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TCAD simulation of 4H-SiC LGADs

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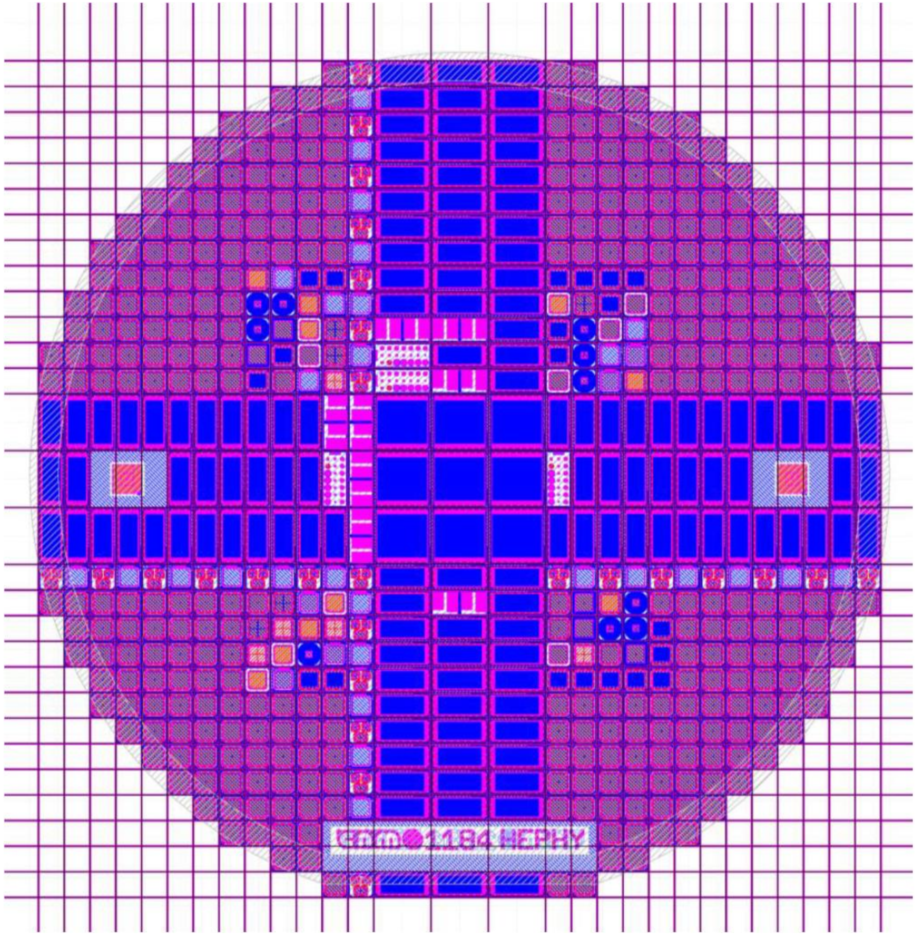
43rd RD50 Workshop
29th November 2023

Outline

- Short recap
- New UV-TCT measurements
  - On irradiated planar samples
  - > 100 % CCE in forward bias
  - Dependence on injected power density
- TCAD simulation of 4H-SiC LGADs

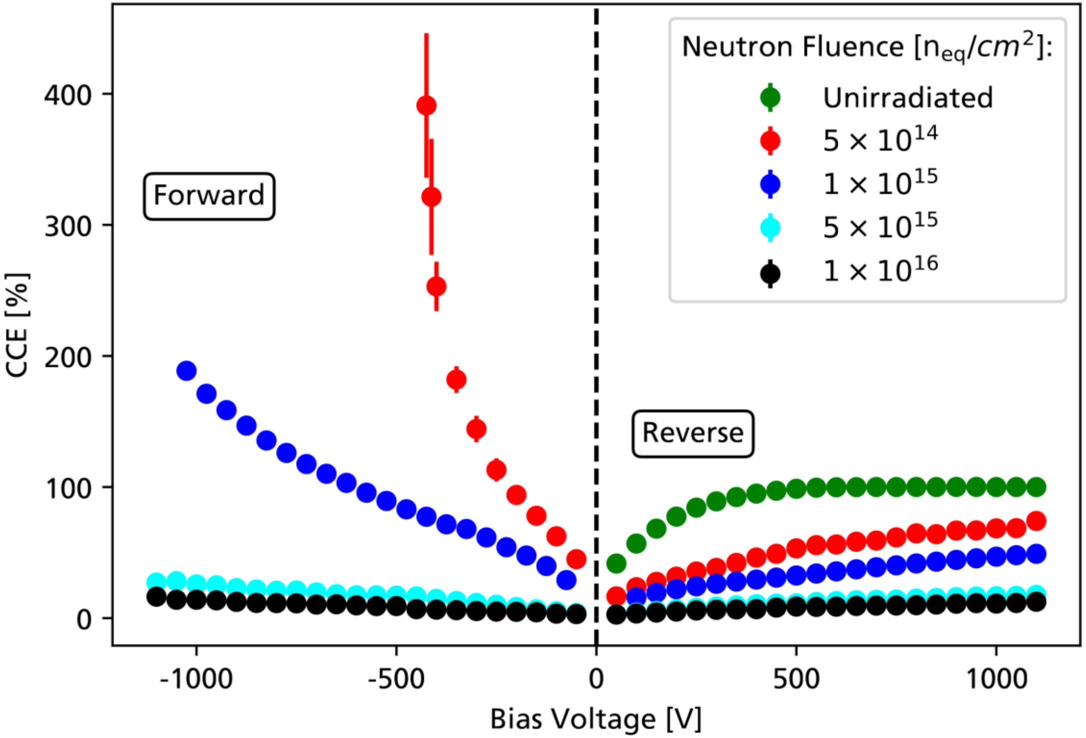
Short recap from last RD50 [1]

- Measurements on planar 4H-SiC (CNM) samples:
  - IV
  - CV
  - CCE
- Implemented SYNOPSYS simulation frame for 4H-SiC
  - Higher floating points accuracy
  - Adapted solver settings
  - Physical model parameters
- Agreement between simulations and experiments
- Current 4HSiC wafer-run:
  - Detectors, MOSCAPs, MOSFETs, Gate controlled diodes, Test structures…
  - Scheduled for mid-February (more from Thomas…)



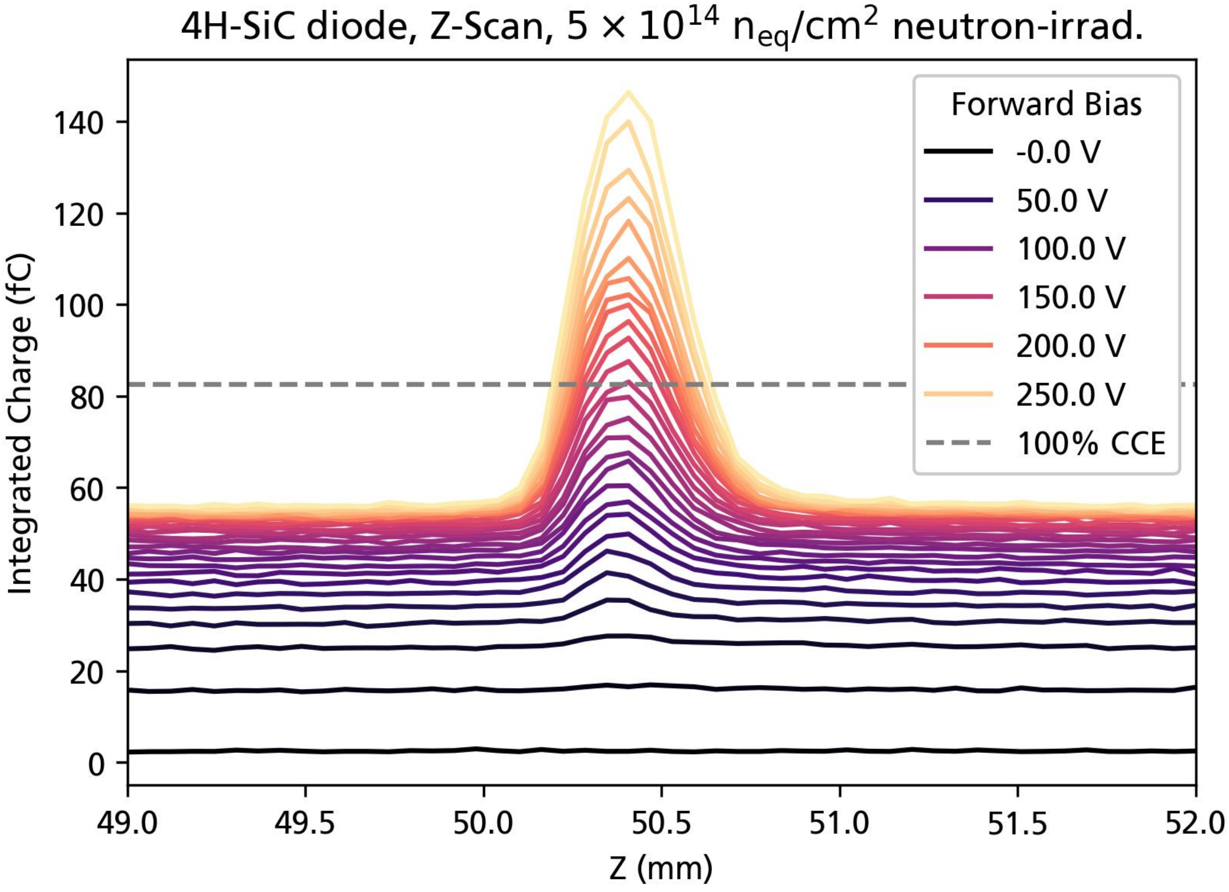
UV-TCT in forward bias

- Continuation of results presented by A. Gsponer at 42nd RD50 [3]
- Neutron-irradiated samples
- Observed a CCE > 100% in forward bias for irradiated diodes [3, 4]
- Also seen in TPA-TCT [5]
- New investigations with samples without metallization
- Vary voltage, laser focus and repetition rate
- Measurement using Cividec Cx-L CSA



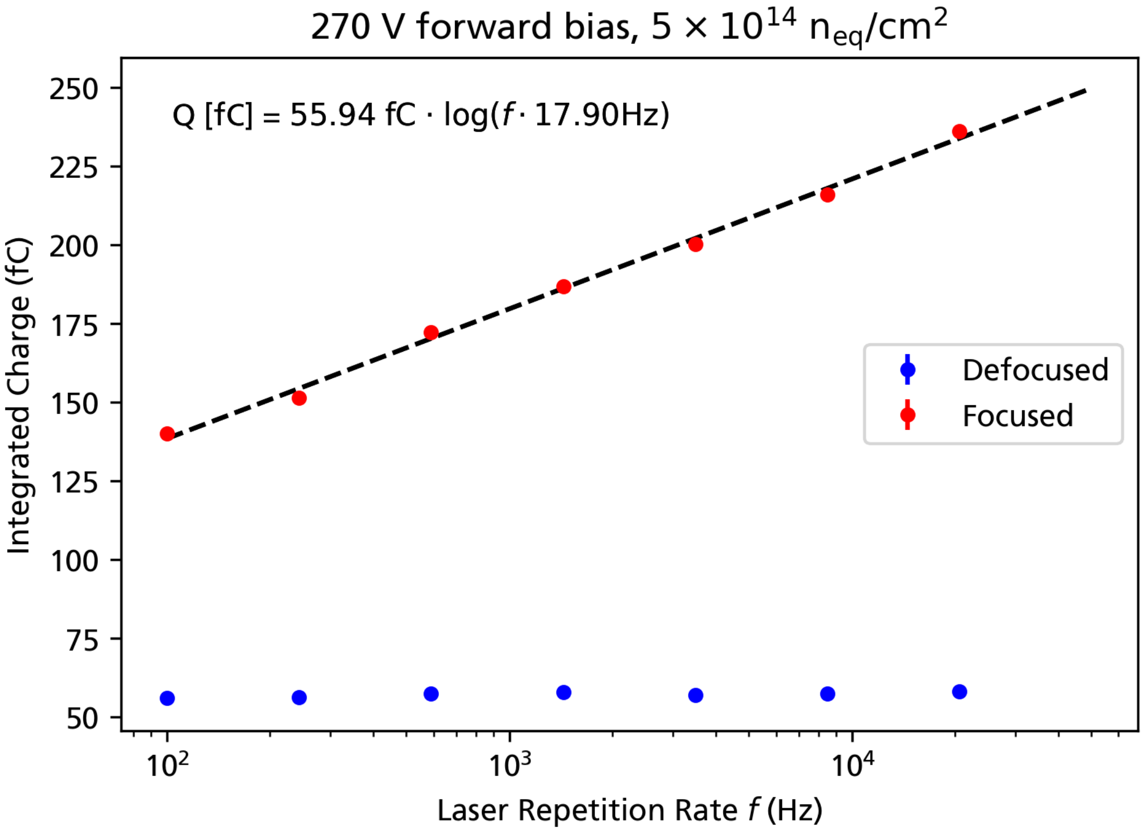
CCE vs Laser Focus

- In forward bias, CCE increase strongly correlates with laser focus
- For sufficiently de-focused laser: Saturation of collected charge
- Exponential increase with voltage in best focus



