SOI SENSING TECHNOLOGIES FOR HARSH ENVIRONMENT

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Abstract–*This paper reviews and addresses certain aspects of Silicon-On-Insulator (SOI) technologies for a harsh environment. The paper first describes the need for specialized sensors in applications such as (i) domestic and other small-scale boilers, (ii) CO_2 Capture and Sequestration, (iii) oil & gas storage and transportation, and (iv) automotive. We describe in brief the advantages and special features of SOI technology for sensing applications requiring temperatures in excess of the typical bulk silicon junction temperatures of 150°C. Finally we present the concepts, structures and prototypes of simple and smart micro-hotplate and Infra Red (IR) based emitters for NDIR (Non Dispersive IR) gas sensors in harsh environments.*

Keywords: *Silicon on Insulator (SOI), CMOS technology for sensing applications, System in Package (SiP).*

1. INTRODUCTION-HARSH ENVIRONMENT APPLICATIONS

Sensors operating in a harsh environment need to cope with one or more of the following extreme conditions: high operating temperature (>150°C), high pressure (>10 bar), significant vibration, high humidity, high radiation levels, aggressive media (corrosive, toxic, explosive), electromagnetic spikes.

Research in harsh environment sensors is driven both by both the current market needs and by the strong legislation requirements regarding the quality of the environmental ambient air. The upper safety limits for emission gases have gradually decreased in the last decade. For this reason, industrial process, automotive, aerospace and marine combustion control for efficient energy generation are performed based on monitoring the input and output concentration of the gases participating (and resulting from) the combustion reaction. Thus, measuring gases such as O_2, CO_2, CO, C_XH_Y, NO_X, together with humidity (i.e. water vapour) are essential. At the same time, measuring toxic gases such as H_2S has become an important issue for avoiding pollution and poisoning and in general for environment safety.

Combustion optimization in domestic and other small-scale boilers, CO_2 Capture and Sequestration (CCS) and deep-well oil and gas exploration, oil and gas storage and transportation, combustion optimization and emission control in automotive, aerospace, and marine are examples of applications that require sensors operating in various harsh environment conditions.

(i) <u>Combustion optimization in domestic and other small-scale boilers</u>

Currently, the domestic boilers market is divided between the HE (Highly Efficient–Premix Condensing) and the SE (Standard Efficient-Atmospheric) systems. The HE boilers are based on the premix system (1:1 gas/air ratio), which is expected to become the dominant system in the near future. The 1:1 gas/air control ensures safe handling (if there is no air, then no gas will be pulled out from the system), a fast dynamic response, low cost and modulation with premix burner [1]. It also leads to lower gas emissions. The novelty of the HE boilers is their auto-adaptability feature. This is achieved, on the one hand, by inserting a CO_2 sensor above the burner (Fig. 1), which is employed to measure or detect the combustion quality, and on the other, by trimming the gas flow via a motor driven throttle. Besides the self adaptive control (at installation and over lifetime), the combustion quality sensing that is performed by the CO_2 sensor also leads to higher efficiency and to a wider gas range measurement.

The CO_2 sensor has to cope with operating temperatures of up to 225°C and water vapour presence in the gas composition above 10% in volume. HE boilers, taking benefit of the flue condensation, have also the option for gas measurement after water vapour condensation. Thus, it is possible to reduce the working temperature, but the relative humidity can be as high as 100%. Therefore, the requirement emerges to measure temperature and water vapour level in parallel with CO_2 concentration. At the same time, the total gas flow also needs to be measured, for maximum improvement in the combustion process efficiency. Fig.1 shows schematically the placement of different sensors within a domestic boiler.

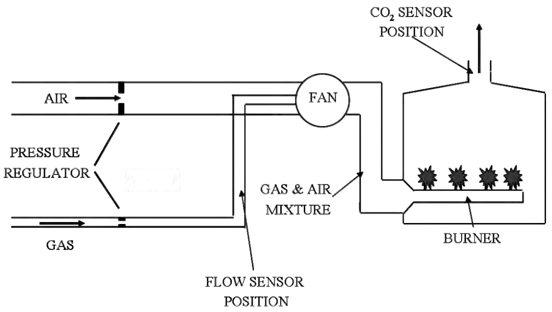

Fig. 1. Schematic view of a HE domestic boiler and the possible positioning of CO_2 and flow sensors.

