Low-power / High-temperature sensors and MEMS in SOI technology

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ABSTRACT

Low-power and high-temperature sensors and MEMS designs based on bulk, SOI and IC compatible materials and processes are presented here. Target markets are in general public sensors for UV, ozone, CO, liquids presence, e.g. in mobile devices. Or in health, sensors for the medical diagnosis (DNA, RNA, bacteria, viruses).

Simple, low cost and low consumption devices are required in medical applications. In our laboratory aluminum oxide interdigitated capacitors have been developed and successfully tested on DNA hybridization test on HIV and cancer (TP-53), as well as on bacteria and humidity or condensation (integrated into a wireless breathing monitoring system), all of them showing comparable results to the state of the art using existing standard biological protocols procedures that open new opportunities for Medical Applications.

For UV light based detections (UV Diode), that are ready for use, packaging must be customized. Customers are the kits fabricator to integrate our device for a fast electrical measurement (for DNA concentration, turbidity or fire detection).

Our technology demonstrates high-performance CMOS integrated circuits; easy integration of special devices, sensors and MEMS; operation in harsh conditions (micro power, high-temperature, remote RF link, etc.); very low power consumption, miniaturized, wireless or high-temperature sensors for process control, monitoring and data acquisition.. Furthermore, our devices deliver excellent performance compared to the state of the art.

It is important to note that this article resumes some of our results from previous papers (see the references). More information can be found in the university website (www.dice.ucl.ac.be) or in www.sensoi.net, in a more commercial way.

Keywords: Biosensor, hybridization, bacteria, capacitive sensors, electrical detection.

1 INTRODUCTION

SOI-CMOS integrated circuits have demonstrated quasi-ideal properties for micropower and RF functionalities, as well as for high-temperature operation up to e.g. 350°C. In UCL microelectronics laboratory, high-performance SOI sensors have also been developed with optimal reliability vs. thermal and electrical insulation tradeoff, on one hand, thin-film silicon sensors such as UV-light photodiode (high efficiency for $\lambda < 400$ nm, and very low dark current). On the other hand, physical/chemical sensors using micromachining technologies, that can be used in health monitoring, biological and environmental detections. The originality of these designs resides in the use of extremely thin layers of micro-electronics traditional materials, which yields high level detection properties and resistance to harsh environments. This technology demonstrates high-performance CMOS integrated circuits; easy integration of special devices, sensors and MEMS; operation in harsh conditions (micro power, high-temperature, remote RF link, etc.); very low power consumption even at high temperature (i.e. 300°C); and broad applications in automotive, aerospace and biomedical sectors. Integration into a wireless system has been also successfully demonstrated. Furthermore, the devices deliver excellent performance compared to the state of the art.

A few examples can be cited of built and characterized integrated sensors.

For biological sensing, interdigitated capacitive transducers have been built on CMOS chips using Al electrodes protected by a thin (50-100 nm) highly-reliable anodized alumina layer. Excellent performance has been demonstrated for DNA hybridization detection; breathe monitoring, bacteria label free detection, etc.

The other well developed microsystem is for measuring optical power in blue/UV wavelengths (from k = 200 nm to k = 450 nm) which includes a photodiode and the analog processing circuit of the photodiode signal, fully integrated in 2 lm SOI CMOS technology. The photodiode has a maximum responsivity for k = 400 nm. The photosensor functions as a current to frequency converter. Measurements of the microsystem illuminated by blue and UV LEDs demonstrate the good linear behavior, sensitivity and efficiency of the system. The architecture of the fully integrated microsystem is low noise; low power and fits in a small die area. Potential environmental and biomedical applications are being evaluated with successful results into DNA concentration determination.

Finally, these technologies allow MOS devices and multiple sensors to be integrated on the same chips, which opens the door to many new emerging applications with higher performance even in harsh environments at lower cost, lower power consumption and higher integration into a wireless system, as demonstrated with our breathing monitoring system integrating humidity or condensation and temperature measurements at the same time located into a nasal system.

