Simulation of Irradiated Silicon Pixel Detectors for Future High Energy Physics Experiments

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Outline

• Introduction & motivation
• Basics of device simulation
• Charge collection in irradiated segmented devices
• Simulation of thin pixel detectors
• Summary & Conclusions
Introduction & Motivation

Position sensitive silicon detectors will be widely used in future HEP experiments. At high particle fluences (up to $10^{16}$ cm$^{-2}$ at SLHC) trapping times become comparable with charge collection times: \textit{loss of drifting charge – trapping}.

**Thin pixel detectors:** a way to cope with high fluences?

**Advantages**
- $V_{fd} \propto D^2$: at high $N_{eff}$ detectors can be fully depleted
- Short collection distance i.e. collection times
- Low mass, small radiation length $X_0$
- Finer detector granularity to cope with higher occupancy

**Disadvantages**
- Small signal: need for radiation hard low noise read-out electronics
Questions

• Can thin pixel detectors be successfully operated at fluences around $10^{16}$ cm$^{-2}$?
• How does the geometry of the electrodes influence the detector performances?
• What is the impact of trapping on the sensor charge collection properties?
Basics of simulations

Current induced at the electrodes by a point charge \( q \) drifting in the electric field of a reversely biased silicon detector:

\[
I_{e,h}(t) = q \exp\left(-\frac{t}{\tau_{\text{eff},e,h}}\right) \tilde{E}_w(\vec{r}_{e,h}(t)) \mu_{e,h} \tilde{E}(\vec{r}_{e,h}(t))
\]

1. **trapping**
   \[
   \frac{1}{\tau_{\text{eff},e,h}} = \beta_{e,h} \Phi_{\text{eq}}
   \]
   \( \beta_e = 5.7 \cdot 10^{-16} \text{ cm}^2/\text{ns} \)
   \( \beta_h = 7.7 \cdot 10^{-16} \text{ cm}^2/\text{ns} \)

2. **weighting field**
   Constant \( I/D \) (diode-like) if pad or pixel pitch \( >> D \)
   In general complex - highest close to collecting electrodes

3. **electric field**
   Irradiation:
   \[
   N_{\text{eff}} = -g \cdot \Phi_{\text{eq}}
   \]
   \( g = 0.0071 \text{ cm}^{-1} \) (DOFZ)
   \[
   \nabla^2 U = -\frac{e_0 N_{\text{eff}}}{\varepsilon \varepsilon_0} \Rightarrow \nabla U = -\vec{E}
   \]

The Ramo field describes the electrostatic coupling between the drifting charge and the sensing electrode.
Basics of simulations (2)

- potentials were calculated with custom-made software and ISE-TCAD package
- \( n \)-type bulk, \( N_{\text{eff}}=10^{12} \text{ cm}^{-3} \)
- all simulations performed at \( T=263 \text{ K} \)

What is not considered in the simulation:
- a uniform charge generation along the track is assumed (no GEANT simulation)
- \( N_{\text{eff}}(r)=\text{const} \): a homogeneous effective dopant concentration is assumed (double-junction effect is not taken into account)
- no further electronic processing of the induced current
Charge collection in irradiated segmented detectors

D=100 µm, Pixel Pitch=70 µm, Implant Width=50 µm

**Diode**: electrons and holes drifting to opposite directions in the diode contribute equally to the induced charge

**Pixel detector**: carriers drifting to the pixel side contribute to the larger part of the induced charge
Irradiated detectors: smaller CCE in p⁺-n detector compared with n⁺-n detector with CCE of the diode in between
Induced charge in segmented detectors

\[ \sum Q_i \equiv Q_{\text{diode}} \]

- \( p^+ \) - induced charge on neighboring electrodes has the same polarity as for the hit electrode
- \( n^+ \) - induced charge on neighboring electrodes has the opposite polarity as for the hit electrode

\( n^+ \) - higher signal in hit electrode \quad \quad \quad \quad p^+ \) - wider clusters
Induced charge in segmented detectors (2)

Current induced in the first neighbors

Absence of trapping \[ \int I(t) dt = 0 \]

This effect is far more important in irradiated detectors with \( p^+ \) pixel due to the much larger hole trapping

Incomplete charge collection due to trapping \( \rightarrow \) Charge sharing mechanism
Simulation of thin pixel detectors

Simulated geometry: 3x3 arrays; pixel pitch 70x70 µm, implant width 50 µm
Thicknesses: 25, 50, 75, 100 µm. Central hits only considered.

Weighting potential along central pixel: no difference between n⁺ and p⁺ pixels is expected for Implant Width/Thickness>1: diode-like case!
Simulated charge collection times are short (at $\Phi_{eq} = 10^{16}$ cm$^{-2}$ of order 0.15 ns for 50 µm thick detector).

What are the consequences?
Thin pixels: collected charge

- At best only 1000-2000 e at high fluences
- Small difference between different pixel thicknesses at 10^{16} cm^{-2}
- Much better performance of n-type pixels for IW/D<1
The charge induced in the neighboring pixels can be significant if Implant Width/Thickness<1.

- Diffusion is negligible due to the short collection times.
- Very beneficial n-type pixels (possible use of signals of opposite polarity to enhance S/N).

D=100 µm,
Pixel Pitch=70 µm,
Implant Width=50 µm,
operated at $V_{FD}$.
What if we make a device that has ideal $N_{\text{eff}} \sim 0$?

- the signals don’t differ much from the case of large $N_{\text{eff}}$
- higher electric field doesn’t improve the induced charge significantly (saturation of the drift velocity)
Summary & Conclusions

**Charge collection in segmented detectors:**

• “Segmentation” in terms of charge collection means how much weighting field deviates from constant (diode)
• In irradiated segmented detectors it is beneficial to collect electrons (n^+-n pixels). Incomplete charge collection due to trapping leads to a charge sharing mechanism

**Thin pixel detectors:**

• Expected signals are ~1000-2000 e after $\Phi_{eq} = 1 \times 10^{16}$ cm$^{-2}$: may be large enough, but put higher requirements on the read-out electronics
• $IW/D > 1$: no differences between n^+ and p^+-type pixels (diode-like case)
• $IW/D < 1$: better performance of n^+ -type pixels
• even if detectors are operated at $N_{eff} \sim 0$ expected signals are ~1000-1600 e after $\Phi_{eq} = 1 \times 10^{16}$ cm$^{-2}$