Simulating Monolithic Active Pixel Sensors Using Generic Doping Profiles

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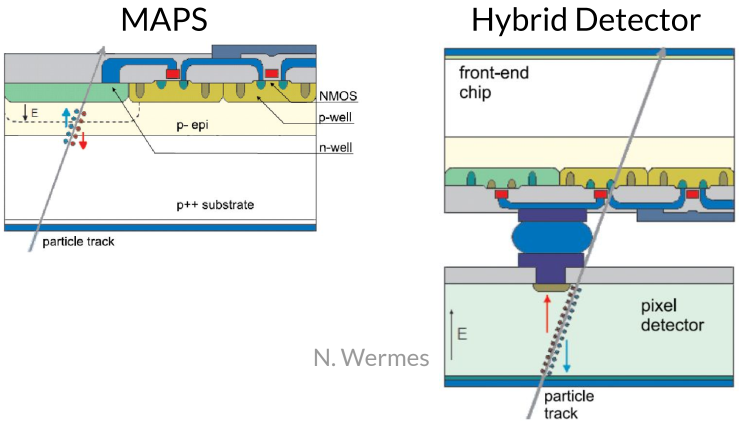
Introduction & Motivation

Monolithic active pixel sensors (MAPS) in particle physics:

★ Reduction in material budget compared to most hybrid detectors



N. Wermes

Science moving to CMOS commercial foundries

Advantages & Disadvantages:

★ Solution to single-vendor problem
★ Profit from state-of-the-art technology
★ Reduce costs in large-scale production
★ Limited access to manufacturing process information

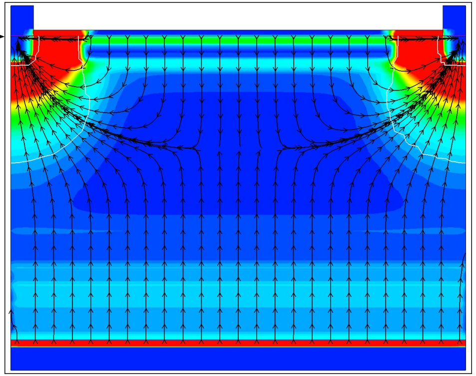
Introduction & Motivation

Developing a new detector:

★ Prototype Testing: characterize sensor under realistic conditions

★ **Simulations:** predict sensor behaviour and test designs

- Electric field distribution in sensor highly dependent on doping concentration and doping profiles
- MAPS with a small collection electrode have highly complex electric fields



A Technology-Independent Approach Using Generic Doping Profiles

★ Performing simulations based on **fundamental principles** of silicon detectors and using **generic doping profiles**

→ MAPS performance parameters can be inferred

★ **Do not** aim to resolve CMOS imaging processes, but merely describe general features relevant for sensor volume response

★ Results shown in context of **Tangerine Project** (see following talks)

★ Methodology described is useful for many different silicon sensor simulations

→ Toolbox for similar simulations

→ Extracting reasonable description of sensor behaviour

Tools

Sentaurus TCAD

SYNOPSYS®
Silicon to Software™

Technology Computer-Aided Design

+

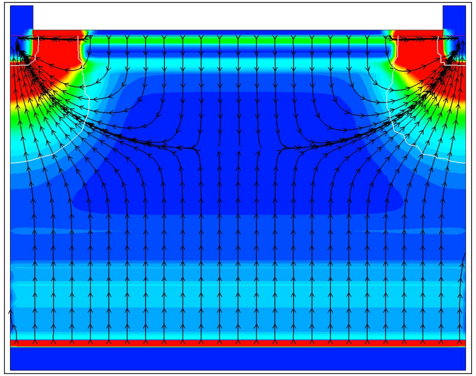
ap² allpix squared

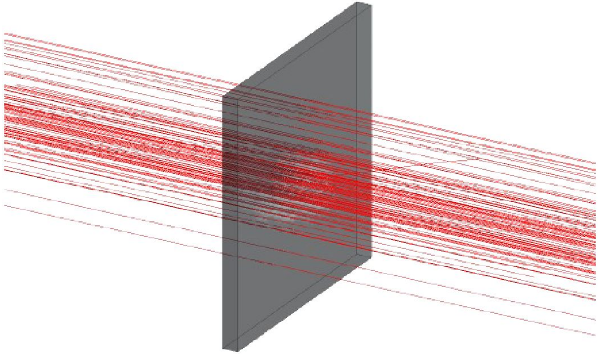
Allpix²: Monte Carlo Simulations for Semiconductor Detectors

https://doi.org/10.1016/j.nima.2018.06.020

- ★ Model semiconductor devices by means of finite element analysis
- ★ Electric Fields: accurate and realistic

- ★ Simulate full response of semiconductor detector
- ★ Particle Events: fast and high statistics