The products advantage compared to competition are the following (based on published information no one else features all the same advantages):

a) The miniaturization rests in the control of technologies of micro/nano-manufacture on Si. In this respect, SOI technology showed many advantages for the Co-integration of MEMS, in one hand, the simplifying of the integration of surface micromachining stages and volume in CMOS process itself (thanks to the single SOI structure comprising a thin layer of Si single-crystal and a buried oxide as an insulation); and in the other, by allowing the easy additional layers post-processing such as amorphous silicon or the thick polysilicium deposited at high temperature.

b) The cost advantages of the preceding techniques rest on the compatibility of the manufacture of our sensors with the chains of production or traditional foundries on Si and, in particular, with the simultaneous realization in batch or series on sections of silicon, including the biochemical functionalization and the integration of the protection layers or encapsulation of significant surfaces, etc.

c) The principles of detection, mainly capacitive, that we use make it possible to limit, in a considerable way, the electric consumption necessary for a measurement. A capacitive measurement of 1 pF at a frequency of 10 kHz requires only one tension of 100 mV maximum, which results in a current about the hundredth part from a microampere and a consumption about the nano-Watt.

Lastly, with regards to the operating conditions, it can be quoted: Unique temperature resistance of the SOI components; the chemical resistance to the biochemistry environment of the dense metallic oxides; adequacy of our joining of sections at low temperature, necessary not to damage biological functions, while getting adhesion, tightness,…; low power consumption (which will allow them being integrated into a wireless system while reducing function cost); small size that will allow miniaturization; and, no stiction problems, high reliability of their functionality.

These innovating devices will be useful for many emerging applications in many industrial sectors. One will quote, for example, integration in the following markets:

- General public: UV sensors, ozone, CO, in the portable telephones of future generation.
- Transport (automobile, aviation, train): sensors for monitoring their operating conditions, and their actuation, mechanics and electric control systems.
- Health: sensors for the medical diagnosis (DNA, RNA, virus,…).
- Etc..

2 DEVICE DESCRIPTION

2.1 Capacitive sensor

The sensing structure consists of 400 µm long Al microfingers protected by a 100 nm aluminum oxide layer covering a full standard spot, organized as a pair of interdigitated electrodes with 50 fingers each (Fig. 1). Fingers width and spacing have been optimized to 2 and 2 µm, respectively.

The structure is embedded in coplanar waveguide access lines for its full electrical on-wafer characterization over a wide frequency band. Electrical measurements were performed on the physical sensors, the extraction of the capacitance between the interdigitated micro-electrodes is obtained using an LCR meter HP4284A, at 0V DC, 100mV AC and for a low frequency band from 10 to 100 kHz.

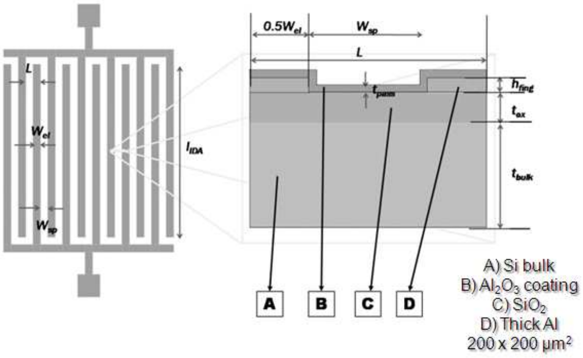

Figure 1: Capacitive sensor architecture [1].

2.2 UV Sensor

A lateral PIN photodiode is constructed using CMOS SOI technology. Its cross-section is introduced in Fig. 2. It features a maximum absorption of the photons whose energy corresponds to a wavelength of $k = 400$ nm in a silicon film. It includes a protective oxide of the device. Its parameters are fixed for a given technology and will allow a good responsivity of the photodiode for UV/blue wavelength and a blindness to visible spectrum. We improved the optical responsivity value by design, changing the intrinsic zone length.

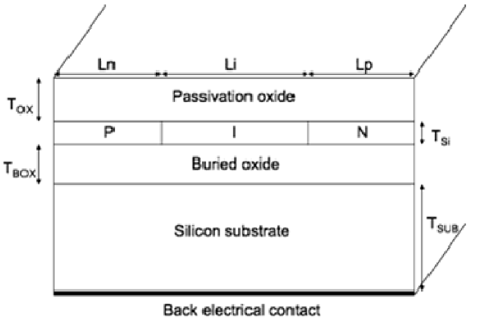

Figure 2: UV sensor design. [2].

