SAND2020-3155C

Exploratory Modeling of Radiation-Induced Photocurrent Response in Vertical GaN Diodes

PRESENTED BY

Matthew J. Jasica, William R. Wampler, Barney L. Doyle, Gyorgy Vizkelethy, Gregory W. Pickrell, William Cowan, Albert Colon, Edward Bielejec

Hardened Electronics and Radiation Technology 2020
Louisville, Kentucky
Mar 26, 2020

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology & Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

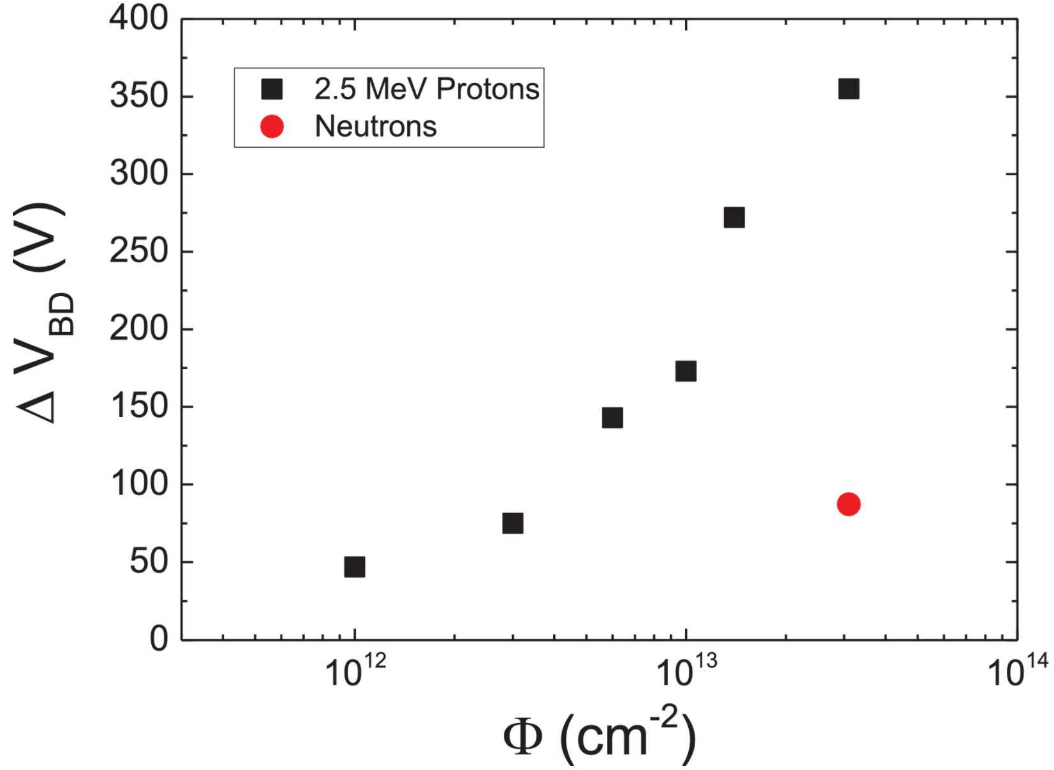
SAND-XXXXXX

Early results of a Sandia-based 1D model for probing defect and radiation response physics in GaN power diodes will be shown

- Introduction – Why defect physics modeling?
- Modeling approach and baselining
- Comparison of model to experimental data

GaN shows potential for high power applications but is known to be susceptible to displacement damage

[King et al., IEEE TNS, 2015]



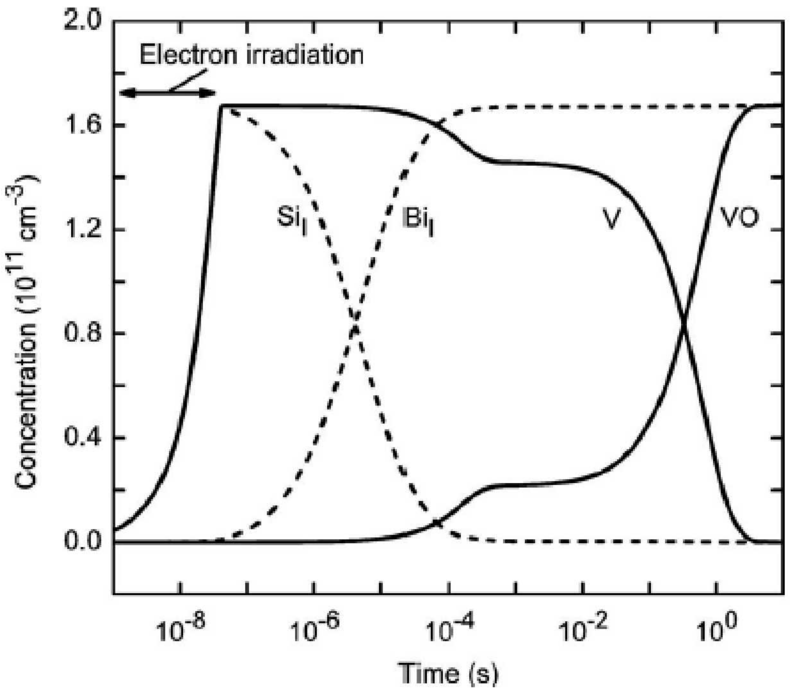
Degradation of vertical GaN PiN diodes breakdown voltage with increasing proton or neutron fluence