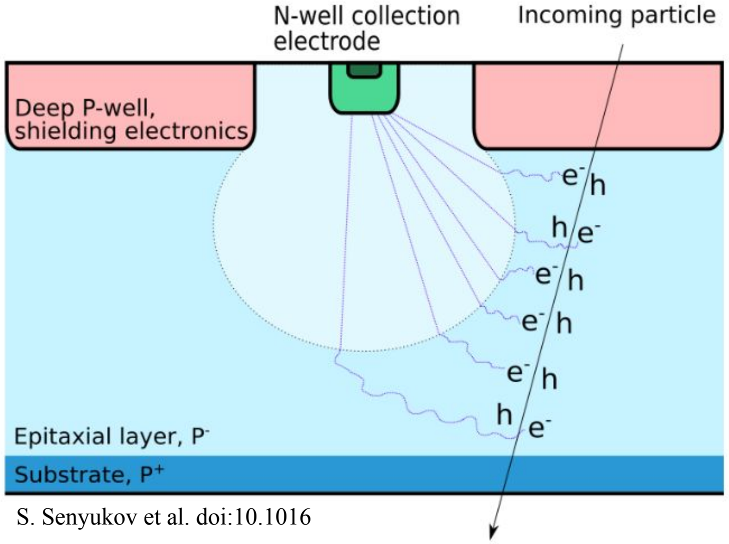




Layouts & Assumptions

General Layout & Assumptions

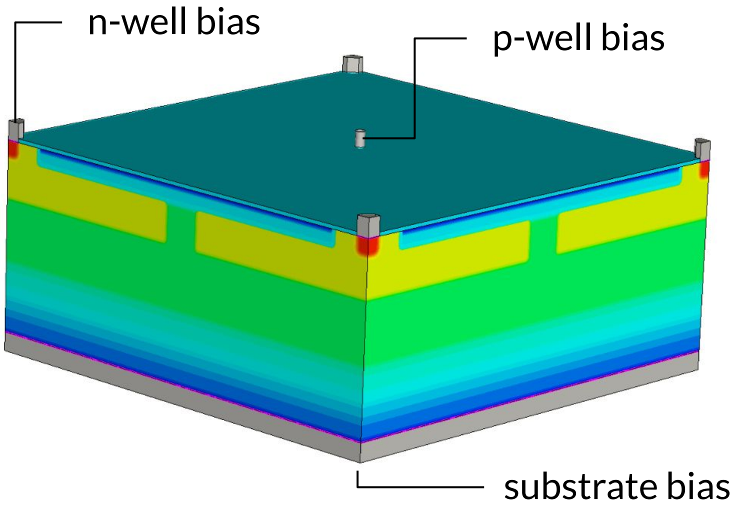
- ★ High-resistivity p-doped epitaxial layer grown on electronics-grade p-doped silicon substrate
- ★ Approximate public doping concentrations:
  - Substrate: 10^{19} cm^{-3}
  - Epitaxial layer: $3 \cdot 10^{13}$ cm^{-3}
  - Doping wells: 10^{15} to 10^{19} cm-^{3}
- ★ Doping wells simulated without internal structure and as flat profiles:
  - Small collection n-well in the centre of the pixel
  - P-well hosts and shields in-pixel CMOS electronics



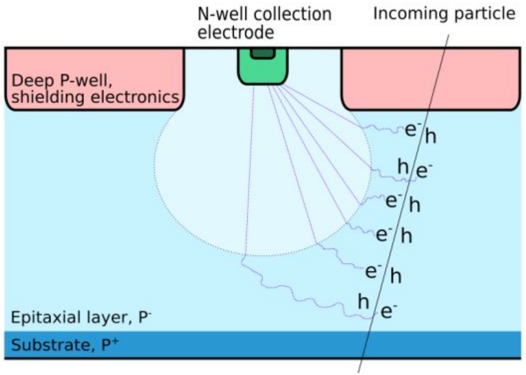
S. Senyukov et al. doi:10.1016

Geometry & Layouts

- ★ 3D geometry with collection wells in corners
- ★ Ohmic contacts simulated to provide bias voltages (highly-doped region)
- ★ Substrate is simulated only in Allpix^2, not in TCAD
- ★ Rectangular and hexagonal pixel geometries (see talk by H. Wennlöf)
- ★ Layouts with modifications to improve electric field



Standard Layout



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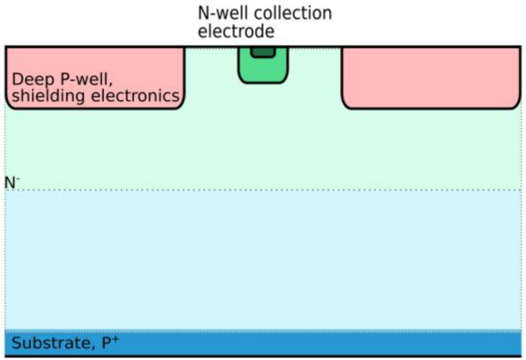
N-Blanket Layout



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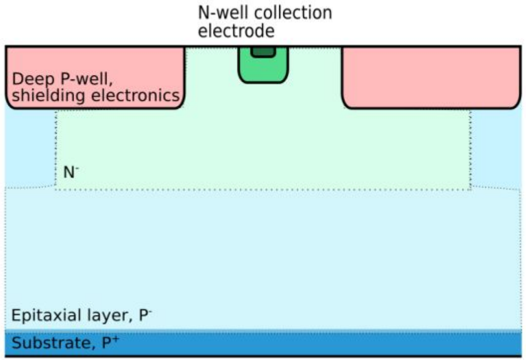
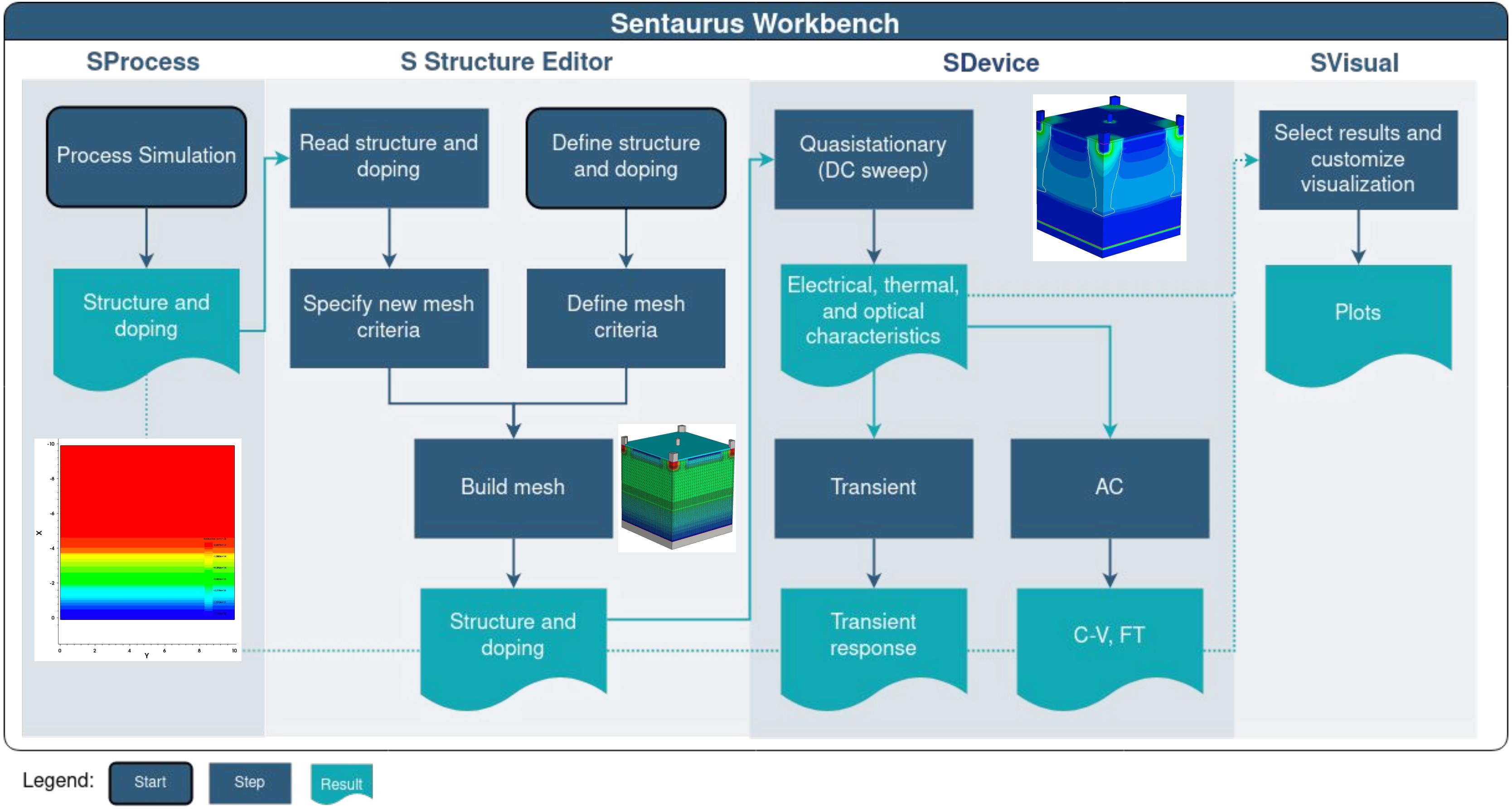
N-Gap Layout



