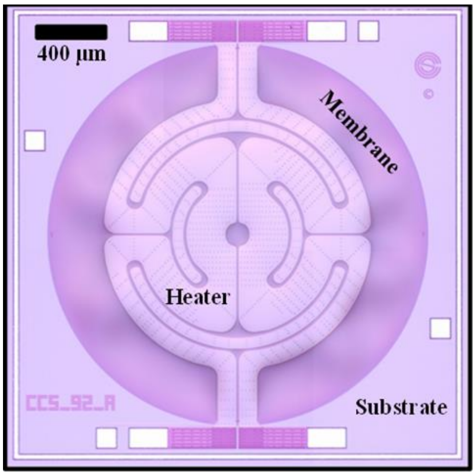

Fig. 4. IR emitter developed by the spin-off company Cambridge CMOS Sensors (CCS) with a 1800 μm heater on a 2000 μm membrane. The chip size is 24 mm × 2.4 mm.

In the past two decades, the development of increasingly miniaturized infrared (IR) detectors has been predominately driven by the steady growth within the IR sensing market, which is expected to be worth $500M by 2020. Applications ranging from automotive, medical, and industrial to navigation, security, and imaging all require IR radiation sensors for two main purposes: non-contact temperature measurement and gas concentration detection via NDIR spectroscopy. Materials commonly used in CMOS foundries often have poor IR absorption properties especially for wavelengths < 8 μm, a spectral window of importance for NDIR gas sensing (*e.g.* methane and CO_2). As a consequence, bolometers and thermopiles often require at least one additional post-CMOS/MEMS processing step for the deposition of a radiation absorbing layer. Such absorption layers are often based on carbon materials. In [13] we showed that the radiation properties of the CNT adlayer significantly enhanced the absorptivity due to its blackbody-like behaviour (nearly unitary absorptivity), compared with an uncoated thermopile, across the entire IR spectrum of interest (3 μm–15.5 μm).

This led to a four-fold amplification of the detected infrared signal (4.26 μm) in a CO_2 NDIR gas sensor system. The presence of the CNT layer was shown not to degrade the mechanical robustness of the devices, whilst the 50% modulation depth of the detector was only marginally reduced by 1.5 Hz. Optical micrographs of a typical bare and CNT coated devices, along with a schematic cross-section are presented in Fig. 5. More information regarding our CMOS MEMS IR detector thermopile technology can also be found in [14].

Very interesting is also our research related to fully CMOS techniques to enhance optical properties of IR devices. In [15] we have engineered a highly efficient nanostructured plasmonic crystal thermal emitter, based on controlled spontaneous thermal generation of surface plasmons and elevated plasmon-to-light coupling as well as exploiting a slow-wave mode allowing, their efficient emission into free space. The plasmonic crystal thermal emitter was designed for wavelengths preferred in NDIR gas sensing of CO_2 and fabricated in a standard and reproducible industrial-standard CMOS process. Application in a commercial NDIR sensing system was demonstrated and an improvement in sensitivity and signal-to-noise ratio of almost 400% achieved (Fig. 6).

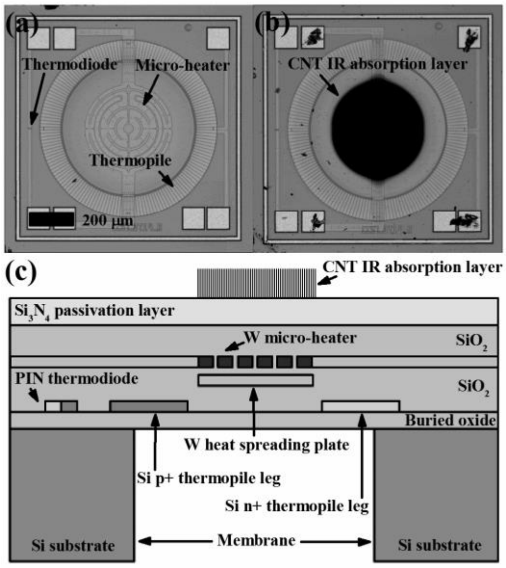

Fig. 5. (a) Optical micrograph of the IR detector chip (1.6 mm × 1.6 mm), (b) optical micrograph of the IR detector chip after CNT radiation absorbing layer in-situ T-CVD growth, (c) schematic cross-sectional depiction of the IR detector. Taken from [13].

