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Simulations of Vertical GaN Diode Performance Under Electron Beam Radiation Exposures

PRESENTED BY

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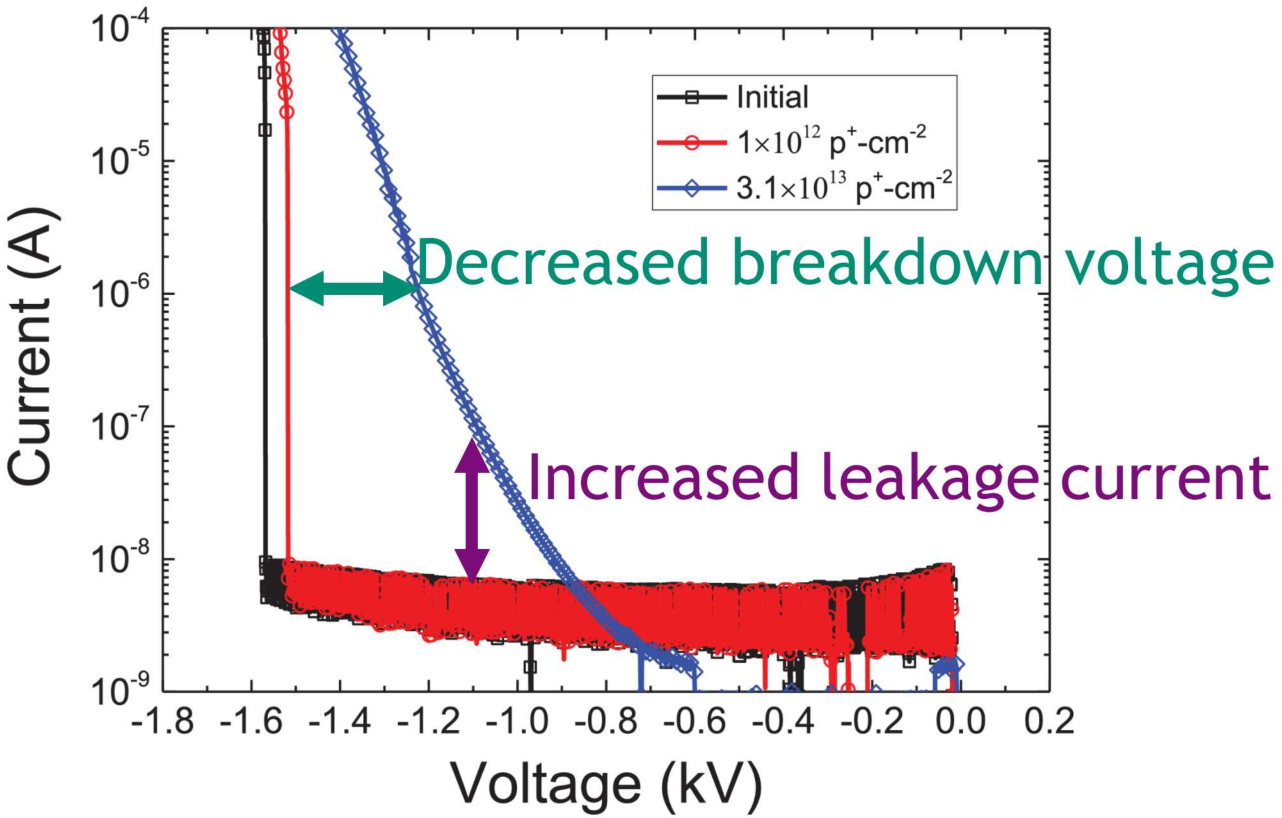
SAND2019-13952 C

What does radiation damage mean in semiconductors?

<u>Cumulative Effects</u>

- Total ionizing dose
- Displacement damage
  - Trap creation (carrier recombination)
  - Degraded performance



I-V curve for GaN vertical diodes exposed to proton fluences illustrating voltage breakdown and leakage current degradation

