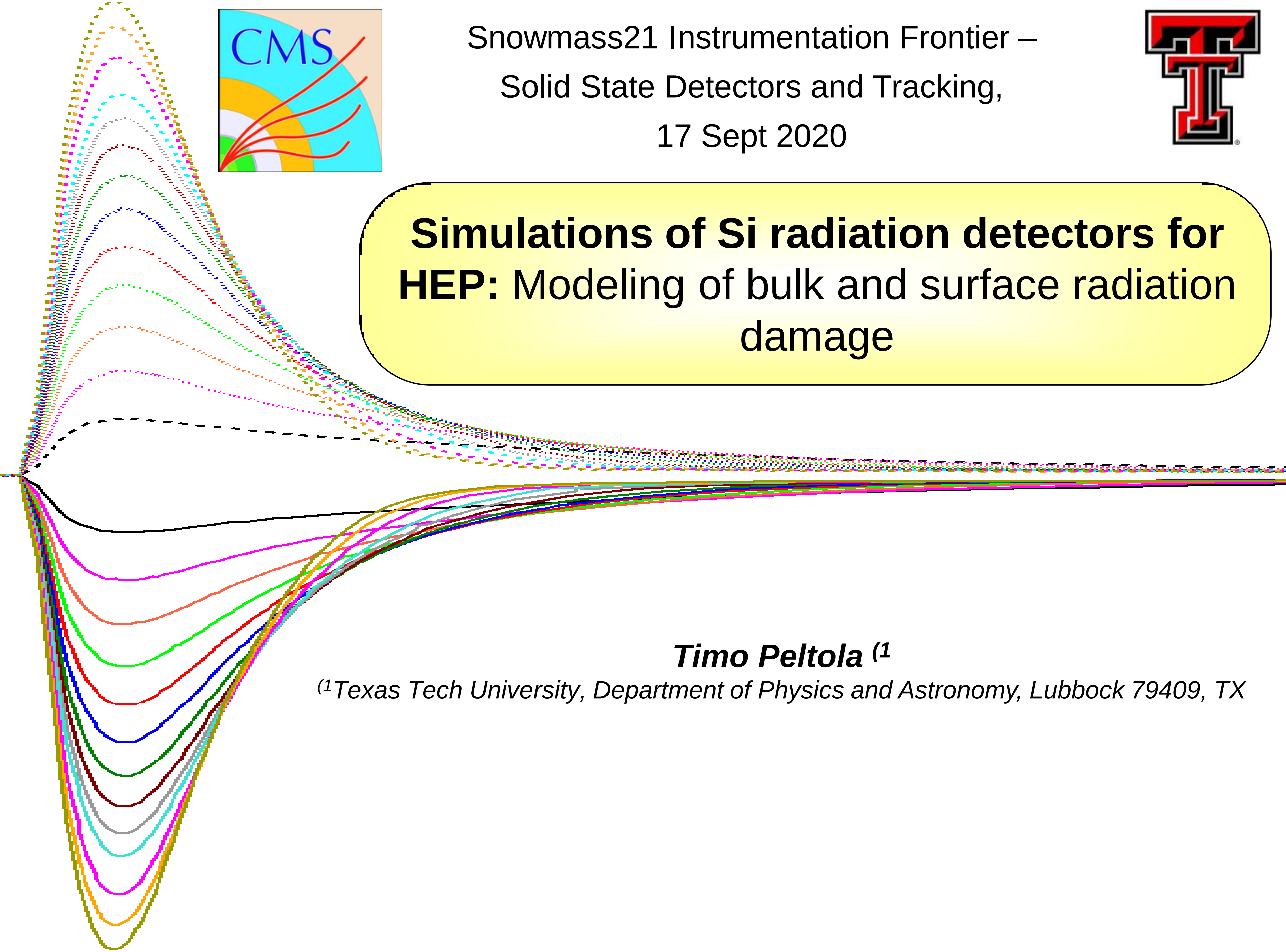
Snowmass21 Instrumentation Frontier –
Solid State Detectors and Tracking,
17 Sept 2020

Simulations of Si radiation detectors for HEP: Modeling of bulk and surface radiation damage



Timo Peltola (1

(1Texas Tech University, Department of Physics and Astronomy, Lubbock 79409, TX

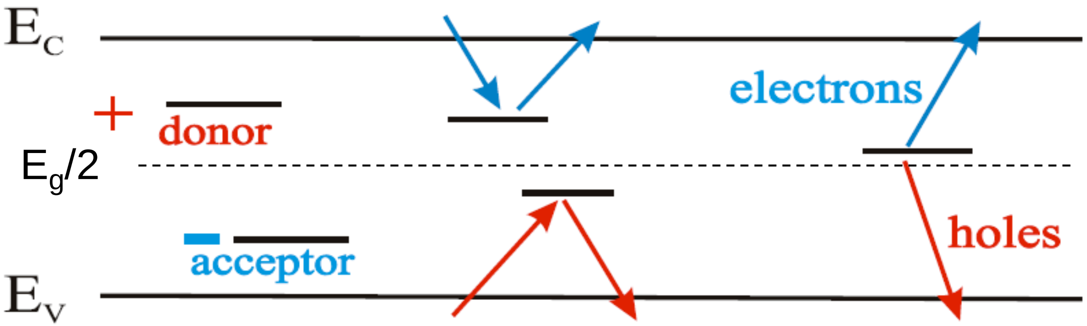
Radiation induced defects in Si: Modeling

Radiation damage in Si: Defect Parameters

- ☐ Radiation (Φ_{eq} >1e13 cm^{-2}) causes damage to Si crystal structure (Φ_{eq} = 1-MeV n_{eq})
- ☐ Φ_{eq} >1e14 cm^{-2} lead to significant degradation of CCE due to charge carrier trapping

- ☐ **Bulk & surface damage affect detector performance:**
  - **Bulk:** Deep acceptor & donor type trap levels
  - **Surface:** Charge layer accumulated inside oxide

Shockley-Read-Hall Statistics



Charged defects: N_{eff} (space charge, E-field), V_{dep}

Captured e, h: trapping → CCE

Generation/ Recombination e, h: LC

[M. Moll, VERTEX 2013]

- ☐ 11 defect levels observed to influence irradiated Si detectors (backups 1-2)
  → Vast parameter space to model

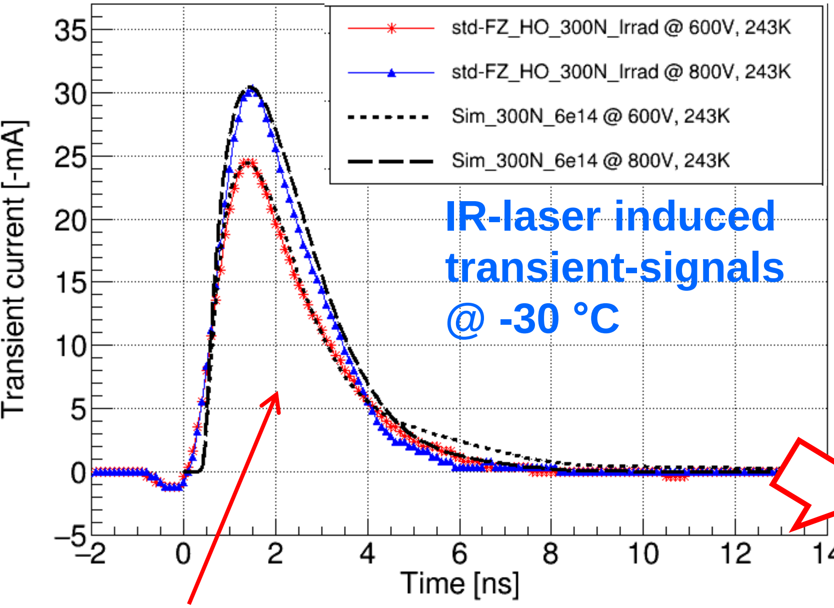
Defect parameters

Defect type	E_a [eV]	σ_n [cm^2]	σ_p [cm^2]	N_t [cm^{-3}]
Acceptor	E_C - x_1	O(1e-14)	O(1e-14)	$\eta_1 \cdot \Phi + c_1$
Donor	E_V + x_2	O(1e-14)	O(1e-14)	$\eta_2 \cdot \Phi + c_2$

Effective models needed for simulation

Simulated defects I: bulk damage

Transient currents & CCE: Measured vs simulated



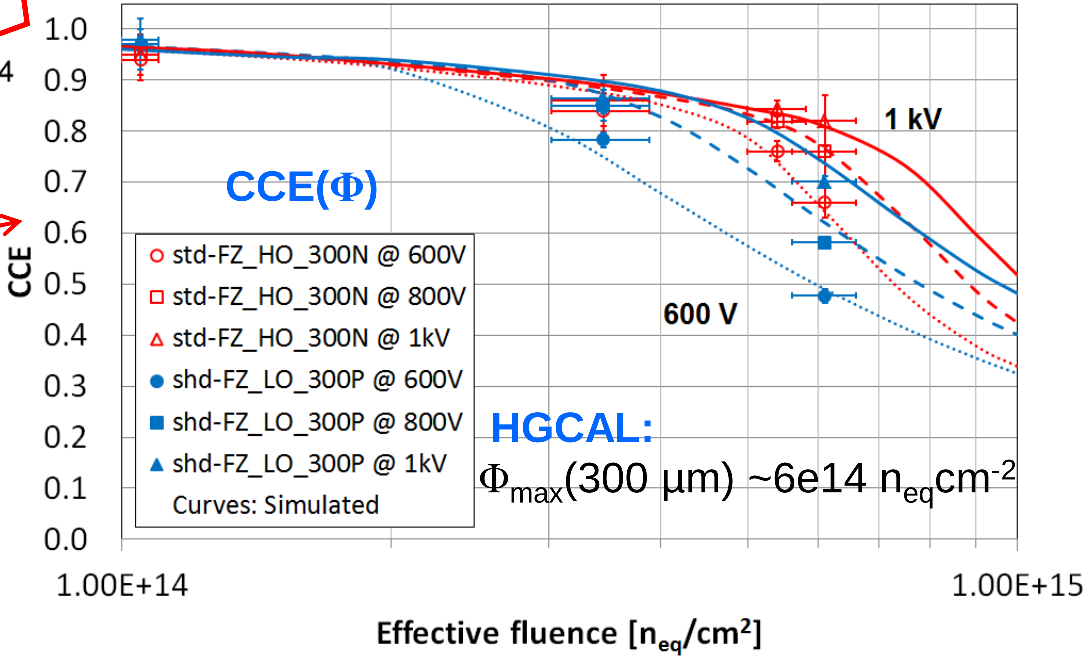
IR-laser induced transient-signals @ -30 °C

