Charge Collection Efficiency Simulations of Irradiated Silicon Strip Detectors

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on behalf of the CMS Tracker collaboration

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Motivation
- Silicon detectors in CMS Tracker
- Tracker upgrade to HL-LHC

Charge collection efficiency (CCE) simulations
- Method
- Results & comparison with measurements

Simulated position dependency of CCE (CCE(x))
- Method
- Results & comparison with measurements

Summary
Motivation
Motivation I: Silicon detectors in CMS Tracker

Tracker position in Compact Muon Solenoid

- Silicon detector module made of APV25 and two 6" detectors.

- 225 m² silicon
- Design: Si strip sensors surrounding the core of Si pixels.

ECAL
Magnet
HCAL
Muon chambers
Motivation II: Tracker upgrade to HL-LHC

Estimated fluence levels in CMS Tracker after 10 years of HL-LHC operation.

Upgrade: LHC → HL-LHC
- \( L = 10^{35} \text{ cm}^{-2}\text{s}^{-1} \) with an event rate of 40 MHz
  - \( \int L = 3000 \text{ fb}^{-1} \)
- Challenges for tracker:
  - Higher radiation hardness
  - High occupancy → higher granularity
  - Reduce material budget → thin sensors (~200 μm)

CMS has initiated extensive measurements & simulation studies within RD50 Collaboration for detectors suitable for HL-LHC.

Very high multiplicity pp collision: more than 110 charged particles produced inside the CMS tracker.
CCE simulations
Radiation ($\Phi_{eq} > 1e13 \text{ cm}^{-2}$) causes damage to silicon crystal structure. ($\Phi_{eq} = 1 \text{ MeV n}_{eq}$)

High fluences ($\Phi_{eq} > 1e14 \text{ cm}^{-2}$) lead to significant degradation of CCE due to charge carrier trapping.

Both bulk and surface damage affect the detector performance

- **Bulk damage**: introduces deep acceptor and donor type trap levels
- **Surface damage**: Positively charged layer accumulated inside $\text{SiO}_2 \rightarrow$ affect to sensor performance through the $\text{SiO}_2/\text{Si}$ interface

**Simulation**: Bulk damage approximated by **effective two-defect model** & surface damage by placing fixed charges $Q_f$ at $\text{SiO}_2/\text{Si}$ interface

Defect models used in Synopsys Sentaurus package tuned by R. Eber from the EVL-model (V. Eremin et al., 2011) for $\Phi_{eq} = 1e14 - 1.5e15 \text{ cm}^{-2}$ at fixed $T=253 \text{ K}$

<table>
<thead>
<tr>
<th>Proton model</th>
<th>Neutron model</th>
</tr>
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<tbody>
<tr>
<td><strong>Type of defect</strong></td>
<td><strong>Level [eV]</strong></td>
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<td>Deep acc.</td>
<td>$E_G - 0.525$</td>
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<tr>
<td>Deep donor</td>
<td>$E_V + 0.48$</td>
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Both models are tuned to produce $V_{fd}$, $I_{leak}$, $E(z)$ & transient signal shapes matching with measurement (see also poster by M. Printz at Posters1)
CCE simulations: Method

Detector characterization:
- Bulk: $V_{fd}$, $I_{leak}$, $E(z)$, and CCE
- Surface: $C_{int}$, $R_{int}$, $E(x)$, and CCE(x)
- CCE($\Phi$): Direct information of the effect of radiation induced defects to the ability of a detector to collect charge carriers generated by traversing MIPs → most important property to determine radiation hardness of a Si detector

Definition: The collected charge of an irradiated detector is a measure of efficiency relative to the non-irradiated detector

- The collected charge is the integral of the transient signal over time → CCE = $Q_{irr} / Q_{non-irr}$

200P: $I(t)$, $Q(t)$
Results I: proton & neutron models

- **Simulation set-up:**
  - 5-strip structure to avoid non-uniformities from border effects to mesh formation at the center
  - Device is depleted by HV provided from the backplane
  - Charge is injected (mip) at the centermost strip
  - $Q_{\text{coll}}$ = sum of charges collected at all 5 strips
  - E.g. FZ320N = 320 $\mu$m thick p-on-n float zone silicon sensor

- **CCE simulations**
  - 320N/P 5-strip sensor structure, pitch=80 $\mu$m, implant width=18 $\mu$m @ $T = 253$ K
  - $Q_f = 5e11$ cm$^{-2}$ @ $\Phi_{\text{eq}} < 7e14$ cm$^{-2}$, $Q_f = 1e12$ cm$^{-2}$ @ $\Phi_{\text{eq}} > 7e14$ cm$^{-2}$
  - Data from mini sensors, measured with the ALiBaVa system

