Nuclear Instruments and Methods in Physics Research A 1080 (2025) 170749

Contents lists available at ScienceDirect

Nuclear Inst. and Methods in Physics Research, A

journal homepage: www.elsevier.com/locate/nima

Full Length Article

Transient simulations of MAPS using TCAD, Allpix squared & SPICE

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ARTICLE INFO

Keywords:
Simulation
Monte Carlo
Silicon detectors
TCAD
Geant4
Allpix squared
Pixel detectors
MAPS

ABSTRACT

Monolithic Active Pixel Sensors (MAPS) designed in a 65 nm CMOS imaging technology are an alternative to hybrid pixel sensors as they eliminate the demand for flip-chip bonding while reducing material budget through thinner active sensor layers. The TANGERINE project aims to create a 65 nm MAPS sensor with a small collection electrode for use in future lepton colliders and beam telescopes. This project encompasses the entire sensor R&D process, including electronics and design, simulations, prototype characterization, laboratory testing, and test beam measurements.

Predicting the behavior of these sensors is challenging due to the intricate interaction between the doping regions in the small collection electrode design, which results in nonlinear electric fields. As a result, detailed simulations are critical for estimating sensor performance and directing design adjustments. The simulation strategy combines Monte Carlo simulations with electric field fields from Technology Computer-Aided Design (TCAD).

Based on this approach, more detailed studies can be performed. This paper focuses on transient simulations to analyze sensor response over time, providing helpful information into charge collection dynamics and timing performance.

1. Introduction

Planning the next generation of particle colliders to succeed the LHC is a central focus of high-energy physics in the coming decades. Among the leading proposals are lepton colliders, such as electron-positron (e^+e^-) machines. Vertex detectors are essential components of these experiments, requiring higher granularity and a reduced material budget to achieve improved spatial and temporal resolution.

As pointed out in the CERN EP R&D program [1] on technologies for future experiments, next-generation vertex detectors must meet stringent performance requirements. These include a material budget below 0.05% X/X_0, a single-point resolution of approximately 3 μm, a time resolution of few nanoseconds, rate capabilities of up to 1 MHz per pixel, and a granularity of around 25 × 25 μm^2. Achieving these specifications demands significant advancements in sensor technology and detector design.

However, developing and optimizing these detectors is a complex and resource-intensive process. Fabrication and testing of prototype sensors require substantial financial investment and long development cycles. To mitigate these challenges, advanced simulation tools are essential for accurately modeling detector performance and guiding design improvements before prototype fabrication.

This paper presents a simulation package that integrates widely used tools for silicon detector modeling. The Allpix^2 framework [2] combines electric fields and doping concentration profiles obtained from TCAD simulations with Geant4 simulations of particle interactions with matter, enabling a detailed investigation of different sensor designs.

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https://doi.org/10.1016/j.nima.2025.170749
Received 15 April 2025; Received in revised form 4 June 2025; Accepted 6 June 2025
Available online 11 July 2025
0168-9002/

2. Methodology

The results presented in this proceeding are based on the concepts and specifications of monolithic active pixel sensors (MAPS) with small collection electrodes in a 65 nm CMOS Imaging Sensor (CIS) technology. However, the core simulation technique and subsequent developments should apply to different sensor technologies, with appropriate modifications to fit individual design features [3].

2.1. The sensor design

Fig. 1 depicts a vertical cross-section of a single pixel cell and displays two types of MAPS layouts: Standard and N-Gap. These layouts originated from the 180 nm CMOS imaging process and are adapted to 65 nm technology.

Both layouts share the same basic pixel structure, consisting of a collection electrode (in red) surrounded by a p-well region that houses the in-pixel electronics. The pixel structure consists of an epitaxial layer grown over a substrate.

In the Standard layout, the depletion region remains small and localized around the collection electrode. The N-Gap layout incorporates an additional n-type implant, which expands the depletion region toward the pixel edge. This modification also enhances the lateral component of the electric field, directing charge more efficiently toward the collection electrode.