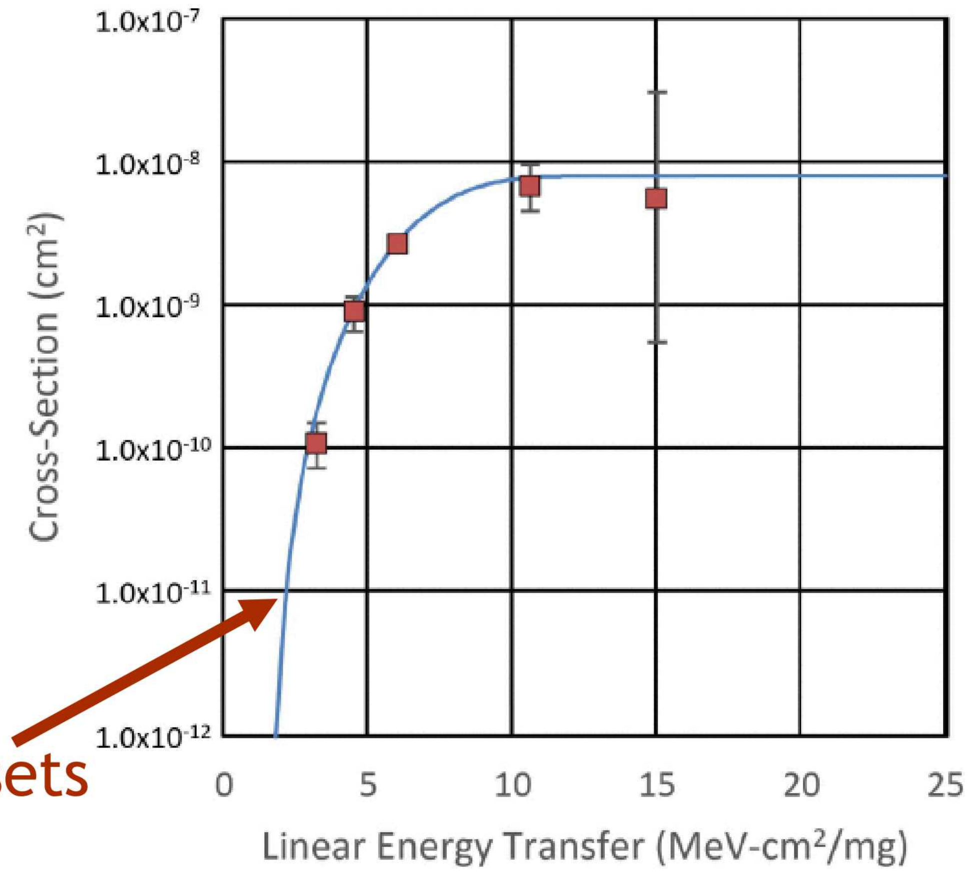
King, Armstrong, et al., *IEEE Transactions on Nuclear Science*, **62**, 2015

What does radiation damage mean in semiconductors?

Transient Effects

- Dose rate effects
- Single event effects
  - Charge carrier generation
  - Bit flips, single event latch-up or burnout

Onset energy of single event upsets



Cross section for 16 nm Xilinx flip flop upsets, per bit, from heavy ion irradiation

Lee, King et al., *IEEE Radiation Effects Data Workshop,* 2018

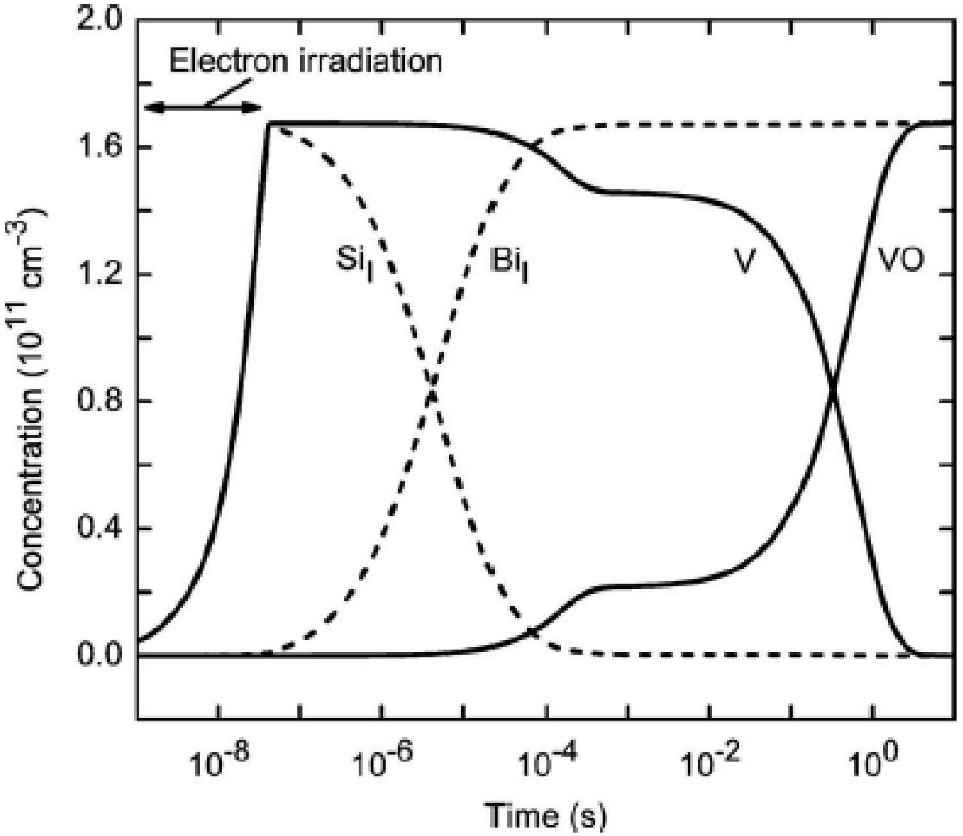
Gallium Nitride (GaN) devices have demonstrated success as radiation-hardened power diodes

	Si	GaN
Band gap at 300 K (eV)	1.1	3.4
Charge carrier generation (eV)	3.6	10.0
Direct/indirect?	Indirect	Direct
E_d (eV)	12.5	20.5 (Ga) 10.8(N)

GaN HV power diodes:

- Higher theoretical performance (Figure of Merit) than Si, GaAs, or SiC
- 4 kV breakdown voltage
- 3-5 MV-cm^{-1} Critical electric field
- 1-2 mΩ-cm^2 On resistance
- < 10% change in breakdown voltage from proton fluences < 10^{13} cm^{-2}

Our objective: Apply exploratory physics modeling approaches exploring defect evolution in gallium nitride

