3D sensors and micro-fabricated detector systems

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A B S T R A C T

Micro-systems based on the Micro Electro Mechanical Systems (MEMS) technology have been used in miniaturized low power and low mass smart structures in medicine, biology and space applications. Recently similar features found their way inside high energy physics with applications in vertex detectors for high-luminosity LHC Upgrades, with 3D sensors, 3D integration and efficient power management using silicon micro-channel cooling. This paper reports on the state of this development. © 2014 The Author. Published by Elsevier B.V. This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/3.0/).

1. Introduction

Micro-fabrication, mainly used for Micro-Electro Mechanical Systems (MEMS), is the process which allows structures to be fabricated three-dimensionally within silicon, or other materials. Currently there are three types of micro-fabrication available:

1. Surface fabrication, where structures are formed by deposition and etching of sacrificial and structural thin films.
2. Bulk or volume, where 3D structures are formed by dry (Deep-Reactive Ion Etching or DRIE) or wet etching of silicon substrates.
3. LIGA, where 3D structures are formed by mold fabrication followed by injection molding or electroplating, and which is mainly used with metals.

Furthermore, 3D printing, where the fabrication is based on alternating steps of chemical vapor deposition of silicon and local implantation of gallium ions by focused ion beam (FIB) writing, is also successfully used for a layer-by-layer fabrication of arbitrarily shaped silicon micro- and nano-sensors [1]. Other materials can be used, together with commercially available printers, to generate three-dimensional objects like the ones shown in Fig. 1. These objects allow fast in-house prototyping and true visualization of complex structures. As an example, the object shown in Fig. 1 is designed and "printed" at the university of Manchester (UK) to see the minimal dimensions reachable by a commercial machine. The minimum diameter of the embedded micro-channels is 600 μm.

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Fig. 1. 3D printed prototype of micro-channels and pillars with features as small as 600 μm fabricated using a commercial printer.
Table 1
Thin (50–100 μm) and thick (200 μm) 3D silicon sensors' parameters. The typical threshold of the ATLAS pixel FE-I4 is 1300e− for a single chip and is 3000e− during operation.

| Substrate thickness (μm) | 50–100 | 200 |
|--------------------------|-------|-----|
| **Technology** | | | Aggressive: single side with support wafer  Conservative: double side no support wafer |
| Electrode size with 25:1 aspect ratio (μm) | 2–4 | 8 |
| Capacitance with electrode distance of 56 μm | Low | High |
| Signal without gain before irradiation (e−) | about 30 fF | about 60 fF |
| Capacitance with electrode distance of 56 μm | 3750 (50 μm) | 7500 (100 μm) |
| Signal without gain after | 1875 (50 μm) | 7500 |
| 2 × 10^15 n cm⁻² 50% efficiency (e⁻) | 3750 (100 μm) |

* Conservative means that the process steps used for the final product are qualified and standard and already used for large scale fabrication while aggressive means that the final product requires processing steps which are not qualified for large scale fabrication and non-standard

2. 3D sensors

3D silicon sensors, where electrodes penetrate fully or partially the silicon substrate, were manufactured using bulk micromachining to etch deep narrow columns or trenches within the silicon wafer which were consequently filled with dopants to form electrodes of p–n diodes. Three main processing techniques were successfully implemented to date: front side etching full3D with active edges which was the original design proposed by the Stanford Nano-Fabrication Facility (SNF) [2,3] and is currently industrially manufactured at SINTEF [4,5]. For full3D a support wafer is used to minimize mechanical stress during wafer handling but will require removing at the end of the process. The second is a double side processing where opposite polarity partially-through column etching is performed from both wafers' sides and is currently fabricated at CNM [6,7] and the third is a double side processing where full-through column etching is performed from both wafers' sides and is currently fabricated at FBK [8,9]. Fig. 2 schematically shows these three different 3D processing approaches.

3D silicon pixel modules are being installed, together with planar pixel modules, in the new innermost detector layer in ATLAS, called the Insertable B-Layer or IBL and are distributed on 14 staves to cover the beampipe envelope [10,11]. 3D sensors will contribute to data taking when the LHC restarts its operation in 2015 with an upgraded centre of mass energy of 14 TeV and increased luminosity. Each of the 112 3D sensors in the IBL have a surface of about 4 cm² and are composed of 250 × 50 μm² pixels distributed in 336 rows and 80 columns for a total of 26 880 elements. Peculiar of this generation of 3D silicon sensors is the unique geometrical configuration, optimized for the expected radiation level at which the IBL will be exposed during its lifetime. The p⁺ and n⁺ electrodes have a mutual distance of 71 μm, and have an average column overlap of 200 μm. This particular configuration allows collecting about 60% of the original signal (about 17 000e−) with a maximum bias voltage of 200 V after a fluence of 5 × 10¹⁵ n cm⁻², where neutrons are 1 MeV equivalent.

To allow for the increased fluence expected in the regions closest to the beam at the High luminosity LHC with 200 proton–proton collisions at each bunch crossing, 3D sensors will use a configuration with a narrower spacing of 56 μm between p⁺ and n⁺ electrodes and a bulk thickness of 200 μm. Data previously published [12] have shown that, with this inter-electrode distance, a residual signal of about 50% can be expected after the 2 × 10¹⁶ n cm⁻² fluence at which the detector will be exposed at the end of its lifetime. Such signal would be obtained with a bias voltage of about 200 V at −10 °C for a total charge of about 7500 e− for a 200 μm thick substrate.

Following the experience with the past generation of ATLAS pixel readout chips FE-I3 and FE-I4 [11,12], this signal should be enough to generate a response during the entire lifetime of the innermost pixel detector layer after its upgrade.

