Simulation of radiation-induced defects

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Outline

- Motivation
- Radiation induced defects
- Simulated defects
  - Implementation: From PTI to TCAD models
  - Bulk damage
  - …and surface damage
- Summary
- Work in progress/future efforts
Motivation I: HL-LHC

- **Upgrade:** LHC → High Luminosity LHC (HL-LHC)
  - Expected $\int L = 3000$ fb$^{-1}$ after 10 years of operation
  - Pseudorapidity coverage from $\eta = 2.5 \rightarrow 4$

- **Challenges for tracker:**
  - Higher radiation hardness
  - High occupancy → higher granularity
  - Reduce material budget → thin sensors (~200 μm)

Silicon detectors will be exposed to hadron fluences more than $10^{16}$ n$_{eq}$ cm$^{-2}$ → beyond the performance level of detectors used currently at LHC

**RD50 mission:** development of silicon sensors for HL-LHC
Radiation induced defects
Radiation damage in silicon: Defect Parameters

- Radiation ($\Phi_{eq} > 1e13$ cm$^{-2}$) causes damage to silicon crystal structure ($\Phi_{eq} = 1$ MeV $n_{eq}$)
- High fluences ($\Phi_{eq} > 1e14$ cm$^{-2}$) lead to significant degradation of Charge Collection Efficiency (CCE) due to charge carrier trapping

- Both bulk & surface damage affect the detector performance:
  - **Bulk damage**: Introduces deep acceptor and donor type trap levels
  - **Surface damage**: Positively charged layer accumulated inside SiO$_2$
    → affect to sensor performance through the SiO$_2$/Si interface

- **Defect parameters**: type: acceptor, donor,…  
  $E_a$: activation energy  
  $\sigma_{n,p}$: capture cross section  
  $N_t$: concentration

### Shockley-Read-Hall Statistics

- Charged defects: $N_{eff}$ (space charge, E-field), $V_{dep}$
- Captured e, h: trapping → CCE
- Generation/Recombination e, h: LC

### Defect Parameters Table

<table>
<thead>
<tr>
<th>Defect type</th>
<th>$E_a$ [eV]</th>
<th>$\sigma_n$ [cm$^2$]</th>
<th>$\sigma_p$ [cm$^2$]</th>
<th>$N_t$ [cm$^{-3}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acceptor</td>
<td>$E_C - x_1$</td>
<td>O(1e-14)</td>
<td>O(1e-14)</td>
<td>$\eta_1 \cdot \Phi + c_1$</td>
</tr>
<tr>
<td>Donor</td>
<td>$E_V + x_2$</td>
<td>O(1e-14)</td>
<td>O(1e-14)</td>
<td>$\eta_2 \cdot \Phi + c_2$</td>
</tr>
</tbody>
</table>

[M. Moll, VERTEX 2013]
Defects in silicon

- Each defect has an energy level in Si bandgap or a variety, depending on the conglomeration of defects.
- Multitude of energy levels, cross sections & concentrations: huge parameter space to model!

11 defect levels proved to influence the performance of irradiated Si detectors (see back-up 2-3) → Effective model is needed for simulation.

Energy levels from Thermally Stimulated Current (TSC) measurement

**H defects:** [I. Pintilie et al., Appl. Phys. Lett. 92, 024101 (2008)]
**BD:** [I. Pintilie et al., NIM A 514, 18 (2003)] & [I. Pintilie et al., NIM A 556, (1), 197 (2006)] & [E. Fretwurst et al., NIM A 583, 58 (2007)]
**E30:** [I. Pintilie et al., NIM A 611, 52-68 (2009)]

[R. Eber, 8th Detector Workshop, Berlin, 2015]
Simulated defects: Implementation
Principle for irradiated detectors simulation

- On basis of minimized set: microscopic parameters of irradiated Si to reproduce the detector performance at certain operational conditions
- 2 midgap energy levels DD and DA applied to reconstruct & predict:
  
  \[ \text{Bulk generated current} + E(x) + \text{trapping} \]

Parameterization for custom made software

[V. Eremin, 20th RD50 Workshop, 2012]

- Parameters for pronounced Double Peak (DP) effect (not corresponding to correct description of other detector properties):

