TCAD simulations of pixel sensors for the ATLAS ITk upgrade and performance of annealed planar pixel modules

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Introduction

... to the future of ATLAS at LHC

- LHC will be upgraded to High Luminosity-LHC
  - instantaneous luminosity (x5)
  - 3000-4000 fb\(^{-1}\) integrated luminosity (total now: ~130 fb\(^{-1}\))

- ITk will replace the current Inner Detector of ATLAS
  - all silicon detector including
    - 5 pixel layers
    - 4 strip layers

- multi-purpose ATLAS detector
- harsher conditions will require a new generation of tracking detector

Inner Tracker (ITk) upgrade in preparation for the ATLAS experiment at the LHC
Introduction
... to the ATLAS ITk upgrade

- higher instantaneous luminosity leads to more tracks requiring smaller pixel cells
  - going from 50x250/450μm² to 50x50μm²
  - new pixel cell layout necessary

- high integrated luminosity causes severe radiation damage
  - no module can withstand the full fluence (~2.6x10^{16} n_{eq}/cm²)
  - exchange of two innermost layers is foreseen
  - the other layers will undergo annealing during maintenance and exchange likely causing performance deterioration

### ITk Baseline

<table>
<thead>
<tr>
<th>#</th>
<th>sensor thickness [μm]</th>
<th>technology</th>
<th>fluence [10^{15} n_{eq}/cm²]</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>150</td>
<td>planar n-in-p</td>
<td>1</td>
</tr>
<tr>
<td>3</td>
<td>150</td>
<td>planar n-in-p</td>
<td>2</td>
</tr>
<tr>
<td>2</td>
<td>150</td>
<td>planar n-in-p</td>
<td>3</td>
</tr>
<tr>
<td>1</td>
<td>100</td>
<td>planar n-in-p</td>
<td>4</td>
</tr>
<tr>
<td>0</td>
<td>150 (active) 250 (total)</td>
<td>3D</td>
<td>13</td>
</tr>
</tbody>
</table>
Outline

1. TCAD Simulation
   - optimisation of the design of 50x50µm² pixel cells, investigation of the effect of different implant sizes on
     - breakdown voltage
     - pixel capacity
     - charge collection efficiency

2. Testbeam measurements
   - investigation of performance of irradiated modules before and after annealing
TCAD Simulation of small pixel cells

• use a 3D TCAD model for the investigation of different properties of small pixels

• due to symmetry, simulation of 4 ¼ pixels is sufficient (and saves time)

• radiation damage in TCAD ($1-5\cdot10^{15} \text{n}_{\text{eq}}/\text{cm}^2$):
  • bulk damage:
    • traps characterised by energy level, e/h cross-section and introduction rate
    • use Perugia\(^1\) irradiation model here
  • surface damage:
    • fixed oxide charge of $5\cdot10^{10}\text{e/cm}^2$ ($1.5\cdot10^{12}\text{e/cm}^2$) for not-irradiated (irradiated) sensors\(^2\)
    • interface traps also according to Perugia model

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\(^1\) F. Moscatelli et al., Effects of Interface Donor Trap States on Isolation Properties of Detectors Operating at High-Luminosity LHC, IEEE Trans. on Nucl. Science 2017

\(^2\) J. Zhang et al., Investigations of X-ray induced radiation damage at the Si-SiO\(_2\) interface of silicon sensors for the European XFEL, Proceedings of IWORID 2012
TCAD Simulation
structure of interest

isolation layers

LTO
Nitride
SiO$_2$
TCAD Simulation
structure of interest

isolation layers

LTO
Nitride
SiO₂

high resistivity p-type bulk material \((5 \cdot 10^{12} \, \text{cm}^{-3})\)
TCAD Simulation

structure of interest

isolation layers

LTO
Nitride
SiO₂

high resistivity p-type bulk material ($5 \cdot 10^{12}$ cm$^{-3}$)
simulated thickness
100 µm
TCAD Simulation
structure of interest

- high resistivity p-type bulk material \(5 \times 10^{12} \text{ cm}^{-3}\)
- simulated thickness \(100 \mu\text{m}\)
- isolation layers:
  - LTO
  - Nitride
  - SiO_2
- n^+ pixel implant
TCAD Simulation
structure of interest

via through isolation layers

isolation layers

LTO
Nitride
SiO₂

high resistivity p-type bulk material ($5 \cdot 10^{12}$ cm$^{-3}$)
simulated thickness 100 µm

n⁺ pixel implant
TCAD Simulation
structure of interest

- high resistivity p-type bulk material \((5 \times 10^{12} \text{ cm}^{-3})\)
- simulated thickness 100 \(\mu\)m

- electrical contact on top of the pixel plus 2\(\mu\)m overhang (\(\equiv\) aluminium pad)
- via through isolation layers

- isolation layers:
  - LTO
  - Nitride
  - SiO\(_2\)

- \(n^+\) pixel implant
TCAD Simulation
structure of interest

- p-spray inter-pixel isolation
- high resistivity p-type bulk material ($5 \times 10^{12} \text{ cm}^{-3}$)
- n$^+$ pixel implant
- electrical contact on top of the pixel plus 2µm overhang (≡ aluminium pad)
- via through isolation layers
- simulated thickness 100 µm