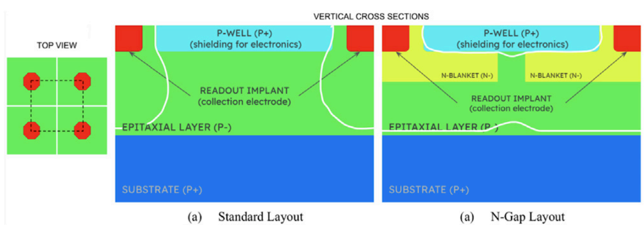


Fig. 1. A schematic cross section of a single pixel cell in the CMOS processes being investigated. The top view's dashed line indicates the area that is simulated in TCAD in Section 2.2.1. The white line indicated the depleted region.

2.2. The simulation approach

2.2.1. Technology Computer-Aided Design simulation

The highly nonlinear electric fields in MAPS require precise simulation, which cannot be achieved with a parameterized approach. This study employs TCAD simulations with generic doping profiles to model sensor behavior [4]. All TCAD simulations were performed in 3D using Sentaurus TCAD from Synopsys [5].

Fig. 2 shows a generic 3D simulation of a single pixel cell (formed by four pixel corners, as indicated by the dashed line) in the N-Gap layout, displaying the doping concentration profile. This plot provides information on the distribution of dopants within the pixel structure. The corresponding electric field characteristics are shown in Fig. 3.

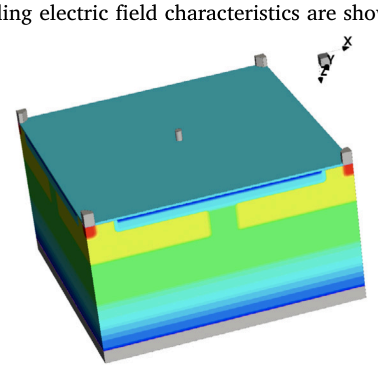


Fig. 2. Generic 3D TCAD simulation of the n-gap layout of single pixel cell showing doping concentration profile (cm^{-3}).

In the Standard layout, a large undepleted region at the pixel edges leads to charge carriers in these areas moving primarily by diffusion, which increases charge sharing with neighboring pixels and thus enhances spatial resolution. In contrast, the N-Gap layout is designed to collect charge more efficiently to the collection electrodes, reducing charge sharing while increasing detection efficiency.

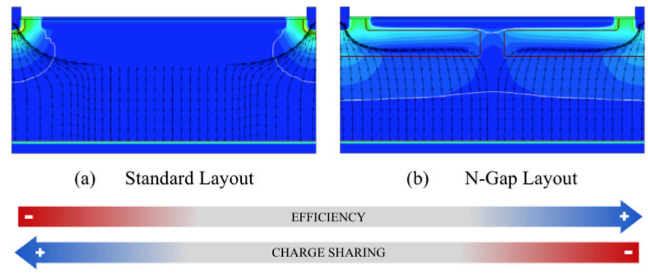


Fig. 3. Electric field profiles ($V \times cm^{-1}$) of two sensor designs produced with TCAD. The overlapped black lines represent the negative charged particles traveling toward the collection electrode. Equivalent results are reported at [4,6,7].

The simulations represent a square pixel with a size of 20, 25, and 35 μm, an epitaxial layer thickness of 10 μm, and a total sensor thickness of 50 μm. The collection electrodes establish ohmic contacts with a bias of 1.2 V, while the p-well and p-substrate are biased to −1.2 V. Similar simulations have been conducted for various layout configurations and pixel sizes, enabling a comprehensive analysis of design variations and their impact on sensor performance.

2.2.2. Monte Carlo simulation

Allpix^2 is a modular simulation framework for modeling semiconductor-based detectors [2]. Externally computed electric field distributions and doping profiles from TCAD simulations can be imported as reported in this proceeding.

3. Studies

Building on the generic simulation approach, more in-depth studies can be conducted. For example, simulated data can be compared with test beam measurements to validate the simulation accuracy, and different pixel geometries, such as square and hexagonal designs [8], can be systematically analyzed to assess their impact on performance. Furthermore, detailed transient simulations allow for the investigation of the sensor response over time, providing insights into charge collection dynamics and timing characteristics. This paper will focus on transient studies, while other study cases have been presented in past publications [3,4,6,7] or will be published in the future.