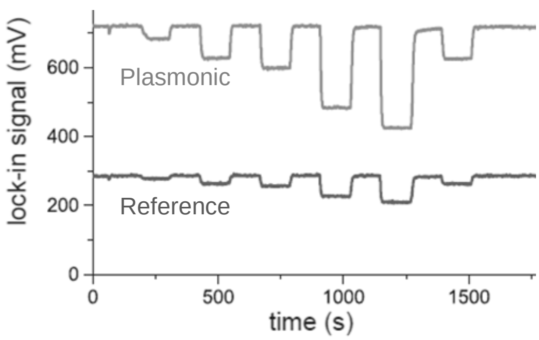

Fig. 6. Time-dependent signal obtained from NDIR measurements in a commercial gas sensing setup for the best plasmonic structure (2.6 μm pitch, 800 nm radius) and the thermal emitter without plasmonic crystal structure. Taken from [15].

4. Flow sensors

Most of the flow sensors developed by our group, and our spin-off company Flusso (see footnote 1) are calibrated for wall shear stress measurements, and to this category we will refer in this paragraph. Newtonian fluids flowing around a solid object exert a shear stress on this objects boundaries due to the viscosity of the fluid itself. The wall shear stress, t, is of prime importance for practical flow fields analysis. It is known that a large part of the drag force experienced by moving vehicles (aerial, terrestrial, and marine) is directly caused by the wall shear stress [16]. Measurements of the sheer stress may also be used to study the complex physics of the near-wall boundary layers [17], which may exhibit laminar, turbulent, separated or transitional flow. Wall shear stress sensors are found in different market sectors, and besides airspace and automotive, they are also used in industrial applications (*e.g.* wind turbine active control, pipe flow), or biomedical applications [18] (*e.g.* to study intravascular and arterial diseases).

Thermal flow sensors are traditionally based on anemometric transduction principle. Due to the incoming flow, the heating element temperature changes and this temperature change, detected by measuring the heating element resistance change is correlated to the flow rate (or wall shear stress). In [19], a SOI CMOS MEMS thermal wall shear stress sensor that uses CMOS tungsten metallization as heating and sensing element, supported by a composite membrane comprising of silicon oxide and silicon nitride, is presented. The metallization was used to create a hot film element with size 200 μm × 2 μm × 0.3 μm. Post-CMOS, the wafers were back-etched in a single DRIE step to create a 250 μm diameter circular membrane. The sensor exhibits a high Temperature Coefficient of Resistance (TCR) (0.21 %/°C), and very effective thermal isolation from substrate evident from its thermal resistance (20,435 °C/W, or equivalently ~ 6 mW for temperature rise of 100 °C). The sensor, calibrated in constant temperature (CT) mode in a 2-D laminar flow wind tunnel for a wall shear stress range of 0-1.6 Pa shows an average sensitivity of 35 mV/Pa at an Over Heat Ratio (OHR) of 1.0, and a cut-off frequency in the range of few kHz.

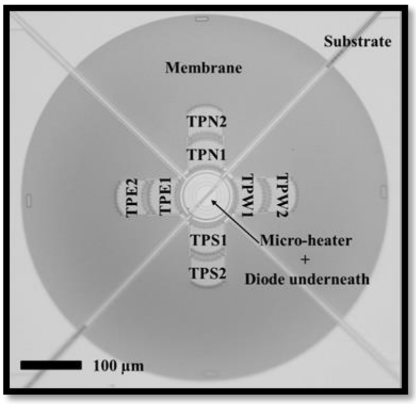

Fig. 7. Optical micrograph of the fabricated multidirectional thermoelectric flow sensor (membrane area close-up). Taken from [21].