*SiO$_2$*
*Nitride*
*LTO*
TCAD Simulation
simulation details and physics

• simulation suite: Synopsys TCAD
  • structure generation using Synopsys SDE\(^1\), analytical doping profiles according to SIMS\(^2\)
    measurements of MPG-HLL sensor production

• accurate physics description in sDevice

  • mobility   doping dependent (Masetti model), high-field saturation (extended
    Canali model, E-field as driving force)
  • recombination Shokley-Read-Hall (doping and temperature dependent, Hurx
    tunnelling)
  • avalanche   van Overstraeten and de Man model
  • bandgap narrowing Old Slotboom

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\(^1\) Sentaurus Structure Editor
\(^2\) Secondary ion mass spectroscopy
TCAD Simulation
influence of implant size: general

• the new RD53 read-out chip will have a 50·50µm² bump-bond pattern
  • pixel implant size and shape can be modified within this boundary condition

• investigate the effect of varying implant size with respect to
  • breakdown voltage
  • pixel capacity
  • charge collection efficiency (CCE)
TCAD Simulation
IV curves for different implant widths

- larger pixel implants shield the p-spray from the backside potential
  - smaller potential difference between p-spray and pixel implant
  - higher breakdown voltage
TCAD Simulation

CV curves and pixel capacitance

- new read-out chip is specified up to a 100 fF input capacitance
- minimal threshold (600e) is guaranteed up to 50 fF
- chip input capacitance has large influence on noise
- inter-pixel capacitance by far outweighs pixel-bulk capacitance
  - inter-pixel capacitance determined by implant size and p-spray doping concentration

C2V, $\Phi = 0$, pixel capacity 40µm implant

- $f=10$kHz
- $d=40$µm

Pixel Size [µm]

9fF (quarter pixel)
36fF (full pixel)
TCAD Simulation
charge collection efficiency setup

• MIP injection: 76 e/h pairs are released per µm
• simulation of the transient current

• collected charge: integration of signal minus leakage current baseline
• sensors are all 100µm thick

• fixed position (10µm/10µm), variable voltage
• before irradiation 0-40V
• after irradiation 0-500V

• fixed voltage, variable position
• before depletion
• in plateau of collected charge
TCAD Simulation
results: fixed position, variable voltage – before irradiation

- once depleted (>40V), charge collection is equal for all implant sizes
- at low voltages, significantly more charge collected by larger pixel implants
- larger pixel implants result in lower depletion voltages
- $1.22 \times 10^{-15}$ C corresponds to approx. 7600e
  - will be used to normalise charge from here on
TCAD Simulation results: two voltages in detail – before irradiation

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- at low voltages, significantly more charge collected by larger pixel implants
- larger pixel implants result in lower depletion voltages
- \(1.22 \times 10^{-15} \text{ C} \) corresponds to approx. 7600e
  - will be used to normalise charge from here on
- before and after depletion particularly more charge from inter-pixel region collected by larger implants
TCAD Simulation
results: two voltages in detail – $1 \cdot 10^{15}$ $n_{eq}$/cm$^2$

- less charge collected in the case of 10/20 $\mu$m wide implants
- 30/40 $\mu$m wide implants practically identical
- more charge at lower voltages for larger implants
TCAD Simulation
results at higher fluences – $3-5 \cdot 10^{15} \text{n}_{\text{eq}}/\text{cm}^2$

- $40 \mu\text{m}$ implant width still allows to collect more than 70% of the charge after irradiation to $5 \cdot 10^{15} \text{n}_{\text{eq}}/\text{cm}^2$ at 400V
Testbeam Measurements
Testbeam studies of annealed irradiated modules

- performance degradation expected and observed with increasing irradiation

- second parameter: annealing of defects
  - short term (days at room temperature)
  - long term (weeks at room temperature)

- RT periods can not be avoided completely
  - maintenance of cooling systems and detector components
  - for ITk: exchange of two innermost layers (fluence of layer 2 during exchange: \(1-2\cdot10^{15} \text{ n}_{\text{eq}}/\text{cm}^2\))

- effect of annealing on the hit efficiency has not yet been systematically studied

- testbeam studies performed for several modules

regarding \(V_{\text{depl}}\)
Testbeam studies
devices under test

<table>
<thead>
<tr>
<th>module</th>
<th>thickness [µm]</th>
<th>fluence [$10^{15}$n$_{eq}$cm$^{-2}$]</th>
<th>irradiation type</th>
<th>annealing [d] at RT</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>100</td>
<td>5</td>
<td>KIT: protons (25MeV)</td>
<td>333</td>
</tr>
<tr>
<td>2</td>
<td>100</td>
<td>2</td>
<td>CERN PS: protons (24GeV)</td>
<td>189</td>
</tr>
<tr>
<td>3</td>
<td>150</td>
<td>2</td>
<td>CERN PS: protons (24GeV)</td>
<td>189</td>
</tr>
</tbody>
</table>

- all modules are read-out with FE-I4 chips
- pixel cells are 250·50 µm$^2$
- effective threshold of read-out chip is about 2ke
- annealing happens at RT

