Wide Bandgap Semiconductors: Opportunities and Challenges for Improved Modeling and Characterization Methods in Power Electronic Applications

Raghav Khanna, Associate Professor
Leidich Family Endowed Professor in Power and Energy Systems
EECS Department
University of Toledo
26 January 2023

Introduction: Career Path

2008-
2014

PhD, Pitt,
PA

2013-
2014

HRL Labs,
Fellowship,
Malibu, CA

2014-
2015

Visiting Prof,
Bucknell U,
PA

2015-
Present Day

Associate Prof
UToledo, OH

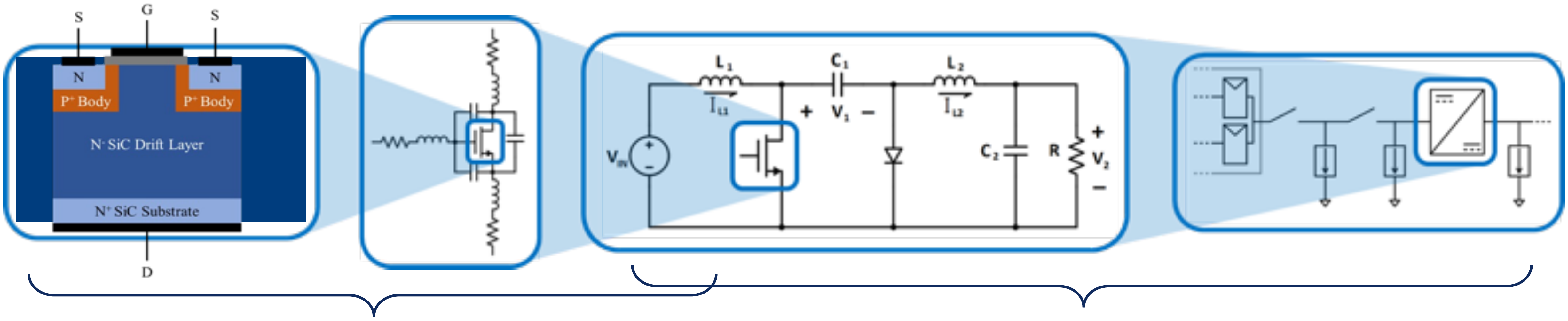
Endowed
Professorship
Jan. 10 2023

Outline

- **Introduction: The Need for WBGs and Models**
- **Physics and Behavioral Modeling**
- **Simple Edge Termination Design for Vertical GaN Diodes: Physics Based Modeling**
- **Hybrid Edge Termination Design for Vertical GaN Diodes: Physics Based Modeling**
- **Modeling of SiC MOSFETs: Behavioral Modeling**
- **Applications of WBGs in Space**
  - MPPT
  - Radiation Intense Environments
- **Future Work**

Introduction: Hierarchical Energy Infrastructure

- Semiconductor → Circuits → Systems

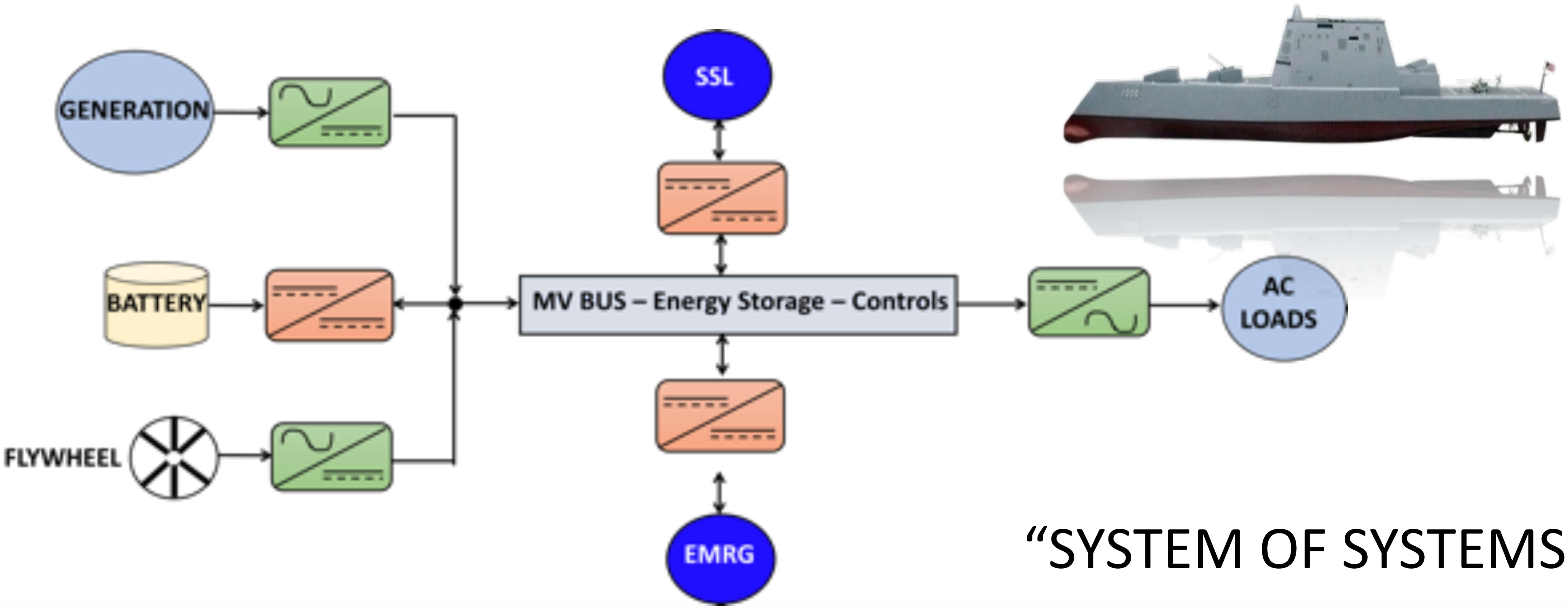


Semiconductors and Power Electronics

Smart Grids and Systems

Introduction: Hierarchical Energy Infrastructure

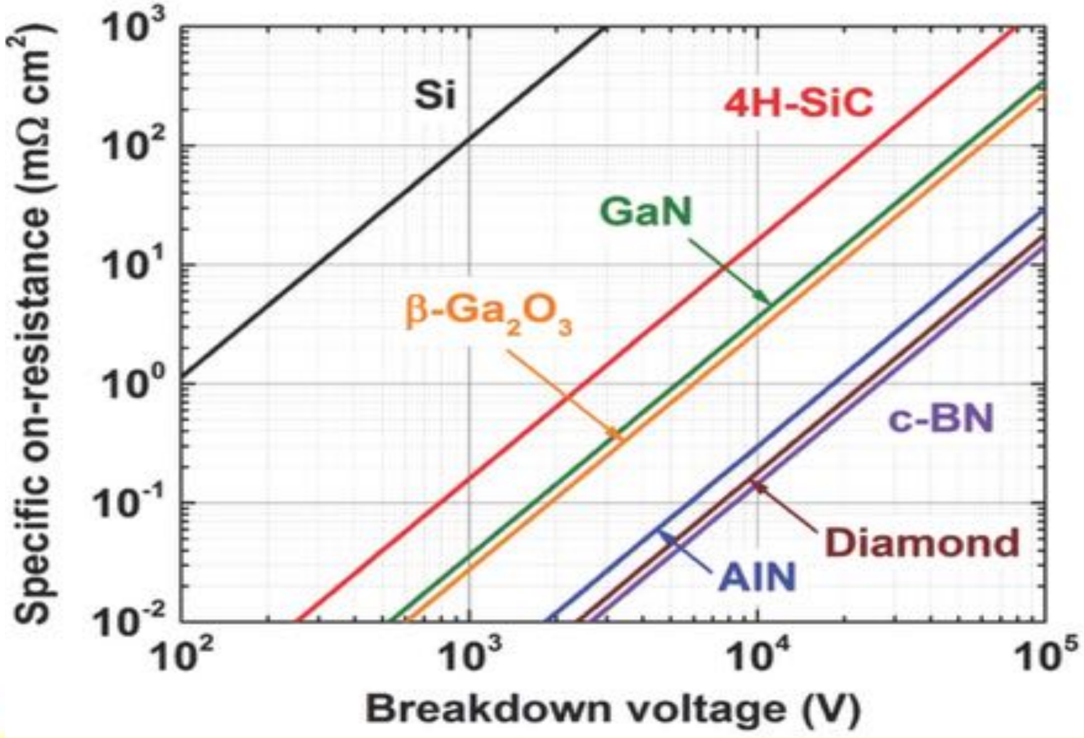
- Example: Electric Navy Ships -- Semiconductor → Circuits → Systems



"SYSTEM OF SYSTEMS"

Introduction: Wide Bandgap Semiconductors

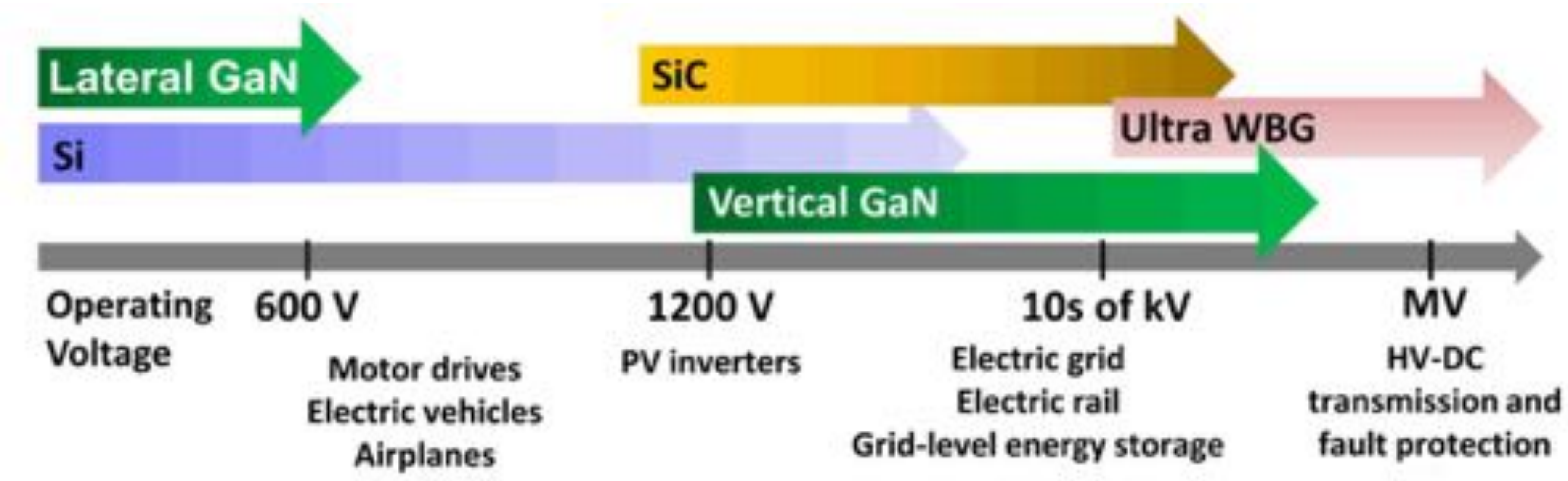
- Higher Voltage Operating Capability
- Fast Switching allowing for Smaller Footprints
- High Temperature for Harsh Environments



J. Y. Taso et al. "Ultrawide Bandgap Semiconductors: Research Opportunities and Challenges," in *Advanced Electronic Materials*. DOI:10.1002/aelm.201600501

Introduction: Wide Bandgap Semiconductors

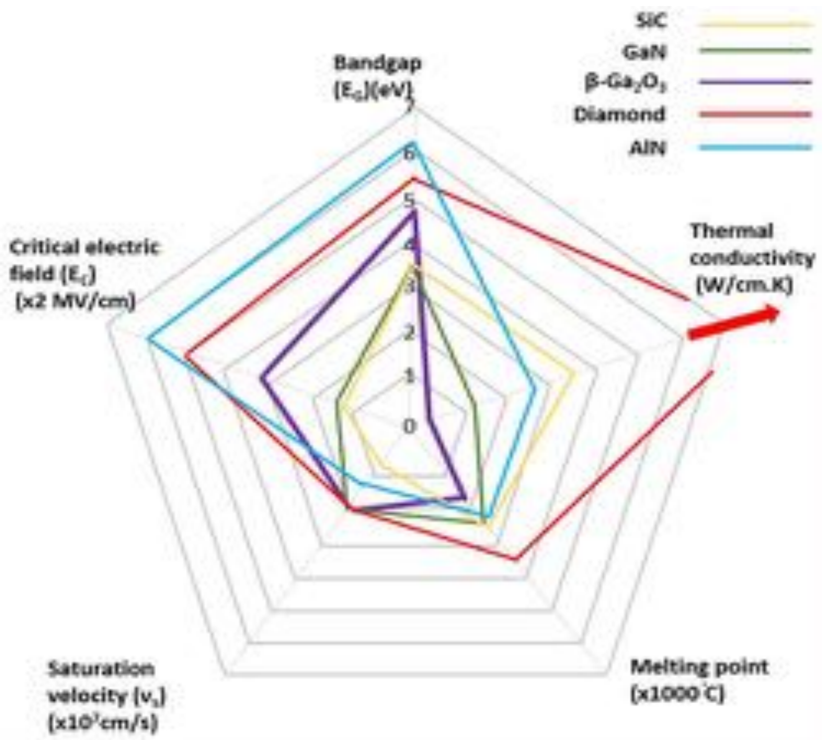
- Applications and Future Roadmap



https://www.osti.gov/servlets/purl/1601091

Introduction: Wide Bandgap Semiconductors

- Complexity and the cost of mass production varies for each material



Ref: Ahmadi, Elaheh & Oshima, Yuichi. (2019). Materials issues and devices of α- and β-Ga 2 O 3. Journal of Applied Physics. 126. 160901. 10.1063/1.5123213

Semiconductor Material	Si	GaN	4H-SiC	β-Ga2O3	AlGaN	Diamond
Band Gap (eV)	1.1	3.4	3.3	4.7-4.9	3.4-6	~5.5
Electron Mobility ($cm^2V^{-1}S^{-1}$)	1400	1200	1000	300	> 1000	>2000
Breakdown Electric Field (MV/cm)	0.3	3.3	2.5	8	> 10 MV/cm	>10 MV/cm
Electron Drift Saturation Velocity($x10^7$ cm/s)	1	2.2	1.9	2	1.4	2.7
Thermal Conductivity λ (W m−1 K−1)	280	253	370	11-27	523-319	2290-3450

Ref: Ultrawide-Bandgap Semiconductors: Research Opportunities and Challenges; J.Y Tsao et.AL

Introduction: Wide Bandgap Semiconductors

- Challenges and Opportunities for Modeling
  - High Voltage Capability and Reliability
    - SiC → 15 kV
    - GaN → 20 kV ----- vertical structures needed
  - Circuit Level Reliability
    - Realizing Application Performance Entitlement: "Near RF" Behavior**
  - Semiconductors Device Models
    - Physics-Based Models
      - ✓ Analytical Equations Based on First Principles
      - ✓ Finite Element Modeling (TCAD)
    - Behavioral Models
      - ✓ Analytical Equations Based on Curve Fitting Algorithms
      - ✓ Circuit Simulation Models

** Dr. A. Lemmon, Associate Professor, ECE Dept. University of Alabama

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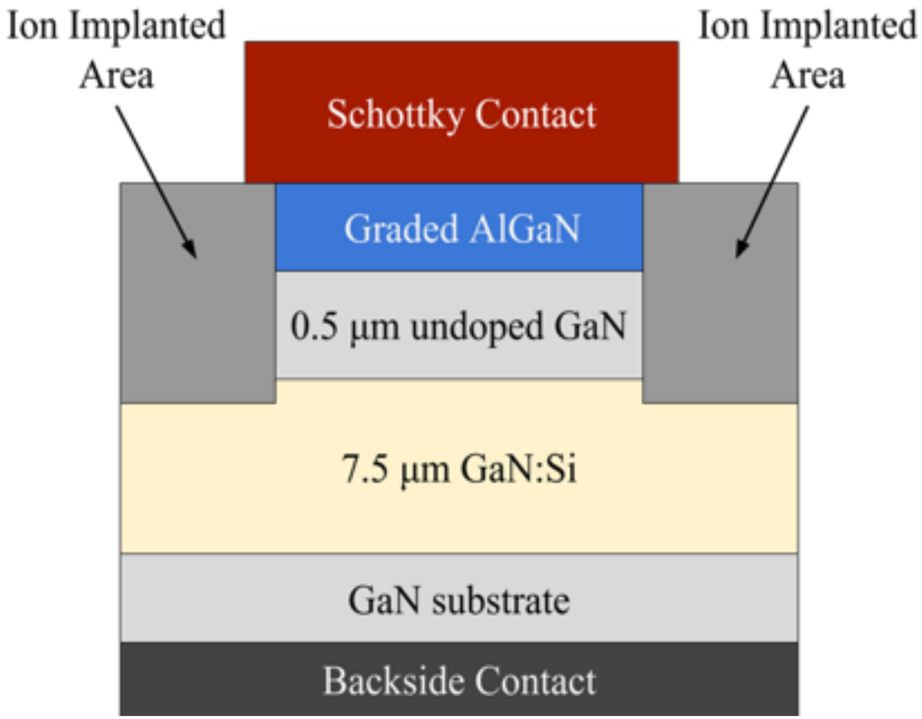
    - Radiation Intense Environments
- Future Work