- **Measured:** $\Phi=(6.1\pm0.5)\text{e}14\ n_{eq}cm^{-2}$
- **TCAD simulated:** $\Phi=6.0\text{e}14\ n_{eq}cm^{-2}$
- **CCE(Φ) @ (1 – ~6.5)e14 $n_{eq}cm^{-2}$:** Measured CCE closely reproduced by simulation
- TCAD input parameters from measured CV/IV & TCT pre-irradiation (devices: backups 5 – 6)

- **HGCAL:** Highly segmented calorimeter @ $1.5 \leq \eta \leq 3.0$ → radiation dominated by neutrons

- Neutron defect model, Φ = 1e14 ~1e15 $n_{eq}cm^{-2}$ [1] (proton & neutron models: backups 3 – 4):

Type of defect	Level [eV]	σ_e [cm^2]	σ_h [cm^2]	*C* [cm^{-3}]
Acceptor	E_C - 0.525	1.2e-14	1.2e-14	1.55*Φ
Donor	E_V + 0.48	1.2e-14	1.2e-14	1.395*Φ

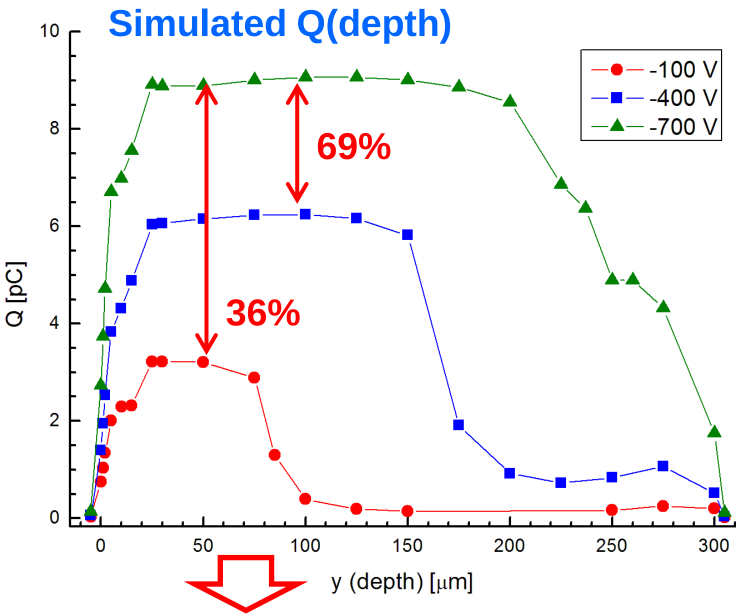


HGCAL: Φ_{max}(300 µm) ~6e14 $n_{eq}cm^{-2}$

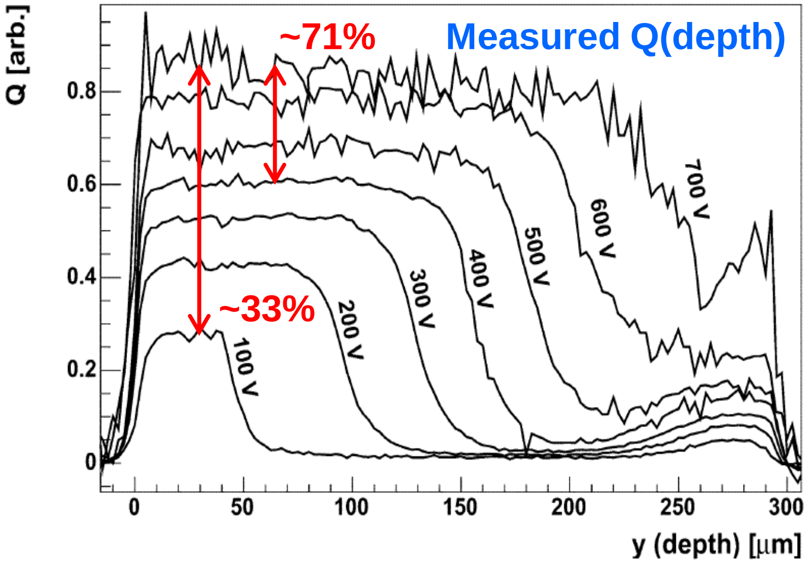
---

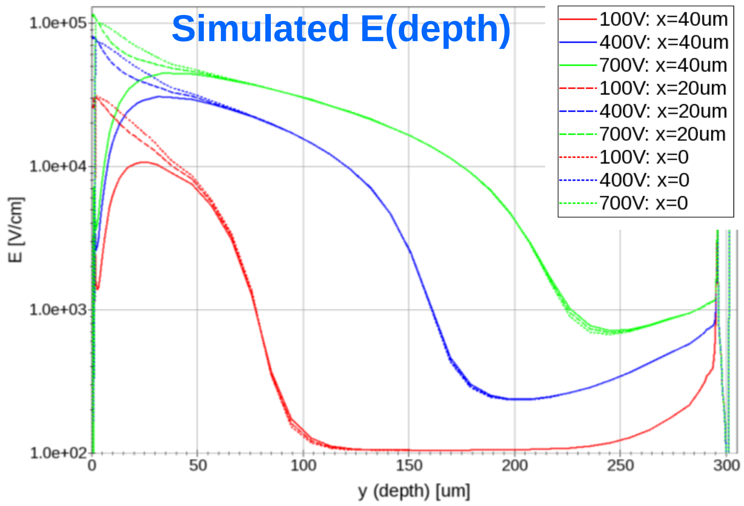
[1] R. Eber, PhD Thesis, KIT (2013)

Edge-TCT: Neutron irradiated strip detector



[G. Kramberger et al. IEEE Trans. Nucl. Sci. 57 (2010) 2294]





x=0:
center
of strip

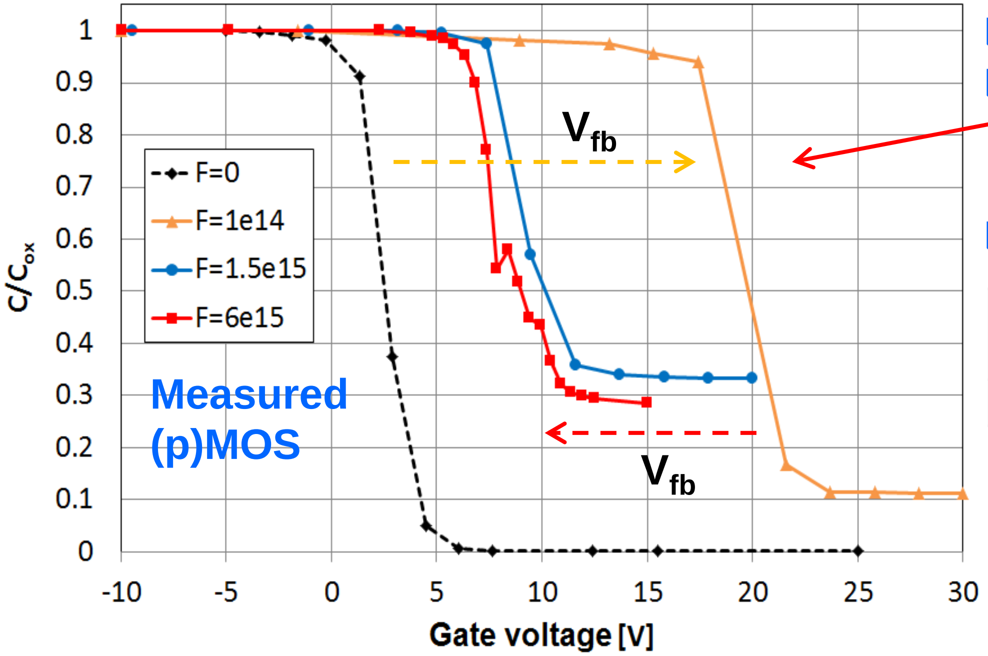
300 µm n-on-p strip sensor:
Φ=5e14 $n_{eq}cm^{-2}$, N_f=1e11 cm^{-2}, pitch=80 µm

- **Experimental:** Estimate E-field from v_{dr} using edge-TCT
- Amplitudes reproduced by simulation (back-up 7)
- Depletion depth accuracy increases w/ V →

Simulation gives reliable estimation of E(depth) @ HV

Simulated defects II:
surface damage

Irradiated MOS: N_f & interface traps (N_{it})

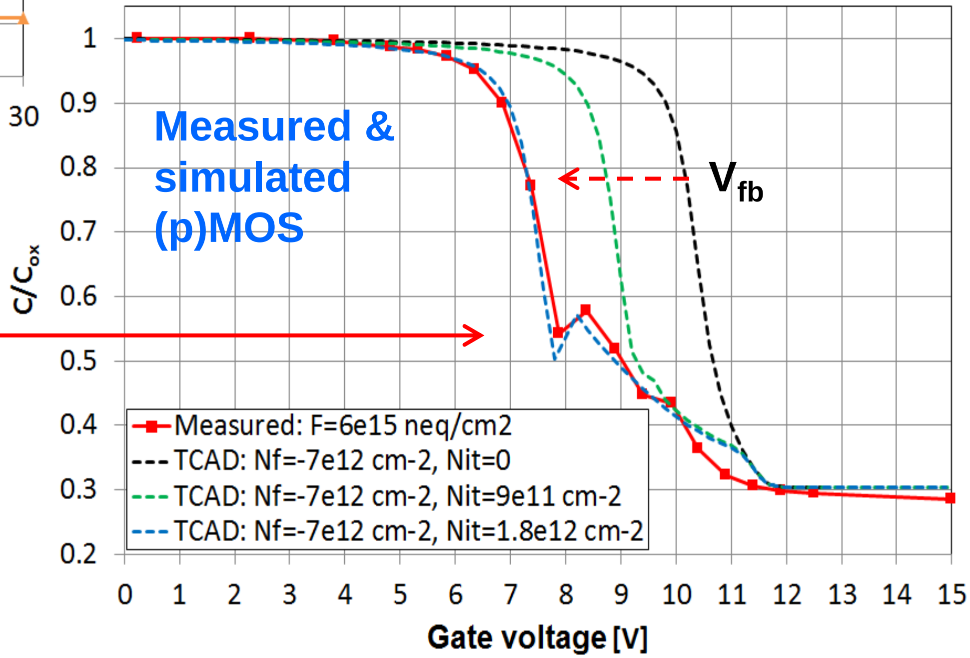


- ☐ **Al$_2$O$_3$ (alumina):** Negative oxide charge (N_f)
- ☐ **Neutron irradiation:** Initial increase of MOS V_{fb}, then decrease → influence of donor N_{it}?
- ☐ **Interface trap test level:**