3. Thin versus thick silicon substrates in 3D sensor geometry

The very high multiplicity at high LHC luminosity will generate unprecedented activity in the entire detector volume. In the central detector region, where particles cross almost perpendicularly the sensor's wafer, the thickness of the silicon substrate is responsible for the generation of the signal while in the forward region, when the particles cross diagonally, for a longer path, the
sensors’ substrate. After irradiation, such signal should be higher than the electronics threshold to be visible. Currently such threshold is exceeding 3000 electrons.

Table 1 shows the implications on performance and fabrication of 3D with different thicknesses and an inter-electrode distance of 56 μm. The spatial resolution and two track separation are particularly crucial in the forward region at high luminosity, where particles would cross the detector at very inclined angles and generate signals in many adjacent pixels. To tackle these requirements, sensors with thin sensitive volume are preferred. Thin planar sensors with charge multiplication have been identified as possible candidates, if the avalanche process responsible for the enhanced charge can be controlled and the mechanical robustness of thin processes can be mastered [13]. 3D technology, on the other hand, offers a unique solution to the fabrication of thin sensors or more generically "modular" sensors, with different "active" thicknesses at different forward positions, since only the region where the p⁺ and n⁺ electrodes overlap have a strong, parallel and homogeneous electric field. This modular active thickness property can be appreciated by comparing the response before and after irradiation of full-through 3D sensors (FBK) and partially through ones (CNM) as shown on the right plot of Fig. 3. The data report the most probable value of Time over Threshold (TOT) units versus sensors bias voltage [14].

As it can be seen from the data plots, the CNM sensors, where electrodes partially overlap, have full sensitivity, even when the sensor is non-irradiated, only when the applied bias voltage is at least 50 V, while the full-through electrodes FBK sensors reach the maximum signal already at about 10 V. This difference is reproduced after irradiation, as can be seen for the data after 5 × 10¹⁵ n cm⁻² with the maximum signal reached at 150 V and 200 V for FBK and CNM sensors, respectively. The region with low electric field, where electrodes partially overlap, can therefore be "suppressed" by operating the device at an adequate bias voltage.

Devices with different columns overlap, like the one sketched in Fig. 4 (left), and the same substrate thickness, to preserve mechanical stability and compatibility at different stave locations, can be used to set "effective" sensor thicknesses. As an extension of this concept, configurations with the same p⁺ full-through electrode, where one single bias voltage is applied, and n⁺ electrodes partially penetrating from both sides could be used to create a simultaneous independent n-type dual-readout (Fig. 4 right).

Furthermore, stacked 3D sensors could be used as "active interposers" to connect several sensitive thicknesses without
spatial resolution degradation, to a single readout electronic chip, like the one shown in Fig. 5. This configuration could be used for improved x-ray detection efficiency and for high $p_t$ track-trigger in high energy physics. A preliminary simulation has shown that the capacitance with two stacks, with an electrode distance compatible with the Medipix2 chip [15] with $55 \times 55 \, \mu m^2$ pixel cell and a full thickness of 600 $\mu m$, is similar to the one obtained with 230 $\mu m$-thick IBL 3D sensors [16].

4. Conclusions

3D sensor modules compatible with the FE-I4 front end electronics chip are being mounted on the IBL staves and will be installed in ATLAS in 2014. Micro-systems using the same processing technology are currently being used in medicine, biology and space applications as well as in everyday life in mobile phones and cars. Future developments in high energy physics might use vertically integrated systems with embedded micro-channels for effective cooling, stacked 3D sensors used as “active-interposers” for improved detection efficiency with preserved spatial resolution or high $p_t$ track-trigger and effectively thin sensors with mechanically stable thick substrates, by using the unique property of 3D sensors of high field in the p–n electrodes overlap.

References

[1] Advanced Functional Materials, vol. 22, No. 19, October 10 (2012).
[2] C.J. Kenney, et al., IEEE Transactions on Nuclear Science NS46 (4) (1999) 1224.
[3] Stanford Nanofabrication Facility, Stanford University, School of Engineering, Stanford, CA 94305-4070, USA. (http://snf.stanford.edu/).
[4] A. Kok, et al., Results from the first prototype of large 3D active edge sensors, 2011 IEEE NSS, Conference Record, Paper N24-5.
[5] SINTEF MiNaLab, Gaustadalleen 23C, 0373 Oslo, Norway. (http://www.sintef.no/microsystems).
[6] G. Pellegrini, et al., Nuclear Instruments and Methods A 592 (2008) 38.
[7] Centro Nacional de Microelectrónica (CNM-IMB-CSIC), Campus Universidad Autónoma de Barcelona, 08193 Bellaterra (Barcelona), Spain. (http://www.imbcnm.csic.es/).
[8] E. Vianello et al., “Optimization of Double Side 3D Detector Technology for First Production at FBK”, 2011 IEEE Nuclear Science Symposium, Conference Record, paper N10-6.
[9] Fondazione Bruno Kessler (FBK), Via Sommarive 18, 38123 Povo di Trento, Italy. (http://www.fbk.eu/).
[10] ATLAS IBL collaboration, Prototype ATLAS IBL modules using the FE-I4A front-end readout chip, 2012 JINST 7 P11010.
[11] Cinzia Da Via, et al., Nuclear Instruments and Methods A 699 (2013) 18.
[12] C. Da Via, et al., Nuclear Instruments and Methods A 604 (2009) S05.
[13] G. Casse, et al., Nuclear Instruments and Methods A 699 (2013) 9–13.
[14] The IBL Collaboration, Prototype ATLAS IBL Modules using the FE-I4A Front-End Readout Chip, arXiv:1209.1906v1 [physics.ins-det].
[15] M. Campbell, Nuclear Instruments and Methods 633 (2011) 51.
[16] Marco Povoli, SINTEF MinaLab, Oslo, Norway. Private communications.