M. Münker et al 2019 JINST 14

Finite Element Simulations with TCAD

TCAD Simulation Workflow Example



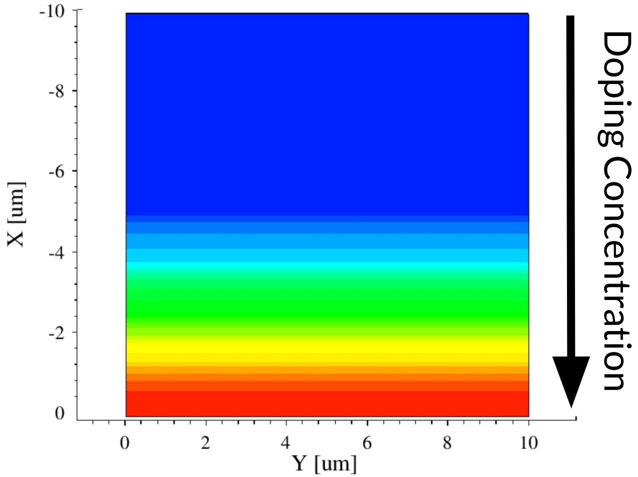
TCAD Simulations

★ Scans over different parameters: well doping concentrations, mask geometries and operational voltage
★ Observe behavior of electric field, lateral electric field and depleted volume
★ Select parameters that reproduce expected physical behaviour

TCAD - Process Simulations

Effects from production process temperatures

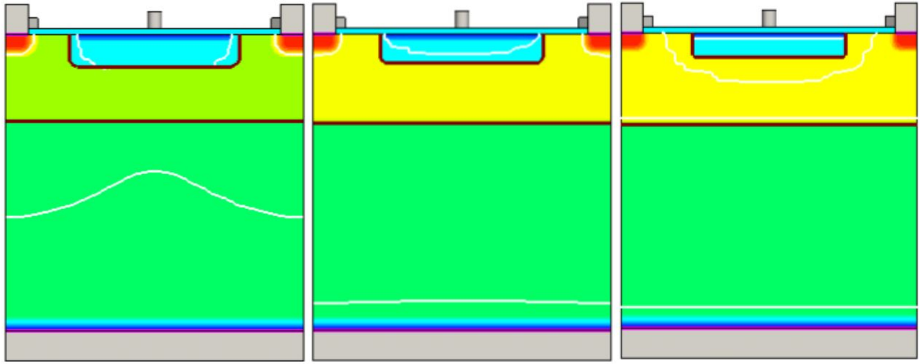
★ Diffusion between different doping regions
★ Continuous interface between epitaxial layer and substrate



TCAD - Quasistationary Simulations

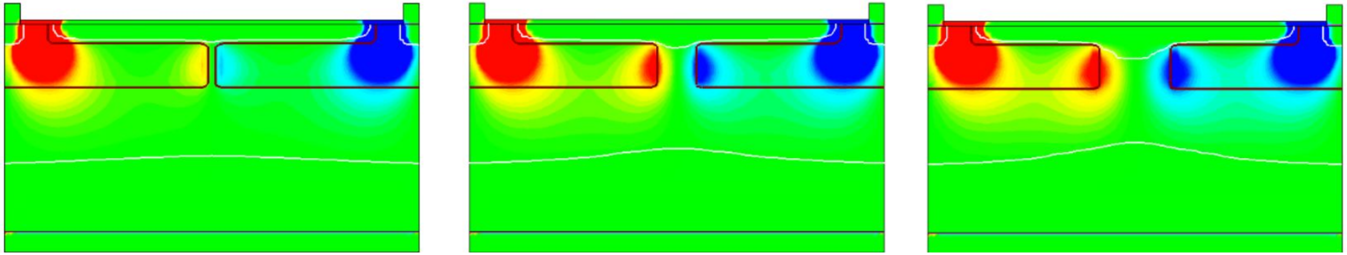
- ★ N-blanket doping concentration scan
  - ○ Impact on depleted volume (white line)
- ★ N-gap size scan
  - ○ Impact on lateral electric field (red and blue regions)