Furthermore, low power consumption is also a requirement, which again is linked to overall system efficiency. Sensing the gas flow, water vapour and temperature values, together with detecting the CO_2 level, is of course a significant benefit provided that a single platform technology can deal with it, otherwise it can result in increased cost and as a result less market appeal. So far, no multi-measurand solution, able to cope to the harsh environment conditions mentioned above, is currently on the market. Boilers that employ the HE system now are currently using only a CO_2 sensor to achieve their auto-adaptability feature. Among other drawbacks, current sensors suffer from poor reliability and reduced lifetime (3 years on average).

SOI could be an ideal solution for multi-measurand sensors resulting in a dramatic increase in the combustion efficiency of the HE system with the corresponding benefit of significant decrease in natural gas consumption and in boiler emission. These sensors could be assembled in dedicated high temperatures SIPs (System in Packages) with a lifetime of 5-10 years, and significantly increased reliability. Moreover, due to its full CMOS compatibility and owing to its intelligent design, the SOI SIP will offer low power consumption and will decrease the overall boiler cost. It is interesting to note that the boiler market is huge and increasing. More than 5 million domestic boilers are currently sold per year in EU and the growth rate is estimated to be around 15% annually.

(ii) CO_2 Capture and Sequestration (CCS)

CO_2 Capture and Sequestration (CCS) is a technology that allows the storage of CO_2 highly undesired emissions in secure, deep underground reservoirs. This is a large-scale application, with tremendous potential.

From the market point of view, the potential is impressive when one considers the increasingly tough legislative demands and the significant decrease in the oil and natural gas reserves. It is important to mention that CCS is part of the European Energy 2020 strategy [2]. Currently, coal-based power plants are the largest contributor to CO_2 emissions. Since renewable energy sources are still struggling to meet global energy demand, coal is expected to remain a major player in the future. Thus, reducing its emission levels is of crucial importance. CCS has the potential to reduce coal-bases power plants CO_2 emissions by 80–90%.

The currently available CCS sites worldwide have the potential of sequestrating 20 million tones of CO_2 per year. By 2015, 6 new projects will be active, thus increasing the sequestered CO_2 amount to about 33 million tones annually [3].

A typical CCS chain contains capture and separation of CO_2 (in fossil fuel-based power plants, iron and steel, cement or paper factories, etc.), compression and dehydration, transportation (pipelines, ships), sequestration (in saline, depleted oil and gas reservoirs, coal mines, etc.). In all these stages, gas sensors (especially for CO_2 and H_2S concentrations monitoring), water vapour and temperature sensors are essential components (especially in tanks, pipelines and ships transportation, but also in storage reservoirs). The conditions in which such sensors are expected to operate for this type of application are harsh (high temperature – up to 170°C, high pressure – up 10-80 MPa, i.e. highly corrosive). An SOI SIP able to reliably measure the 4 measurands mentioned above (i.e. temperature, water vapour, CO_2 and H_2S) would make a significant impact, both in terms of CO_2 transportation performance and for increasing safety and security in the other stages of the CCS chain.

(iii) Oil & Gas Storage and Transportation

Similar to the above mentioned application, the Oil & Gas Storage and Transportation business requires increased performance and safety. A multi-measurand SOI-based sensing solution will help monitoring the oil & gas conditions within tanks and pipes. When filling a tank with gas or oil, it is essential to monitor the flow of gas or oil, respectively. At the same time, measuring the temperature, pressure and flow within the tank and transportation pipe will increase the safety of the operation [4]. For similar safety reasons, it is compulsory to measure precisely the temperature and H_2S level within the tank during ship transportation. When storing oil and gas in tanks, monitoring temperature and water vapour level provides essential information with respect to the storage efficiency. Harsh environment conditions, such as relative humidity up to 100% and high corrosion rates, are again expected.