Semiconductor Device Modeling

- **Physics-Based: Analytical**

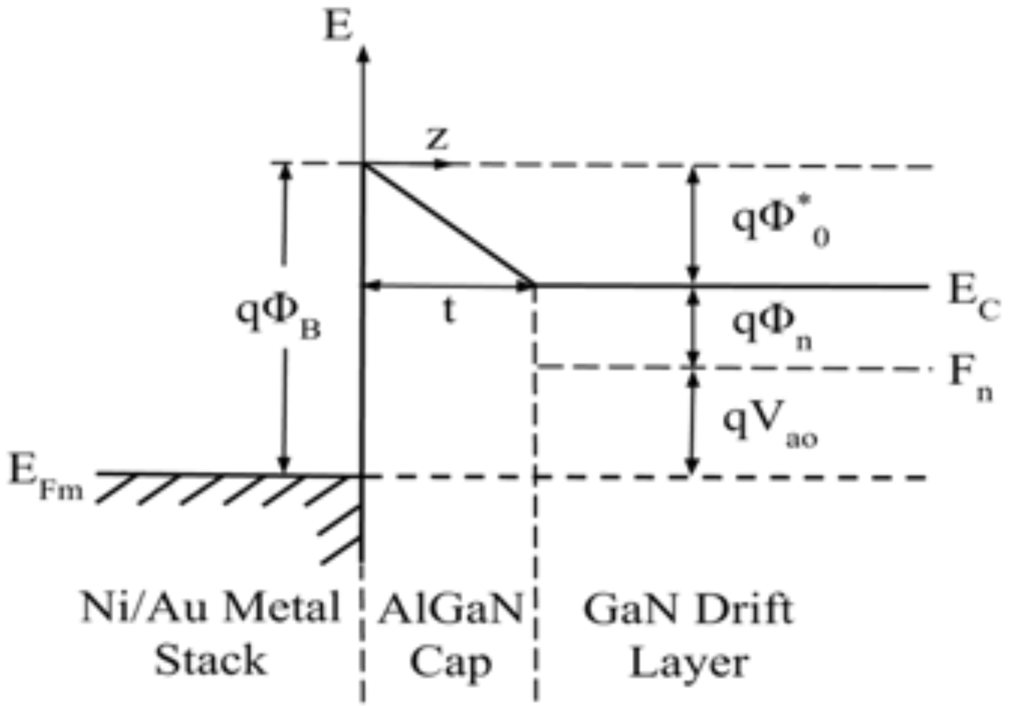


600 V TBS vertical GaN diode structure, developed by HRL Labs

M. R. Hontz, Y. Cao, M. Chen, R. Li, A. Garrido, R. Chu, and **R. Khanna**, "Modeling and characterization of vertical GaN schottky diodes with AlGaN cap layers," in *IEEE Transactions on Electron Devices*, vol. 64, no. 5, pp. 2172-2178, May 2017. DOI: 10.1109/TED.2017.2686778

Semiconductor Device Modeling

- **Physics-Based: Analytical**
  - Forward conduction model
    - ❑Thermionic current
    - ❑Diffusion current
    - ❑Field emission (tunneling)



Combine all 3 effects

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Semiconductor Device Modeling

- **Physics-Based: Analytical**
  - Forward conduction model

❑ Thermionic current

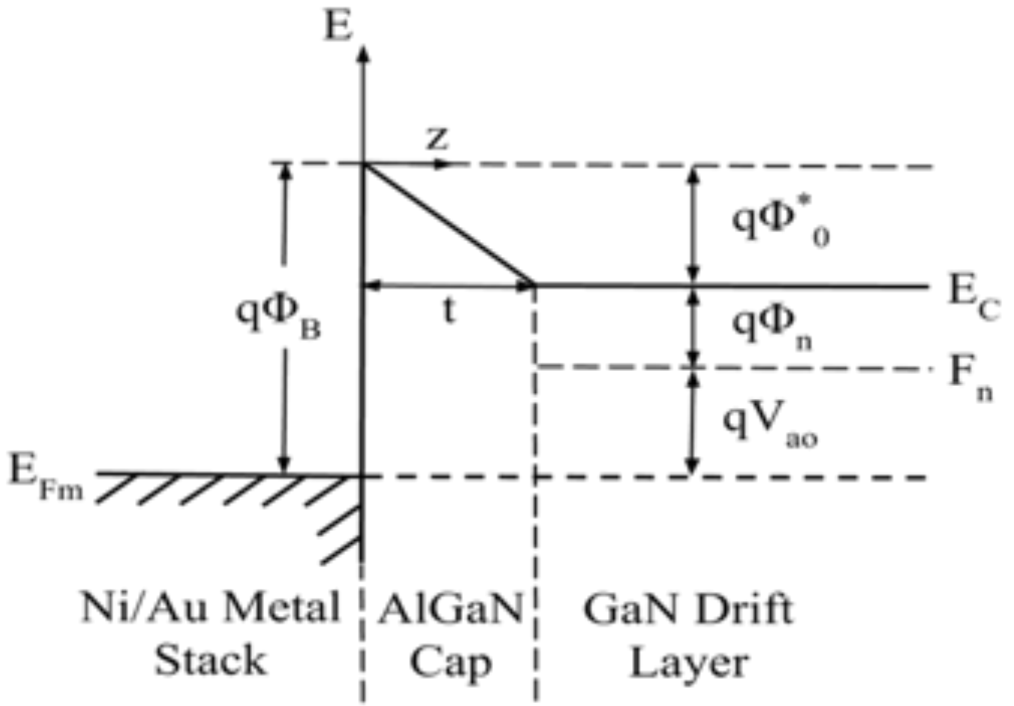
$$J_{\mathrm{TE}} = A^{*}T^{2}\exp\left(\frac{-q\Phi_{\mathrm{B}}}{kT}\right)\left(\exp\left(\frac{qV_{\mathrm{a}}}{kT}\right)-1\right)$$

❑ Diffusion current

$$J_{\mathrm{Diff}} = \frac{qD_{\mathrm{n}}N_{\mathrm{c}}}{\int_{0}^{z_{\mathrm{d}}}\exp\left(\frac{E_{\mathrm{c}}}{kT}\right)dz}\left(\exp\left(\frac{qV_{\mathrm{a}}}{kT}\right)-\frac{\rho(0)}{N_{\mathrm{c}}}\exp\left(\frac{q\Phi_{\mathrm{B}}}{kT}\right)\right)$$

❑ Field emission (tunneling)

$$J_{\mathrm{FE}} = qv_{\mathrm{R}}N_{\mathrm{d}}\Theta$$

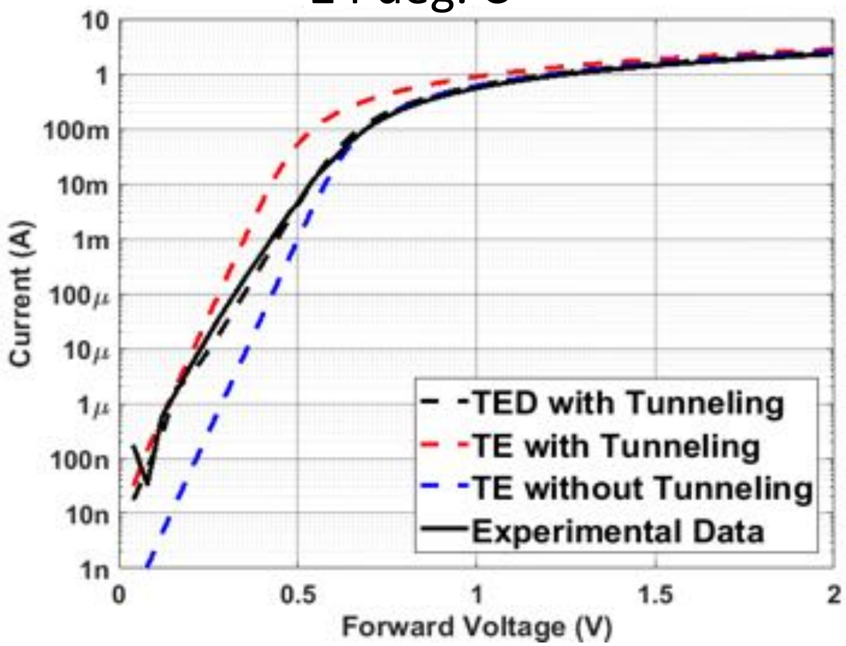


Combine all 3 effects

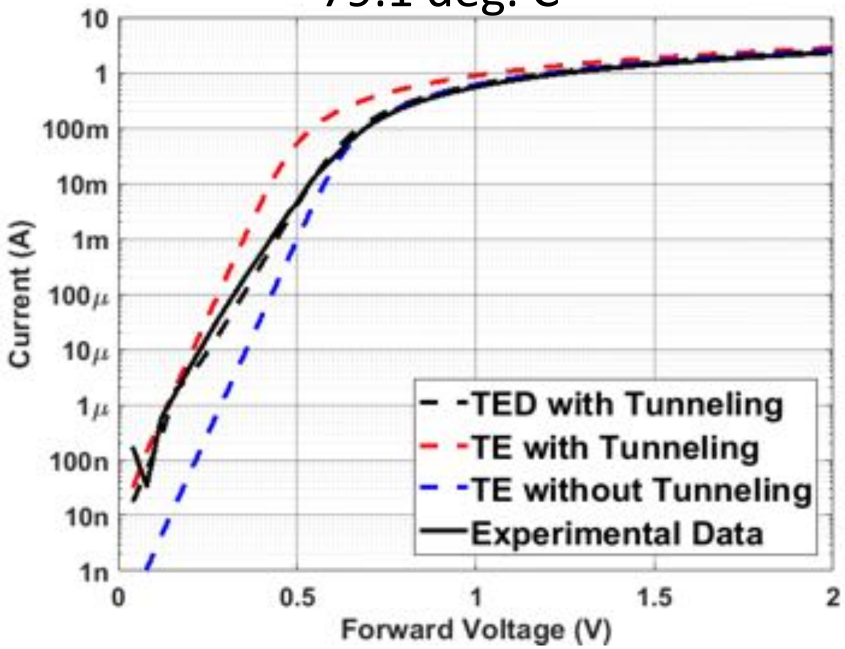
Semiconductor Device Modeling

- **Physics-Based: Analytical**
  - Forward conduction model

24 deg. C



79.1 deg. C



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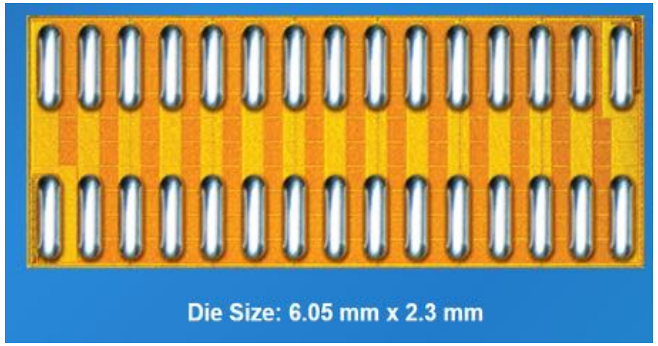
Semiconductor Device Modeling

- **Physics-Based**
  - SPICE Models based on Analytical First Principle Equations
    - Accurate but very slow
    - Can be used to predict circuit-level performance
  - Amenable to the development of *scaling* rules from analytical equations to project the performance and characteristics of future high voltage devices.
  - Observed and simulated circuit-level performance can be correlated with underlying device physical parameters

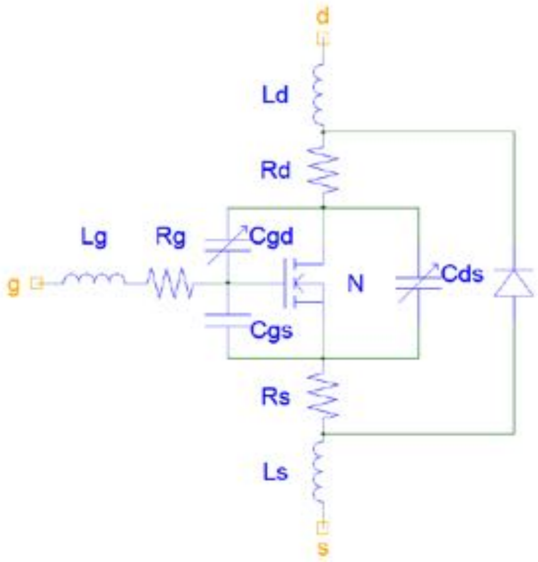
Semiconductor Device Modeling

- **Behavioral: Circuit Simulation**

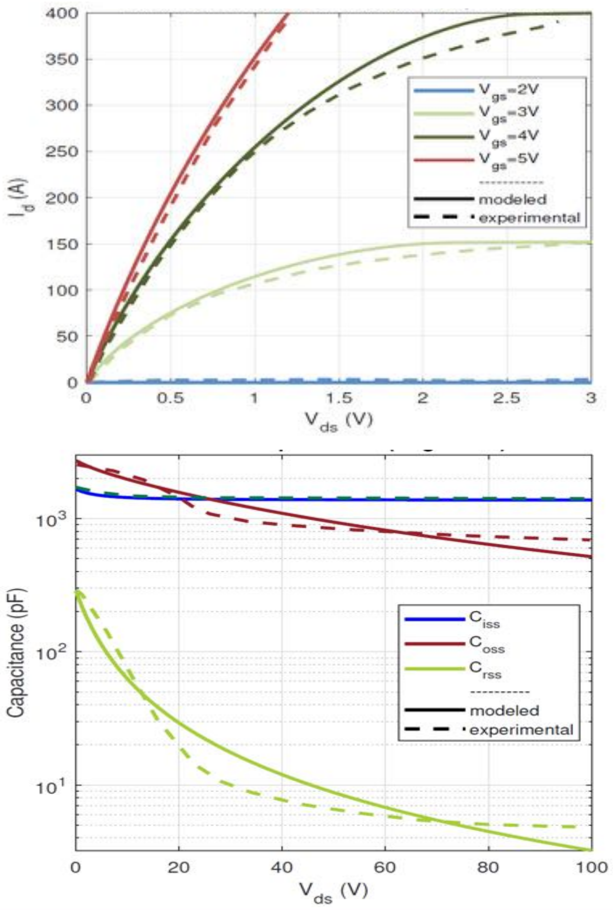
100 V GaN HEMTs from EPC



Saber Simulator



Modeled IV and CV Curves



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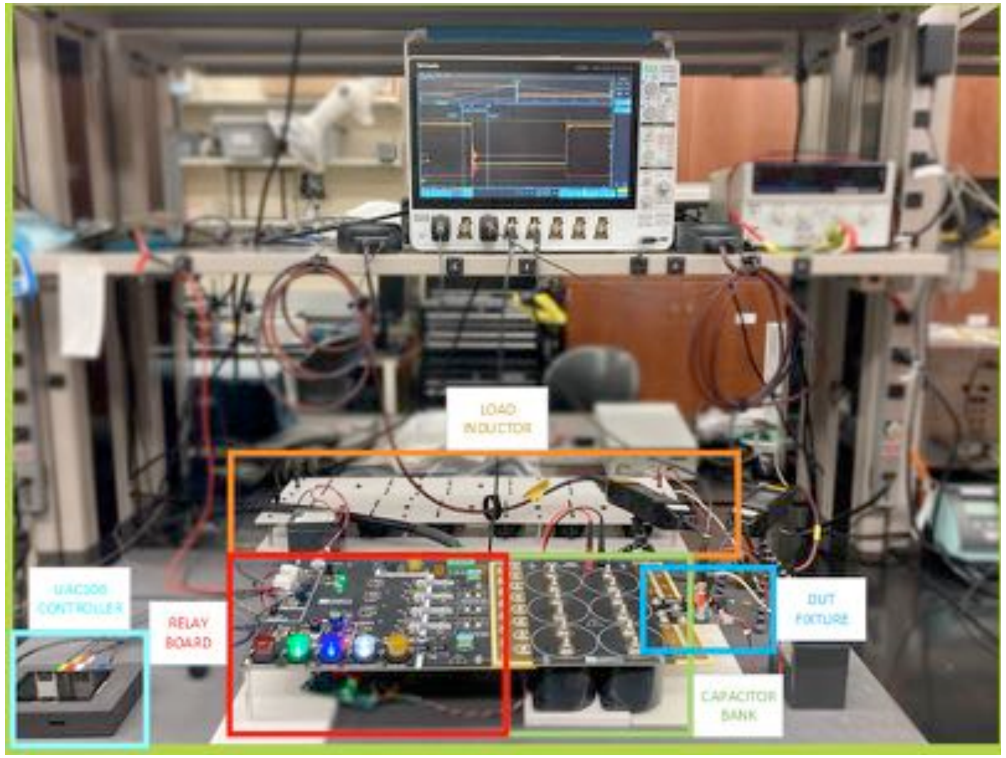
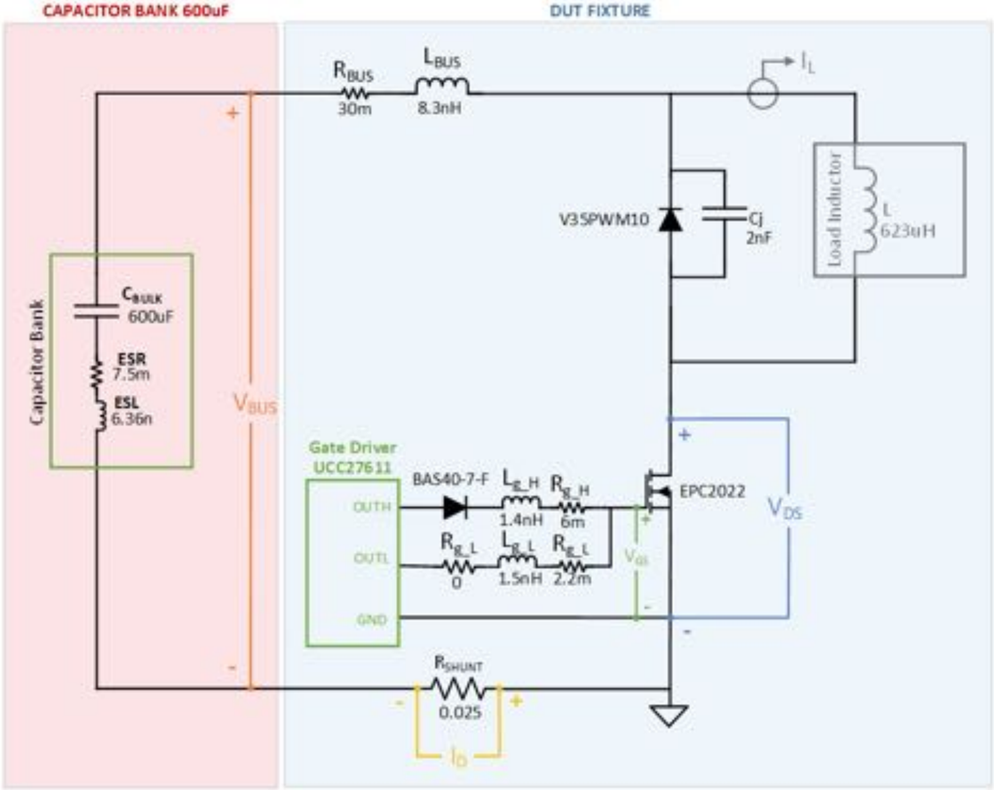
Semiconductor Device Modeling

