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## 3D sensors and micro-fabricated detector systems



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## ARTICLE INFO

Available online 29 May 2014

## Keywords:

3D silicon sensor

MEMS

3D integration

ATLAS pixel upgrade

LHC upgrade

FE-14

Pixels

Radiation hardness. Micro-channel-cooling

3D printing

## ABSTRACT

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.

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## 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  $\mu\text{m}$ .

In biology and space applications micro-fabrication is mainly used for smart and low mass systems miniaturization and high precision mechanical actuators. High energy physics pioneered the use of bulk etching for the fabrication of radiation hard and fully active sensors (3D) and now is using etched micro-channels for cooling and vertical signal transmission (through-silicon vias, TsV).

Future developments are motivated by the need of new pixel detectors systems in upgraded HL-LHC experiments. Such requirements span from extreme radiation tolerance, up to  $2 \times 10^{16}$  neutron equivalent per  $\text{cm}^2$ , to unprecedented event multiplicity, up to 200 vertices per bunch crossing, and the necessity to resolve very closely spaced tracks as well as primary and secondary vertices. Low mass is therefore a necessity for such systems to prevent multiple scattering events and consequent fake tracks to be produced.

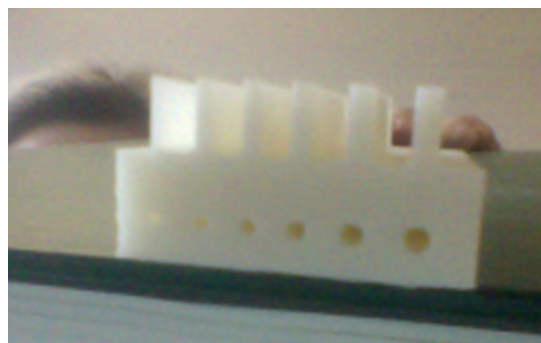
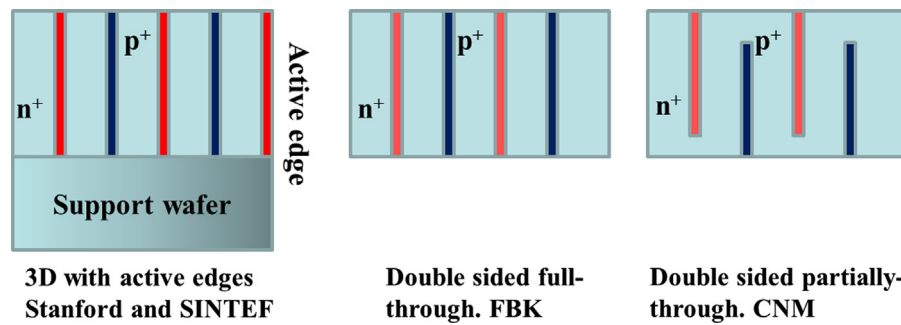


Fig. 1. 3D printed prototype of micro-channels and pillars with features as small as 600  $\mu\text{m}$  fabricated using a commercial printer.

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**Fig. 2.** Sketch of the three 3D sensor options presently studied within the 3D ATLAS R&D Collaboration. Left, full-through with active edges. This follows the original design [2,3] and was fabricated at Stanford and is currently industrially manufactured at SINTEF [4,5]. This processing method requires a support wafer to guarantee mechanical stability which is afterwards removed. Middle: Double-side processing with full-through columns and slim edges proposed by FBK [8,9]. Right: Double side processing with partially-through columns and slim edges proposed by CNM [6,7].

**Table 1**  
Thin (50–100  $\mu\text{m}$ ) and thick (200  $\mu\text{m}$ ) 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 ( $\mu\text{m}$ )	50–100	200
Technology	<sup>a</sup> Aggressive: single side with support wafer	Conservative: double side no support wafer
Electrode size with 25:1 aspect ratio ( $\mu\text{m}$ )	2–4	8
Capacitance with electrode distance of 56 $\mu\text{m}$	Full sensitivity at orthogonal particle impact	Possible insensitivity at orthogonal particle impact
Signal without gain before irradiation ( $e^-$ )	Low	High
Signal without gain after $2 \times 10^{16} n \text{ cm}^{-2}$ 50% efficiency ( $e^-$ )	about 30 fF 3750 (50 $\mu\text{m}$ ) 7500 (100 $\mu\text{m}$ )	about 60 fF 15000
	1875(50 $\mu\text{m}$ ) 3750(100 $\mu\text{m}$ )	7500

<sup>a</sup> 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 at the Stanford Nano-Fabrication Facility (SNF)[2,3] and is currently industrially fabricated 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 wafer's 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 wafer's 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  $4 \text{ cm}^2$  and are composed of  $250 \times 50 \mu\text{m}^2$  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  $\mu\text{m}$ , and have an average column overlap of 200  $\mu\text{m}$ . 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  $5 \times 10^{15} n \text{ cm}^{-2}$ , 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  $\mu\text{m}$  between  $p^+$  and  $n^+$  electrodes and a bulk thickness of 200  $\mu\text{m}$ . Data previously published [12] have shown that, with this inter-electrode distance, a residual signal of about 50% can be expected after the  $2 \times 10^{16} n \text{ cm}^{-2}$  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  $-10^\circ\text{C}$  for a total charge of about  $7500 e^-$  for a 200  $\mu\text{m}$  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