Type of defect	**Level** [eV]	**σ_e** [cm^2]	**σ_h** [cm^2]	**Density** [cm^{-2}]
Donor	$E_V + 0.6$	1e-15	1e-15	variable

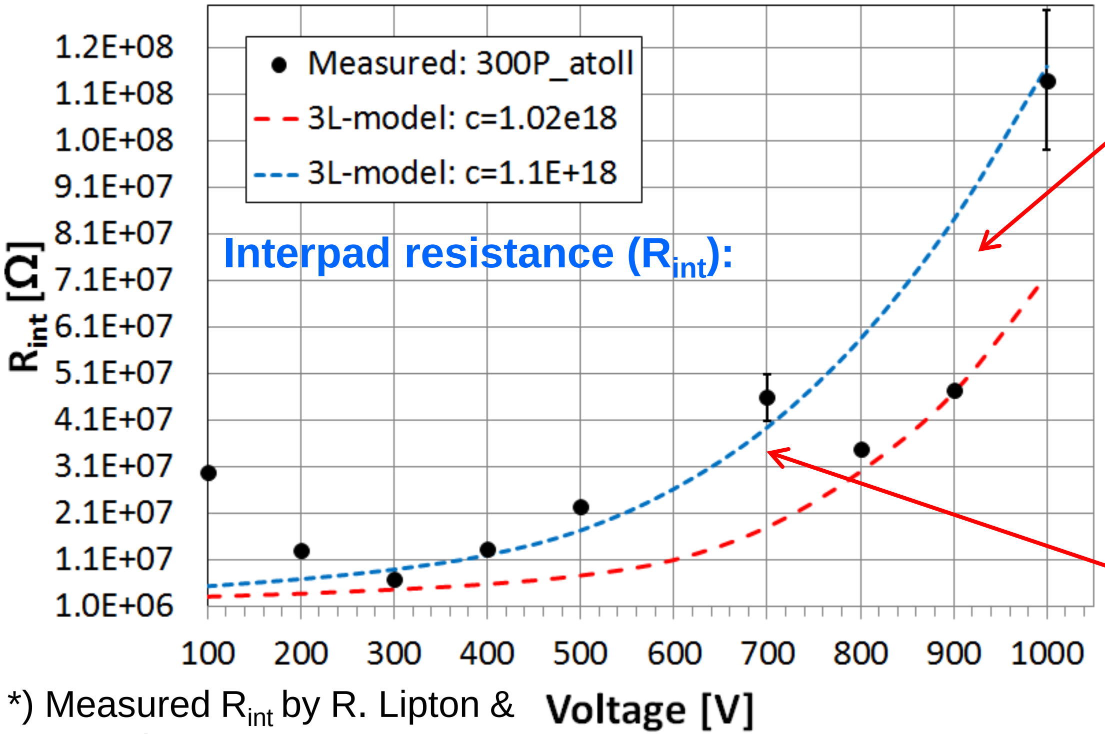
- ☐ Decreased V_{fb}, slope change & dip @ depletion reproduced by simulation → evidence that $N_{it,donor} \approx N_f$ @ high neutron Φ
- ☐ **SiO$_2$:** Positive N_f

$$\boxed{N_{\mathrm{f,eff}} = \pm N_{\mathrm{f}} + N_{\mathrm{it,donor}}}$$



Simulated defects III: bulk & surface damage

Measured/TCAD R_{int}: 3L-model @ 1e15 n_{eq}/cm^2



Interpad resistance (R_{int}):

- ❑ **Neutron irradiated pad sensor:** Φ_{eff}=1.2e15±20% n_{eq}/cm^2*
- ❑ **Measured:** Pads isolated @ all V
- ❑ **Neutron defect model [1]:** Φ=1e15 n_{eq}/cm^2, N_f = (1.41±0.15)e12 cm^{-2} → Pads isolated @ V > 450 V (backup 9) → need more realistic surface model
- ❑ **Preliminary 3L-model @ ≤ 2 μm depth & 1e15 n_{eq}/cm^2, N_f=1.4e12 cm^{-2}:** Pads isolated @ all V, stable C_{int} (backup 10)

*) Measured R_{int} by R. Lipton & M. Alyari

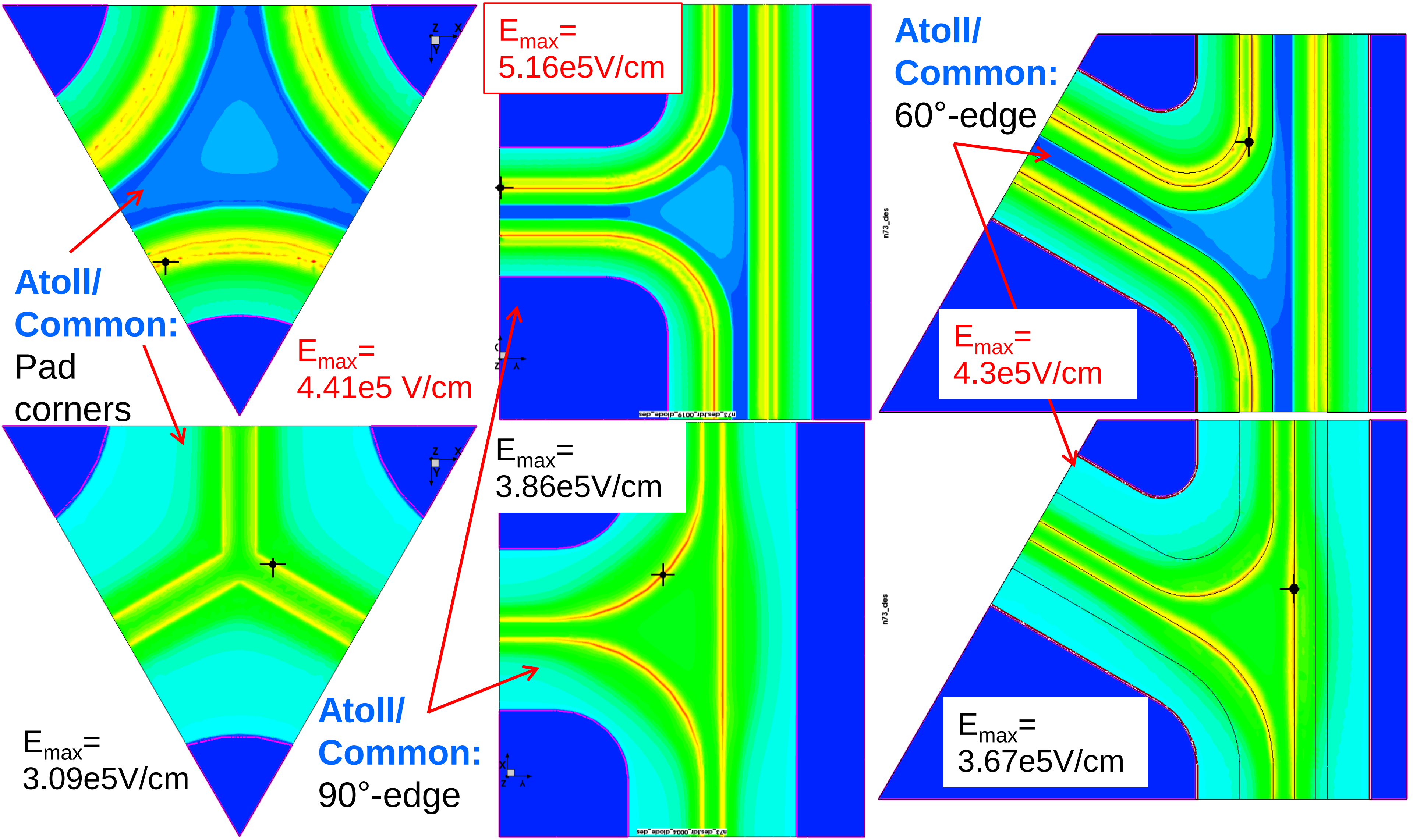
- ❑ Bulk properties of neutron model unaffected

Type of defect	Level [eV]	σ_e [cm^2]	σ_h [cm^2]	C [cm^{-3}]
Deep acc.	E_C - 0.525	1.2e-14	1.2e-14	1.550*Φ
Deep donor	E_V + 0.48	1.2e-14	1.2e-14	1.395*Φ
Shallow acc.	E_C - 0.40	8e-15	2e-14	**1.1e18**

[1]