(iv) Automotive (combustion optimization and emission monitoring)

Gas sensors can be mounted either in the engine or in the exhaust system, where detecting the levels of CO_2 and CO is essential both for the optimum combustion of the engine and for reducing as much as possible the level of the emission gases. The conditions in which such devices are expected to operate are harsh due to the high temperature levels (up to 550°C in the engine, up to 225°C in the exhaust system).

2. THE ARGUMENT FOR SOI TECHNOLOGY

SOI is one of the most advanced CMOS technologies today. Its main advantages compared to bulk silicon technologies are [5-7]:

- low leakage currents (often by one to two order of magnitude)
- enhanced hardness against radiation and cosmic rays
- latch-up free due to effective isolation
- less parasitic components and low substrate leakage again due to its highly improved isolation
- enhanced CMOS performance (better sub threshold/less influence of the parasitic bipolar transistors/less charge wasted in the depletion/stronger inversion)
- higher operating temperature (due to reduced leakage and less parasitic bipolar action)
- the buried oxide can be used as a very effective etch stop to form membranes for pressure sensors, gas sensors, IR emitters, IR detectors etc.
- the buried oxide can be etched under the SOI layer to leave a free standing monocrystaline silicon structure for resonators/pressure sensors, accelero-meters etc.
- the buried oxide can withstand high electric fields in lateral high voltage structures
- excellent for integrating more than one power or high voltage device and allowing fast recovery diodes, and
- excellent for lateral bipolar transistors as plasma is constricted to the SOI region resulting in very high commutation speed.

These remarkable features make SOI a very attractive platform for application in four main areas:

- sensors
- high voltage integrated circuits
- electronics for harsh environment (high temperature/ high radiation)
- high speed electronics

Interestingly, here we are addressing two of these areas in *sensing technologies for harsh environments*. An important question is: ‘are there other semiconductor technologies that can cover such areas?’. The answer is both yes and no. Bulk silicon struggles to operate above 150-200°C, but its reduced cost makes it highly attractive and therefore there has been and will always be a strong industrial/commercial interest to extend its limits of operation. For example several bulk silicon devices and IC technologies are approaching the 200°C limit, while isolation techniques using DTI (deep trench isolation) and highly doped buried layers have been developed. SiC and Diamond on the other hand have some very attractive properties, such as a very wide bandgap, low intrinsic carrier concentration, great mechanical resistance but their success is or will be limited to niche and high end applications, as they suffer from high wafer and processing costs, low yield and poor availability of materials from suppliers.

3. BUILDING BLOCKS IN SOI TECHNOLOGY

In this section we present the main structures/devices used in SOI sensors at high temperatures: MOSFETs, thermo-diodes, micro-hotplates, smart micro-hotplates and micro-wires.

The typical I-V characteristic of an n-channel SOI MOSFET operating from room temperature to 300°C is shown in Fig. 2. Tungsten metallization is used instead of the usual aluminium in order to allow higher operating temperatures. The leakage current and the parasitic bipolar transistor action are minimized through extensive use of body shorts in the third dimension. The MOSFET is an important component of any electronics and therefore its demonstration and stability at high temperatures in excess of 200°C is compulsory in harsh environments. An SOI MOSFET can also be used as a micro-heater driver (in series with the micro-heater) or as a micro-heater itself. In the latter case the MOSFET is embedded within a SOI membrane [8, 9]. Fig. 3 shows a photo of a micro-heater using a p-channel MOSFET and its self-heating characteristics. The MOSFET can reach 550°C before the parasitic p-n-p transistor kicks in.

Instead of a MOSFET, one can use a resistive heater [10-12]. The heater can be made of tungsten as either a micro-wire (for thermal flow sensors) or a micro-hotplate (for resistive gas sensors, pellistors or IR emitters) [13]. Fig. 4 shows a photograph of a micro-wire suspended on a SOI membrane for use as a flow or sheer stress sensor. The wire will dissipate more heat due to convection to the flow and therefore it is cooled down when operated at constant power [14, 15]. The typical power consumption is 0.1mW/°C. Given that the wire is much thinner (~ 2 μm×0.3 μm cross section) than in state-of-the-art devices fabricated via screen printing, the response is extremely fast (60 kHz frequency) with a sensitivity >50 mV/Pa. Typically, microwires operate at a maximum temperature of 300°C.