- **Behavioral: Circuit Simulation**
    - Experimental Setup and Circuit Topology



**Courtesy Professor A. Lemmon Research Group, University of Alabama



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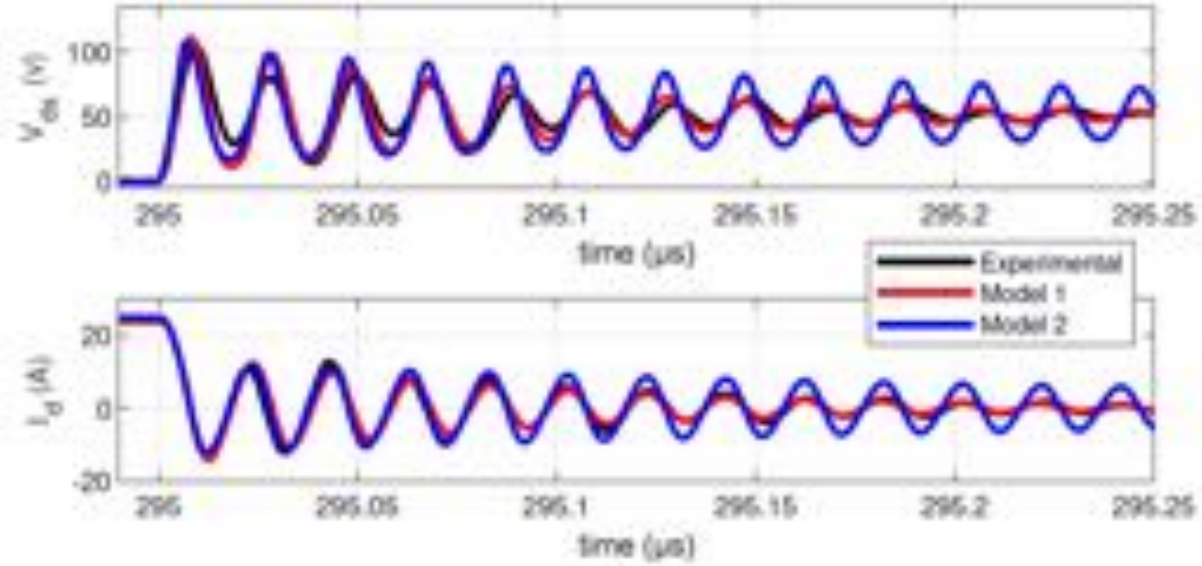
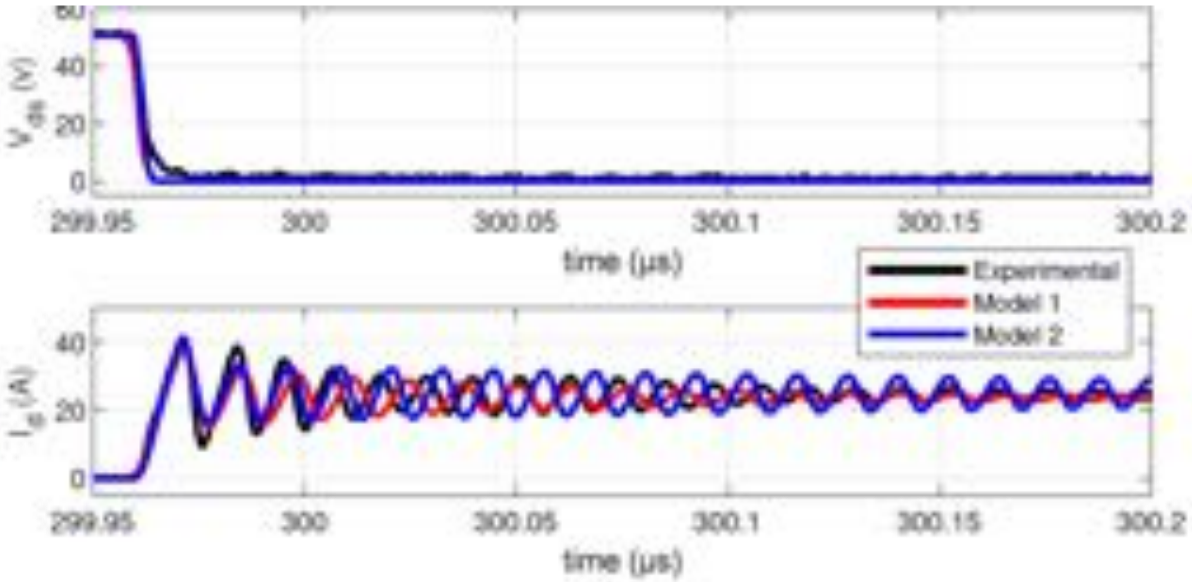
Semiconductor Device Modeling

- **Behavioral: Circuit Simulation**
  - Transient Overlay of Experiment and Simulation



Turn Off



Turn On

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Semiconductor Device Modeling

- **Behavioral: Circuit Simulation**
  - Error Reduction in Experiment vs Simulation Comparison

Data Set	Model 1 Error (μ)		Model 2 Error (μ)	
	Nominal	Tuned	Nominal	Tuned
Original Data Set	92.59	3.46	55.84	25.34
Orthogonal Data Set	223.49	25.34	67.14	30.83

Model 1 is able to find a better optimal through tuning despite a less optimal nominal starting point – an advantage offered by behavioral modeling since parameters do not have physical meaning

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Semiconductor Device Modeling

- **Behavioral Models**
  - Circuit Simulation Saber Models Based on Curve Fitting
    - Can be tuned efficiently to achieve more accurate results
  - Faster convergence with a cost to accuracy
  - Not amenable to correlating observed circuit-level performance with underlying physical device parameters

Outline

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  - Radiation Intense Environments
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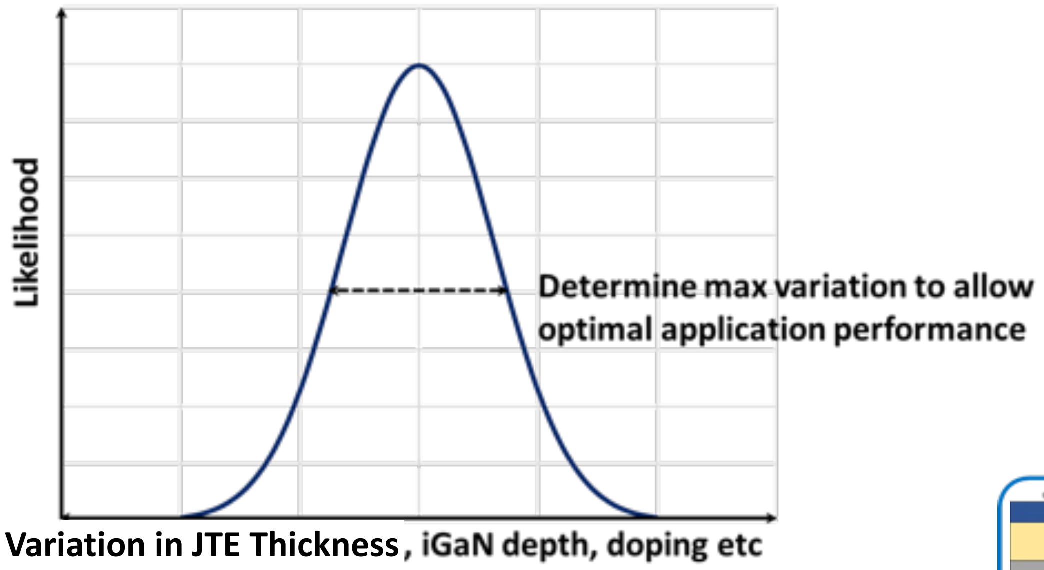
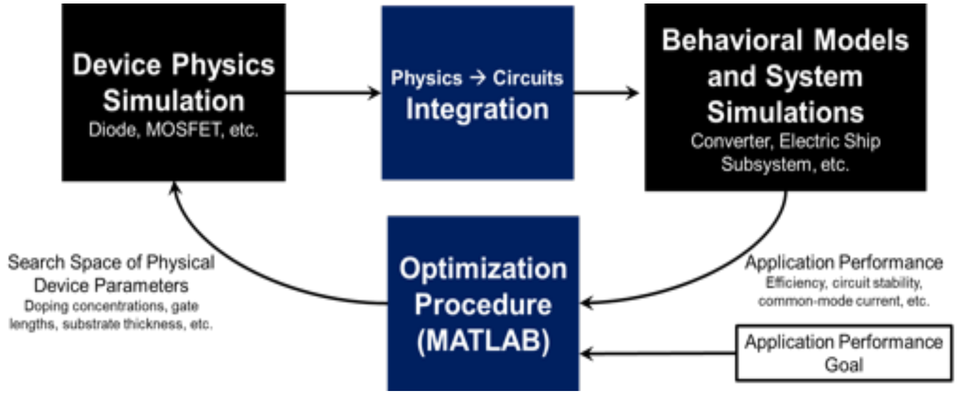
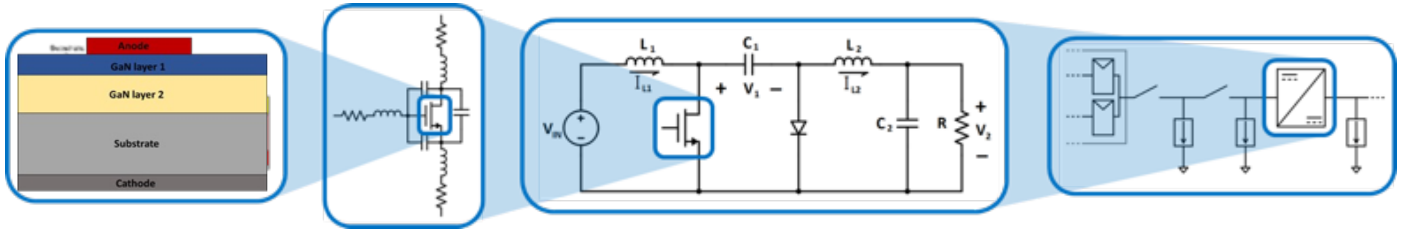
Models: Physics-Based Modeling

- Determine parameter values for that enable optimal application performance? Assess how much variability/tolerance in the parameter values is allowable through **experimental validation with NRL and Sandia**.

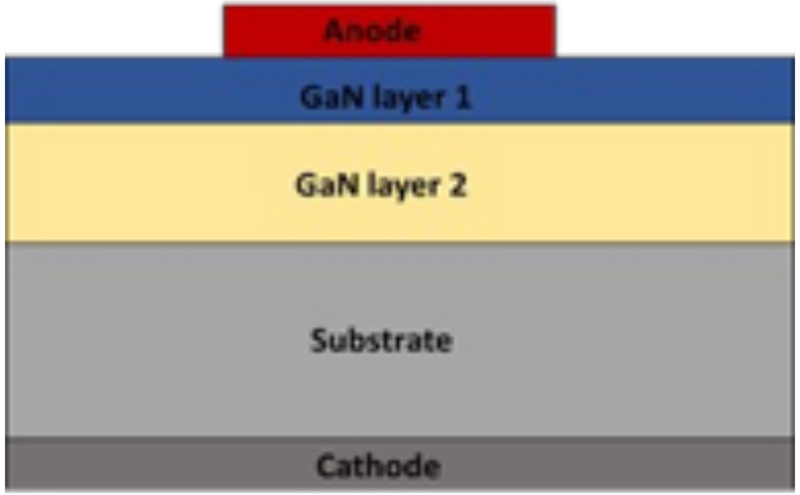


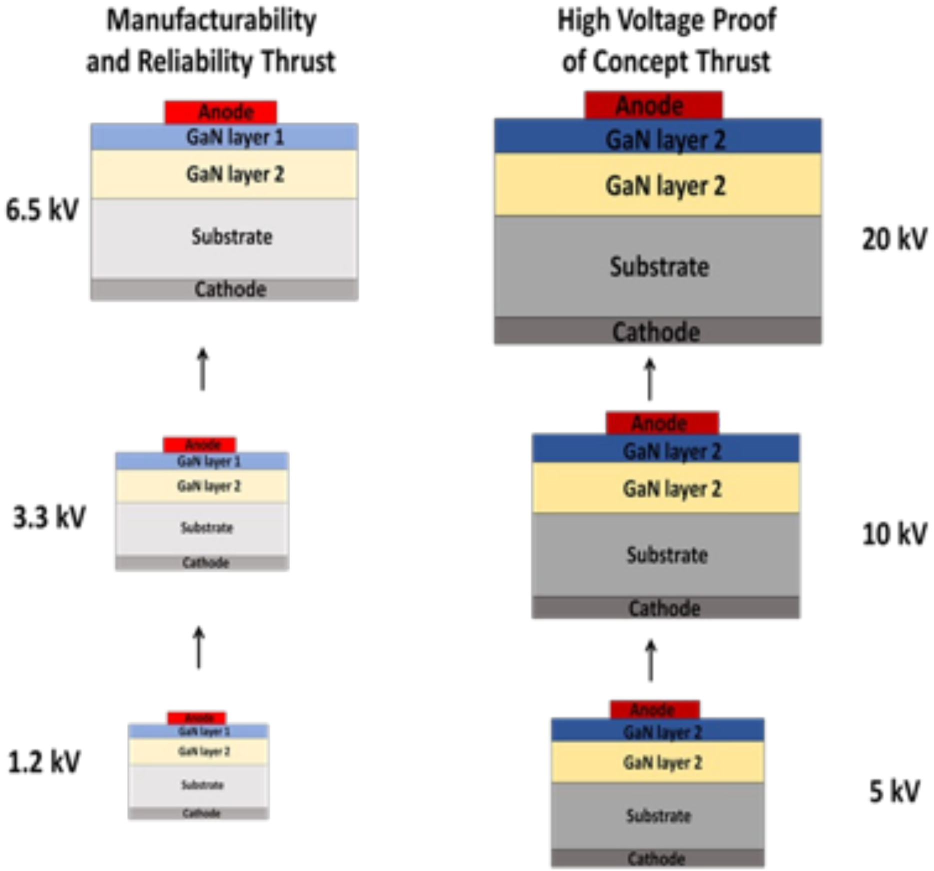




Objectives

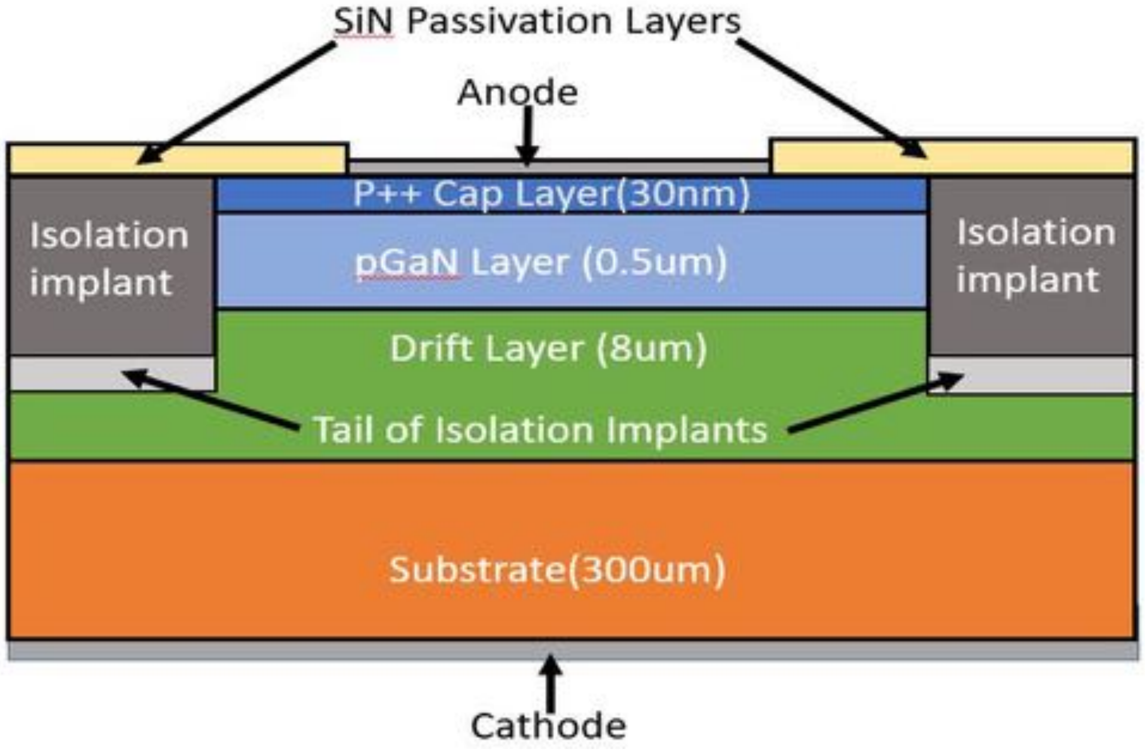
- Develop simple structure, scalable to ~ 20 kV