- Diodes: decreased V_{BD}, increased R_{on}, increased I_{leak}
- HEMTS: Decreased I_{DS} and shifted V_{th}
- Photodetectors: Shift in sensitivity
- GaN defects not as well understood

  What defects most influence charge carrier behaviors?

What do we gain from modeling defect physics?

[*Myers, Journal of Applied Physics, 2008*]

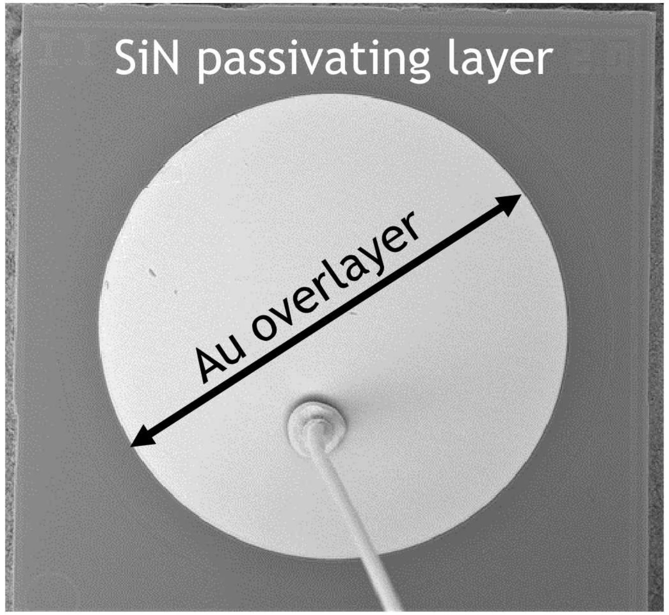


Time-dependent defect concentrations for electron-irradiated Si.

- Sandia-developed exploratory physics development (XPD) program solves 1D carrier transport equations
  - Defect-carrier interactions not addressed as well by commercial TCAD
  - Previously applied to Si BJTs [*Myers, JAP, 2008*] and GaAs HBTs [*Myers, JAP, 2016; Wampler, JAP 2015*]
- Strategic objectives:
  - Create defect evolution model to better predict GaN device response over time in combined environments
  - Inform significant GaN defect physics for more sophisticated models
- **Near-term goals (this work):**
  - **Compare model baseline response with as-grown GaN power diodes**
  - **Validate diode photocurrent response (no displacement damage)**