Doping Concentration



(a) $1 \cdot 10^{14}$ cm^{-3} (b) $9 \cdot 10^{14}$ cm^{-3} (c) $4 \cdot 10^{15}$ cm^{-3}

Lateral Electric Field



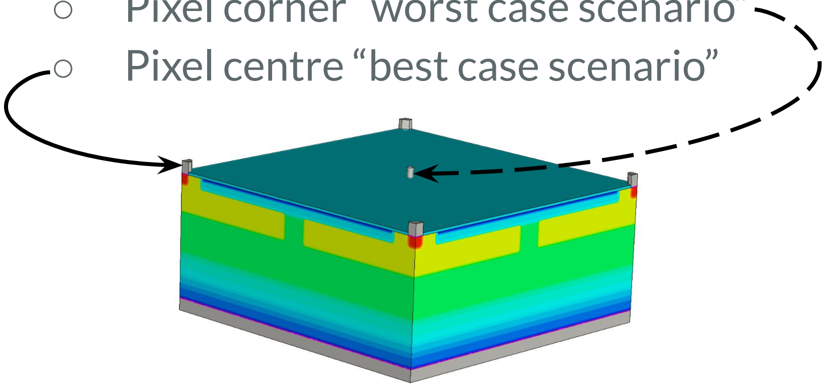
(a) 1 µm gap (b) 2.5 µm gap (c) 4 µm gap

TCAD - Transient Simulations

Time-dependent induced signal by MIP

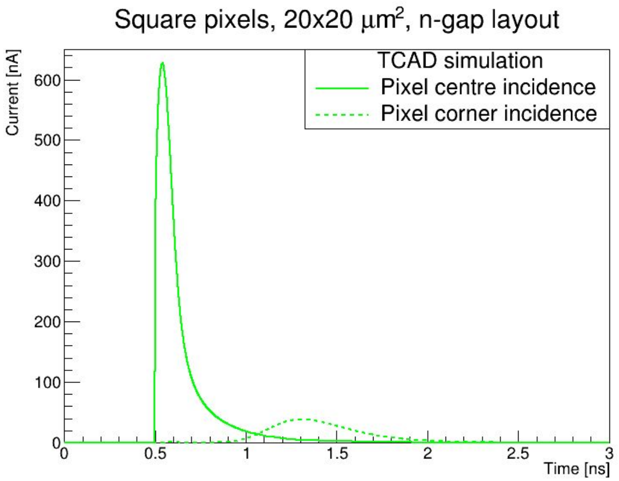
★ MIP incidence comparison

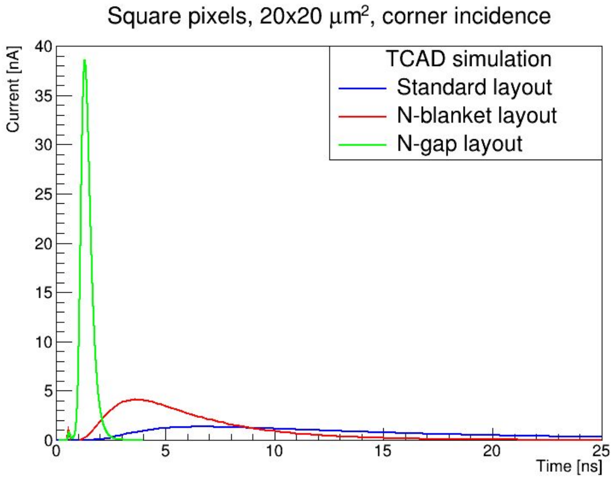
- ○ Pixel corner “worst case scenario”
- ○ Pixel centre “best case scenario”