3 APPLICATION EXAMPLES

3.1 Capacitive sensor

a) DNA Hybridization. We experimented on our CMOS compatible chips, a standard biological DNA hybridization procedure based on signal enhancement by silver precipitation via biotin-antibody coupled gold nano-particles labels. The measurement technique based on capacitive measurement show significant electrical results sensitivity for a concentration as low as 30 pM (Fig. 3) [1].

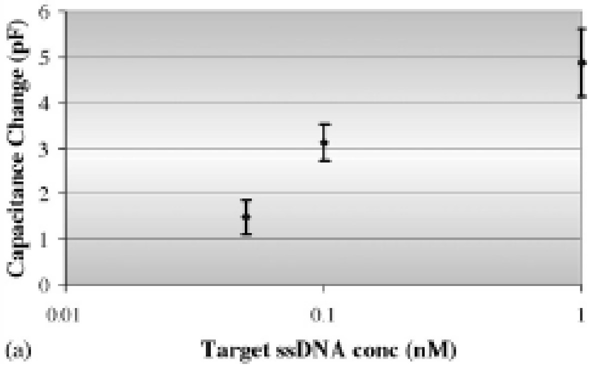

Figure 3: DNA hybridization detection of target molecules down to the pM range [1].

This technique was also tested on TP53 (tumor suppressor) mutating test with a good discrimination found between the wild type and its mutated one (Fig. 4).

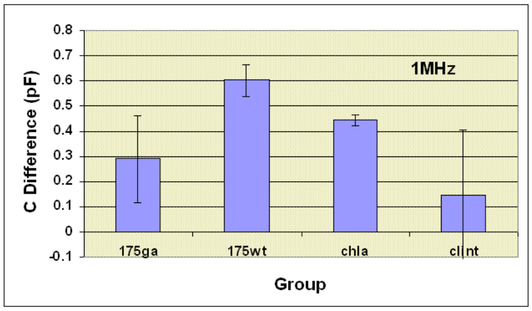

Figure 4: TP53 discrimination between wild type and its mutated one.

b) Bacteria. We demonstrate a new microsensor, for rapid, sensitive Staphylococcus aureus bacteria detection. The protocol used was the direct immobilization of the corresponding antibody specific for these bacteria and tested using S. Epidermis as a negative control. Very significant detection signals have been obtained for about 240 bacteria immobilized on the sensor surface, with capacitance contribution par bacteria of 50 fF and conductance contribution par bacteria of 10 nS 5Fig 5) [3].

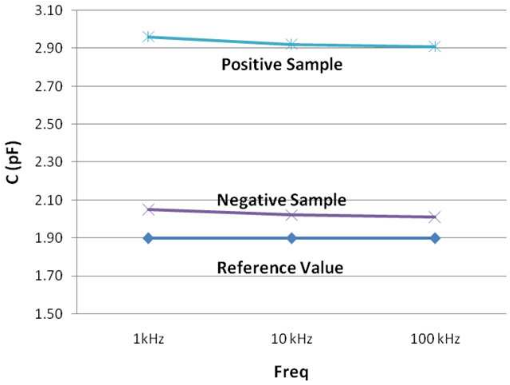

Figure 5: Staphylococcus aureus capacitance variation compared to Staphylococcus epidermis (negative sample) confirming the specificity of our device [3].

c) Breathing monitoring. Thanks to the hydrophilic properties of the aluminum oxide in our interdigitated fingers, these sensors showed good sensitivity to humidity. When breathing, humidity is expulse and absorbed, if the device is placed close to the nose, this humidity increases the capacitance value drastically and then desorbed (returning fast to its original value), then our device is capable of following this phenomena in a real time situation. This feature was tested during training over a fixed speed band and the breathing rhythm was obtained (Fig. 6). The sensor was placed over a nasal system. The response time of our device was below 200 ms, and did not show any problems or deterioration during its use [4].

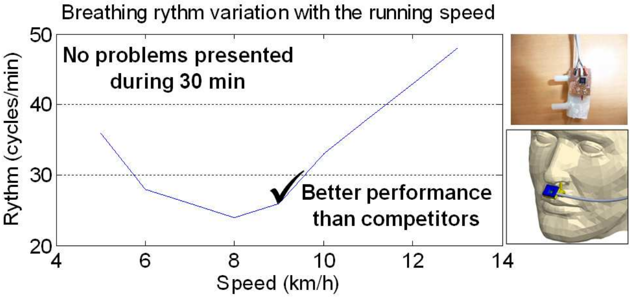

Figure 6: Breathing monitoring [4].