<table>
<thead>
<tr>
<th>Type of defect</th>
<th>Level [eV]</th>
<th>$\sigma_{e,h}$ [cm$^2$]</th>
<th>Introduction rate [cm$^{-1}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Deep acceptor (DA)</td>
<td>$E_C - 0.525$</td>
<td>1e-15</td>
<td>1</td>
</tr>
<tr>
<td>Deep donor (DD)</td>
<td>$E_V + 0.48$</td>
<td>1e-15</td>
<td>1</td>
</tr>
<tr>
<td>Current generating level</td>
<td>$E_C - 0.65$</td>
<td>1e-13</td>
<td>1</td>
</tr>
</tbody>
</table>

Trapping of free carriers from detector reverse current to midgap energy levels of radiation induced defects leads to DP E(x)

**PTI model:** Simulated E-field in irradiated detector

**PTI 1D simulations:**
- $E(x)$ profile formation in irradiated Si detector described as: Carrier generation + trapping to midgap DDs and DAs
- **TCAD:** Not possible to introduce exclusively current by adding PTI trap $E = E_C - 0.65eV$ (current governed in non-irradiated device by SRH, Auger & radiative recombination)

**Alternative approach:**
Generation may be considered via carrier lifetime

**Can trapping be explained in the frame of 2-DL model?**
- Estimations:
  - $\beta = 5e^{-7} s^{-1}cm^2$ and fluence $\Phi = 1e14 \text{ cm}^{-2} \rightarrow$ trapping time $\tau = 20$ ns
  - trapping cross-section $\sigma = 1e^{-14} \text{ cm}^2$
  - thermal velocity $V_{th} = 2e7 \text{ cm/s}$
  - $N_t = 1/[(\sigma V_{th} \tau)] = 2.5e14 \text{ cm}^{-3}$ or intro rate $\eta(N_t) = 2.5$
  - From PTI bulk generated current parameterization:
    - $\eta(DA) = 1.6$
    - $\eta(DD) = 0.8$

$\eta(N_t)$, $\eta(DA)$ & $\eta(DD)$ have equal range
→ **2-DL model has a chance to be extended to CCE($\Phi$)**

[V. Eremin, RD50 SWG meeting, March 2013]

[E. Verbitskaya, RD50 SWG meeting, March 2013]
Defect simulations: TCAD

- **Why Technology Computer-Aided Design (TCAD) simulations:**
  - E-fields not possible to measure directly → predict E-fields & trapping in irradiated sensors
  - Verify measurements → Find physics behind ‘weird’ results
  - Predictions for novel structures & conditions → device structure optimization in 2D/3D

- **Applied frameworks:** Synopsys Sentaurus & Silvaco ATLAS TCAD tools
- **Working with ‘effective levels’ for simulation of irradiated devices**
  - **Bulk damage:** approximated by 2 deep levels from PTI model
  - **Surface damage:** Fixed charge density $Q_f$ placed at SiO$_2$/Si interface w/ interface traps $N_{it}$ of varying depth distributions
  - **Defect concentrations & cross sections tuned to match experimental data**

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**Measured defects**

- Conduction Band
  - V$_{O}$(0)
  - C$_{Cs}$(0)
  - V$_{I}$(0)
  - P(0/+)
  - B(0/+)
  - E$_{30}$(0/+)
  - E$_{295a}$(0+)
  - E$_{4}$(0/-)
  - E$_{5}$(0/-)
  - ClO(0/+)
  - H$_{152}$(0+)
  - H$_{140}$(0+/
  - H$_{116}$(0+)
  - B(0+)

- Valence Band
  - C$_{I}$(0/-)
  - I$_{I}$(0)
  - $Q_f$(0+)

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**TCAD input**

- Conduction Band
  - Deep Acceptor (+/-)
  - Deep Donor (0/+)

Donor: $E = E_V + 0.48$ eV
Acc.: $E = E_C - 0.525$ eV

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[M. Moll, VERTEX 2013]

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T. Peltola, VERTEX 2015, June 4th - Simulation of radiation-induced defects
Simulated defects:
Bulk damage
Parameterization of current generated by cross sections of each defect at a defined concentration:

- 1st constraint given by \( V_{fd} \rightarrow \) set a ratio of donors to acceptors to match \( \rightarrow \) tune the current again \( \rightarrow \) repeat until match with measured CV, IV