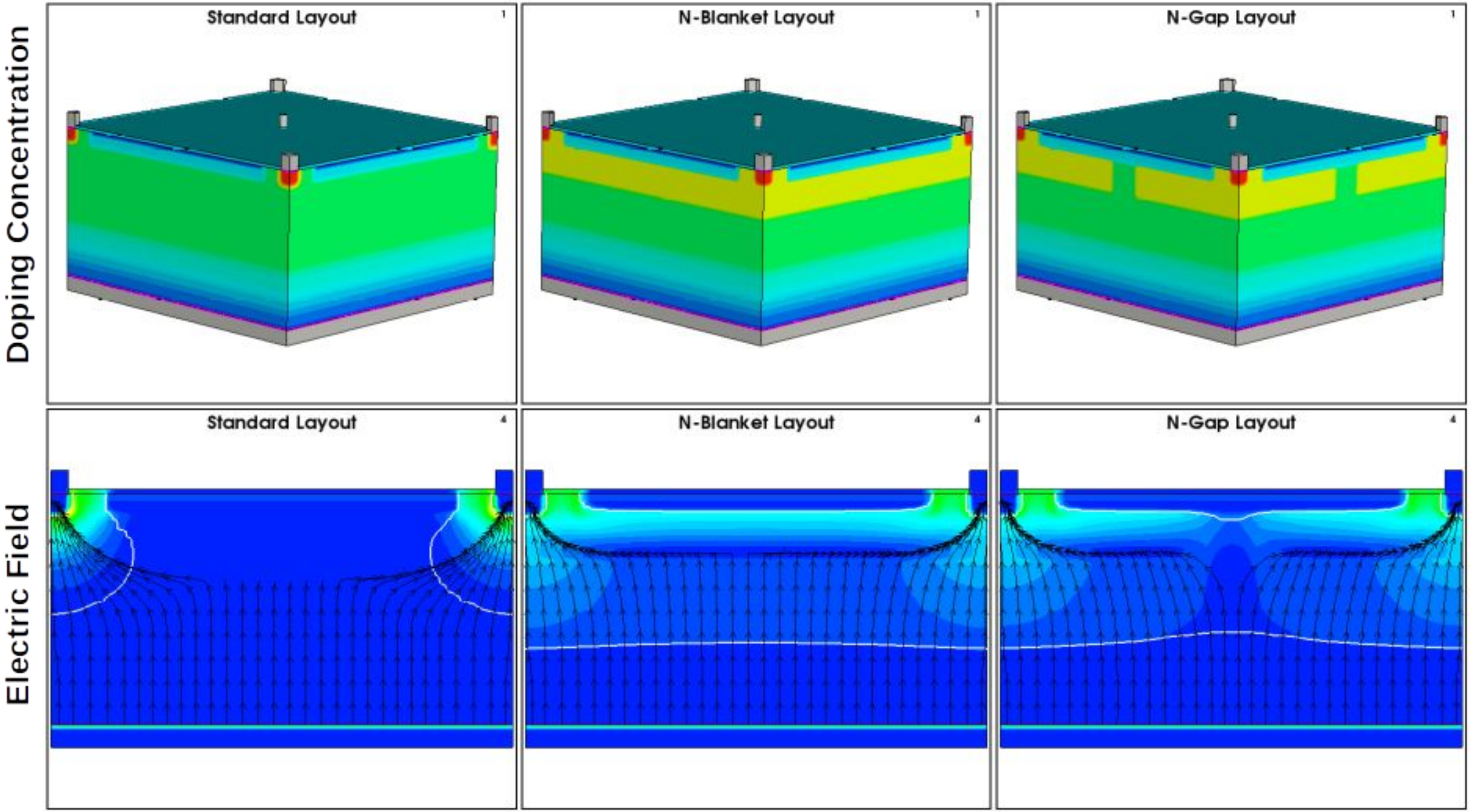
★ Layout comparison

- ○ Improvements brought on by modifications



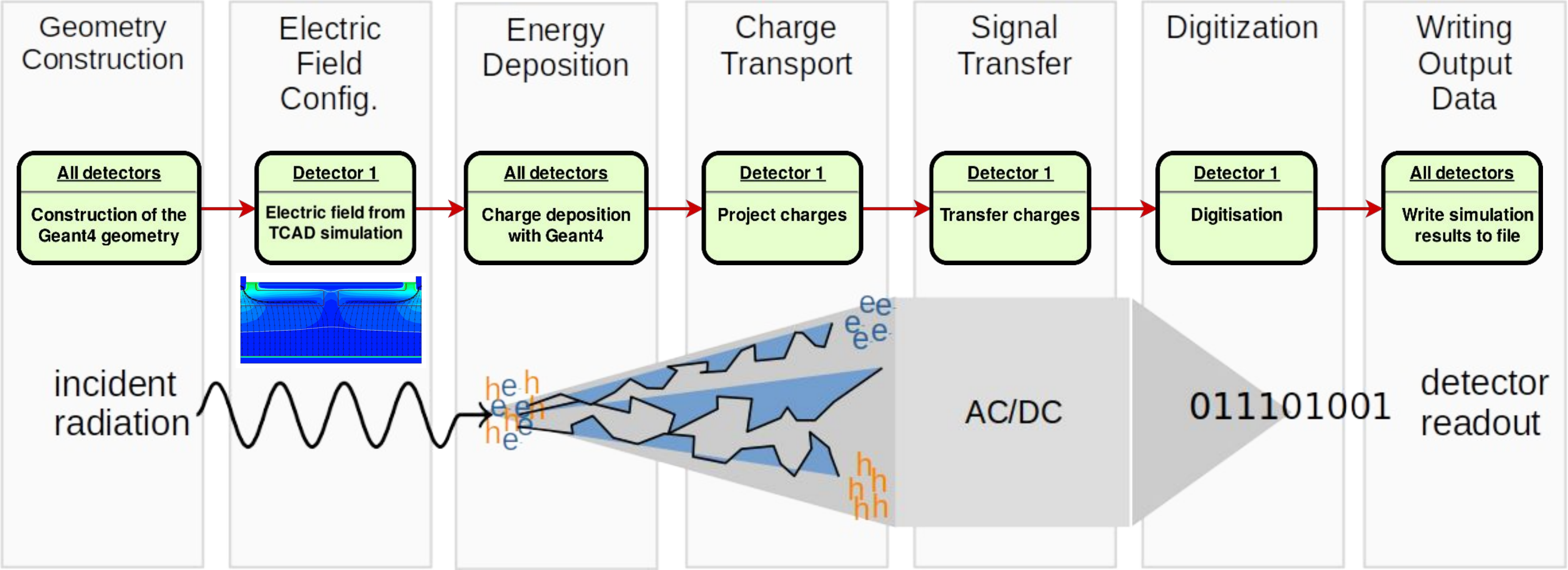


TCAD Simulations - Final Result



Monte Carlo Simulations with Allpix^2

Monte Carlo Simulation Workflow Example



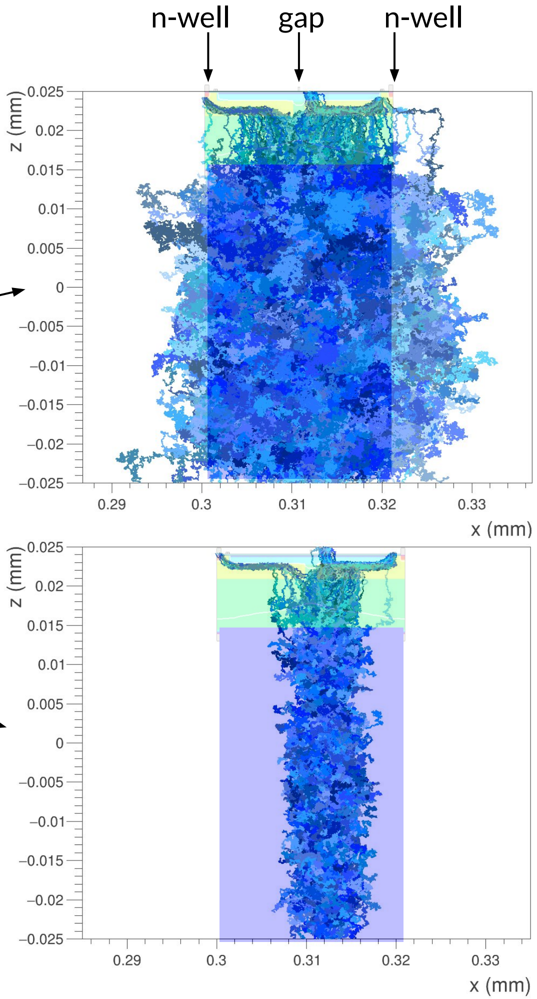
Monte Carlo Simulations - Mobility

Take into account important details…

E.g.: Mobility Models

★ Jacoboni-Canali (doping-independent)
  - Sufficient for low doping concentration
  - For high doping concentration (substrate) diffusion is unphysically large