- ❑ 2D-devices: backup 8
- ❑ 3L-model for protons: backups 11 – 12

3D-HGCAL regions & p-stops: E_{max} @ 1 kV



Atoll/ Common: Pad corners

E_{max}= 4.41e5 V/cm

E_{max}= 3.09e5V/cm

Atoll/ Common: 90°-edge

E_{max}= 5.16e5V/cm

E_{max}= 3.86e5V/cm

Atoll/ Common: 60°-edge

E_{max}= 4.3e5V/cm

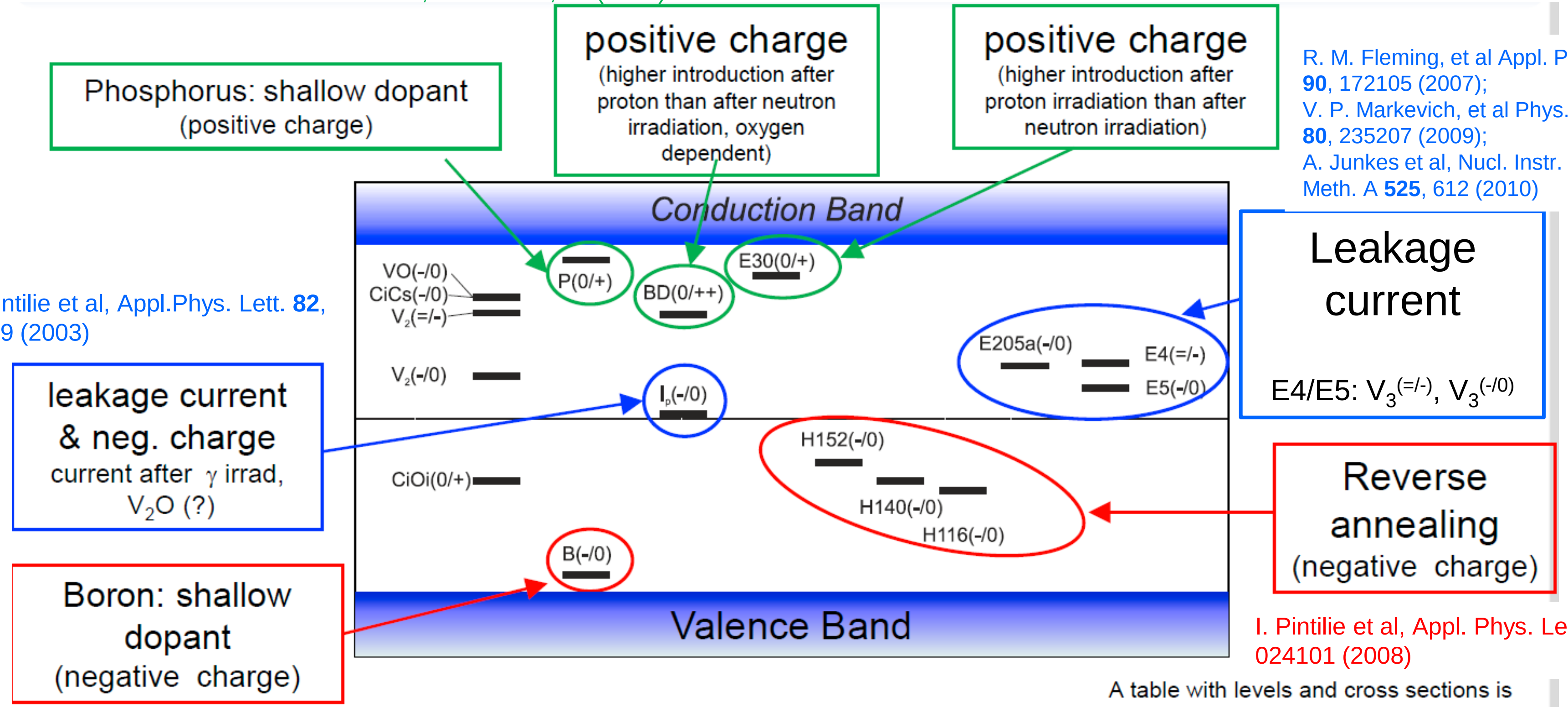
E_{max}= 3.67e5V/cm

Outlook: Sensors at extreme fluences

- ☐ **Si sensors @ extreme fluences ($\Phi \geq 1e16\ n_{eq}cm^{-2}$):**
  - **Low-T operation:** Mitigate leakage current
  - **Cryo-T operation:** Mobility & trapping times increase → faster output signals & higher Q_{coll}
  - **Electron collection:** ~3 times higher mobility & longer trapping times to holes
  - **Oxygenated bulk:** Suppressed build-up of negative space charge (charged hadrons)
  - **Short drift distance (<100 µm):** Minimize trapping probability
  - **Large signal & short drift distance:**
    - **LGAD:** Charge-multiplication layer (p-well)
    - **3D-pixels:** Decoupled signal amplitude & drift distance
- ☐ **Extreme-Φ defect model:**
  - Start by tuning against measured CCE & N_{eff} evolution @ $\Phi > 1e15\ n_{eq}cm^{-2}$ (level depths, trap concentrations,..)
  - Add E-field tuning (edge-TCT) & surface properties (R_{int}, C_{int}, charge sharing,...)

Back-up 1: Defect Characterization Overview

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



Phosphorus: shallow dopant
(positive charge)

positive charge
(higher introduction after proton than after neutron irradiation, oxygen dependent)

positive charge
(higher introduction after proton irradiation than after neutron irradiation)

R. M. Fleming, et al Appl. Phys. Lett. **90**, 172105 (2007);
V. P. Markevich, et al Phys. Rev. B **80**, 235207 (2009);
A. Junkes et al, Nucl. Instr. and Meth. A **525**, 612 (2010)

Leakage current

E4/E5: $V_3^{(=/-)}$, $V_3^{(-/0)}$

I. Pintilie et al, Appl.Phys. Lett. **82**, 2169 (2003)

leakage current & neg. charge
current after γ irrad, V_2O (?)

Reverse annealing
(negative charge)

Boron: shallow dopant
(negative charge)

I. Pintilie et al, Appl. Phys. Lett. **92**, 024101 (2008)

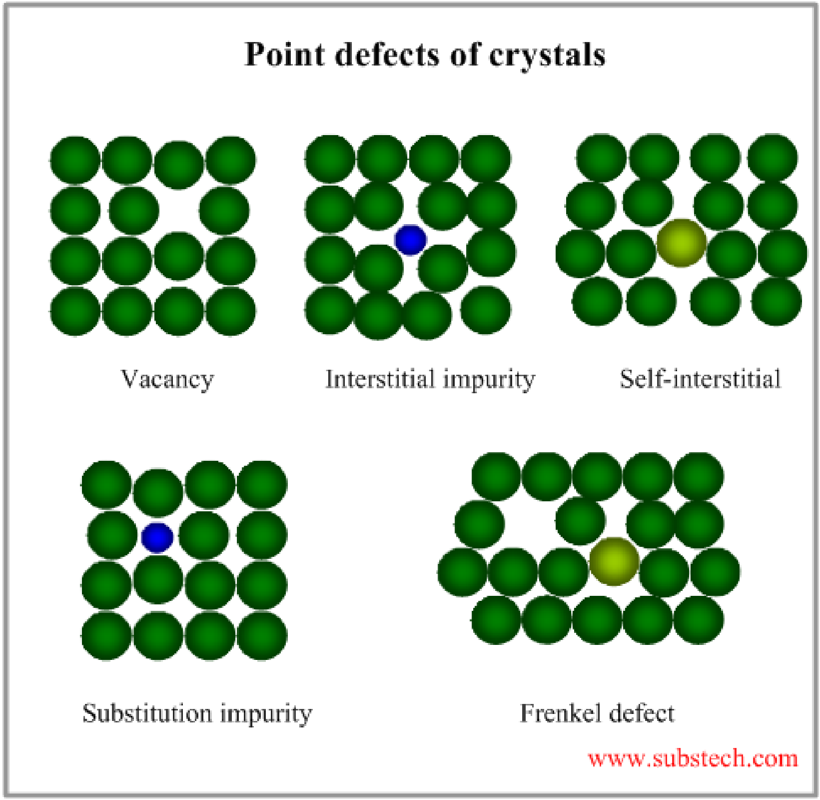
[M. Moll, VERTEX 2013]

A table with levels and cross sections is given in the Annex (spare slides).

- ☐ **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

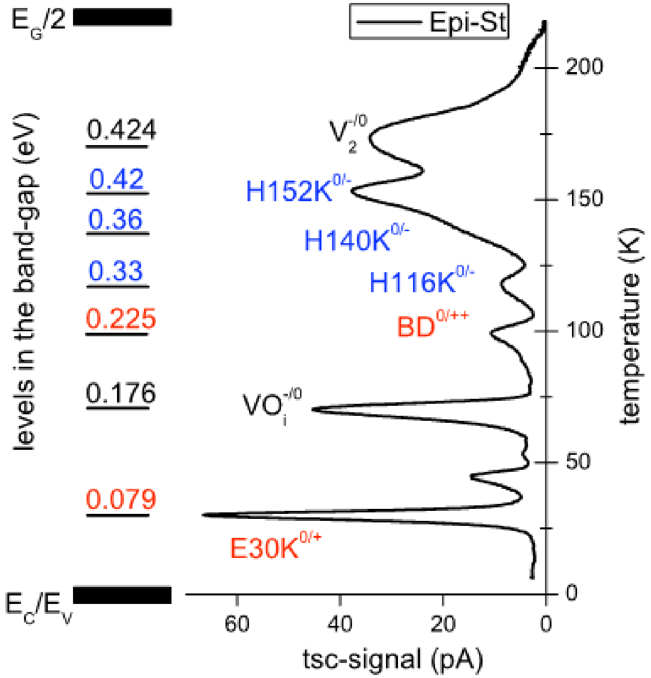
Back-up 2: Defects in silicon: Overlook

- **Each defect:** Energy level in Si bandgap or variety, depending on conglomeration of defects
- Multitude of E-levels, cross sections & concentrations: huge parameter space to model
- 11 defect levels proved to influence performance of irradiated Si detectors → **Effective model is needed for simulation**



[R. Eber, 8th Detector Workshop, Berlin, 2015]

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)]

Back-up 3: Defect simulations - TCAD

❑ **Motivation for 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 unexpected results
- Predictions for novel structures & conditions → Device structure optimization

❑ **Principle for irradiated Si detector TCAD simulation:**

- **Minimized set:**
  - ○ **2 midgap levels DD & DA applied to reproduce & predict:** Bulk generated current + E(depth) + trapping
  - ○ **Surface damage:** Fixed charge density N_f @ SiO_2/Si interface w/ interface traps N_{it} of varying depth distributions

❑ **Sentaurus TCAD proton & neutron defect models for Φ_{eq} =1e14 ~ 1e15 cm^{-2} @ T=253 K** [1]

Defect type	Level [eV]	σ_e [cm^2]	σ_h [cm^2]	Concentration [cm^{-3}]
Deep acc.	E_C - 0.525	1e-14	1e-14	1.189*Φ + 6.454e13
Deep donor	E_V + 0.48	1e-14	1e-14	5.598*Φ - 3.959e14

Defect type	Level [eV]	σ_e [cm^2]	σ_h [cm^2]	Concentration [cm^{-3}]
Deep acc.	E_C - 0.525	1.2e-14	1.2e-14	1.55*Φ
Deep donor	E_V + 0.48	1.2e-14	1.2e-14	1.395*Φ

❑ **Can trapping be explained in frame of 2-DL model?** [2]

- $\beta \approx 5e\text{-}7\ s^{-1}cm^2$ & Φ=1e14 cm^{-2} → τ = 20 ns
- Trapping X-section σ=1e-14 cm^2, v_{th}=2e7 cm/s

→ $N_t = 1/[\sigma v_{th}\tau]$ = 2.5e14 cm^{-3} or intro rate $\eta(N_t)$ = 2.5

$\eta(N_t)$, η(DA) & η(DD) have equal range →
2-DL model has potential to model CCE(Φ)

---

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

Back-up 4: DP & LC for neutron & proton defect models

- 300 μm thick p-on-n pad detector @ T=253 K

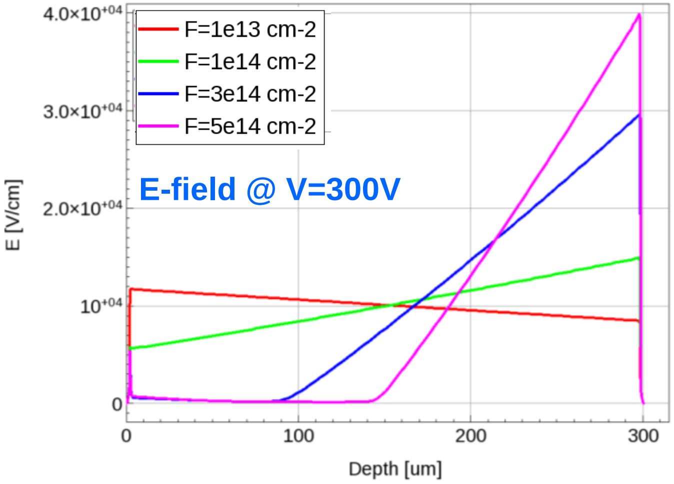
- **Fluences :** Φ = 1e13 – 5e14 n_{eq} cm^{-2}