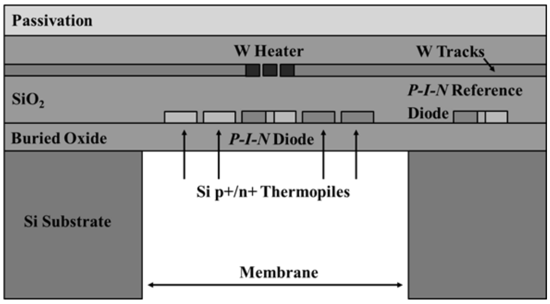

Fig. 8. Multidirectional thermoelectric flow sensor schematic cross-section (not to scale) fabricated in SOI CMOS MEMS technology. Taken from [21].

The CMOS technology also allows for the use of active elements within the thin silicon layer. In [20] a novel high sensitivity, low noise single thermopile readout configuration was proposed. The thermoelectric flow sensors show an electro-thermal transduction efficiency of 50 μW/°C, and a very small zero flow offset. Calibration for wall shear stress measurement in air in the range of 0-0.48 Pa was performed using a suction type, 2-D flow wind tunnel. The sensors were found to be extremely sensitive, up to 4 V/Pa for low wall shear stress values. Furthermore, we demonstrated the superior signal-to-noise ratio (up to five times higher) of a single thermopile readout configuration compared with a double thermopile readout configuration (embedded for comparison purposes within the same device). We have also proposed a multidirectional flow sensor and reported it for the first time in [21]. The thermoelectric flow sensor chip (Fig. 7) comprises a 60 μm diameter tungsten micro-heater, connected to the pads via tungsten tracks. Underneath the microheater a diode temperature sensor is integrated as well. Eight thermopiles are symmetrically arranged in pairs around the micro-heater. All thermopiles have both junctions embedded within the membrane. The chip (cross sectional view presented in Fig. 8) also features a diode temperature sensor placed on the substrate, outside the membrane for ambient temperature referencing.

5. Pressure sensors

The most common type of MEMS pressure sensors are deflectable diaphragm pressure sensors. The two most common sensing mechanisms used in diaphragm pressure sensors are capacitive and piezoresistive. Capacitive pressure sensors work on the principle of parallel plate capacitor, where the capacitance changes due to deflection of diaphragm. Piezoresistive pressure sensors, on the other hand, employ piezoresistors at the edges of the diaphragm, which detect the deflection due to applied pressure and hence relate the deflections to the pressure. Alternatively, active elements, such as diodes and transistors can be used. In [22] a pressure sensing structure based on the piezoresistive effect occurring in four Metal Oxide Semiconductor Field Effect Transistors (MOSFETs) placed in stress sensitive differential amplifier (SSDA) configuration on a Silicon-on-Insulator (SOI) membrane is reported. An excellent review of MEMS pressure sensors is given by Eaton *et al.* [23].

One of the advantages of the sensing technology platform described in this work is the possibility of integrating more sensors on a single die. [24]. For example flow, pressure and temperature sensors could be provided in a single chip. For a pressure sensor a square diaphragm piezoresistive pressure sensor is preferred to a circular membrane one, because the stress distribution along the sides of the diaphragm is in this way enhanced. Four piezoresistors are embedded at the middle points of four sides in a Wheatstone bridge configuration. To allow for absolute pressure measurements, the sensor is sealed on its lower side with the help of an adhesive at atmospheric pressure. The sensor sensitivity curve is shown in Fig. 9. Linear sensor response is always desirable to reduce complexity of sensing circuitry. And this is the advantage offered by piezoresistive pressure sensors over their capacitive counterparts, where compensatory circuits are required to reduce non-linearity.

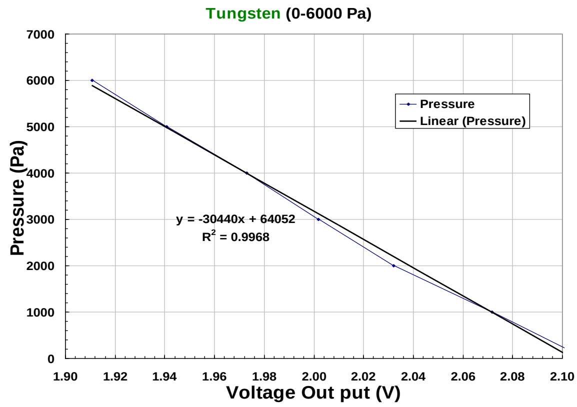

Fig. 9. Sensitivity results for a tungsten based piezoresistive pressure sensor fabricated using SOI CMOS technology.

