Journal of Physics: Conference Series

PAPER • **OPEN ACCESS**

3D detectors with high space and time resolution

To cite this article: A Loi 2018 *J. Phys.: Conf. Ser.* **956** 012012

IOP Conf. Series: Journal of Physics: Conf. Series **956** (2017) 012012 doi:10.1088/1742-6596/956/1/012012

3D detectors with high space and time resolution

A Loi[1,2]

[1] Università di Cagliari, Dipartimento di Fisica, Complesso Universitario di Monserrato - S.P. per Sestu Km 0.700, 09042 Monserrato (Cagliari), Italy

[2] INFN-Sezione di Cagliari, Complesso Universitario di Monserrato - S.P. per Sestu Km 0.700, 09042 Monserrato (Cagliari), Italy

E-mail: angelo.loi@ca.infn.it

Abstract. For future high luminosity LHC experiments it will be important to develop new detector systems with increased space and time resolution and also better radiation hardness in order to operate in high luminosity environment. A possible technology which could give such performances is 3D silicon detectors. This work explores the possibility of a pixel geometry by designing and simulating different solutions, using Sentaurus Tecnology Computer Aided Design (TCAD) as design and simulation tool, and analysing their performances. A key factor during the selection was the generated electric field and the carrier velocity inside the active area of the pixel.

1. Introduction

In future high luminosity LHC (HL-LHC) experiments planned over the next 10 years, the number of collisions per unit of time is expected to increase by more than a factor of 2 [1]. This will make possible to study rare phenomena and extend the knowledge of fundamental interactions. To detect particle collisions, their products and also the interaction processes in these extreme conditions, detectors with very high space and time resolution will be needed (less than 100 μm in space and 100 ps in time). To date, there are no particle detectors with such performances. A new approach to improve especially the time resolution is to use three-dimensional (3D type) detectors. 3D Detectors are solid state devices introduced for the first time

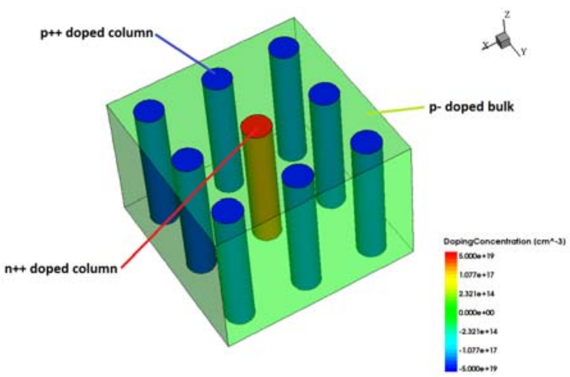


Figure 1. Schematic view of a typical 3D-detector pixel. In this model the electrodes have a cylindrical design and cross the wafer through all the thickness.

by Sherwood Parker during the nineties [2] and have been used increasingly in particle physics experiments in the last decade, like at ATLAS IBL [3]. Unlike classic planar detectors, the main feature of these devices is to have their electrodes oriented perpendicularly to the wafer surface (Fig. 1) and penetrating deep inside the bulk (up to hundreds of μm). The main structural advantage of this approach is that the distance between the electrodes is decoupled from the wafer thickness, which gives the detector a lower bias voltage, rapid charge collection and so a faster time response (less than 500 ps) and a higher current signal amplitude [4]. High intrinsic radiation tolerance, due to the shorter inter-electrode distance and the lower bias voltage, is another main feature of those devices, demonstrated with an intense proton irradiation [5].

The realization of this kind of particle detectors requires non-standard realization processes that allows to excavate with accuracy for several hundreds of μm without damaging the wafer. Main techniques used actually by the foundries to build such structure are, for example, etching techniques like DRIE (Deep Reactive Ion Etching)[6].

The possibility to use the shorter charge collection time of 3D detectors for timing application has not yet been thoroughly investigated. First studies about timing performances and possible associate fast front-end electronics are analysed by Sherwood Parker et al. in 2011 [4].

The aim of this work is to study the possibility of a particle detector with high time and space resolution and also high radiation hardness in order to operate in the extreme conditions in future HL-LHC experiments, starting with a first selection of possible pixel geometries.