CCE vs Laser Repetition Rate

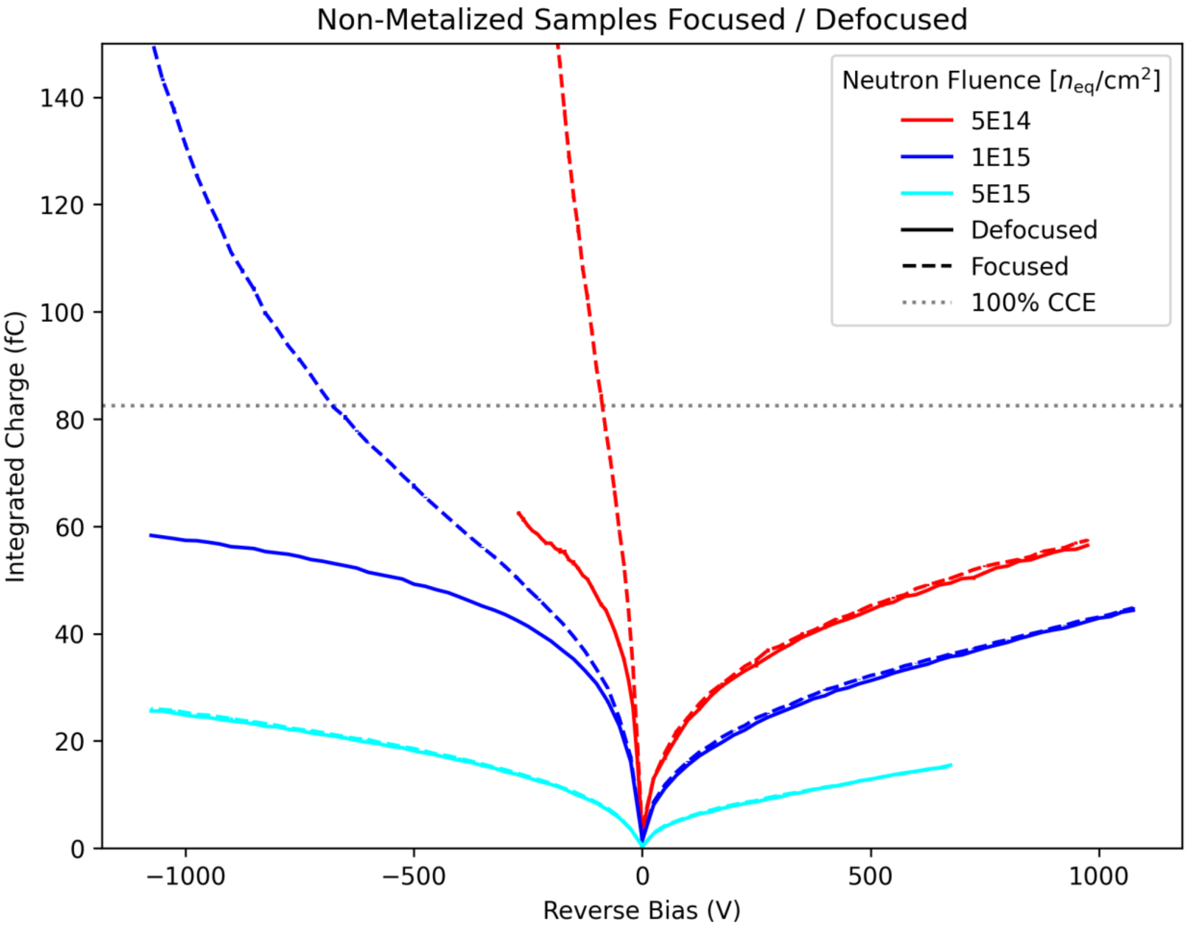
- Laser repetition rate : #triggers/s
- If defocused : Collected charge independent of repetition rate
- At best focus: Logarithmic increase of charge
- Current hypothesis:
  - SiC epi becomes intrinsic due to traps → high resistivity
  - Increase of free charge carriers via UV-TCT decreases resistivity
  - Transient forward current is integrated as "signal"



CCE Curves Focused/Defocused

- With sufficiently defocused laser, exponential increase of the CCE in forward bias can be avoided

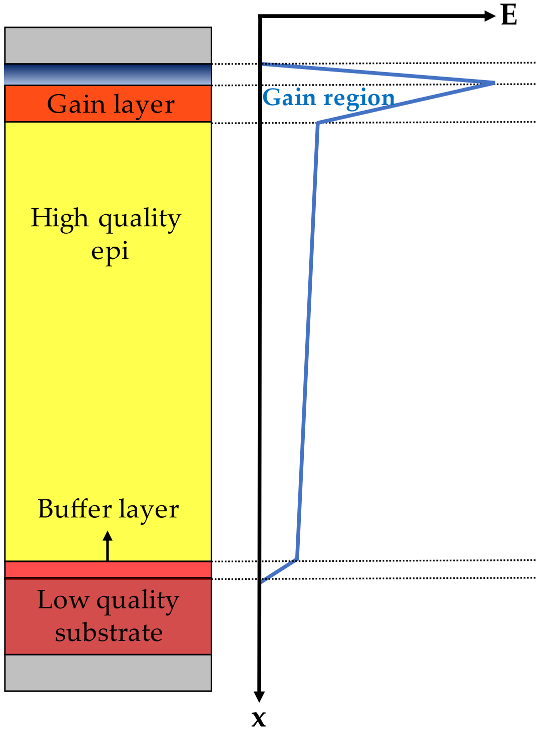
- To-do:
  Reproduce CCE-curves and behavior in-focus via TCAD simulations



4H-SiC LGAD - principle

- 4H-SiC drawback: High ionization energy & small epi-thickness
  → Small signal (especially for MIPs)
- Solution: **L**ow **G**ain **A**valanche **D**iode
- High field region at implant through “gain-layer”
- Carrier multiplication via impact ionization → gain
- Contrary to Si: $\alpha_{\text{holes}} > \alpha_{\text{electrons}}$
  - → P-in-N design (higher quality for n-epi available)
  - → Good timing performance (fast drift of electrons from gain to bottom)
- Amplification very sensitive to sensor design!!!
  → TCAD simulations to determine optimal design

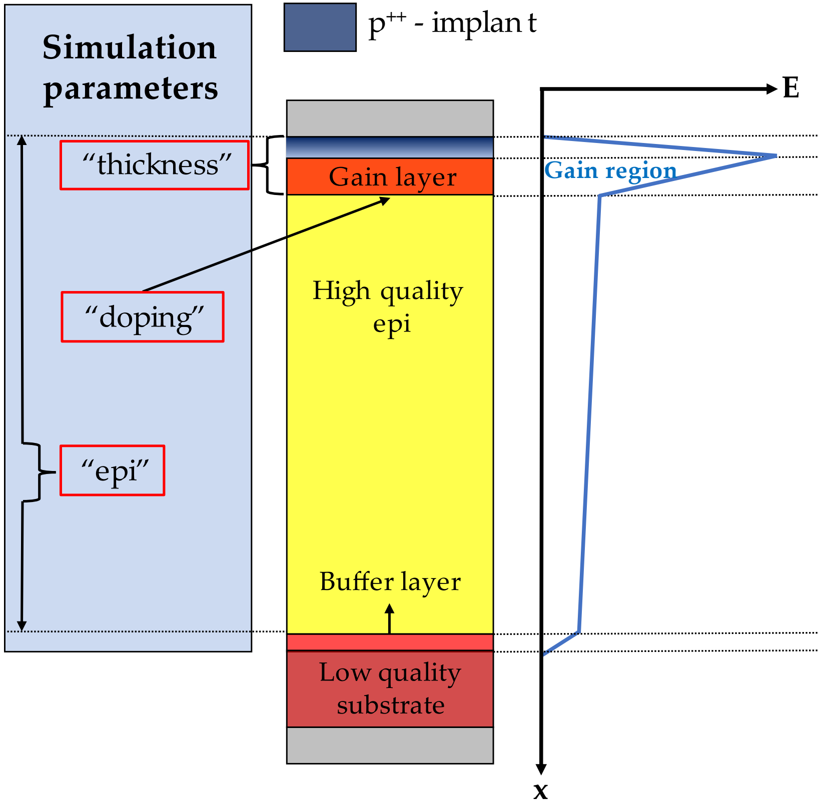
⬜ Contact metal (Al, Ni, Ti)
🟨 n - doped epi-layer (≈ $1.5 \cdot 10^{14}$ cm^{-3})
🟥 n^+
🟦 p^{++} - implant



4H-SiC LGAD simulation

- „Non-buried" gain layer → no worries what happens above gain layer in production [1]
- TCAD (SYNOPSYS) simulation setup:
  - 2D (Quasi - 1D), PiN-diode to determine gain
  - Ideal doping (box profiles)
  - IV/CV up to 1000 V reverse bias
  - Transient pulse simulation (10 V steps) using *HeavyIon*
  - Impact ionization model: *Okuto*
  - Included models: SRH, N-dopant energy split, anisotropy, bandgap-narrowing, incomplete ionization
- Constraints:
  - *Epi* ≤ 50 µm → limitation, costs
  - *Gain layer thickness* ≥ 2 µm → Mitigate manufacturing uncertainties
  - *Gain layer doping* ≥ 5·10^{16} → Mitigate manufacturing uncertainties

⬜ Contact metal (Al, Ni, Ti)
🟨 n - doped epi-layer (≈ 1.5·10^{14} cm^{-3})
🟥 n$^+$
🟦 p^{++} - implan t



Simulation parameters

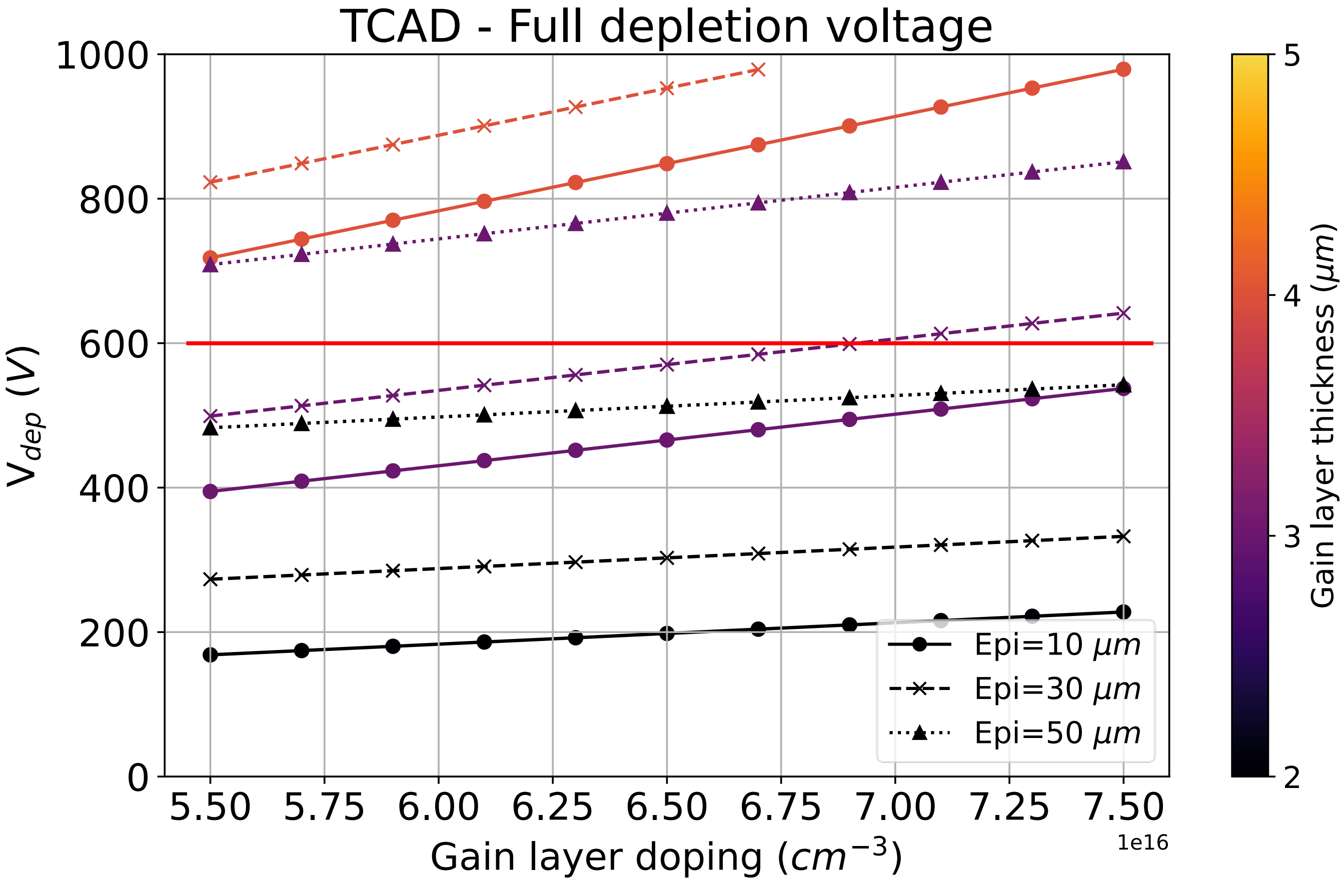
"thickness"