**Result:** Trap concentration \( (c_{test}, \sigma_{test}, \alpha) \) for given \( \Phi \rightarrow c(\Phi) \) by linear fit

### Proton model

- **Deep acceptor** \( E_C - 0.525 \text{eV} \)
  - \( \sigma_e \): 1e-14 cm²
  - \( \sigma_h \): 1e-14 cm²
  - Concentration: \( 1.189\Phi + 6.454\text{e13} \)
- **Deep donor** \( E_V + 0.48 \text{eV} \)
  - \( \sigma_e \): 1e-14 cm²
  - \( \sigma_h \): 1e-14 cm²
  - Concentration: \( 5.598\Phi - 3.959\text{e14} \)

### Neutron model

- **Deep acceptor** \( E_C - 0.525 \text{eV} \)
  - \( \sigma_e \): 1.2e-14 cm²
  - \( \sigma_h \): 1.2e-14 cm²
  - Concentration: \( 1.55\Phi \)
- **Deep donor** \( E_V + 0.48 \text{eV} \)
  - \( \sigma_e \): 1.2e-14 cm²
  - \( \sigma_h \): 1.2e-14 cm²
  - Concentration: \( 1.395\Phi \)

**Sentaurus defect models for \( \Phi_{eq} = 1e14 \sim 1.4e15 \text{ cm}^{-2} @ T=253 \text{ K} \)**

Current essentially from \( \sigma \) of one charge carrier type


[T. Peltola, VERTEX 2015, June 4th - Simulation of radiation-induced defects]
Proton model: From TCT to E-field

- Double peak E-field simulated by matching TCT pulses (DP & LC: back-up 4)
- Carrier drift in double peak E-field produces DP in TCT
- Matching TCT signals w/ measured: basic requirement for reliable CCE simulations

Measurement

1e14 n_{eq} cm^{-2}

TCT

Signal (a.u.)

0 0.01

Time (ns) 10 20

Simulation

1e14 n_{eq} cm^{-2}

TCT

Signal (a.u.)

0 0.005

Time (ns) 10 20

[T.Eber, 22nd RD50 Workshop, June 2013]
Proton model: Trapping time

Electrons in the device:
- Integration of electron density at each $t \rightarrow$ total # of electrons
- **Simple approach**: fit linear decay with trapping time $\tau$
- Mean $\tau(1e14 \text{ cm}^{-2}) \approx 28.5 \text{ ns}$

$$n_e = n_{e0} \times \exp\left(-\frac{t - t_0}{\tau}\right)$$

- Signal corrected by trapping time
- $\tau \approx 28.5 \text{ ns}$ is in the range also found in the literature:

($\tau \sim 25 \text{ ns} @ 1e14 \text{ n}_{eq}\text{cm}^{-2}$ e.g. by G.Kramberger et al., NIMA 476, 645 and NIMA 481, 297)
**Edge-TCT:** Neutron irradiated strip detector

- **300P strip sensor**, $\Phi_{eq}(n)=5\times10^{14}$ cm$^{-2}$, $Q_f=1\times10^{11}$ cm$^{-2}$, $w_{ps}=20$ $\mu$m, $w_{impl}=20$ $\mu$m, pitch=80 $\mu$m

**Experimental goal:** extract E-field from drift velocity using edge-TCT

- Measured amplitudes reproduced by simulation (see back-up 5 for method)
- Simulated depletion depth $\sim$10-30 $\mu$m deeper at lower V → accuracy increases with voltage
- Simulation gives reliable estimation of E(depth)

[T. Peltola, 23rd RD50 Workshop, 2013]
Simulated n-on-p strip detector front surface (not to scale)

- Simulated CCE: close agreement with measurement
- Problem: need to use low $Q_f$ values @ high $\Phi$ to preserve strip isolation in n-on-p sensors

- Simulated CCE has dependence on $Q_f$:
  - Too low $Q_f$ for high $\Phi$ → too high CCE due to charge multiplication
  - Too high $Q_f$ → no strip isolation & undepleted region extends from front surface & negative component of $Q_{coll}$ increases → too low CCE

  → $Q_f$ can be applied as further tuning parameter for CCE (find 'correct' $Q_f$)
CCE & Trapping II