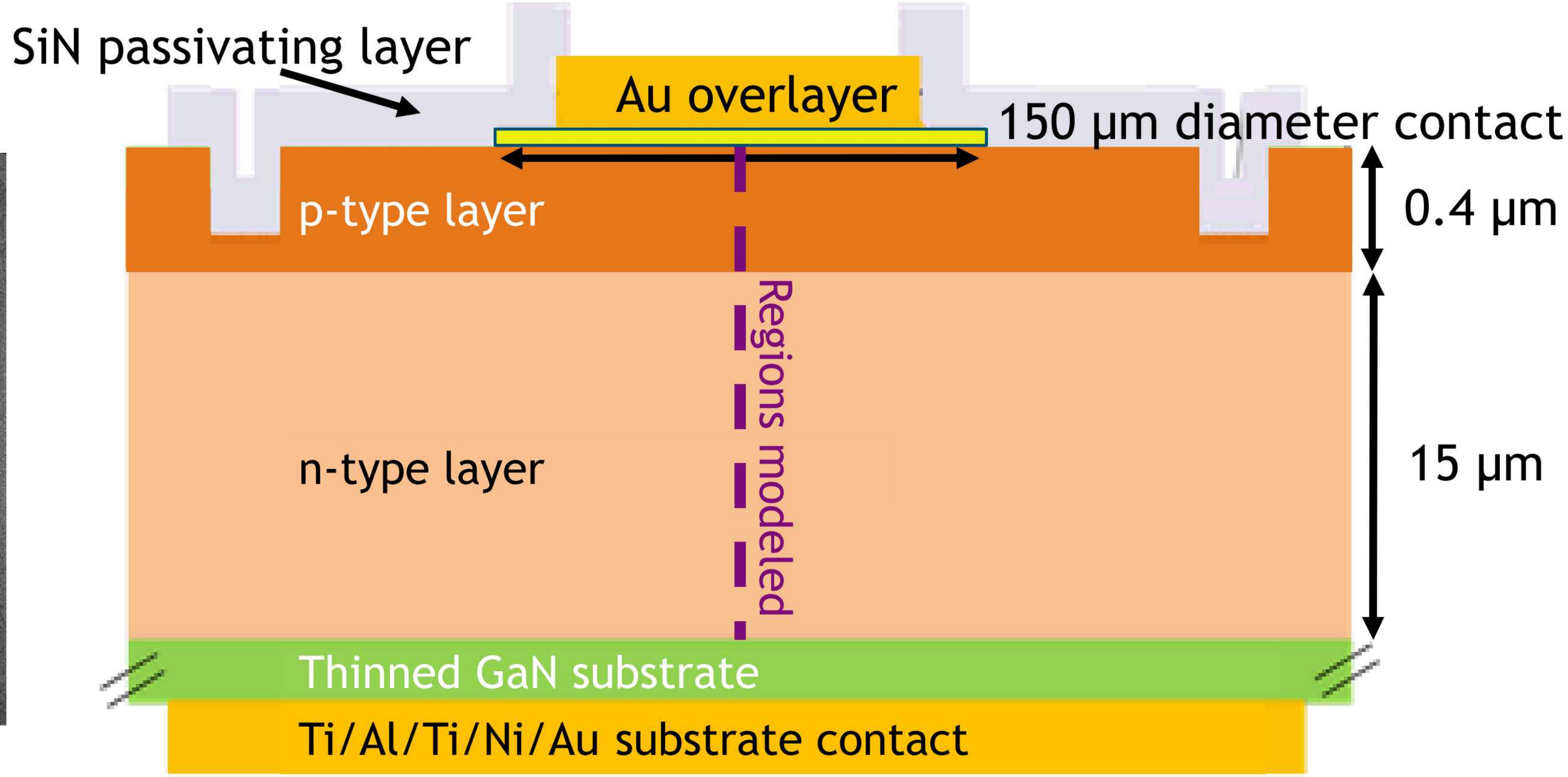
1D model of a Sandia vertical GaN power p-n diode

[A. Colon, CAARI, 2018]



Top-down SEM micrograph of diode

Cross-section of diode (not to scale)



Device diameter >> thickness
Reverse bias breakdown ~1700 V

Charge carrier transport deterministic model

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

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

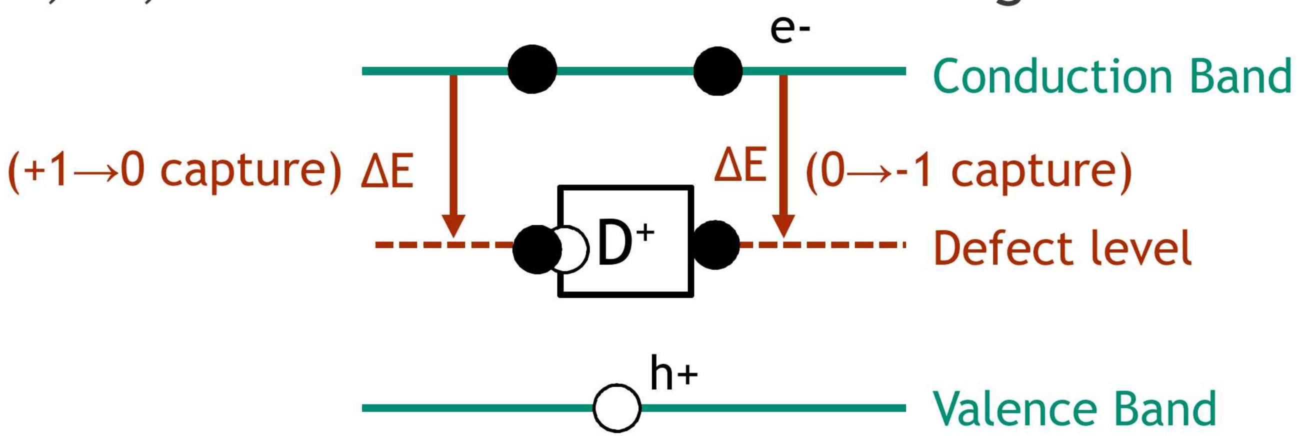
$$\nabla^2 \varphi = -\frac{(n - p + N_D - N_A + Q_d)}{\varepsilon_s} \quad \text{(Poisson's Equation)}$$

XPD models defects in more detail than TCAD

- User-defined material parameters tailored to device design
  - Material constants from literature or Sandia measurements
  - Impact ionization
  - Partial ionization of acceptor dopants (Mg for this work)
  - Multi-phonon emission model for carrier capture/emission
- User-defined radiation fields and defect concentrations
  - Uniform defects as-grown for this work