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**Proton model**

FZ320N: CCE($\Phi$)

$V = 1$ kV

**FZ320P: CCE($\Phi$)**

max. $Q_f = 7e11$ cm$^{-2}$

$V = -1$ kV
Simulated CCE has dependency on $Q_f$:

- If $Q_f$ is set too low for high fluences, charge multiplication sets in too early → Unphysically high CCE
- If $Q_f$ is set too high strip isolation is lost & undepleted region extending from front surface results in low CCE not matching with measurement @ $V < 1$ kV

320P 5-strip sensor structure, pitch=80 μm, implant width=18 μm @ $T = 253$ K

Further tuning of models to produce correct CCE for expected $Q_f$ @ high fluences
Results III: SiBT data vs simulation @ T=0°C

- SiBT = Silicon Beam Telescope
- 5-strip sensor, pitch=120 μm, implant width=28 μm
- Tuning to match $I_{\text{leak}}$ @ T = 273 K for both models: $\sigma_{\text{e, h}}(273\text{K}) = 0.75 \cdot \sigma_{\text{e, h}}(253\text{K})$

![Graph showing measured and simulated CCE vs fluence (1 MeV n$_{\text{eq}}$)](image)

**SiBT data fluences**

<table>
<thead>
<tr>
<th>Detector</th>
<th>$\Sigma \Phi$ (1 MeV n$_{\text{eq}}$) [cm$^{-2}$]</th>
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</thead>
<tbody>
<tr>
<td>FZ320P</td>
<td>4.0e14</td>
</tr>
<tr>
<td>FZ320P</td>
<td>1.3e15</td>
</tr>
<tr>
<td>FZ200P</td>
<td>3.0e14</td>
</tr>
<tr>
<td>MCz200P</td>
<td>1.4e15</td>
</tr>
</tbody>
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- Thicknesses of the reference detectors and DUTs are not equal → measured CCE is determined by:
  \[
  \text{CCE}_{\text{data}} = \frac{Q_{\text{DUT}}}{Q_{\text{ref}}} \cdot \frac{d_{\text{ref}}}{d_{\text{DUT}}}
  \]
  
  $Q =$ collected signal
  
  $d =$ detector thickness

- $Q_f$ & $V$: iteration parameters to match CCE with measured
- Find $Q_f$ producing matching CCE with measured detector & irradiation type
- Use the fixed $Q_f$ to make prediction to detector with equal irradiation type/dose
- Uncertainty in data from detector T & effective thickness

<table>
<thead>
<tr>
<th>Fluence [cm$^{-2}$]</th>
<th>$Q_f$(neutron) [cm$^{-2}$]</th>
<th>$Q_f$(proton) [cm$^{-2}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1e14</td>
<td>6e10</td>
<td>1.4e11</td>
</tr>
<tr>
<td>3e14</td>
<td>-</td>
<td>3e11</td>
</tr>
<tr>
<td>4e14</td>
<td>9e10</td>
<td>-</td>
</tr>
<tr>
<td>8e14</td>
<td>3.25e11</td>
<td>7.1e11</td>
</tr>
<tr>
<td>1.3e15</td>
<td>6e11</td>
<td>-</td>
</tr>
<tr>
<td>1.4e15</td>
<td>-</td>
<td>1.2e12</td>
</tr>
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Timo Peltola, PSD10, 9 Sept 2014
CCE(x) simulations
Surface damage induced by protons is significantly higher than for neutrons.

Experimentally observed $Q_f$ is in the range $1e12 \text{–} 2e12 \text{ cm}^{-2}$ @ $\Phi_{eq} > 1e15 \text{ cm}^{-2}$ for proton irradiation.

E.g. when $Q_f \geq 1.3e12 \text{ cm}^{-2}$ is applied for proton model @ $\Phi_{eq} = 1.4e15 \text{ cm}^{-2}$ in n-on-p strip detector:

- No strip isolation $\rightarrow$ no CCE(x) (measured: strip isolation ok, CCE loss between strips $\sim30\%$)
- $C_{int}$ increases $\sim O(1)$ over measured

→ Need to add another acceptor trap level that compensates for both inversion layer electrons and signal electrons.

