Silicon sensors and their quirks - understanding humidity sensitivity

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DESY Zeuthen Particle Physics Mini-Retreat 2023

Monday, June 12th, 2023

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

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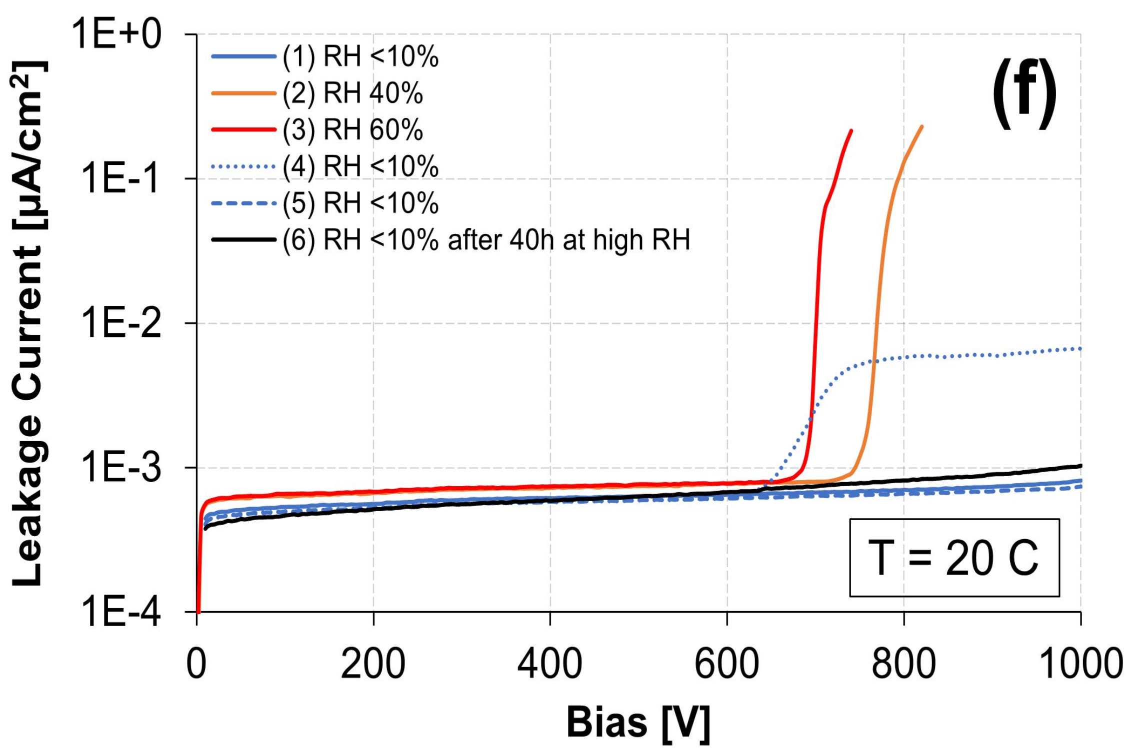
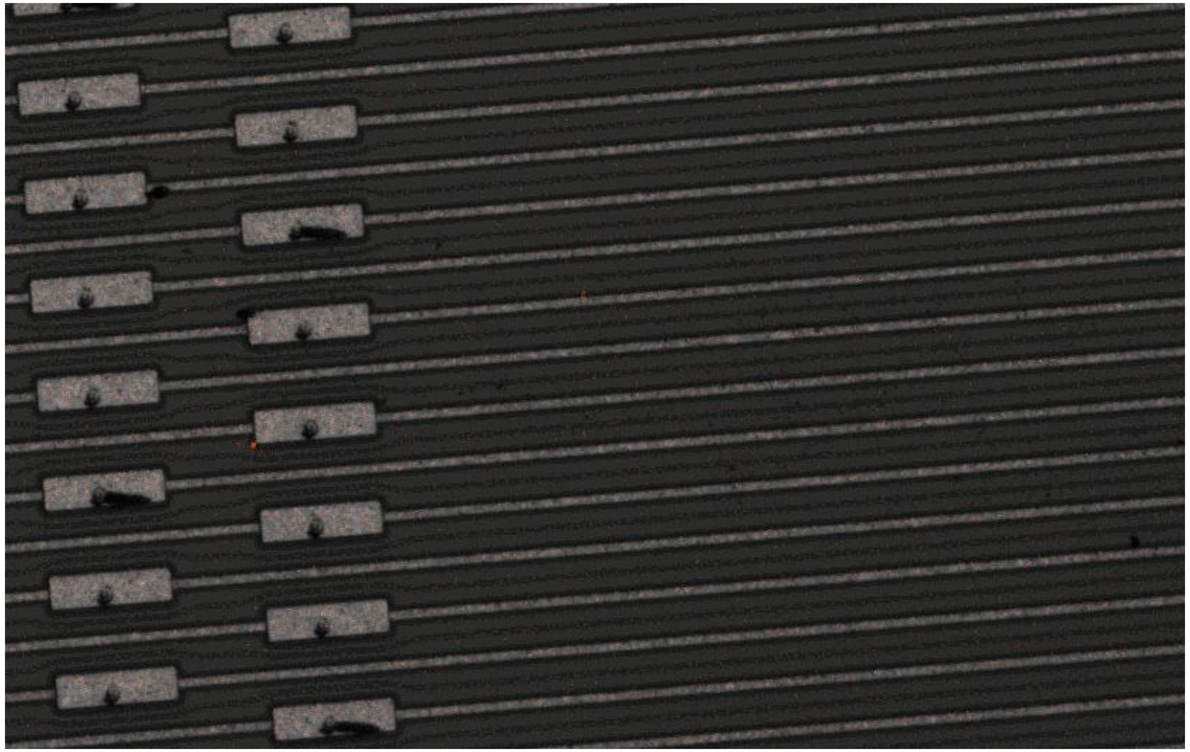
Humidity Studies Motivation

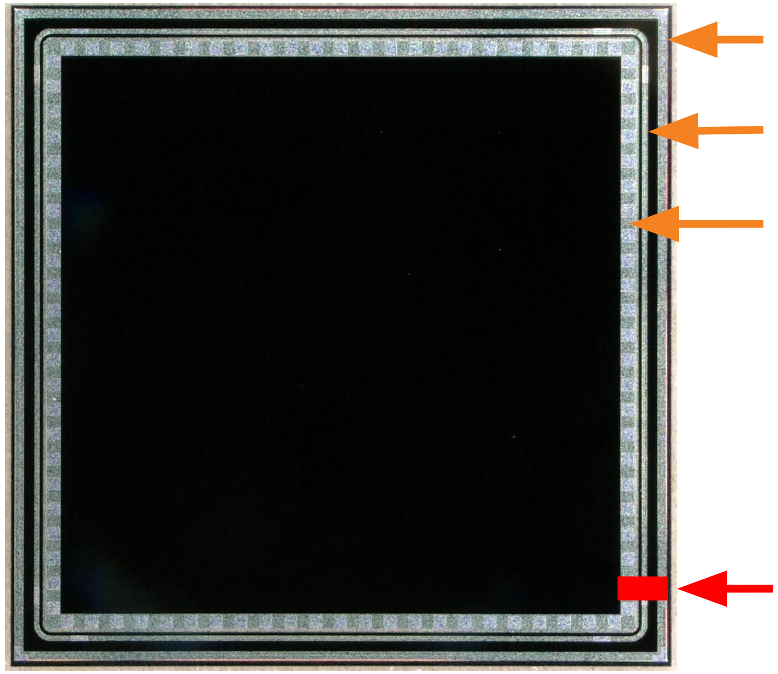




ATL-ITK-PROC-2022-009

- Large area sensors in ATLAS ITk showed humidity sensitivity => early breakdown
  - => can irreversibly destroy the sensor
- pn junction with reverse-bias => blocks current flow
  - small amount of current, called leakage current, can still flow through the sensor
- Region where breakdown happens: visible as bright spots