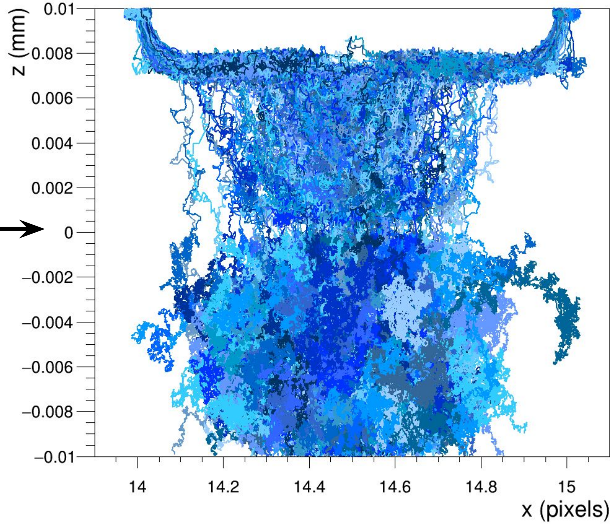
★ Masetti-Canali (doping dependent)
  - Fit for high doping concentration

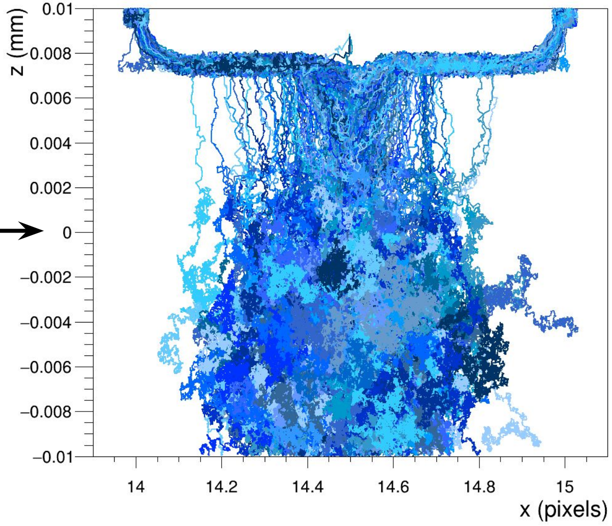


Monte Carlo Simulations - Diffusion

Comparing effect of electric field between substrate and epitaxial layer

- ★ Without dopant diffusion: significant electric field in interface region
  - ○ Unphysical
- ★ With dopant diffusion: smooth transition region





Monte Carlo vs. TCAD - Transient

See talk by M. A. D. R. Viera

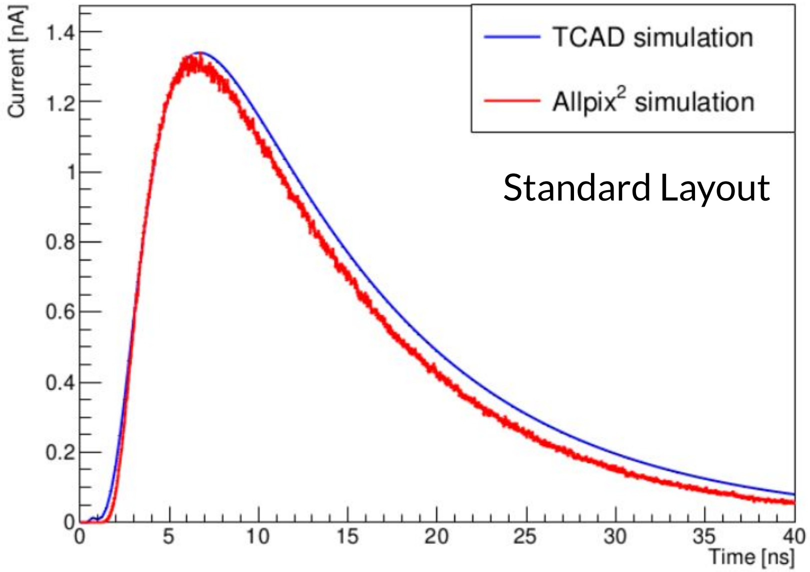
Electrostatic potentials from TCAD can be used to generate weighting potentials

→ Perform **transient simulations** with Allpix^2

- ★ Lower computational cost
- ★ Reproduce many events
- ★ Allows use of Geant4 energy deposition (see next slide)

Comparison Allpix^2 vs. TCAD:

- ★ Same settings for charge carrier creation and mobility
- ★ Results in general agreement

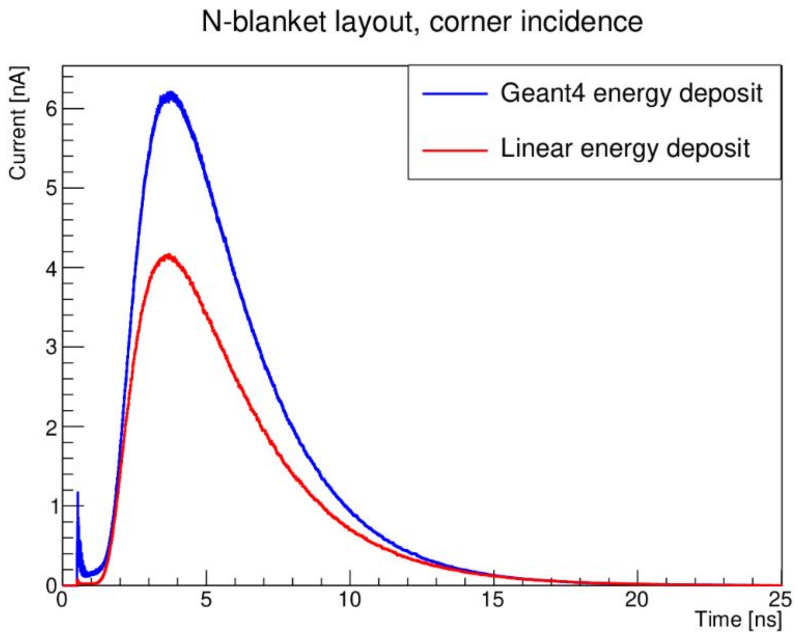


Monte Carlo Simulations - Energy Deposition

Transient simulations comparing:

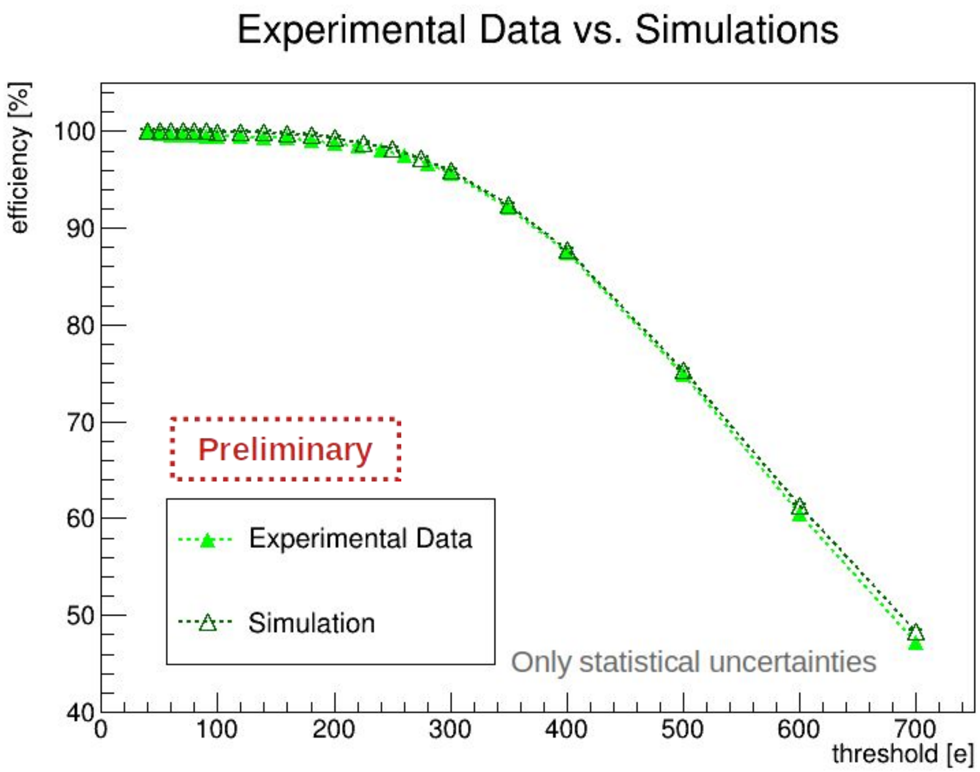
- ★ Linear energy deposition (TCAD)
  - ○ Generates 63 electron-hole pairs per μm → most probable value
- ★ Geant4 (Allpix^2)
  - ○ Includes stochastic effects → takes into account all values from energy deposition distribution

Each signal is the average of 10 000 events, incident in the pixel corner



Simulation vs. Experimental Data

- ★ First comparison with test-beam data
- ★ Analog Pixel Test Structure (APTS - W. Deng et al.)
  - N-gap layout
  - 4x4 pixel matrix
  - 25 µm pitch
  - -4.8 V bias voltage
- ★ Similar trend in experimental data and simulations
- ★ More results presented at BTTB11



Summary & Conclusions

- ★ Description of simulation procedure for MAPS → **generic toolbox** for performing similar studies
- ★ Starting from generic doping profiles and semiconductor principles → realistic doping and electric field maps are produced with TCAD
- ★ Parameters are varied to find sensible values
- ★ Maps are imported into Allpix^2 → high-statistics Monte Carlo simulations are performed
- ★ Sensor performance observables are extracted and compared to data

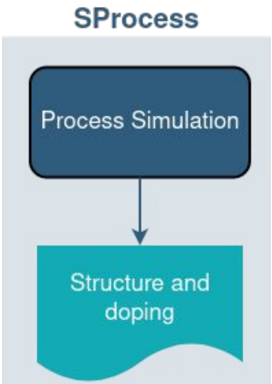
Outlook

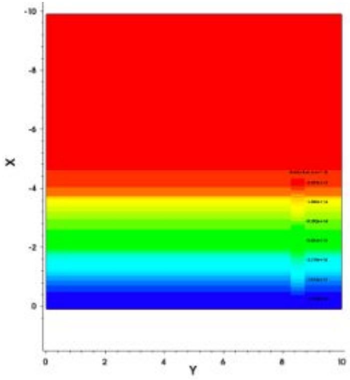
- ★ Validation with experimental data
- ★ Add uncertainties on simulation results