Gaussian beam profile leads to non-uniform irradiation
- pixels with equal fluences were selected and results merged together
- can study multiple fluences within a single device
Testbeam studies
setup

CERN
• SPS testbeam area
• 120 GeV pions
• cooling box with chiller

DESY
• 3-6 GeV electrons
• cooling box with dry ice

General
• EUDET type telescopes based on MIMOSA26 monolithic planes
• 3+3 planes up- and downstream
• 18.5µm pixel pitch
• about 2µm resolution
Testbeam studies

module 1: $5 \cdot 10^{15} \text{n}_{eq}/\text{cm}^2$, 100 $\mu$m, up to 333 days at RT

- detector fully efficient at around 200V
- depletion voltage not significantly increased by annealing
- differences observed at 100V will be monitored closely to identify whether or not it is just a fluctuation
Testbeam studies
module 2/3: $2 \cdot 10^{15} \text{n_{eq}/cm}^2$, 100/150 μm, up to 189 days at RT

- non-uniform irradiation enables extraction of results for two different fluences from same module
  - no difference between $1.5 \times 10^{15}$ and $2 \cdot 10^{15} \text{n_{eq}/cm}^2$ found
- later saturation of hit efficiency for 150μm thick module

- no effect of annealing visible
  - would expect shift of hit efficiency saturation towards higher bias voltages
Testbeam studies

module 3: $2 \cdot 10^{15} \text{n}_{\text{eq}}/\text{cm}^2$, 150 $\mu$m, up to 189 days at RT

- fixed voltage of 500V
- inefficiency due to punch-through testing structure and charge sharing changes with annealing time
- worse resolution at DESY due to multiple-scattering enhances the effect
- first and last measurement very similar
Testbeam studies

**module 3**: $2 \cdot 10^{15} \text{n_{eq}/cm}^2$, 150 µm, up to 189 days at RT

- fixed voltage of 500V
- inefficiency due to punch-through testing structure and charge sharing changes with annealing time
- worse resolution at DESY due to multiple-scattering enhances the effect
- first and last measurement very similar
Testbeam studies
modules 2+3: $2 \cdot 10^{15} \text{n}_{eq}/\text{cm}^2$, up to 189 days at RT: comparison

- efficiency at
  - 100V (100 µm thickness)
  - 200V (150 µm thickness)

- consistently lower efficiency at higher doses for both modules

- no significant trend of hit efficiency as function of annealing time observable
Testbeam studies
modules 2+3: $2 \cdot 10^{15}$ $n_{eq}/cm^2$, up to 189 days at RT: comparison

• looking at the plateau (at 500V)
  • lower efficiency at second measurement seen as well
  • pointing to systematic effect

Efficiency [%] vs. $t_{annealing}$ [days]

Hit Efficiency [%] vs. $t_{annealing}$ [days]
Summary

1. TCAD simulation
   • breakdown voltage increases drastically for increasing implant width
   • capacitance acceptable for operation with RD53 read-out chip for all implant sizes
     • the smaller the implant, the lower the capacitance
   • larger implant sizes can collect charge more efficiently already at lower voltages before and after irradiation
     • reduced charge-sharing for larger implants

1. Testbeam measurements
   • effect of annealing on hit efficiency studied at different fluences, annealing times and thicknesses
     • no significant degradation in performance found after up to 333 days at RT
Summary

1. TCAD simulation
   • breakdown voltage increases drastically for increasing implant width
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1. Testbeam measurements
   • effect of annealing on hit efficiency studied at different fluences, annealing times and thicknesses
     • no significant degradation in performance found after up to 333 days at RT

Thank you for your attention!
Backup
Testbeam studies

module 3: $2 \times 10^{15} \text{n}_{\text{eq}}/\text{cm}^2$, 150 μm, up to 189 days at RT

- non-uniform irradiation enables extraction of results for two different fluences from same module
- no effect of annealing visible
  - would expect right shift of turn-on
- will compare efficiency at 200V later
- lets look at in-pixel hit efficiency:
Testbeam studies

module 2: $2 \times 10^{15} \text{n}_{eq}/\text{cm}^2$, 100 $\mu$m, up to 189 days at RT

- non-uniform irradiation enables extraction of results for two different fluences from same module
- no effect of annealing visible
  - would expect right shift of turn-on
- will compare efficiency at 100V later
- lets look at in-pixel hit efficiency:
Testbeam studies

module 2: $2 \cdot 10^{15} \text{n}_{\text{eq}}/\text{cm}^2$, 100 µm, up to 189 days at RT

- fixed voltage of 500V
- inefficiency due to punch-through testing structure and charge sharing changes with annealing time
- worse resolution at DESY due to multiple-scattering enhances the effect
Testbeam studies

module 2: $2 \cdot 10^{15} \text{n}_{\text{eq}}/\text{cm}^2$, 100 μm, up to 189 days at RT

- fixed voltage of 500V
- inefficiency due to punch-through testing structure and charge sharing changes with annealing time
- worse resolution at DESY due to multiple-scattering enhances the effect
Title
subtitle

• text