3.2 UV sensor

In the biomedical field, applications of UV sensors concern for example the absorption by bacteria in the low wavelengths or the quantification of the concentration of a solution of DNA. Such applications require a precise, miniaturized and portable system. Basically, it consists in a photodiode and a read-out analog to digital circuit.

Our photodiodes were used to measure DNA concentration by an in tube optical setup based on UV transmittance through DNA solution at k = 280 nm corresponding to a region of high absorbance by DNA [2] [5]. We achieved a DNA detection range from 400 ng/ll to 40 pg/ll (Fig. 7), which corresponds to photocurrents from 20 to 200 pA, respectively in laboratory (i.e. in a controlled temperature room of about 300 K).

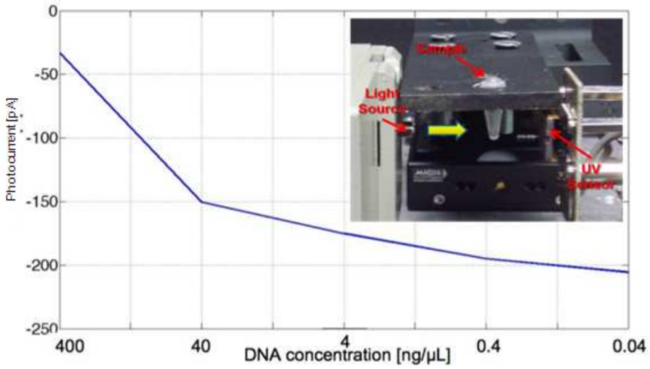

Figure 7: DNA concentration obtained using our UV detection system.

4 CONCLUSIONS

With our capacitive sensor, DNA hybridization detection was successfully achieved, limit of detection = 30 pM which is lower than in current fluorescent methods (<1 nM). Results obtained without modifying the standard biological procedures and materials with metallic labels, through their capacitance variations. Bacteria was successfully detected in the same way but with direct antibody immobilization label free methodology.

Furthermore, the same device was successfully tested for humidity detection, leading to application for breathing monitoring thanks to its capability of detecting condensation and humidity with a fast recovery after each cycle comparable to the state of the art, with 5 times better sensitivity.

In our laboratory, high-performance SOI (Silicon-on-Insulator) UV-light photodiode sensors (for λ < 400 nm, and very low dark current) were tested for direct assay tubes DNA concentrations measurement with good correlation with the corresponding measured photocurrent in the device, thus allowing for a non destructive method.

With advantages such as temperature and chemical resistance, simplified fabrication in a 100% CMOS compatible system (allowing IC integration), low power consumption, wireless system integration and miniaturization, now characterization and industrialization is being studied in more applications like in bacteria, viruses, biological reactions, micro fluidics, etc., detections and monitoring systems.

REFERENCES

[1] L. Moreno-Hagelsieb, B. Foultier, G. Laurent, R. Pampin, J. Remacle, J.P. Raskin, D. Flandre, Biosensors and Bioelectronics 22, pp. 2199–2207, 2007.

[2] O. Bulteel, P. Dupuis, S. Jeumont, L.M. Irenge, J. Ambroise ; B. Macq, B., et al. (2008). In Proceedings of the fourth European congress for medical and biomedical engineering 2008 (p. 290). Antwerpen, Belgium.

[3] L. Moreno-Hagelsieb, Y. Nizet, X. Tang, J.-P. Raskin, D. Flandre, L. A. Francis; Available online at www.sciencedirect.com, Procedia Chemistry 00 (2009) 000–000.

[4] N. André, S. Druart, P. Gerard, R. Pampin, L. Moreno-Hagelsieb, T. Kezai, L. Francis, D. Flandre, J.-P. Raskin ; IEEE Sensors Journal 10, Issue: 1, 2010 , pp 178 – 184.

[5] O. Bulteel, A. Afzalian, D. Flandre; Analog Integr Circ Sig Process, Accepted: 25 September 2009.