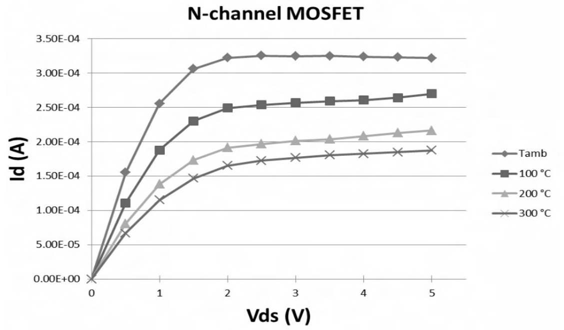

Fig. 2. I-V characteristics of an n-channel SOI MOSFET at different temperatures (up to 300 °C) and V_{gs}=5 V.

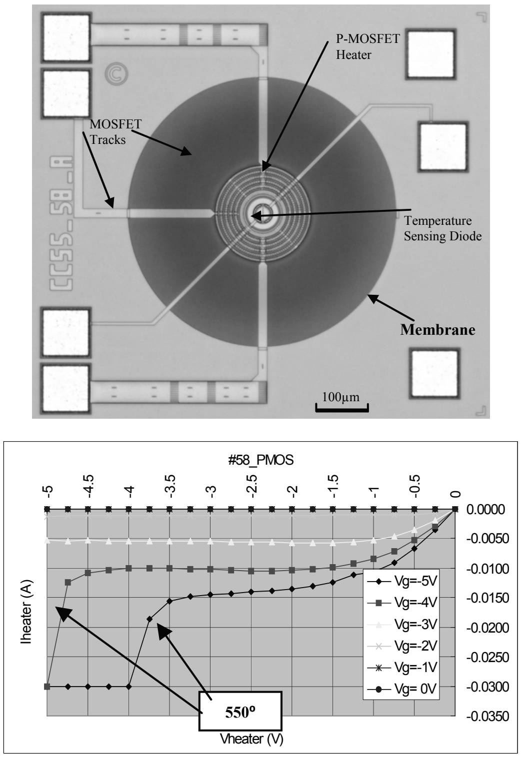

Fig. 3. Photograph (top) of an SOI micro-heater using a p-channel FET and the self-heating characteristics showing normal operation up to about 550 °C followed by the turn-on of the parasitic p-n-p bipolar transistor (below).

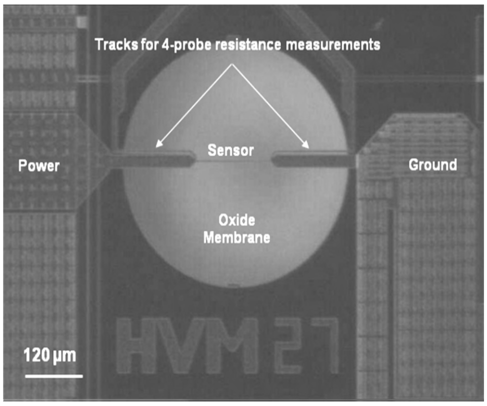

Fig. 4. Photograph of a micro-wire made of tungsten in SOI technology for use as a flow or sheer stress sensor.

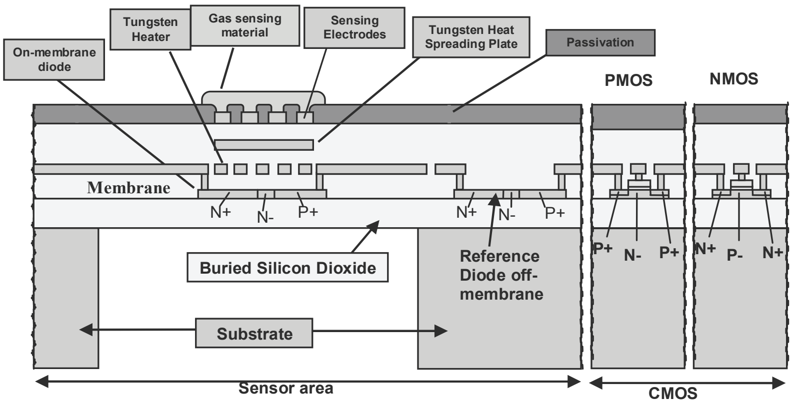

Fig. 5. Schematic drawing of an SOI CMOS microhotplate with integrated thermodiodes for peak and ambient temperatures and CMOS cells outside the membrane. In this schematic drawing the micro-hotplate features top electrodes and a sensitive layer.