- Same set of data used to simulate CCE measurements taken in a CMS test beam with strip sensors
  - E.g. FZ320P = 320 μm thick n-on-p float zone silicon sensor

- CCE simulations using 2 trap model + tuned $Q_f$
- Test beam measured CCE of FZ320P and MCz/FZ200P samples is reproduced
- Fixed $Q_f$ values used to predict CCE of non-measured detectors w/ equal irradiation type/dose to measured detectors

<table>
<thead>
<tr>
<th>Fluence $[\text{cm}^{-2}]$</th>
<th>$Q_f(\text{neutron}) [\text{cm}^{-2}]$</th>
<th>$Q_f(\text{proton}) [\text{cm}^{-2}]$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$1 \times 10^{14}$</td>
<td>$6 \times 10^{10}$</td>
<td>$1.4 \times 10^{11}$</td>
</tr>
<tr>
<td>$3 \times 10^{14}$</td>
<td>-</td>
<td>$3 \times 10^{11}$</td>
</tr>
<tr>
<td>$4 \times 10^{14}$</td>
<td>$9 \times 10^{10}$</td>
<td>-</td>
</tr>
<tr>
<td>$8 \times 10^{14}$</td>
<td>$3.25 \times 10^{11}$</td>
<td>$7.1 \times 10^{11}$</td>
</tr>
<tr>
<td>$1.3 \times 10^{15}$</td>
<td>$6 \times 10^{11}$</td>
<td>-</td>
</tr>
<tr>
<td>$1.4 \times 10^{15}$</td>
<td>-</td>
<td>$1.2 \times 10^{12}$</td>
</tr>
</tbody>
</table>

[T. Peltola, PSD10, Sept. 2014]
Simulated defects:  
…and surface damage
**RD50**

**Silvaco TCAD: Bulk & surface damage**

- **Delhi Univ. defect model for Silvaco ATLAS**
  - Bulk damage model (for proton irradiation)
  - Produce experimentally measured currents for irradiated diodes
  - Correct full depletion voltages (say, ~500V for 1e15neq/cm² fluence of proton irradiation)
  - Produces electric fields from both sides

[Bulk:

<table>
<thead>
<tr>
<th>Type of defect</th>
<th>Level [eV]</th>
<th>$\sigma_e$ [cm²]</th>
<th>$\sigma_h$ [cm²]</th>
<th>Introduction rate [cm⁻¹]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acceptor</td>
<td>$E_C - 0.51$</td>
<td>2e-14</td>
<td>2.6e-14</td>
<td>4</td>
</tr>
<tr>
<td>Donor</td>
<td>$E_V + 0.48$</td>
<td>2e-14</td>
<td>2e-14</td>
<td>3</td>
</tr>
</tbody>
</table>

**Surface:**

<table>
<thead>
<tr>
<th>Interface trap</th>
<th>Level [eV]</th>
<th>$\sigma_{e,h}$ [cm²]</th>
<th>Density ($N_{it}$) [cm⁻²]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Deep Acceptor</td>
<td>$E_C - 0.60$</td>
<td>1e-15</td>
<td>0.6·$Q_f$</td>
</tr>
<tr>
<td>Shallow Acceptor</td>
<td>$E_C - 0.39$</td>
<td>1e-15</td>
<td>0.4·$Q_f$</td>
</tr>
</tbody>
</table>

**Estimation for $N_{it}$ implementation:** $N_{it} \approx Q_f$ [1]

[1] J. Zhang, DESY Thesis 2013, “X-ray radiation damage studies and design of a Si Pixel sensor for different fluences for science at the XFEL”

**Interstrip resistance of irradiated strip detectors**

- Close agreement for measured & simulated $R_{int}$
- **Errors**: Measured $R_{int}$ variations in different samples & simulated $R_{int}$ (assuming different $Q_f$)

[Measured: [A. Dierlamm, VERTEX 2012]]

- LC($\Phi$) in 1x1x300 μm³ diode @ T=253 K
RD50 DU model: Peak E-fields in p-on-n & n-on-p sensors

\[ \Phi_{eq} = 1 \times 10^{15} \text{ cm}^{-2}, \quad Q_f = N_{it} = 1.2 \times 10^{12} \text{ cm}^{-2} \] @ V=500 V

