Simulation and measurement of charge transport in the periphery of planar silicon sensors to understand humidity-induced breakdown

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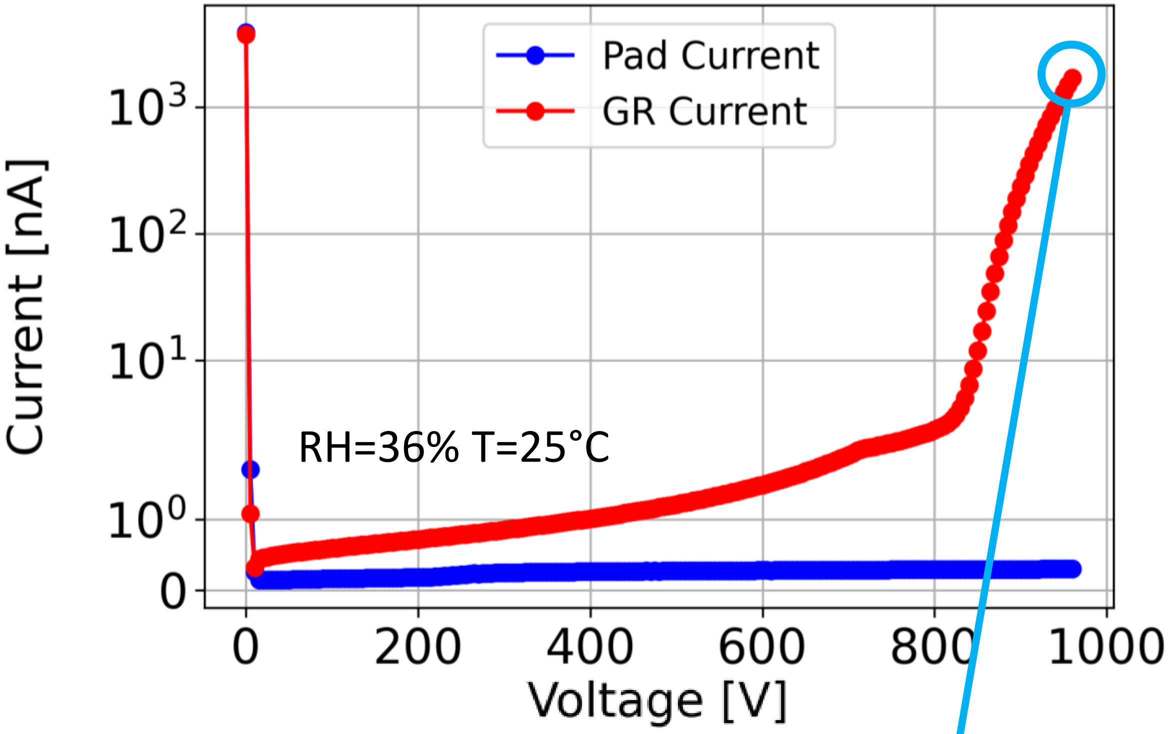
Humidity Study Background

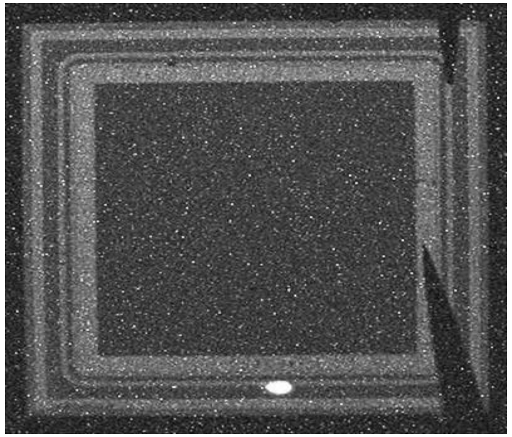


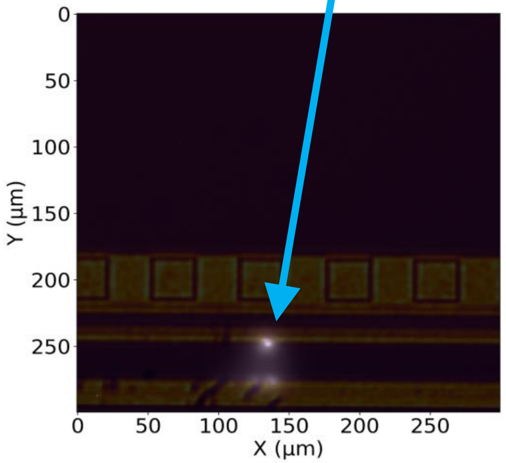
- ATLAS ITk strip sensors break down earlier in humid environment

  → High leakage current

- Prevention method: dry storage and testing

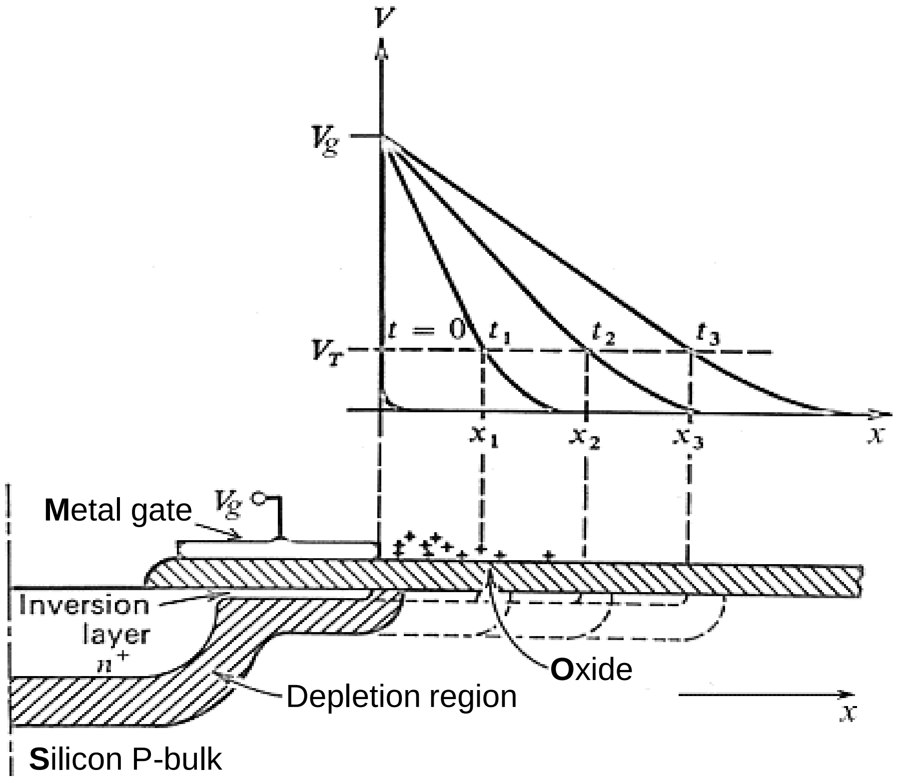
  → time and money consuming!





- Avalanche breakdown produces photons by bremsstrahlung and band-band transitions

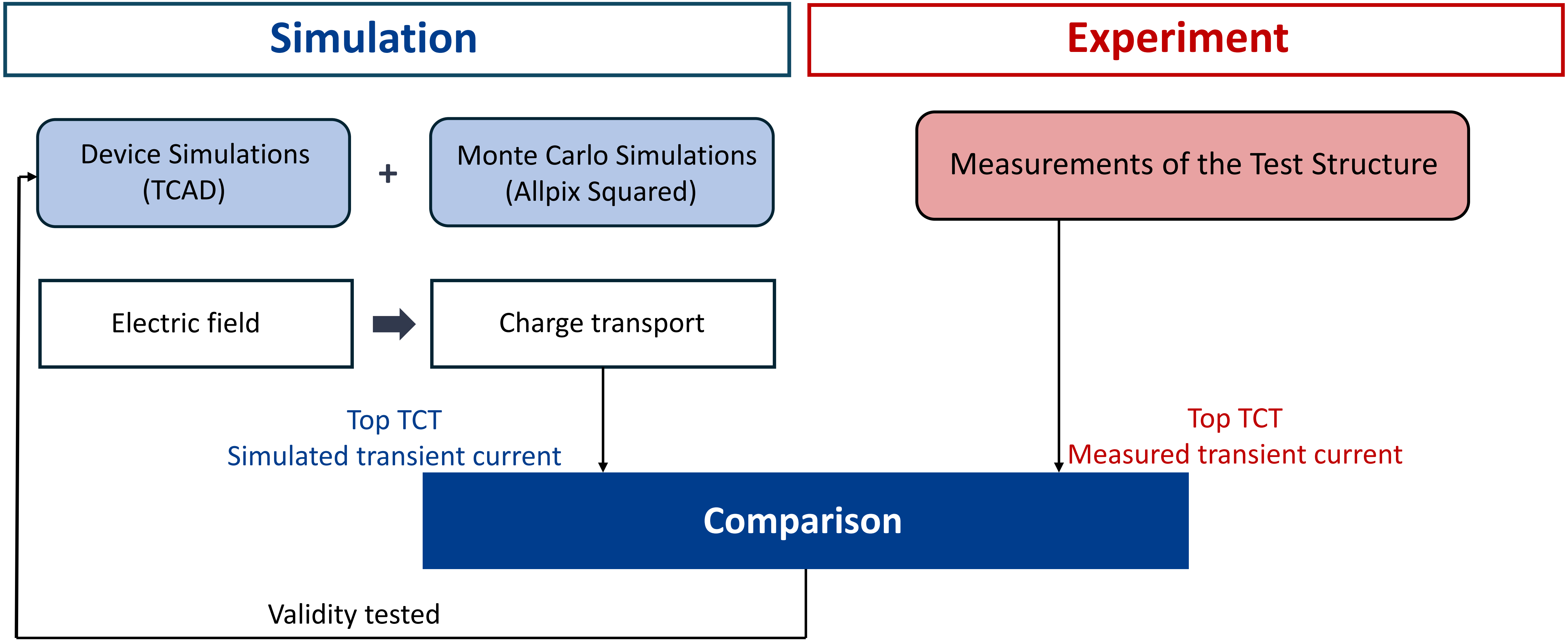
  → Breakdown region visible as bright spot at at the edges of sensors



→ Schrödinger, E. "Über die Leitung der Elektrizität auf der Oberfläche von Isolatoren an feuchter Luft." 1910
→ M. M. Atalla, A. R. Bray, R. Lindner. "Stability of thermally oxidized silicon junctions in wet atmospheres." 1959
→ W. Shockley, et al. "Mobile electric charges on insulating oxides ..." 1964
→ Y. C. Kao and E. D. Wolley. "High-voltage planar pn junctions." 1967
→ R. Stengl and E. Falck. "Surface breakdown and stability of high-voltage planar junctions." 1991.