Micro-hotplates use a larger heater for applications in gas sensors. Fig. 5 shows the cross-section of a micro-hotplate in SOI technology with the circuitry on the same chip. Depending on the area of the heater and the membrane, the DC power consumption can vary between 0.05 mW/^{o}C and 0.2 mW/^{o}C.

This of course can be lowered significantly if the micro-hotplate is operated in pulse conditions, taking into account that typical thermal time constants are around 10-20 ms. Furthermore, the ambient temperature (outside the membrane) can reach 225^{o}C, without impacting the operation of the micro-hotplate. The CMOS process is qualified at this temperature against electro-migration or TDDB (time dependent dielectric breakdown). Thus, this SOI micro-hotplate is an essential platform for harsh-environments. A top-view photo of asmart micro-hotplate using feedback electronics to maintain the temperature constant is shown in Fig. 6.

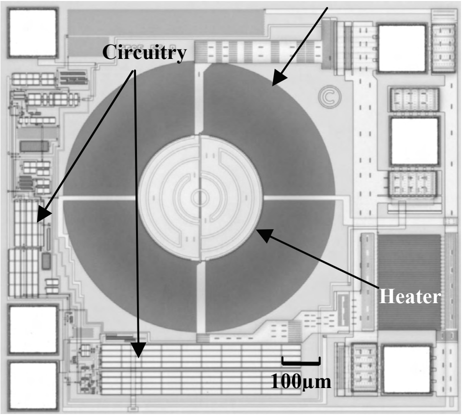

Fig. 6. Photograph of a smart SOI micro-hotplate with integrated electronics, MOSFET drive and temperature sensor.

An important aspect in harsh environments is the stability of the micro-hotplate and the other building blocks at extreme temperatures. In Fig. 7(a) the stability of the micro-heater in pulse conditions at 10 Hz with 50% duty cycle is shown. In Fig. 7(b) 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.

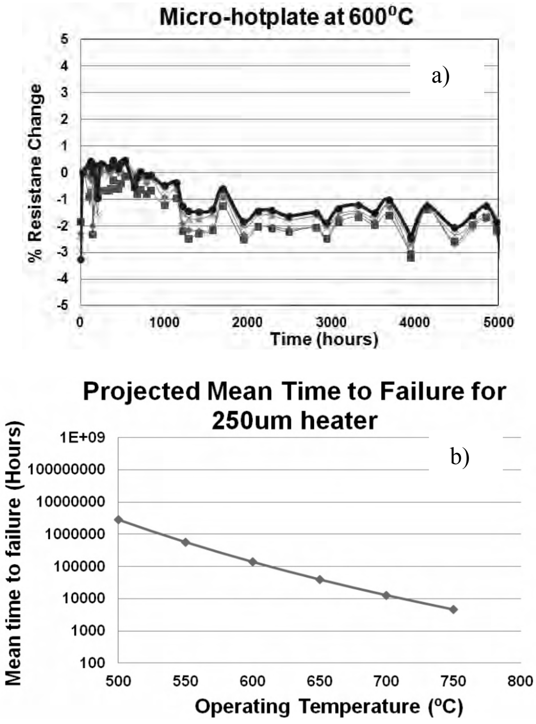

Fig. 7. Stability of the micro-heater in (a) DC and (b) pulse conditions (over 3 million pulses).

The thermo-diode is also an important building block for any sensor as we rely on it for accurate temperature detection or temperature compensation in some cases. The thermo-diodes are not known to operate commercially above 200°C and there are very few research studies [16, 17] reporting their behaviour beyond this temperature. Here we show that a carefully designed thermo-diode, with extremely low leakage current (specific to SOI) can be operated up to 600°C reliably giving a linear response of (approx −1.3 mV/°C), as shown in see Fig. 8. Moreover the diode is stable, and for over 500 hours at 500°C, the change in the output voltage was below 1%. Furthermore the diode was found to have a minimal piezo-junction response and therefore the effect of the stress induced by the high temperatures in the membrane on the output voltage of the diode can be neglected.