"doping"

"epi"

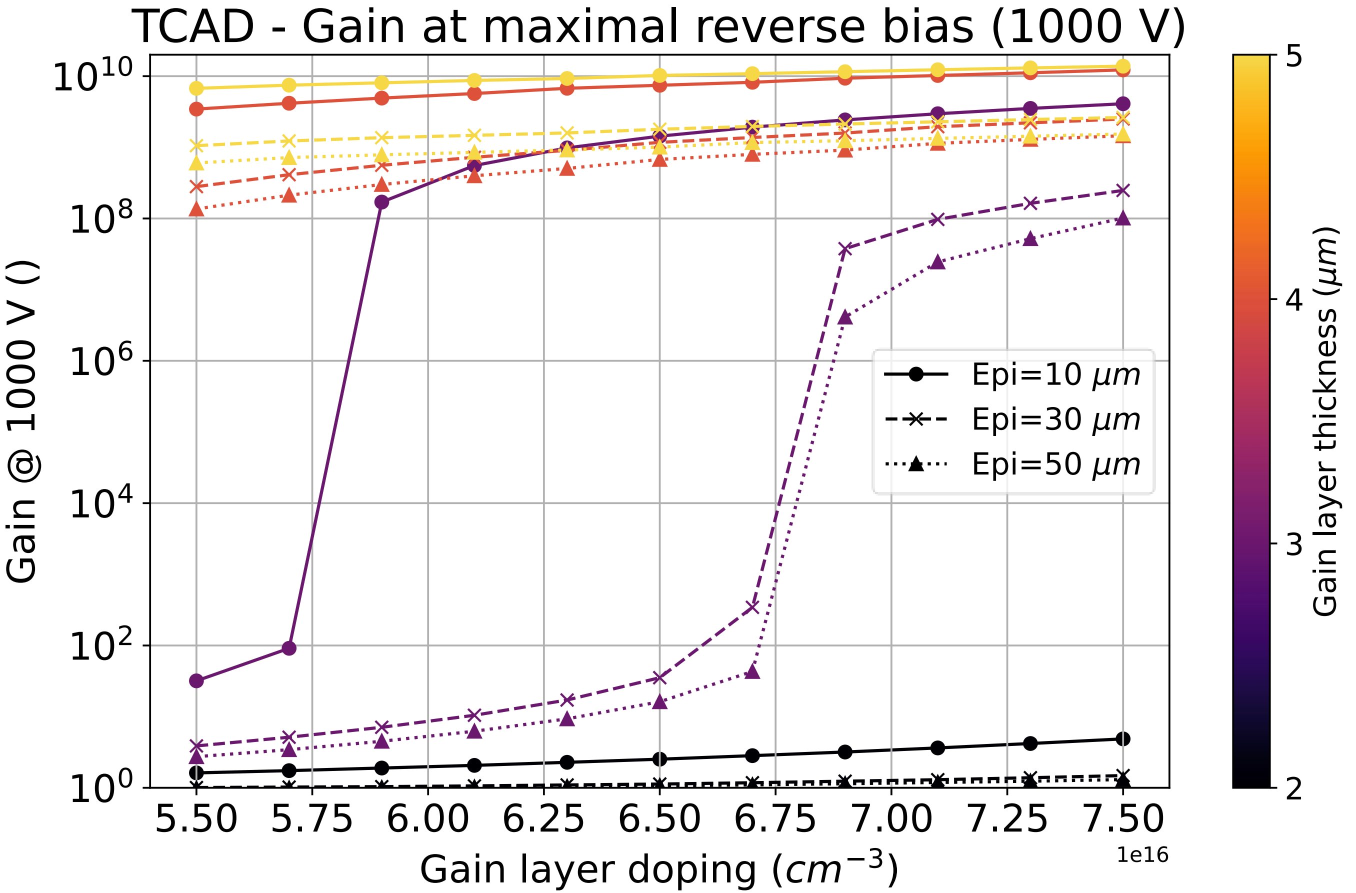
1st iteration: Full depletion

- Favorable:
  - $V_{dep} < 600$ V
- Gain layer increases full depletion voltage
- 50 µm planar diode ≈ 350 V
- Take away:
  - Epi < 50 µm
  - Gain layer thickness < 3 µm



1st iteration: Maximal gain

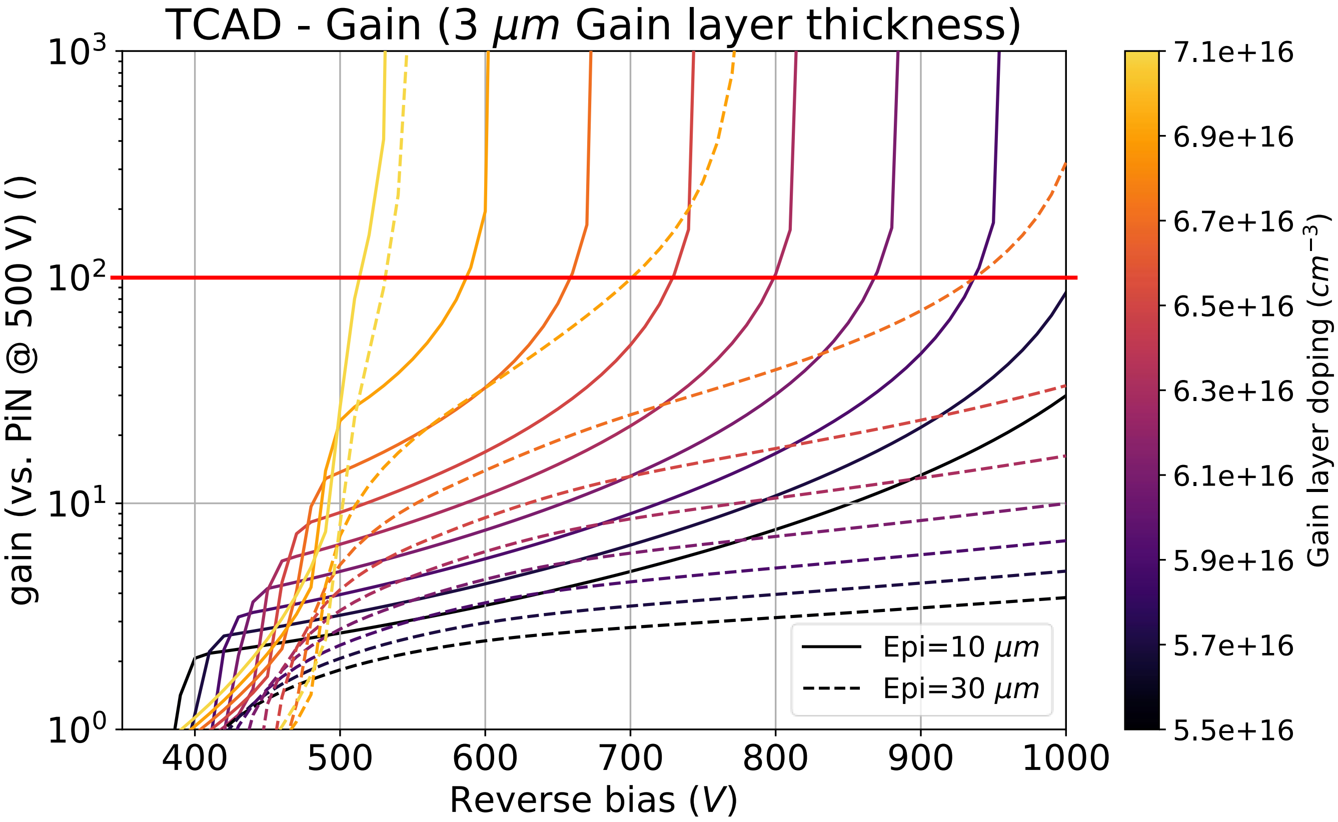
- Favorable:
  - 2 < gain < 100
  - No breakdown at 1000 V bias
- Gain is very sensitive to variations in the gain layer
- Take away:
  - Epi < 50 µm
  - Gain layer thickness < 3 µm



1st iteration: Gain curves

- Thinner sensors show steeper gain curves due to earlier full depletion

- Take away:
  - Thinner sensors are risky, as, uncertainties of manufacturing could render them unusable
  - Thicker sensors are harder to deplete
  - **Compromise:**
    Sensor thickness: 30 µm

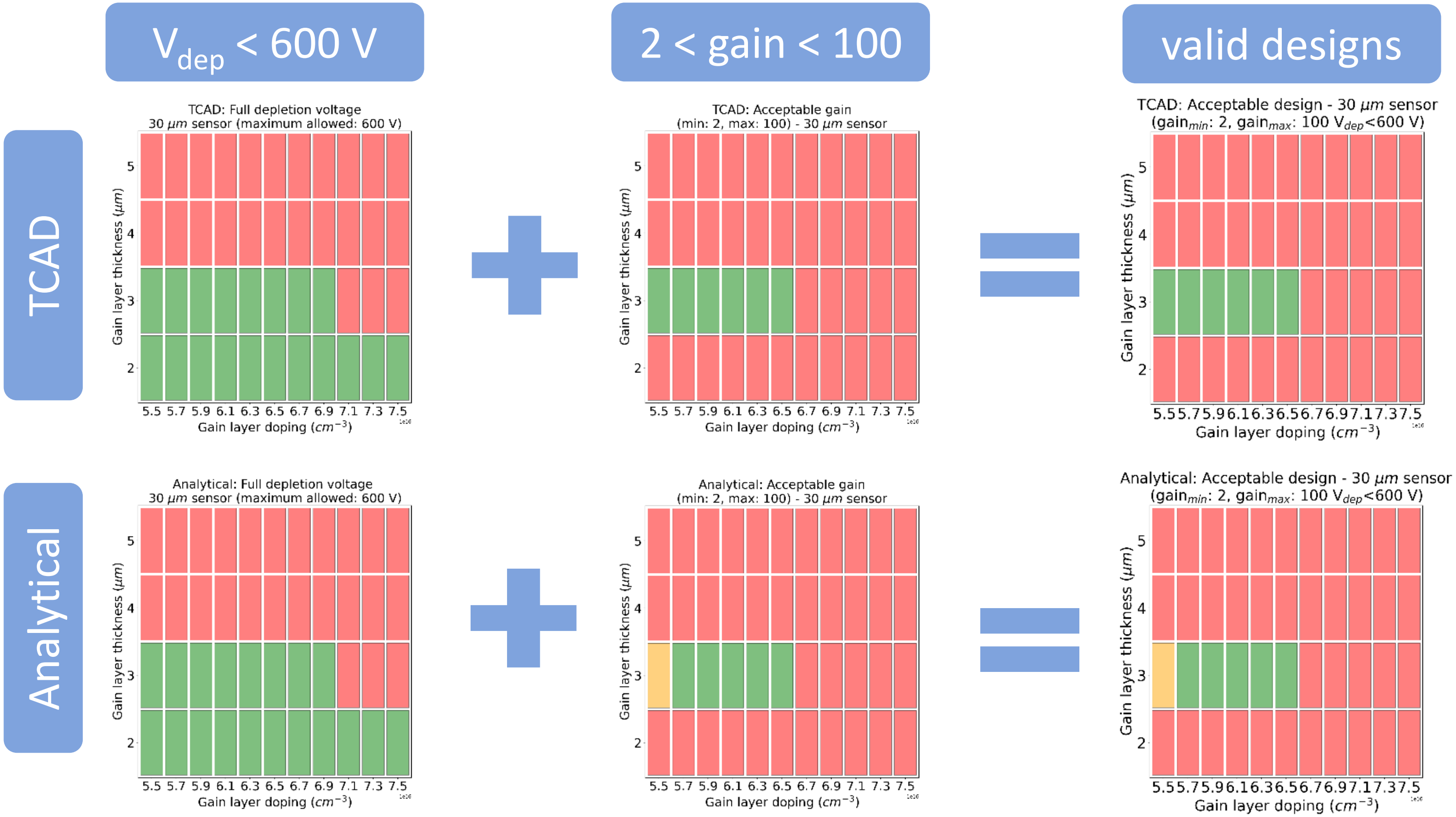


Analytic prediction model

- Simple analytical model for (non buried gain) LGADs
- Constrain design parameter space before time consuming simulations
- $V_{dep\_gain} = \frac{qN_{implant}N_{gain}t_{gain}^2}{2\varepsilon(N_{implant}+N_{gain})} - V_{bi}$
- $V_{dep\_full} = V_{dep\_gain} + \frac{qN_{implant}N_{epi}t_{epi}^2}{2\varepsilon(N_{implant}N_{epi})} - V_{bi}$
- $E_{max} = q\,\frac{t_{dep}N_AN_D}{\varepsilon(N_AN_A)}$ (simple case)
- Use simulation results to couple minimal/maximal gain to maximal electric field
- Approximation: Uniform implant profile of certain dimension