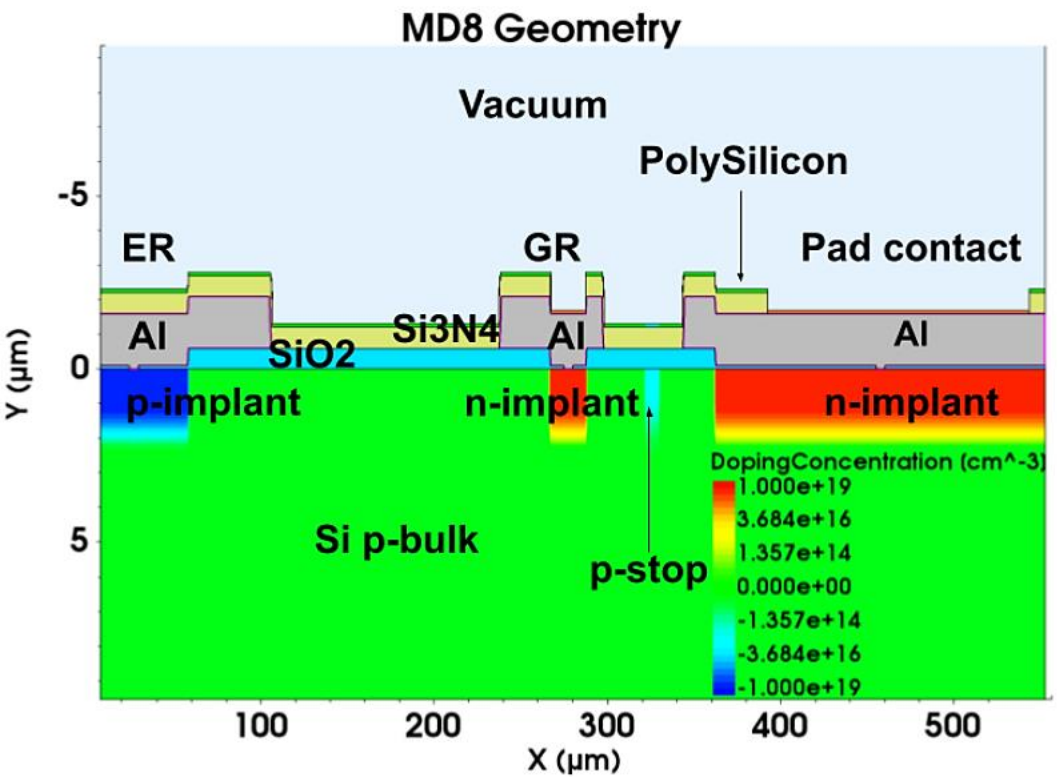
- Impurities on the surface of SiO_2/Si_3N_4
- SiO_2 attracts ambient H_2O
  → Ions become mobile in humid environment
  → Oxide surface sheet resistance decreases drastically → Gate potential Vg extends
  → The surface can interact with electrodes and the bulk

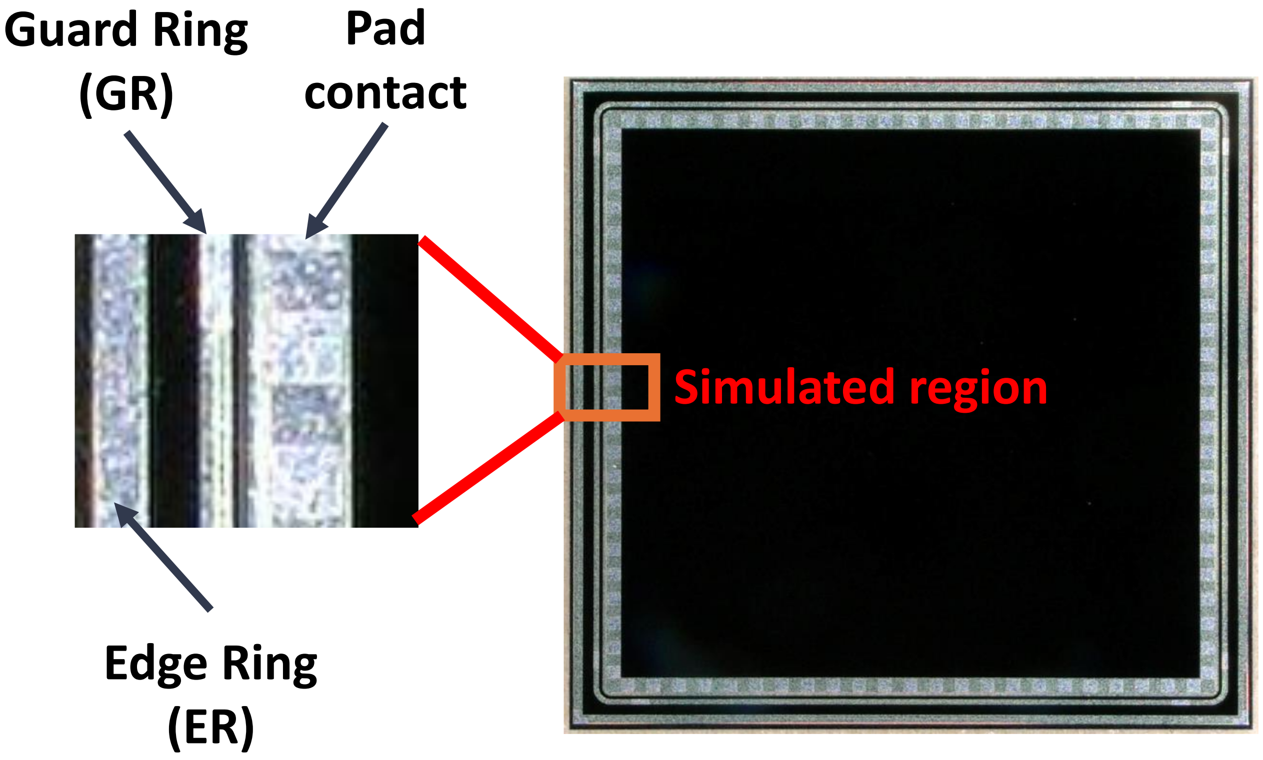
Plan



Simulation
Experiment
Device Simulations (TCAD)
+
Monte Carlo Simulations (Allpix Squared)
Measurements of the Test Structure
Electric field
Charge transport
Top TCT
Simulated transient current
Top TCT
Measured transient current
Comparison
Validity tested

TCAD Simulation was conducted by Ilona Ninca☺



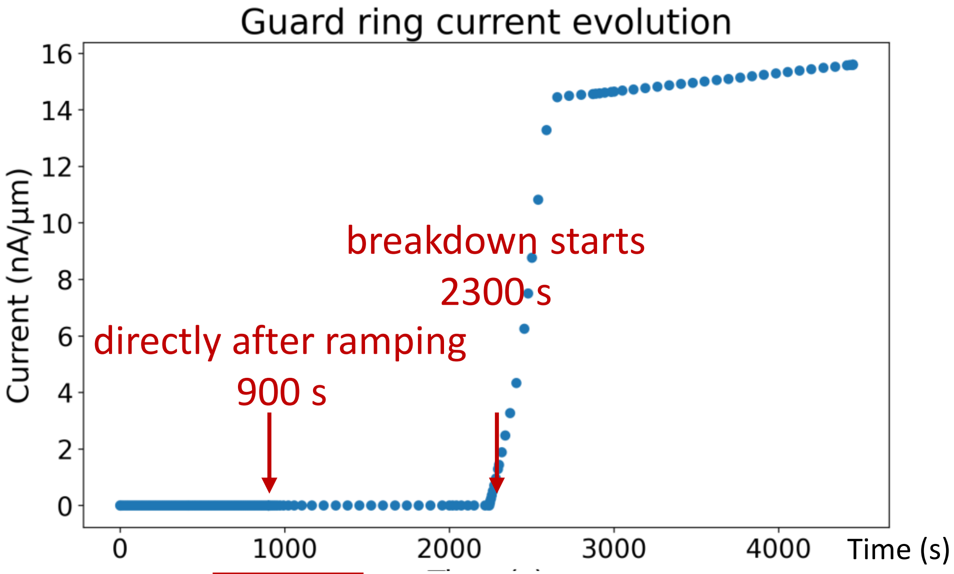


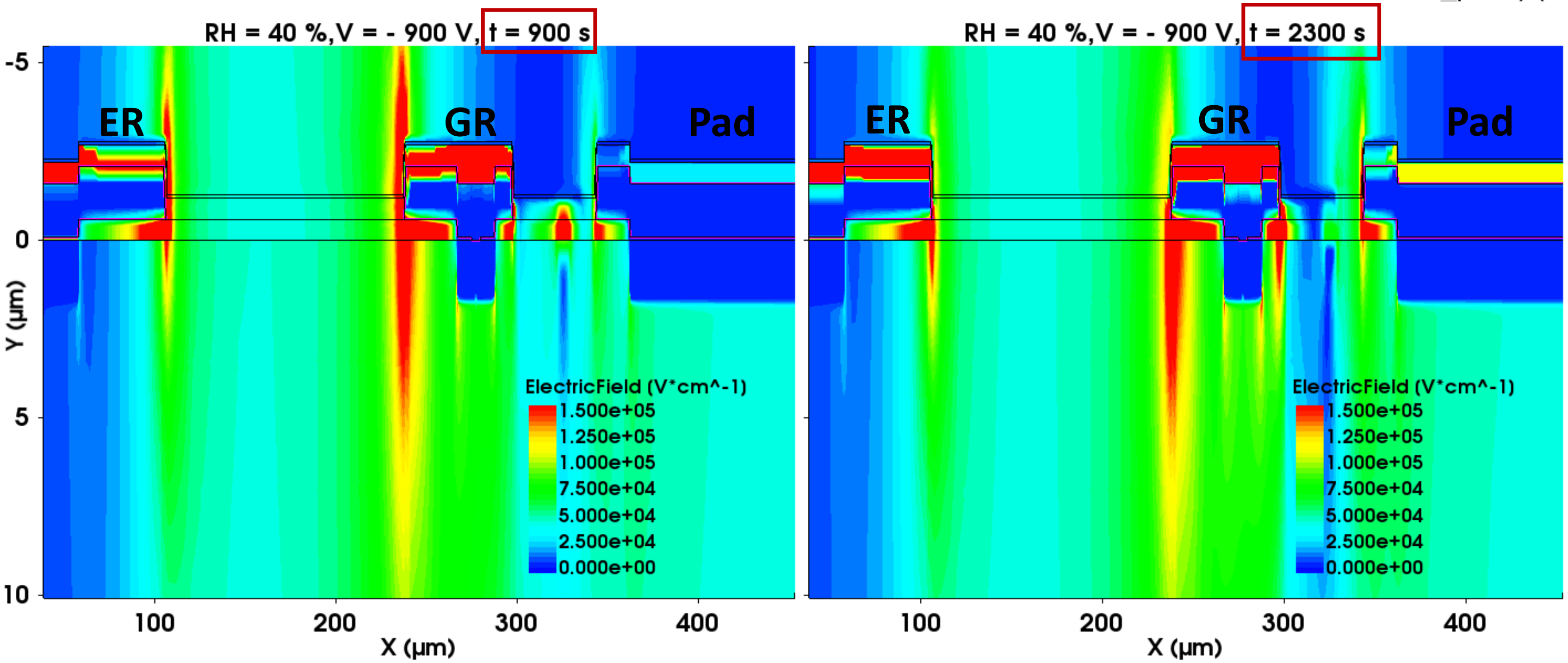
- 8 mm x 8 mm n^+pp^+ diode
- Active thickness: 295 µm, bulk doping: 4.2×10^{12} cm^{-3}, full depletion voltage: 274 V
- 0.6 µm SiO_2 + 0.6 µm Si_3N_4 passivation
- 10^{11} cm^{-2} fixed oxide charge
- 0.1 µm polysilicon on passivation with fixed mobilities (→ 10.1109/NSSMIC.2014.7431261)