- **Peak E-fields in Silvaco**: significantly lower for n-on-p sensor for given voltage
  - Micro-discharges much more probable in p-in-n sensors
  - \( Q_f \) & \( N_{it} \) are used (in equal amounts) for the surface damage

[R. Dalal, 25\textsuperscript{th} RD50 Workshop, 2014]
Sentaurus: CCE(x)

Principle of CCE(x) simulation for given c (shallow acc.) & voltage

$\Phi_{eq} = 1.5e15 \text{ cm}^{-2}$

- Strips isolated: Cluster CCE decreases towards midgap
- Strips shorted: Cluster CCE independent of position

Heavily irradiated strip detectors demonstrate significant position dependency of CCE

Sentaurus non-uniform 3-level model:

$N_{it}$ cannot be used: measured $C_{int}$ not reproduced (see back-up 6-7) $\rightarrow$ need deeper distribution

$\rightarrow$ 3-level model within 2 $\mu$m of device surface + proton model in bulk:

- $R_{int}$ & $C_{int}$ in line w/ measured also at high $\Phi$ & $Q_f$ (see back-up 8)
- Tunable to bulk properties (TCT, $V_{td}$ & LC) of proton model $\rightarrow$ suitable tool to study CCE(x)

CCE loss between strips

Cluster CCE loss [%]

- Negative space charge dominates
- Oxide charge density dominates

**Test beam measurement:**
- Strips isolated
- CCE loss between strips ~30%

**Interpretation:** Irradiation produces non-uniform distribution of shallow traps close to surface → greater drift distance, higher trapping of carriers

**Measured & simulated CCE(x)**

- Traps remove both interface & signal electrons: better radiation induced strip isolation → higher CCE loss between strips
- Higher $Q_f$ → more traps filled → charge sharing between strips increases → CCE loss decreases

**CCE(x): Simulated vs measured**

$\Phi_{eq} = 1.4 \times 10^{15}$ cm$^{-2}$

$Q_f = (1.6 \pm 0.2) \times 10^{12}$ cm$^{-2}$

**Preliminary parametrization for $\Phi = 3 \times 10^{14} - 1.4 \times 10^{15}$ cm$^{-2}$**

<table>
<thead>
<tr>
<th>Type of defect</th>
<th>Level [eV]</th>
<th>$\sigma_e$ [cm$^2$]</th>
<th>$\sigma_h$ [cm$^2$]</th>
<th>Concentration [cm$^{-3}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Deep acceptor</td>
<td>$E_C - 0.525$</td>
<td>1e-14</td>
<td>1e-14</td>
<td>$1.189\Phi + 6.454e13$</td>
</tr>
<tr>
<td>Deep donor</td>
<td>$E_V + 0.48$</td>
<td>1e-14</td>
<td>1e-14</td>
<td>$5.598\Phi - 3.959e14$</td>
</tr>
<tr>
<td>Shallow acceptor</td>
<td>$E_C - 0.40$</td>
<td>8e-15</td>
<td>2e-14</td>
<td>$14.417\Phi + 3.168e16$</td>
</tr>
</tbody>
</table>

See back-up 9-10
**Motivation:** Simulations are essential in e.g. device structure optimization & predicting E-fields and trapping

**Objective:** Develop an approach to model & predict the performance of irradiated silicon detectors (diode, strip, pixel, 3D) using professional software (Sentaurus, Silvaco)

**Measured defects:** Initial input to the simulations

**Simulation of radiation damage in Si bulk:** Based on effective midgap levels (DA & DD levels w/ energies $E_c - (0.525 \pm 0.025)$ eV and $E_v + 0.48$ eV). Model 1st proposed in 2001 → entitled later as ‘PTI model’

**Main idea:** Two peaks in the E(z) profile of both proton & neutron irradiated detectors explained via interaction of the carriers from bulk generated current w/ electron traps & simultaneously w/ hole traps

**1st successful quantitative models:** Proton & neutron models, for simulation of LC, $V_{fd}$ & CCE were built on PTI model’s two deep levels