6. Temperature sensors

Temperature is undoubtedly one of the most measured physical parameters, not only in science and technology but also in the everyday life. Some applications [25] where the temperature needs to be measured accurately are as follows: meteorology, agriculture, automotive, medical, process industries, cryogenics, and consumer electronics. Temperature sensors are also required in other sensors (such as Chemoresistive gas sensors, Thermal conductivity gas sensors, Humidity sensors, Pellistors, Thermal flow sensors, Infrared emitters, and Infrared detectors, *etc.*). Such sensors often require their hot element temperature to be monitored and controlled in order to improve their accuracy (and possibly avoid reliability problems). It is also important to monitor the ambient temperature for compensation purposes. Moreover, chip temperature monitoring and over-temperature protection circuits are embedded in complex ICs in order to prevent thermal failures or reliability problems. In harsh environments temperatures in excess of the CMOS maximum junction temperature (150 °C for standard CMOS and 225 °C for SOI) need to be monitored. Diodes are the perfect candidates for temperature measurements in such applications: (i) they can be extremely small, (ii) they do not offer a thermal bridge between hot and cold zones, (iii) they are ‘quite’ linear, (iv) they have a wide range and (v) their sensitivity can be significantly enhanced by putting them in an array form.

Few studies outside our group focus on diodes performance at high temperature [26-28]. Throughout the years we have shown that is possible to fabricate a thermodiode that can operate at record temperatures for silicon (from -

200 °C to over 700 °C) [29, 30]. The diode performance was theoretically and experimentally investigated with good agreement between experiments, simulations and analytical results [29, 30]. The piezo-junction effect was shown to be negligible (up to 300 °C) by comparing a diode embedded in the membrane with a reference diode placed on the substrate [29]. The thermodiodes have also shown to be fairly reliable after 100 hours DC continuous operation at 500 °C and highly reproducible within the same wafer, wafer to wafer and lot to lot [30, 31]. More recently [32], we also show via TCAD simulations that by employing a double diode readout scheme it is possible to reduce the non-linearity down to ±0.1 K, in the calibration range 300–600 K.

It is well known that, given a fixed driving current, the diode forward voltage linearly decreases with the temperature. The voltage drop across an ideal p-n junction is given by:

$$V = \frac{kT}{q} ln\left(\frac{I_d}{I_S(T)} + 1\right) \qquad (1)$$

where Is is the saturation current, k is the Boltzmann's constant, T is the temperature, q is the electron charge, and Id is the driving current. The saturation current can be expressed as:

$$I_s(T) = CA_jT^{\eta}e^{-\frac{qV_g}{KT}} \qquad (2)$$

here, C is a constant (dependent on the density of states, effective mass and mobility of carriers, doping density, lifetime etc.), Aj is the junction area, η is a process dependent parameter, and Vg is the extrapolated bandgap voltage at 0 K. C is inversely proportional with the carrier lifetime. Given the high quality of the employed SOI wafers (no epi layers are involved) and the small thickness of the silicon layer (~ 250 nm), the lifetime is very high and the volume of the depletion region is very small. This results in a very wide linear range. Significant deviations from this linear behaviour can be observed at very low temperatures, where the voltage abruptly increases, and at very high temperatures, where the voltage saturates. Fig. 10 depicts the measured diode forward voltage drop as a function of the temperature for different driving currents (1 µA, 10 µA and 100 µA). Low values of driving current were chosen in order to avoid self-heating. A decrease in the driving current results in an improvement in the sensitivity (dV/dT increases), but also in narrowing of the linear range (*i.e.* the voltage saturates at a lower temperature).