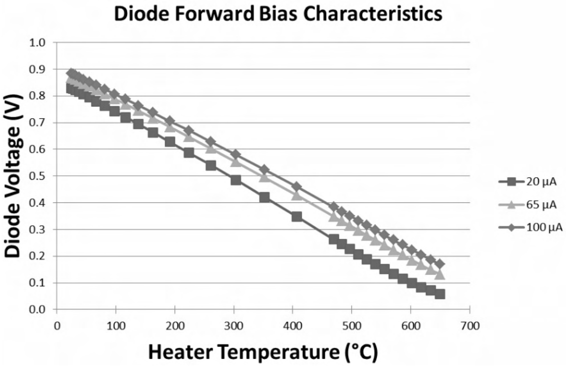

Fig. 8. The output voltage across an SOI diode in the forward bias mode operation vs temperature. The forward currents injected were 20 µA, 65µA and 100 µA. The diode shows a linear response with a slope of (−1.3mV/°C) up to 600°C.

4. NDIR BASED SOI GAS SENSOR SUITABLE FOR HARSH ENVIRONMENTS

IR sensors operate using thermal radiation from hot devices to detect the presence of heat or to use radiometric conversions to obtain the actual temperature of the device. The principle of operation is to detect IR wavelengths in the range of 1 to 15 µm using sensitive materials, such a pyro-electric crystals, resistive devices such as bolometers, thin-film or silicon based planar thermopiles. The principle of a Non-dispersive IR gas sensor (NDIR) is based on an IR emitter at one end of an optical path while at the other an IR detector with an optical filter is inserted (Fig. 9). The gas is allowed in through some holes on top of the optical path and depending on its concentration it absorbs a certain amount of radiation at a specific wavelength. This is detected by the IR sensor, amplified and eventually read out in a suitable format through a transducing circuit. The filter is used to enhance selectivity to a specific gas absorption band (*e.g.* 4.3 and 15 µm for CO_2). Generally all the NDIR systems operate below 100°C. The use of a micro-bulb as an IR emitter at higher ambient temperatures (i.e. in harsh conditions) is prohibited due to its poor lifetime. Its glass cap also limits the absorption wavelengths of the gases that can be detected to below 5 µm. Furthermore, the bulbs are very slow and cannot be operated above 5 Hz, making the system sensitive to high 1/f noise. LEDs cannot be used either in harsh environments as the temperature variation would lead to high variations in the optical power and alter the wavelength at which the radiation peak occurs.

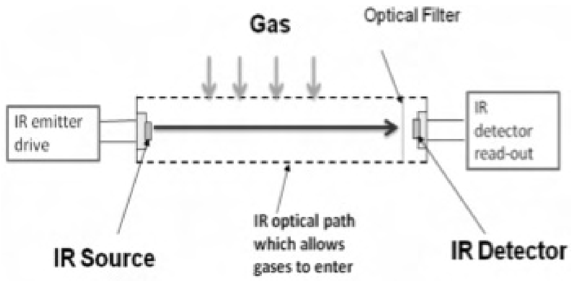

Fig. 9. A schematic drawing of a NDIR gas sensor.

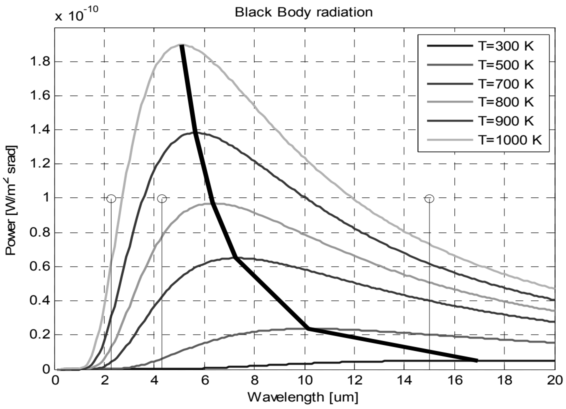

Fig. 10. Emission power vs wavelength for different micro-hotplate temperatures (the markers indicate the CO_2 absorption lengths). For increased sensitivity temperatures > 500°C are needed.