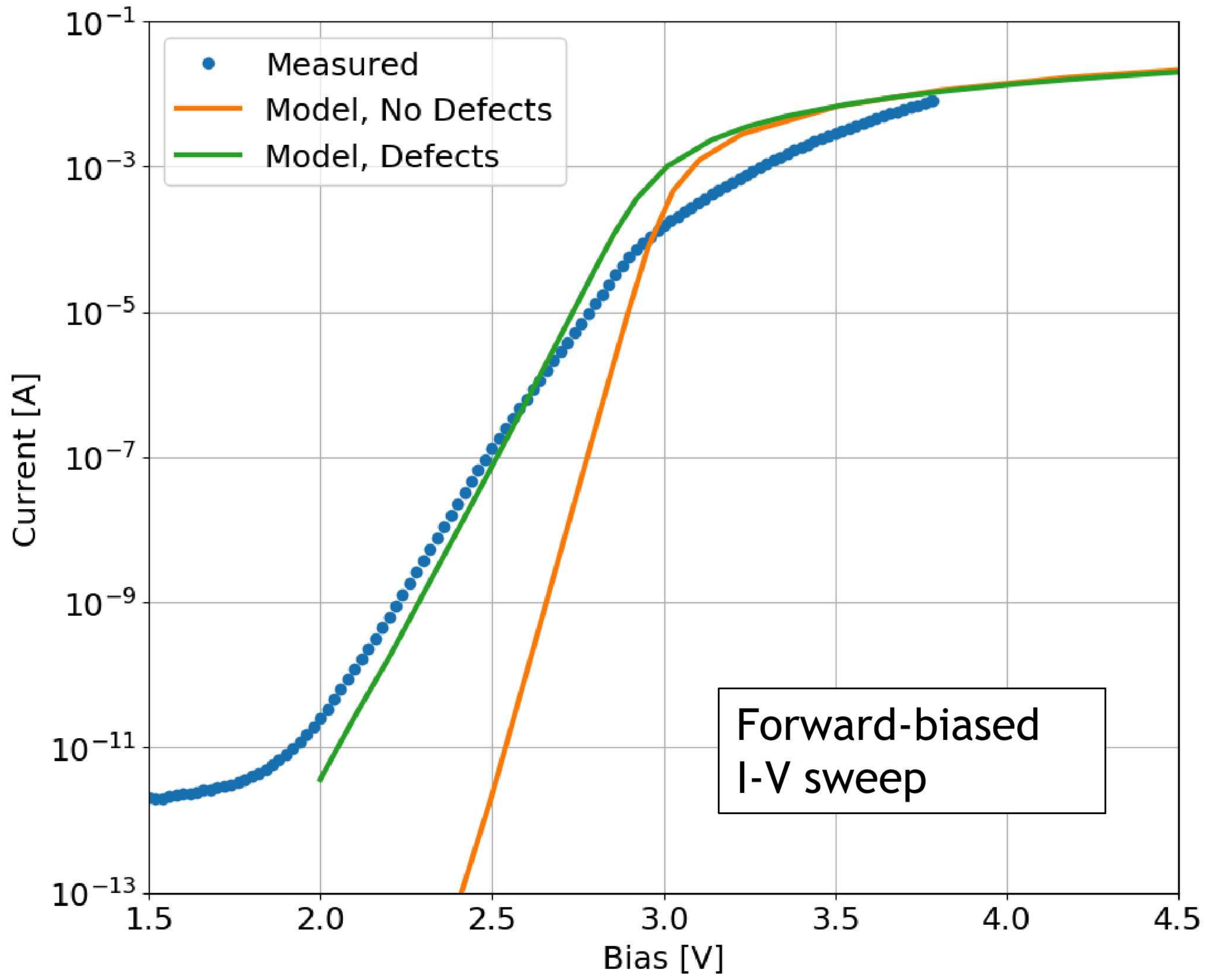
Defect treatment distinguishes this work from TCAD

- Implements single generic defect at defined energy level in band gap
  (assumed mid-band for this work)
- Defects can be:
  As-grown (this work) or from displacement damage
  Uniform (this work), or user-defined spatial profile
- 3 charge states: D^-, D^0, D^+, transitions occur between charge states

