The Radiation Hardness of the ATLAS Pixel Sensor

- Requirements
- Design
- Surface Damage
- Bulk Damage
- Performance

Olaf Krasel, Universität Dortmund for the ATLAS Pixel Collaboration

1st Workshop on Radiation Hard Semiconductor Devices for Very High Luminosity Colliders,
The ATLAS-Pixel-Detector

- innermost part of tracking system
- 3 points for tracking
- coverage $0 \leq \eta \leq 2.5$
- 3 barrel layers, 6 wheels
- total active area $\approx 2m^2$
  (1744 modules with $\approx 80$ million pixel)
Requirements for Sensor

- pixel size 50 µm × 400 µm
- 10 years operation in harsh radiation environment:
  - up to $10^{15} \text{n}_{\text{eq}}/\text{cm}^2$
  - and 500 kGy
- difficult access conditions require high reliability
- testability of sensor before module assembly
Development Strategy

**Design Studies**
performed within ATLAS
- isolation technique
- design of pixel cell

**Silicon Studies**
performed within ROSE
- various Si impurities
- damage parameters
- fabrication process

Radiation Hard Sensors
Detector Concept: $p^+$-on-$n$ vs. $n^+$-on-$n$

Before irradiation:

- $n^+$
- $p^+$

After type conversion:

- have to be (almost) fully depleted
- potential drop on the read out side
- only single sided processing necessary

- can be operated partially depleted
- potential drop on the back side
- double sided processing needed
Pixel Isolation: Design Options

Before irrad.:
- p-stop: low E-field $\Rightarrow$ high breakdown voltage
- uniform p-spray: high E-field $\Rightarrow$ low breakdown voltage
- moderated p-spray: low E-field $\Rightarrow$ high breakdown voltage

After irrad.:
- p-stop: high E-field $\Rightarrow$ low breakdown voltage
- uniform p-spray: low E-field $\Rightarrow$ high breakdown voltage
- moderated p-spray: low E-field $\Rightarrow$ high breakdown voltage

under irradiation:
- p-stop: degrades
- uniform p-spray: improves
- moderated p-spray: improves
Pixel Isolation: Breakdown Voltage

IV-Characteristics:

- higher breakdown voltage for p-spray
- IV-curve is flatter
Pixel Isolation: Noise

- with p-spray less noise
- further advantages:
  - no additional mask step
  - possibility of bias grid

![Graph showing noise (ENC) vs. bias (V) for different designs with p-stop and p-spray, showing lower noise for p-spray with less noise at 250 V at 7450±202.](image)
Pixel Isolation: Surface Damage

Direct test of interpixel isolation on real sensors by measuring pinch-off voltages

Worst case test:
• irradiation with 20 keV electrons
• no bulk damage
• no type conversion
• 500 V bias during irradiation

Pinch-off at higher voltages, but pixels still isolated
• effect of p-spray isolation
• ≈100 MΩ at 100 V bias
• saturation at about 50 kGy
• no contribution to leakage current

⇒ p-spray intrinsically radiation hard
Biasgrid

punch-through contact to pixels
⇒ testability before module assembly (quality assurance)
⇒ biasing of uncontacted pixels
Bulk Damage: oxygenated vs. standard material

ROSE-Results:
- oxygenation improves radiation hardness w.r.t charged hadrons:

Measurement with Am-source:
- measurement of hit bus frequency with varied bias voltages
- oxy and not-oxy sensors irradiated with $4.3 \times 10^{14}$ n$_{eq}$/cm$^2$

$\Phi = 4.3 \times 10^{14}$ n$_{eq}$/cm$^2$
Overall Design

- oxygenated Si substrate
- $n^+\text{-on-}n\text{-pixel}$
- moderated p-spray isolation
- bias grid for testability
- 3 sensor tiles per wafer
- various test and monitor structures
Performance: Depletion Voltage

Measurement with Am-source:

- sensors irradiated with $3.0 \cdot 10^{14} \text{n}_{eq}/\text{cm}^2$, $5.0 \cdot 10^{14} \text{n}_{eq}/\text{cm}^2$, and $11 \cdot 10^{14} \text{n}_{eq}/\text{cm}^2$

- devices can be fully depleted
- results for depletion voltages are consistent with Hamburg model
Prediction for Depletion Voltage

Scenario:
100 d Beam/a at 0°C
20 d warm-up at 20°C
rest of year at -10°C

sensor thickness
B-layer 200 µm
Layer 1 250 µm

oxygenated material
calculated with Hamburg model

Max. Operation Voltage 600 V

B-Layer $\Phi_{\text{tot}} = 2.8 \cdot 10^{15}$ $n_{\text{eq}}/\text{cm}^{-2}$
Layer 1 $\Phi_{\text{tot}} = 6.6 \cdot 10^{14}$ $n_{\text{eq}}/\text{cm}^{-2}$
Performance: Charge Collection

- homogenous charge collection over pixel
- charge loss of about 10% at bias dots, but still above threshold, only small area affected
Performance: Lorentz Angle

- knowledge of Lorentz angle important for achieving best resolution
- measurements were done in testbeam
Performance: Spatial Resolution

- charge sharing confined to $\pm 5 \, \mu m$ between adjacent pixels
- fraction of 2 pixel clusters
  - 15% at $0^\circ$ unirradiated
  - 7.5% after $10^{15} \, n_{eq}/cm^2$
- space resolution:
  - flat top: $22 \, \mu m \rightarrow 23 \, \mu m$
  - double hit: $5 \, \mu m \rightarrow 6 \, \mu m$
  - after irradiation
Conclusions

• 10 years operation in ATLAS no problem
• a radiation hard design has been achieved:
  - operable up to fluences of $1 \cdot 10^{15}$ 1-MeV n/cm²
  - tolerance for surface damage tested up to 500 kGy
• design enables testing prior to module building (quality assurance)
• production of sensor has started
• high potential for Super-LHC, to be tested