2. Geometry Design and Simulation

At first more than 20 different geometry solutions have been explored and two of them have been selected for a more accurate analysis. The geometries are divided up into 2 main categories: square pixel geometries with a dimension of 50 μm times 50 μm and hexagonal pixel geometries with 50 μm in diameter. With these dimensions the charges reaches in less time the electrodes, reducing charge collection time and thus increasing the time resolution. All solutions share the same constant doping profiles, with concentrations of $5{*}10^{19}/\text{cm}^3$ for the p++ (Boron) and n++ (Arsenic) doped electrodes and $7{*}10^{11}/\text{cm}^3$ for the p−− doped bulk (Fig. 2). Design and

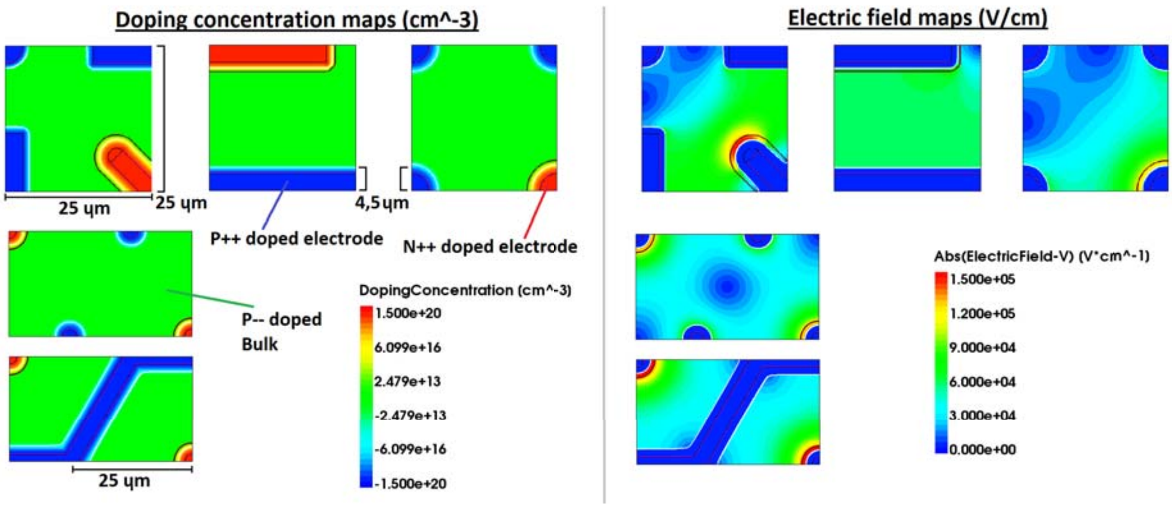


Figure 2. Doping concentration and electric field maps of 5 of the 20 explored geometry solutions. Hexagonal and square pixels are not in same scale.

simulation were performed using Synopsys Sentaurus TCAD [7] to predict mainly the electric field and the carrier velocity inside the active area of the device. Those informations are found by solving the continuity and Poisson's equations, which relates charge density and potential.

Also the simulation takes into account all charges inside the device and possible presence of traps, level defects and carrier recombinations [8]. Simulation was set in quasi stationary mode with a P-electrode bias voltage ramp starting from 0 V and decreasing to -200 V, while the N-electrode potential was set constant at 0 V. During the simulation, electric field and carrier velocity maps were saved at voltages of -50 V, -100 V, -150 V and -200 V. The second bias voltage was chosen as reference voltage to compare the performances of all geometries. During the first selection step only 2D models of the geometries were designed in order to understand the electric field behaviour between the electrodes and the velocity for electrons and holes inside the devices. This approach, including 2D models which represents only 1/4 of the entire pixel, reduces computational resources and simulation time thus increasing the number of explored solutions. The analysis of the electric field was focused mainly by inspecting its amplitude in relation to the position inside the active region, which needs to be around 10-100 kV/cm, conditions to which velocity saturation occurs. In this way it is guarantee that the output signal of the detector has a constant shape independent of the position. This is possible thanks to the charge carrier velocity which is at its maximum value and stays constant. For pure silicon $1.07 * 10^7 cm/s$ for electrons and $8.37 * 10^6 cm/s$ for holes at 300 C[8].