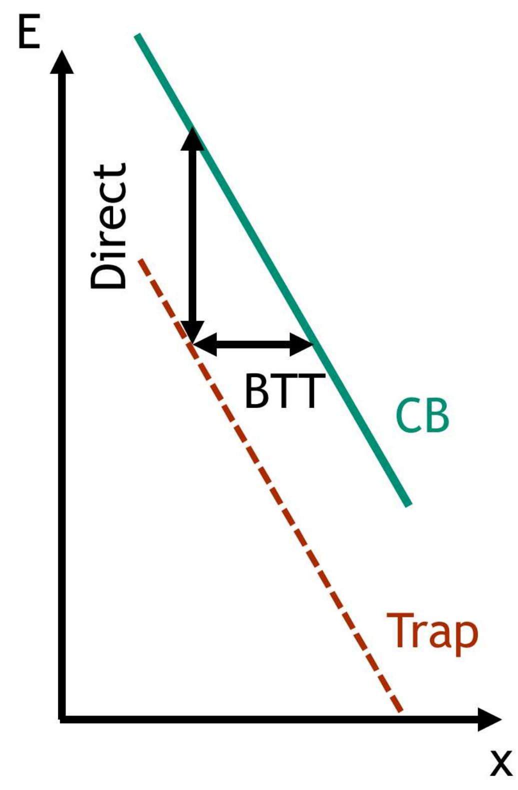


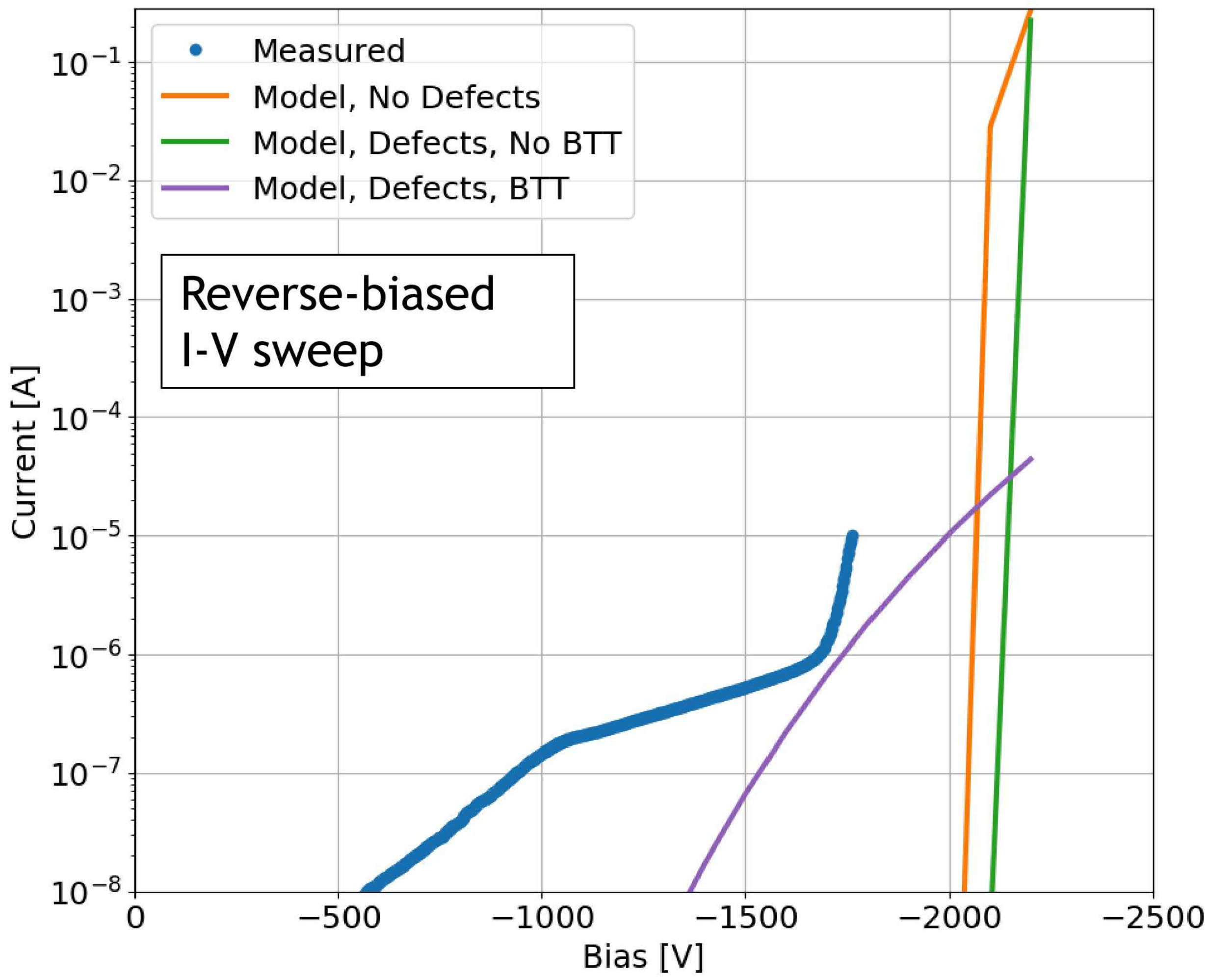
- Carrier-defect reaction rate equations → generation, recombination terms
- Track concentrations of e, h, D^-, D^0, D^+ vs depth and time
  Which interactions contribute most to current?