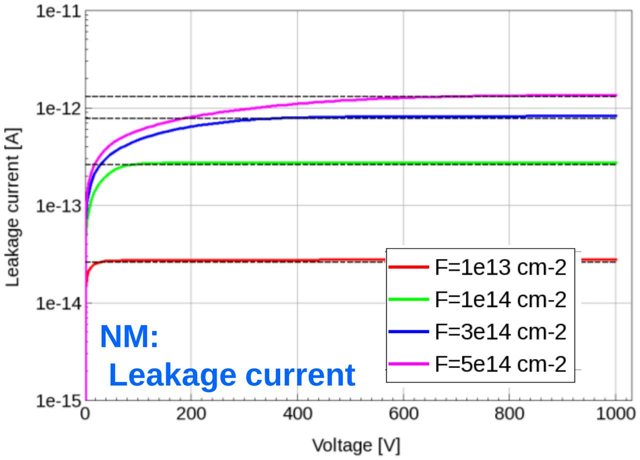
- DP is produced by both models (more pronounced in PM due to higher trap concentration for given Φ)

- **Dashed black lines:** experimental LC by $\Delta I = \text{Volume} \cdot \alpha \cdot \Phi$, $\alpha(253K) \approx 8.9 \cdot 10^{-19}$ $A \cdot cm^{-1}$

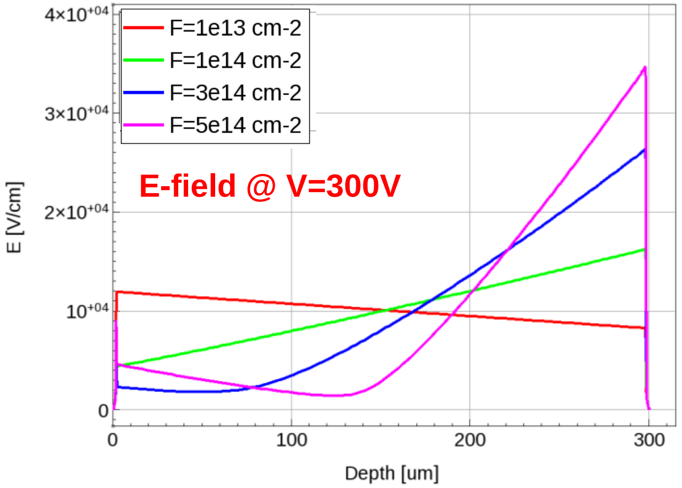
- LC has perfect match with experimental values

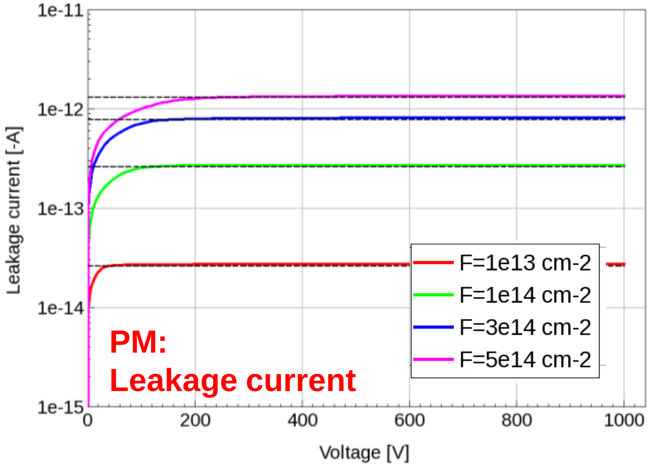
NEUTRON MODEL (NM)





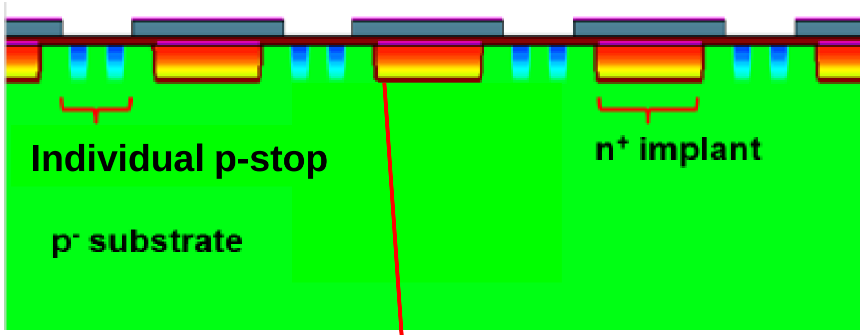
PROTON MODEL (PM)

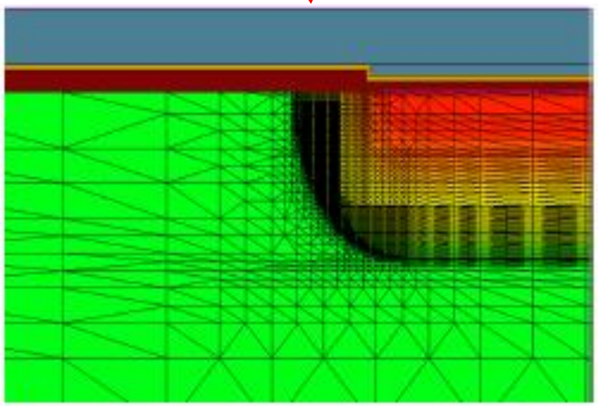


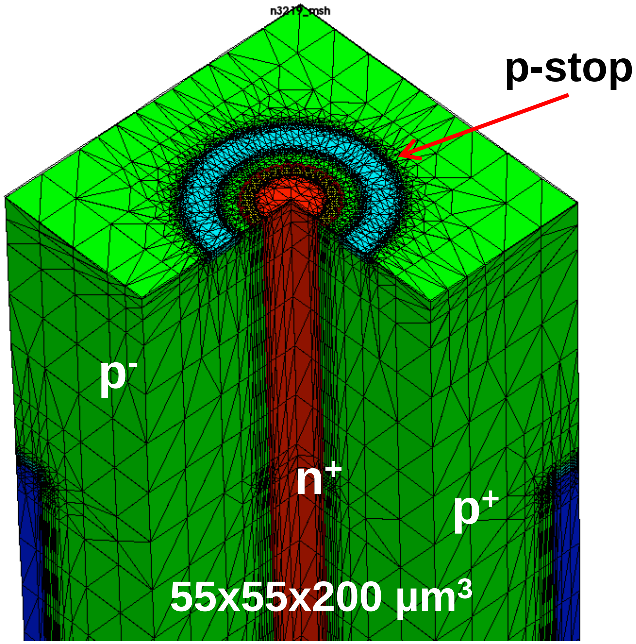


Backup 5: Simulated sensors - 2D & 3D designs

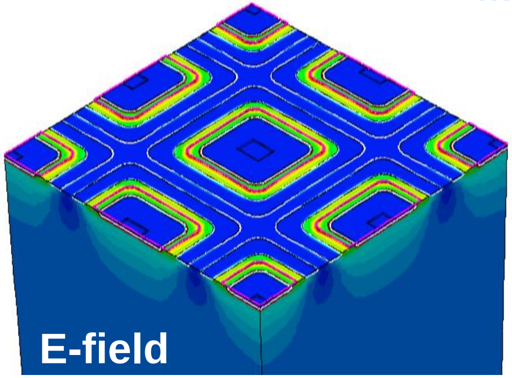
- ☐ **Pad & strip sensors:** Constant E-field in 3rd dimension → 2D structures sufficient for accurate results → extend to real device dimensions by area factor
- ☐ **Planar & 3D-columnar pixel sensors:** 3D-design required for correct modeling of E-fields