The micro-hotplate, with its wide spectrum and very high lifetime is ideal for use as an IR emitter. In addition, the micro-hotplate can be driven in pulse mode by an internal MOSFET and/or can have intelligence incorporated on-chip. Furthermore, the SOI micro-hotplate with tungsten metallization can operate at ambient temperatures of 225^{o}C making it ideally suitable for harsh environments. The electronics and detectors must also be designed to operate at such temperatures (this is one of the aims of the SOI-HITS EU FP7 project [18]). The micro-hotplate gives a spectrum close to that of a black body. This is adjusted by a unitless factor called ‘emissivity’. The closer the emissivity to one, the closer the emission is to the ideal black-body radiator. The emissivity however varies with temperature and often time. Fig. 10 shows the typical emission spectrum for a micro-hotplate operated at different temperatures. For CO_2, strong radiation absorption peaks occur at 4.3 and 15 µm wavelengths. For CO the absorption peak is at 4.6 µm. To increase the emissivity one can grow or deposit nanomaterials, such as carbon nanotubes CNTs [19], or silver and gold particles.

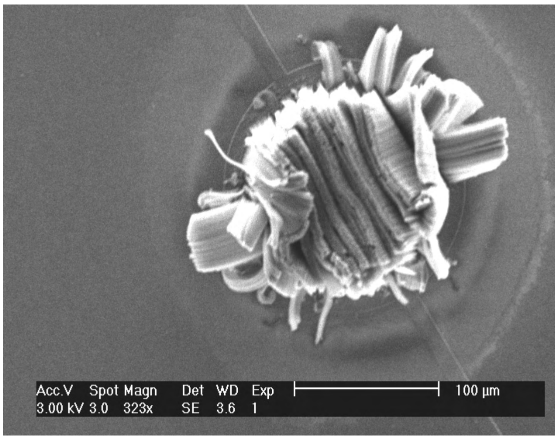

Fig. 11. SEM showing the CNTs grown self-aligned on top of one of the SOI micro-hotplates.

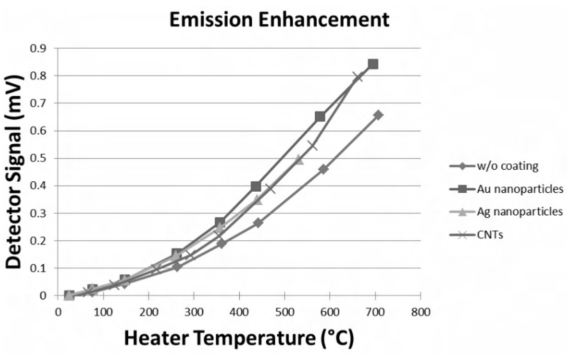

Fig. 12. Emission enhancement using different nano-materials. The signal shown is the output voltage on a thermopile for different temperatures of the IR emitter microheater.

Fig. 11 shows a picture of single walled CNTs grown locally on top of the micro-hotplate using a PECVD technique and the high temperature (~700°C) generated by the micro-heater itself. These particles or nanomaterials can enhance significantly the emissivity (or indeed the absorption on the detector), but the most important issues are reproducibility and stability for prolonged periods at high temperatures. Fig. 12 shows the enhancement of the emission when using different type of nanomaterials on top of the CMOS SOI micro-hotplate. The signal shown is the detector voltage (a thermopile) for different temperatures of the IR emitter microheater.

5. CONCLUSIONS

In this paper we have described different harsh environment applications (HE boilers and carbon capture systems) that demand new advanced sensing technologies. We have shown here that SOI CMOS technology provides an ideal platform for such applications, owing to its higher operating temperature, ease of MEMS manufacturability, possibility of integrating high temperature electronics and, last but not least, high reproducibility, yield and reliability. We have shown different components that have been fabricated in SOICMOS technology such as resistive and FET micro-heaters, thermo-diodes, and flow sensors. Finally, we have described a prototype NDIR gas sensor with a suitable IR emitter for CO_2 and possibly CO detection for application in harsh environments.