TCAD Simulations: Electric Field

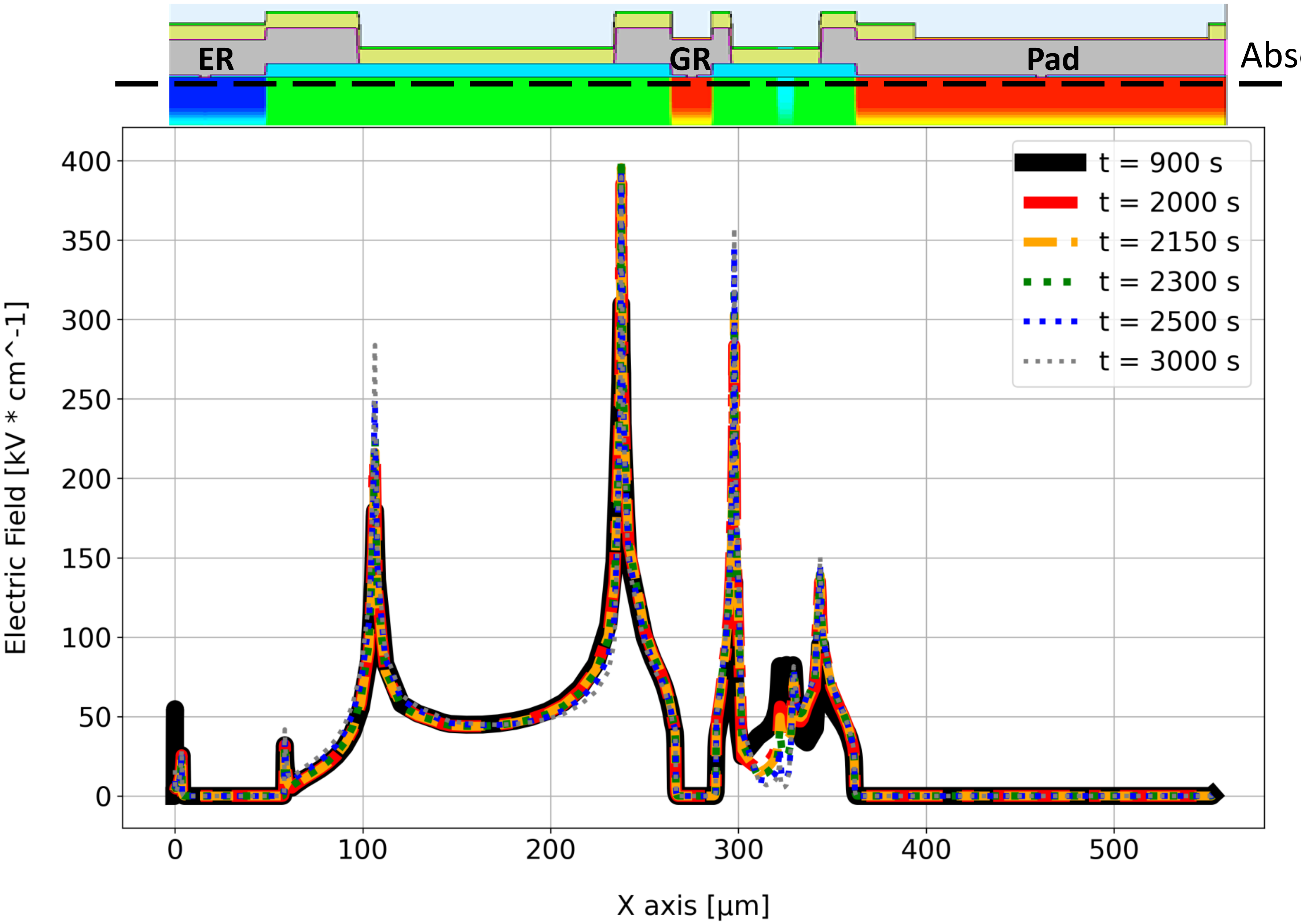
Relative Humidity = 40%
Bias voltage ramped from 0 V to -900 V in 900 s and kept constant

- Two high field regions observed near the ER and near the GR
- Peak fields at the GR and ER metal edge increase over time



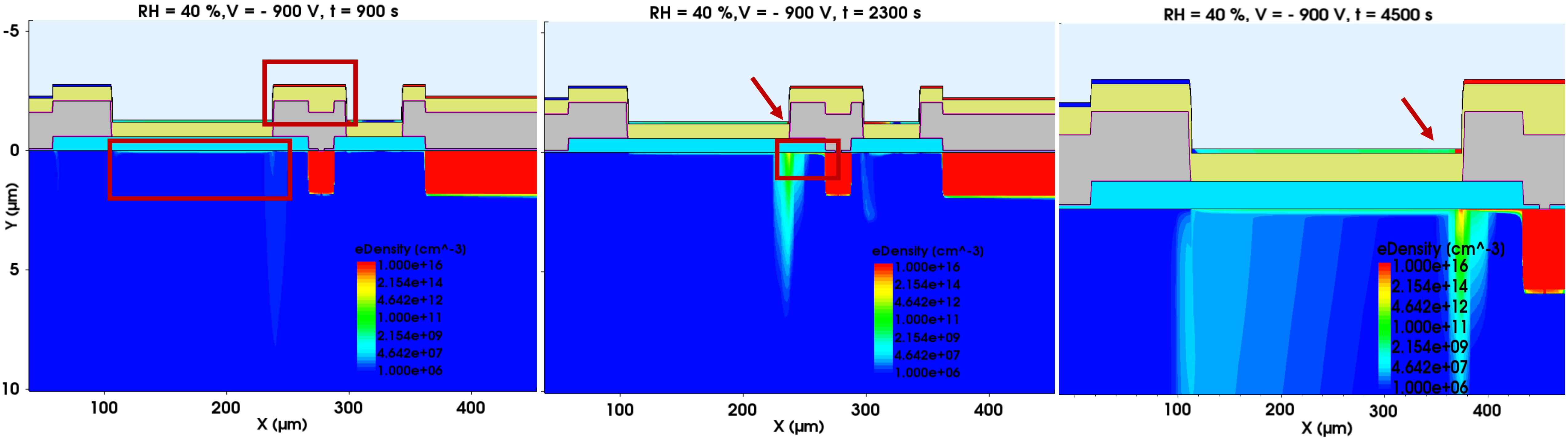


TCAD Simulations: Electric Field



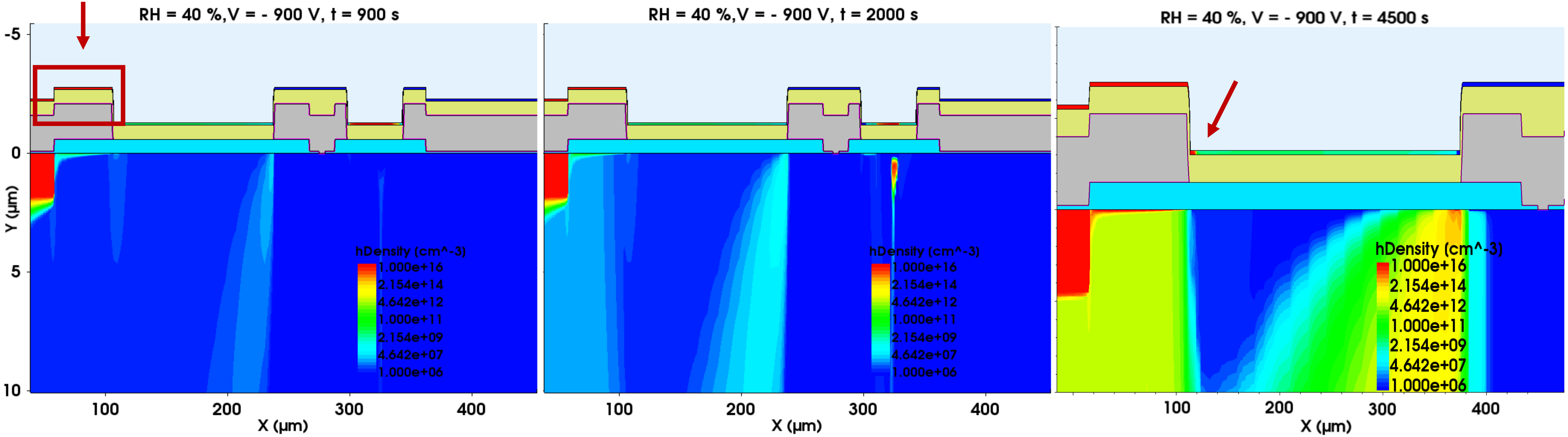
Absolute electric field at y = 100 nm

Peak field at ER and GR increase over time



- An electron channel is present at the Si-SiO2 interface
- High density of electrons in the polysilicon layer on top of GR

- High density of electrons in the polysilicon layer on top of GR moving laterally towards the ER
- Free electrons generated by charge multiplication in the high field region at the GR metal edge
- The electron channel connected to the GR implant



High density of holes in the polysilicon layer on top of ER

- High density of holes in the polysilicon layer on top of ER moving laterally towards the GR
- Holes generated by charge multiplication in the high field region at the GR metal edge

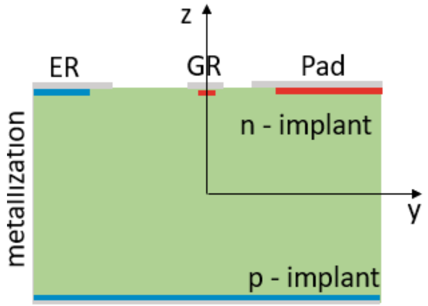
External electronics
Transfer function T(t)

Geometry Construction → Fields Configuration → Charge Deposition → Charge Transport → **Final Results**

Fields Configuration
- Electric Field
- Weighting Field
- Doping Profile

Charge Deposition
- Initial charge distribution

Charge Transport
- Drift
- Diffusion
- Induction



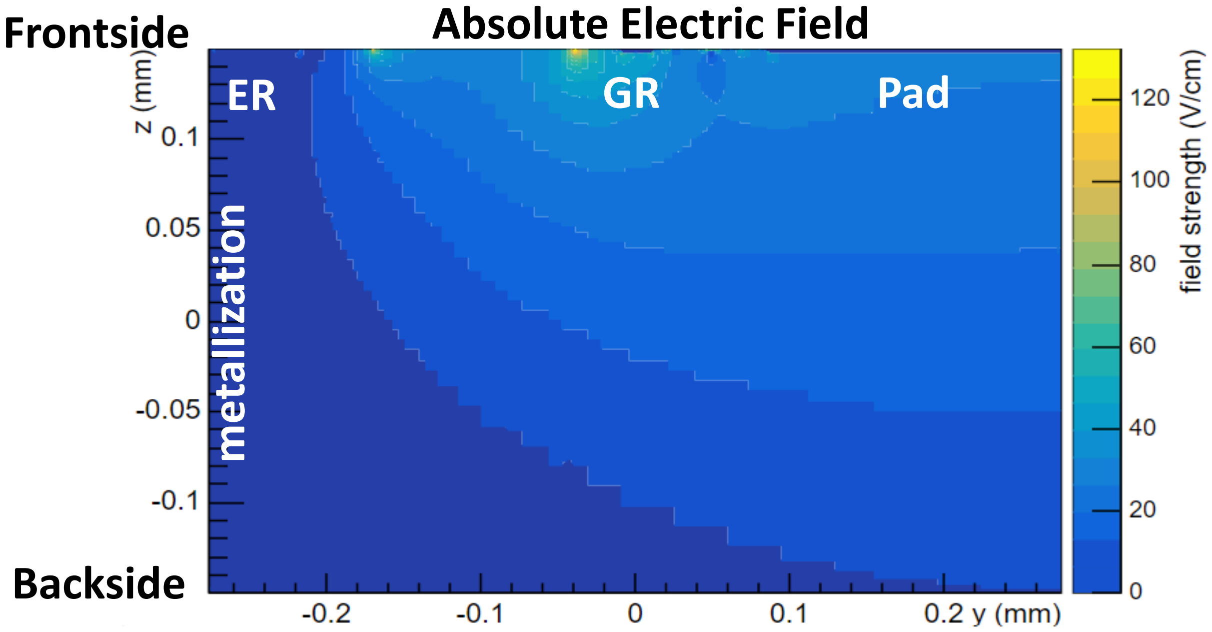
Sentaurus TCAD
SYNOPSYS

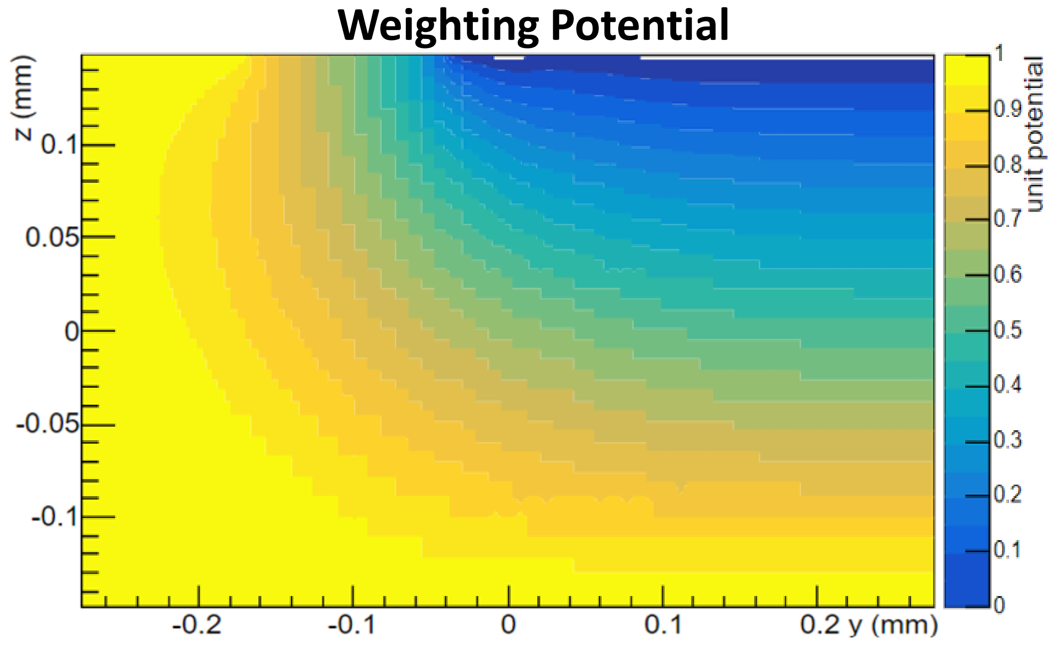
Laser beam waist
Pulse duration

Charge Mobility model
Charge Multiplication model

Semiconductor Detector
Monte Carlo Simulation Framework

From TCAD to Allpix Squared





Electrostatic potential:

- Guard Ring and Pad: grounded (~0 V)
- Edge Ring: -500 V

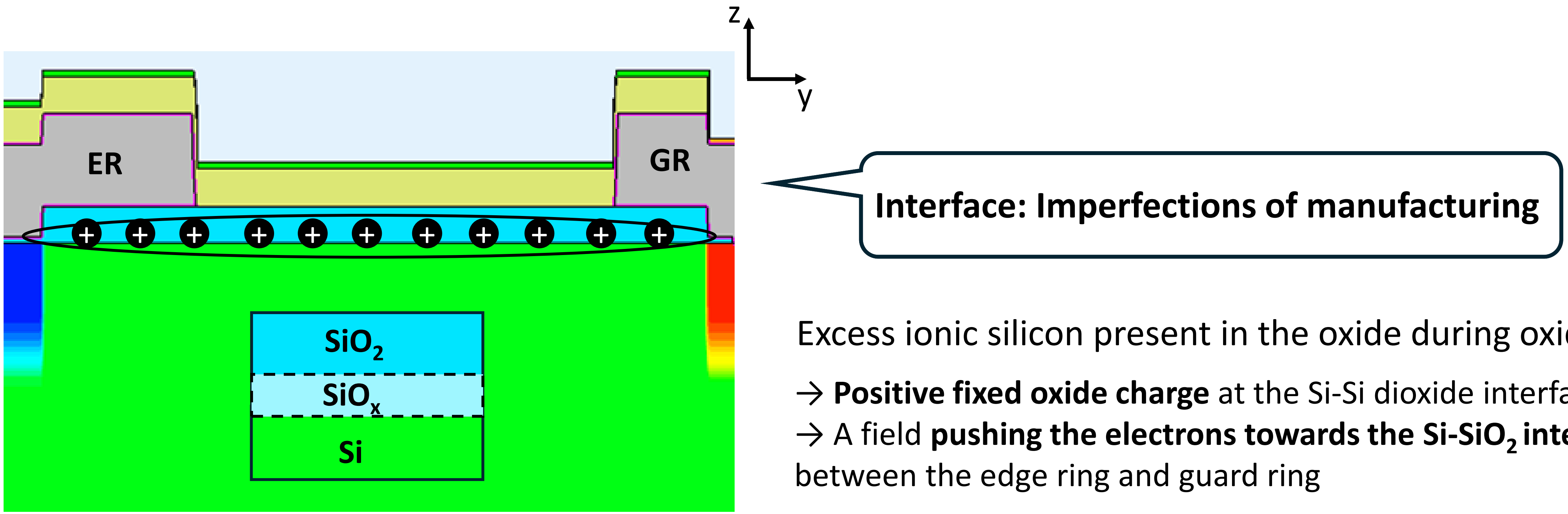
Electric Field:

- High electric field near the GR metal and ER metal
- Field strength approaches zero within the implant regions

Weighting Potential:

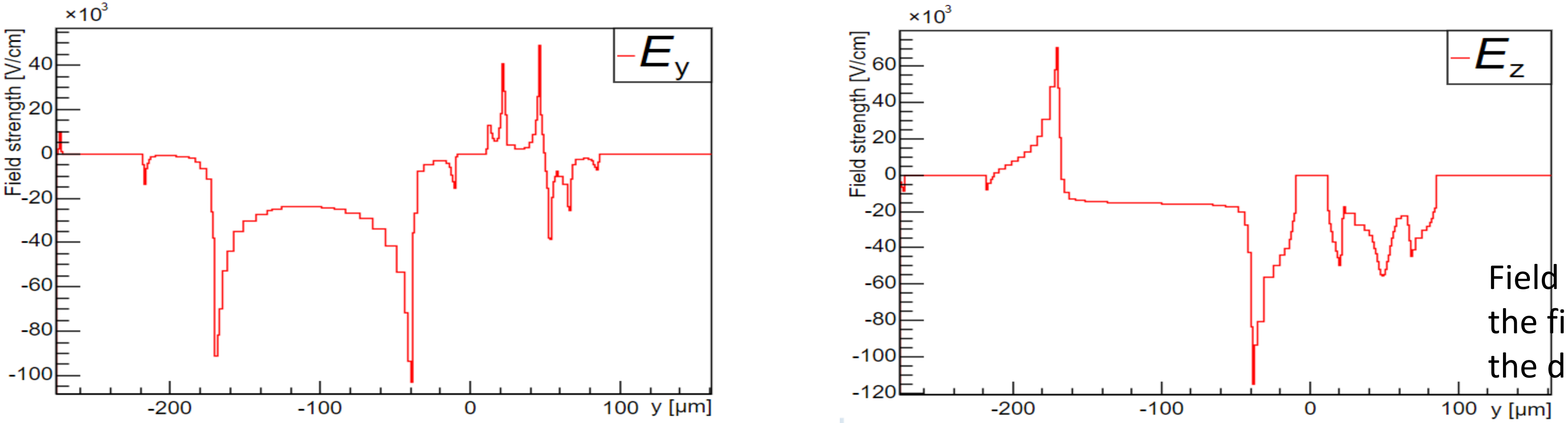
- Determined from a potential difference
- Normalized to 0 to 1 (ER/Backside~1, GR/Pad~0)

SiO2- Si Interface Properties



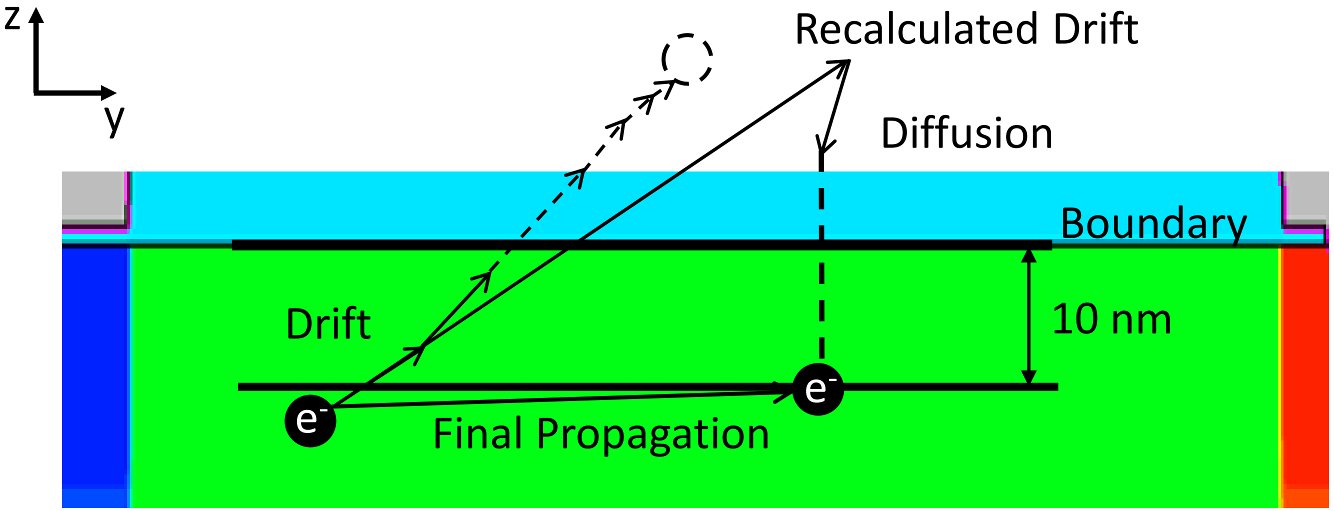
Excess ionic silicon present in the oxide during oxidation

→ **Positive fixed oxide charge** at the Si-Si dioxide interface
→ A field **pushing the electrons towards the Si-SiO_2 interface** between the edge ring and guard ring



Field strength within the first 0.6 um from the diode surface

Surface Reflectivity



- Drift
  - Mobility model: Hamburg High-Field model
  - Iterative method: Fifth-order Runge-Kutta

- Diffusion
  - Monte Carlo method
  - Gaussian probability distribution

- Propagation: Drift + Diffusion

Surface_reflectivity

```
[TransientPropagation]
surface_reflectivity = 1
```

All the charge carriers will be “reflected” back to the bulk

```
[TransientPropagation]
surface_reflectivity = 0
```

Charge carriers considered as “halted” when they drift outside the boundary

Signal Generation

1. Charges carriers generated by laser pulses
2. Drift under the influence of the electric field
3. Induction of mirror charges on the electrodes

Transient Current

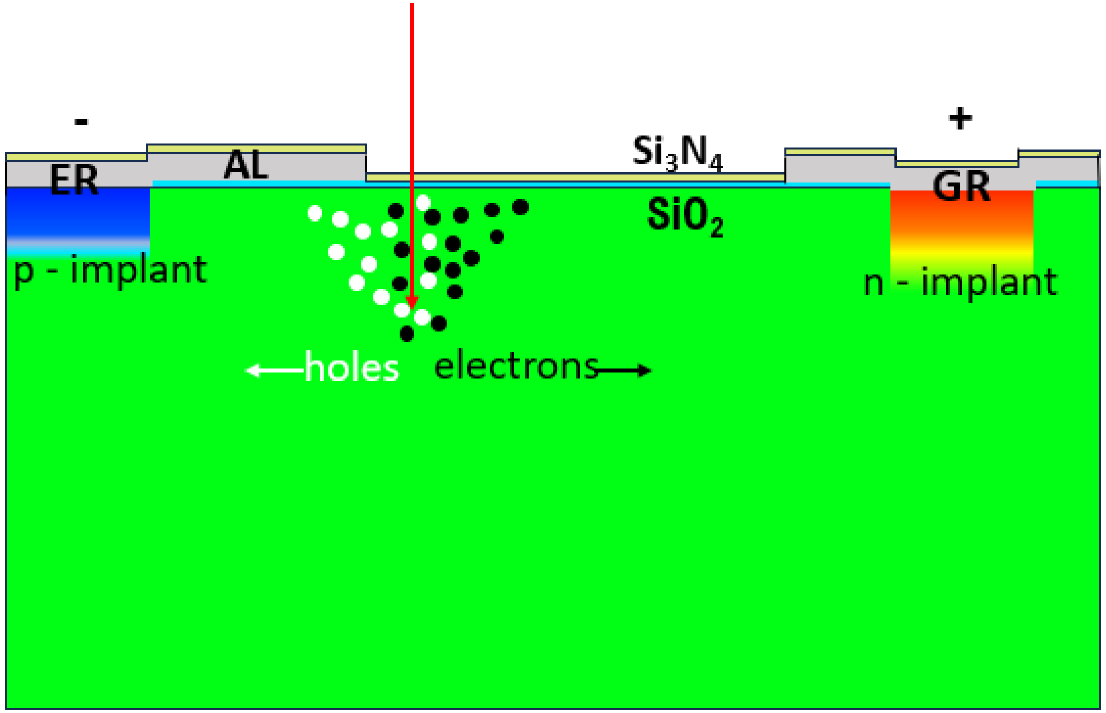
- Amount of drifting charge
- Charge velocity