Simple Edge Termination Design

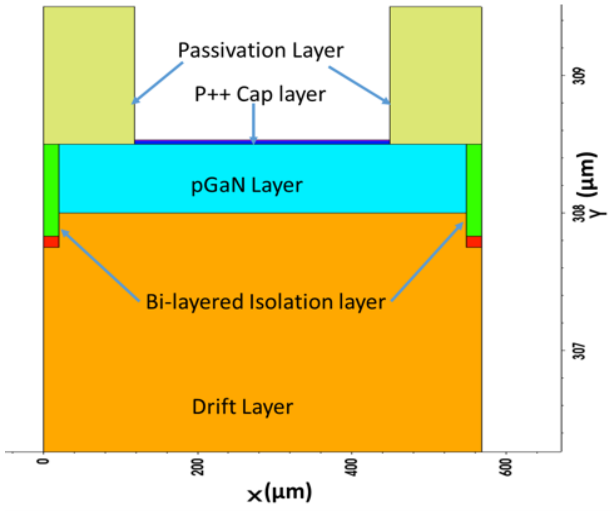
- **Device structure and model: isolation implant only. Only design space is doping/thickness of p-type layers**



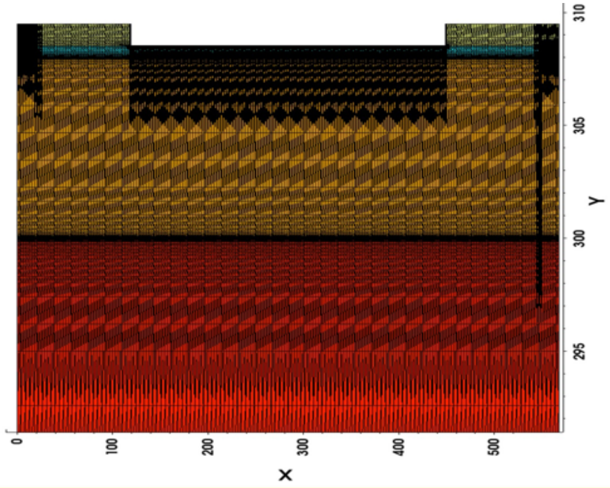
P. Pandey, T. M. Nelson, W. M. Collings, M. R. Hontz, D. G. Georgiev, A. D. Koehler, T. J. Anderson, J. C. Gallagher, G. M. Foster, A. Jacobs, M. A. Ebrish, B. P. Gunning, R. J. Kaplar, K. D. Hobart, and R. Khanna, "A simple edge termination design for vertical GaN P-N diodes," in *IEEE Transactions on Electron Devices*, vol. 69, no. 9, pp. 5096-5103, September 2022. DOI: 10.1109/TED.2022.3192796

Simple Edge Termination Design

- **Considerations: Spring 2020 – Present Day**
  - GaN's low intrinsic concentration
  - Optical generation of carriers
  - Mobility variability in experiment and literature
  - Defects and trap states
  - Contact resistances
  - Range of reported impact ionization coefficients



Simulated device structure

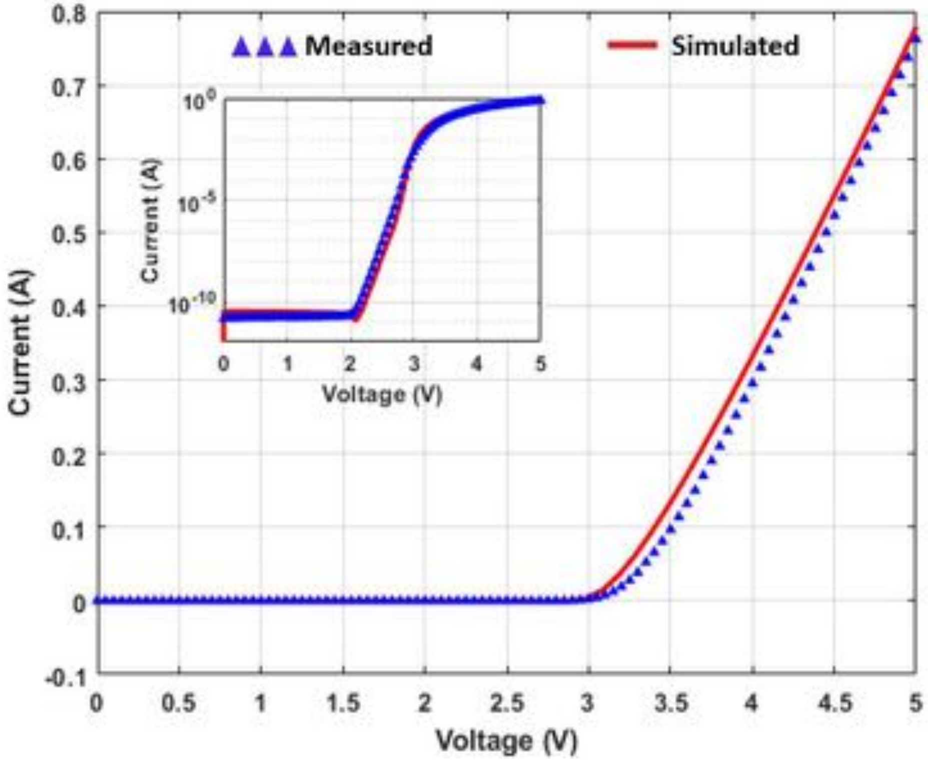


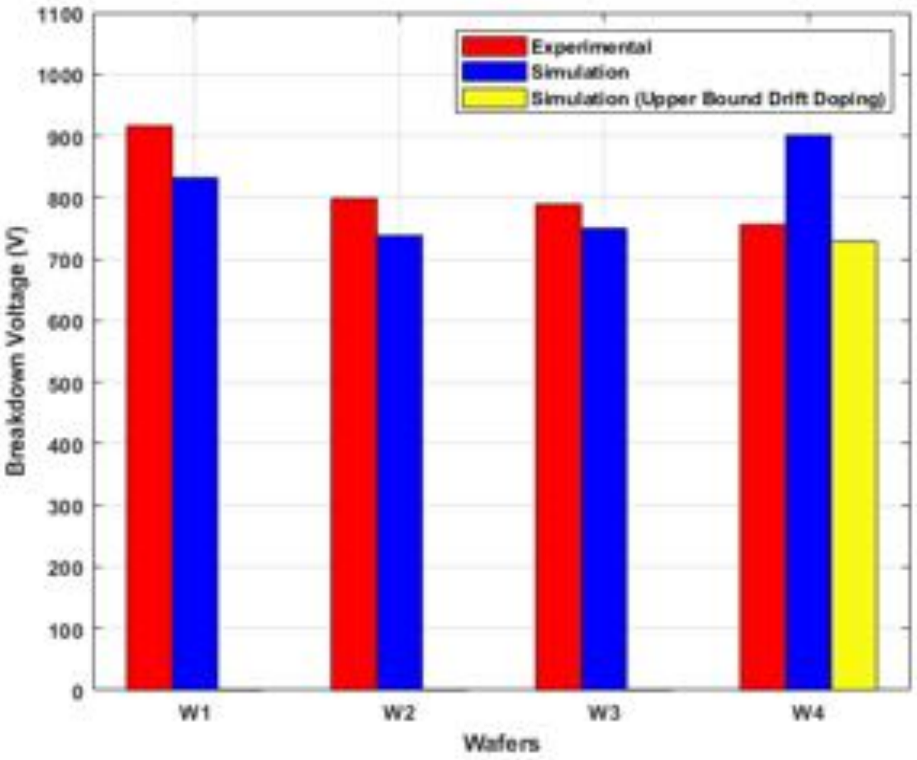
Simulated mesh structure

P. Pandey, T. M. Nelson, W. M. Collings, M. R. Hontz, D. G. Georgiev, A. D. Koehler, T. J. Anderson, J. C. Gallagher, G. M. Foster, A. Jacobs, M. A. Ebrish, B. P. Gunning, R. J. Kaplar, K. D. Hobart, and R. Khanna, "A simple edge termination design for vertical GaN P-N diodes," in *IEEE Transactions on Electron Devices*, vol. 69, no. 9, pp. 5096-5103, September 2022. DOI: 10.1109/TED.2022.3192796

Simple Edge Termination Design

- **Forward and Reverse Characteristics**



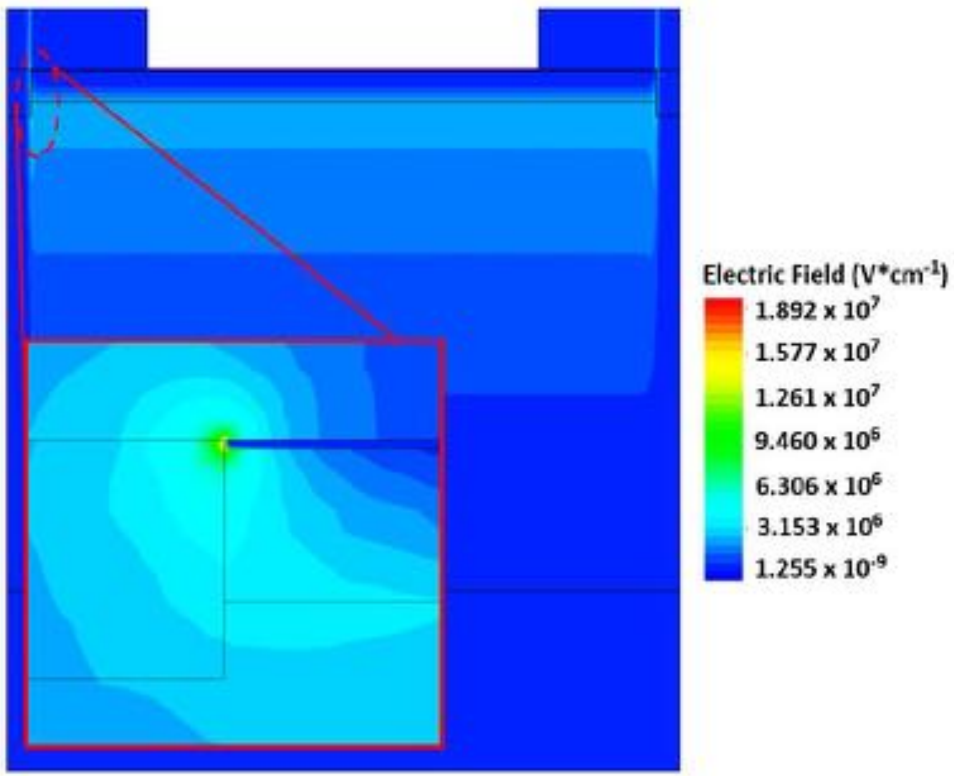


Initially, simulated and experimental breakdown less than anticipated!

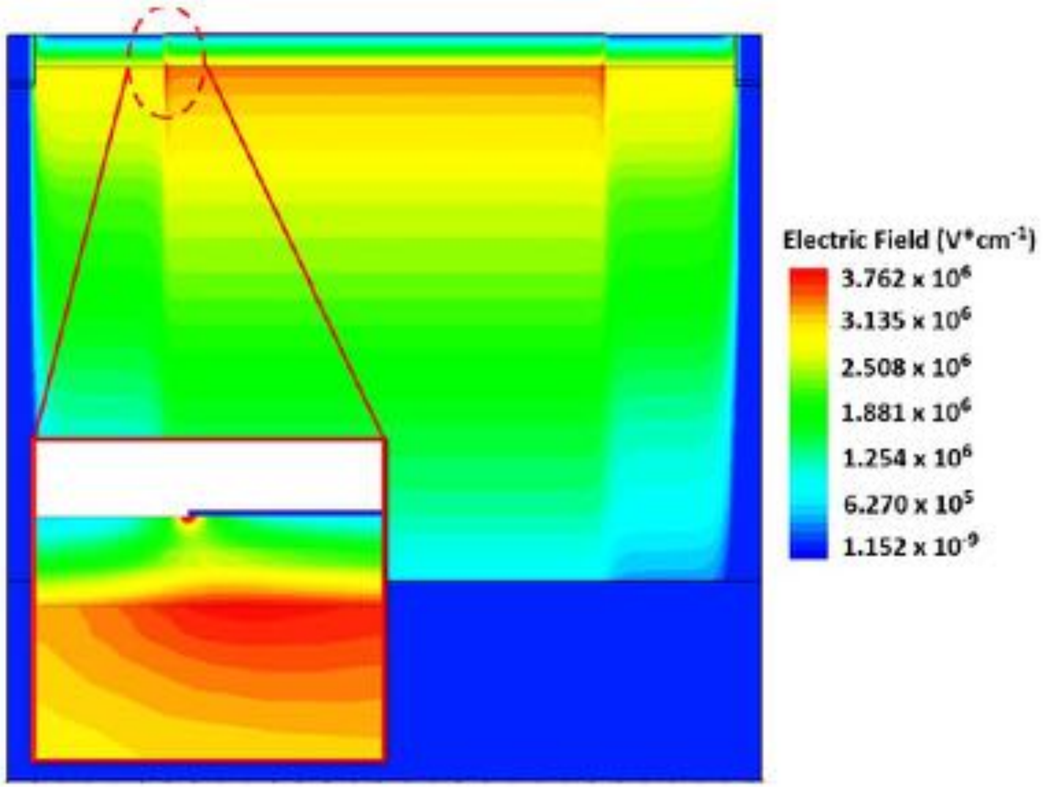
P. Pandey, T. M. Nelson, W. M. Collings, M. R. Hontz, D. G. Georgiev, A. D. Koehler, T. J. Anderson, J. C. Gallagher, G. M. Foster, A. Jacobs, M. A. Ebrish, B. P. Gunning, R. J. Kaplar, K. D. Hobart, and R. Khanna, "A simple edge termination design for vertical GaN P-N diodes," in *IEEE Transactions on Electron Devices*, vol. 69, no. 9, pp. 5096-5103, September 2022. DOI: 10.1109/TED.2022.3192796

Simple Edge Termination Design

- **Simulated electric field distribution at breakdown before and after removal of *p*++ cap**



Before removal: W3 breakdown @ 751 V



After removal: W3 breakdown @ 1796 V

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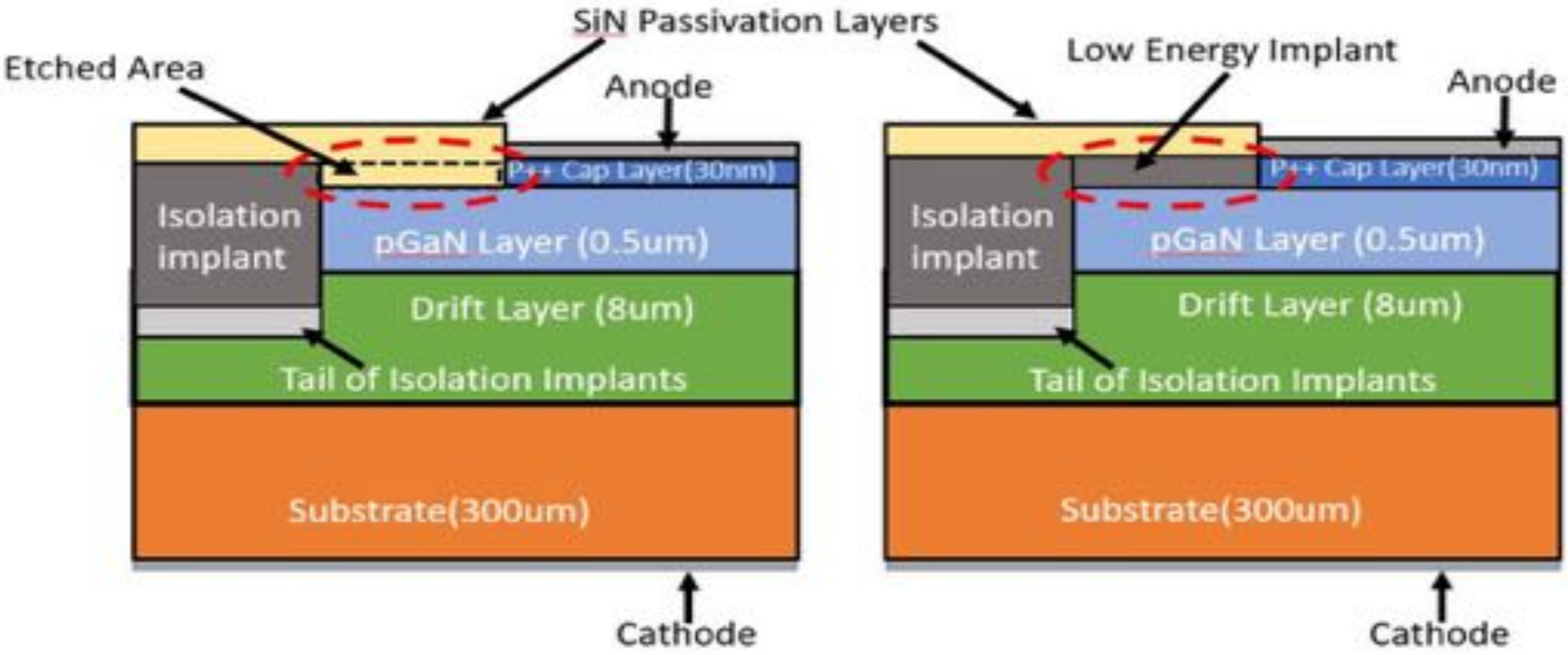
Simple Edge Termination Design

- **Two methods for experimental removal of *p*++ cap: etching vs low energy implant**