Particular attention was paid to control the behaviour of the electric field in the critical regions, for example the space between electrodes at same potential. In these areas the electric field decreases too much and signal generation could potentially become too inefficient. In this case it is important that the electric field amplitude stays high enough to guarantee velocity saturation. If it is not possible to ensure velocity saturation inside those regions, charge collection becomes slower, making the device practically useless for the requested high performances. From

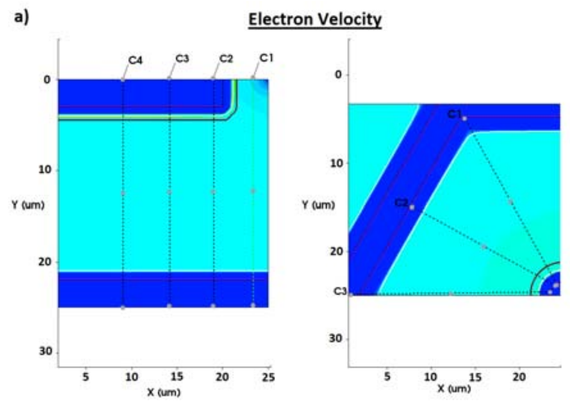
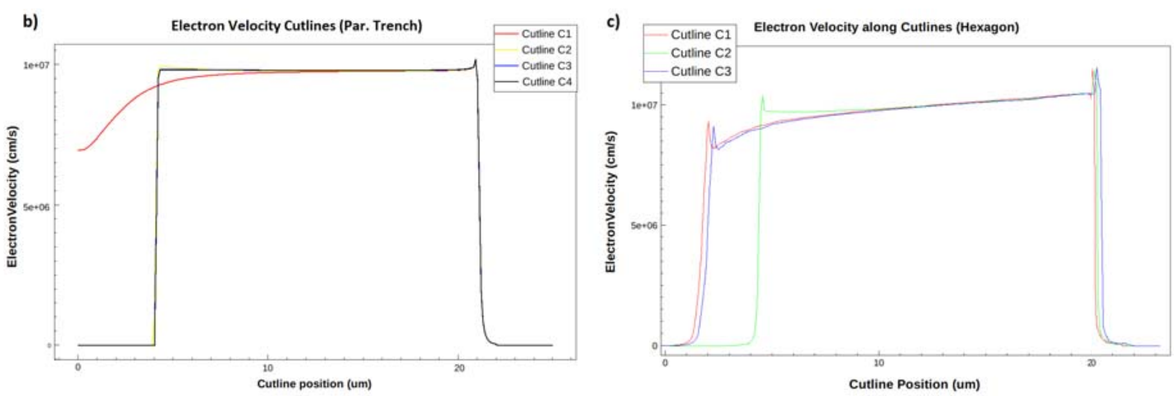


Figure 3. Electron velocity analysis for parallel and hexagonal geometry: (a) Electron velocity maps for the chosen geometry solutions. The plots (b) and (c) represent the electron velocity along the cut lines drawn over the velocity maps (a).



this first analysis only two solutions were chosen for the next step: one square pixel design with parallel trench geometry and one hexagonal solution with closed trench geometry. The parallel

IOP Conf. Series: Journal of Physics: Conf. Series **956** (2017) 012012 doi:10.1088/1742-6596/956/1/012012

trench pixel solution was chosen because it has an uniform electric field over all the active area. In the region between two n++ doped electrodes carrier velocity is below saturation level but can be neglected because this region is close the electrodes, ensuring a fast charge collection. Instead of the parallel trench, the hexagonal solution presents a less uniform field but the velocity saturation covers almost the entire active area, except the angular regions, where charge velocity goes under saturation level (Fig. 3). It is possible to restore the saturation in those regions by increasing depletion voltage from 100 V to 150 V.