Inclusion of defects was significant in establishing a matching baseline comparison

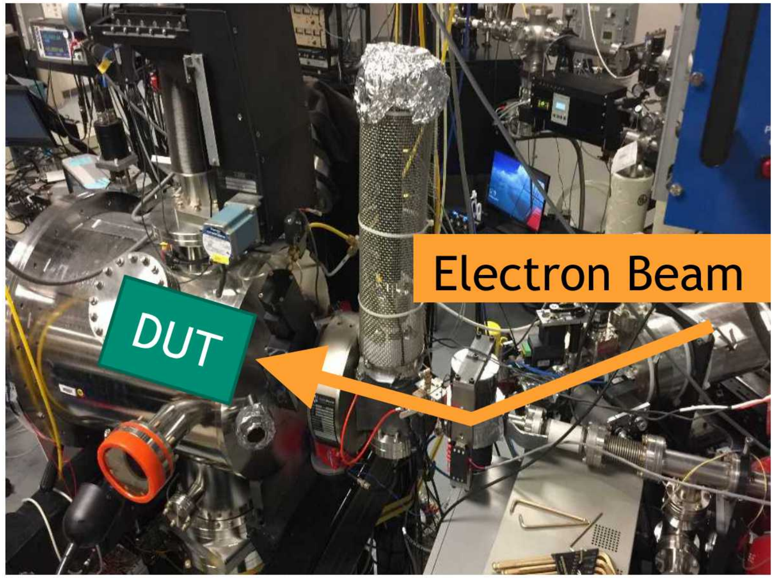


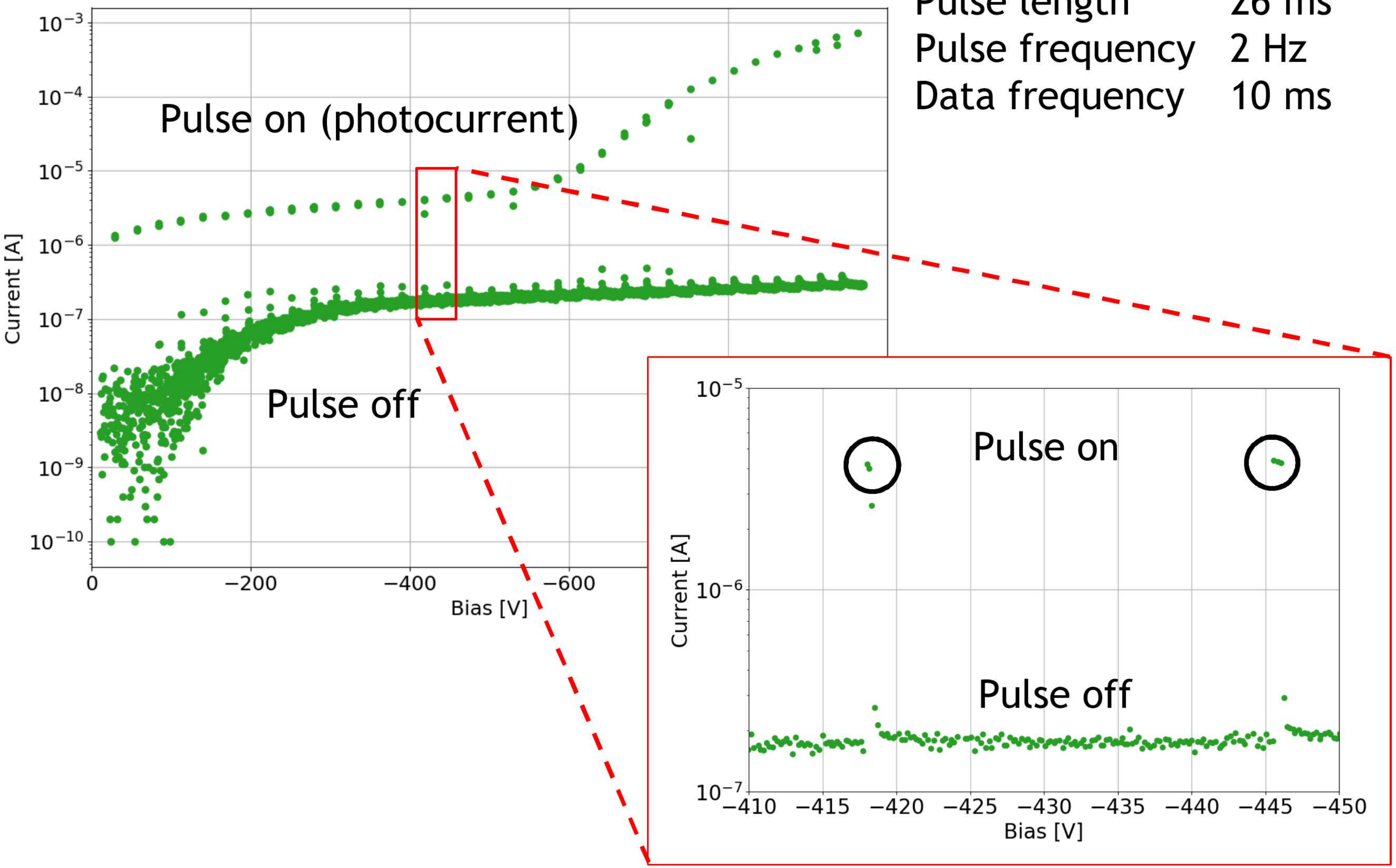
Field-enhanced carrier emission by band-trap tunneling (BTT) significant for modeling diode leakage current