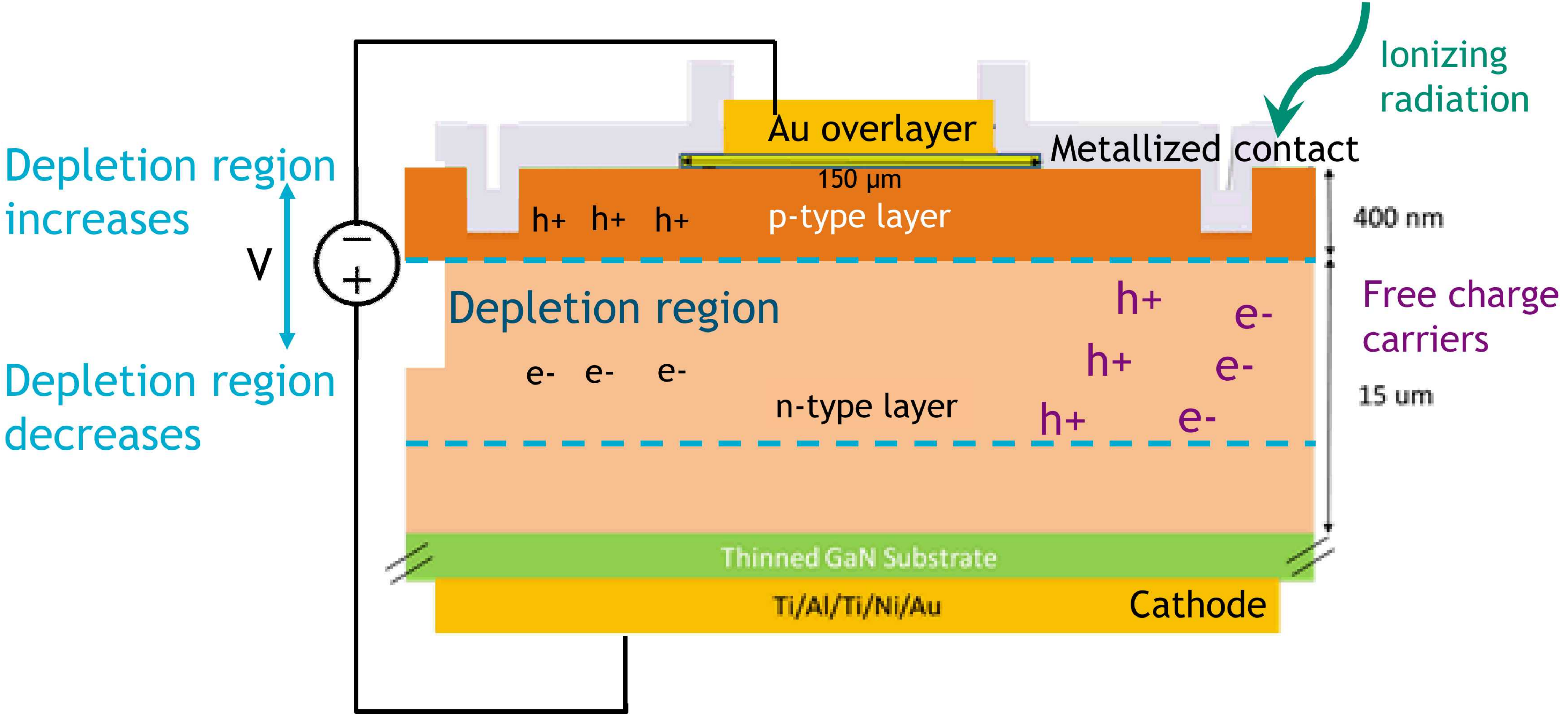


Previous efforts have been successfully applied to exploring time-dependent defect concentrations for electron-irradiated Si.

- GaN defects not well-understood
- Defect evolution not incorporated in commercial modeling software
- **What defect physics and mechanisms are most significant for higher-order device or circuit models?**
- **Initial goals:**
  - **Compare baseline response with unexposed power diodes**
  - **Validate device response to ionizing dose (no displacement damage)**

Myers, Cooper, and Wampler, *Journal of Applied Physics*, **104**, 2008

Model physics—Device geometry is a simple p-n junction



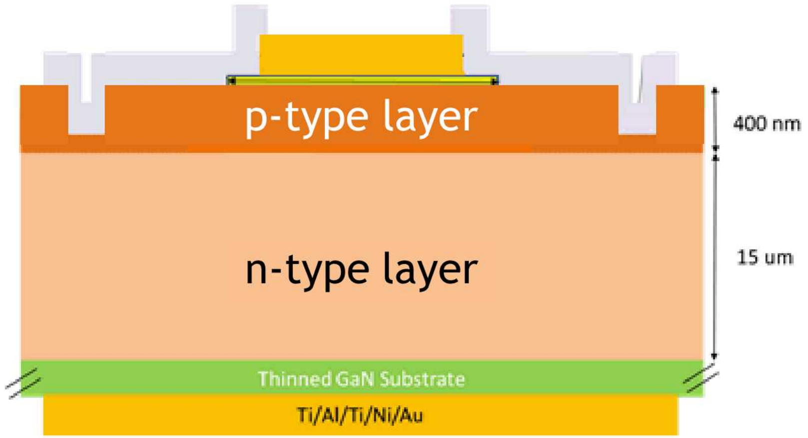
Model physics—carrier transport

- Numerically solves coupled 1D ODE's for charge carrier transport:

$$\frac{\partial n_i}{\partial t} = \vec{\nabla} \cdot \left(-\mu_i n_i \bar{F} - \frac{kT}{q} \mu_i \nabla n_i\right) + generation\ - recombination \qquad \text{(Drift-Diffusion)}$$

$$\nabla^2 \varphi = -\frac{(n-p+N_D-N_A)}{\varepsilon_s} \qquad \text{(Poisson's Equation)}$$