During the second step, three dimensional models of the chosen pixels were designed and simulated. The models include more details of the real devices like p-spray surface doping, details of the electrode structure, silicon oxide layers and also metallic contacts. In this way it is possible to achieve a deeper understanding of the electric field behaviour inside the device. The results obtained from the simulation of the two models have shown that the electric field inside the parallel square geometry changes heavily along the bulk surface. Especially a high electric field was observed along the upper surface between the n++ doped electrode and the p-spray layer (Fig. 4). At the bottom of the pixel, the electric field decreases too much and charge velocity goes under its saturation value. A similar behaviour has also been observed for the hexagonal geometry, suggesting to find solutions in order to minimize this problem.

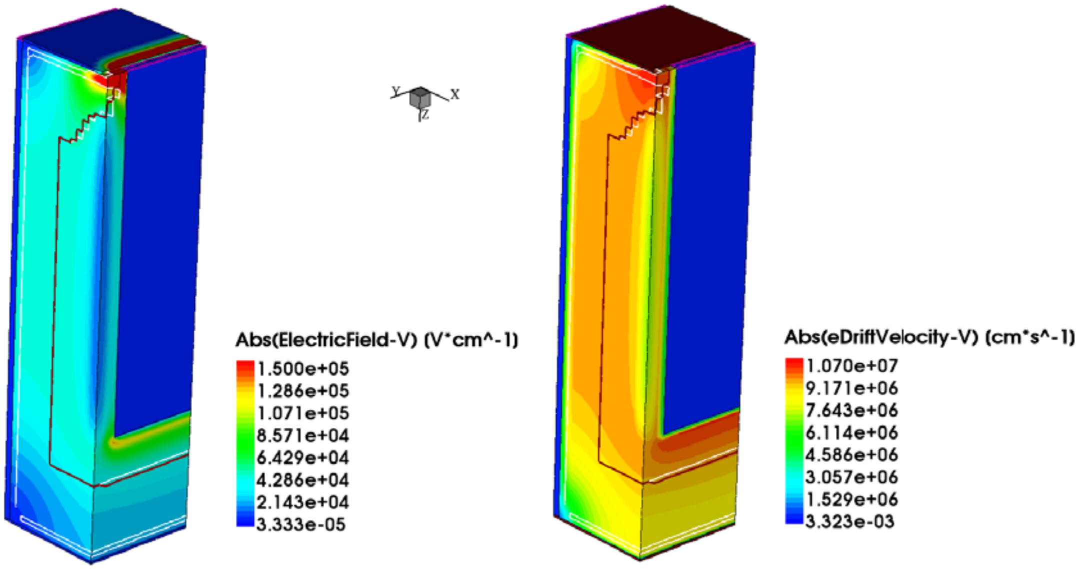


Figure 4. Electric field (left) and electron velocity (right) maps for the 3D model of the parallel trench pixel design. Velocity saturation is not maintained over all the active area, only between the main electrodes..

3. Next steps

The possibilities to simulate, using TCAD, the operation of the detector when crossed by a high energy particle are limited. This is due to the fact that the software is more oriented in the development and simulation of semi-conducting devices for mass production such as MOSFETs or LEDs, instead of particle detectors for high energy particle physics. The only way to simulate in first approximation the passage of a high energy particle through the detector and observe the generated current signal is to use the Sentaurus device Heavy Ion model (HI) [8], which is an implemented physical process developed for the main purpose of studying the effects of charge deposition from a high energy particle impact, like Single Event Upsets (SEU). It is