3.1. Transient studies

Performing transient simulations [9] with TCAD requires significant computational resources, making the combination of Allpix^2 and TCAD a practical alternative. The Shockley–Ramo theorem is used to calculate the signal produced by each charge carrier at the collecting electrode. To apply the theorem [10,11] in transient simulations, the weighting potential must be determined. This is done by computing the difference between the electrostatic potentials obtained when slightly varying bias voltages to one collecting electrode while keeping the other electrodes at a constant bias voltage.

Fig. 4 illustrates the data flow for executing transient simulations using the combined electrostatic TCAD+Allpix^2 approach. To model the electronics, the output signal from Allpix^2 can be imported into circuit simulation software such as Cadence or LTSpice, as discussed in Section 3.1.1.

The charge collection studies involve placing a vertical path of charge carriers at predefined positions within the high-resistivity epitaxial layer. The technique known as Linear Energy Transfer (LET),

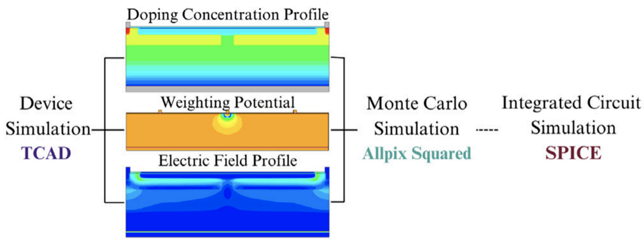
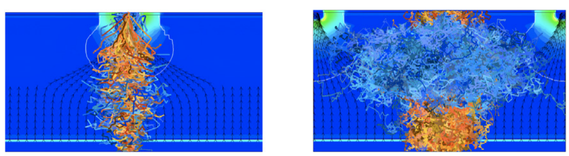


Fig. 4. Simulation data flow.

emulates the energy loss of a charged particle as it passes through silicon. All LET simulations in this study employed a value of 63 eh/μm. However, simulations with larger charge deposition produced comparable results.

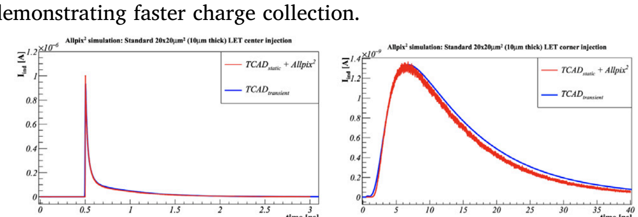
Two charge injection locations, at the pixel center and corner, were explored to determine the optimal and worst instances for charge sharing. Figs. 5(a) and 5(b) represent the paths of charge carriers using Allpix^2 linegraphs.



((a)) Center injection ((b)) Corner injection

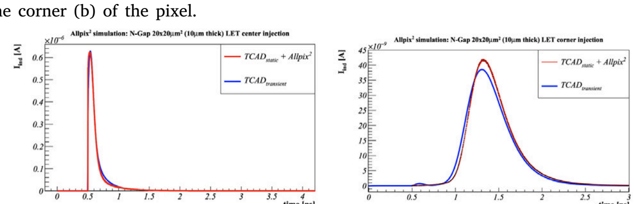
Fig. 5. Example of charge injection at the pixel center (a) and corner (b) at 1 ns for the Standard layout. The linegraphs are artificially overlapped with the electric field profile for visualization purposes. The electron and hole paths are represented in blue and orange, respectively.

The simulation results are presented in Figs. 6 and 7. In the transient TCAD approach, the output represents a single pulse, whereas in the combined approach, it corresponds to an average of 1000 pulses. The charge injection near the pixel corner results in maximum charge sharing and diffusion, delaying charge collection. In the Standard sensor layout (Figs. 6(a) and 6(b)), charge collection is slower due to the small depletion region around the collection electrode. In comparison, the N-Gap arrangement (Figs. 7(a) and 7(b)) exhibits larger currents and collection times of less than 4 ns at both injection positions, demonstrating faster charge collection.