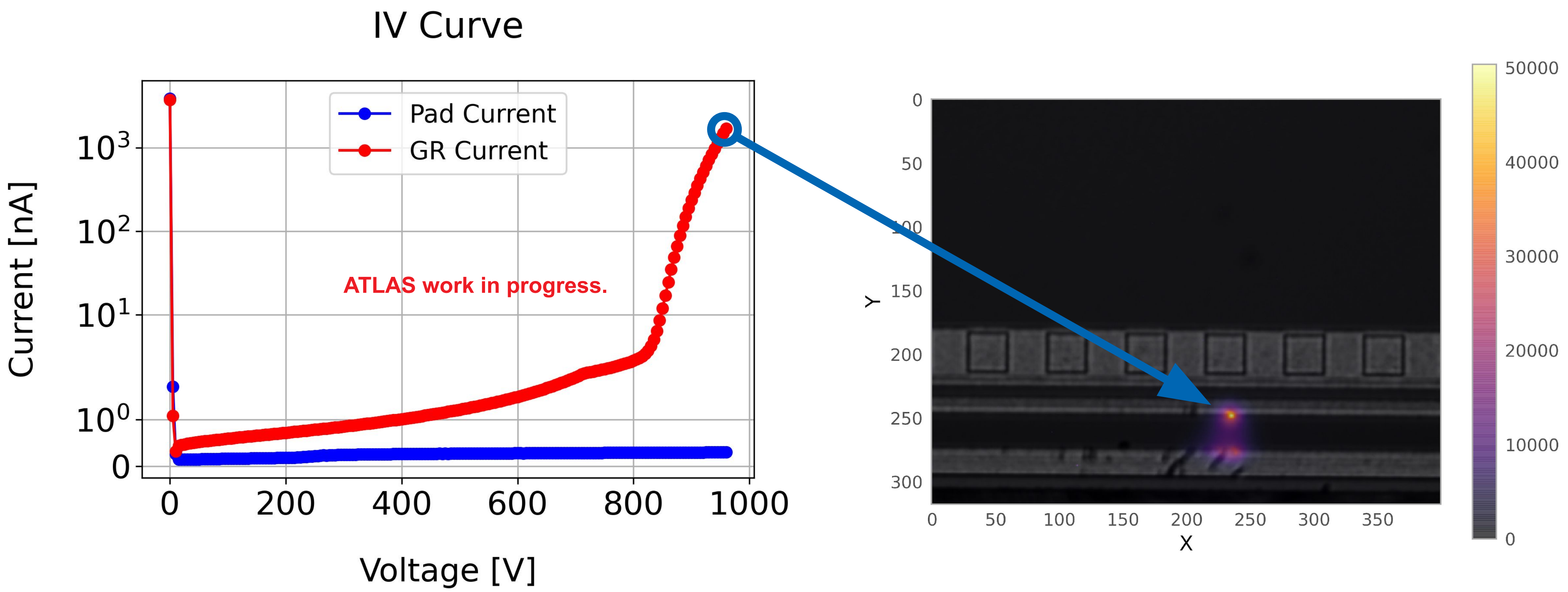
ATLAS18 Test Structures



- Test structures monitor the characteristics of silicon bulk
- Similar properties as the strip sensor
- More cost-effective to stress test than a large area sensor
- Goals:
  - Identify cause of the sensor's high humidity sensitivity
  - Develop a more robust geometry

- 8 mm x 8 mm $n^{+}pp^{+}$ (n-in-p) diodes (**MD8 diodes**)
- Active thickness ~ 296 µm
- Bulk doping: p-type concentration ~ 4.8×10^{12} cm^{-3}
- $V_{Full\ Depletion}$ = ~ - 330 V

Current – Voltage Characterization

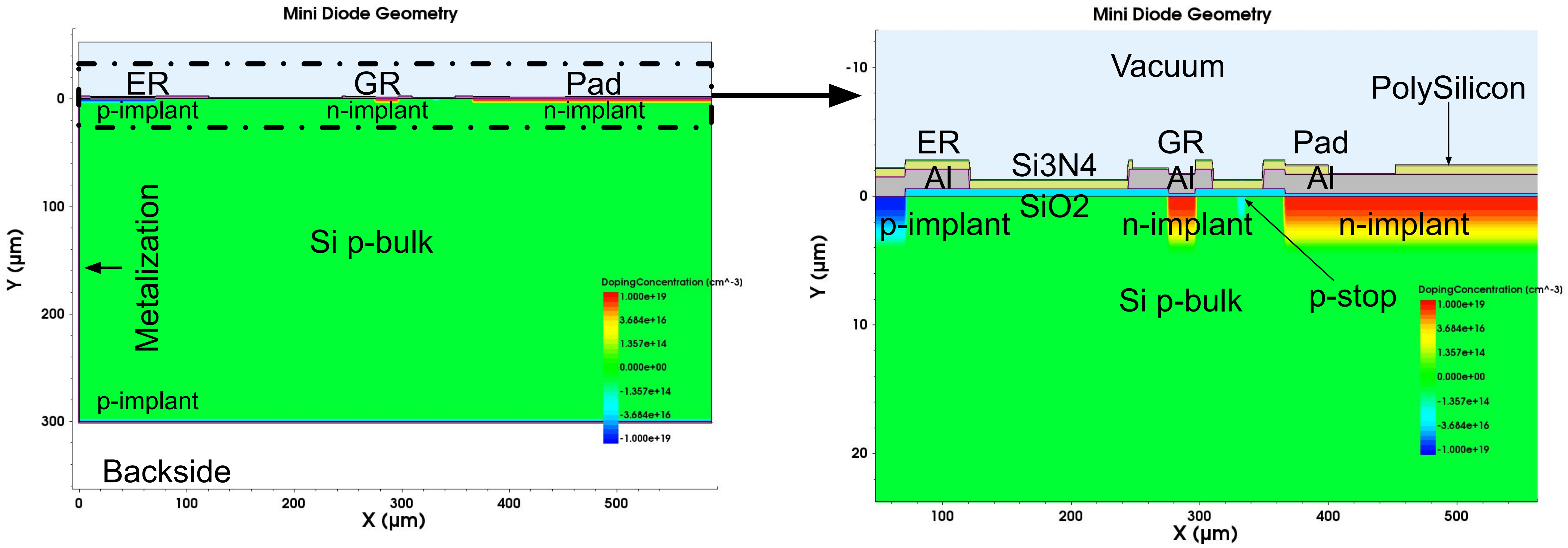


Measured GR and pad currents in respect to the applied bias voltage for RH = 36 % and T = 25° C. Breakdown at – 825 V.

Imaged hot electron emission at RH = 36 % and T = 25° C. V_{bias} = - 990 V.