- Solved carrier transport → device field structure
- User-defined material parameters tailored to device design
- User-defined radiation fields and defect concentrations

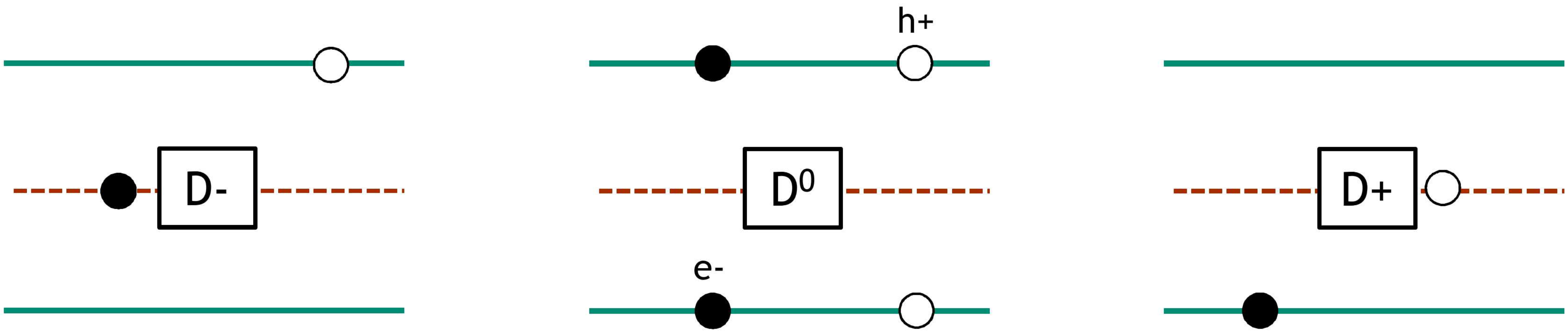


Device area >> depth

Sandia vertical power p-n diode

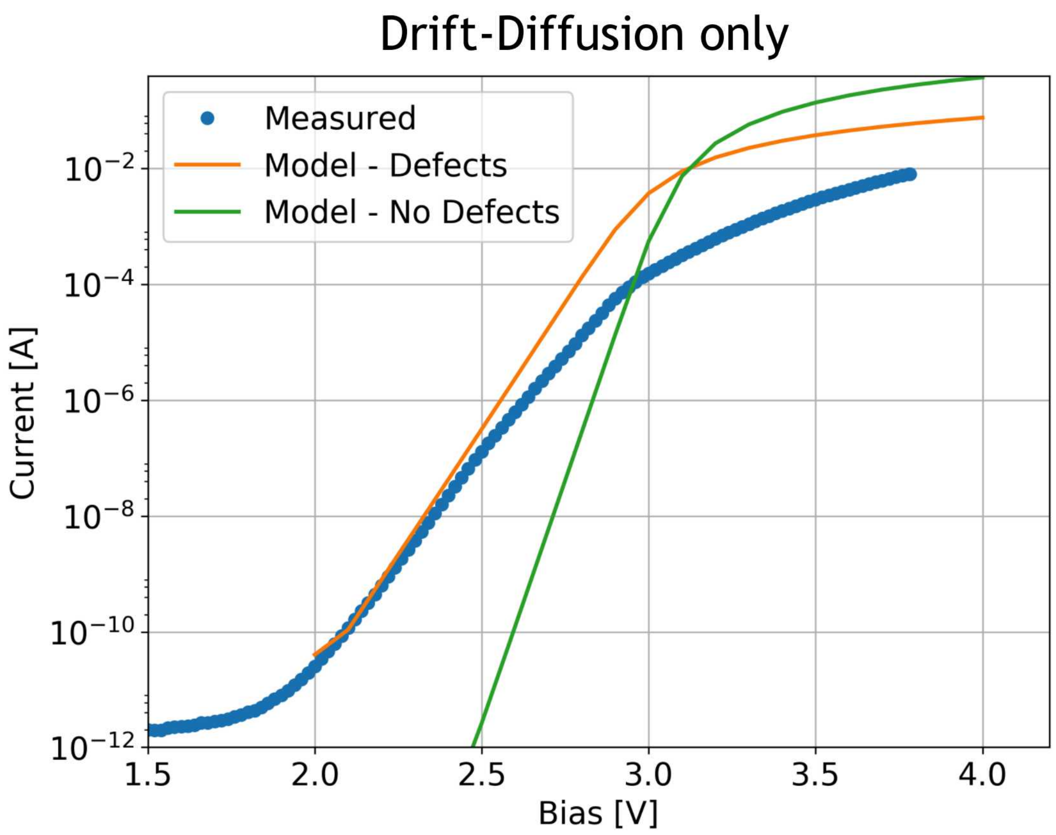
Model physics—how do we deal with defects?

