Neutron Irradiation of Silicon Sensors for the Phase 2 Upgrade

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Why is Irradiation Testing Important?

▪ A silicon lattice can acquire defects from radiation
▪ During the run of the HL-LHC the innermost part at the CMS detector will receive an unprecedented radiation dose of $2.3 \cdot 10^{16}$ $n_{eq}/cm^2$
▪ There are vital parts of the Phase 2 CMS detector which are largely composed of silicon. We need to make sure that these parts will perform optimally throughout the lifetime of the CMS detector
Silicon Semiconductor Lattice Defects

- Lattice defects can occur when heavy particles scatter off and displace nuclei in a semiconductor lattice.
- These defects can trap charge carriers.
- Through annealing, some detector defects can be recovered.
Neutron Irradiation

- Test sensors will be irradiated at nuclear reactors to test radiation hardness of materials
- Neutron irradiation will happen at the Rhode Island Nuclear Science Center (RINSC) located near Brown University
- Two different delivery methods
  - Beam port
    - Samples placed in beam port before ramp up and removed after ramp down
    - 6” diameter and 8” diameter ports
  - Pneumatic Rabbit System
    - Samples are delivered and removed from reactor when it is at full power
    - Only samples 35 mm by 90 mm can fit in rabbit system carrier
Beam Port Fluence Measurements

Beam port fluence has been measured using two methods

- **Silicon Diodes**
  - D0 diodes were irradiated in reactor
  - The increase in leakage current of the fully depleted diode is proportional to the 1-MeV equivalent fluence that the diode received.

- **Spectrum Unfolding Via Foil Activation**
  - Foils composed of different pure elements are irradiated in reactor
  - Activity is measured via gamma spectroscopy
  - A parametrized model of the flux spectrum is used to predict the activation of the foils
  - The parameters are varied until the predicted activations agree with the observed values
  - Silicon damage function can be used to obtain a 1 MeV equivalent flux
Diode Measurements

- Post irradiated diode leakage current is measured after 80 minutes of annealing at 60°C
- Leakage current is proportional to fluence received by diode

Diode measurements for 8” beam port:

<table>
<thead>
<tr>
<th>Diode</th>
<th>I_leak</th>
<th>Flux</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO16</td>
<td>0.73 mA</td>
<td>5.7×10^{11} n/cm^{2}/s</td>
</tr>
<tr>
<td>CO17</td>
<td>0.73 mA</td>
<td>5.7×10^{11} n/cm^{2}/s</td>
</tr>
<tr>
<td>CO18</td>
<td>0.77 mA</td>
<td>6.0×10^{11} n/cm^{2}/s</td>
</tr>
<tr>
<td>CO19</td>
<td>0.79 mA</td>
<td>6.1×10^{11} n/cm^{2}/s</td>
</tr>
<tr>
<td>Average</td>
<td>0.76 mA</td>
<td>5.9×10^{11} n/cm^{2}/s</td>
</tr>
</tbody>
</table>

Plot taken from The Phase 2 Upgrade of the CMS Tracker 2017 TDR
Foil Activation

- Foils which were irradiated
  - 6” beam port – Al, Au, Cu, Fe, In, Ni, Ti, V, Zr
  - 8” beam port – Al, Cu, Fe, Zr
- Neutron interactions we looked at:
  - Al27 (n,α) Na24
  - Ti48 (n,p) Sc48
  - V51 (n,α) Sc48
  - Fe54 (n,p) Mn54
  - Fe56 (n,p) Mn56
  - Fe58 (n,γ) Fe59
  - Ni58 (n,p) Co58
  - Cu63 (n,γ) Cu64
  - Zr90 (n,2n) Zr89
  - In113 (n,γ) In114
  - W186 (n,γ) W187
  - Au197 (n,γ) Au198
Foil Activation