Technology Computer Aided Design (TCAD) Simulations

- Sentaurus TCAD is a suit of software tools developed by **Synopsis**

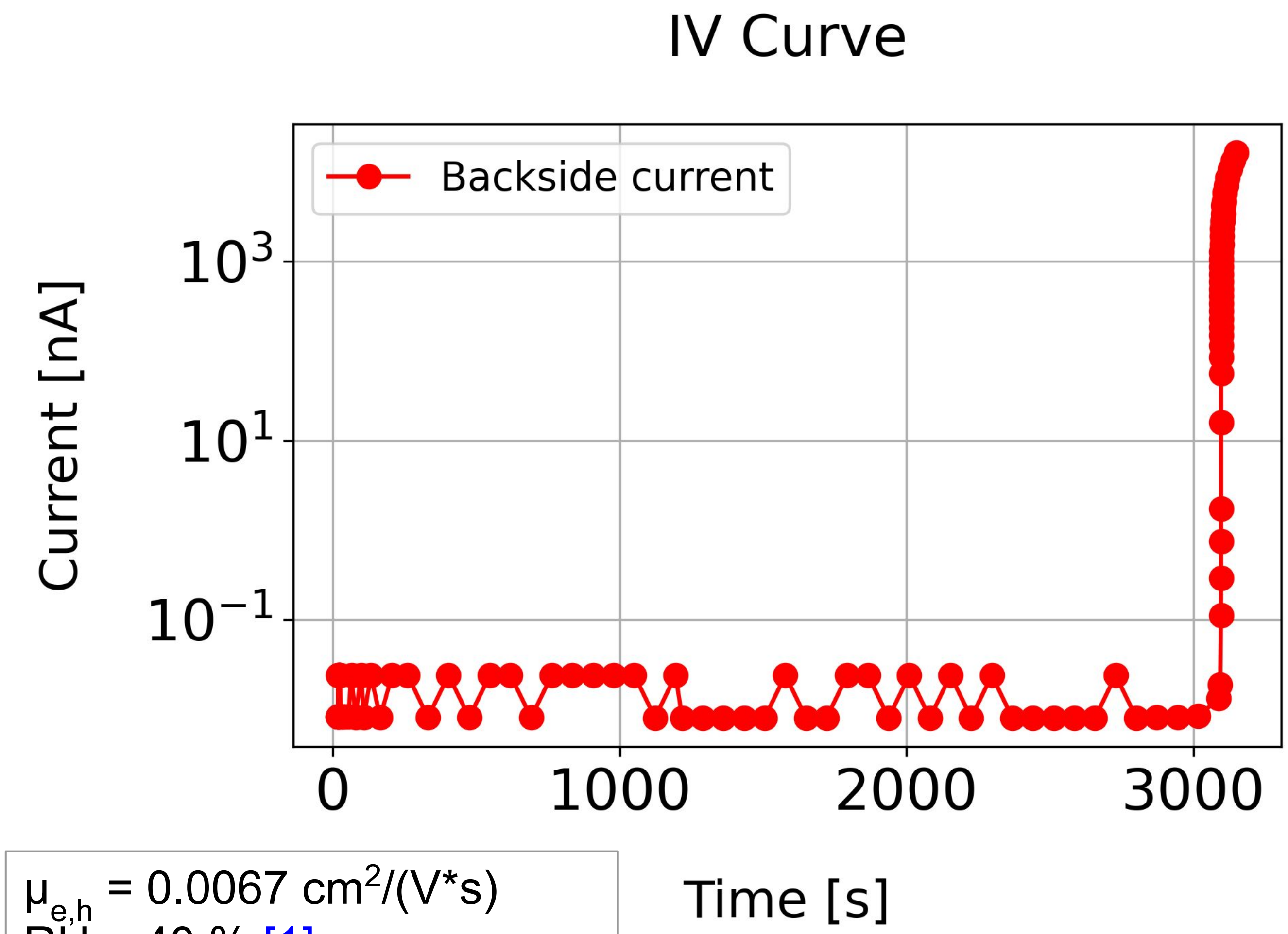


- 0.1 µm thick PolySilicon layer on top of the passivation
- GR and pad at ground
- - 900 V applied on the ER and backside

Mobile Charge at the Surface and TCAD Modeling

- During wafer manufacturing, charges can become trapped
  - For RH > 10 %, trapped charges become mobile
    - ⇒ can affect device characteristics such as threshold voltage, leakage current, and capacitance
- Modeling Mobile Charge in TCAD
  - TCAD utilizes advanced numerical techniques to simulate and predict the behavior of semiconductor devices
  - Mobile charge at the surface is modeled through surface potential and charge equations
  - Surface states and their energy levels are considered to accurately capture the impact of mobile charge
- TCAD Simulation Steps
  - Surface Potential Calculation:
    - ⇒ Solve Poisson's equation to determine the electrostatic potential at the semiconductor surface
  - Surface Charge Calculation:
    - ⇒ Utilize charge equations to compute the density and distribution of mobile charges at the surface
  - Iterative Process:
    - ⇒ The simulation iterates until a self-consistent solution is reached, considering the interaction between charge and potential

TCAD Results of MD8 Diode with p-stop



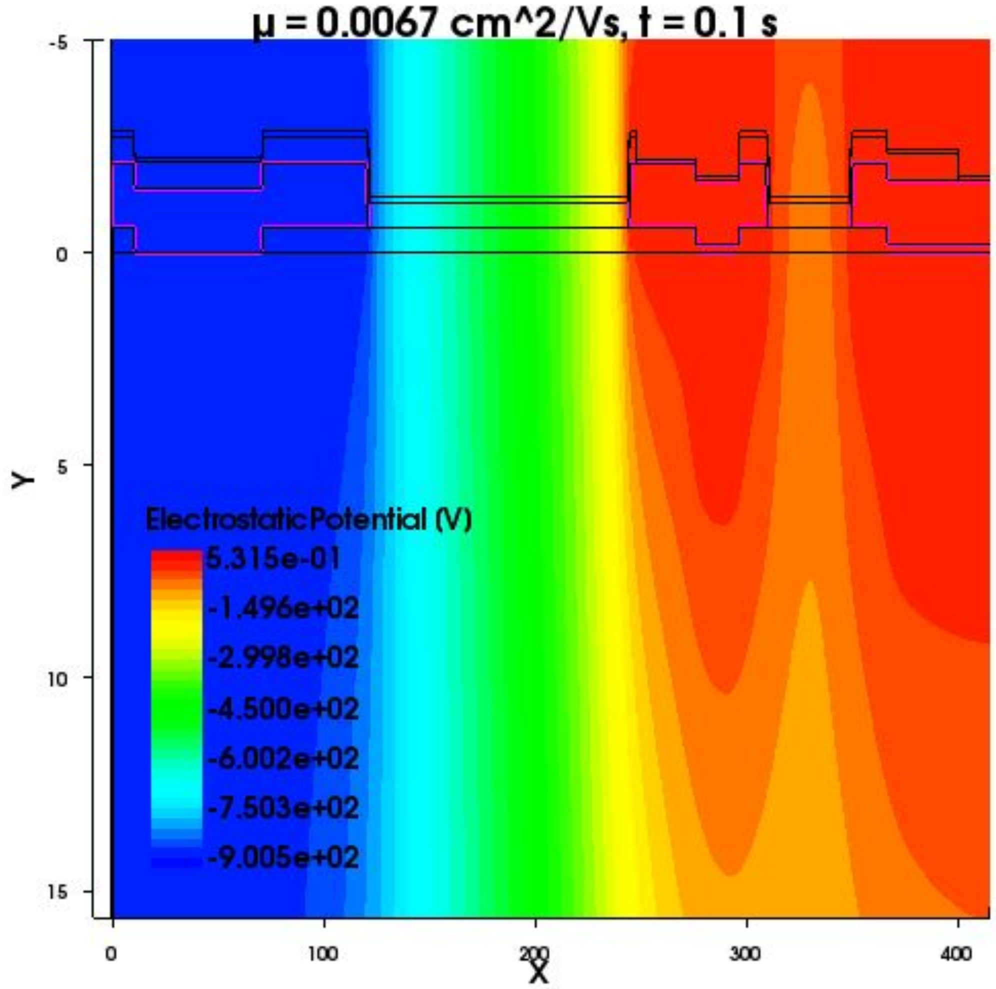
$\mu_{e,h}$ = 0.0067 cm^2/(V*s)
RH = 40 % [1]
V_{bias} = - 900 V

- For RH = 40 % and V_{const} = - 900 V, breakdown at 3097 s
- For dry conditions V_{const} = - 900 V, no sign of breakdown after 3 hours