Back-up

TCAD Simulation Workflow Example

Sentaurus Workbench

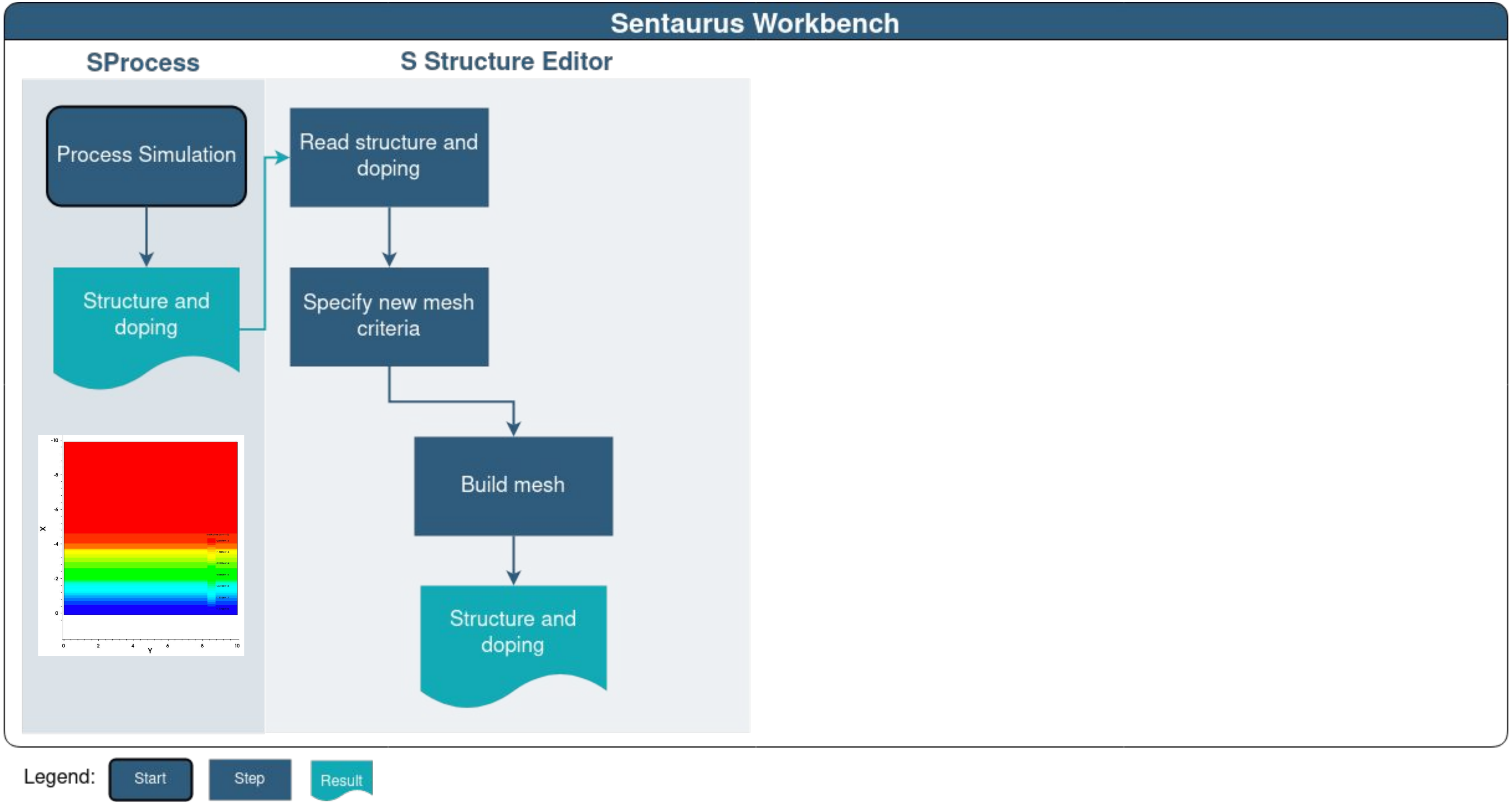




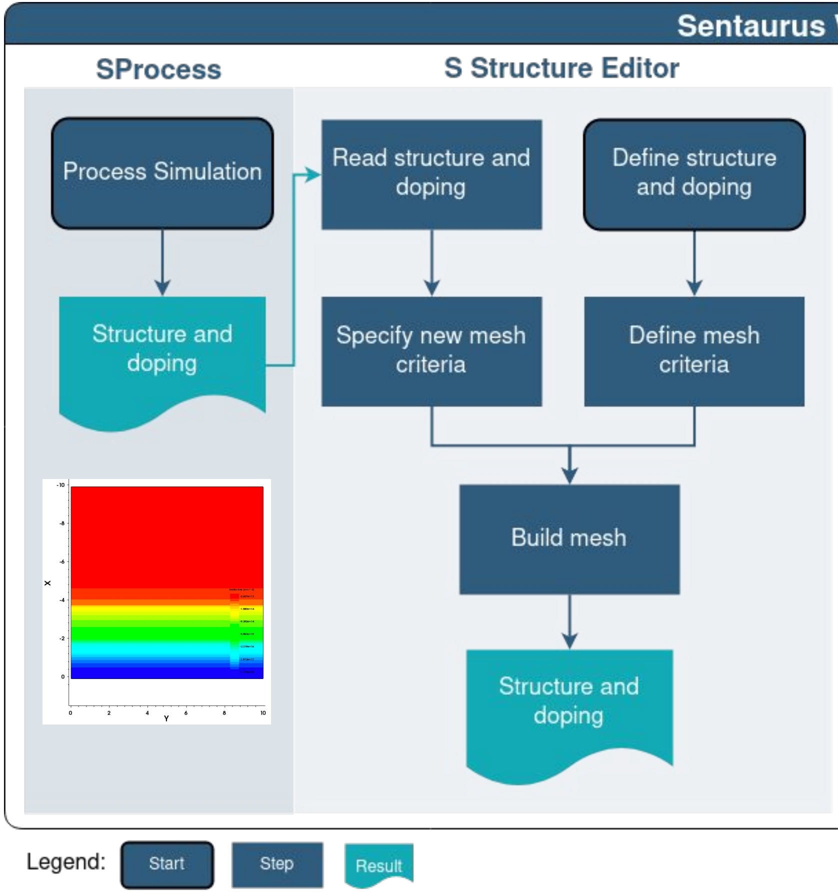
1D profile of diffusion from high to low doping under specific temperature and time conditions

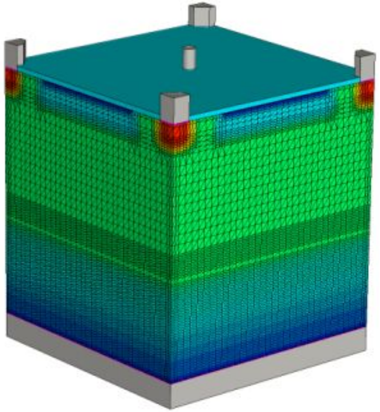
Legend: Start | Step | Result

TCAD Simulation Workflow Example



TCAD Simulation Workflow Example





3D structure created with geometrical operations, analytical doping profiles and doping dependent mesh

TCAD Simulation Workflow Example