$$I_{ind} = e_0 \cdot \vec{v}(\vec{E}) \cdot \vec{E}_w$$

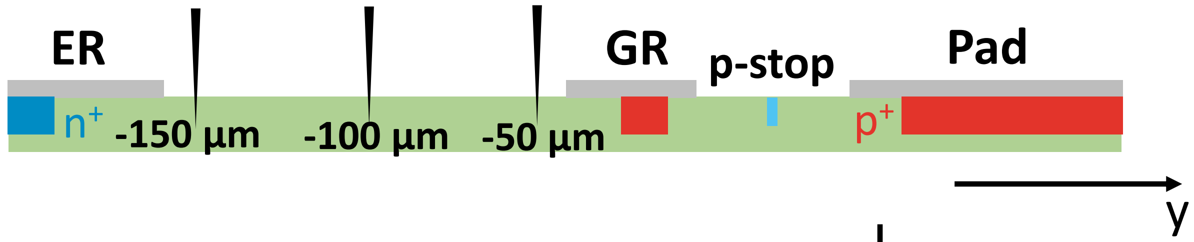
Electric Field Distribution

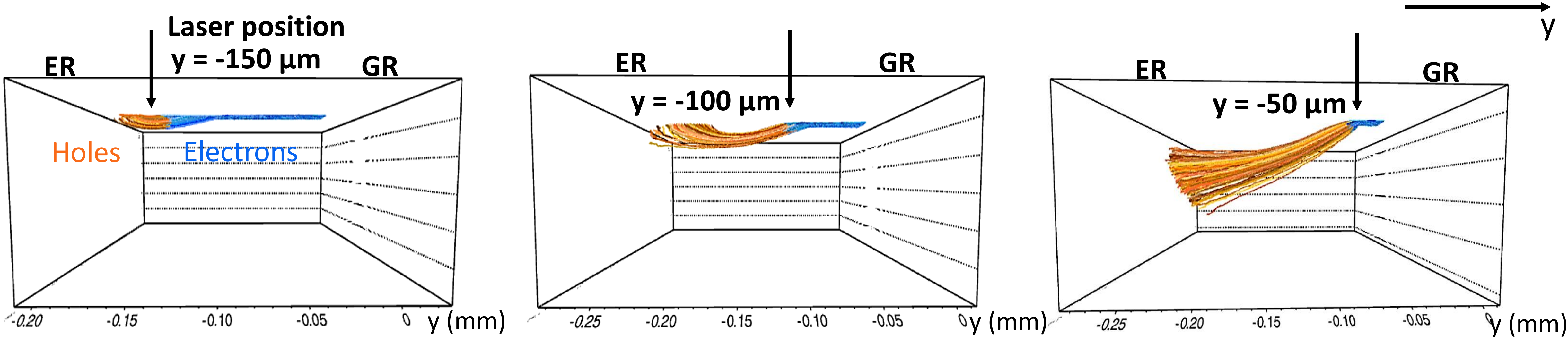
Red Laser (660 nm) properties:

- FWHM: 10 µm
- Pulse duration: ~ 50 ps
- Absorption length in Si: 3.5 µm

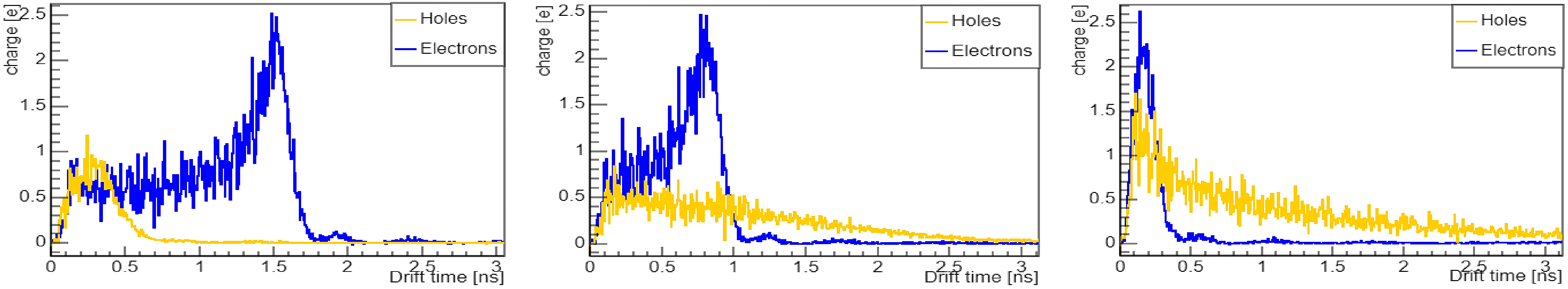


Simulated Charge Movement & Resulting Induced Currents





Resulting induced charges per time step (bias voltage: -500V, time step: 1ps)

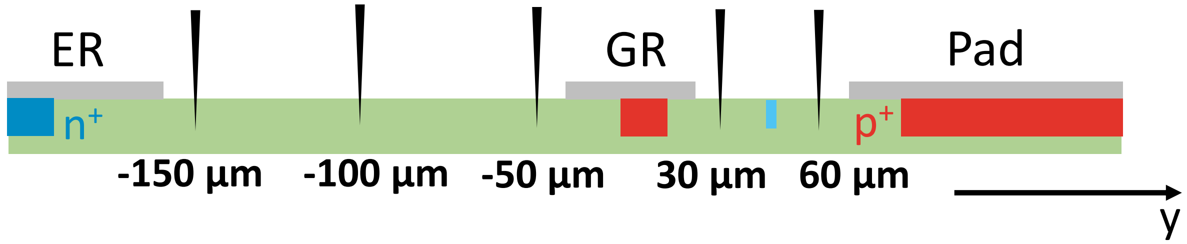


Waveforms Comparison

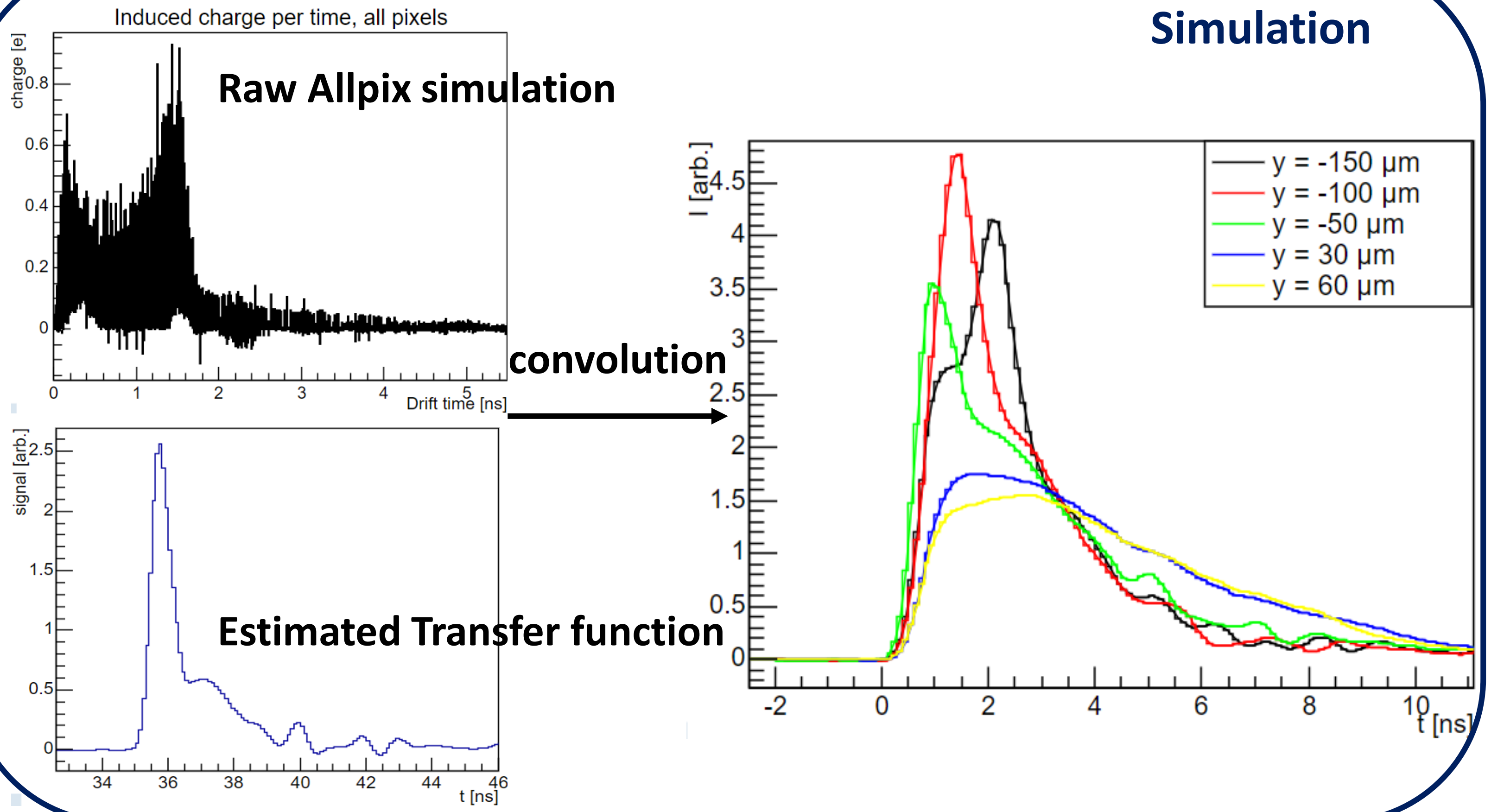
Raw Allpix simulation is convoluted with an **estimated transfer function** to obtain the final **simulation** results

⬇

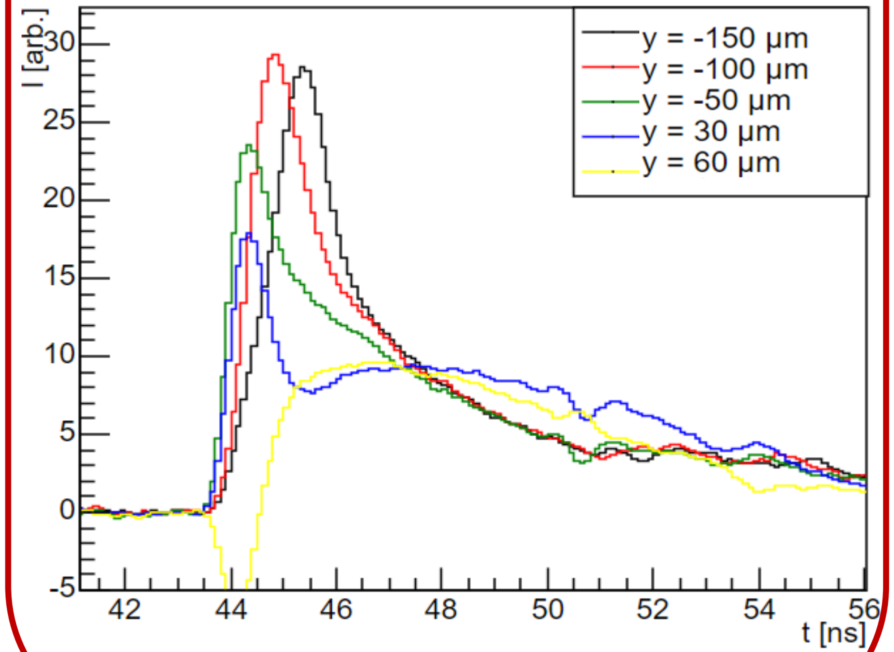
Comparison: **Simulation** and **Measurement**