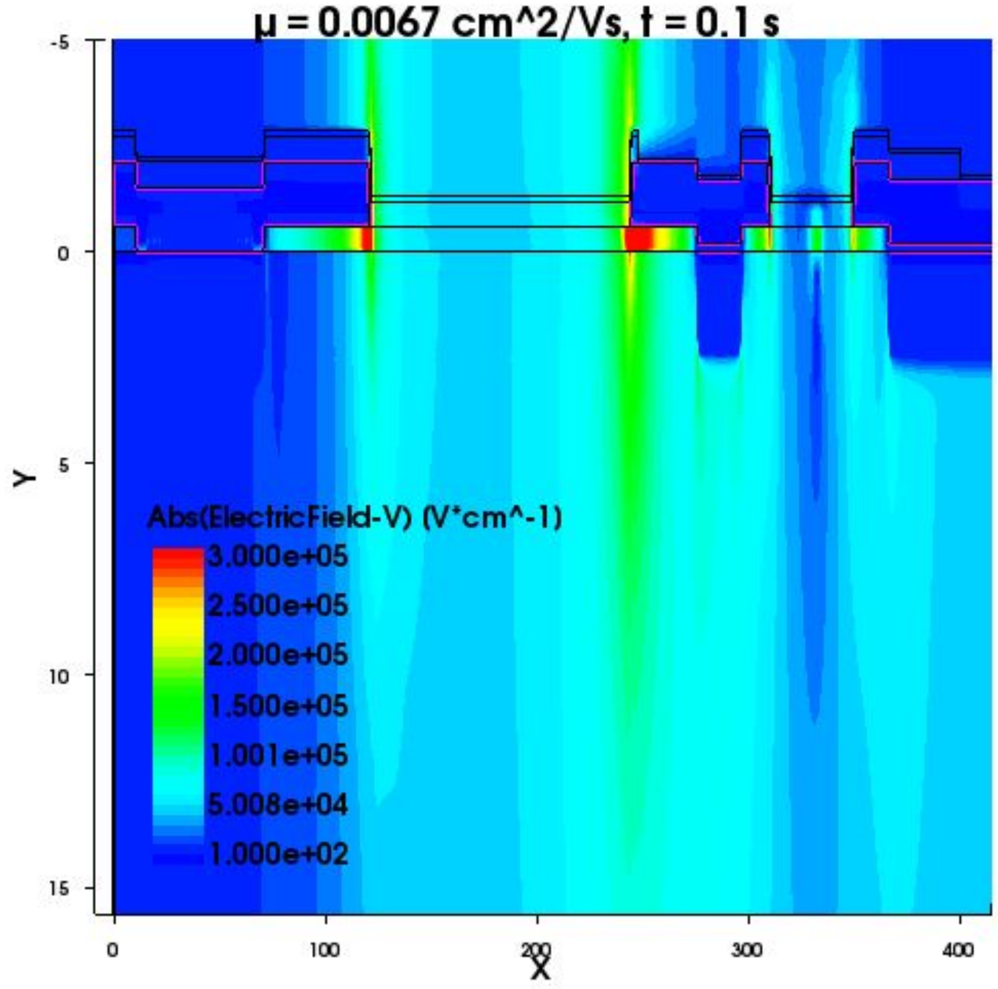
TCAD Results of MD8 Diode with p-stop

$\mu_{e,h}$ = 0.0067 $cm^2/(V*s)$
RH = 40 % [1]
V_{bias} = - 900 V

Electrostatic Potential (V)

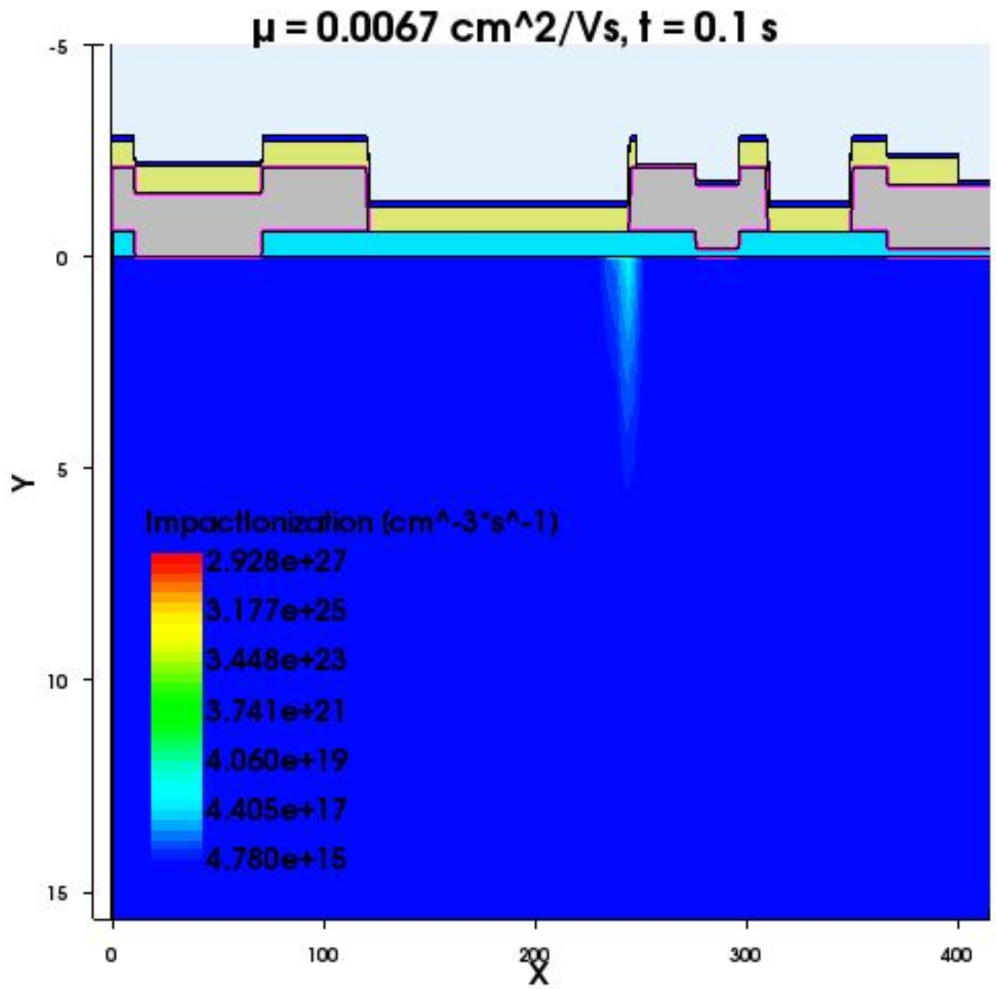


Electric Field (V*cm^-1)



TCAD Results of MD8 Diode with p-stop

Impact Ionization (cm^-3*s^-1)



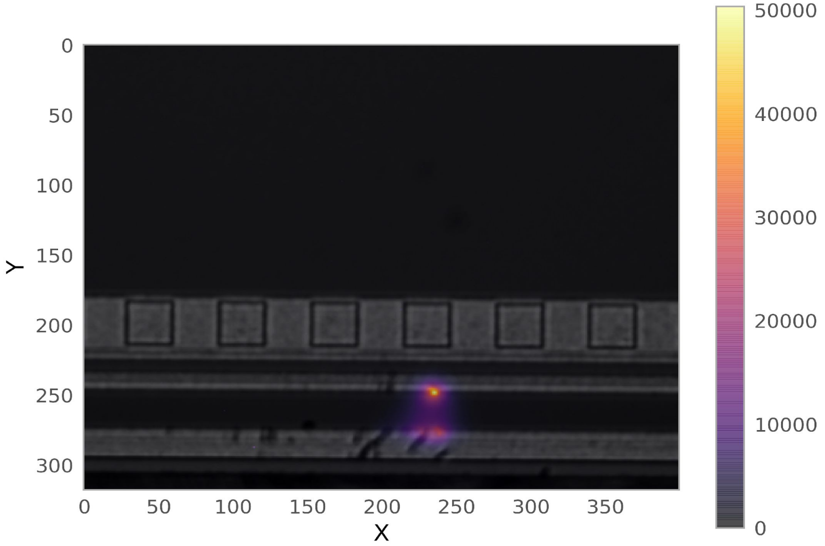
$\mu_{e,h}$ = 0.0067 $cm^2/(V*s)$
RH = 40 % [1]
V_{bias} = - 900 V
τ = 10^{-6} s
U = 4.78 × 10^{15} cm^{-3} s^{-1}