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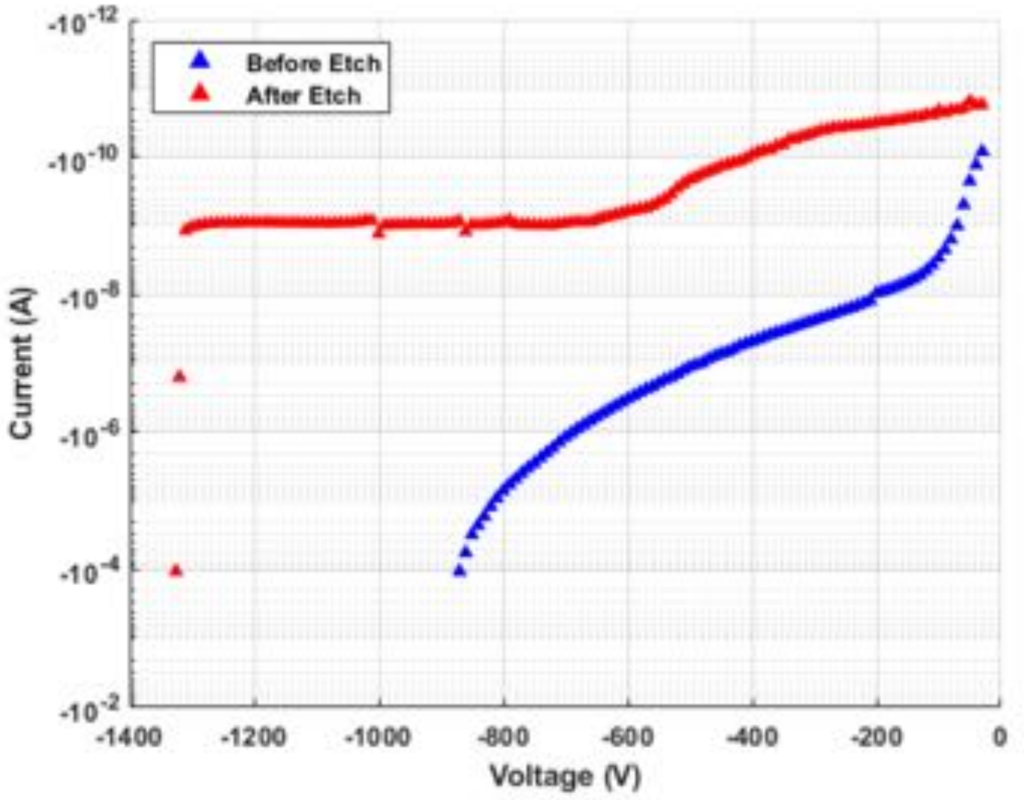
Simple Edge Termination Design

- **Empirical off-state IV measurements demonstrating improvement in leakage current and breakdown voltage after p++ etch. Simulation helped to unveil this new result!**



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Simple Edge Termination Design

- **Summary**
  - Simple edge termination design and model
    - Good agreement with forward characteristics
    - Good agreement with reverse characteristics, before *p*++ removal
  - After removal of *p*++ cap,
    - Simulated breakdown occurs at ~1800 V
    - Empirical breakdown occurs at ~1300 V – However, *simulated* trend is empirically validated.
  - **With the model trends validated, optimization studies can be pursued to improve breakdown capability**

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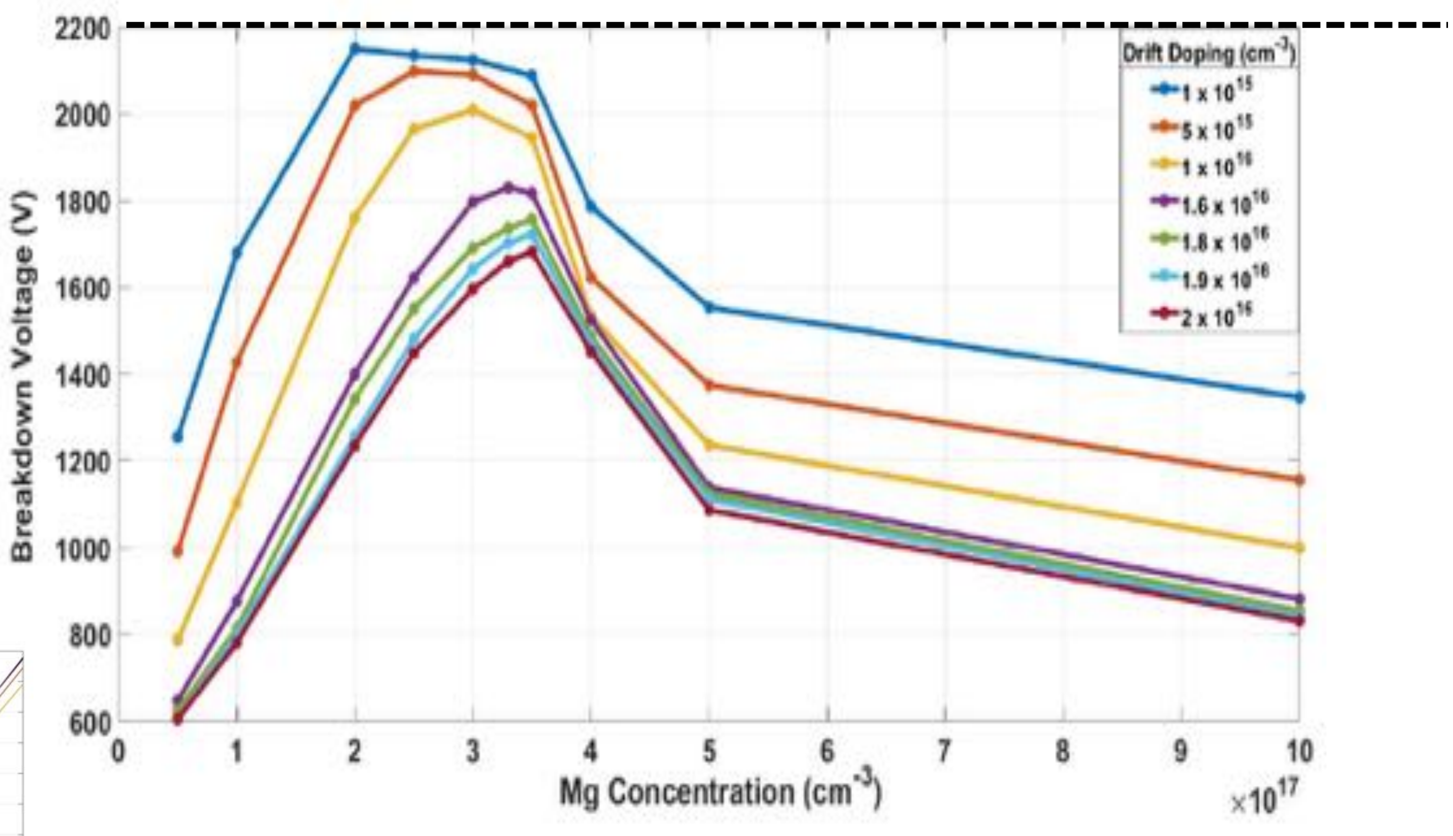
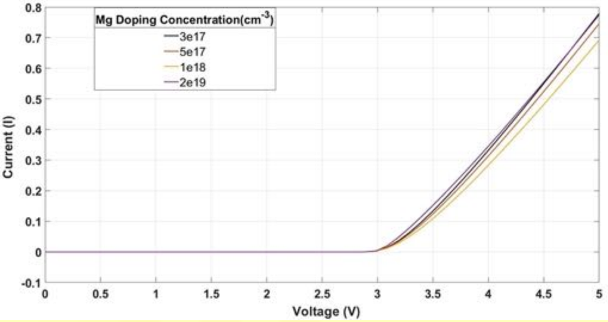
Simple Edge Termination Design

- **Effect of p(Mg) doping and drift-layer doping levels on breakdown**



Parallel Plane Breakdown is 2200 V!



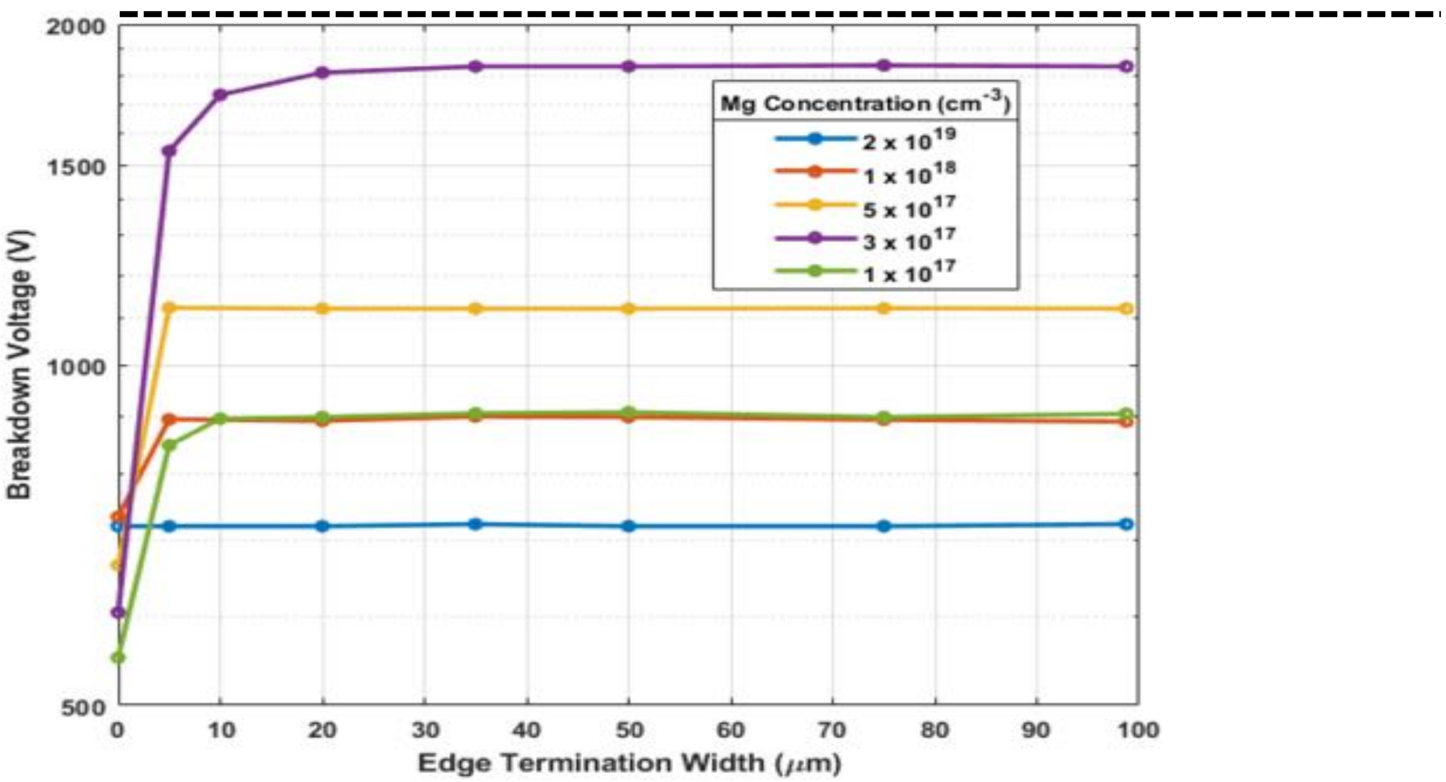
TOLERANCE AND SCALABILITY!

P. Pandey, T. M. Nelson, W. M. Collings, M. R. Hontz, D. G. Georgiev, A. D. Koehler, T. J. Anderson, J. C. Gallagher, G. M. Foster, A. Jacobs, M. A. Ebrish, B. P. Gunning, R. J. Kaplar, K. D. Hobart, and R. Khanna, "A simple edge termination design for vertical GaN P-N diodes," in *IEEE Transactions on Electron Devices*, vol. 69, no. 9, pp. 5096-5103, September 2022. DOI: 10.1109/TED.2022.3192796

Simple Edge Termination Design

- **Effect of p(Mg) doping levels and edge termination width on breakdown**

Parallel Plane Breakdown is 2200 V!

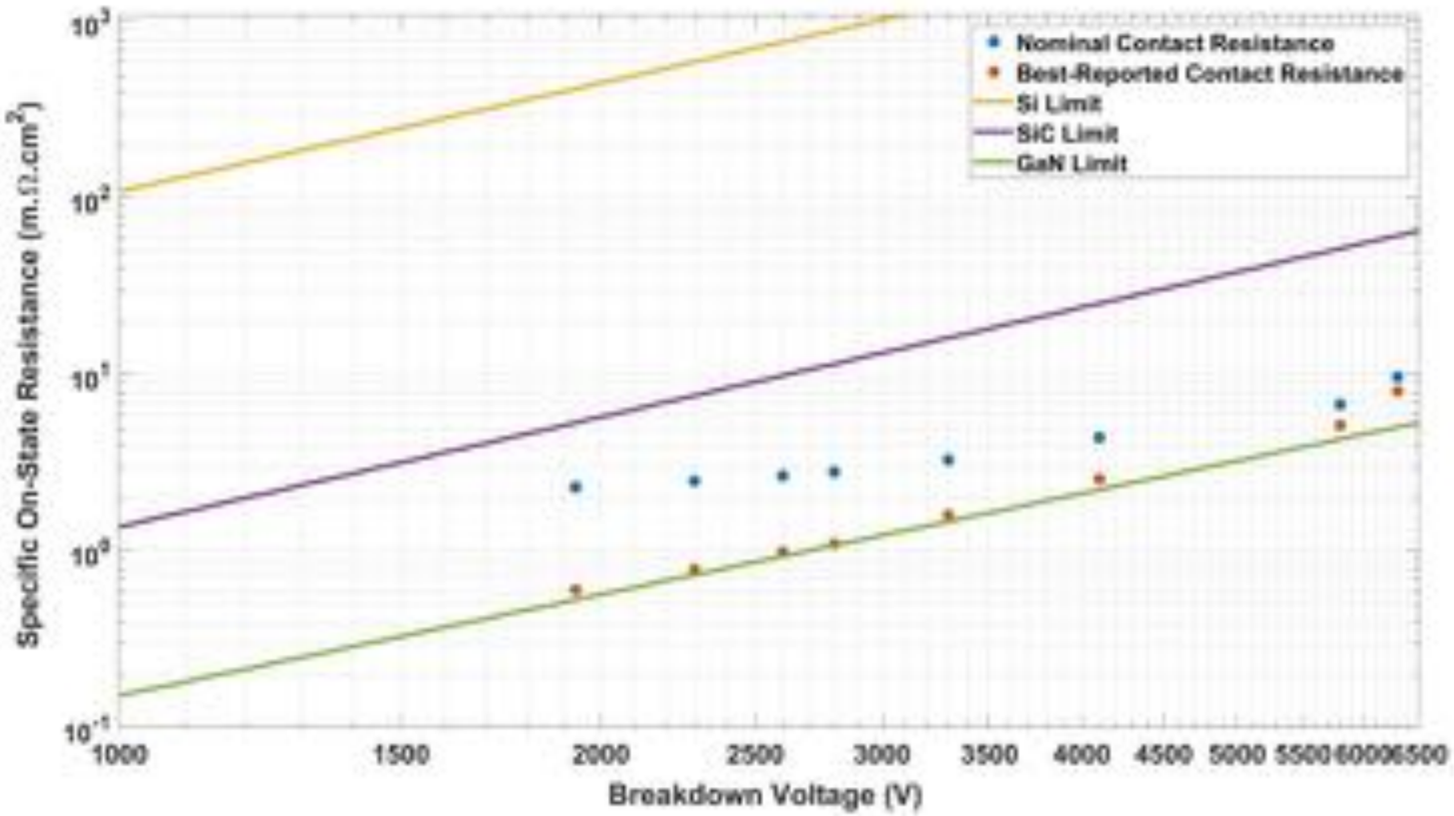


More compact die size ($$ effective)

P. Pandey, T. M. Nelson, W. M. Collings, M. R. Hontz, D. G. Georgiev, A. D. Koehler, T. J. Anderson, J. C. Gallagher, G. M. Foster, A. Jacobs, M. A. Ebrish, B. P. Gunning, R. J. Kaplar, K. D. Hobart, and R. Khanna, "A simple edge termination design for vertical GaN P-N diodes," in *IEEE Transactions on Electron Devices*, vol. 69, no. 9, pp. 5096-5103, September 2022. DOI: 10.1109/TED.2022.3192796

Simple Edge Termination Design

- **BFOM reaching technology performance limit with best reported contact resistance**



