Annealing studies of irradiated p-type sensors designed for the upgrade of ATLAS Phase-II Strip Tracker

Motivation: HL-LHC / ATLAS Inner Tracker

2024 luminosity upgrade of the LHC to the HL-LHC
ATLAS: replace Inner Detector with all silicon Inner Tracker (ITk) ➔ Challenges:
• Fivefold instantaneous luminosity
• Tenfold increase in integrated luminosity ($\sim$3000 fb$^{-1}$):
  • Increased particle flux ➔ radiation damage ➔ need more radiation tolerant silicon

Radiation leads to:
• Increase in depletion voltage
• Loss of charge carries due to trapping
• Higher leakage current

Move from current n-type bulk silicon p-bulk silicon for upgrade mandatory
Motivation: HL-LHC run-time

- Expected runtime ~10 years
- Shutdown for machine maintenance on yearly basis
- Detectors will potentially not be cooled during these periods ➔ annealing
- Annealing describes migration of radiation induced defects in silicon
- Measurement standard: 80 min annealing at 60°C
- Current annealing model based on n-bulk
  - Understanding of annealing of p-type silicon bulk mandatory for HL-LHC
Hamburg Annealing Model

- Temperature and time dependent

\[ \Delta N_{\text{eff}} = N_0 e^{-t/\tau} + N_C + N_{\infty}(1 - e^{-kt}) \]

- Three annealing terms: constant, beneficial and reverse:

\[ \alpha(t) = \alpha_i e^{-t/\tau_i} + \alpha_0 + \beta \ln(t) \]

- Damage rate \( \alpha \) proportional to leakage current

\[ \alpha(t) = \frac{\Delta I}{\Phi_{\text{eq}} V} \]
Method and Devices under Test

Measurements:
• Charge collection using a $^{90}$Sr source
• Leakage current
• Impedance (capacitance)
• Annealing two set of sensors: one room-temperature (23°C) (RT) one at 60°C

- ATLAS12 Hamamatsu Photonics
- Mini strip sensors (1x1 cm$^2$)
- p-type with n-type readout strips
- 74.5µm pitch, 320µm thickness
- Float-zone technology
- Irradiated with 24 MeV protons to fluences between $5 \times 10^{13}$ and $2 \times 10^{15}$ n$_{eq}$ cm$^{-2}$
Long Term Annealing at 60°C: $2 \times 10^{15}$ n$_{eq}$

**Charge collection:**
- Increase during beneficial annealing (<300 min)
- Decrease during reverse annealing
- Strong increase for $t > 3000$ min due to charge multiplication
- Corresponding behaviour found in ATLAS07 sensors

**Leakage current:**
- Decrease during beneficial and reverse annealing
- Strong increase in charge multiplication regime
Long Term Stress : Signal Stability @ 1100V

Charge multiplication under long term bias:
• Signal declines under permanent bias
• Annealing: 80 min at 60°C recuperates CM
• Stronger decline in following measurement
• Resting of sensor only recuperates a fraction of signal
• Leakage current and noise measurement follow the trend

2x10^{15} \text{n}_{eq} \text{cm}^{-2}, 5000 \text{ min annealing}
at 60°C, sensor in charge multiplication

No reliable operation mode
Temperature Scaling Factor: RT vs 60°C

- Determine scaling factor between RT and 60°C annealing
- Scaling factors between k=100/110
- Literature value is k=325,
- This indicates different annealing behaviour of p-type sensors
Temperature Scaling Factor: RT vs 60°C

<table>
<thead>
<tr>
<th>Fluence $\frac{neq}{cm^3}$</th>
<th>$5e13$</th>
<th>$1e14$</th>
<th>$5e14$</th>
<th>$1e15$</th>
<th>$2e15$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scaling Factor $k$</td>
<td>$108 \pm 8^*$</td>
<td>$101 \pm 15^*$</td>
<td>$108 \pm 12$</td>
<td>$101 \pm 9$</td>
<td>$108 \pm 8$</td>
</tr>
</tbody>
</table>

- Smaller temperature factor may be attributed to:
  - Different oxygen concentration
  - Effect of moving from n-type to p-type leads to changes in defect annealing
  - Change in sensor properties

Measure effective doping concentration using impedance measurements

$$\frac{1}{C^2} = \frac{1}{A^2} \frac{2V}{\varepsilon q N_{eff}}$$

differences in the activation energy and half-life time of annealing process
Impedance Measurements: $1 \times 10^{14} \, n_{eq}$

- C/V profiles only accessible for low fluences
- At higher fluences a strong dependency on frequency is found
- Measure $N_{eff}$ after each annealing step for RT and 60°C sensors
- Access to annealing parameters $k$ and $\tau$
$N_{\text{eff}}$ and Charge Collection: $2 \times 10^{14} n_{eq}$

- Correlation between charge collection and $N_{\text{eff}}$
- Decrease of effective doping concentration during beneficial annealing, increase during reverse annealing (measurement still ongoing)
- More than 14 d of annealing at 60°C (4 years at RT)
- No clear sign of charge multiplication yet
$N_{\text{eff}}$ and damage parameter

- Hamburg model describes $N_{\text{eff}}$ and damage factor $\alpha$
- ATLAS12 anneal slower minimum at about $t=150$ min (was 80 min in Hamburg Model)
- Factor $k=100$ between RT and $60^\circ \text{C}$ is reproduced
Conclusion and Outlook

- Long term study on annealing behaviour of p-type silicon up to 4d at 60°C
- Hamburg Model with slight alterations describes sensor behavior
- Smaller temperature scaling factor (O(100) vs. 325) between RT and 60°C annealing is found
- This means sensors anneal faster at 60°C than predicted
- Can not simply use measurement standard of 80 min at 60°C annealing
- Extension: annealing sensors at 40°C and 80°C

- Charge multiplication effect appears in long term annealing
- CM signal dissapers over time, some recovery after further annealing

Acknowledgement: The irradiations were performed at Karlsruhe Institute of Technology (KIT) by A. Dierlamm, supported by the Initiative and Networking Fund of the Helmholtz Association, contract HA-101 (Physics at the Terascale) and the European Commission under the FP7 Research Infrastructures project AIDA, Grant agreement no. 262025,
Backup slides
Radiation Damage in Silicon Sensors

**Higher depletion voltage**
Due to change in doping concentration
After high fluences: no full depletion possible
**Solution:** different silicon material, modified detector geometry (3D, thin detectors)

**Higher trapping**
Liberated charge carriers get trapped at crystal defects
Measured signal decreases
**Solution:** modify detector geometry (3D, thinner)

**Higher leakage current**
More generation-recombination centres
Higher noise, higher power consumption, thermal runaway
**Solution:** cooling of detector

Dose: inner strip layers

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![Graphs showing radiation damage effects on silicon sensors.](image-url)
Motivation: Phase-II Radiation Environment

- 36 MRad, $8.1 \times 10^{14} \text{n cm}^{-2}$
- 50 MRad, $1.2 \times 10^{15} \text{n cm}^{-2}$
- 1700 MRad, $2.3 \times 10^{16} \text{n cm}^{-2}$