- Spectrum is modeled using the following form:
  - Maxwellian energy distribution for thermal spectrum:
    \[ \varphi(E) \propto \frac{E}{(kT)^{3/2}} e^{-E/kT} \]
    - Where:
      - \( k \) = Boltzman’s Constant
      - \( T \) = temperature of thermal neutrons
        - approximated as the temperature of the water the core is submerged in ≈70°F
    - \( 1/E \) distribution for intermediate neutrons
    - Watt Distribution for fission neutrons
      \[ \varphi(E) \propto \sinh(\sqrt{2.29E})e^{-E/0.965} \]
Foil Activation

- All elements sensitive to thermal neutrons have an exponentially falling cross section for thermal neutrons, causing the low energy portion of the fit to be poorly constrained.

\[ 1 \text{MeV Equiv Flux} = 2.4 \times 10^{11} \pm 0.5 \times 10^{11} \, n_{eq}/\text{cm}^2/\text{s} \]

\[ 1 \text{MeV Equiv Flux} = 5.6 \times 10^{11} \pm 1.2 \times 10^{11} \, n_{eq}/\text{cm}^2/\text{s} \]
# Reactor 1 MeV Equivalent Flux

<table>
<thead>
<tr>
<th>Delivery Method</th>
<th>6” Port</th>
<th>8” Port</th>
</tr>
</thead>
<tbody>
<tr>
<td>Approximate Irradiation Time For $1 \times 10^{15}$ $n_{eq}/cm^2$</td>
<td>$2.4 \times 10^{11} \pm 0.5 \times 10^{11} n_{eq}/cm^2/s$</td>
<td>$5.6 \times 10^{11} \pm 1.2 \times 10^{11} n_{eq}/cm^2/s$</td>
</tr>
<tr>
<td>Approximate Irradiation Time For $2.3 \times 10^{16}$ $n_{eq}/cm^2$</td>
<td>$2.3 \times 10^{11} \pm 0.2 \times 10^{11} n_{eq}/cm^2/s$</td>
<td>$5.9 \times 10^{11} \pm 0.6 \times 10^{11} n_{eq}/cm^2/s$</td>
</tr>
</tbody>
</table>

When ignoring the thermal neutron’s contribution to the 1 MeV equivalent flux measured found using the foil activation method, good agreement is seen between the two measurement methods.
Summary

▪ Silicon sensors need to undergo irradiation testing to make sure they will still work after withstanding the predicted irradiation dose of the HL-LHC
▪ Neutron irradiation tests will take place at the RINSC reactor located near Brown University
▪ Reactor flux at the different irradiation delivery sites have been measured using two different methods
  ▪ Measuring the leakage current of irradiated D0 diodes
  ▪ Obtaining a spectrum of the neutron energy flux using foil activation
  ▪ After correcting for overestimation of the thermal spectrum in the 6” and 8” port, diode and foil measurements show good agreement
Backup
### Desired Fluence

<table>
<thead>
<tr>
<th>Desired Fluence</th>
<th>Approximate Irradiation Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>$10^{14} \text{n}_{eq}/\text{cm}^2$</td>
<td>6 – inch port: 7 minutes, 8 – inch port: 3 mins</td>
</tr>
<tr>
<td>$10^{15} \text{n}_{eq}/\text{cm}^2$</td>
<td>6 – inch port: 1 hour 10 mins, 8 – inch port: $\frac{1}{2}$ hour</td>
</tr>
<tr>
<td>$10^{16} \text{n}_{eq}/\text{cm}^2$</td>
<td>6 – inch port: 12 hours, 8 – inch port: 5 hours</td>
</tr>
<tr>
<td>$2.3\cdot10^{16} \text{n}_{eq}/\text{cm}^2$</td>
<td>6 – inch port: 28 Hours, 8 – inch port: $11\frac{1}{2}$ Hours</td>
</tr>
</tbody>
</table>

Expected fluence of inner tracker after 3000 fb$^{-1}$ of data is approximately $2.3\cdot10^{16} \text{n}_{eq}/\text{cm}^2$
Silicon Sensor Annealing

Post-irradiation diode leakage current and depletion voltage improves with annealing. After a threshold, further annealing will cause damage to the sensor.

$N_{eff}$ vs Annealing Time (F512, 1kHz)

$I_{leak}$ vs Annealing Time at -400V (F512)