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Outline

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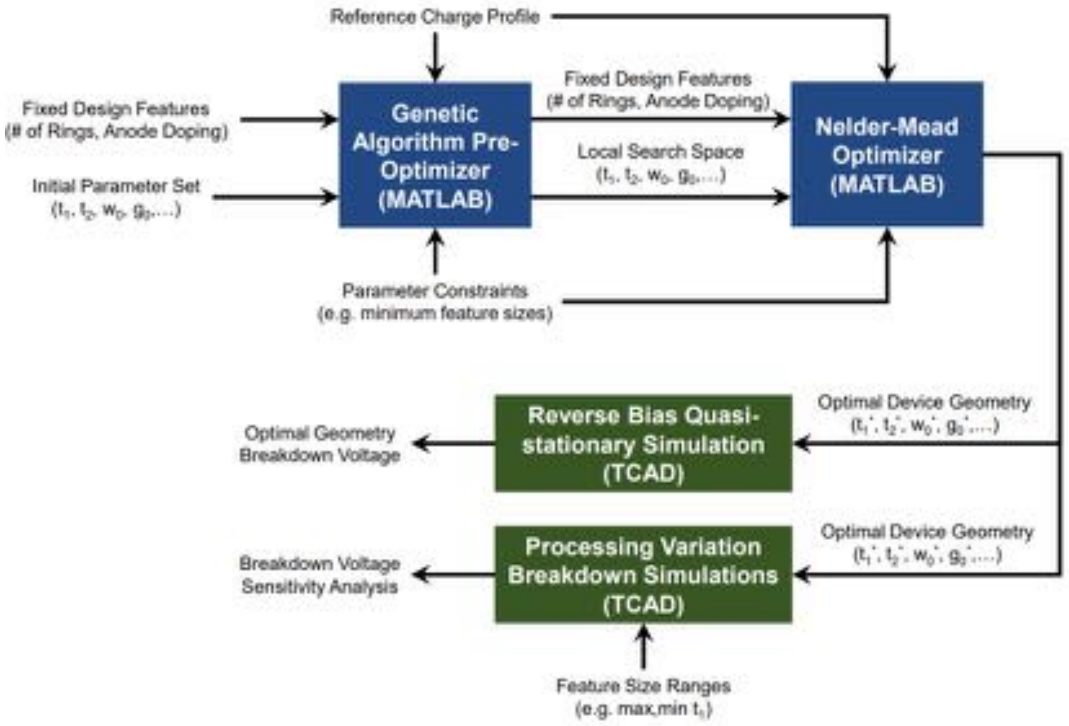
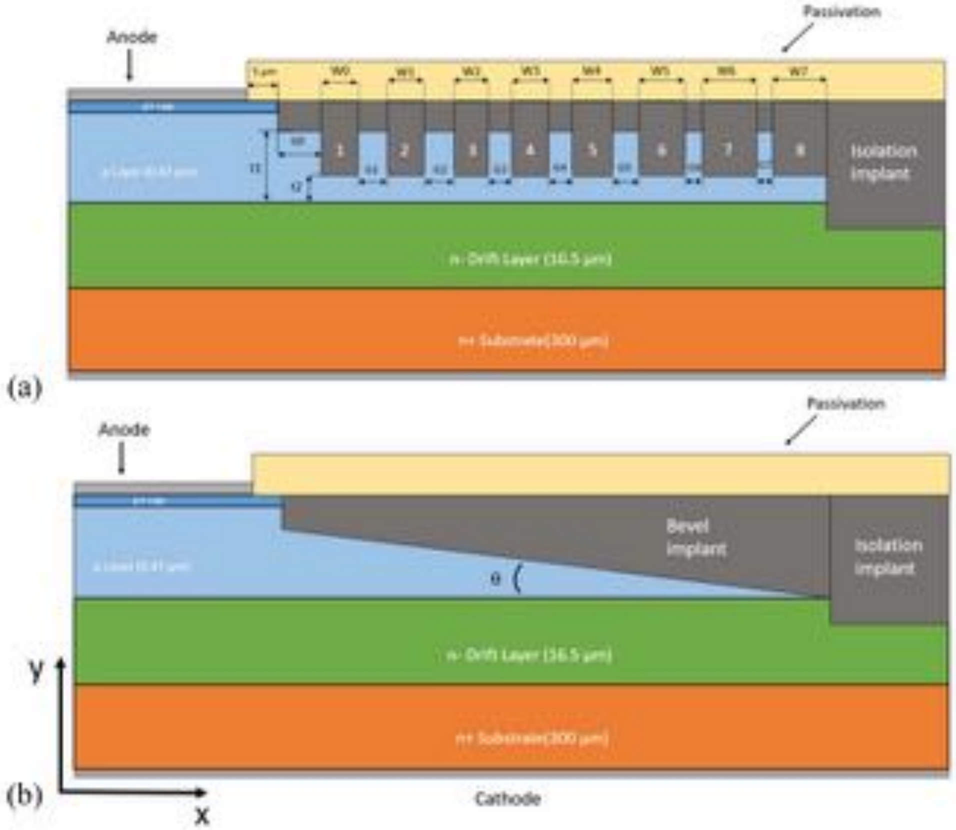
- **Applications of WBGs in Space**
  - MPPT
  - Radiation Intense Environments
- **Future Work**

Hybrid Edge Termination Optimization in GaN

- Hybrid-edge termination with guard rings and junction termination extensions

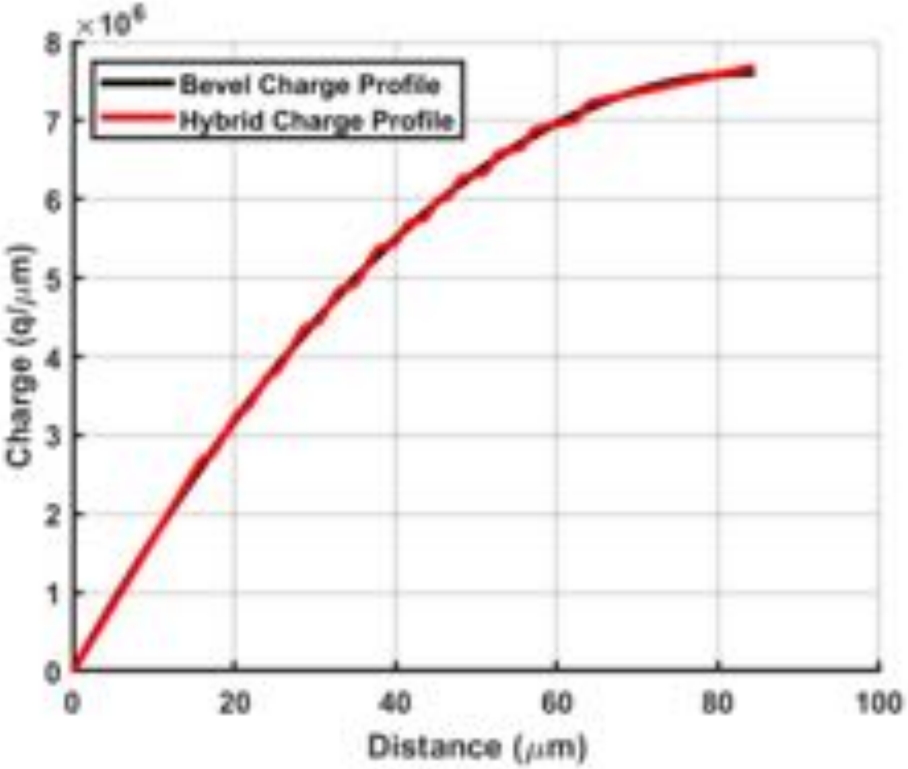




T. M. Nelson, P. Pandey, D. G. Georgiev, M. R. Hontz, A. D. Koehler, K. D. Hobart, T. J. Anderson, A. Ildefonso, and R. Khanna, "Hybrid edge termination in vertical GaN: Approximating beveled edge termination via discrete implantations," in *IEEE Transactions on Electron Devices*, pp. 6940-6947, vol. 69, no. 12, October 2022.
DOI: 10.1109/TED.2022.3215107

Hybrid Edge Termination Optimization in GaN

- Charge profile of bevel fit to HET device. HET device significantly more manufacturable!



$$\rho_{hybrid}(x) = \begin{cases} N_A t_1, & 0 < x < g_0 \\ N_A[t_1 g_0 + t_2(x - g_0)], & g_0 < x < (g_0 + w_0) \\ N_A[t_1(x - w_0) + t_2 w_0], & (g_0 + w_0) < x < (g_0 + w_0 + g_1) \\ N_A[t_1(g_0 + g_1) + t_2(x - (g_0 + g_1))], & (g_0 + w_0 + g1) < x < (g_0 + w_0 + g_1 + w_1) \\ \vdots & \\ N_A\left[t_1 \sum_{i=0}^{n-1} g_i + t_2\left(x - \sum_{i=0}^{n-1} g_i\right)\right], & \left(\sum_{i=0}^{n-2}(g_i + w_i) + g_{n-1}\right) < x < \left(\sum_{i=0}^{n-1}(g_i + w_i)\right) \end{cases} \quad (4)$$

T. M. Nelson, P. Pandey, D. G. Georgiev, M. R. Hontz, A. D. Koehler, K. D. Hobart, T. J. Anderson, A. Ildefonso, and R. Khanna, "Hybrid edge termination in vertical GaN: Approximating beveled edge termination via discrete implantations," in *IEEE Transactions on Electron Devices*, pp. 6940-6947, vol. 69, no. 12, October 2022.
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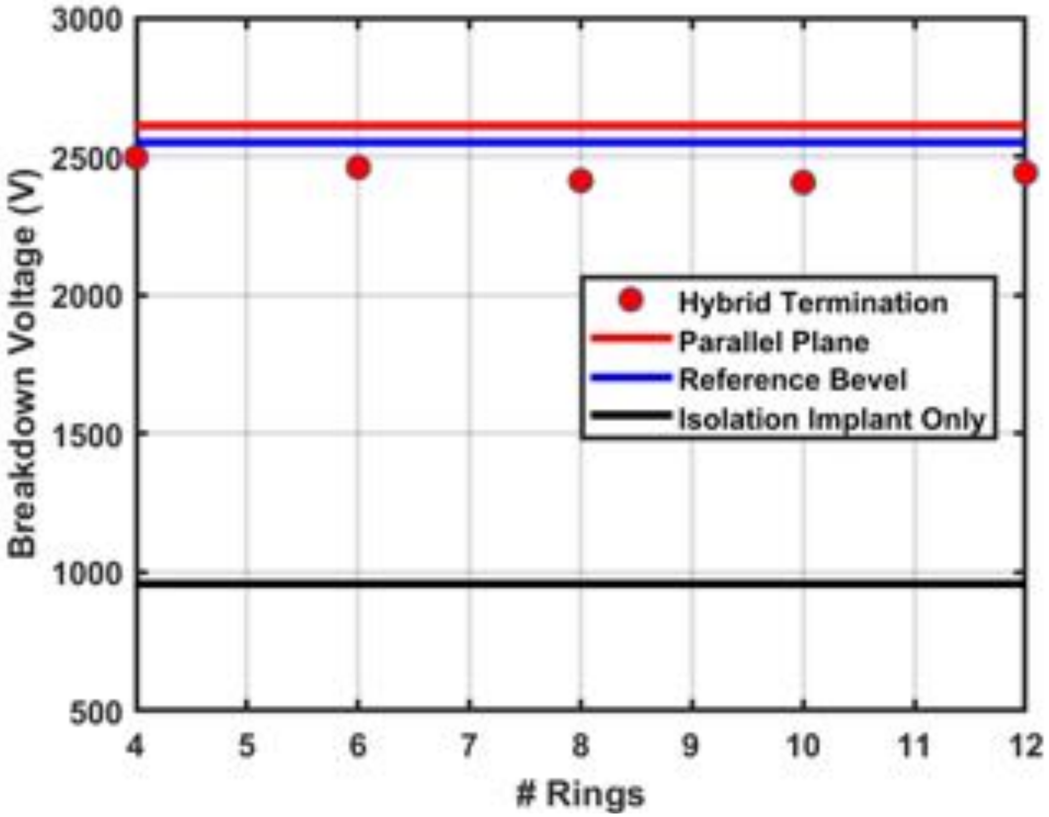
Hybrid Edge Termination Optimization in GaN

- Breakdown voltage vs number of rings



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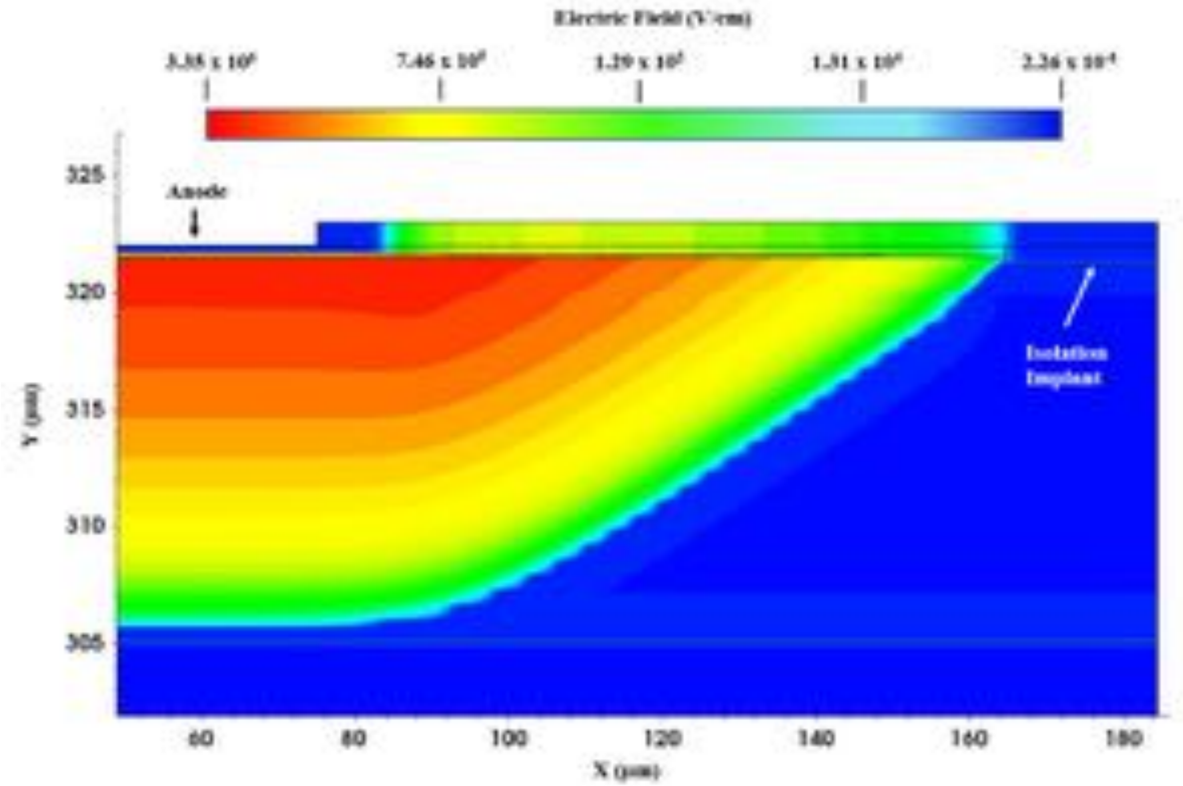
Hybrid Edge Termination Optimization in GaN

- E-field distribution for reference bevel. Breakdown at 2550 V



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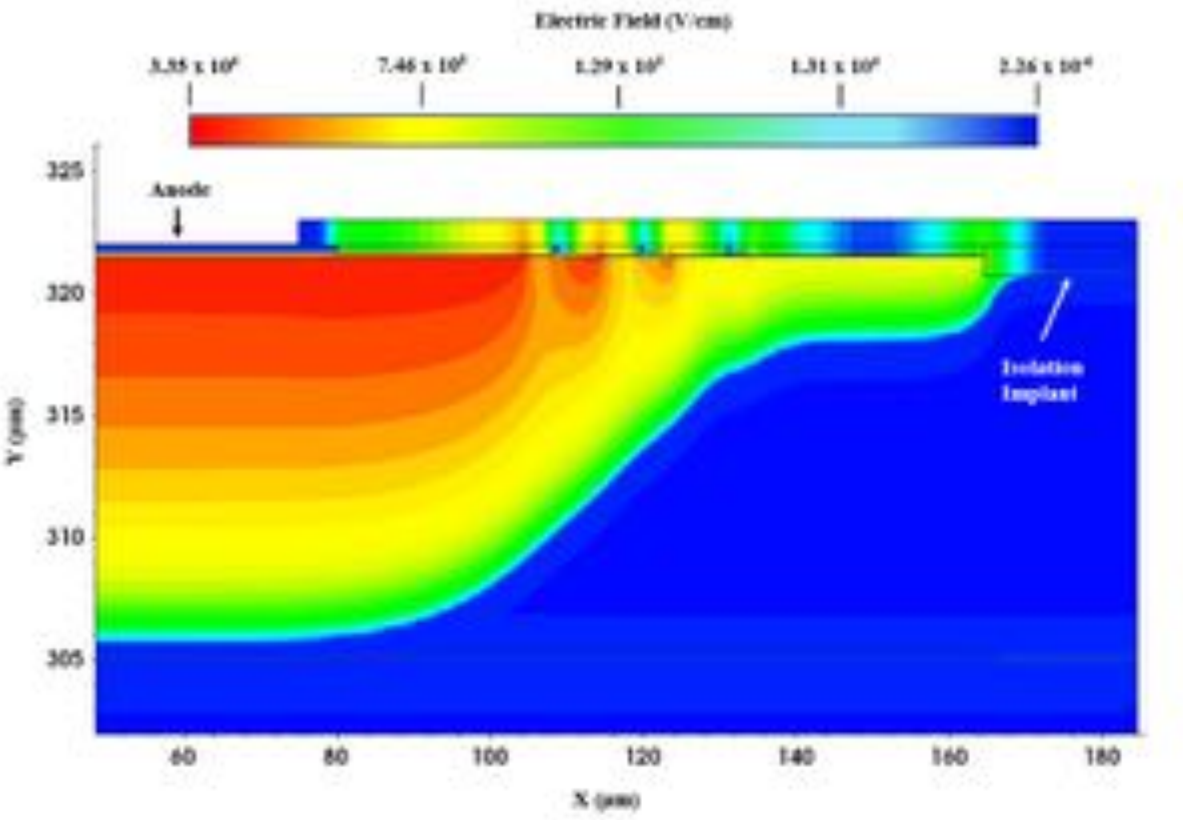
Hybrid Edge Termination Optimization in GaN

- E-field distribution for 4 ring-structure. Breakdown at 2496 V.