- Charge spread between GR and pad ⇒ possibility of a short
- High electric field near ER and GR ⇒ high chances of hot electrons to be emitted

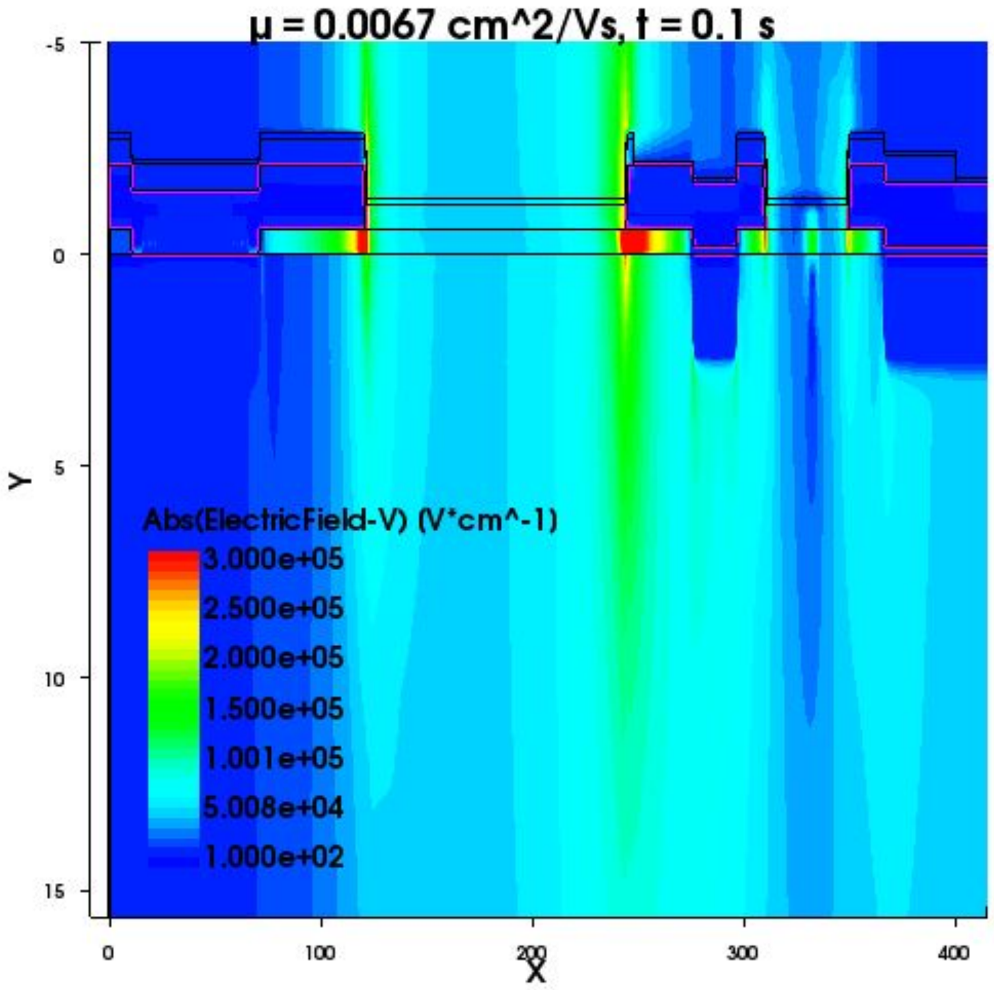
Hot Electron Emission

- Photo-emission mechanisms in semiconductors:
  - radiative recombination involving both carrier types (conduction band to valence band)
  - radiative transitions which involve one type of carrier (conduction/valence band to conduction/valence band)

- High electric field
  - accelerated free electrons -> hole electron pairs formation -> increased current -> avalanche breakdown



RH = 36 %
T = 25° C
V_{bias} = - 990 V
$I_{leakage}$ = 2 μA
Exposure = 60 s



Top Transient Current Technique (Top-TCT)

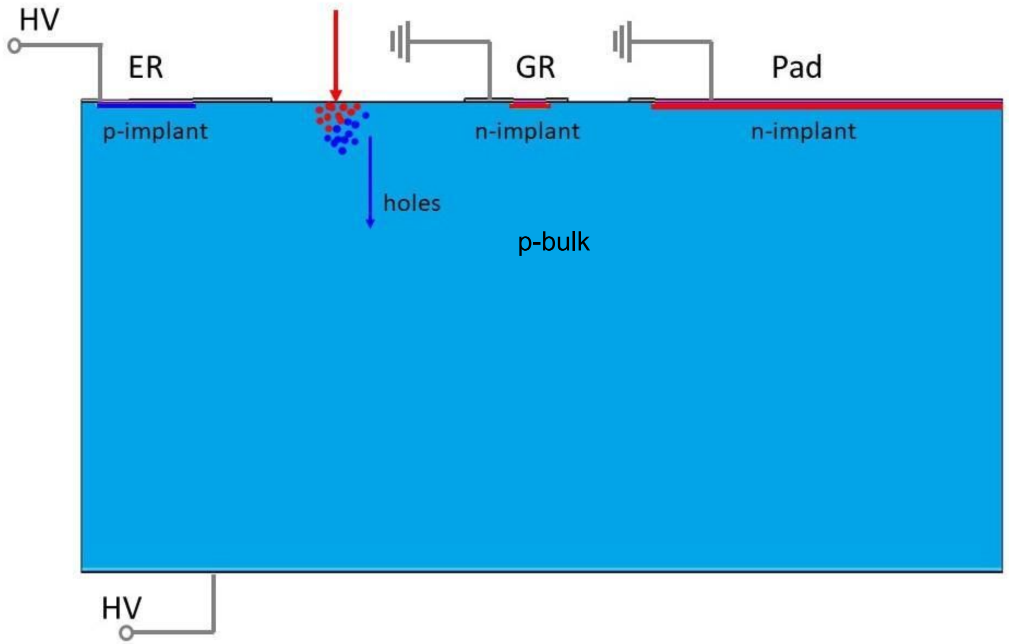
- Employ Top-TCT to investigate EF near GR region
- Method: red laser illumination (λ = 660 nm) from top
- Measure: transient current generated by the electron-hole pairs drift:

$$I_{e,h}(t) = A\, e_0 N_{e,h} \vec{v}_{e,h}(t) E_w(y) = const\, \vec{v}_{e,h} E_w(y)$$