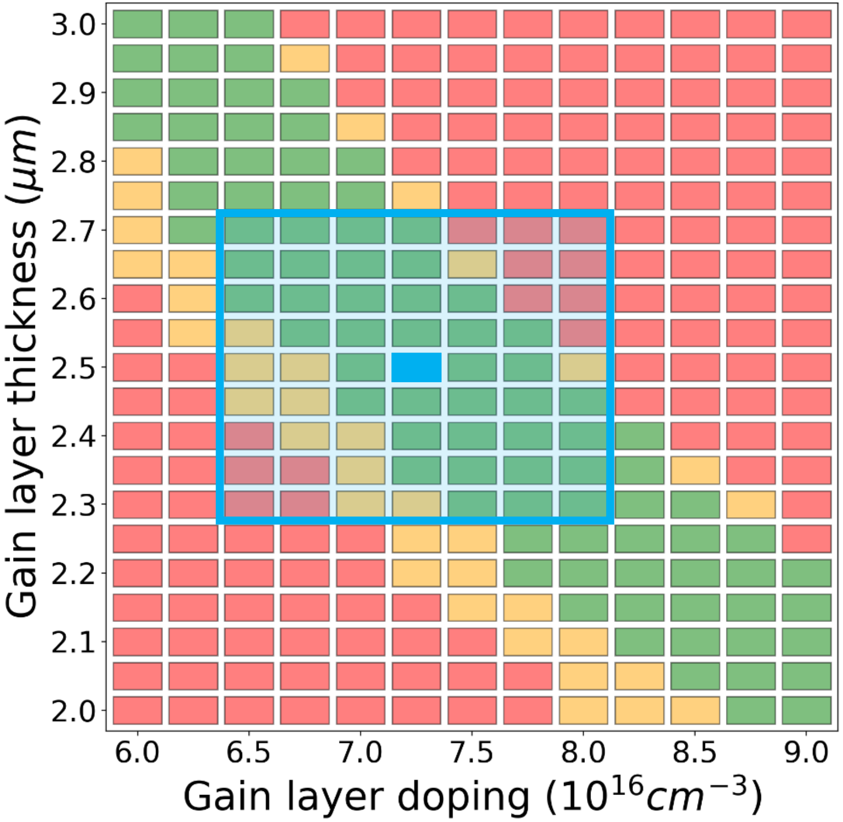
Analytic prediction model

- Use simulation results to feed & check analytical model
    - Gain depletion
    - Full depletion
    - Gain



Potential 4H-SiC LGAD wafer-run

V_{depl} : 380 V – 520 V

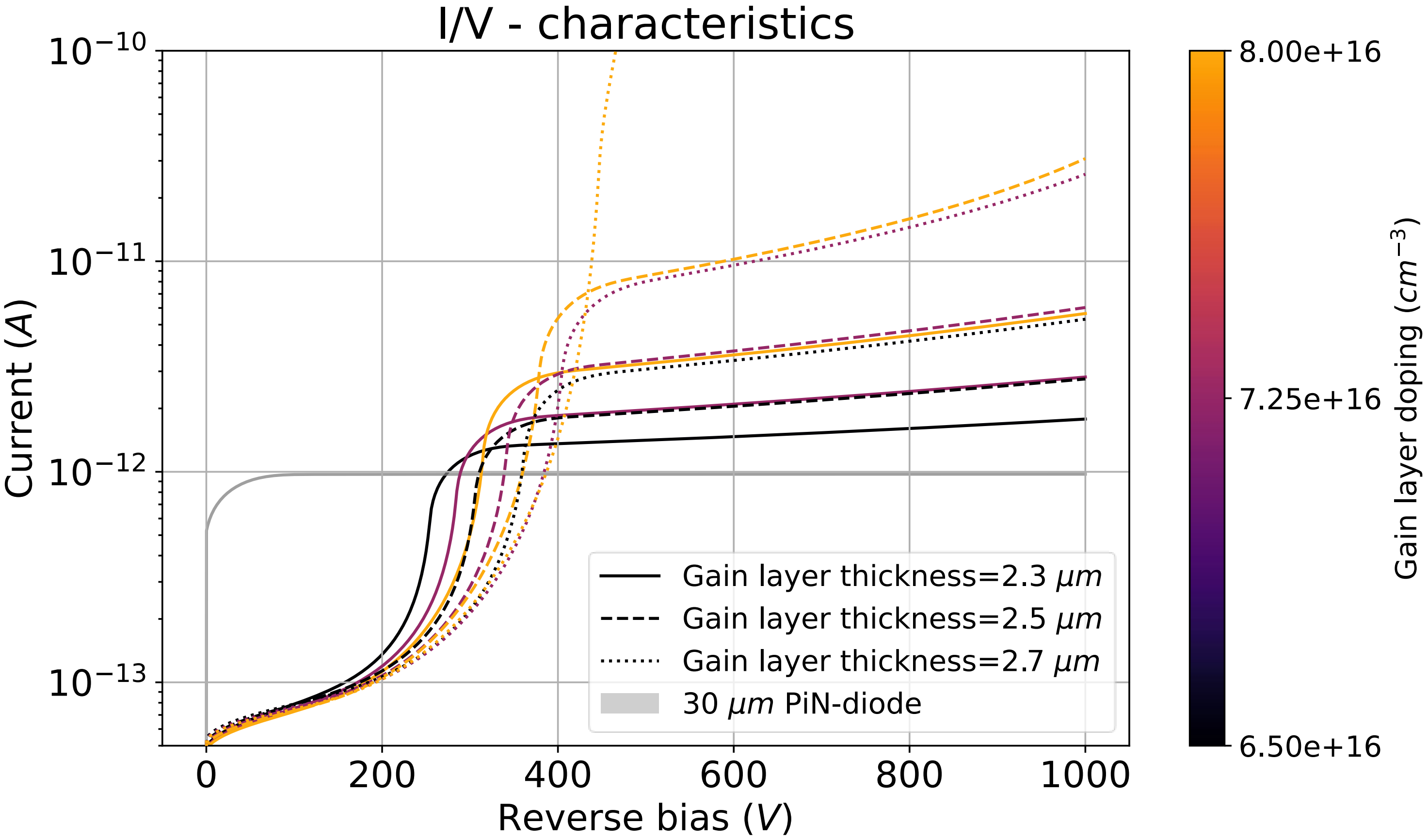


Specification	Target	Error
Sensor thickness	30 µm	-
Gain layer thickness	2.5 µm	0.2 µm
Gain layer doping	$7.25 \cdot 10^{16}$ cm^{-3}	10 %

- Provided uncertainties of potential manufacturer cover most of the acceptable parameter space
- Multiple wafers with slight doping variations planned to increase chance of success
- Additional finer simulations (2nd iteration):
  - Finer grid
  - Reproduce measured dark currents (≈ pA)
  - *Heavylon* energy deposition = 1 MIP

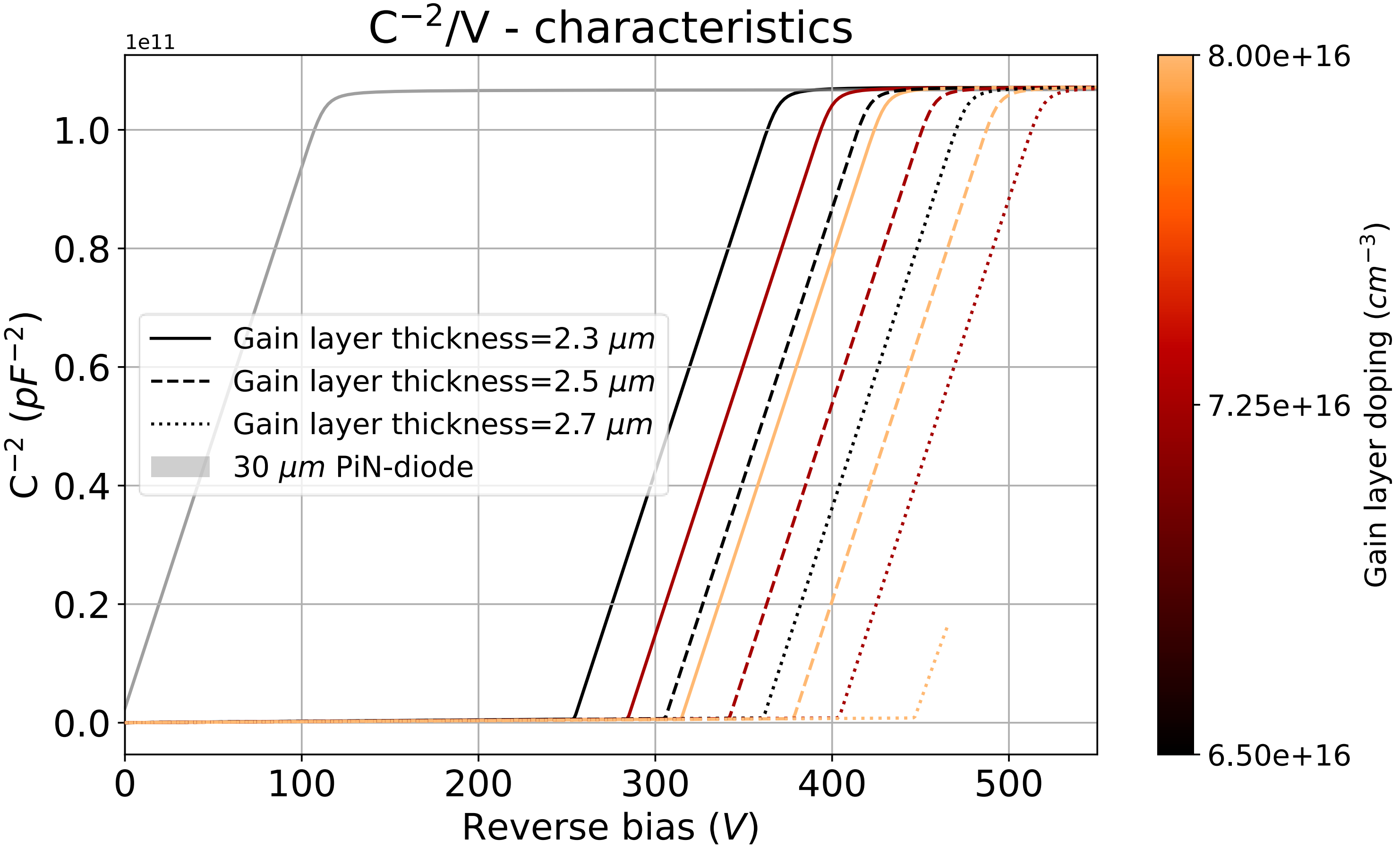
2nd iteration: IV

- Dark current increases with gain
- Only one combination breaks down (2.7 µm & 8·10^{16} cm^{-3})
- Simulated dark current levels well below nA