((a)) Center injection ((b)) Corner injection

Fig. 6. Comparison of the induced current between TCAD and TCAD + Allpix^2 of a 20 μm × 20 μm pixel in Standard layout. Plots show the injection in the center (a) and the corner (b) of the pixel.



((a)) Center injection ((b)) Corner injection

Fig. 7. Comparison of the induced current between pure TCAD and TCAD + Allpix^2 of a 20 μm × 20 μm pixel in N-Gap layout. Plots show the injection in the center (a) and the corner (b) of the pixel.

Nevertheless, both sensor configurations exhibit strong qualitative agreement between methods, with slight discrepancies likely arising from differences in the computation of the induced current across frameworks.

3.1.1. Integrated circuit simulation

By combining Monte Carlo and SPICE (Simulation Program with Integrated Circuit Emphasis) simulations (as shown in Fig. 4), the full detector response can be reconstructed. In this approach, transient current signals are applied to the readout electronics' input node, and the output signal at the output node is measured.

This method provides an accurate comparison with experimental data. The Analog Pixel Test Structure (APTS) [12], developed at CERN, is a chip prototype with an analog readout designed to evaluate different sensor layouts and support studies for the ALICE ITS3 upgrade. It serves as a case study for this simulation method, demonstrating its ability to reproduce the analog output of the APTS-SF source follower.

The detector prototype was calibrated using a ^{55}Fe source, which was placed over the four central pixels, and the resulting waveforms were recorded. A corresponding simulation was performed in Allpix^2, following the same setup as the experiment. The simulated waveforms were exported and used as a current source in the SPICE simulation. The ^{55}Fe measurements were used to determine the input capacitance and noise of the sensor to calibrate the SPICE simulation.

A comparison between experimental data and simulations for the N-Gap layout is presented in Fig. 8. To improve statistical accuracy, signals from all pixels were combined. In both simulation and data, a threshold of 300 electrons was applied.

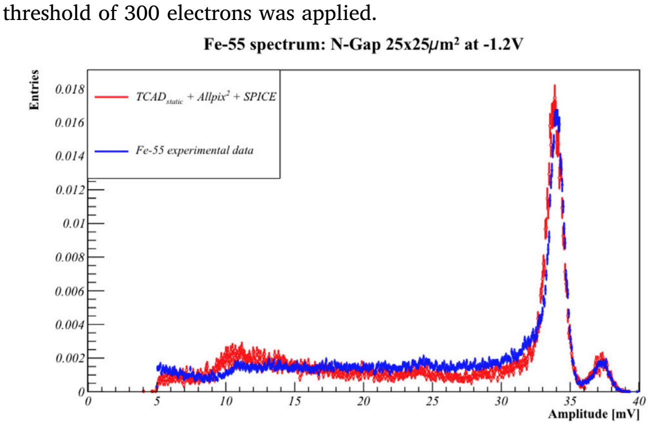


Fig. 8. Comparison between simulation and data amplitudes using ^{55}Fe source.

The plot illustrates that most events fall within the K-alpha or K-beta peaks, reflecting the improved charge collection efficiency of the layout. Events involving multiple pixels contribute to most of the remaining distribution.

4. Summary

Simulations were performed using TCAD and Allpix^2 frameworks to simulate a sensor using generic doping profiles. TCAD-based device simulations generate the complex electric fields characteristic of small collection electrode MAPS, while Monte Carlo simulations provide performance parameters that can be directly compared with experimental data. Additionally, a time-efficient transient simulation approach was developed, offering deeper insights into charge collection dynamics. These techniques form a foundation for optimizing sensor design and improving performance assessment in future detector developments.

The transient simulation methods investigated exhibit qualitative agreement between data simulation methods (electrostatic TCAD+Allpix^2 and pure TCAD), despite minor deviations likely arising from differences in the calculation of the induced signal. SPICE simulations of the front-end response show a strong match in peak values of the ^{55}Fe spectrum, validating the simulation method.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

This work was conducted within the framework of Tangerine group, a Helmholtz Innovation Pool Project. The presented simulation studies were carried out in collaboration with the CERN EP R&D program.

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