Simulation



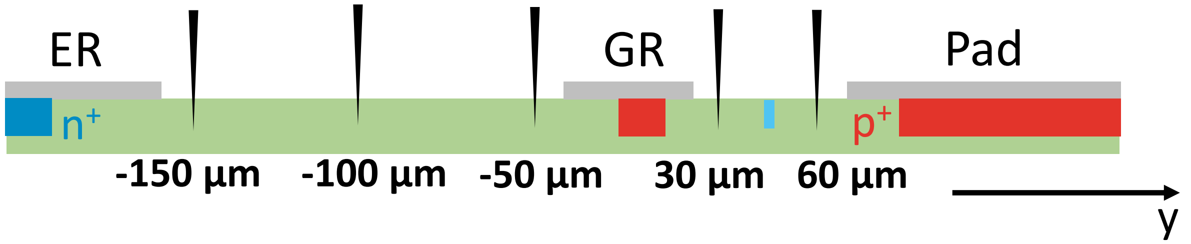
Measurement

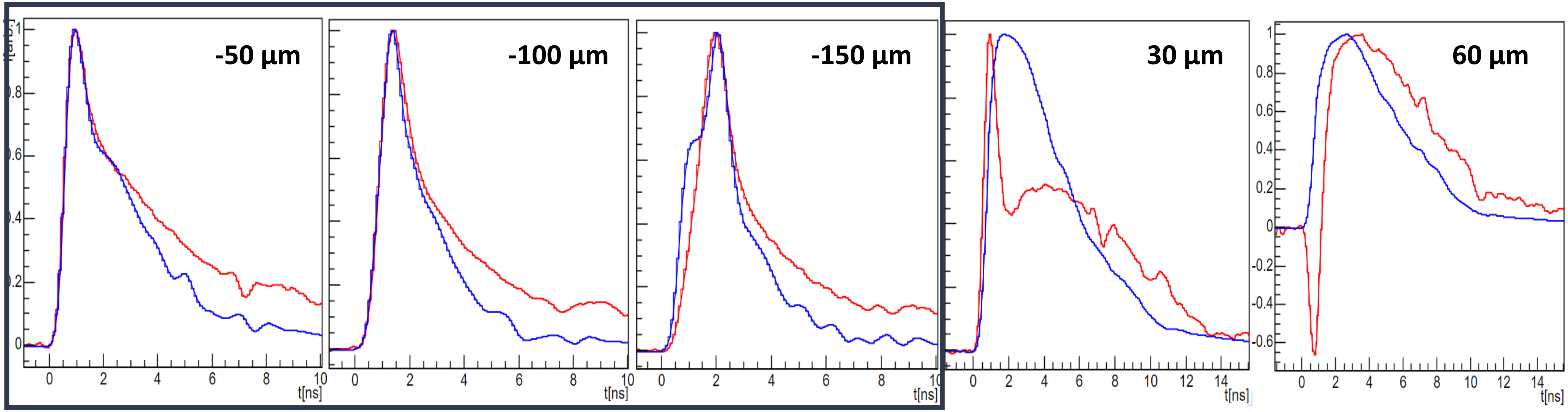


Waveforms Comparison

Simulation

Measurement





Good agreement for the main signal

↓

We are happy

Discrepancy in signal rise

↓

Higher simulated field near the ER?

Discrepancy due to the presence of p-stop

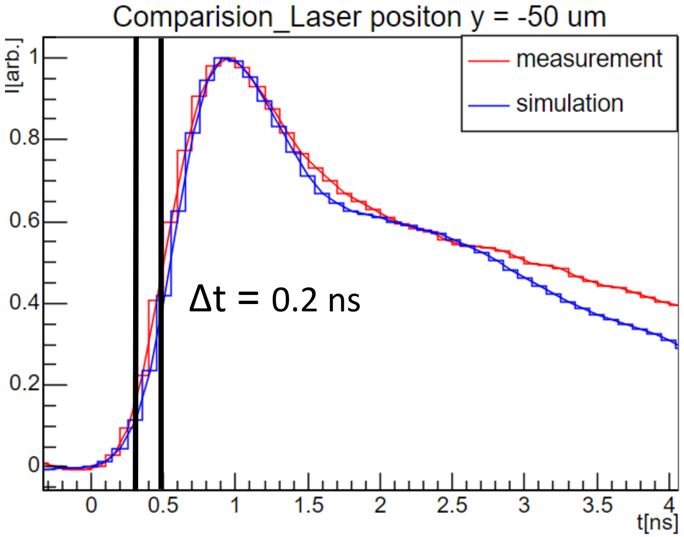
↓

ongoing

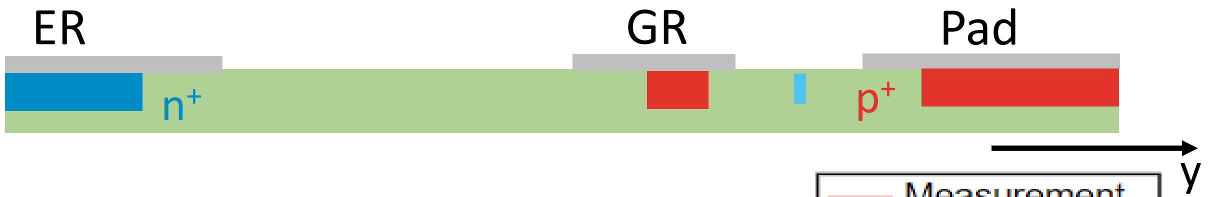
TCT y-Scan: Laser injection at various y-positions

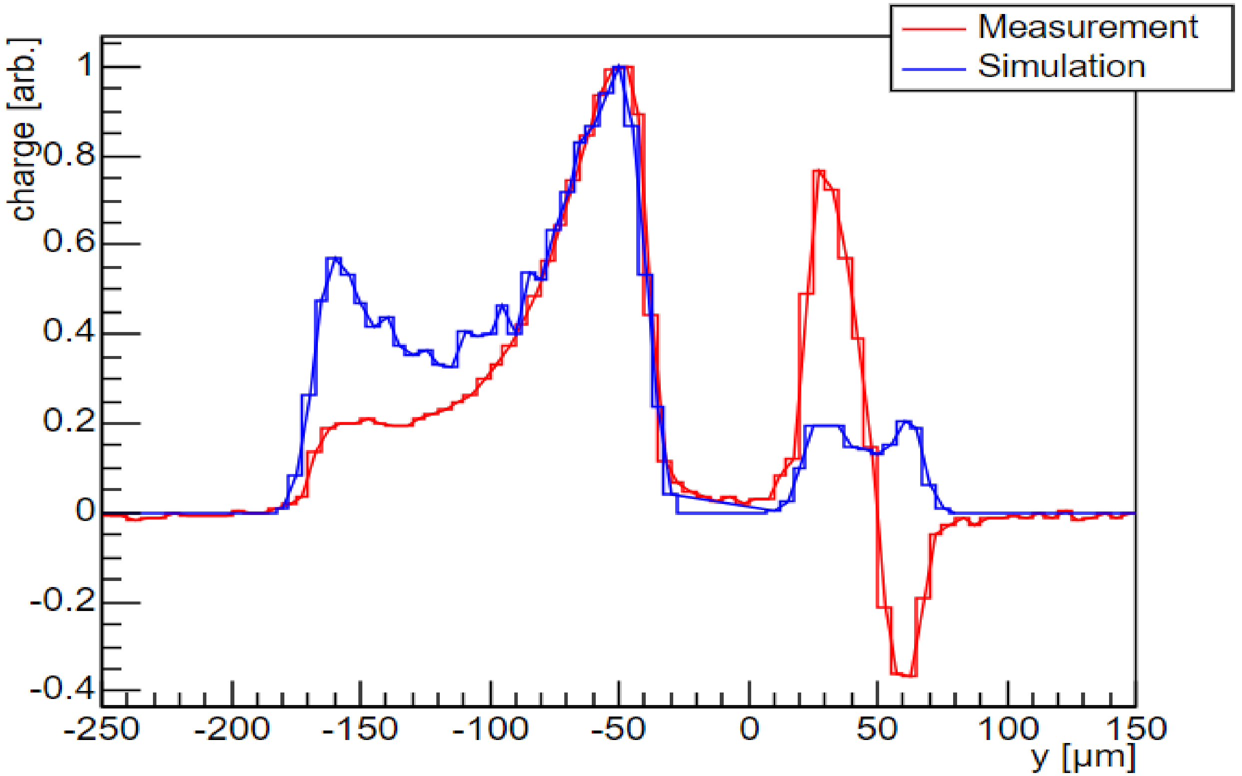
Prompt current profile:

- Obtained by integrating the initial rise(0.2 ns) of the transient currents
- Δt→0: Reflect local electric field



$$Q(y) \approx C \cdot \left(\vec{v}_e(\vec{E}(y)) + \vec{v}_h(\vec{E}(y))\right) \cdot \vec{E}_w$$





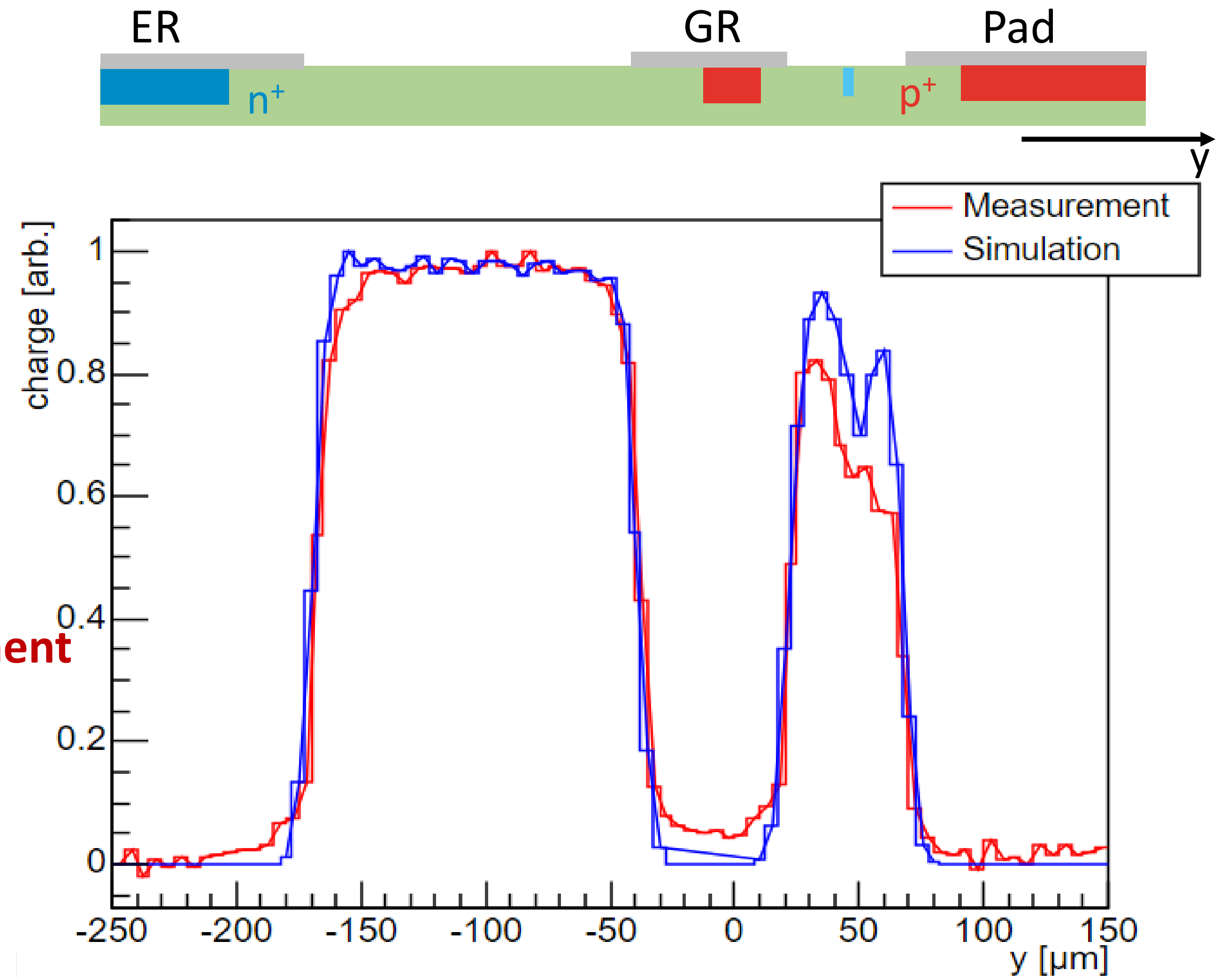
- y < -100 μm (close the ER): **A peak in simulation** while **homogenous in measurement**
- y > -100 μm (far away from the ER): In general good agreement between measurement and simulation

Charge Collection Estimation: Full Charge Profile

Full charge profile:

- Obtained by integrating the full pulses
- Estimation of charge collection

Between the ER and GR:
Good agreement between **Simulation** and **Measurement**

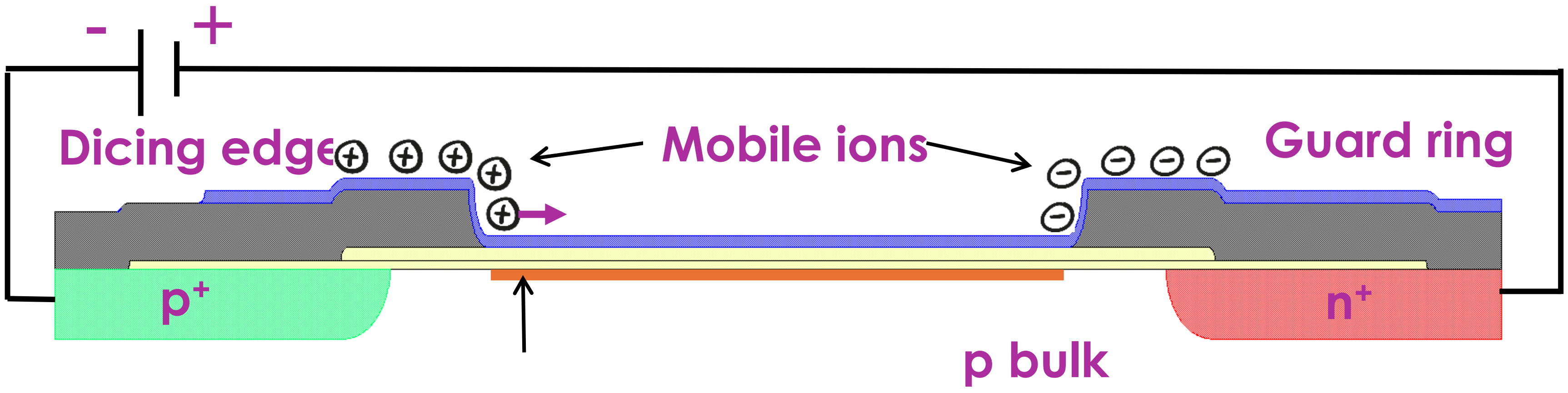


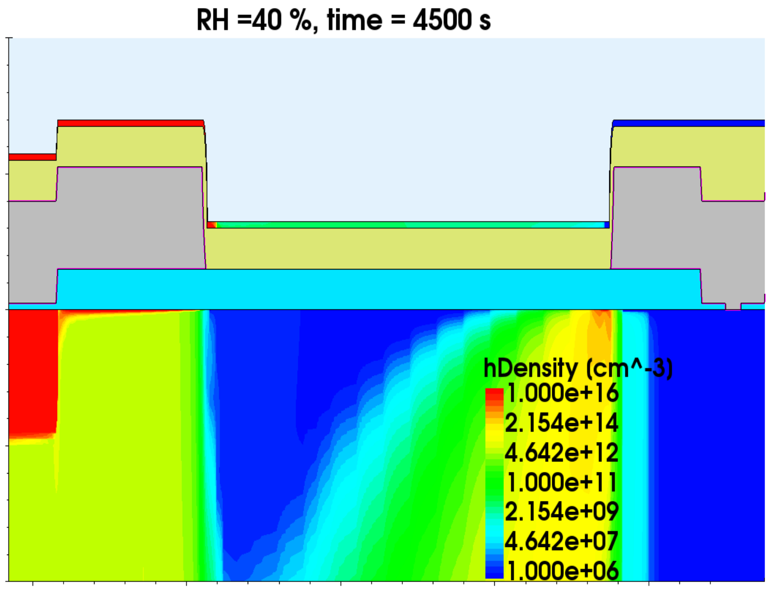
That’s it! :)

Thanks for your attention!

Back up

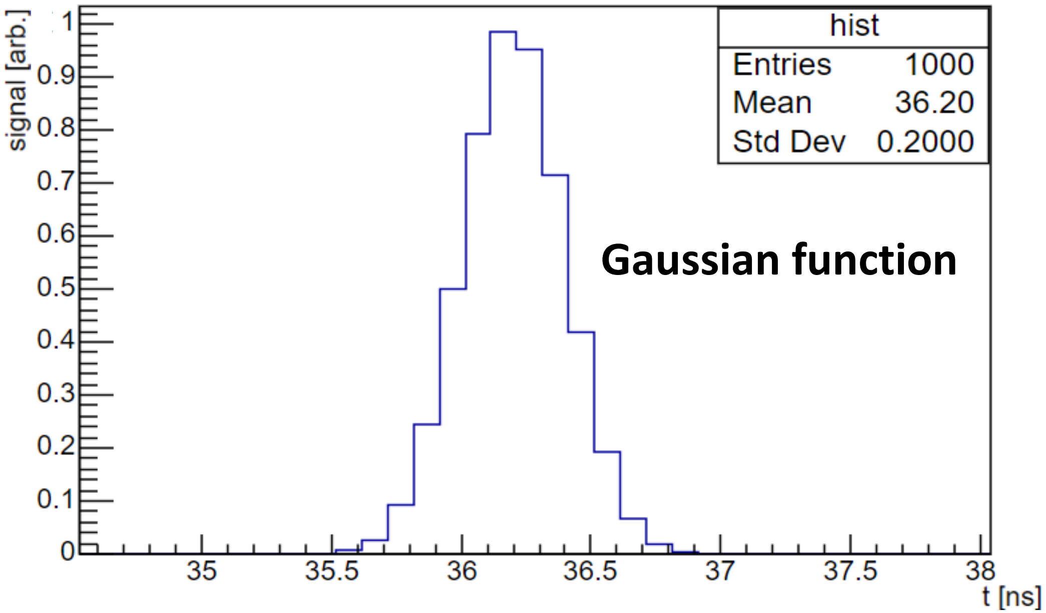
Charge carriers density

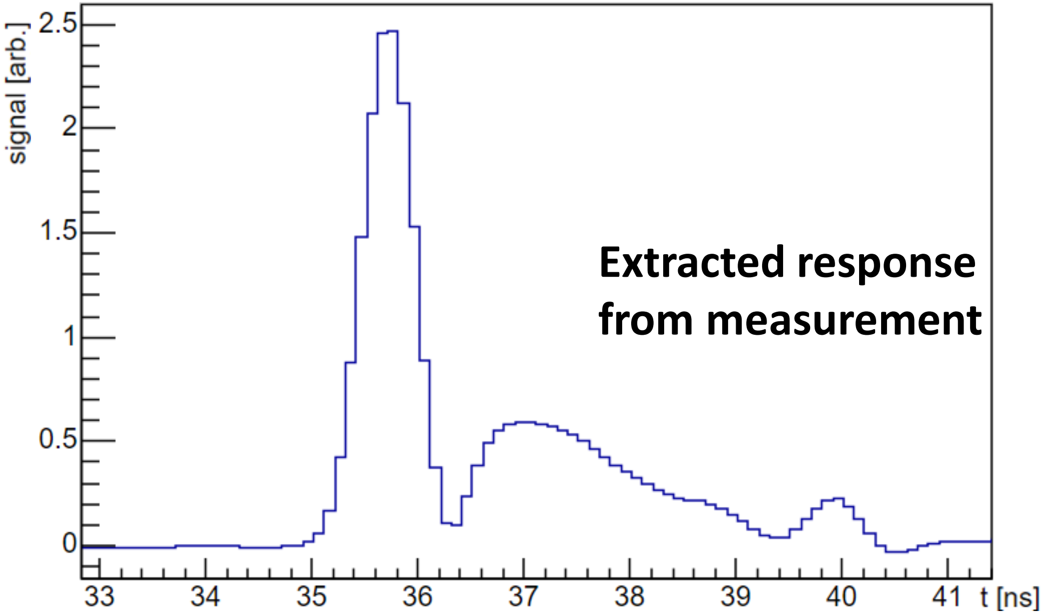




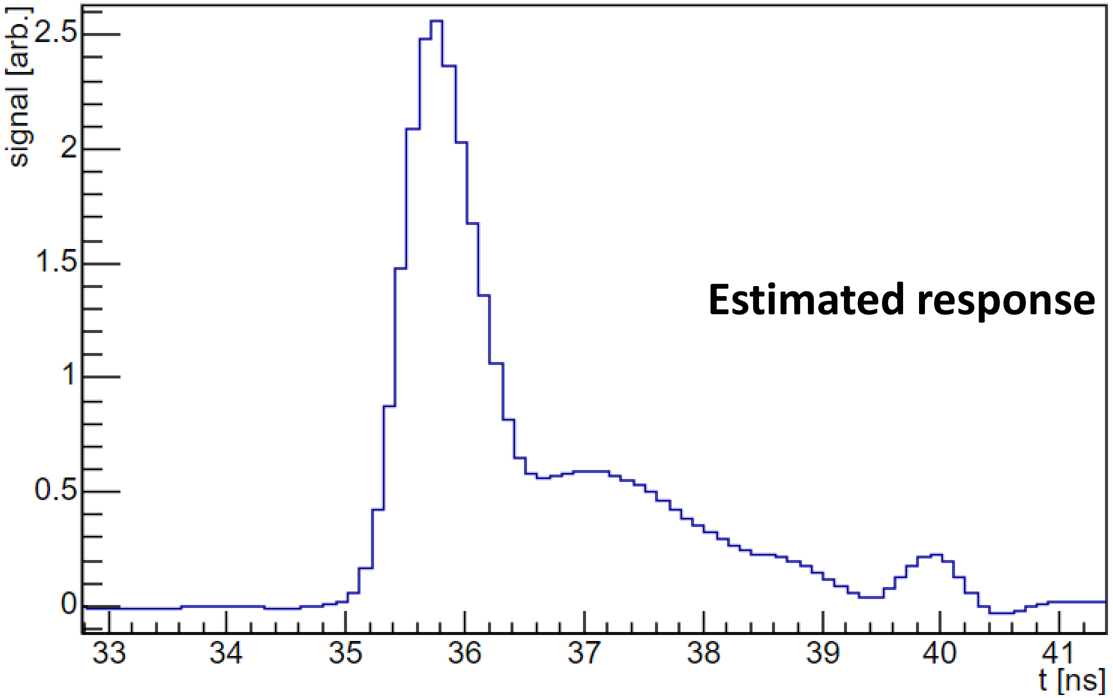
Hole density

Estimated Transfer Function



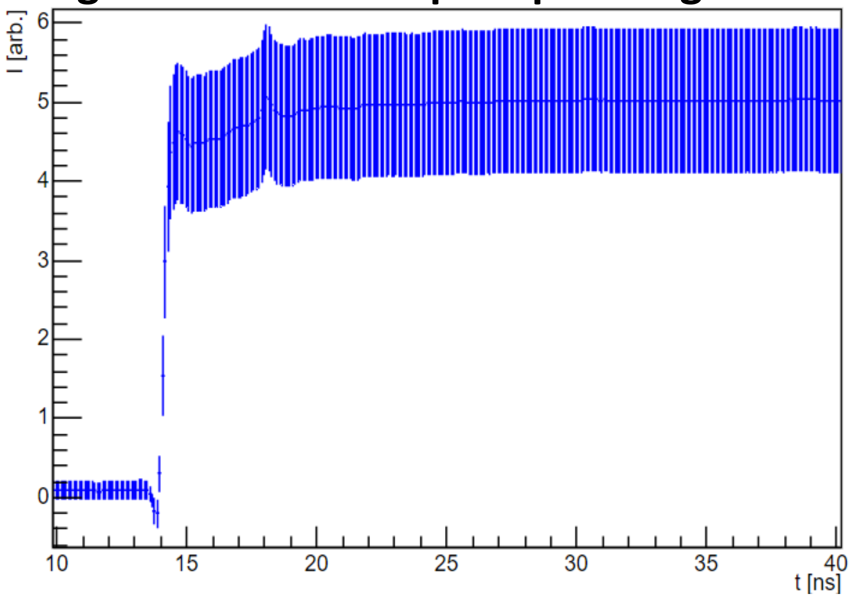


estimated response = Gaussian + measured response

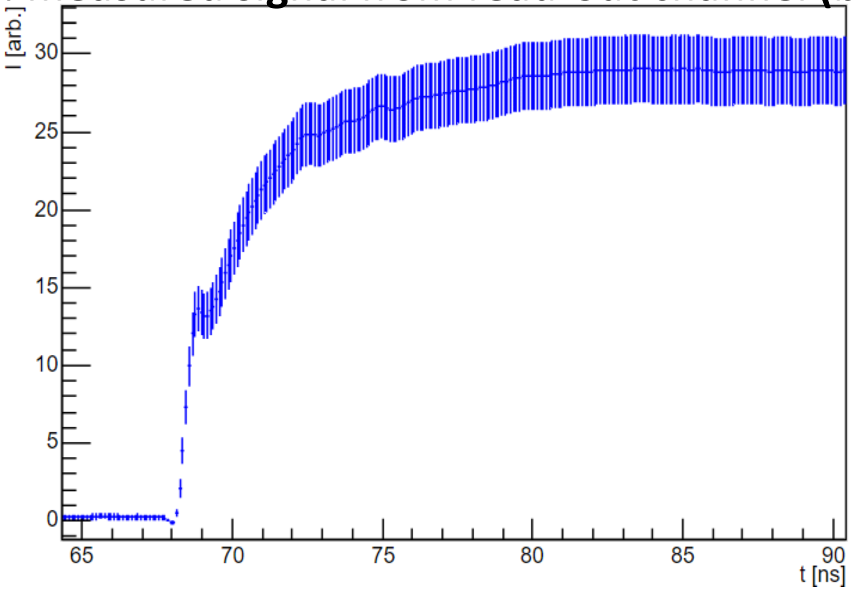


Deconvolution

Signal 1: measured pure pulse signal



Signal 2: measured signal from read-out channel (backside)