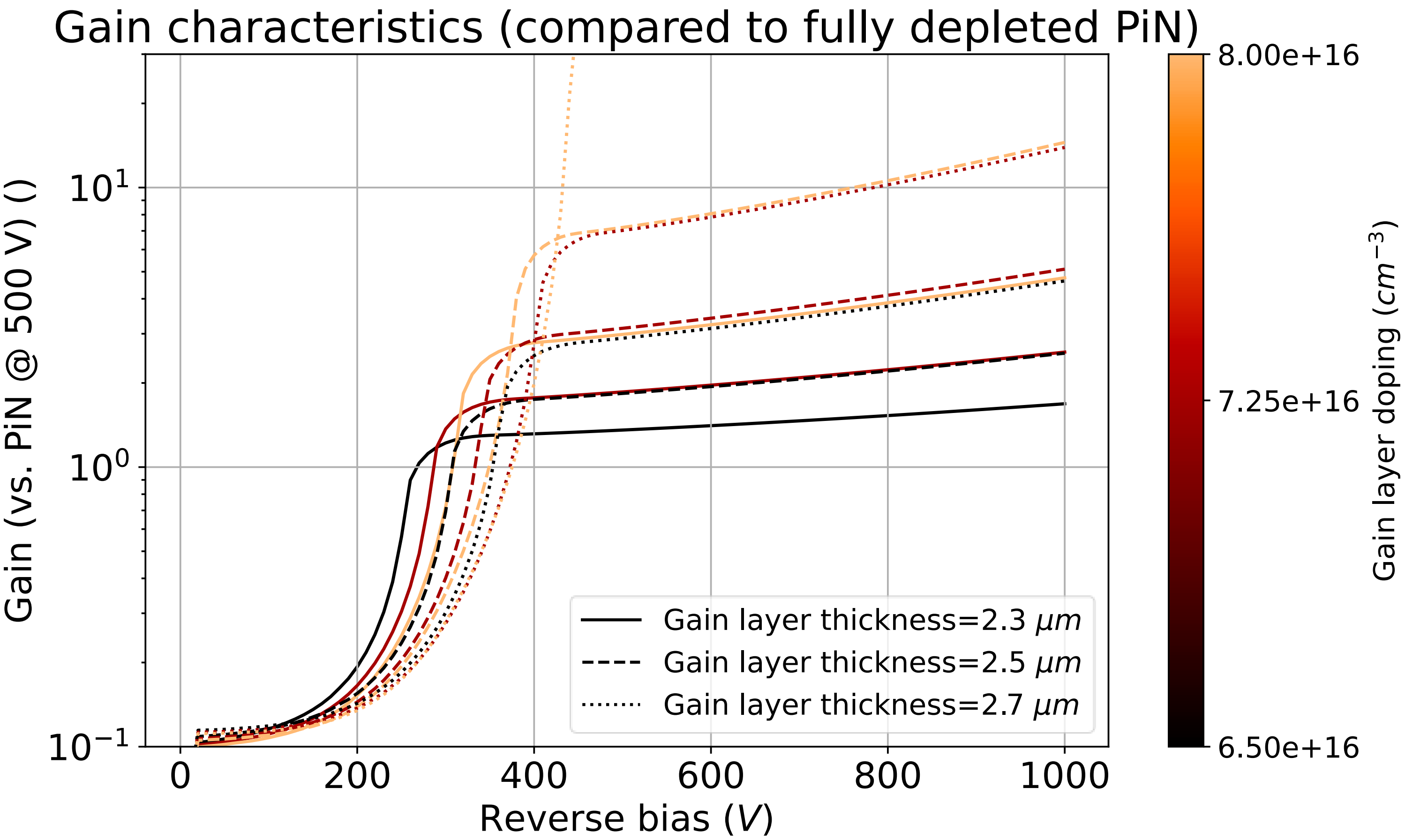
2^{nd} iteration: CV

- Full depletion voltage increases with gain layer thickness and doping
- Acceptable for all combinations:
  - Min ≈ 380 V
  - Max ≈ 520 V
- Gain depletion at minimum 250 V



2nd iteration: Gain

- Compared to 500 V PiN
- No stable gain > 20
- Several combinations only offer small gain
- Potential gain: 2 – 20
- Higher gain would require thinner and higher doped sensors (No pain no gain?)



References

[1]: P. Gaggl, “Improving TCAD simulation of 4H silicon carbide particle detectors”, presented at the 42nd RD50 Workshop, Tivat, Montenegro, 20.06.2023, https://indico.cern.ch/event/1270076/contributions/5450202/

[2]: Information from G. Pellegrini, IMB-CNM-CSIC

[3]: A. Gsponer, “Investigation of neutron-irradiated 4H-SiC p-in-n Diodes in forward and reverse Bias,” presented at the 42nd RD50 Workshop, Tivat, Montenegro, 20.06.2023, https://indico.cern.ch/event/1270076/contributions/5450198/

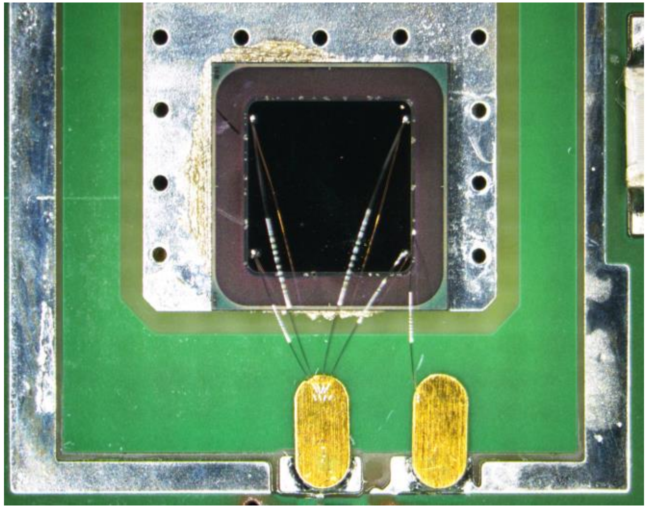
[4]: A. Gsponer, et. al. “Neutron Radiation induced Effects in 4H-SiC PiN Diodes.”, submitted to JINST, Oct. 03, 2023. arXiv: http://arxiv.org/abs/2310.02047

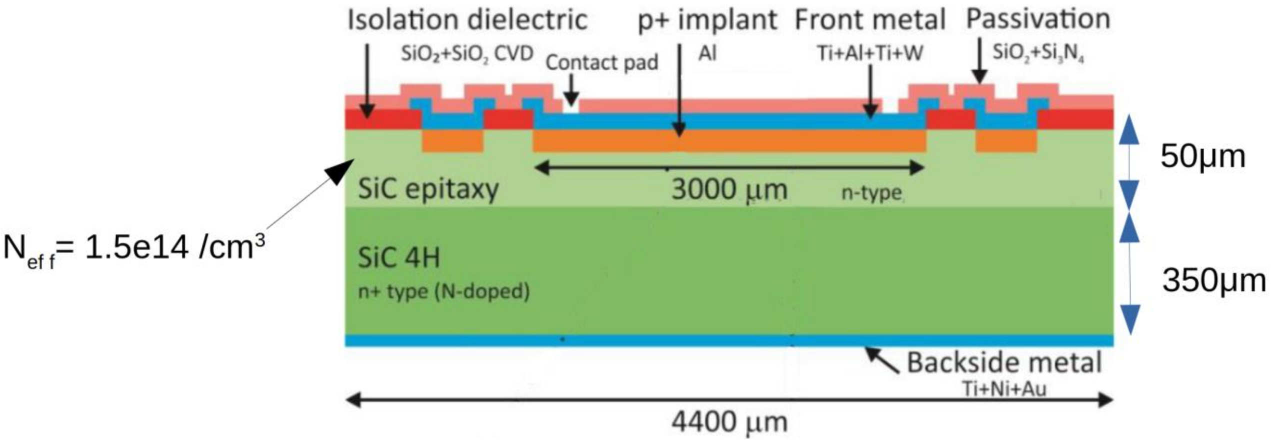
[5]: E. Currás et al., Radiation tolerance study of neutron-irradiated SiC pn planar diodes, 18th “Trento” Workshop, Trento, Italy, 28 February–2 March 2023, https://indico.cern.ch/event/1223972/contributions/5262058/

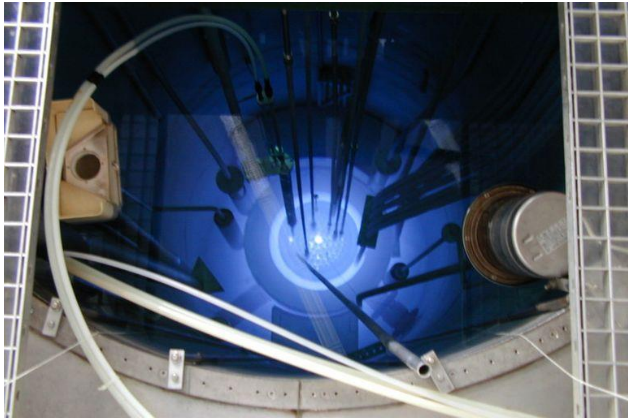
BACKUP

SiC Samples

- 4H-SiC p-in-n Diodes from Run 13575 of CNM Barcelona [2]
- 3 x 3 mm² active area, 50 µm epi
- Full depletion voltage : 300-400 V, C_{det} = 18 pF
- Neutron irradiated ($5 \cdot 10^{14} – 1 \cdot 10^{16}$ n_{eq}) at ATI Vienna
- Characterization after neutron irradiation