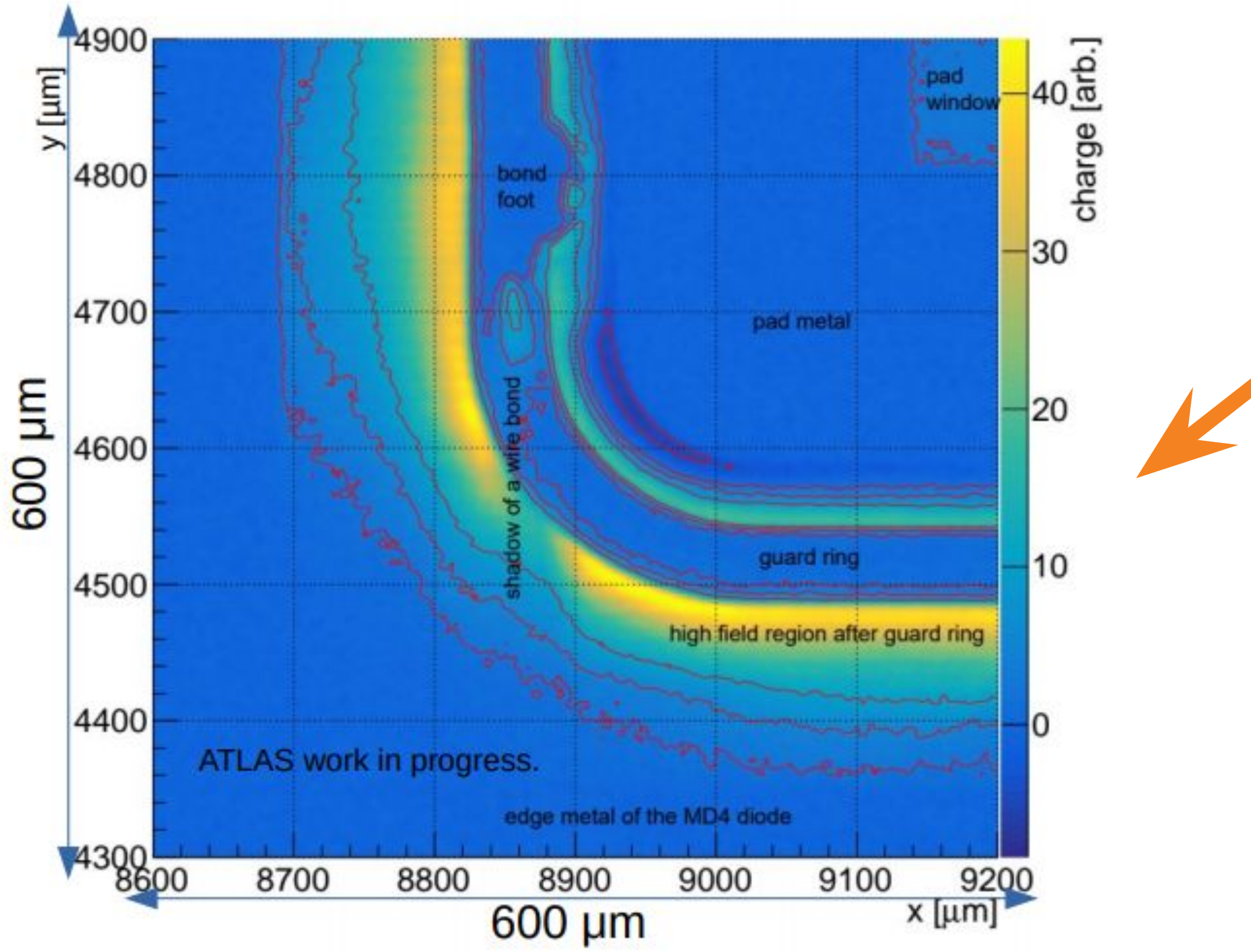
- The amplitude of the current after charge formation can be calculated with:

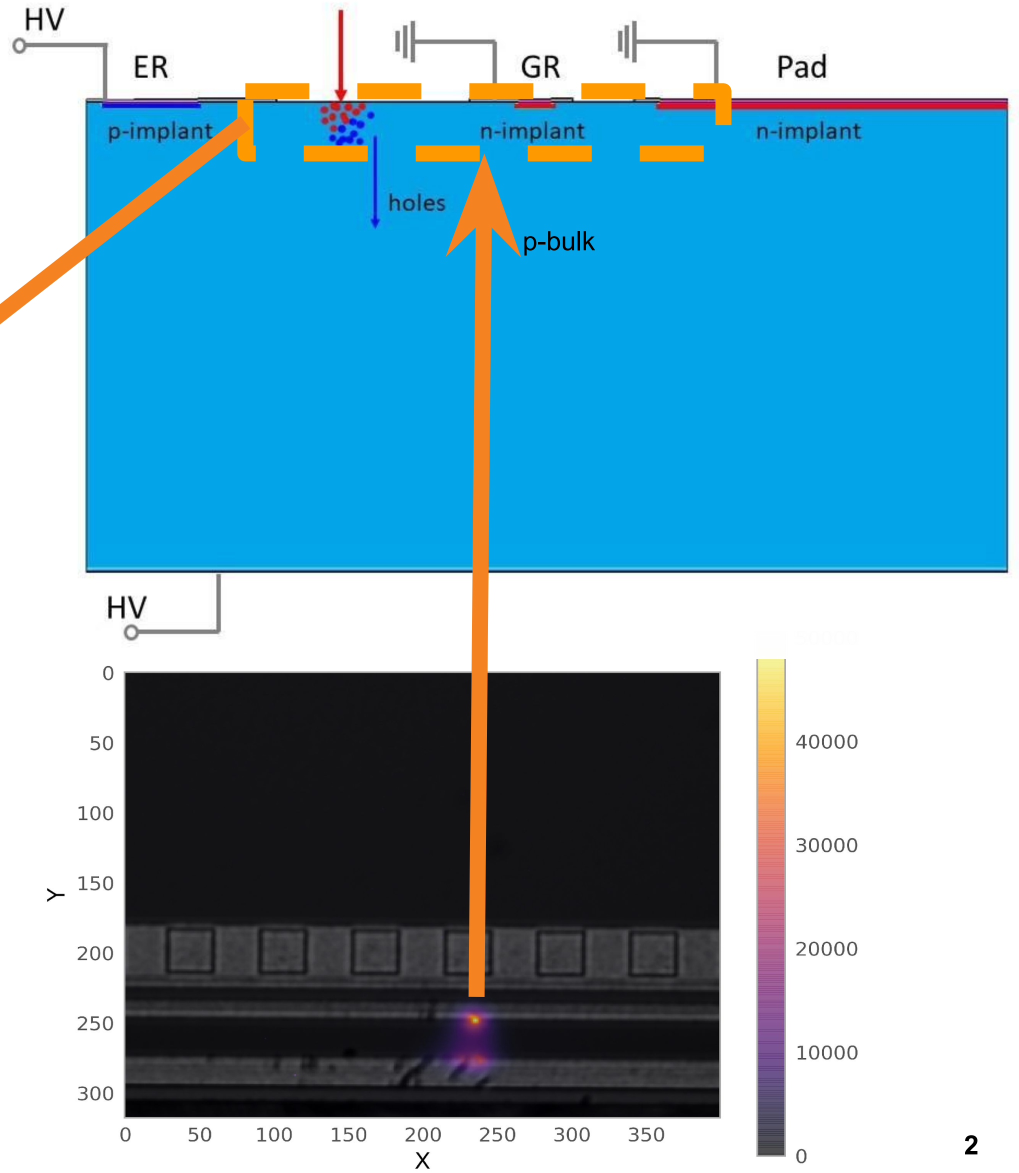
$$I(y, t \sim 0) = const\, \mu_{e,h} E_W(y) E(y)$$

- e_0 = elementary charge
- $N_{e,h}$ = number of created e-h pairs
- $v_{e,h}$ = drift velocity
- $\mu_{e,h}$ = mobility
- $E_w(y)$ = weighting field



Top Transient Current Technique (Top-TCT)





