TCAD simulation of small-pitch 3D sensors for pixel detector upgrades at High Luminosity LHC

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Abstract. Applications at the High Luminosity LHC (HL-LHC) have required the development of a new generation of 3D pixel sensors with increased pixel granularity, extreme radiation hardness and low material budget. To this purpose, new 3D pixels have small pitch (e.g., 50×50 or 25×100 µm²) and reduced active thickness (∼100 µm). Owing to the small inter-electrode spacing (∼28 µm in the most aggressive designs). These 3D pixels are expected to be radiation hard even after irradiation at the hadron fluences. Indeed, they are of interest for the innermost tracking layers of ATLAS and CMS (∼2×10¹⁶ nEQ cm⁻²), and beyond. In order to estimate the charge collection efficiency (CCE) after irradiation, TCAD simulations can be conveniently used, providing useful information for the optimization of sensor design and fabrication technology. Within the AIDA-2020 project, with reference to the new single-sided 3D technology from FBK (Trento, Italy), we have simulated the CCE of pixel sensors with different inter-electrode spacing irradiated at different fluences. For these simulations, a 2D domain was used, consisting of a horizontal slice taken at half the depth of a 3D sensor. Simulations consider the hit of a minimum ionizing particle, described by the Heavy Ion model at different points within the active area. In addition, bulk radiation damage is accounted by using advanced deep-level trap models. This paper reports a comprehensive description of the simulation results based on a radiation model validated by comparison to experimental results from n-in-p strip detectors at 248 K and 900 V bias.

1. Introduction

3D silicon sensors have applications in a wide scope of fields; most outstandingly, they are gotten ready for the use in experiments at the Large Hadron Collider (LHC) because of their high luminosity [1],[2], lower power dissipation and enhanced radiation hardness. Planar detectors are reached their limits at high fluences and are not preferred in this case [3]. The increase in the effective doping concentration would not allow to reach full depletion, and charge trapping could lead to the charge carrier drift length to be at most 50 µm, so that the collected charges would be drastically diminished [4]. Because of that 3-D detectors where emerged. Indeed, parker et al proposed the first standard 3D
detectors in 1997 [5]. This structure presents a 3-D array of vertical columnar electrodes arranged in adjacent cells etched perpendicularly to the wafer surface and penetrating through the entire substrate of a high resistivity Silicon. This architecture offers certainly some advantages with respect to the planar one [6], making 3D detectors ideal candidates for important applications such as in high energy physics (HEP). The electric field lines start from one electrode type and ends on the electrode of opposite type, in parallel with detector surface [5]. In 3D detectors, the depletion voltage and collected charges don’t depend to the substrate thickness as in the case of planar detectors, they depend to the substrate concentration and the detectors layout. Lower the inter-electrodes distance more collected charges with less collection time.

During the operation at LHC, the radiation makes damage to the detector, by introducing a deep-levels Donor-type and acceptor, this can give rise to leakage current, change in the effective space charge concentration and certainly a decrease of the charge collection efficiency as a result of the charge trapping [7].

In the light of the improvements to the HL-LHC "Phase2" detector, new generation of 3D pixel sensors have been developed by INFN-FBK collaboration [8]. A single-sided technology on Si-Si Direct Wafer Bonded 6'' substrates used to fabricate the devices [9]. Figure 1 shows the schematic cross-section of the proposed sensors.

![Figure 1. Schematic cross-section of the proposed single-sided 3D sensors on Si-Si DWB substrates [9].](image)

Indeed, in recent years, there has been a surge of interest in these kind of detectors as a result of their intrinsic capability to act on the layout of vertical electrodes because very high hit-rate capabilities is needed for nowadays applications, also high pixel granularity and extreme radiation hardness (up to a fluence of 2x1016 neq/cm2). hence, new 3D pixels have small pitch (e.g., 50x50 µm2 or 25x100 µm2) and reduced active thickness (~100 µm). Owing to the small inter-electrode spacing (~28 µm in the most aggressive designs), these 3D pixels are expected to be radiation hard even after irradiation at the hadron fluences of interest for the innermost tracking layers of ATLAS and CMS (~2x1016 neq cm-2), and beyond.

The overall aim of this study is to estimate the charge collection Efficiency TCAD simulation with a new combined TCAD radiation damage modelling scheme featuring both bulk and surface radiation damage effects.

2. Experimental measurements
In order to estimate the charge collection efficiency (CCE) after irradiation, TCAD simulations can be conveniently used, providing useful information for the optimization of sensor design and fabrication technology. Within the AIDA-2020 project, with reference to the new single-sided 3D technology
from FBK (Trento, Italy), we have simulated the CCE of pixel sensors with different inter-electrode spacing irradiated at different fluences [10]. For these simulations, a 2D domain was used, consisting of an horizontal slice taken at half the depth of a 3D sensor. Simulations consider the hit of a Minimum Ionizing Particle at different points within the active area. The terms source of the defect are provided by the expression Shockley Read Hall generation recombination [11],[12]. In addition, bulk radiation damage is accounted for by using the Perugia model proposed and tested by comparing models and experimental measurements from [13] as illustrated in Figure.2.