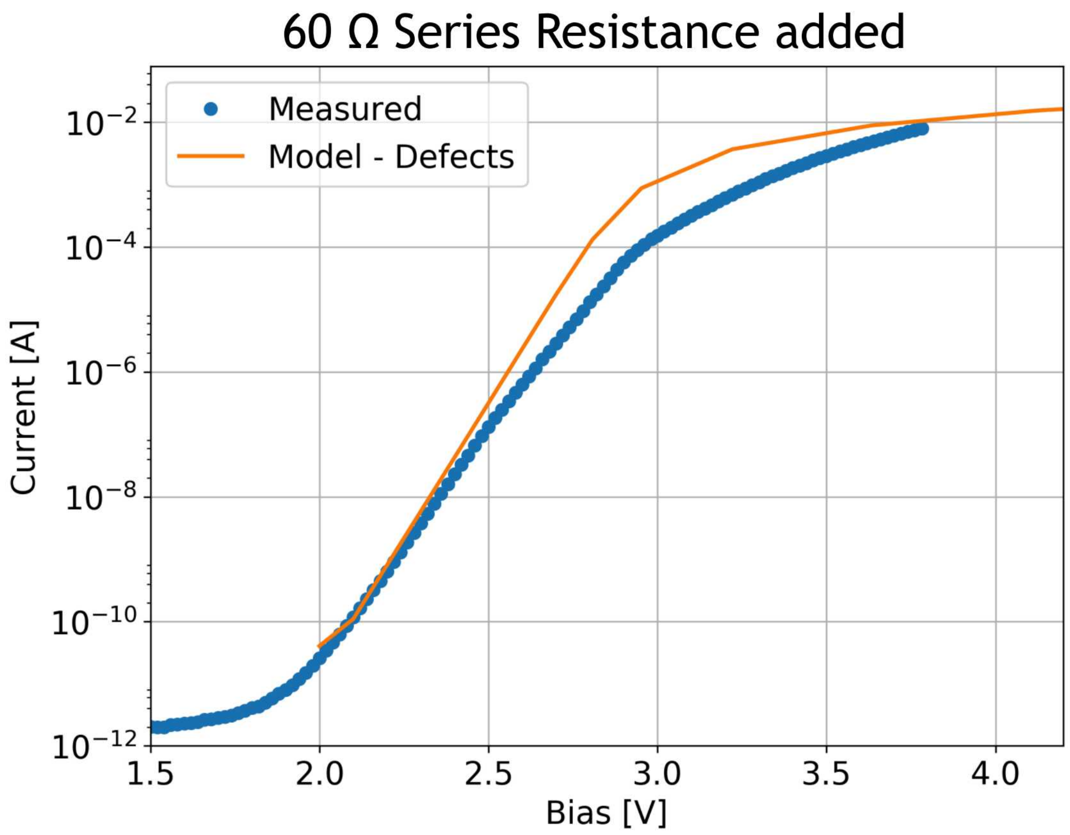
- Assumes single generic defect at single energy (adjustable, assumed mid-band)
- 3 generic charge states: D^-, D^0, D^+



- Track concentrations of e, h, D^-, D^0, D^+ vs depth and time:
- Carrier-Defect reaction rates calculated alongside coupled Drift-Diffusion and Poisson's equations

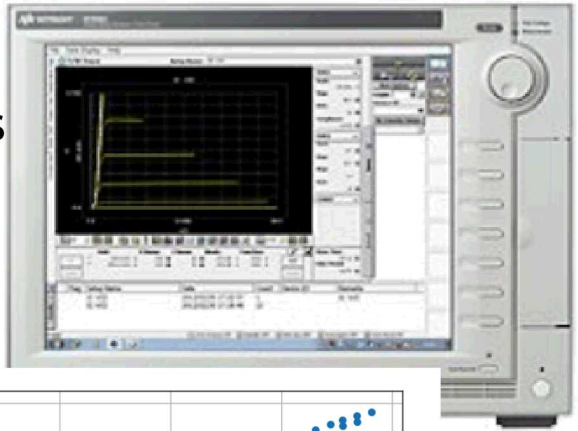
Treatment of defects was significant in establishing a matching baseline comparison to forward-biased experiment in ideal diode regime