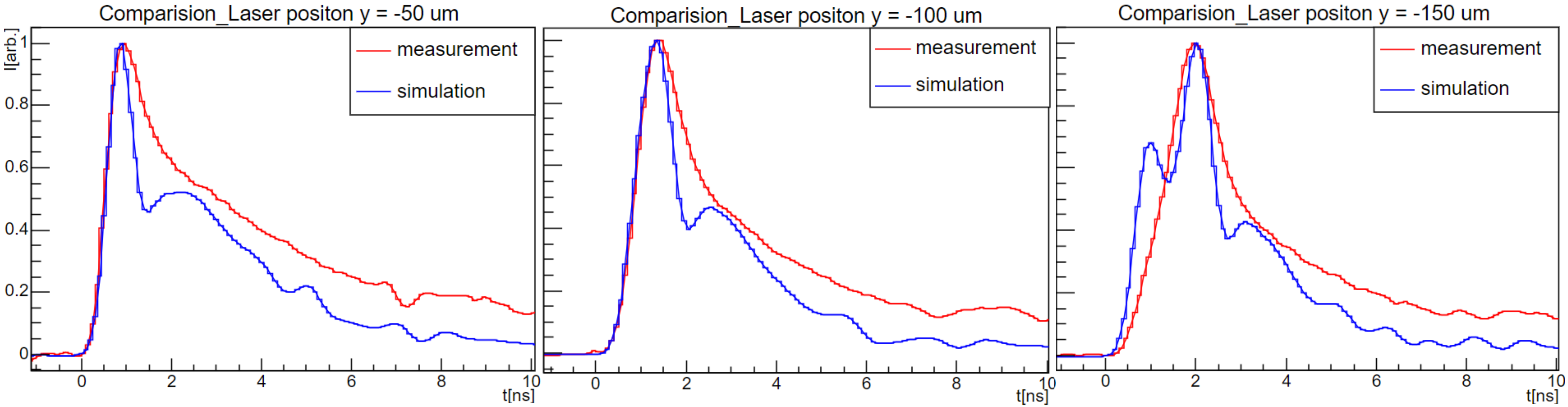
Using convolution theorem:

$$\mathcal{F}\left(\text{signal}_2\right) = \mathcal{F}\left(\text{signal}_1 \star T\right) = \mathcal{F}\left(\text{signal}_1\right) \cdot \mathcal{F}\left(T\right)$$

The response T(t) can be extracted by:

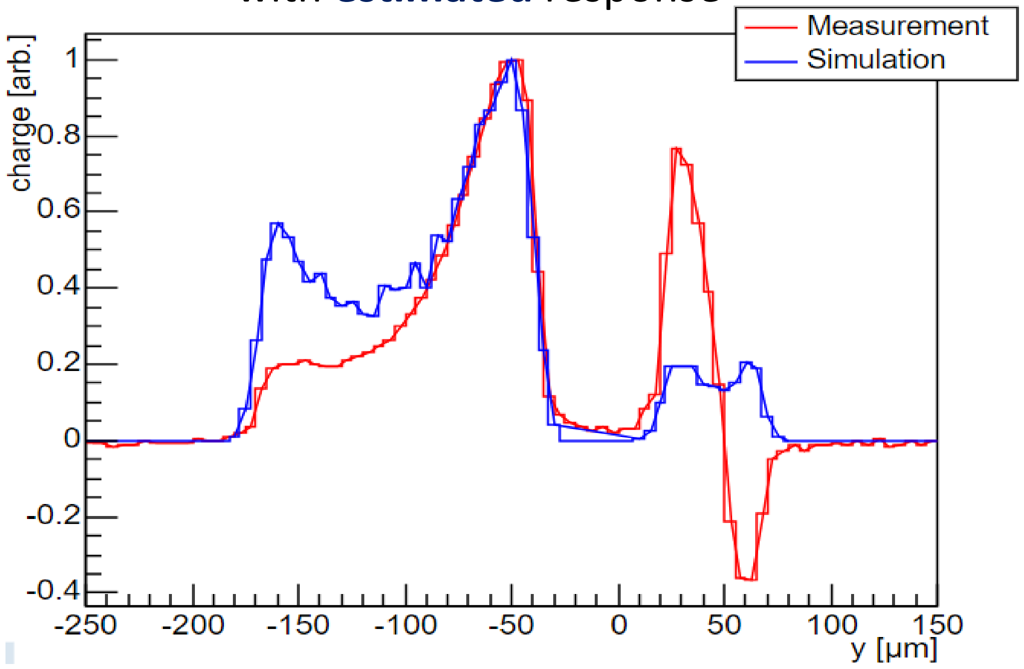
$$T(t) = \mathcal{F}^{-1}\left(\frac{\mathcal{F}\left(\text{signal}_2\right)}{\mathcal{F}\left(\text{signal}_1\right)}\right)$$

Convoluted Simulations with Measured Response

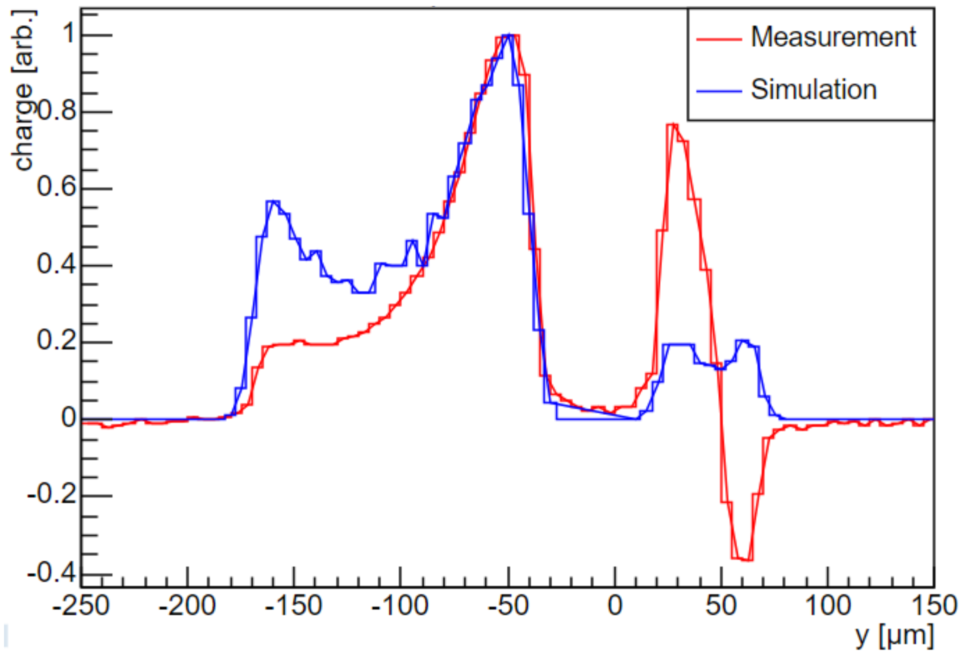


Prompt Current Profile

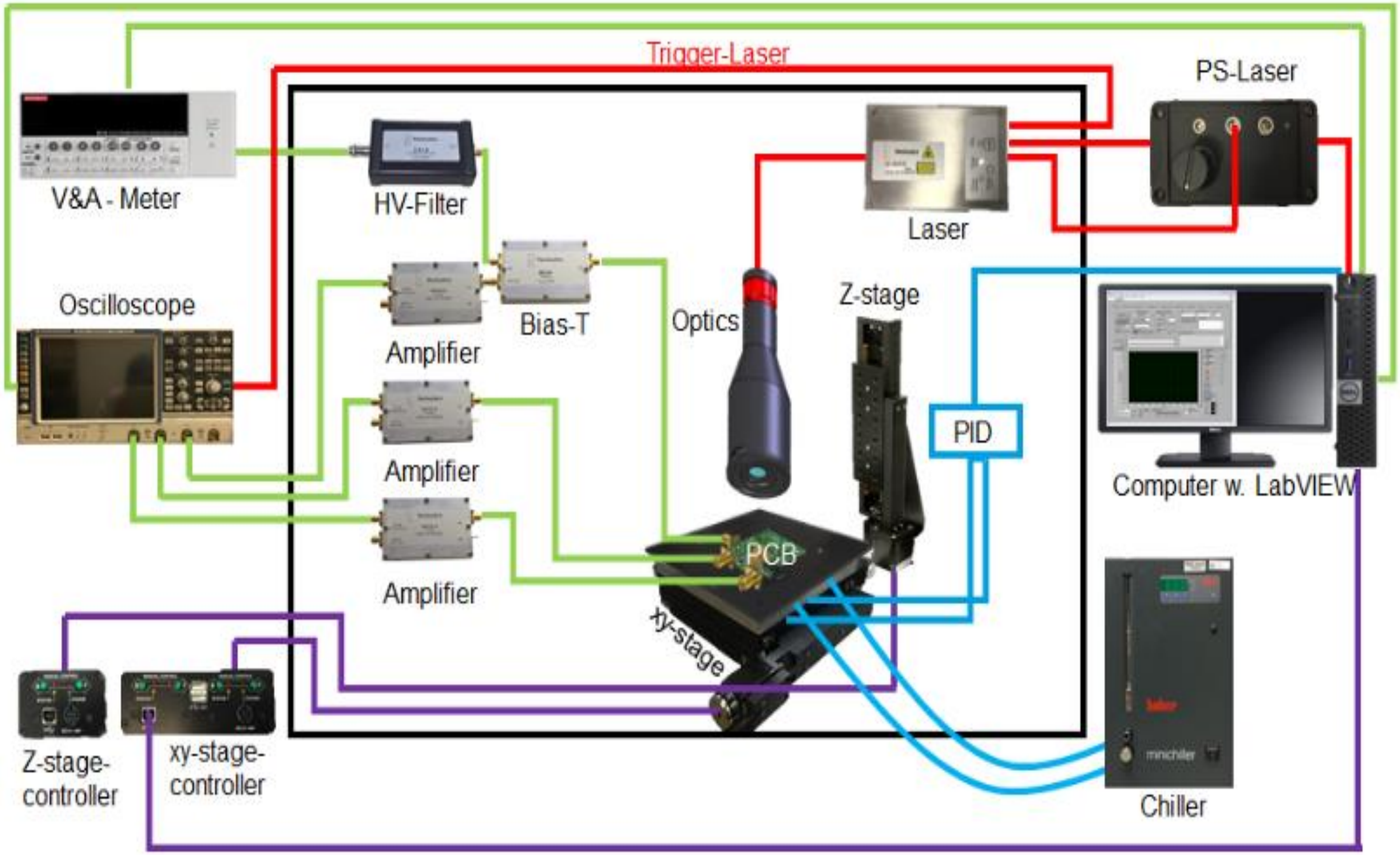
with **estimated** response



with **measured** response



Experiment Set up



Taken from: Nicky Potters. Investigation of Irradiated Silicon Strip Sensors using the Edge Transient Current Technique. Master's thesis, Universität Heidelberg, 2021.

Laser properties:

- FWHM: 10 µm
- Pulse duration: ~ 40 ps
- Absorption length in Si: 3.5 µm

Amplifier:

- Bandwidth: 0.01 to 3000 MHz.

Oscilloscope:

- Sampling rate 10^{10} s^{-1} , (acquisition time for each data point 100 ps).
- Bandwidth ≥ 2 GHz, corresponds to a rise time and a fall time of 175 ps each.

Conditions:

- Temperatur: 295 k
- Humidity: 55%