Figure 2. Comparison between simulated and experimental charge collection [13] in n-in-p strip detectors at 248 K and 900 V bias. In the inset the effect of the surface damage on the charge collection is shown for high fluences (for particle hit interesting the high high-field regions) [7].

The layout of small pitch 3D sensor is very simple, the major drawback of it is on the basic of the bump-bonding pad which has a very specific size (see Figure. 3, referring to FBK technology [13],[10] with 5 µm column diameter and 20 µm bump pad diameter).

Figure 3. Layout of small pitch 3D pixels made with single-sided FBK technology : (a) 50×50 µm2, (b) 25×100 µm2 (1E), and (c) 25×100 µm2 (2E) [10].

For the size of the two-pixel cases 50×50 µm2 (Figure. 3a) and the 25×100 µm2 with one read-out electrode (1E, Figure. 3b). The bump pad can be positioned safely away from the columns: although it is so important to mention that for the latest layout there is a serious limitation due the inter-electrode spacing (L) is ~51.5 µm that is insufficient for the requests of high radiation hardness. A neater solution for this problem is to improve the design by adding another readout electrode (2E, Figure. 3c), leading to L~28µm. Although this solution is interesting, it suffers from closer distance between the read-out and the Ohmic columns. Consequently it’s very important to use a better lithography system, another solution is to place the bump-pad directly on top of the columns.

3. Results
Initial studies were executed using the conditions described above. The charge collection efficiency (CCE) has been estimated for three different structures 50×50 µm², 25×100 µm² with one read-out
electrode (1E, Figure 3b), and 25x100 µm² with two read-out electrodes (2E, Figure 3c) by considering a Minimum Ionizing Particle (MIP) hitting the sample diode perpendicularly in different positions, after that an average of these amount of charges was made to better match the experimental results.

In order to do this, three different fluences were applied to the structures; 1e15 neq/cm², 1e16 neq/cm², 2e16 neq/cm². The charge collection efficiency (CCE) has been obtained by applying a different reverse voltages between P and N columns up from 0 to 250V.

For the 50x50 µm² structure which has inter-electrode distance of 36 µm we clearly note that the collection charge efficiency decreases with the increases of the fluences (figure 4), what stands out also is that saturation in collected charges attend firstly in low fluence (1e15neq/cm²). These results may help us understand the effect of radiation damage to the detector. The big dose makes some trapping in the bulk of the detector, in this case some charges will never arrive to the electrodes, or arrive after long time (ms), that would make no sense, because the detector is very fast (ns).

![Figure 4. The CCE for the structure (50µm-50µm).](image)

Figure 4. The CCE for the structure (50µm-50µm).

For the, 25x100 µm² structure with one read-out electrode (1E, Figure 3b) were not very encouraging owing to the lowest charge collection efficiency (Figure 5). This is due to the increased inter-electrode spacing (L) is ~51.5 µm. However, adding new readout electrode (2E, Fig. 2c) decreases the inter-electrode spacing; L~28µm, therefore we could have more collected charges (Figure 6).

![Figure 5. The CCE for the structure (25µm-100µm, 1E) (one readout column).](image)

Figure 5. The CCE for the structure (25µm-100µm, 1E) (one readout column).

![Figure 6. The CCE for the structure (25µm-100µm, 2E) (two readout columns).](image)

Figure 6. The CCE for the structure (25µm-100µm, 2E) (two readout columns).
Now Figure 7 shows the two hitting points (5.9 µm -5.9 µm),(1.5 µm -23.5 µm) at the fluence of 5e15 neq/cm². What is striking in this figure is the difference between the collected charges in this two hitting points (Figure 8), when the particle hit the detector in the diagonal (5.6µm-5.6µm) which is one of the preferable hitting points, the amount of collected charge can be at the highest value, this is due to the high electric field between the two electrodes of opposite types, however when the particle hits in between two electrodes from the same type where the electric field is very low, the collected charges would be at the lowest value.

![Figure 7. schematic of the hitting points positions](image)

![Figure 8. CCE for the two points (5.9 µm-5.9 µm),(1.5µm -23.5µm) at 5e15 neq .cm²](image)

4. Conclusion
In this paper, we have reported a TCAD simulation of small-pitch 3D sensors for pixel detector upgrades at High Luminosity LHC. In order to estimate the charge collection efficiency (CCE) after irradiation. For this, a 2D domain was used, consisting of an horizontal slice taken at half the depth of a 3D sensor. Different inter-electrode spacing irradiated at different fluences was presented. The DDM model was considered and the net rate of generation-recombination was estimated with the Perugia model.

We have essentially noted that the fluences, the inter-electrode spacing and the readout electrode have a considerable effect on the CCE.

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