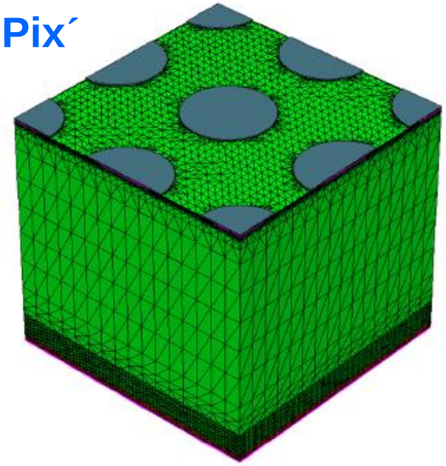




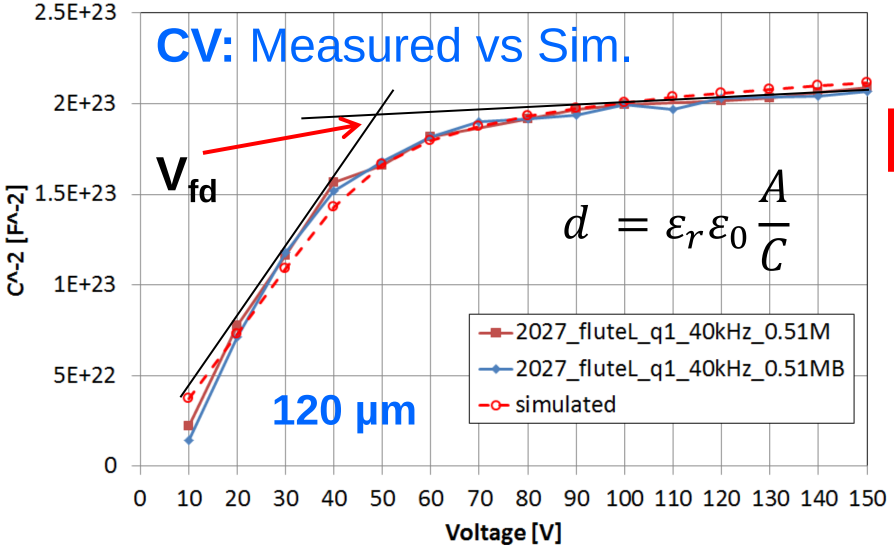
50x50 pixel sensor

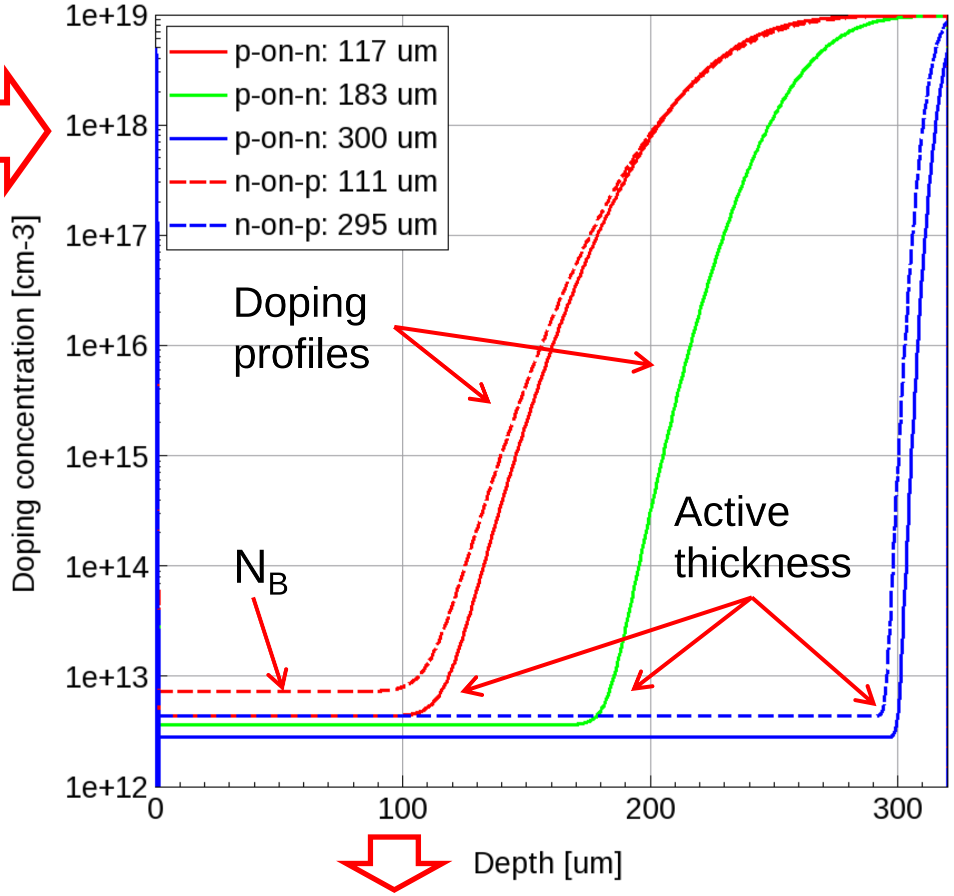


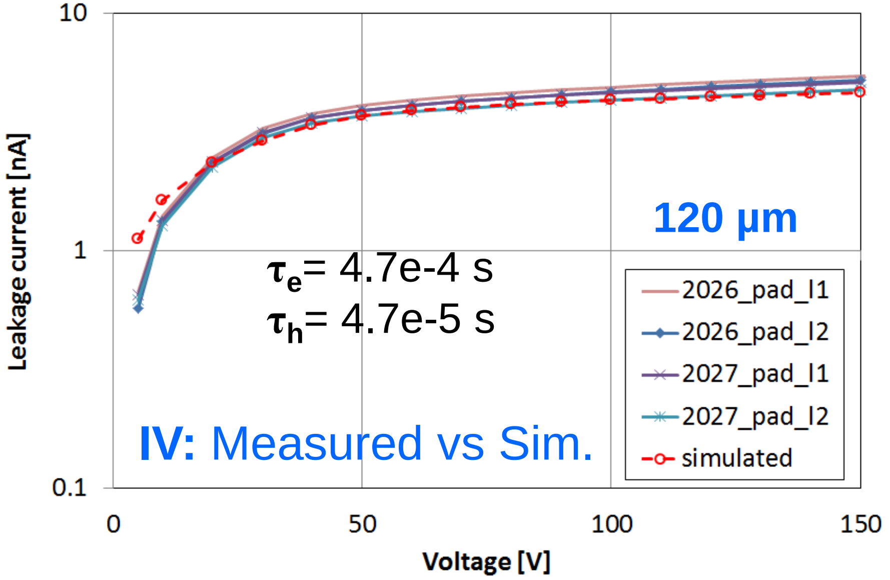
´MediPix´



Backup 6: Measured CV/IV - Simulation input





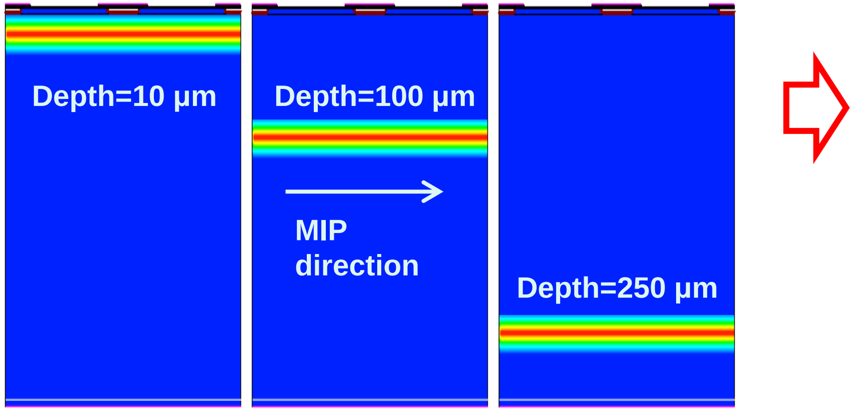


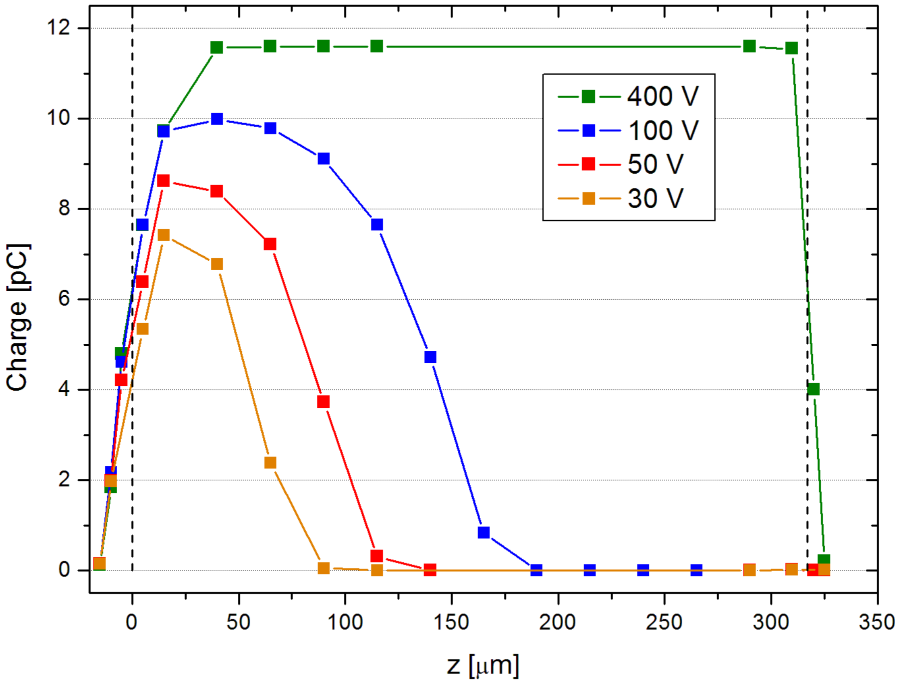
Extracted parameters to tune simulation to measured LC by carrier trapping times

Back-up 7: Method for simulated edge-TCT

- **Experimental:** Estimate E-field from drift velocity v_{drift} using eTCT → provides measurement of collection time $t_c \propto v_{drift}$

Principal of edge-TCT simulation:

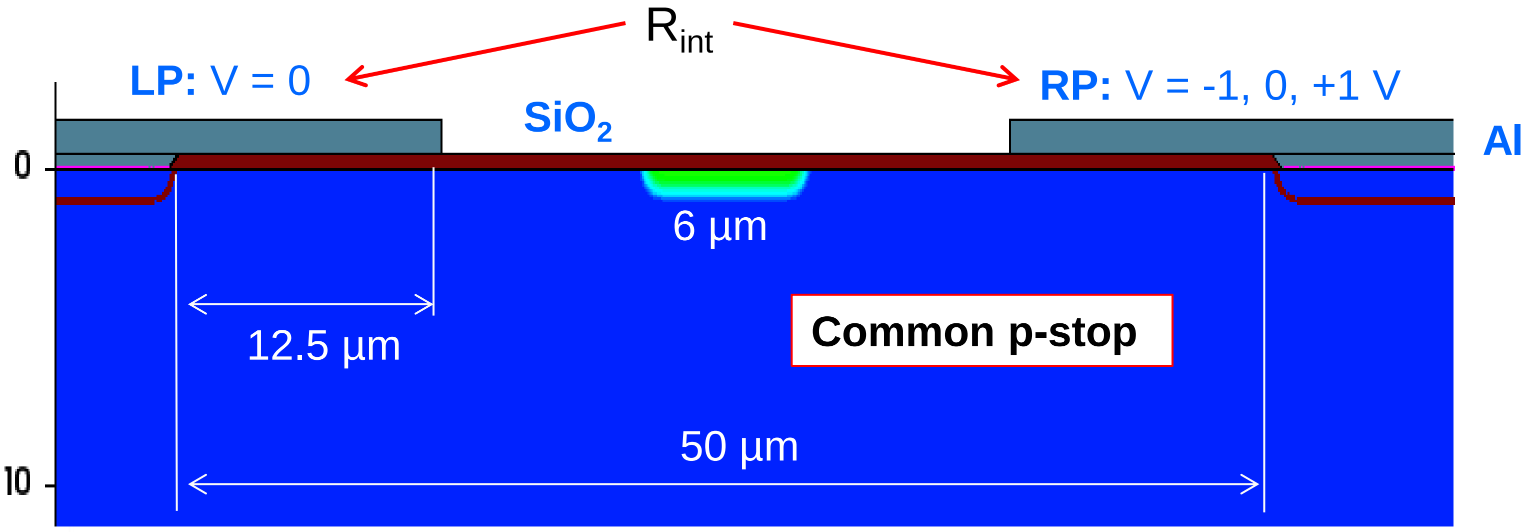


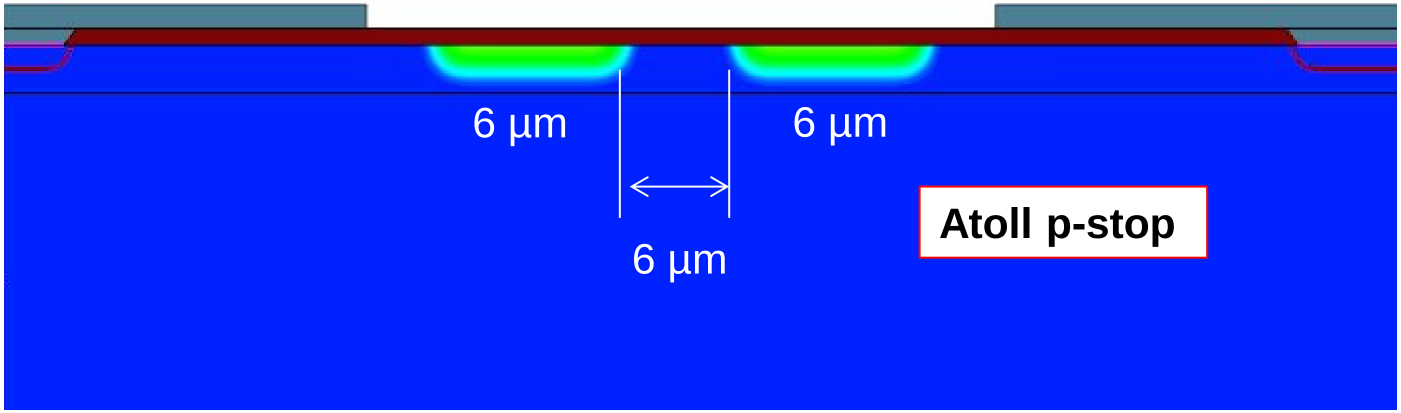


- TCAD simulated edge-TCT collected charges Q(z) for non-irradiated 320 µm p-on-n strip detector @ $V<V_{fd}$ & $V>V_{fd}$, T = 293 K
- **Dashed vertical lines:** Active region of detector (defined from center of rising & descending slopes of Q(z) distribution) → Different E-field extensions into bulk from pn-junction at z=0 are reflected by Q(z)
- **Differences in Q(z) amplitude:** Reproduced by using laterally extended device structure → extension of E-field to detector edges

Backup 8: 8-in sensors - Common/atoll p-stops

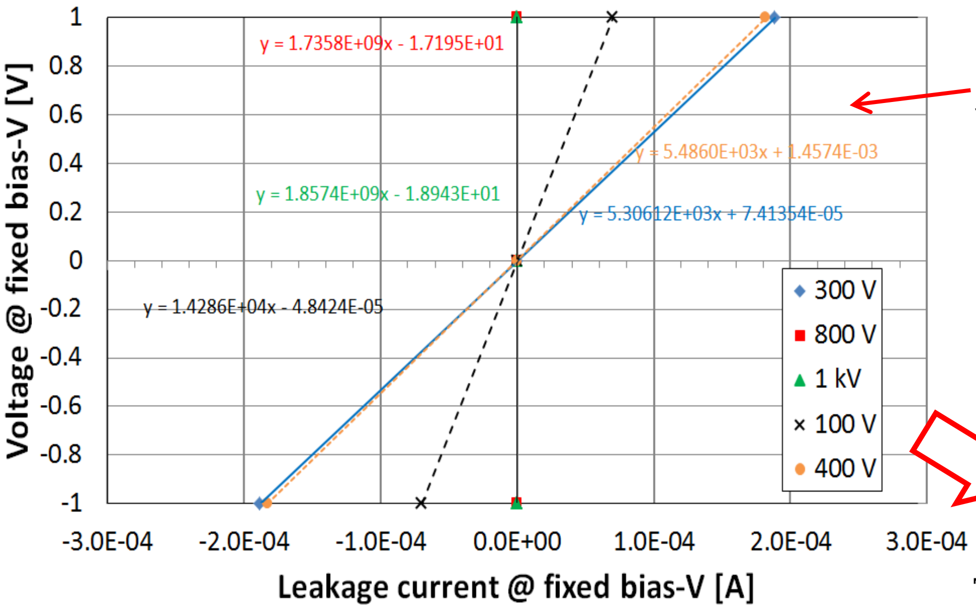
- **TCAD structures:** DC-coupled 200P





Open p-stop parameters: Peak doping (N_{ps}) & depth (d_{ps})

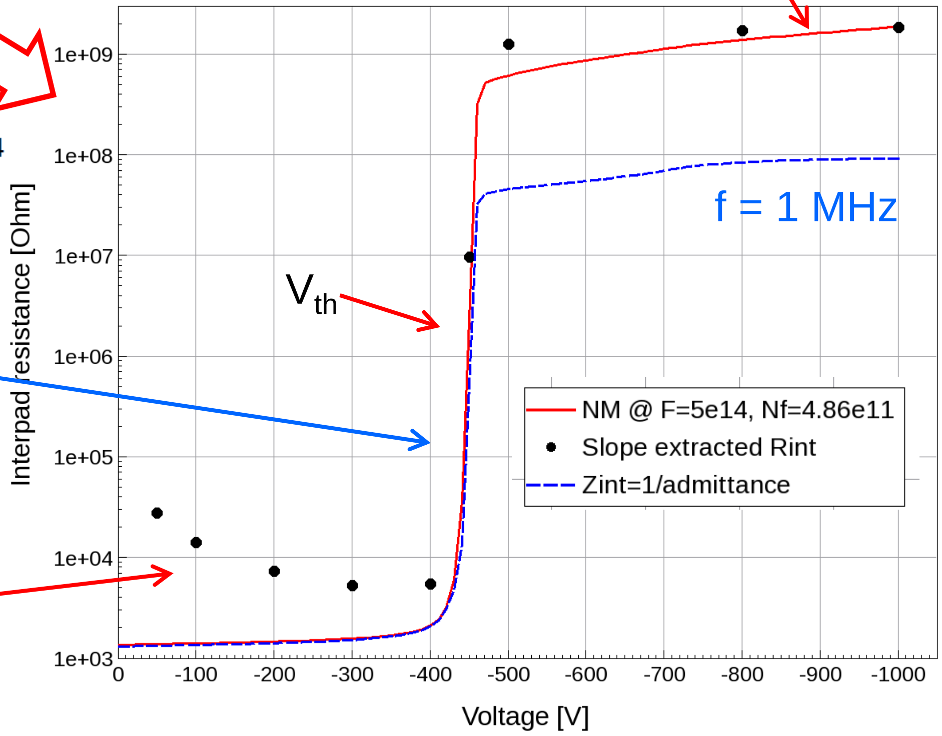
Backup 9: TCAD R_{int} - 3 extraction methods



M1: R_{int} = slope of V(RP) vs I(RP) for fixed bias V (laborous) → same as FNAL measured R_{int}*

M2: V(on/off) @ RP: $R_{int} = \frac{U(1\,V)}{I(1\,V) - I(0\,V)}$

→ given directly by simulation (fast)

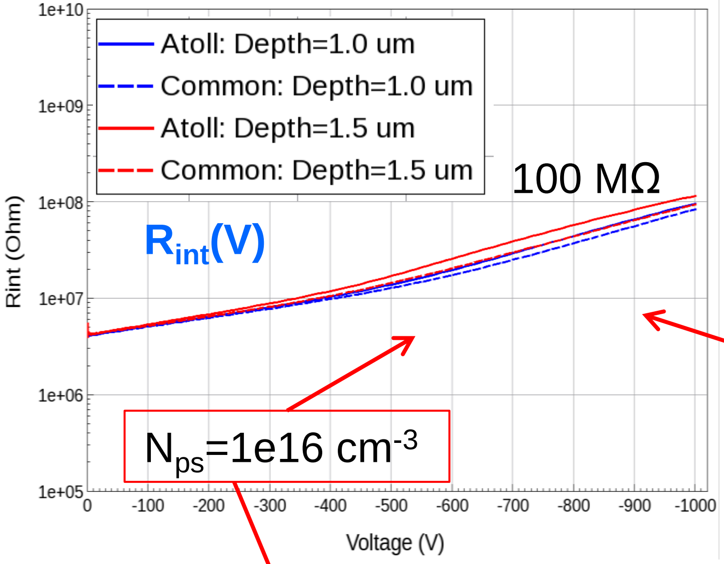


M3: $R_{int} \approx Z_{int}$ = 1/admittance → given directly by simulation (fast)

- ☐ **3 methods:** Different features, same V(threshold) (V_{th})
  - **Method 1:** Anomalous increase of R_{int} @ LV (not expected)

*) Measured R_{int} by R. Lipton & M. Alyari

Backup 10: Common vs atoll p-stop - R_{int}/C_{int}

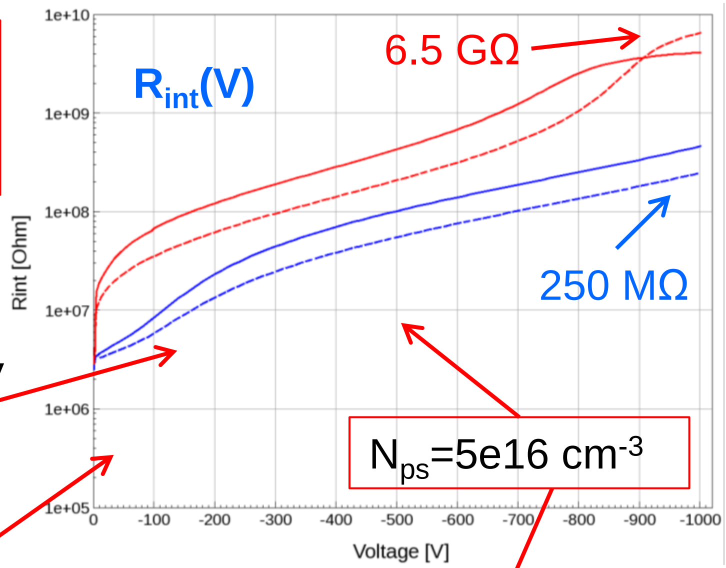


100 MΩ

N_{ps}=1e16 cm^{-3}

- ❑ Φ_{eff}=1e15 n_{eq}/cm^2, N_f=1.4e12 cm^{-2}, 3L-defect model

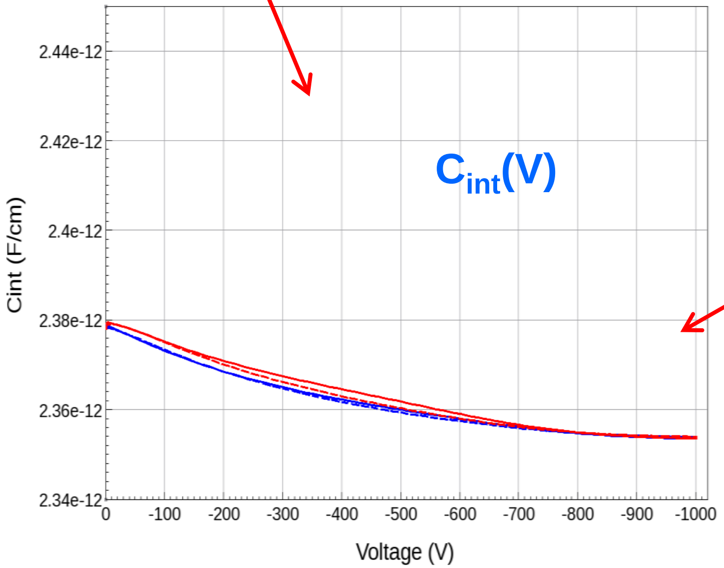
- ❑ **Common & atoll:** Pads isolated @ all V
- ❑ **Atoll 1 µm:** ~1.8-fold higher R_{int} @ HV
- ❑ **Common 1.5 µm:** ~1.6-fold higher R_{int} @ 1 kV