Electron beam-induced current used to generate photocurrent benchmark data

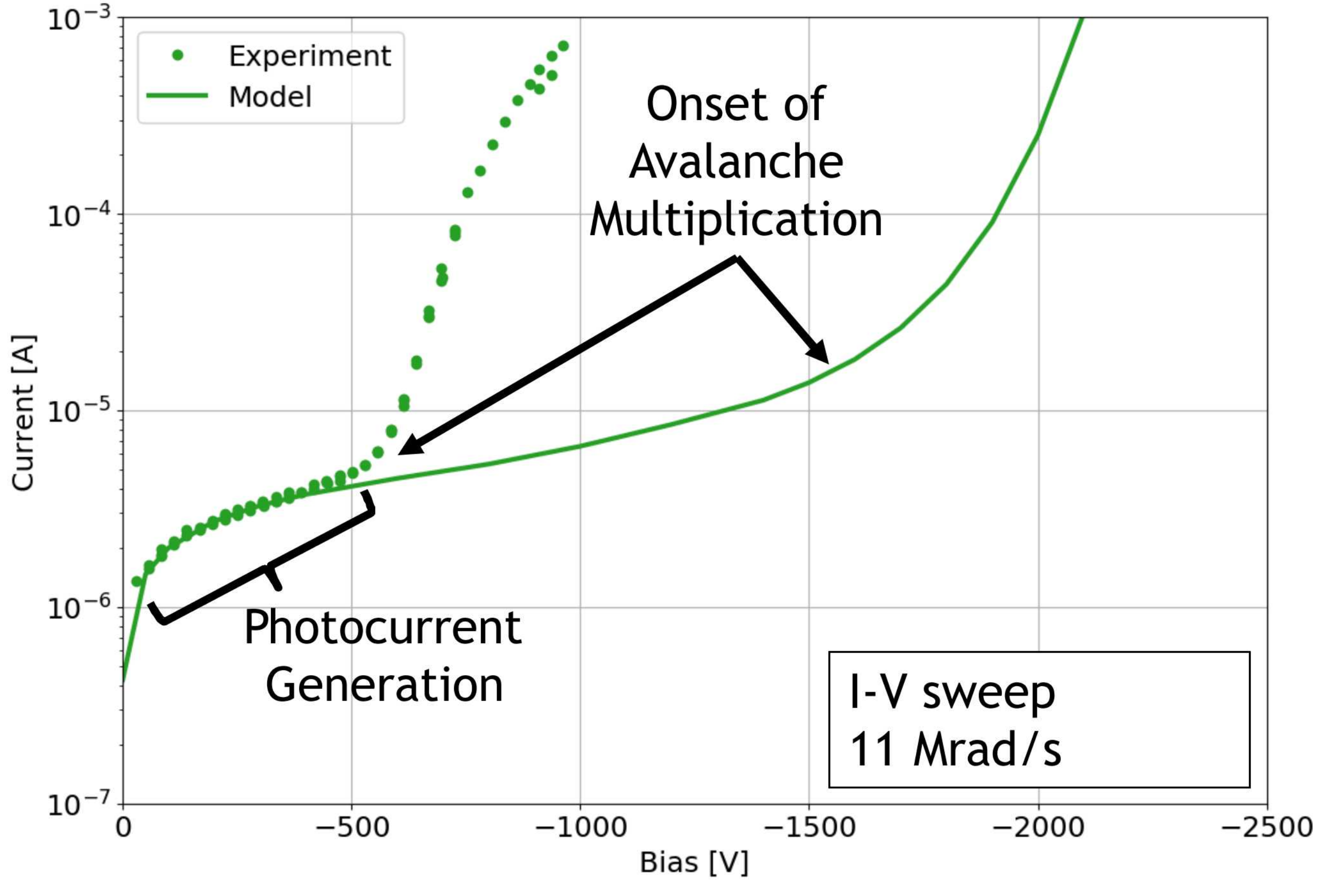




Pulse length	26 ms
Pulse frequency	2 Hz
Data frequency	10 ms

[*Experimental data following Pickrell, HEART, 2018*]