**Recent implementations:** Additional traps at SiO₂/Si interface or close to it → scope of simulations expanded to include $R_{int}$, $C_{int}$, & CCE(x) of strip sensors irradiated up to $\sim 1.5 \times 10^{15}$ $n_{eq}$cm$^{-2}$
Comparison of simulated \( E(x) \) w/ results of edge-TCT

- Measured edge-TCT data for:
  - Modeling tools calibration (non-irradiated detectors)
  - Models development/proofs (\( \Phi \) & \( V \) dependences for irradiated detectors)

- \( \text{CCE} (\Phi) \) modeling up to \( 2 \times 10^{16} \text{ } n_{eq} \text{cm}^{-2} \) for pixel & 3D detectors

- The new subject – ‘Interstrip resistance radiation hardness’

http://www.cern.ch/rd50

[V. Eremin, 25th RD50 Workshop, 2014]
Back-up 1: Defect model overview

Bulk damage

- M. Petasecca et al. [NIM A 563 (2006) 192–195]: 3 levels
- Pennicard et al. [NIM A 592 (2008) 16–25]: 3 levels, increased capture cross-sections $\sigma_n$, $\sigma_p$
- E. Verbitskaya et al. [JINST 7 C02061, 2012; and NIM A 658 (2011)]: 2 levels, avalanche multiplication, 1D (“analytical”) approach

Surface damage

- Y Unno et al., [NIM A 636 (2011) S118–S124]

Bulk & surface damage

- T. Peltola, [JINST 9 C12010, 2014]: 2 levels, +1 level in 2µm at surface
- Delhi University [R. Dalal et al., Vertex - 2014, 23rd RD50 CERN, Nov. 2013]: 2 levels + $Q_F + N_{il}$
<table>
<thead>
<tr>
<th>Defect Label</th>
<th>Assignment and particularities</th>
<th>Configurations and charge states</th>
<th>Energy levels (eV) &amp; cross sections (cm$^2$)</th>
<th>Impact on electrical characteristics of Si diodes @ RT</th>
</tr>
</thead>
<tbody>
<tr>
<td>E(30K)</td>
<td>Not identified extended defect</td>
<td>E(30K)$^{0/+}$</td>
<td>$E_c$ - 0.1</td>
<td>Contributes in full concentration with positive space charge to $N_{eff}$</td>
</tr>
<tr>
<td></td>
<td>Donor with energy level in the upper part of the bandgap, strongly generated by irradiation with charged particles. $^{10,29}$</td>
<td>$E_c$ - 0.1 $\sigma_n = 2.3 \times 10^{-14}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Linear fluence dependence. $^*$this work</td>
<td>$\sigma_n = 2.3 \times 10^{-14}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>BD</td>
<td>Thermal double donor (TDD2) - point defect</td>
<td>BD_A$^{0/+}$</td>
<td>$E_c$ - 0.225 $\sigma_n = 2.3 \times 10^{-14}$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Bistable donor existing in two configurations (A and B) with energy levels in the upper part of the bandgap, strongly generated in Oxygen rich material, $^{24,26,27}$</td>
<td>$E_c$ - 0.225 $\sigma_n = 2.3 \times 10^{-14}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Linear fluence dependence. $^*$this work</td>
<td>$\sigma_n = 2.3 \times 10^{-14}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ip</td>
<td>Not identified point defect</td>
<td>Ip$^{+}$</td>
<td>$E_V$ + 0.23 $\sigma_p = (0.5-9) \times 10^{-15}$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Suggestions: V$_2$O or a Carbon related center. $^{22-24,10}$</td>
<td>$E_V$ + 0.23 $\sigma_p = (0.5-9) \times 10^{-15}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Amphoteric defect generated via a second order process (quadratic fluence dependence), strongly generated in Oxygen lean material, $^{22-24}$, this work</td>
<td>$\sigma_p = (0.5-9) \times 10^{-15}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>E$_{75}$</td>
<td>Tri-vacancy (V$_3$) - small cluster</td>
<td>FFC</td>
<td>$E_c$ - 0.075eV $\sigma_n = 3.7 \times 10^{-15}$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Bistable defect existing in two configurations (FFC and PHR) with acceptor energy levels in the upper part of the bandgap. $^{10,28,30-33}$</td>
<td>$E_c$ - 0.075eV $\sigma_n = 3.7 \times 10^{-15}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>E4</td>
<td>Linear fluence dependence. $^*$this work</td>
<td>PHR</td>
<td>$E_c$ - 0.359 $\sigma_n = 2.15 \times 10^{-15}$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Acceptor energy levels in the upper part of the bandgap. $^{10,28,30-33}$</td>
<td>$E_c$ - 0.359 $\sigma_n = 2.15 \times 10^{-15}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>E5</td>
<td>Linear fluence dependence. $^*$this work</td>
<td>PHR</td>
<td>$E_c$ - 0.458 $\sigma_n = 2.4 \times 10^{-15}$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Acceptor with energy level in the lower part of the bandgap. $^{10,29}$</td>
<td>$E_c$ - 0.458 $\sigma_n = 2.4 \times 10^{-15}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Linear fluence dependence. $^*$this work</td>
<td>$\sigma_p = 2.15 \times 10^{-15}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>H(116K)</td>
<td>Not identified extended defect</td>
<td>H(116K)$^{0/-}$</td>
<td>$E_V$ + 0.33 $\sigma_p = 4 \times 10^{-14}$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Acceptor with energy level in the lower part of the bandgap. $^{10,29}$</td>
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</tr>
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<td></td>
<td>Linear fluence dependence. $^*$this work</td>
<td>$\sigma_p = 2.15 \times 10^{-13}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>H(140K)</td>
<td>Not identified extended defect</td>
<td>H(140K)$^{0/-}$</td>
<td>$E_V$ + 0.36 $\sigma_p = 2.5 \times 10^{-15}$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Acceptor with energy level in the lower part of the bandgap. $^{10,29}$</td>
<td>$E_V$ + 0.36 $\sigma_p = 2.5 \times 10^{-15}$</td>
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<td></td>
<td>Linear fluence dependence. $^*$this work</td>
<td>$\sigma_p = 2.5 \times 10^{-15}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>H(152K)</td>
<td>Not identified extended defect</td>
<td>H(152K)$^{0/-}$</td>
<td>$E_V$ + 0.42 $\sigma_p = 2.3 \times 10^{-14}$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Acceptor with energy level in the lower part of the bandgap. $^{10,29}$</td>
<td>$E_V$ + 0.42 $\sigma_p = 2.3 \times 10^{-14}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Linear fluence dependence. $^*$this work</td>
<td>$\sigma_p = 2.3 \times 10^{-14}$</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- Consistent set of defects observed after p, π, n, γ and e irradiation $^{[R.Radu et al., J. Appl. Phys. 117, 164503, 2015]}$  