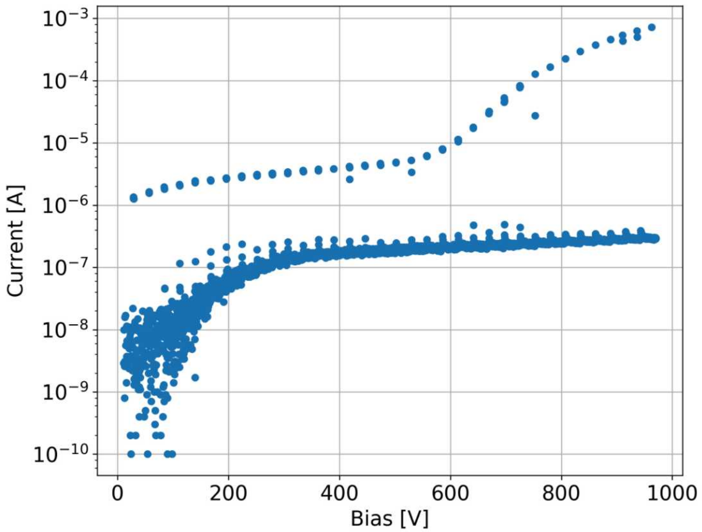


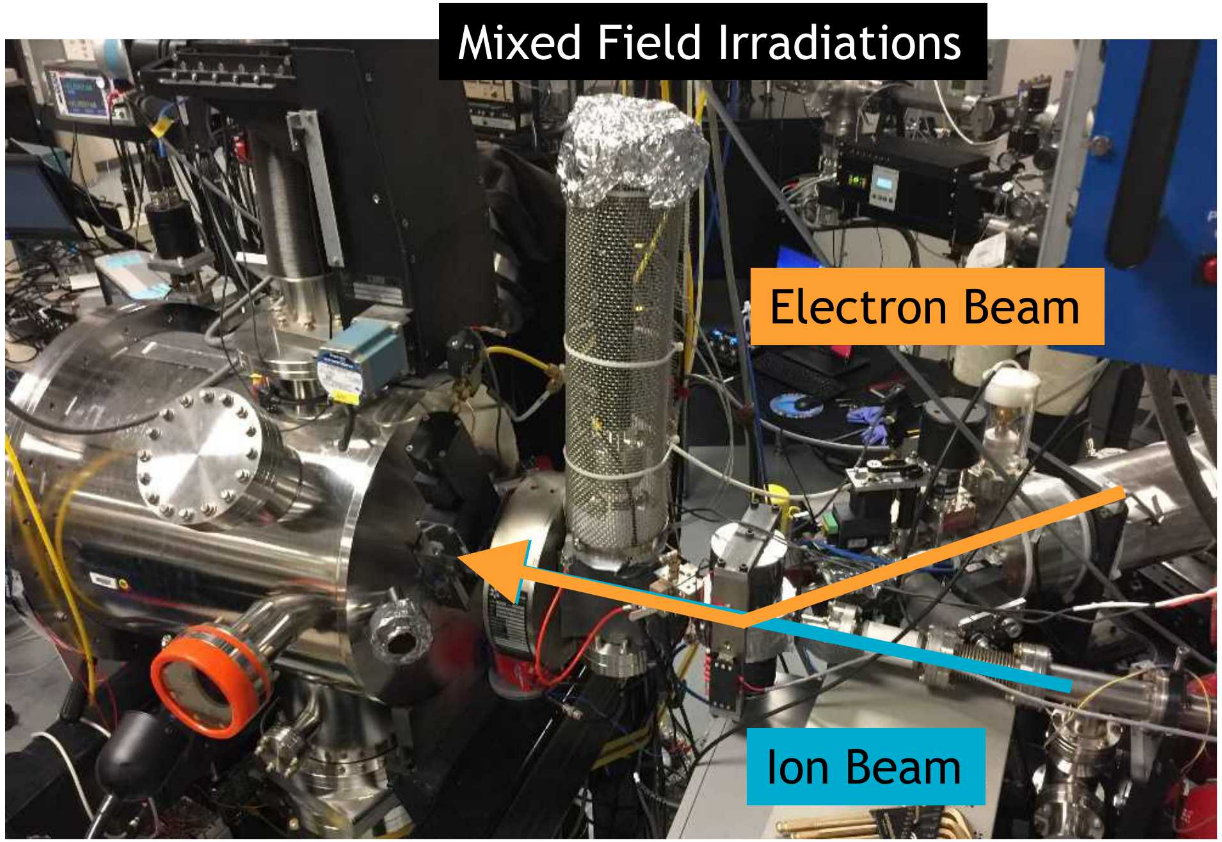


Benchmarking experiment measures photocurrent response to electron beam, simulating Compton electron generation from gamma irradiation