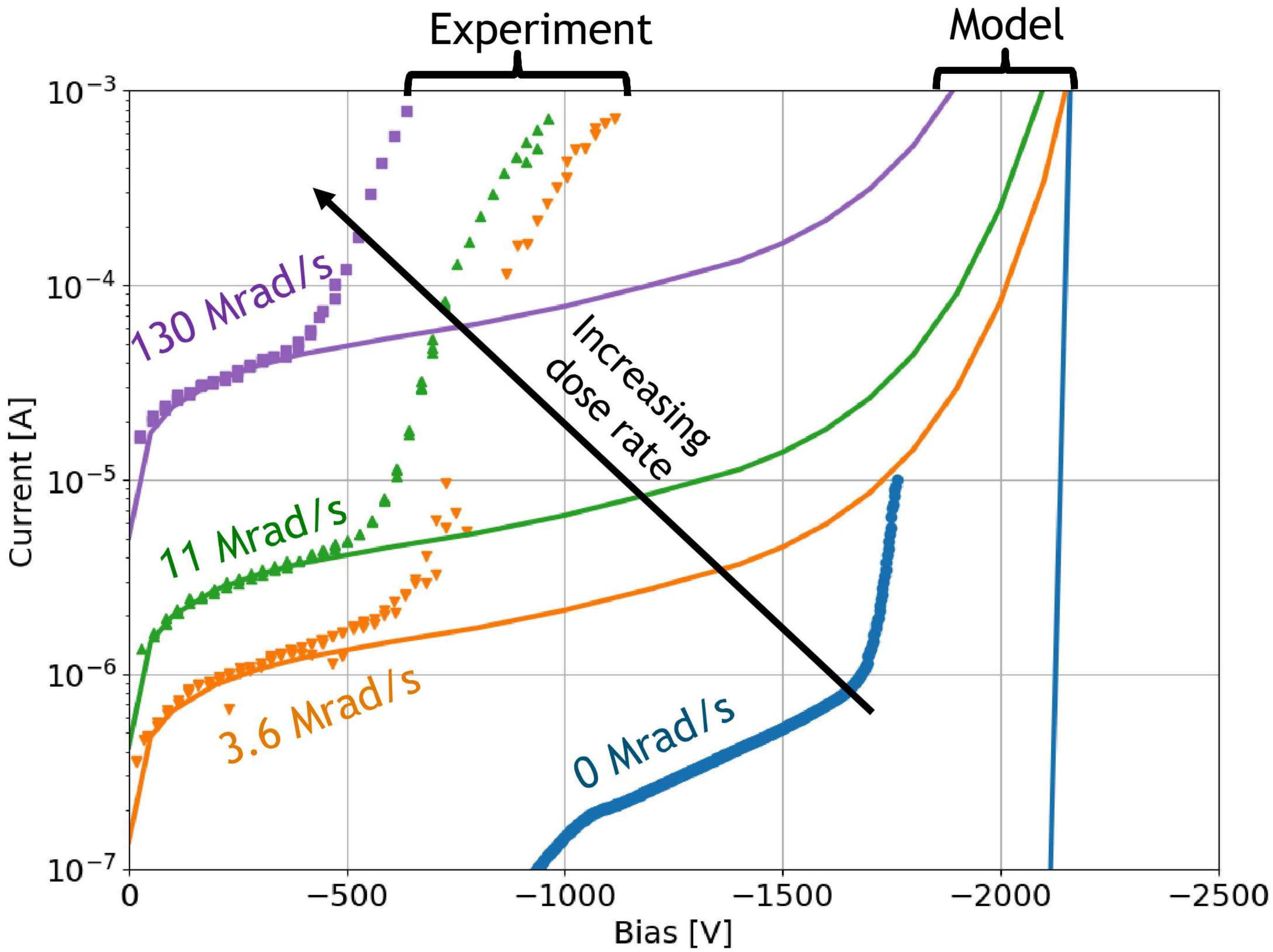
Two photocurrent response regimes observed when exposed to ionizing radiation



Impact ionization alone seemingly does not adequately explain multiplication

Are these disagreements due to missing geometry, inaccurate parameters, or missing physics?

Model and measured data demonstrate decrease in breakdown voltage with increasing dose rate



Measured data show more dramatic shift in breakdown voltage.

What could we be missing?

- 2D or 3D geometries/ field structures
- Non-uniform defect density profile
- Multiple defects levels
- Space-charge limited conduction breakdown mechanisms

Where are we going next?

- Defects from heavy ion or neutron displacement damage
- Combined environment models and experiments evolving over time
- 2D TCAD simulations to probe higher-dimension effects

Summary

- An exploratory physics code examining defect evolution in GaN is being developed
- Successes:
  - Baseline agreement for forward-biased GaN power diodes
  - Band-trap tunneling significant for modeling leakage current in reverse bias
  - Agreement with experiment for photocurrent response to radiation at lower biases → **Good predictive quality**
- Long-Term Objective: Predictive capability for GaN device performance that specifically addresses defects and defect evolution in radiation environments not available in commercial software