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References

[1] M. Schultz, “Gas Appliance Modulating Controls Technology”, *American Society of Gas Engineers Conference*, Las Vegas, USA, June 2011.
[2] http://ec.europa.eu/energy/energy2020/
[3] http://www.globalccsinstitute.com/

[4] L. Xie, S. Wang, Z. Zheng, Q. Song, "Design and Realization of Safety Monitoring and Controlling System for Pipelines in Oil Depot", *Proceedings of the International Conference on Pipelines and Trenchless Technology ICPTT*, pp. 529–537, Shanghai, China, 2009.

[5] S. Cristoloveanu, "Introduction to Silicon on Insulator Materials and Devices", *Microelectronic Engineering*, **39**, pp. 145–154, 1997.

[6] F. Udrea, *et al.*, "SOI Power Devices", *Electronics and Communication Engineering Journal*, **12**(1), pp. 27–40, 2000.

[7] G.G. Shahidi, "SOI Technology for the GHz era", *IBM Journal of Research and Development*, **46**(2/3), pp. 121–131, 2002.

[8] F. Udrea, J.W. Gardner, D. Setiadi, J.A. Covington, T. Dogaru, C.C. Lu, W. I. Milne, "Design and simulations of SOI CMOS micro-hotplate gas sensor", *Sensors and Actuators B*, **78**, pp. 180–190, 2001.

[9] P.K. Guha, S.Z. Ali, C.C.C. Lee, F. Udrea, W.I. Milne, T. Iwaki, J.A. Covington, J.W. Gardner, "Novel design and characterization of SOI CMOS micro-hotplates for high temperature gas sensors", *Sensor and Actuator B*, **127**, pp. 260–266, 2007.

[10] M. Graf, D. Barrettino, K.U. Kirstein, A. Hierlemann, "CMOS microhotplate sensor system for operating temperatures up to 500°C," *Sensor and Actuator B*, **117**, pp. 346–352, 2006.

[11] A. Hierlemann, D. Lange, C. Hagleitner, N. Kerness, A. Koll, O. Brand, H. Baltes, "Application-specific sensor systems based on CMOS chemical microsensor", *Sensors and Actuators B*, **70**, pp. 2–11, 2000.

[12] M. Graf, D. Barrettino, H.P. Baltes, A. Hierlemann, "CMOS hotplate Chemical microsensors", *Springer-Verlag Berlin Heidelberg*, pp. 29–58, 2007.

[13] S.Z. Ali, P.K. Guha, C.C.C. Lee, F. Udrea, W.I. Milne, T. Iwaki, J.A. Covington, J.W. Gardner, "High temperature SOI CMOS tungsten micro-heater", *Proceedings of the 5th IEEE conference on sensors*, pp. 847–850, Daegu, Korea, , 2006.

[14] I. Haneef, S.Z. Ali, F. Udrea, J.D. Coull, H.P. Hodson, "High performance SOI-CMOS wall shear stress sensors", *Proceedings of the 6th IEEE conference on sensors*, pp. 1060–1064, Atlanta, GA, 2007.

[15] [15] Z. Wang, K. Tian, Y. Zhou, L. Pan, C. Hu, L. Liu, "A high-temperature silicon-on-insulator stress sensor", Journal of Micromechanics and microengineering, vol. 18, pp. 045018-045028, 2008.

[16] S. Santra, P.K. Guha, S.Z. Ali, I. Haneef, F. Udrea, "Silicon on Insulator Diode Temperature Sensor – A Detailed Analysis for Uktra-High Temperature Operation", *IEEE Sensor Journal*, **10**(5), 2010.

[17] Y.M. Shwarts, V.L. Borblik, N.R. Kulish, E.F. Venger, V.N. Sokolov, "Limiting Characteristics of Diode Temperature Sensors", *Sensors and Actuators*, **86**, pp. 197–205, 2000.

[18] www.soi-hits.eu

[19] Z.P. Yang, L. Ci, J.A. Bur, S.Y. Lin, P. Ajayan, "Experimental Observation of an Extremely Dark Material Made by a Low-density Nanotube array", *Nano Letters*, **8**(2), pp. 446–451, 2008.