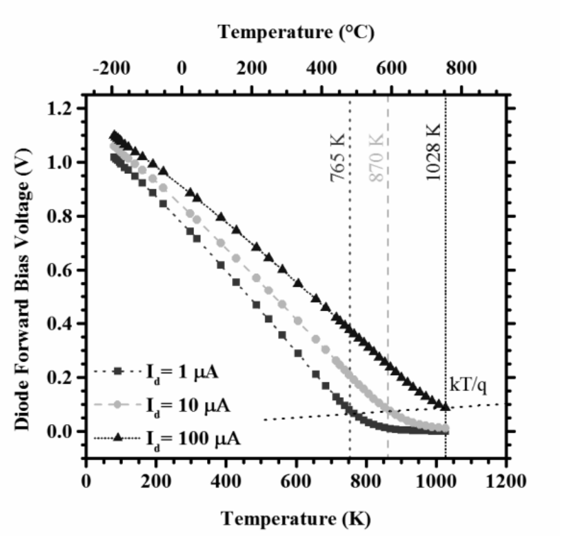

Fig. 10. Measured diode forward bias voltage *vs.* heater temperature of a thermodiode with 5 µm² junction area for different driving currents (1 µA, 10 µA and 100 µA). Maximum operating temperatures, obtained equating thermal voltage and diode voltage, are also shown. Taken from [32].

7. Other aspects

A. Harsh environment suitability

The prime motivation behind research and development of sensors able to operate in harsh environments is one and very simple: market need. There is an abundance of applications (*e.g.* combustion optimization and emissions control in moving vehicle and boilers, gas capture and sequestration, oil and gas exploration, smart infrastructure, space exploration and so forth) which would benefit from the employment of sensors able to cope with harsh environment conditions, and many more might flourish if such sensors became available with an attractive price/performance ratio. The real issue is understanding which technologies are capable of satisfying this market demand [33]. Bulk silicon micro-sensors are a reality. A number of products, price wise and performance wise very attractive, is available off the shelf. However, they are usually not suitable for harsh environment applications, since they struggle if operated at temperature above 125 °C and can incur in serious reliability problems if exposed to corrosive atmospheres, radiations, and mechanical stresses. Silicon on insulator (SOI) devices, on the other hand, are provided with an extended working temperature range (up to 300 °C) and are radiation resistant, but still chemically and mechanically not too different from bulk-silicon-based sensors. In the last decade, much effort has been put from both industry and academia in the development of new materials able to overcome these issues. Silicon carbide (SiC), Gallium Nitride (GaN) and diamond have certainly very attractive intrinsic properties [34, 35]. They can operate at temperature in excess of 300 °C and are chemically and mechanically more robust than silicon. However, their availability, processing cost and yield severely limit their mass market use, relegating them to niche and high-end applications, which bulk Si or SOI absolutely cannot access (for instance T > 300 °C). Additionally, circuitry integration is possible and easily achievable if silicon technologies are employed; much more challenging this would be for SiC, GaN and diamond. In this scenario, SOI is surely an excellent compromise.

An example showing the potential of our SOI CMOS MEMS technology platform for harsh environment sensing application is reported in [21], where, surprisingly for the first time, a thermal flow sensor was shown to operate at 150 °C.

B. Sensing and nano materials integration

As we have seen in the previous paragraphs, integration of non-CMOS materials onto our CMOS platform is mandatory in case of gas sensors (deposition of the gas sensing layer on top of the electrodes) or, even if optional, can provide the devices with enhanced properties (like in the case of improved IR detection).

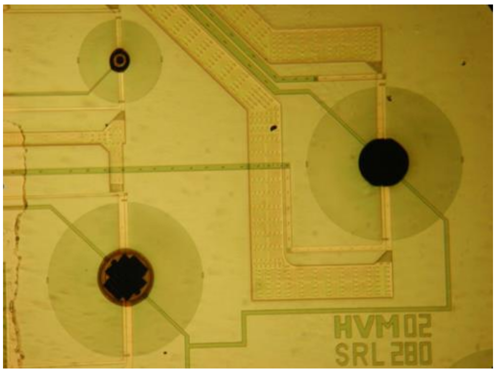

Fig. 11. Photograph of CNTs grown on different size micro-hotplates using the local heater.