- - 500 V applied on the back
- Temperature and RH at room

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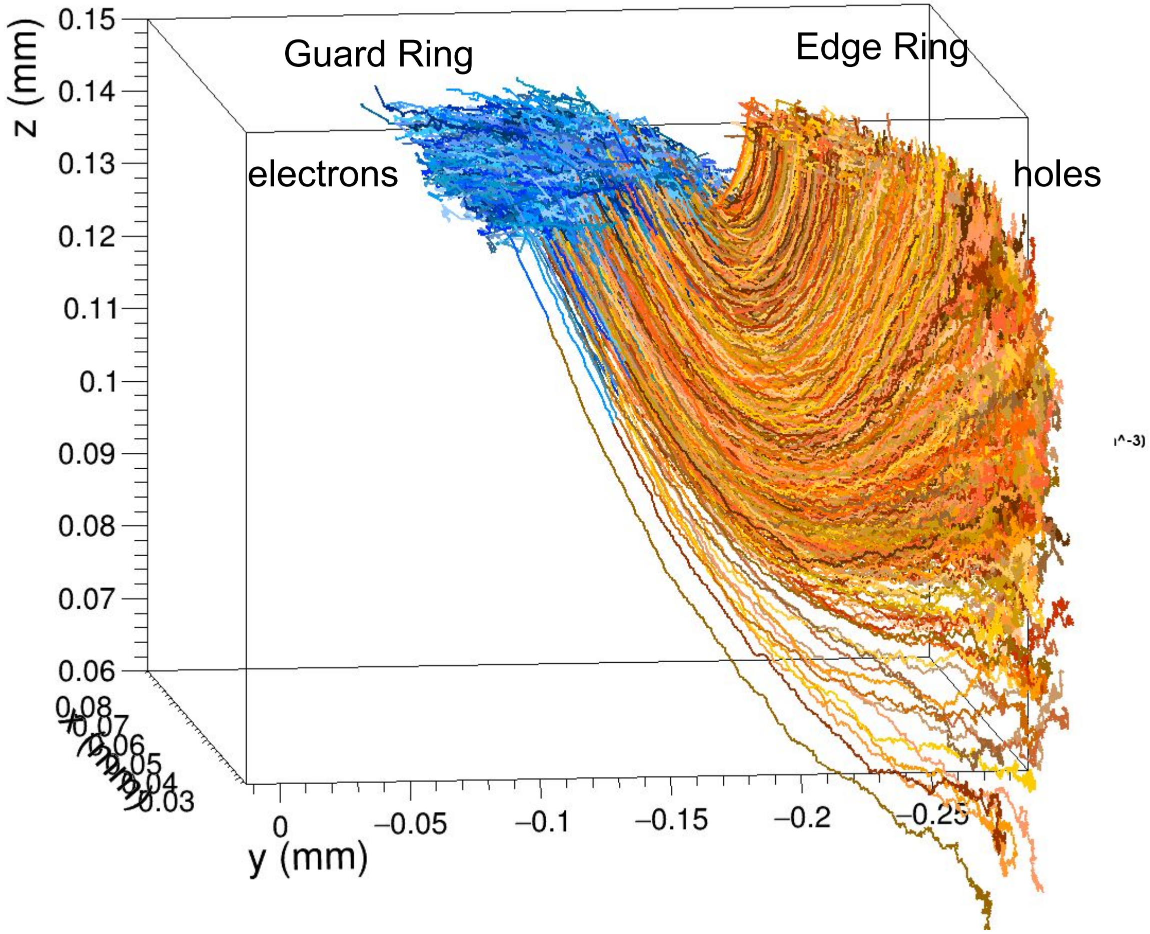
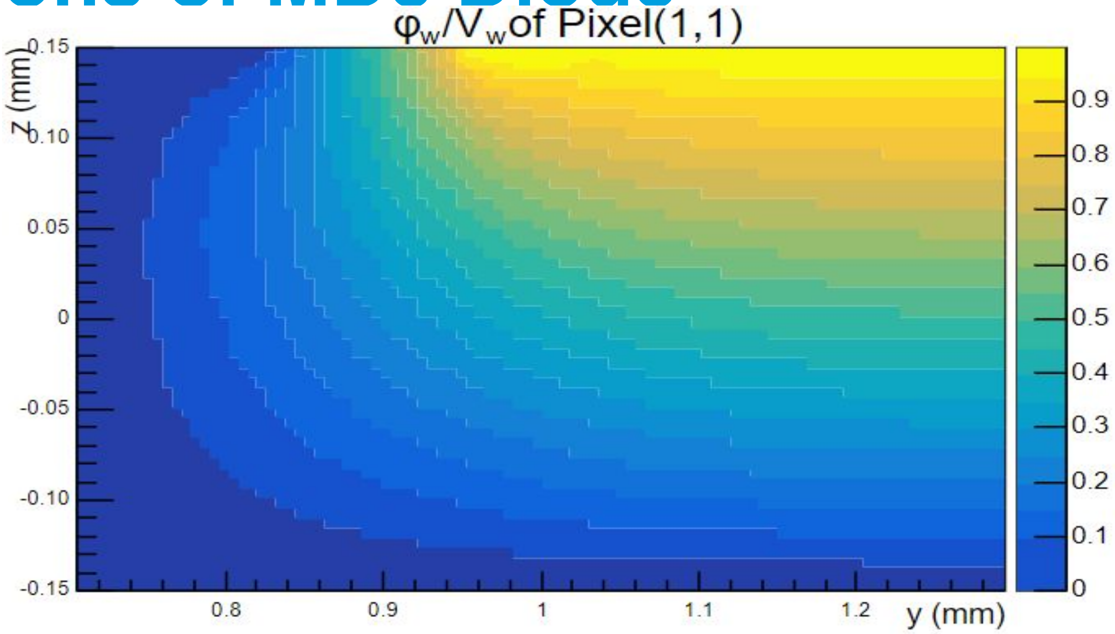
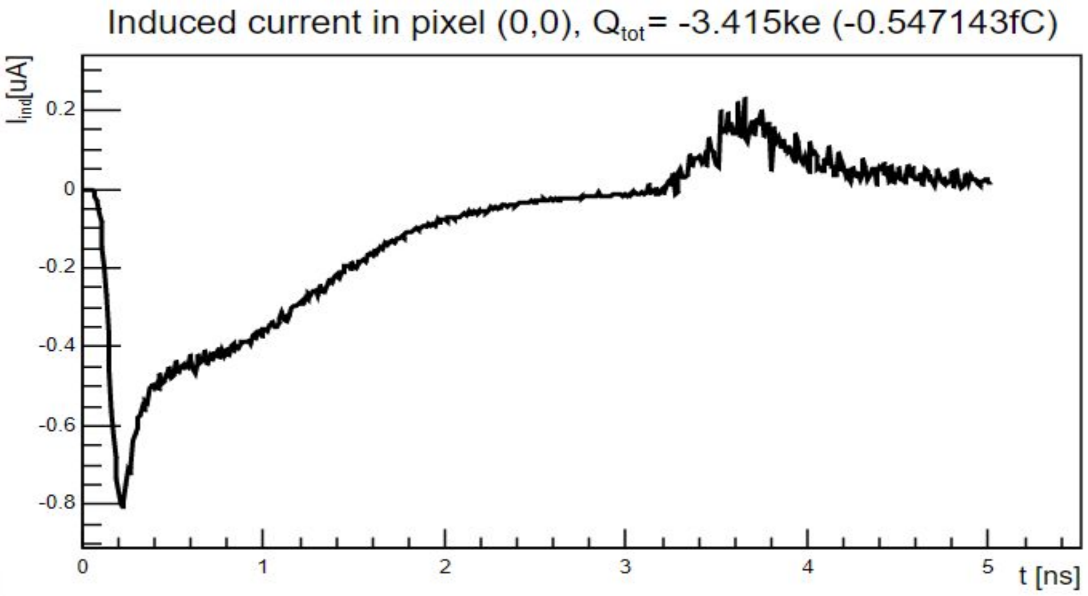
Allpix Squared Top-TCT Simulations of MD8 Diode