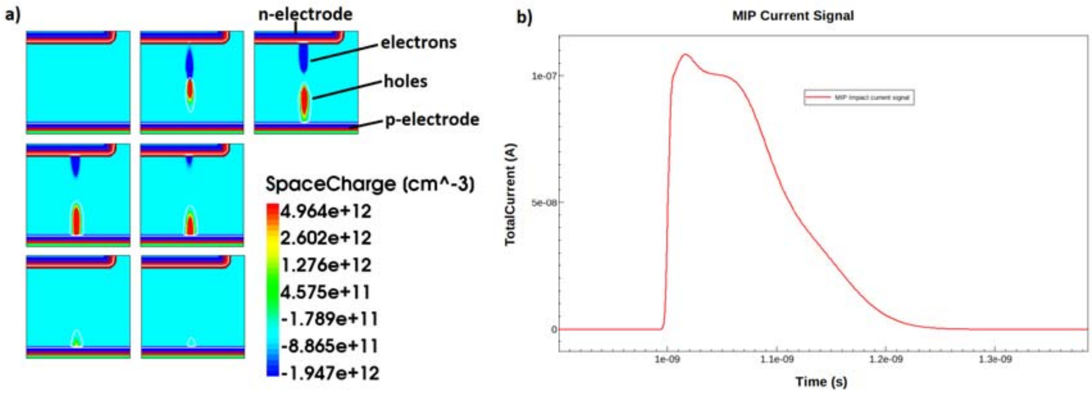


Figure 5. (a) Sequence showing the passage of electrons and holes generated by a passing MIP along the middle of the chosen pixel and respective current signal (b).

possible to tune an HI for many different cases, changing its specific parameters, which are the coordinates of the starting point, the direction and the length of the path and also the Linear Energy Transfer (LET) of the heavy ion [8]. In this case, the LET was set at 80 pair/μm in order to emulate the passage of Minimum Ionizing Particle (MIP), which can be for example a high energy proton. Using this kind of radiation model, only primary emission charge is considered, which is useful only to have a first charge collection time estimation.

Second emission particle, like delta rays, which are very important in understanding the timing error introduced by the detector, as mentioned by Sherwood Parker [4], are not considered in the HI model.

HI interaction was simulated in transient mode, saving every 30 ps a space charge map (Fig. 5a). The results obtained with this approximated approach showed current signals with 200-400 ps duration and rise time of 15-30 ps, in the case of parallel trench geometry [Fig. 5b].

Considering that the TCAD simulation is less accurate for describing a particle detector and its operation, a specific Monte Carlo simulation is under development, which will use the exported electric field maps from TCAD and will implement further interaction processes, like delta ray emission, in order to have a more accurate view of the time performances of the device. An other approach, based on Geant4 is currently under evaluation.

4. Conclusions

A first selection of detector pixel geometries has been completed and 2 main designs have been chosen (a square and a hexagonal). These geometric solutions have the best characteristics in terms of electric field amplitude and coverage, allowing to work in velocity saturation regime (with some limitations), which is the recommended operating configuration in order to keep an output signal with a specific shape.

First particle strike simulations show that the output signals were of the order of hundreds of ps with rise times around 20 ps.

Considering the lack of information about the performances of the detector in working conditions, it is important to investigate this issue by using other approaches, such as implementing a Monte Carlo simulation or using specific simulation tools like Geant4.

Acknowledges

I would like to thank Prof. Gianfranco Dalla Betta and Dr. Roberto Mendicino of the University of Trento for introducing me to 3D-detector design and simulation and for their initial support and guidance in this complex discipline.

References

[1] Schmidt B 2015 *The High-Luminosity upgrade of the LHC*, J.Phys.Conf.Ser. **706** no.2, 022002
[2] Parker S I, Kenney C J and Segal J 1997 *3D - A proposed new architecture for solid-state radiation detectors*, Nucl. Instrum. Meth A **395** 328-343
[3] ATLAS Collaboration 2010, *ATLAS Insertable B-Layer Technical Design Report*, ATLAS TDR 19, CERN/LHCC **2010-013**
[4] Parker S I *et al.* 2011 *Increased Speed: 3D Silicon Sensors; Fast Current Amplifiers* IEEE Trans. Nucl. Sci NS-**58**(2) 404
[5] Parker S I and Kenney C J 2001 *Performance of 3-D Architecture Silicon Sensors After Intence Proton Irradiation* IEEE Trans. Nucl. Sci NS-**48**(5) 1629
[6] Wu B *et al.* 2010 *High aspect ratio silicon etch: A review* J. Applied Physics **108** 051101
[7] Synopsys Inc. 2015 *Synopsys Sentaurus TCAD* Version 2015.06, https://www.synopsys.com/silicon/tcad.html
[8] Synopsys Inc. 2015 *Synopsys Sentaurus Device User Manual* Version 2015.06