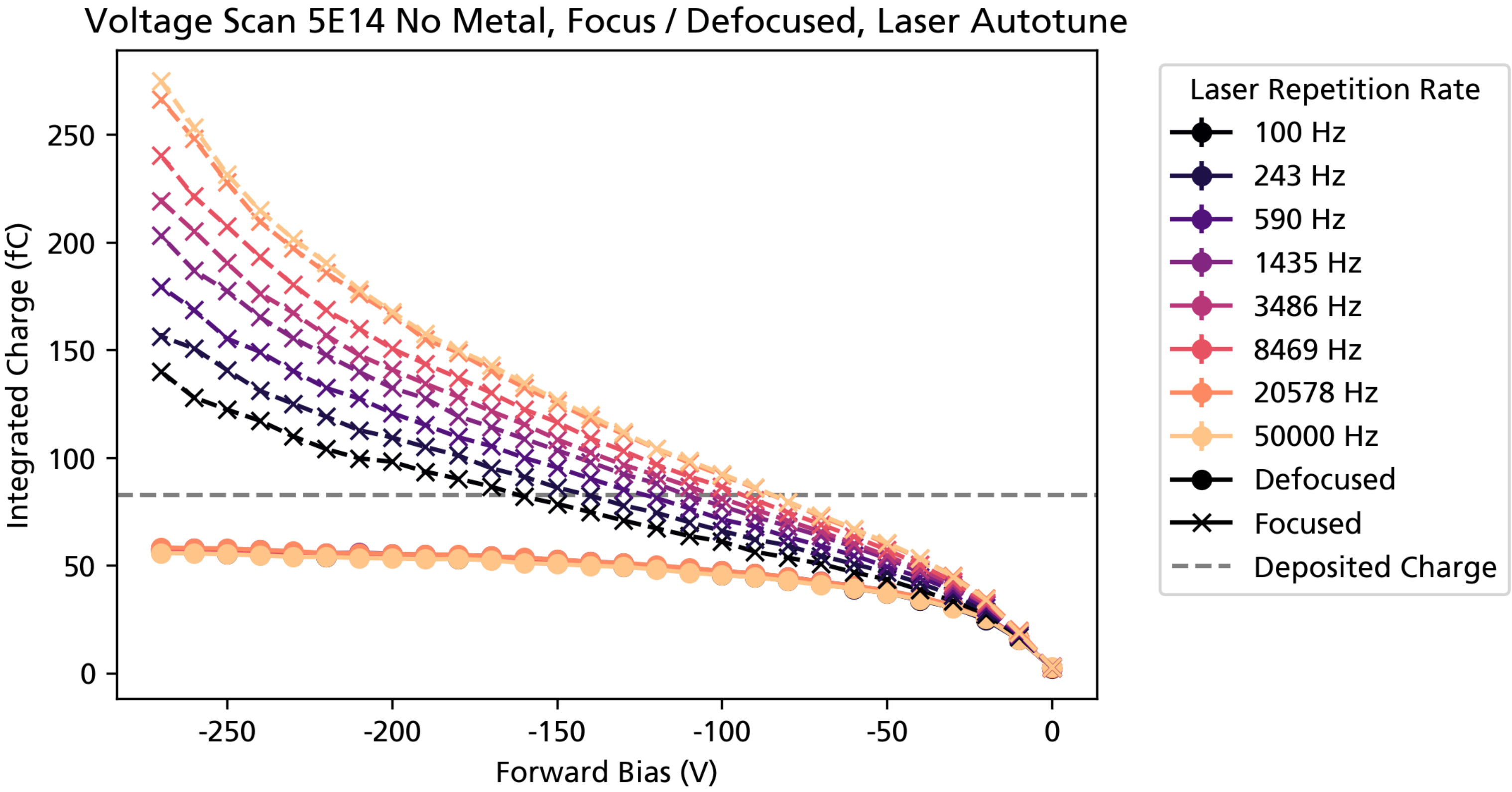






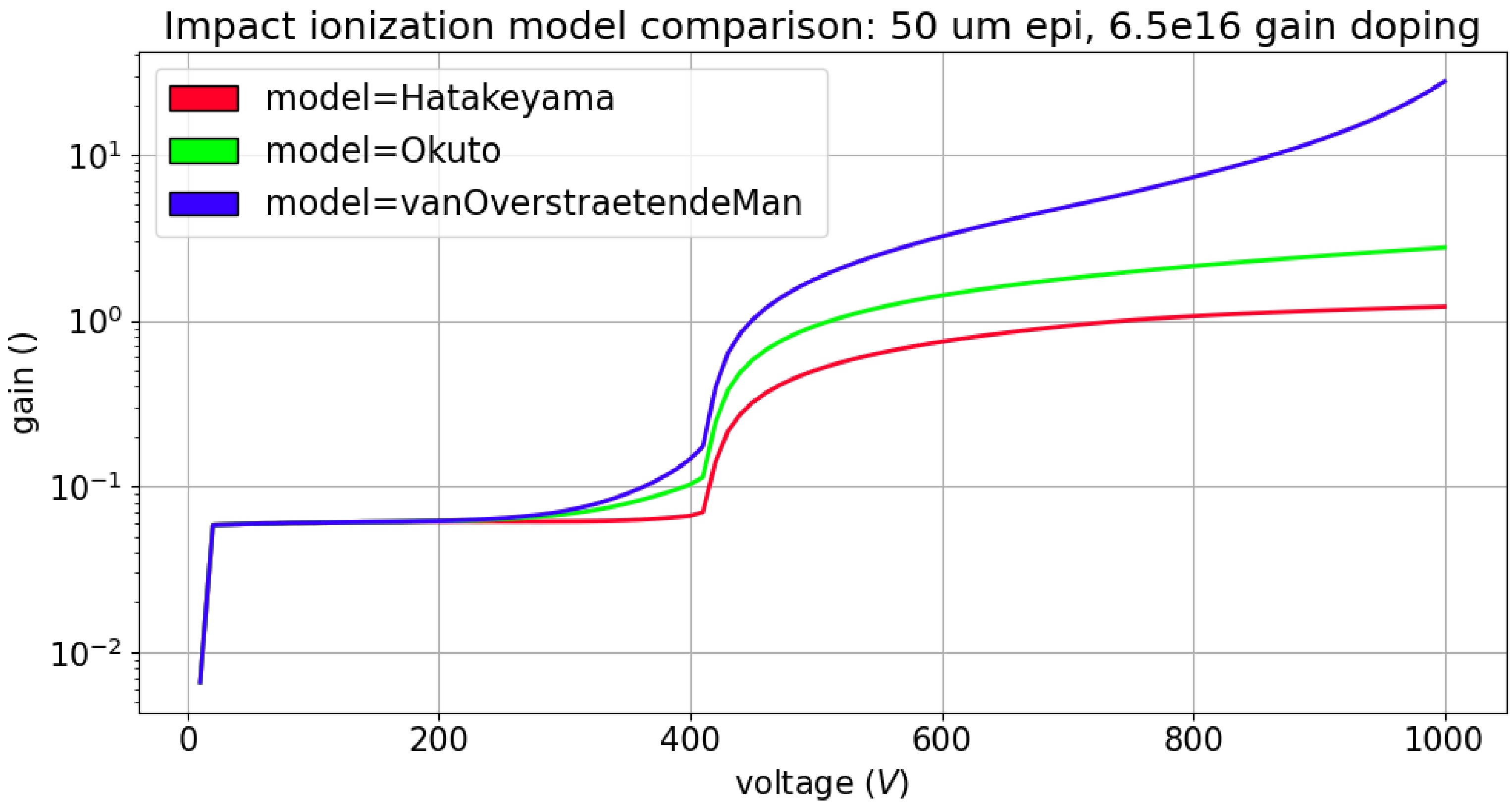
CCE vs Voltage (focused/defocused)

- Observed a CCE > 100% in forward bias for irradiated diodes [3, 4]



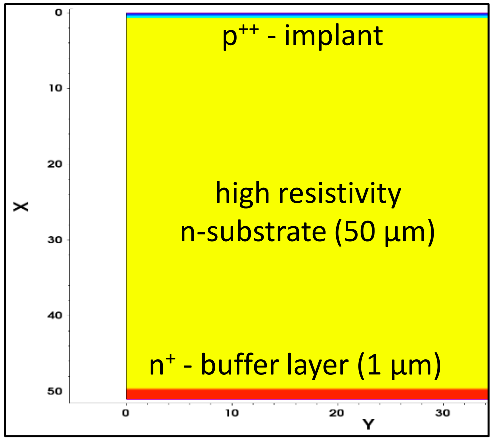
Impact Ionization models (SYNOPSYS)

- **Different impact ionization models deliver different results**

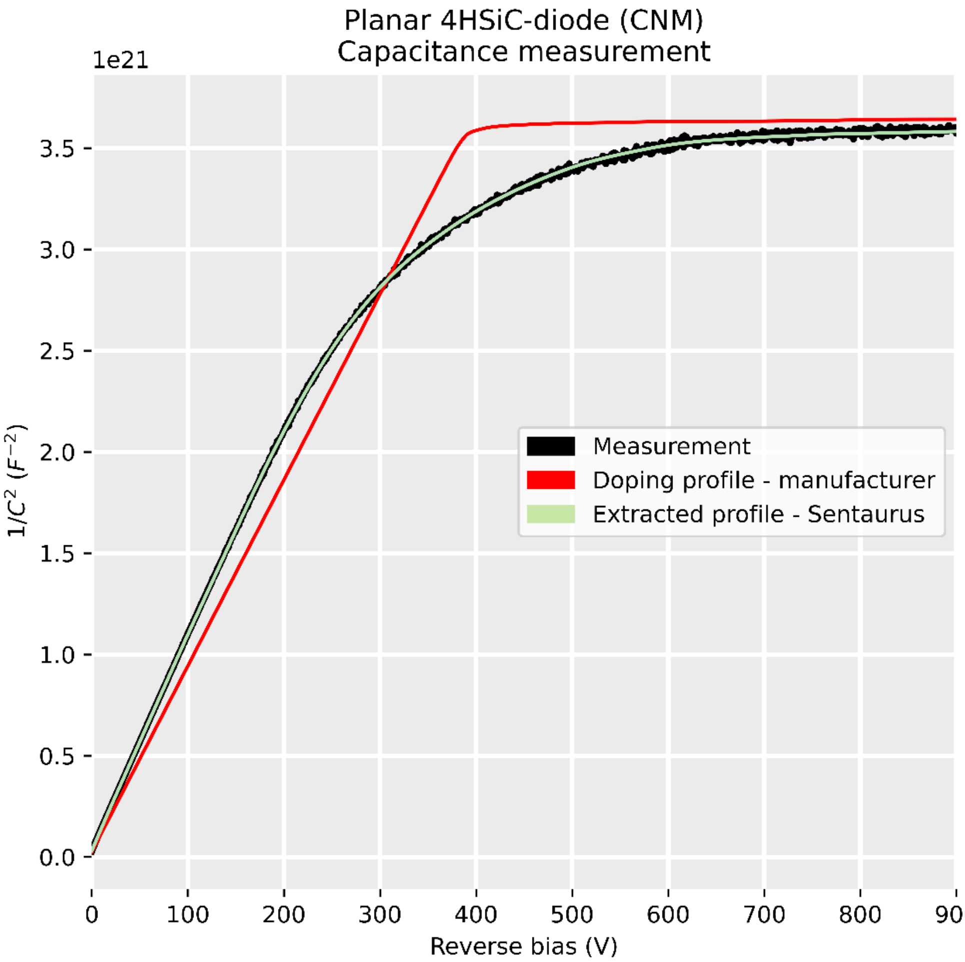


Potential N-dopant diffusion

- Planar 4H-SiC p-in-n diodes from CNM
- Capacitance measurements show strong deviation from suggested doping profile
- Slower propagation of the depletion zone due to higher doping concentration at the back
- Most likely due to diffusion processes during growth

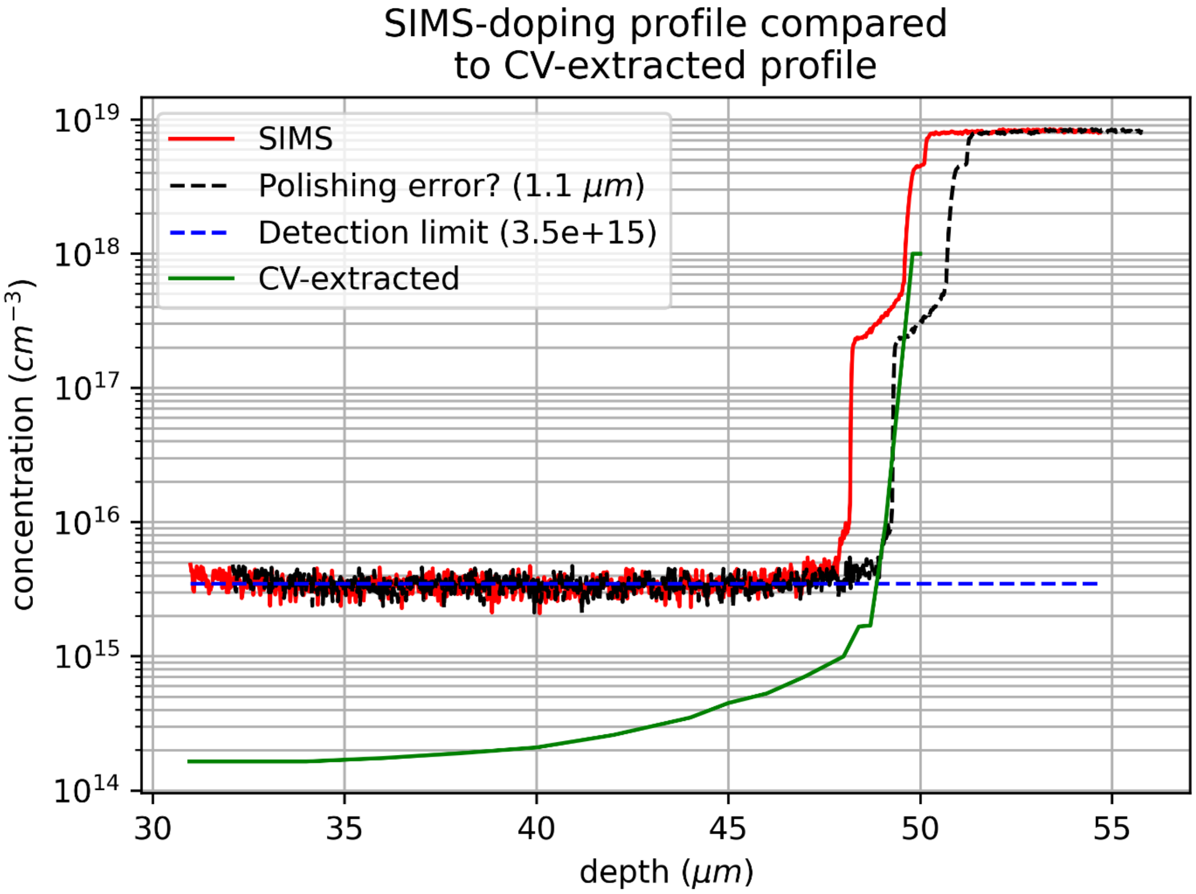


Initially modelled doping profile of the 4H-SiC planar diode



Potential N-dopant diffusion

- CV-measurements indicated high doping near buffer layer
- Unknown if diffusing from substrate or buffer
- SIMS measurements confirm this
- Can have huge influence especially for thinner samples
- Similar effect possible above (and beyond) a gain layer



SYNOPSYS-HeavyIon: Mesh dependencies

- The mesh influences the accuracy of deposited charges by the HeavyIon model!!!

$$G(l, w, t) = G_{\mathrm{LET}}(l) R(w, l) T(t)$$

Gaussian temporal distribution
Accessed via *s_hi* in parameter file

Deposited charge
- Usually via LET-factor
- pC/µm
- Uniform in simple case

Lateral beam distribution (Gaussian)
Set in .cmd file

$$\boxed{R(w, l) = \exp\left(-\left(\frac{w}{w_{\mathrm{t}}(l)}\right)^2\right)}$$

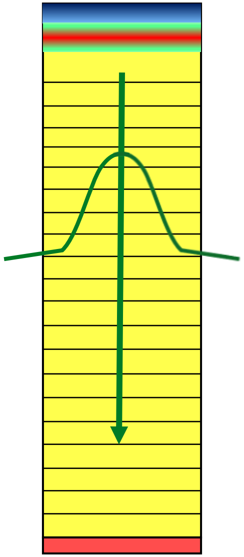
Norm factor: Fixes total deposited charge to LET

LET_f has units of pC/µm and $R(w, l)$ is Gaussian	$k' = \frac{k}{\sqrt{\pi} w_t d}$ $d = 1 \mu\mathrm{m}$

SYNOPSYS-HeavyIon: Mesh dependencies

- The mesh influences the accuracy of deposited charges by the HeavyIon model!!!
- Deposition is non-instant (Gaussian time distribution) and lateral distributed

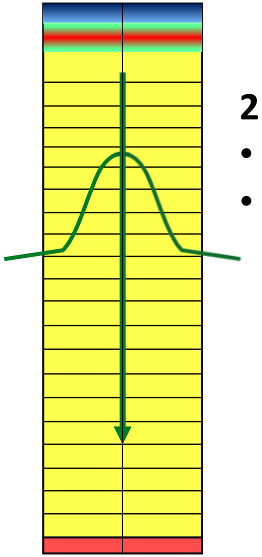
1D-structure



1 mesh point

- R(w, l) becomes constant!!!
- **BUT:** Norm factor includes *w_t!!!*
- Deposited charge scales with *w_t* for constant LET!!!