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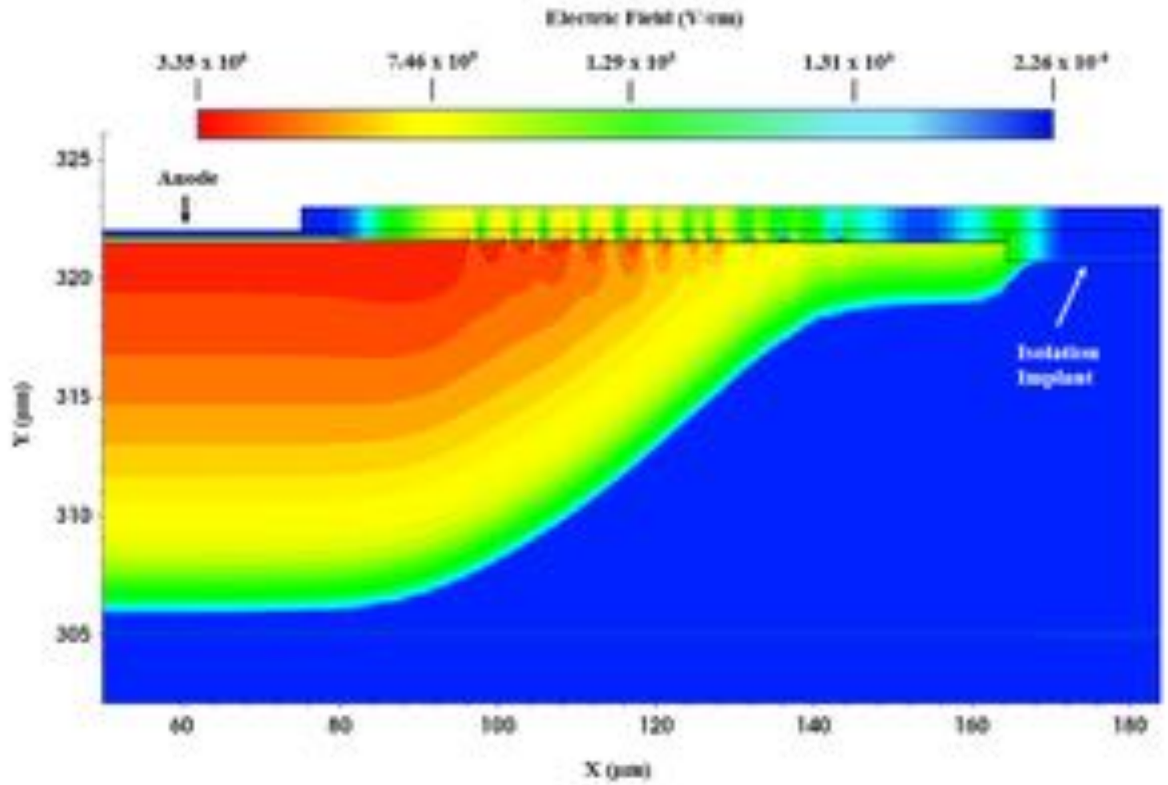
Hybrid Edge Termination Optimization in GaN

- E-field distribution for 12-ring structure. Breakdown at 2441 V.



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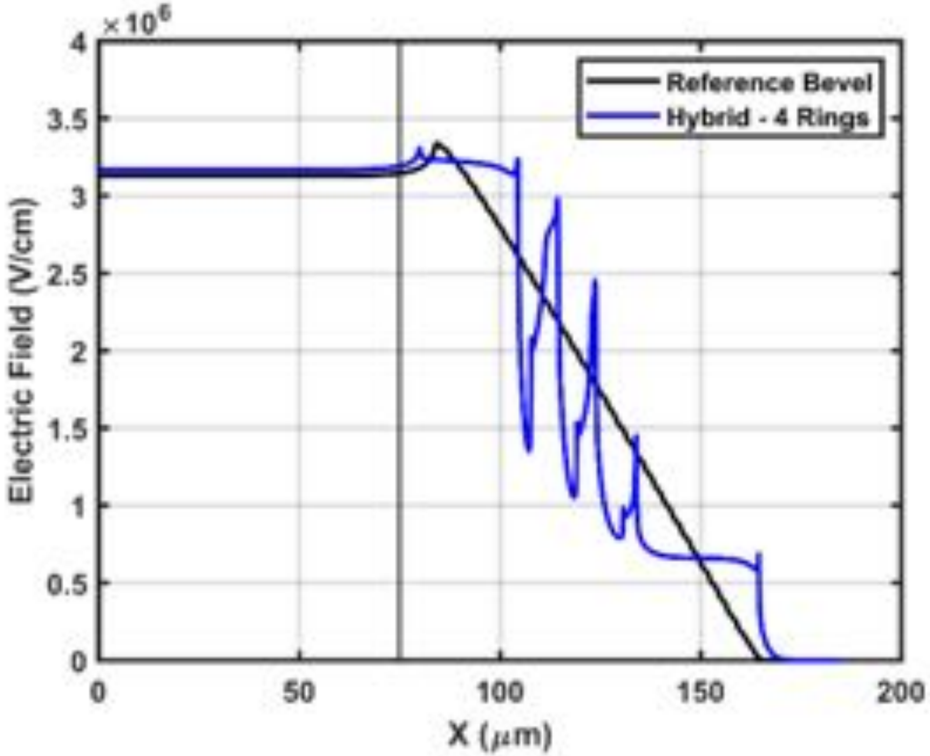
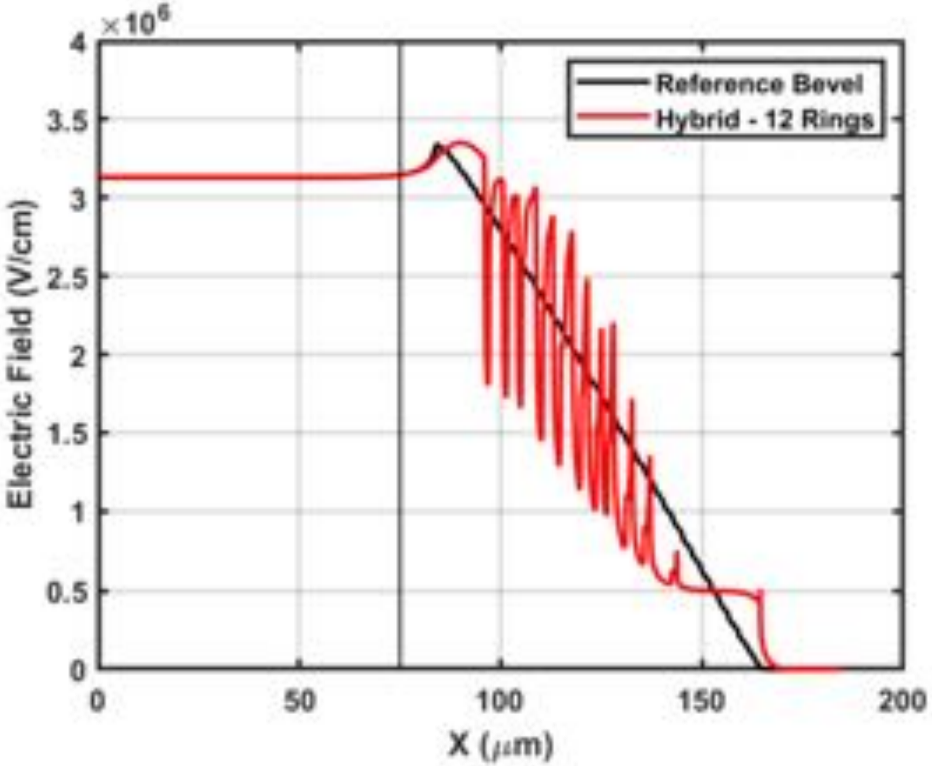
Hybrid Edge Termination Optimization in GaN

- Electric field distribution vs length along the p-n junction





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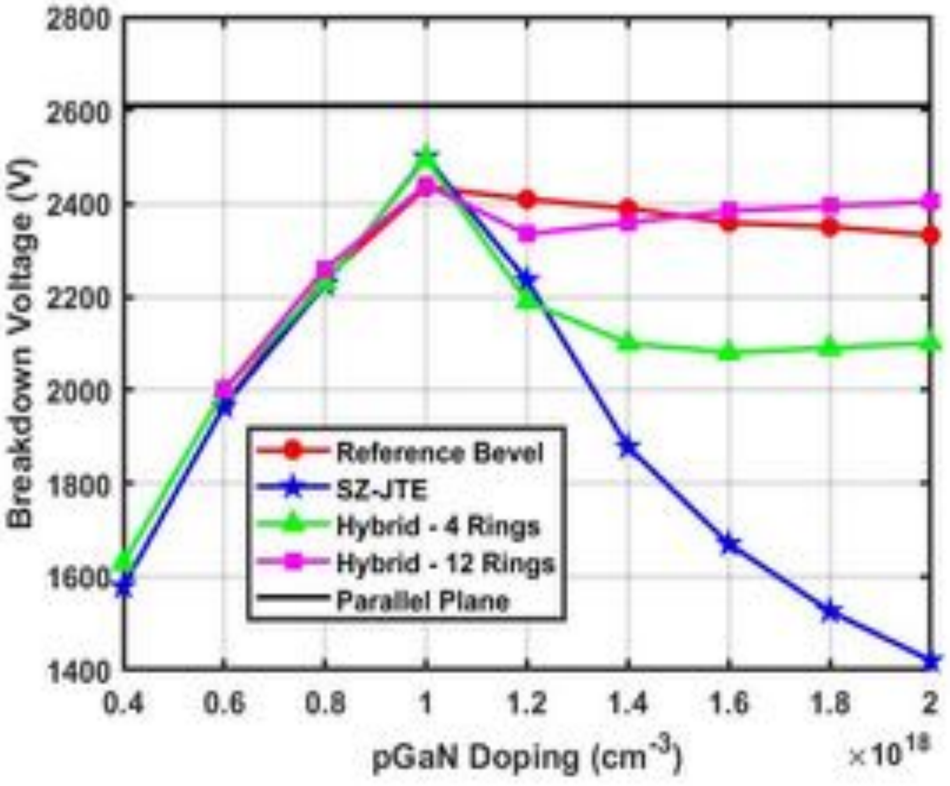
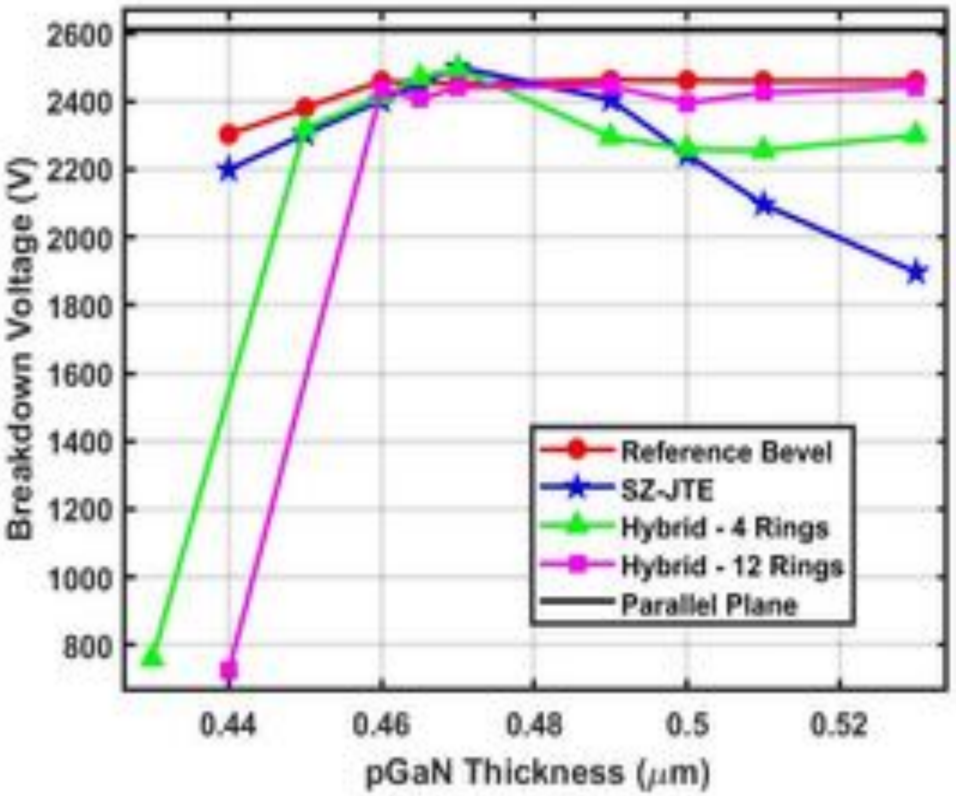
Hybrid Edge Termination Optimization in GaN

- Process tolerance





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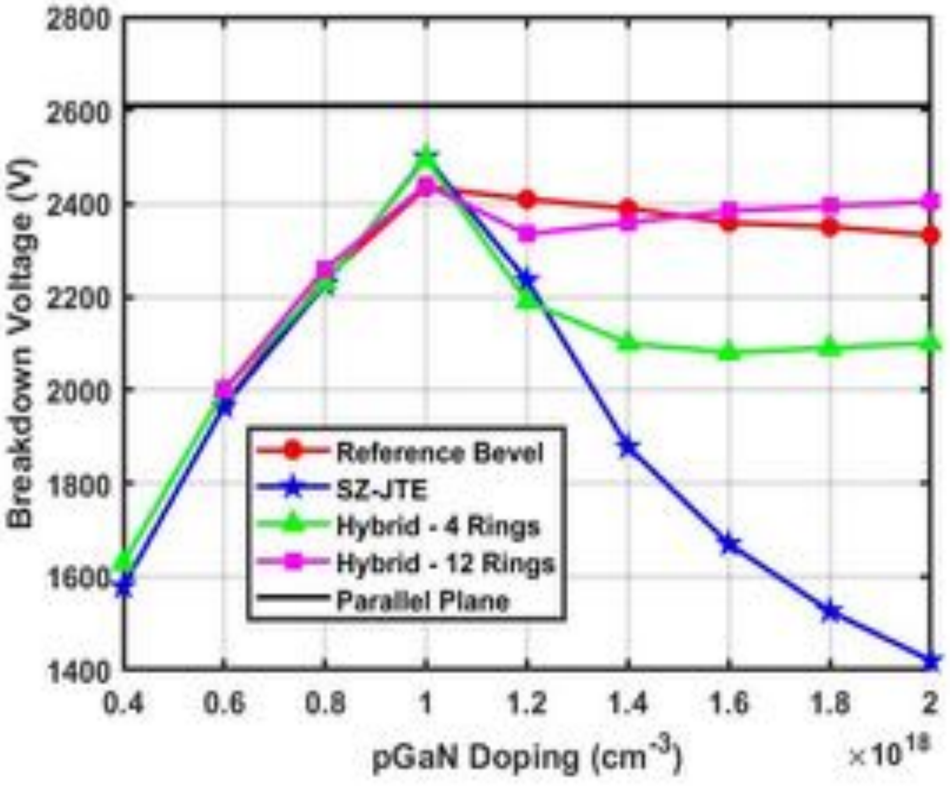

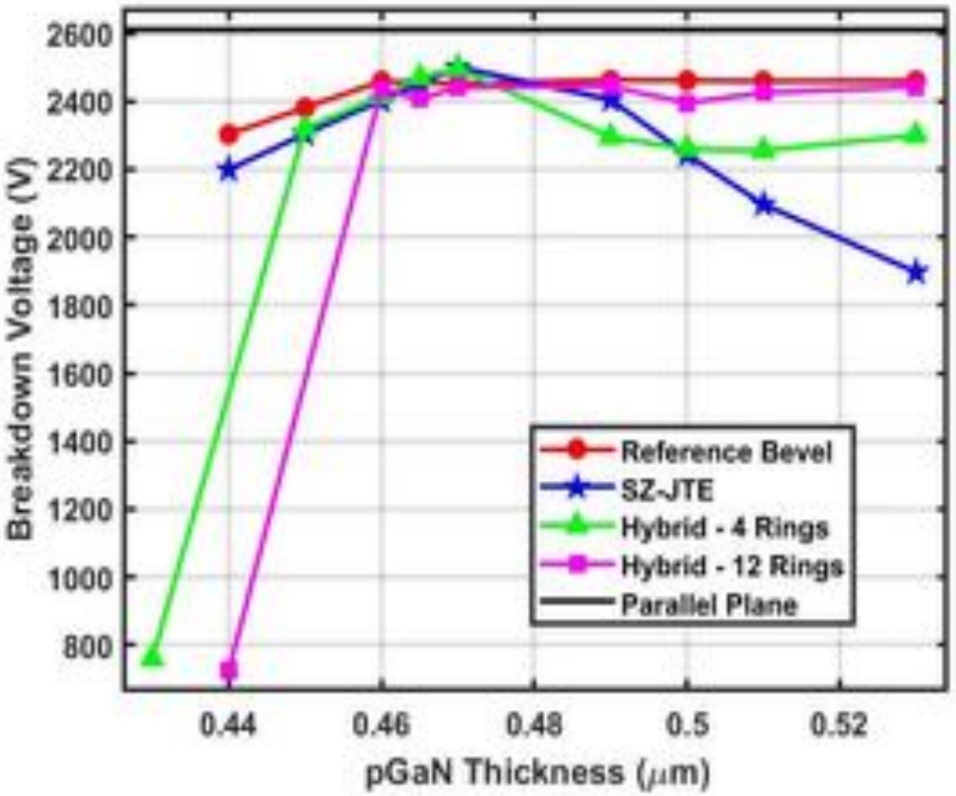

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Behavioral Modeling of SiC MOSFETs