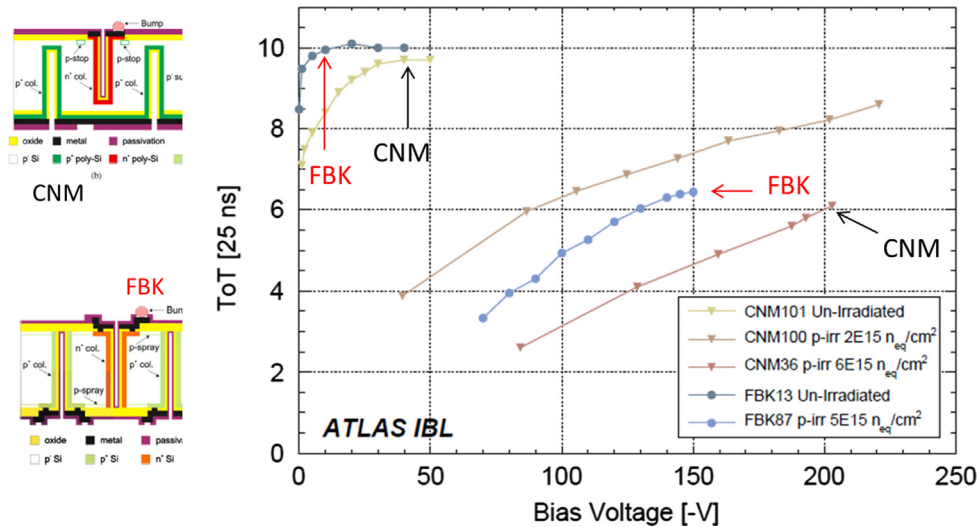


Fig. 3. Signals from 3D sensors with full-through FBK electrodes compared with partially through CNM electrodes before and after irradiation where the different electric field distribution is clearly visible from the bias voltage required for full response to minimum ionizing particles [14].

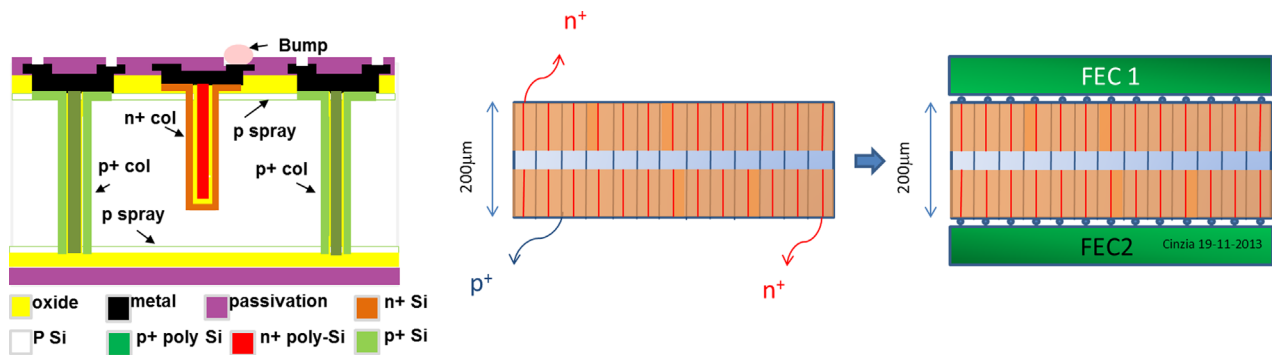


Fig. 4. Left: possible partially-overlapping electrode 3D sensor where only the  $n^+$  electrode is used to define the 'effective' thickness of the sensor while the  $p^+$  electrode is fully through. Right: possible dual readout with common  $p^+$  electrode and separate  $n^+$  readout for a combination of thin sensor's properties and improved spatial precision and two track resolution in particular in the forward regions. FE1 and FE2 refer to front-end readout chips for the readout of the top and bottom  $n^+$  electrodes.

sensors' substrate<sup>1</sup>. 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

<sup>1</sup> For minimum ionizing particles (MIP) the signal is generated by the path the incident particle crosses in the depleted region and corresponds to 75e<sup>-</sup> per micron traversed. In the forward regions where the incident angle is very inclined the path corresponds to the diagonal of the pixel size or even the lateral pixel dimension which can be very different from the pixel thickness.

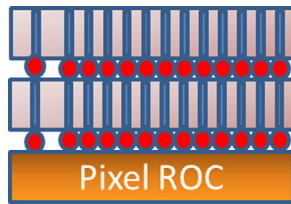
before and after irradiation of full-through 3D sensors (FBK) and partially through ones (CNM) as shown on the right plot of Fig. 3. The data report the most probable value of Time over Threshold (TOT) units versus sensors bias voltage [14].

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  $5 \times 10^{15} n \text{ cm}^{-2}$  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 stage locations, can be used to set "effective" sensor thicknesses.

Such thicknesses could be different in different locations, if necessary, since only one electrode defines the effective overlap. 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



**Fig. 5.** Stacked 3D sensors used as “active-interposers”. Simulations of two stacked sensors compatible with Medipix2 for a total thickness of 600  $\mu\text{m}$  have shown to be the same of 230  $\mu\text{m}$  thick IBL 3D sensors [16]. Pixel ROC is the Pixel Read-Out Chip.

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  $55 \times 55 \mu\text{m}^2$  pixel cell and a full thickness of 600  $\mu\text{m}$ , is similar to the one obtained with 230  $\mu\text{m}$ -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.

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