T. Peltola, VERTEX 2015, June 4th - Simulation of radiation-induced defects
Back-up 3: Defect Characterization Overview

- **Trapping**: Indications that E205a and H152K (midgap levels) are important
- **Consistent set of defects observed after p, π, n, γ and e irradiation**
- **Understanding of defect properties/macroscopic effects is essential for the implementation of defect simulation**

**Leakage current**
- \(E_{4/5}: V_3^{\pm/-}, V_3^{\pm^-}\)

**Reverse annealing**
- (negative charge)

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Pintilie et al, NIM A 514, 18 (2003) & NIM A 556, (1), 197 (2006);
E. Fretwurst et al, NIM A 583, 58 (2007)

V. P. Markevich, et al Phys. Rev. B 80, 235207 (2009);
300 μm thick p-on-n pad detector @ T=253 K

Fluences: 
Φ = 1e13 – 5e14 n_{eq} cm^{-2}

DP is produced by both models (more pronounced in PM due to higher trap concentration for given Φ)

Dashed black lines: experimental LC by 
ΔI = Volume · α · Φ,
α(253K)≈8.9·10^{-19} A·cm^{-1}

LC has perfect match with experimental values
RD50 Back-up 5: Method for simulated edge-TCT

- **Goal:** extract electric field $E$ from drift velocity $v_{\text{drift}}$ using eTCT
- eTCT provides measurement of collection time $t_c$ that is proportional to the $v_{\text{drift}}$
- $v_{\text{drift}}$ is related to the $E$ → possible to determine $E$ out of drift velocity?