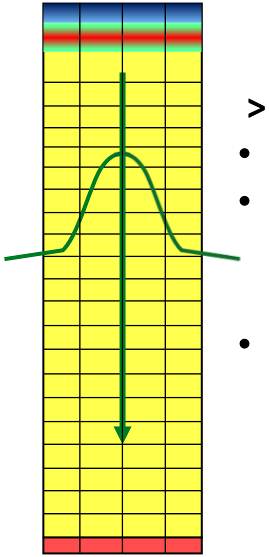
2D-structure



2 mesh points

- Accurate scaling
- **BUT:** Overall deposited charge is too low in all cases!!!

2D-structure

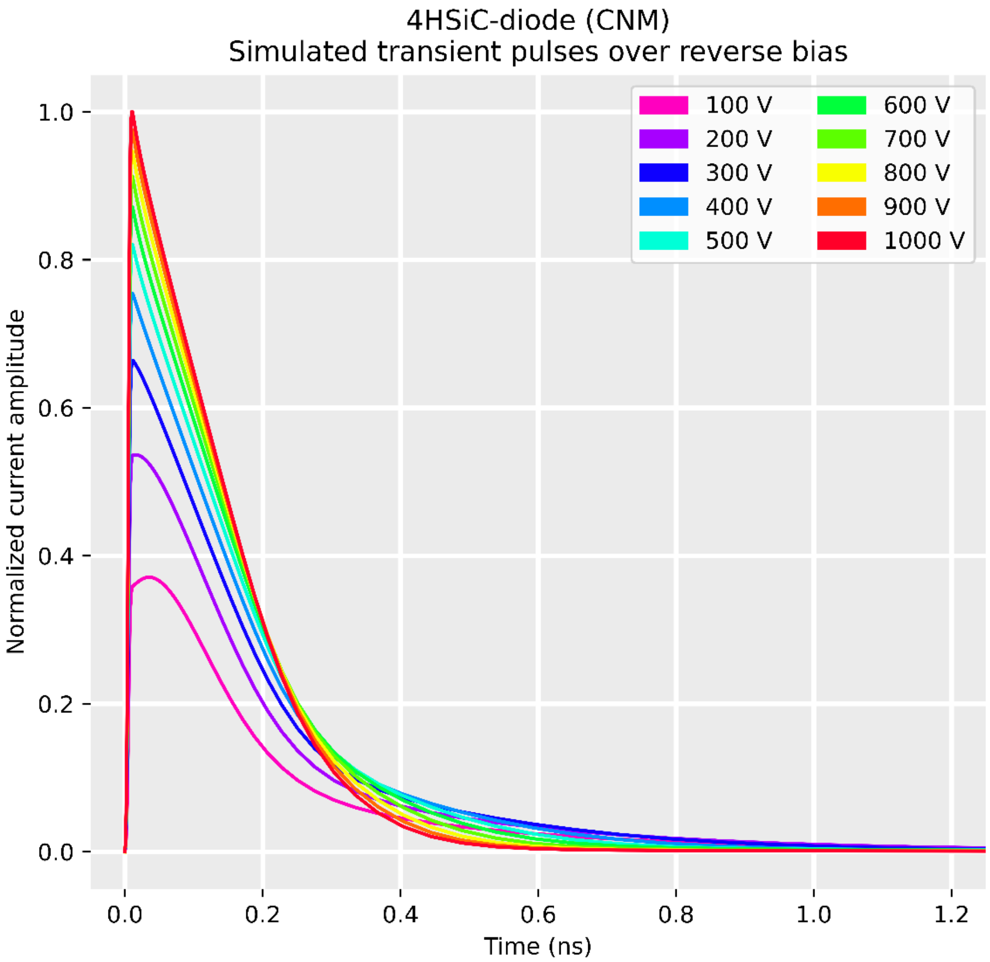


> 2 mesh points

- Accurate results
- Impact **needs to be inside mesh point (no border)**
- σ_{Gauss} needs to be small enough

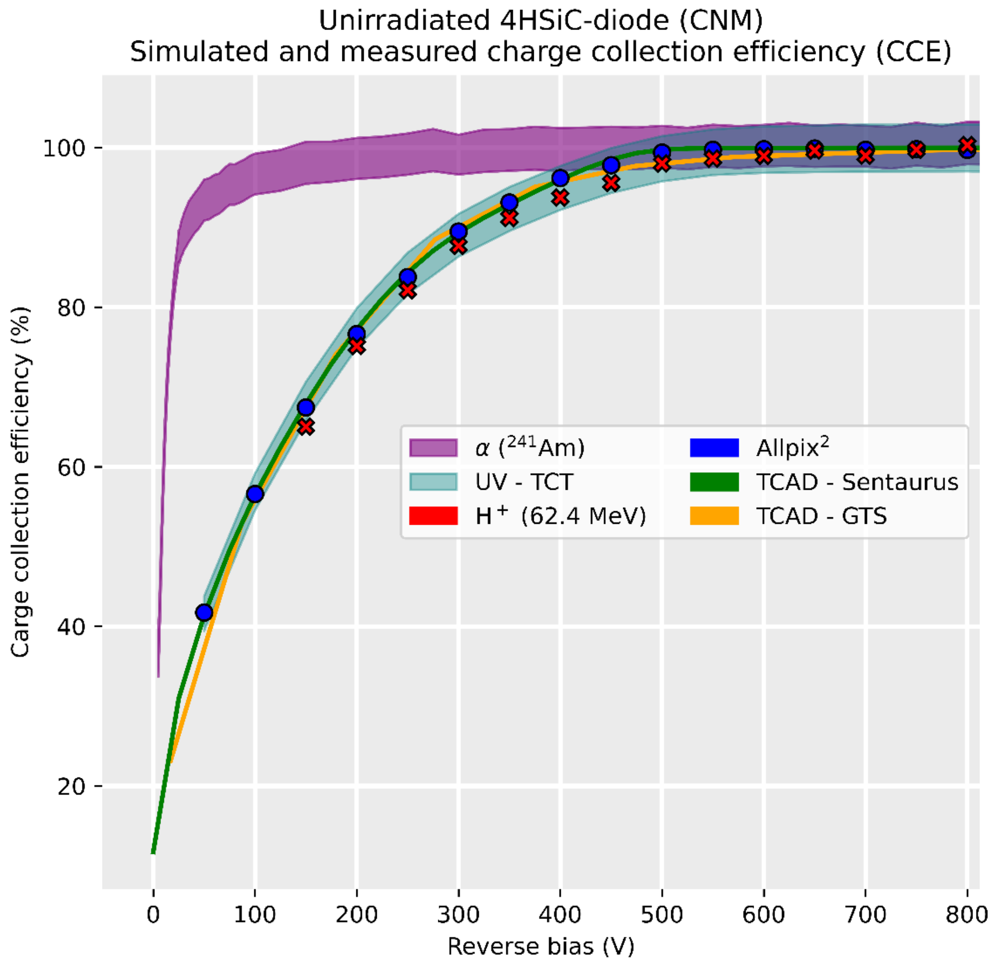
Simulations – Transient pulses

- Transient pulse simulations are crucial to model and compare the detector response
- *HeavyIon* option in SENTAURUS
- Deposits a given amount of energy across a specified particle path
- Not instantly, but over very short time (*s_hi*)
- Load fields from quasistationary simulation over reverse bias
- “Empty” transient simulation before energy deposition necessary to numerically stabilize the current