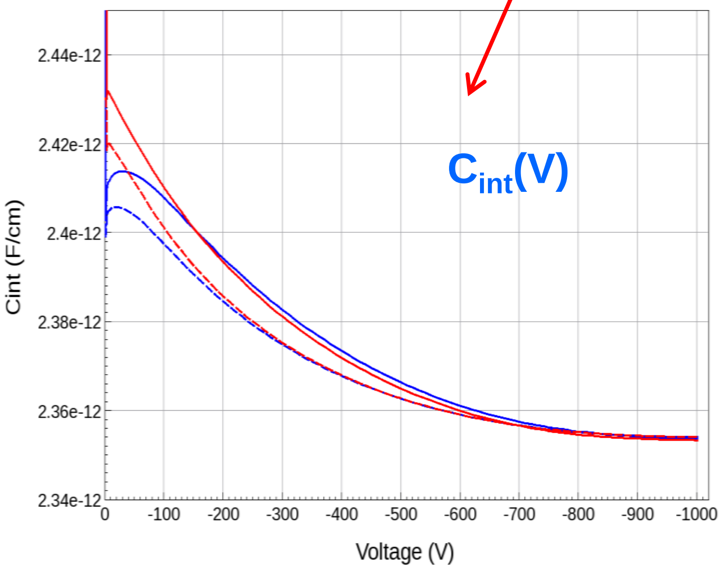
6.5 GΩ

250 MΩ

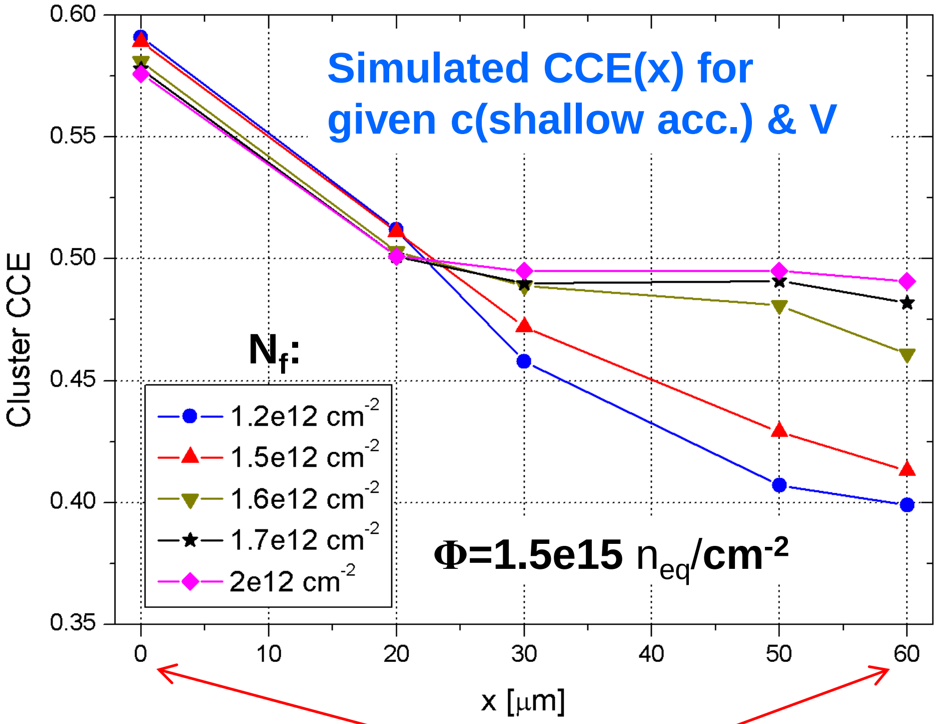
N_{ps}=5e16 cm^{-3}



- ❑ **Common & atoll:**
  - ▪ ΔC_{int}≈0.03 pF/cm
  - ▪ ΔC_{int}≈0.08 pF/cm



Back-up 11: Proton bulk & surface damage: CCE(x)



CCE loss

16%

17%

20%

29%

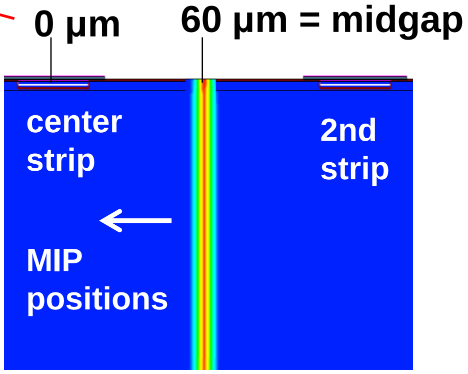
32%

- ☐ **Heavily irradiated strip detectors demonstrate significant position dependency of CCE [CCE(x)]**

- ☐ **Non-uniform 3-level model:**

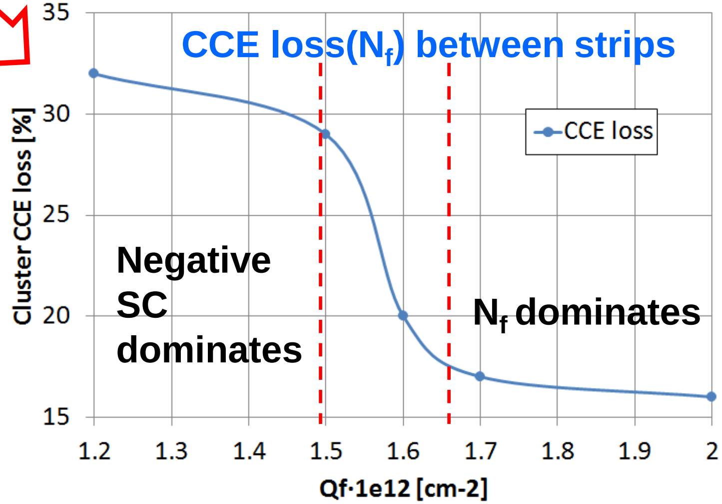
N_{it} cannot be used: measured C_{int} not reproduced → need deeper distribution → **3-level model within 2 μm of device surface + proton model in bulk:**

  - ○ R_{int} & C_{int} in line w/ measured also @ high Φ & N_f (back-up 13)



Strips isolated:
Cluster CCE decreases towards midgap

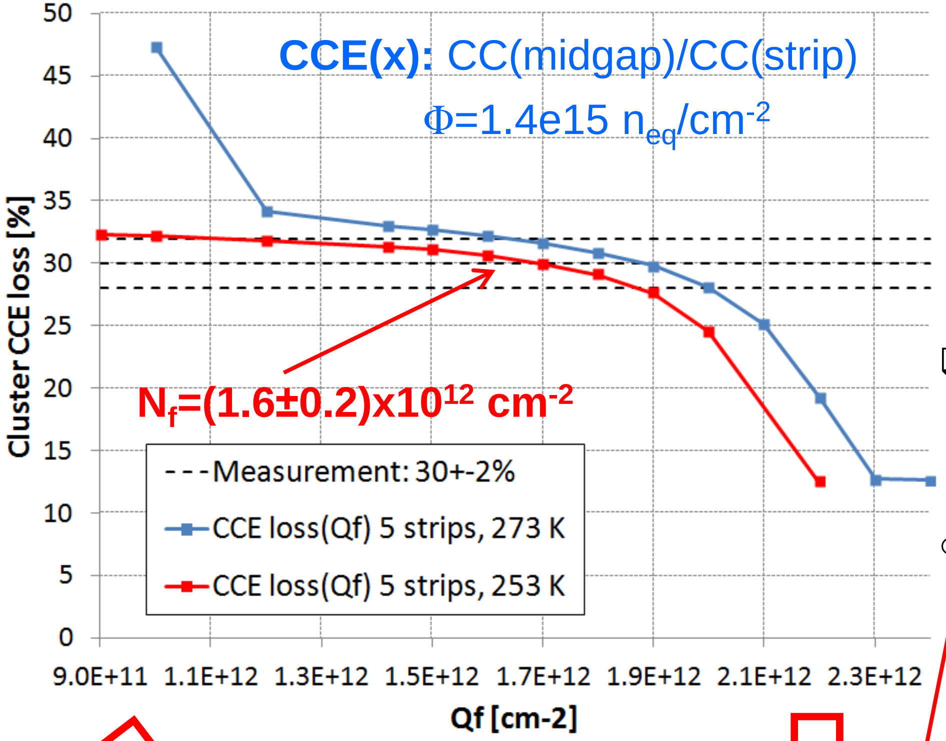
Strips shorted:
Cluster CCE independent of position



[T. Peltola, JINST 9 (2014) C12010 & T. Peltola et al., JINST 10 (2015) C04025]

Back-up 12: Proton 3L-model

- ☐ **Heavily irradiated strip detectors demonstrate significant position dependency of CCE [CCE(x)]**



CCE(x): CC(midgap)/CC(strip)

Φ=1.4e15 n_{eq}/cm^{-2}

N_f=(1.6±0.2)x10^{12} cm^{-2}

- ☐ **3-level model within 2 µm of device surface + proton model in bulk:**
  - ○ R_{int} & C_{int} in line w/ measured also @ high Φ & N_f

Test beam measured:

- Strips isolated
- CCE loss ~30%

- ☐ Irradiation produces shallow traps close to surface → greater drift distance, higher trapping of carriers

Preliminary parametrization for Φ = 3e14 – 1.4e15 n_{eq}/cm^{-2}

Defect type	**Level** [eV]	σ_e [cm^2]	σ_h [cm^2]	***C*** [cm^{-3}]
Deep acc.	E_C - 0.525	1e-14	1e-14	1.189*Φ + 6.454e13
Deep donor	E_V + 0.48	1e-14	1e-14	5.598*Φ - 3.959e14
Shallow acc.	E_C - 0.40	8e-15	2e-14	14.417*Φ + 3.168e16

[T. Peltola, JINST 9 (2014) C12010]