### Principal of edge-TCT simulation:

- Synopsys Sentaurus simulated edge-TCT collected charges $Q(z)$ at voltages both below and above $V_{fd}$ for a non-irradiated 320N strip detector at $T = 293$ K.
- **Dashed vertical lines:** active region of the detector, defined from the center of the rising and descending slopes of the $Q(z)$ distribution. The different electric field extensions into the bulk from the pn-junction at the front surface (front: $z=0$, backplane: $z=320 \ \mu m$) are clearly reflected by $Q(z)$
- **Differences in $Q(z)$ amplitude:** Reproduced by using laterally extended device structure → extension of E-field to the detector edges is taken into account
Back-up 6: $C_{\text{int}}: N_{\text{int}}$ vs non-unif. 3-level model @ $\Phi_{\text{eq}}=1.4\times10^{15}$ cm$^{-2}$

- Device structure corresponding to previous slide
- **Dashed lines:** $Q_f$ values where CCE loss between strips matches measurement
- **3-level model @ 2 $\mu$m from surface:**
  - Geometrical value $\sim 1.8$ pF/cm reached within 0-400 V when CCE loss matches measurement
- **Interface traps:**
  - Geometrical value reached within 180 V -1 kV when CCE loss matches measurement
  - Over $O(1)$ higher initial values at high $Q_f$

- **Measurement:** $C_{\text{int}} \sim 1.8$ pF/cm reached at 0 V

Proton model + interface traps, $N_{\text{it}} = 1.4\times10^{12}$ cm$^{-2}$

Proton model + 3-level model @ 2 $\mu$m

Higher $Q_f \rightarrow$ higher $V$ needed to reach geometrical $C_{\text{int}}$
RD50  Back-up 7: $C_{int}: N_{int}$ vs non-unif. 3-level model @ $\Phi_{eq}=3e14$ cm$^{-2}$

- Device structure corresponding to previous slide
- **3-level model @ 2 µm from surface:**
  - Geometrical value $\sim 1.8$ pF/cm reached at 0 V when CCE loss matches measurement
- **Interface traps:**
  - Geometrical value reached at low V up to $Q_f=1e12$ cm$^{-2}$ (no match with measured CCE loss)
- **Measurement:** $C_{int} \sim 1.8$ pF/cm reached at 0 V

---

**Conclusion from slides 7-10:** Deeper distribution of shallow acceptors reproduces measured CCE loss between strips & $C_{int}$ more closely
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 also at high fluence & $Q_f$

3-level model within 2 μm of device surface

<table>
<thead>
<tr>
<th>Type of defect</th>
<th>Level [eV]</th>
<th>$\sigma_e$ [cm$^2$]</th>
<th>$\sigma_h$ [cm$^2$]</th>
<th>Concentration [cm$^{-3}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Deep acc.</td>
<td>$E_C$ - 0.525</td>
<td>1e-14</td>
<td>1e-14</td>
<td>1.189*Φ + 6.454e13</td>
</tr>
<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)

Interstrip capacitance

Interstrip resistance

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3-level model within 2 μm of device surface + proton model in bulk:
- $R_{int}$ & $C_{int}$ in line with measured also at high fluence & $Q_f$
- Tunable to equal bulk properties ($TCT$, $V_{fd}$ & $LC$) with proton model → suitable tool to investigate $CCE(x)$

Interpretation: Irradiation produces non-uniform distribution of shallow acceptor traps close to detector surface → greater drift distance, higher trapping of charge carriers

**Observation:** Heavily irradiated strip detectors demonstrate significant position dependency of $CCE$

- $\Phi_{eq} = 1.4e15$ cm$^{-2}$
- MCz 200P, $p=120$ μm, $w=28$ μm

**Test beam:** strip isolation ok, $CCE$ loss between strips ~30%

<table>
<thead>
<tr>
<th>Preliminary parametrization for $\Phi = 3e14$ – $1.4e15$ cm$^{-2}$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Type of defect</strong></td>
</tr>
<tr>
<td>-------------------</td>
</tr>
<tr>
<td>Deep acceptor</td>
</tr>
<tr>
<td>Deep donor</td>
</tr>
<tr>
<td>Shallow acceptor</td>
</tr>
</tbody>
</table>
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]
RD50: 280 Members from 49 Institutes

- 41 European institutes
- 6 North-American institutes
- 1 Middle East institute
- 1 Asian institute

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