SiBT measured CCE(x) (T. Määnpää, 2013)

$q_{eq}=1.4e15 \text{ cm}^{-2}$

Center of strip

Center of pitch

MCz 200P sensor, pitch=120 $\mu$m, implant width=28 $\mu$m
Method I: Non-uniform 3-level model

- Non-unif. 3-level model can be tuned to equal bulk properties (TCT, $V_{fd}$ & $I_{leak}$) with proton model → suitable tool to investigate CCE($x$)
- 3-level model within 2 μm of device surface + proton model in the bulk: $R_{int}$ & $C_{int}$ in line with measurement (see back-up slides) also at high fluence & $Q_f$

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<th>Level [eV]</th>
<th>$\sigma_e$ [cm$^2$]</th>
<th>$\sigma_h$ [cm$^2$]</th>
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<td>1e-14</td>
<td>1.189*Φ + 6.454e13</td>
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<tr>
<td>Deep donor</td>
<td>$E_V + 0.48$</td>
<td>1e-14</td>
<td>1e-14</td>
<td>5.598*Φ - 3.959e14</td>
</tr>
<tr>
<td>Shallow acc.</td>
<td>$E_C - 0.40$</td>
<td>8e-15</td>
<td>2e-14</td>
<td>40*Φ</td>
</tr>
</tbody>
</table>

- Effect of acceptor traps in non-unif. 3-l. model is clearly visible: O(5) lower electron density to proton model between strips
- Strips are isolated at $V=0$ for $\Phi_{eq}=5e14$ cm$^{-2}$ as in real detectors

- $\Phi_{eq}=1.5e15$ cm$^{-2}$ & $Q_f=1.2e12$ cm$^{-2}$: $C_{int}$ at geometrical level ~2 pF/cm (pitch=80 μm)
Method II: Variation of oxide charge

- Principle of CCE(x) simulation for given c (shallow acc.) & voltage
- 5-strip 200P (pitch=120 μm, implant width=28 μm) @ $\Phi_{eq} = 1.5 \times 10^{15}$ cm$^{-2}$, V=-1 kV, T=253 K

- Acceptor traps remove both accumulation layer & signal electrons: better radiation damage induced strip isolation → larger CCE loss between the strips

- Increased $Q_t$ → more traps are filled → charge sharing between strips increases, undepleted region between strips grows → CCE loss decreases
Results I: CCE(x) of proton model & non-unif. 3-l model

When strips are isolated: $Q_{coll}$ at center strip increases as position of charge injection moves closer to it & $Q_{coll}$ at 2$^{nd}$ strip drops down

- $Q_I = 1.2e12$ cm$^{-2}$: CCE loss $\approx 15\%$
- $Q_I \sim 1.5e12$ cm$^{-2}$: no strip isolation & cluster CCE $\sim 0.5$ of expected due to even charge sharing between all strips (total strip # = 3*1 + 2*0.5 = 4)

- $Q_I = 1.2e12$ cm$^{-2}$: CCE loss $\approx 41\%$
- $Q_I = 2e12$ cm$^{-2}$: increased charge sharing when mip position $\geq 30$ μm from center strip, but still producing position information

Charge injected at the center of strip:
Both models produce essentially same total collected charge at the 5 strips
Results II: Measured CCE(x) vs simulation

- Target $Q_f \approx 5 \times 10^{11}$ and $1.5 \times 10^{12}$ cm$^{-2}$ for given fluences (estimation from measured data)
- $c$ (shallow acc.) parametrized by using 'fixed' values of $Q_f \rightarrow$ fixed $c$, parametrized $Q_f$

- Measured average CCE loss (FZ200P/Y, MCz200P) @ $\Phi_{eq} (p^+) = 3 \times 10^{14}$ cm$^{-2}$, $V = 600 - 990$ V: $26.5 \pm 1.1\%$

\[ \Phi_{eq} = 3 \times 10^{14} \text{ cm}^{-2} \]
\[ V = -990 \text{ V} \]

\[ Q_f = (4.6 - 6.0) \times 10^{11} \text{ cm}^{-2} \]

- Two low CCE loss regions observed in $Q_f$ scan for $\Phi_{eq} = 3 \times 10^{14}$ cm$^{-2}$
- At very low $Q_f$ charges of opposite sign are collected at strips further away of charge injection point → injection at center of strip produces cluster $Q_{coll}$ closer to $Q_{coll}$ @ injection at center of pitch