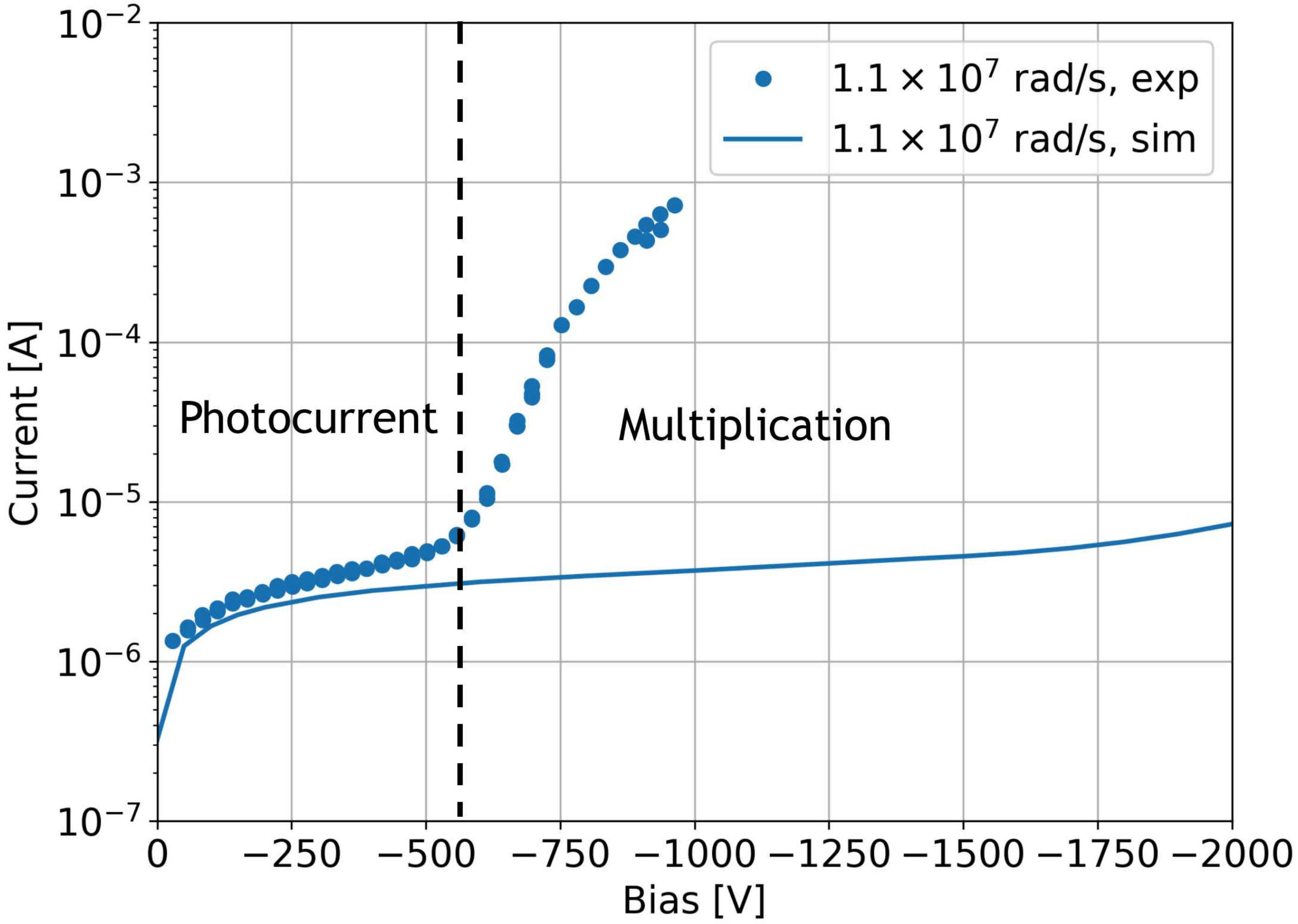
Parameter analyzer for IV measurements



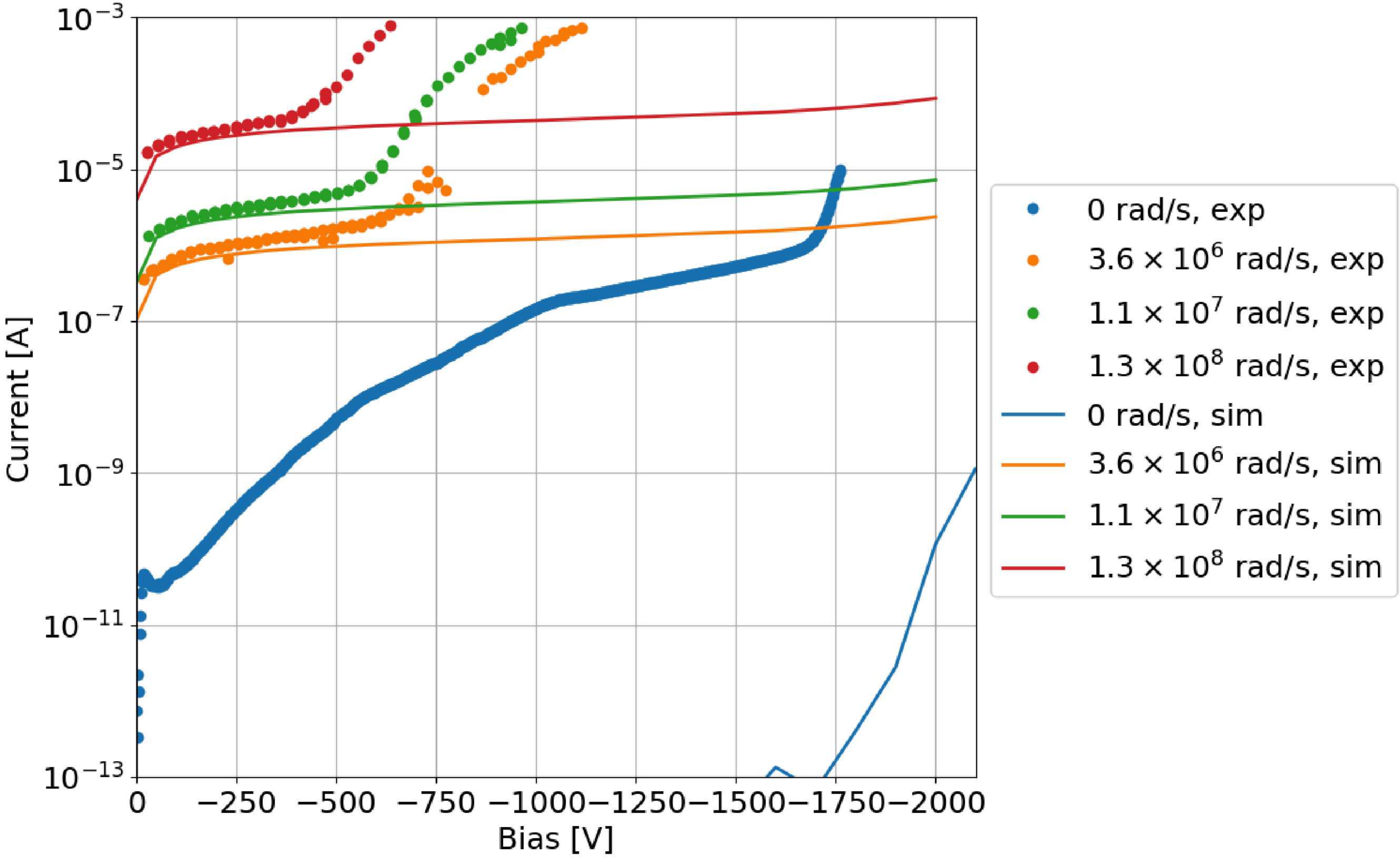




Real devices demonstrate two photocurrent response regimes when exposed to ionizing radiation. This phenomenon is not properly modeled by impact ionization alone.



Increased dose rate results in the onset of multiplication at lower biases.



What could we be missing?

- Space-charge limited conduction breakdown mechanisms
- Multiple defects/ GaN-specific defects
- Higher-dimension geometries/ field structures

Where are we going next?

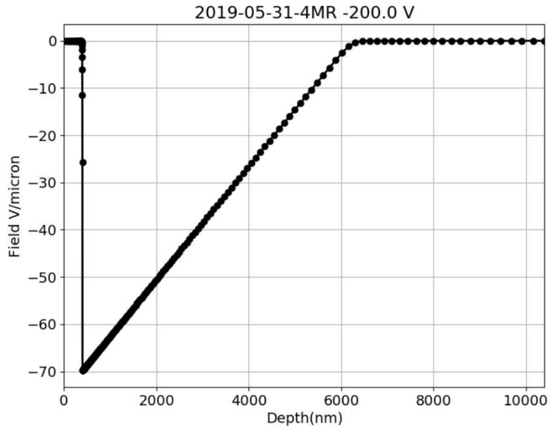
- Exploration of breakdown mechanisms
- Role of defects from heavy ion radiation or neutrons and photocurrent to be explored
- Mixed field models and experiments

Conclusions

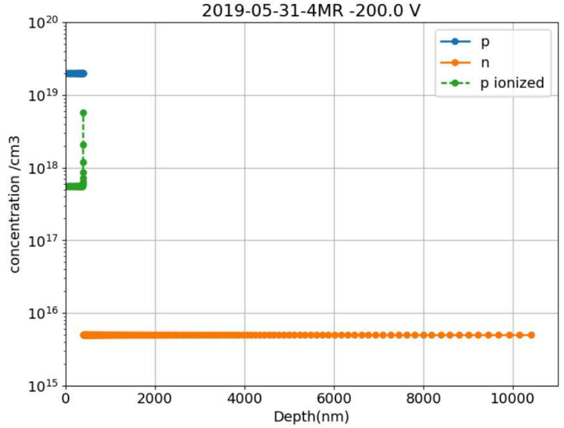