Outlook

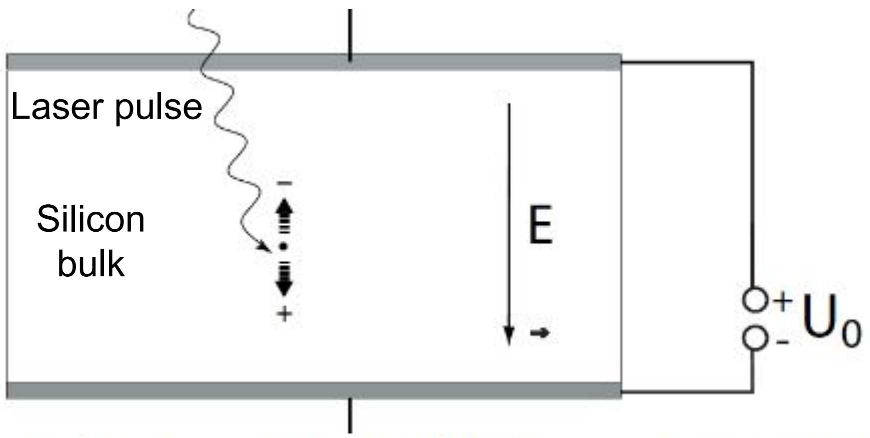
- Can image hot electron emission using a near-IR camera
- TCAD simulation seems to estimate hot carrier emission and TCT measurements in first comparison
- Allpix Squared simulations provide comparable results to experiment
- Next steps:
  - Take multiple pictures over a long period of time to study the evolution of the hot electron emission
  - Systematically compare TCAD results with lab measurements
  - Try to estimate Electric Field from Top-TCT measurements
  - Have a systematic study for several sensors at different humidity values

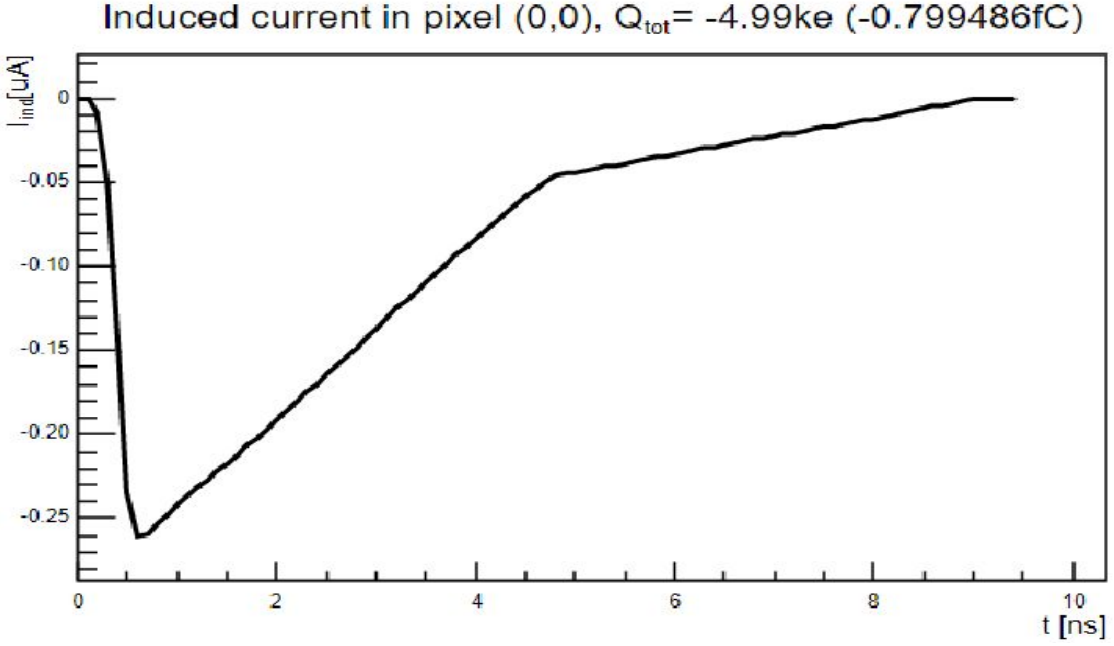
Thank you!

Back up

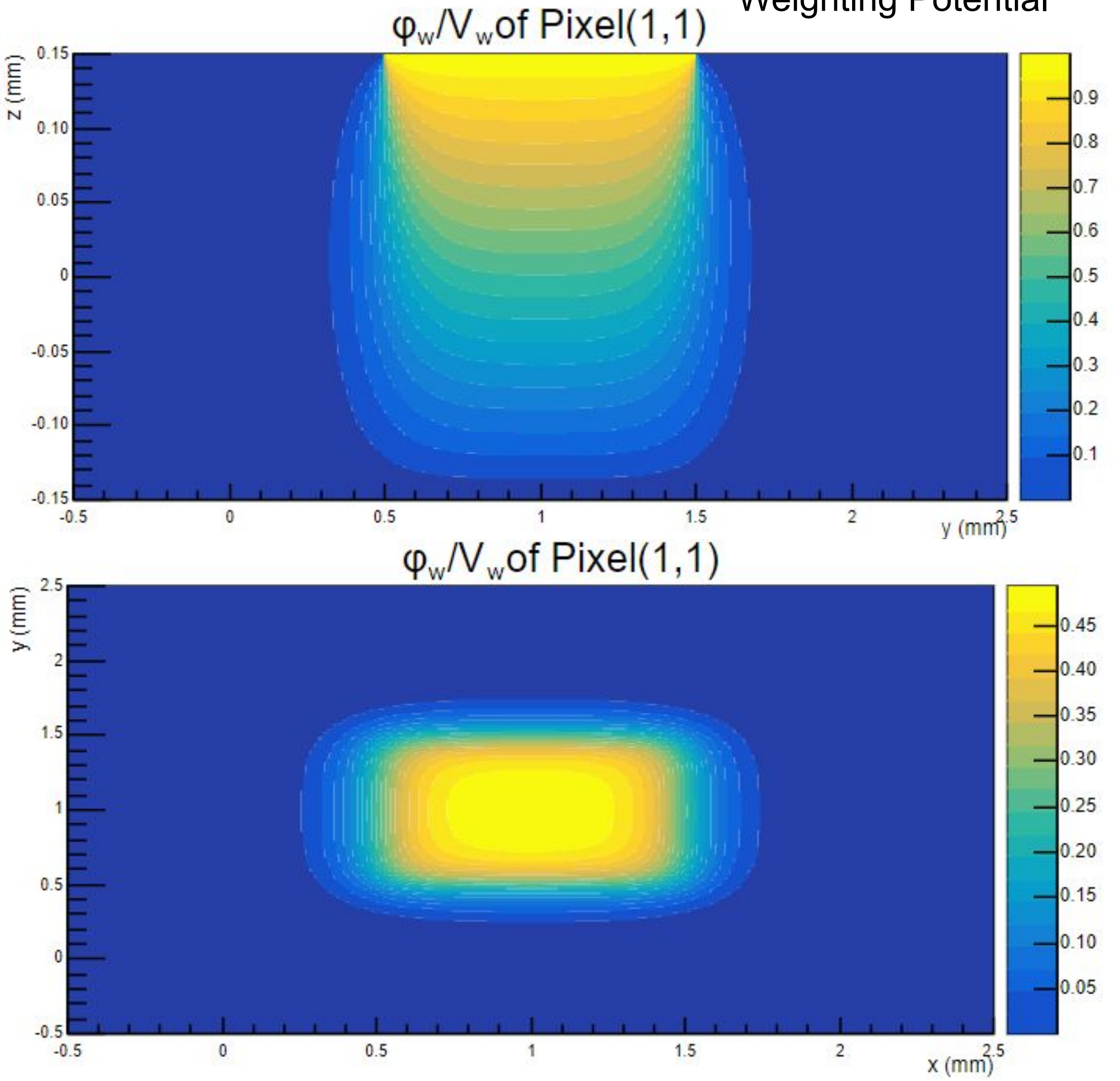
Allpix Squared Top-TCT Simulations of a Simple Diode

Simple diode geometry





Weighting Potential



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