- Measured average CCE loss (FZ200P/Y, MCz200P) @ $\Phi_{eq}$ (mixed) = $(1.4 \pm 0.1) \times 10^{15}$ cm$^{-2}$, $V = 606 \pm 2$ V: $30 \pm 2\%$

\[ \Phi_{eq} = 1.5 \times 10^{15} \text{ cm}^{-2} \]
\[ V = -608 \text{ V} \]

\[ Q_f = (1.405 - 1.425) \times 10^{12} \text{ cm}^{-2} \]

Type of defect | Level [eV] | $\sigma_e$ [cm$^2$] | $\sigma_h$ [cm$^2$] | Concentration [cm$^{-3}$]
--- | --- | --- | --- | ---
Deep acceptor | $E_C - 0.525$ | $1 \times 10^{-14}$ | $1 \times 10^{-14}$ | $1.189 \Phi + 6.454e13$
Deep donor | $E_V + 0.48$ | $1 \times 10^{-14}$ | $1 \times 10^{-14}$ | $5.598 \Phi - 3.959e14$
Shallow acceptor | $E_C - 0.40$ | $8 \times 10^{-15}$ | $2 \times 10^{-14}$ | $40 \Phi$
Shallow acceptor | $E_C - 0.40$ | $8 \times 10^{-15}$ | $2 \times 10^{-14}$ | $14.417 \Phi + 3.1675e16$

Timo Peltola, PSD10, 9 Sept 2014
Summary

- 2-level defect models for both protons and neutrons were applied for the CCE simulations of 320N/P and 200P strip sensors up to $\Phi_{\text{eq}} = 1.5\times10^{15} \text{ cm}^{-2}$
  - By adjusting $V_d$ and $Q_f$ it is possible to reach good agreement with both ALiBaVA and SiBT measured CCE data
  - Problem: realistic values of oxide charge $Q_f$ for proton irradiation

- By applying non-uniform 3-level defect model, matching CCE(x) with SiBT measured data was reached
  - Simulated CCE(x) is governed by $Q_f$ and the shallow acceptor concentration
  - By tuning these, the measured CCE loss between strips for given $\Phi_{\text{eq}}$ is reproduced
  - Realistic values of $Q_f$ for proton irradiation without compromising strip isolation, strip noise, etc.
  - Preliminary parametrization of the model for fluence range $3\times10^{14} - 1.5\times10^{15} \text{ cm}^{-2}$
Backup: SiBT measured CCE loss between strips

Signal loss in-between strips (p=120µm, w/p∼0.23)

No loss before irrad.; after irrad. ~30% loss; all technologies similar [Phase-2 Outer TK Sensors Review]
Backup: Measured $R_{\text{int}}$ & $C_{\text{int}}$

Interstrip Resistance after 40 cm mixed irradiation

- $F=5\times10^{14}$ cm$^{-2}$

- P and Y types: $R_{\text{int}}$

Interstrip Resistance after 20 cm mixed irradiation

- $F=1\times10^{15}$ cm$^{-2}$

Measurement (W. Treberspurg)
- DC-CAP

Simulations by Silvaco Atlas 5-trap model

NO-1

- Red: Experimental result (flux-5e14)
- Blue: Flux=5e14neq, & QF =8e11 cm$^{-2}$
- Green: Flux=1e15neq, & QF=1.2e12 cm$^{-2}$

N type: $C_{\text{int}}$

Str-1

- Red: Experimental result (flux-5e14)
- Blue: Flux=5e14neq, & QF =8e11 cm$^{-2}$
- Green: Flux=1e15neq, & QF=1.2e12 cm$^{-2}$

P type: $C_{\text{int}}$

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3 strip structure, $V_{\text{strip1}} = V_{\text{strip3}} = 0$, $V_{\text{strip2}} = LV$ and $0$ V

- $V = -HV$ at the backplane

Interstrip resistance ($R_{\text{int}}$) is defined as (Induced Current Method):

$$R_{\text{int}} = \frac{V_2(LV)}{I_1(LV)+I_3(LV) - I_1(0)+I_3(0)}$$

- $R_{\text{int}}$ is plotted as a function of applied voltage $V$

Electrical circuit diagram of $R_{\text{int}}$ measurement:

$C_{\text{int}}$ simulation principle:

$$C_{\text{int}} = 2*[AC(1,2)+DC(1,2)+AC(1)DC(2)+DC(1)AC(2)]$$

$R_{\text{int}}$ simulation principle:

$V_{\text{strip1}} = 0$

1: $V_{\text{strip2}} = LV$

2: $V_{\text{strip2}} = 0$

$V_{\text{strip3}} = 0$