- An exploratory physics code examining defect evolution in GaN is being developed
- Near-term objectives:
  - Compare baseline electrical response of real GaN power diodes
  - Validate radiation response under pure-ionizing dose (no displacement damage)
- Successes:
  - Baseline agreement for forward-biased devices
  - Near-agreement in breakdown voltage for baseline reverse-biased devices, but no leakage current
  - Strong agreement with experiment for photocurrent response in low-biased regimes

Further understanding of device physics enabled by examining depth profiles

Electric Field



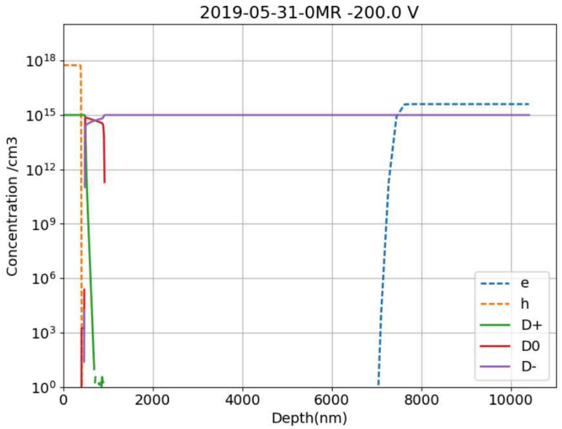
Doping Concentrations

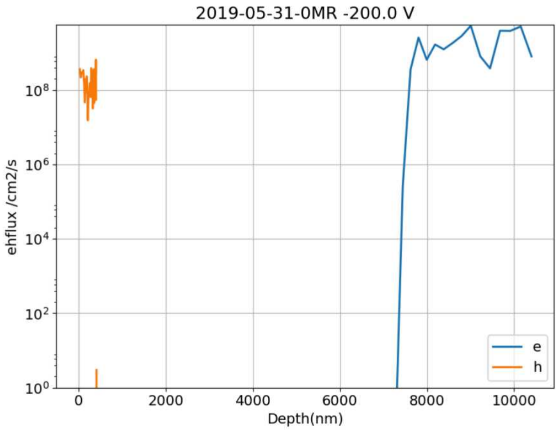


Carrier/Defect Concentration Profiles

Carrier Flux Profiles

No radiation





Radiation