This integration step is not trivial. There are a number of constrains posed by the CMOS membrane based technology, such as (i) aluminium PADs degrade above 350 °C, (ii) on-chip circuitry can be damaged at even lower temperature (< 300 °C), (iii) any additional layer has to be deposited after CMOS and MEMS process steps (foundries would not allow otherwise for contamination issues), (iv) photolithography is extremely challenging after CMOS and MEMS steps, thus mask-less or other innovative approaches have to be considered, (v) low pressures have to be avoided, because might result in membrane breakage, (vi) deposition areas are small (< 300 µm diameter), and (vii) wafer level processes for low cost high volume production must be considered.

Our group has considered different approaches [36-39], and as a result of our investigations we found that ink-jet printing, drop coating and sputtering are the main techniques which satisfy the previously described constrains and are amenable to high volume production at relatively low cost.

Local growth of nano-materials such as CNTs has also shown to be successful in the lab. The micro-hotplate could be used to facilitate the growth of the nano-materials (an example shown in Fig 11) and this can be done on multiple chips in parallel [38]. Yet, this is unlikely to be of use in commercial foundries because of the low throughput and the high cost associated with this method.

C. Monolithic electronics integration

The integration of sensors and electronics on the same silicon substrate could be beneficial if this provides additional functionalities and results in superior performance. In addition, multiple and complex analysis can be performed very precisely with on-chip analogue/digital circuits and processors. Noise and parasitic components , such as stray inductors and capacitors could also be cut. This is commercially supported by the value of the European smart sensor market, which was valued at $336M in 2013, and is expected to reach $2.4B by 2018, at a CAGR of 48.3%.

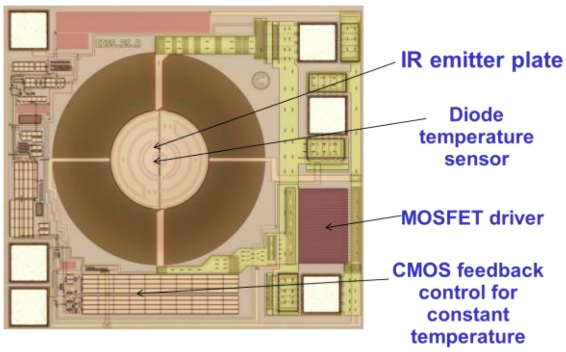

Fig. 12. Photograph of a smart SOI micro-hotplate with integrated electronics, MOSFET drive and temperature sensor. Adapted from [42].

In our group we follow this trend of "sensors smartening" too [40, 41]. In Fig. 12 a smart SOI micro-hotplate, featuring some monolithically integrated electronics for micro-heater driving and ambient temperature compensation, is presented. However it is essential to say that while integration could be in many cases desirable, a hybrid solution could still have the advantages of flexibility, lower cost and offer the possibility of using separate, optimised CMOS processes, one for sensors and one for the electronics.

D. Reliability

An important aspect is the stability of the micro-hotplate or, more in general, of the heating/sensing elements operated at high temperature. In [42] the stability of the micro-heater in pulse conditions at 10 Hz with 50% duty cycle is shown. The Mean Time To Failure (MTTF) function of temperature is extracted using an Arrhenius relationship. In order to obtain a very high MTTF the design of the heater has been carefully optimized to minimize mechanical stress and concomitantly reduce electro-migration. The composition of the passivation layer and the residual stress in the ILDs and the buried oxide play an important role in balancing the overall stress in the membrane.

8. Conclusions

This paper reviewed a range of microsensors incorporated in a commercial CMOS process based on tungsten metallization. The research was the results of the work done at Cambridge University for over two decades which resulted in commercial exploitation, through two spin-offs. Different aspects of the technology have been discussed, from concept to development, integration and suitability of such sensors in harsh environments. Our strong belief is that CMOS is the way forward in sensors as this provides a path to low cost, high reproducibility with tight tolerances, small form factor, low power consumption and high performance.

Acknowledgments.

We would like to thank many people who participated in this body of research and development. We particularly like to thank current and ex students and postdocs at Cambridge University. We also thank the staff at Warwick University led by Julian Gardner. We also would like to acknowledge the contribution of researchers at ams and in particular that of Zeeshan Ali. We would also like to thank other partners from Microsemi (Tracy Wotherspoon) and Honeywell (Mihai Brezeanu and Octavian Buiu) for collaborating with us.

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