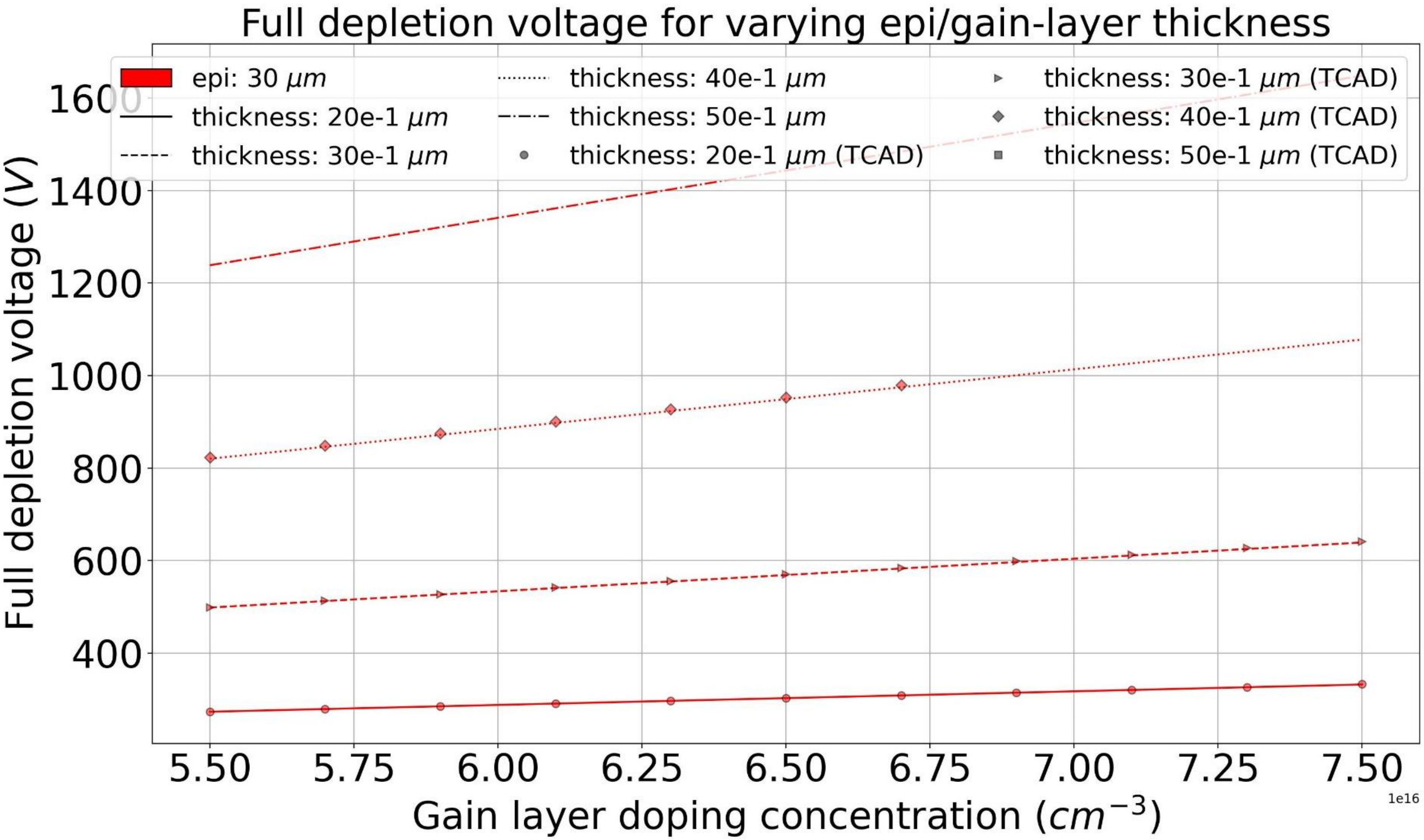


Simulations – Transient pulses

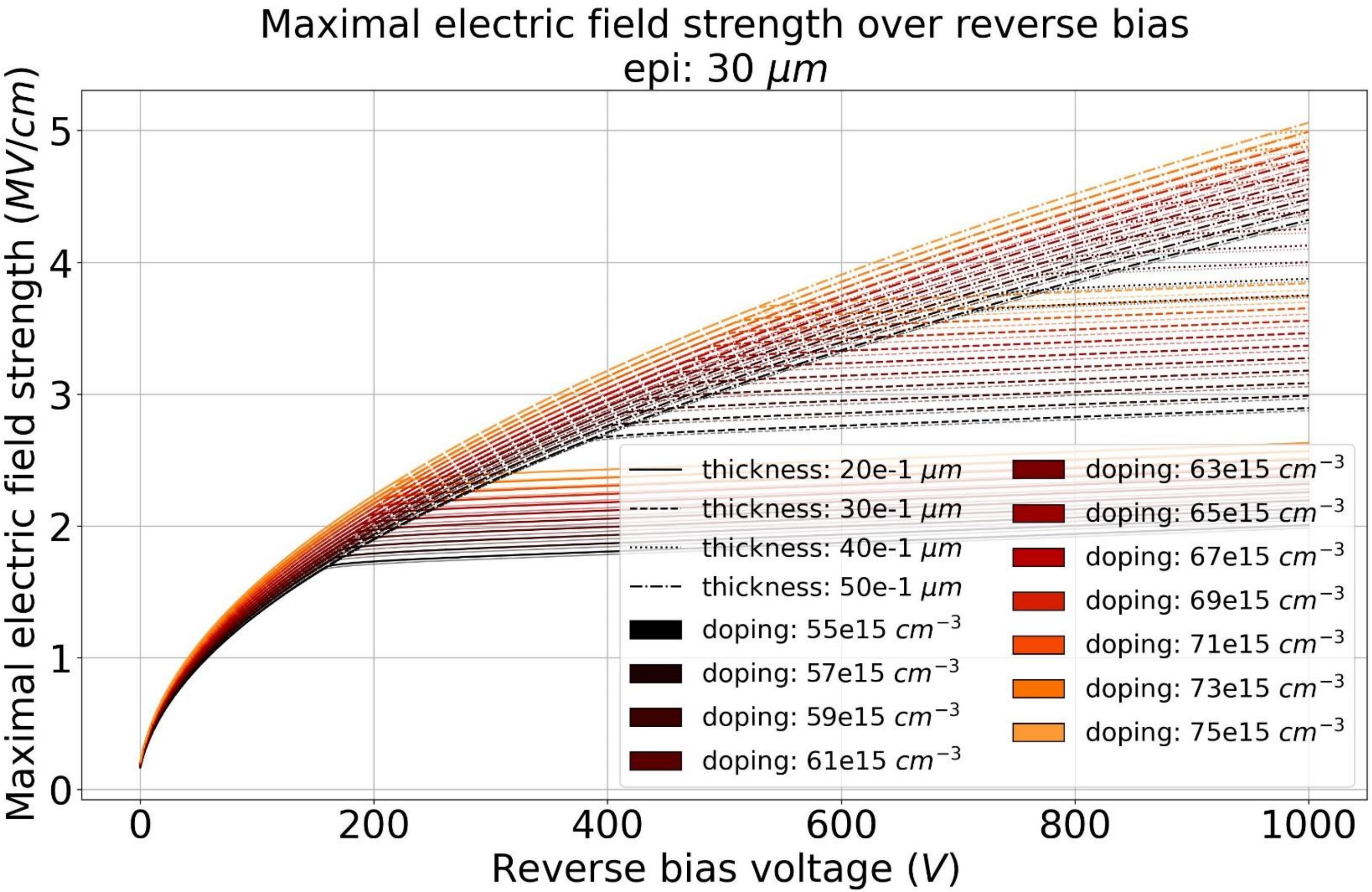
- Performed charge collection measurements using multiple signal sources
- Also on neutron irradiated devices with fluxes ($5 \cdot 10^{-14}\ n_{eq}cm^{-2}$ - $1 \cdot 10^{-16}\ n_{eq}cm^{-2}$)
- α – particles (^{241}Am)
  Proton beam (62.4 MeV)
  UV-Laser (TCT)
- Comparison with several simulation software for cross-checking
- Simulation results agree very well in the unirradiated case


Unirradiated 4HSiC-diode (CNM)
Simulated and measured charge collection efficiency (CCE)

Analytic model – Depletion check

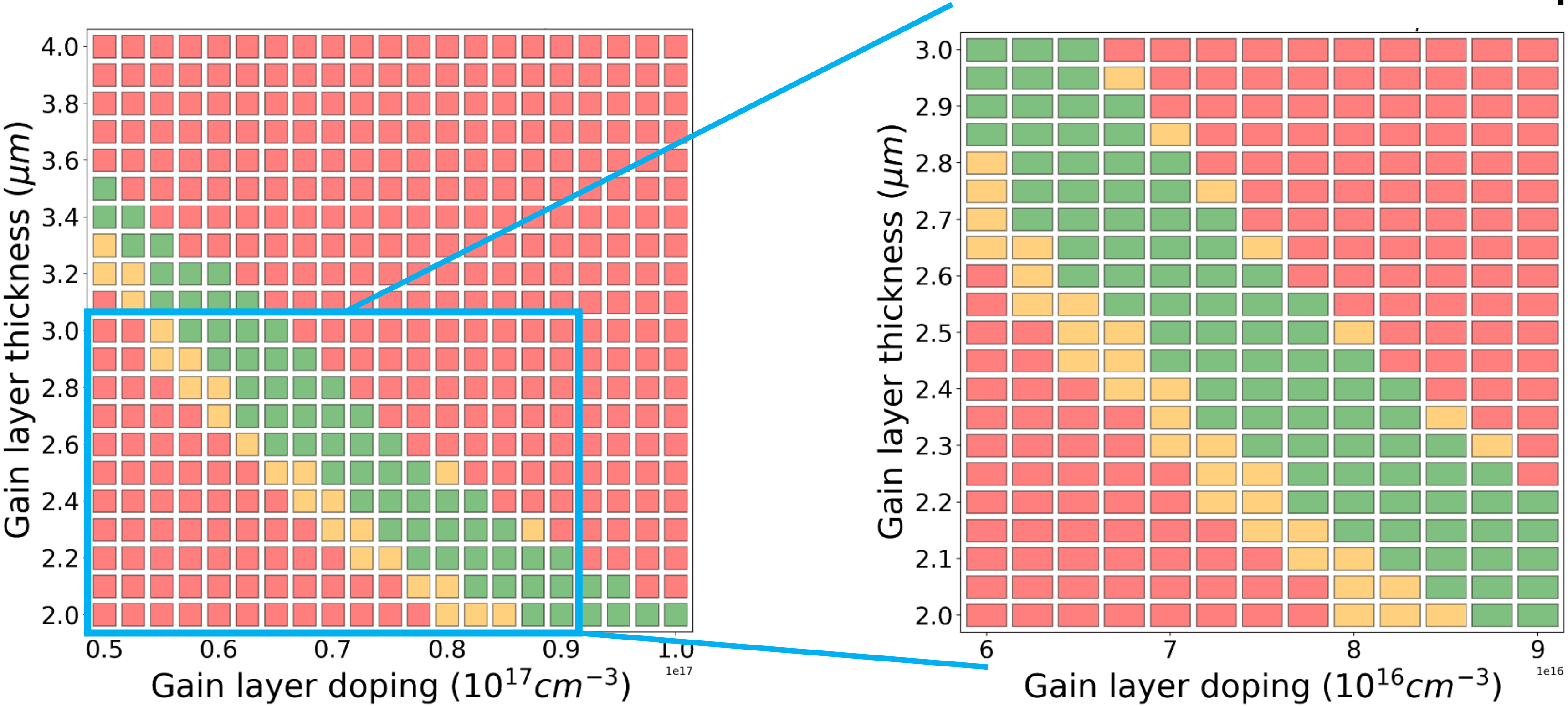


Analytic model – E-field check



Analytic prediction model

- Set a target depending on predictions



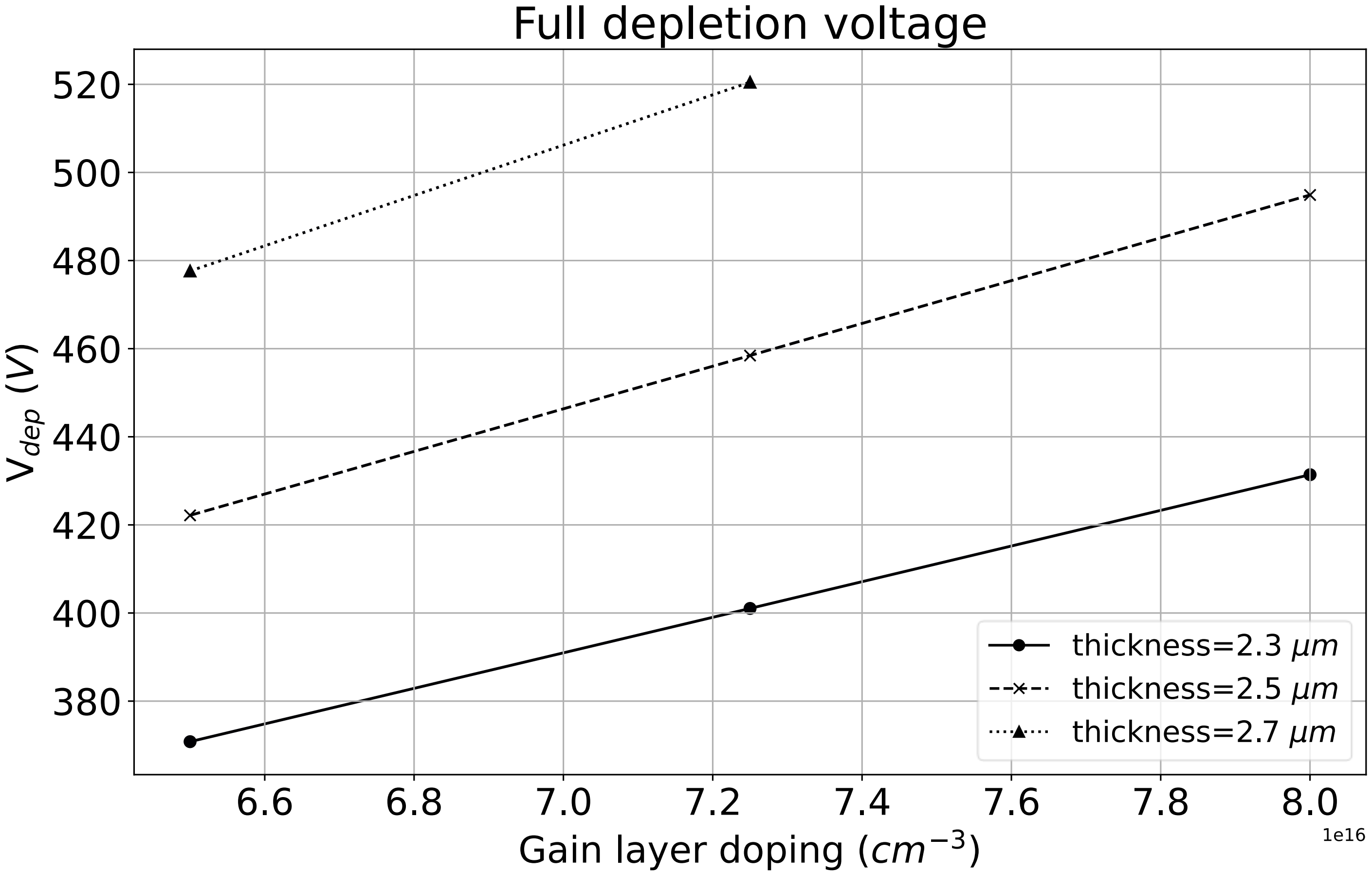
Target:

2.5 µm gain layer

$7.25 \cdot 10^{16}$ cm^{-3} gain doping

2^{nd} iteration: Full depletion voltage

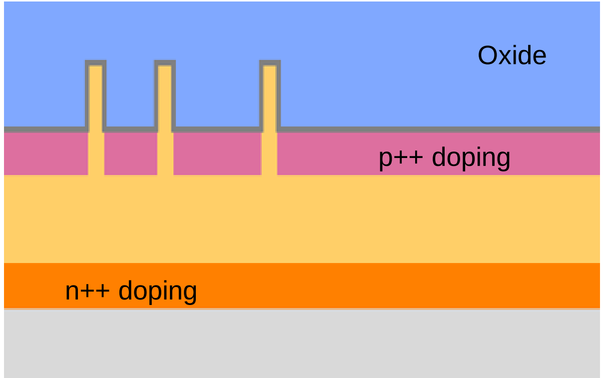
- Full depletion voltage acceptable for all combinations:
    - Min ≈ 380 V
    - Max ≈ 520 V
- Gain depletion at minimum 250 V

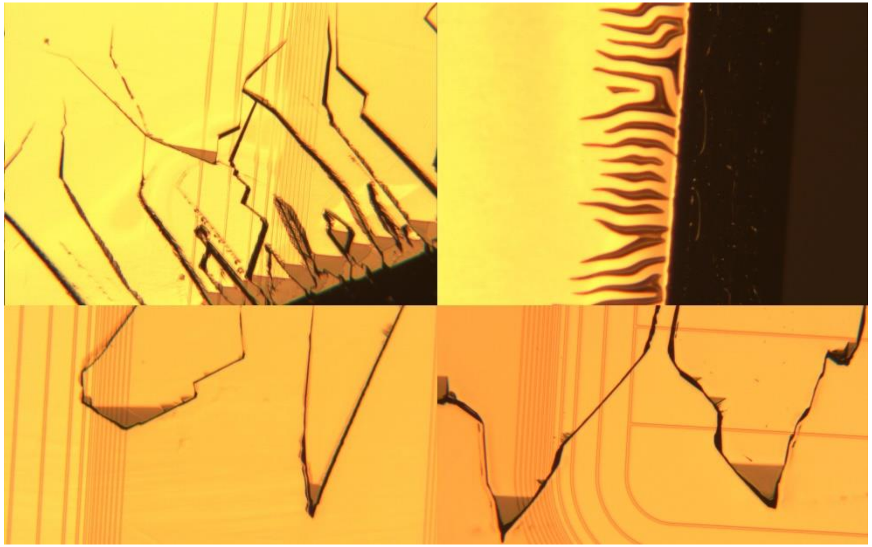


Wafer-run: Status

- Completed:
  - 25 / 58 stages (large delay for the implantation, external company)
  - Photolithography P-DIFF
  - Ion Implantation
  - Thermal Oxidation
  - Dry Etching
  - Oxide Deposition
- To do:
  - Windows opening
  - Metallization
  - Passivation

[2]





Formation of defects on all wafers after ion implantation and activation. Mainly localized at wafer-edges [2]

Completion expected mid February 2024