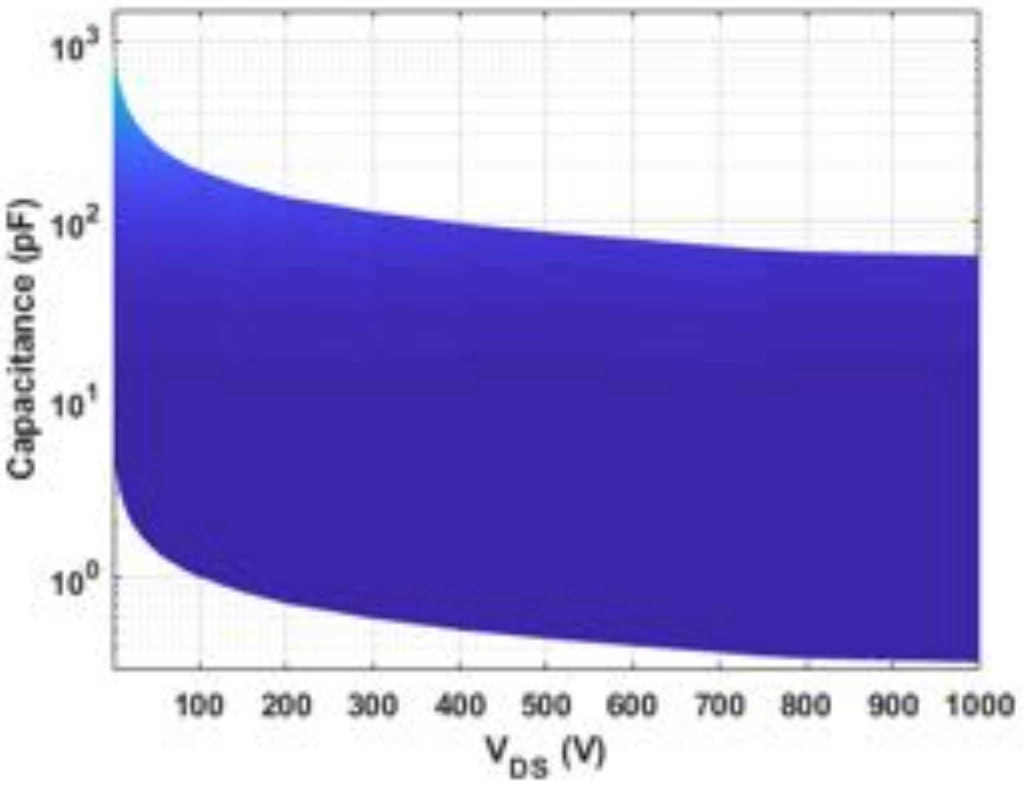
- **Limitations with existing behavioral models**
  - Unable to fully capture high slew rates, ringing frequencies, capacitive dispersion and other high-frequency effects

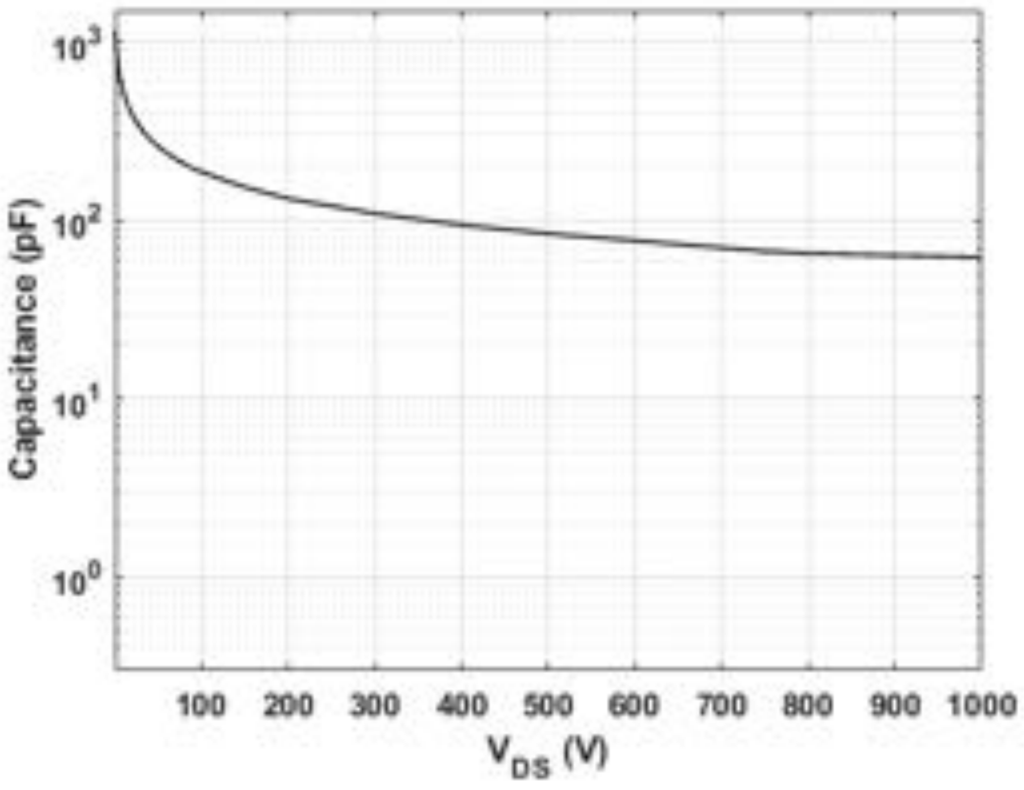
"When the time-domain waveforms are measured at high frequencies, the contribution of the channel current is mixed with the one arising from the transistor's nonlinear capacitances and (is) therefore not distinguishable. DC measurements can be used as (a) starting point for the modeling of channel current. Nevertheless, for transistors fabricated with compound semiconductors, the channel current measured under static conditions may differ from the one measured under dynamic conditions due to dispersive phenomena, such as charge trapping mechanism."

*Taken from I. Angelov et al. "Hybrid measurement-based extraction of consistent large-signal models for microwave FETs," in *2013 IEEE European Microwave Conference,* Nuremberg, Germany, pp. 267-270, October 2013.

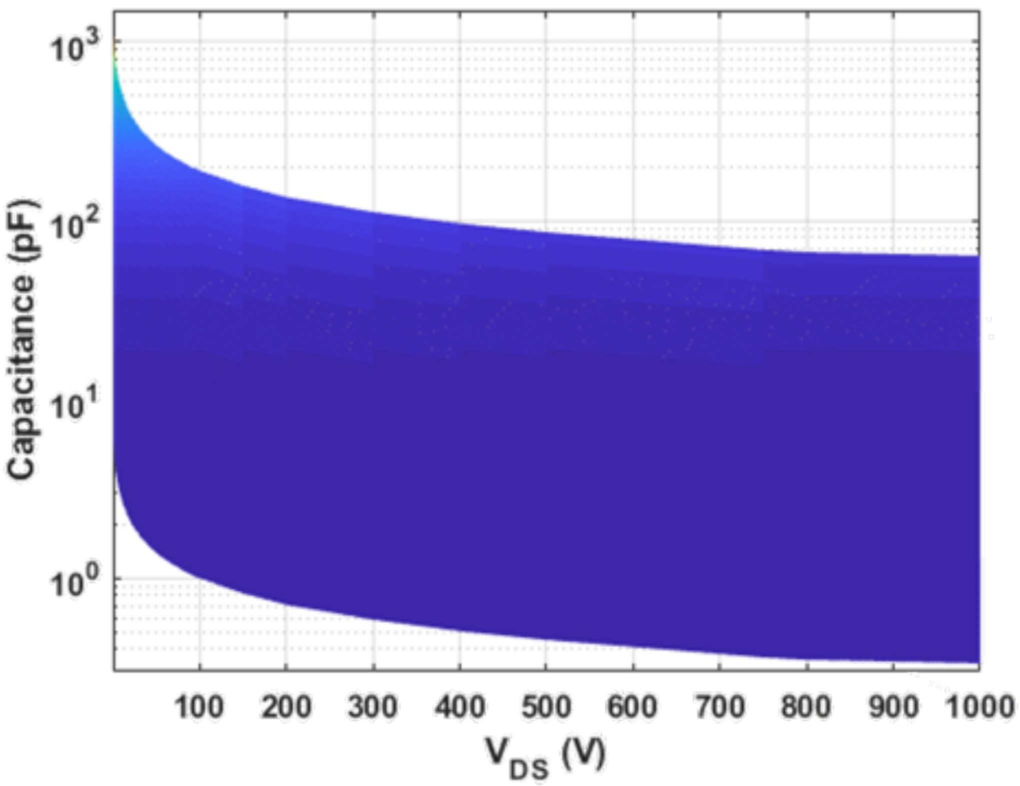
Behavioral Modeling of SiC MOSFETs

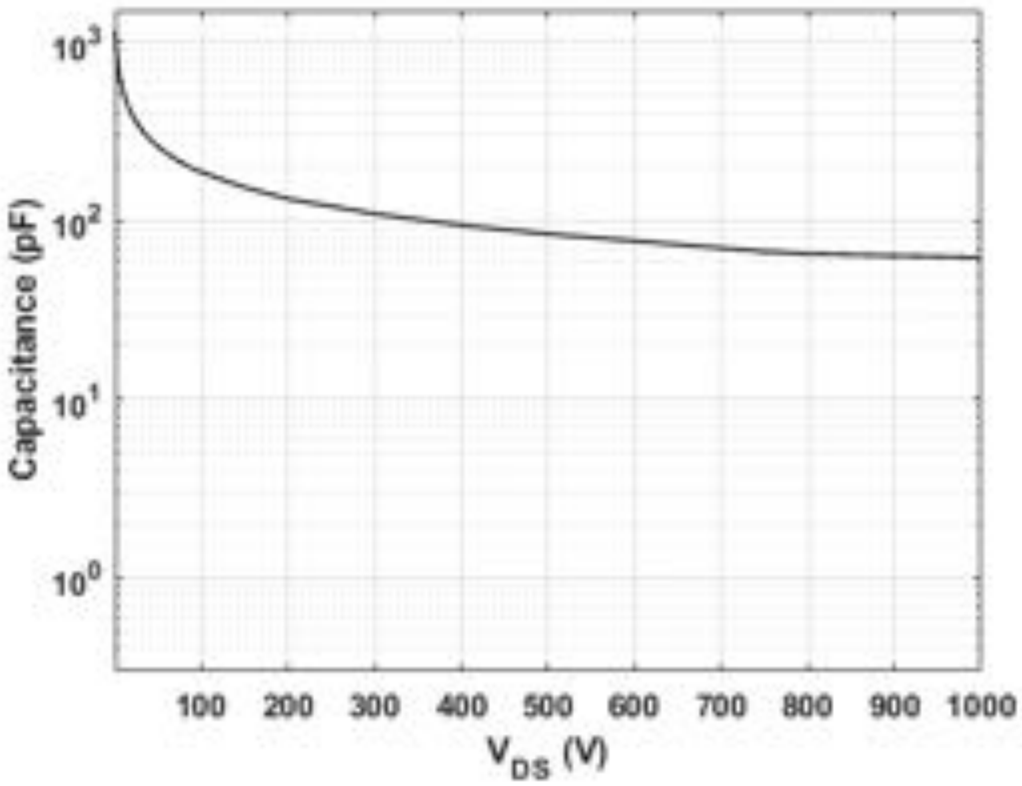
- **Capacitive dispersion**



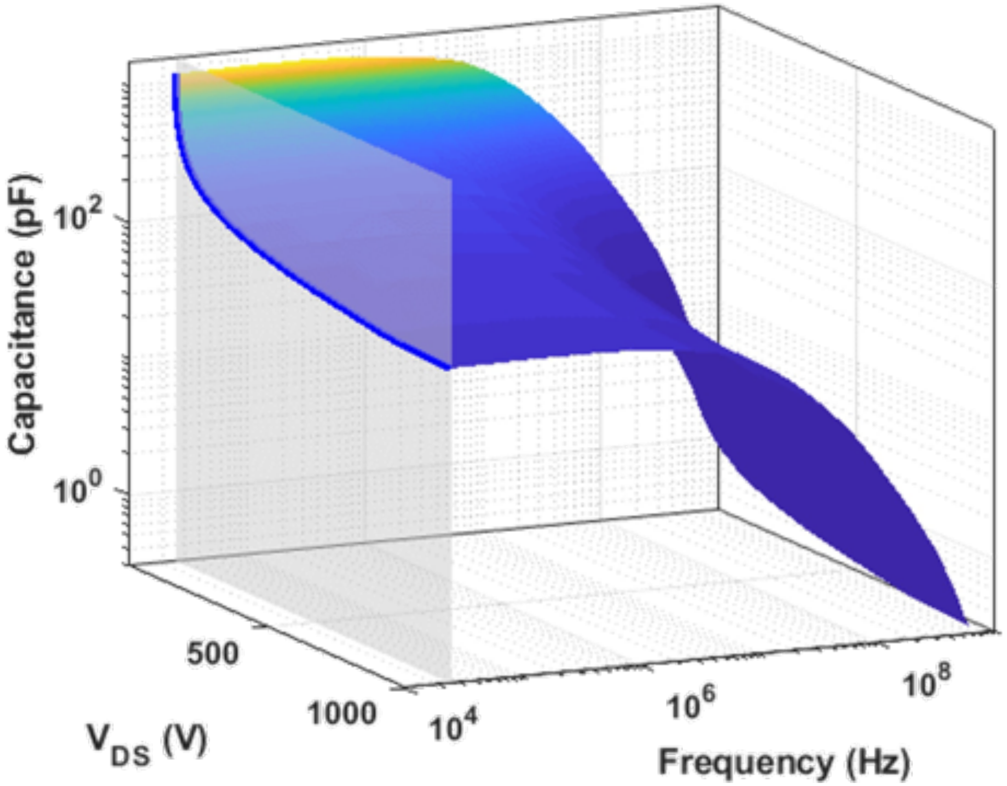


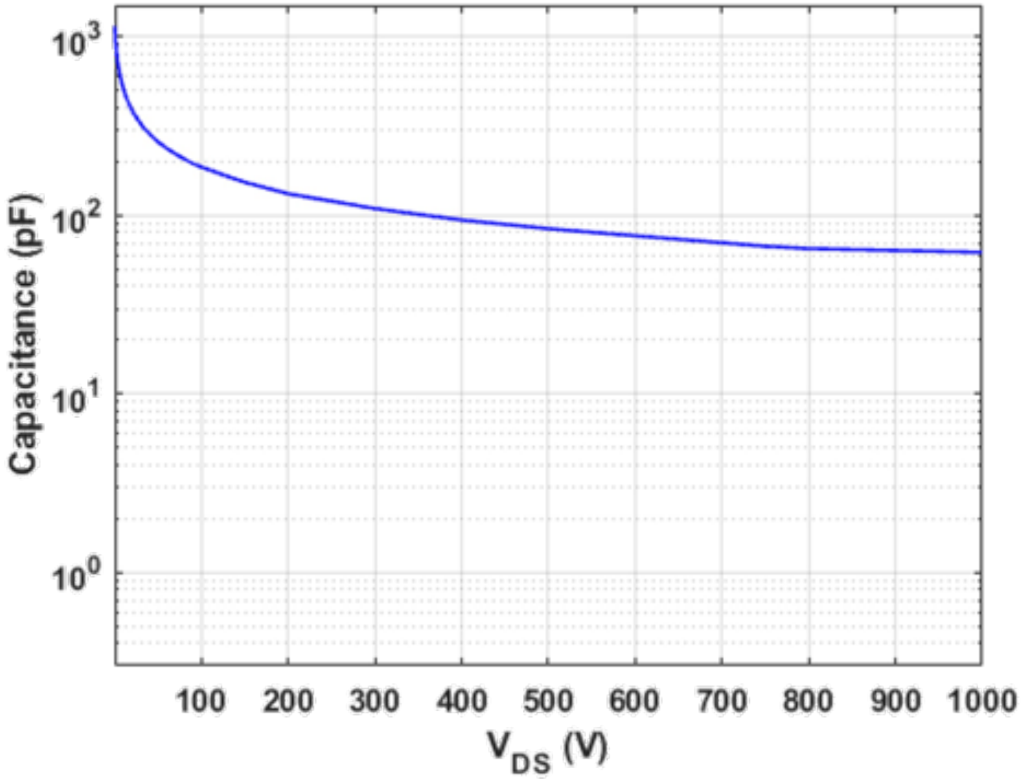
Behavioral Modeling of SiC MOSFETs



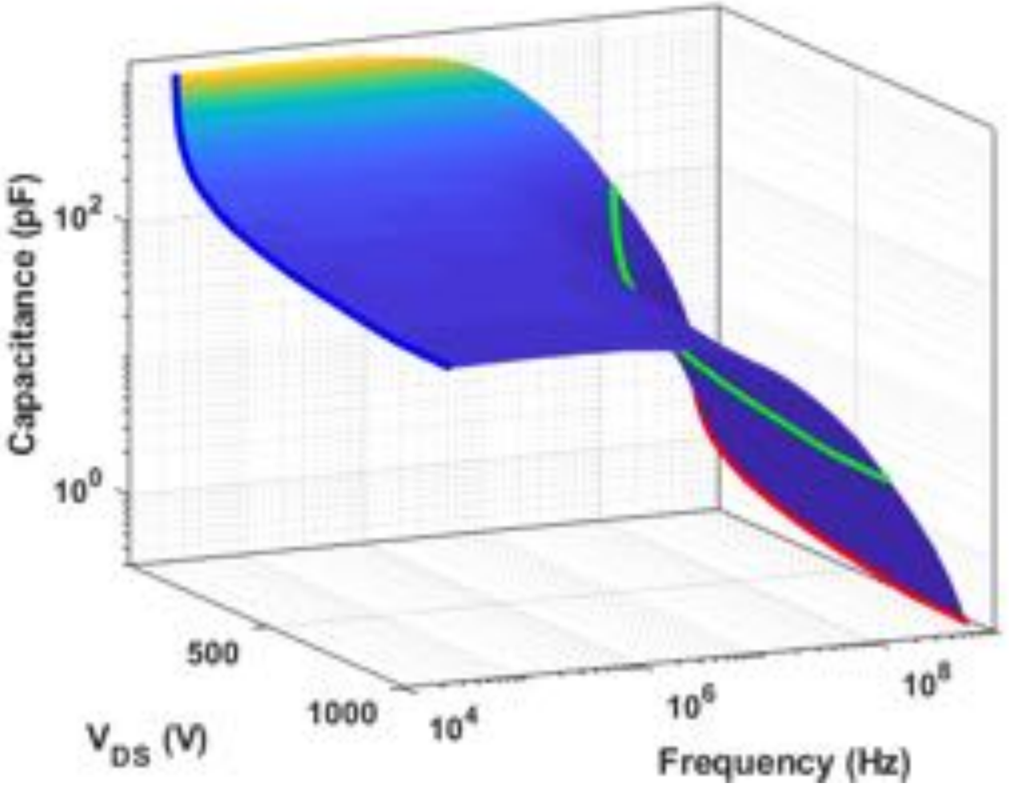


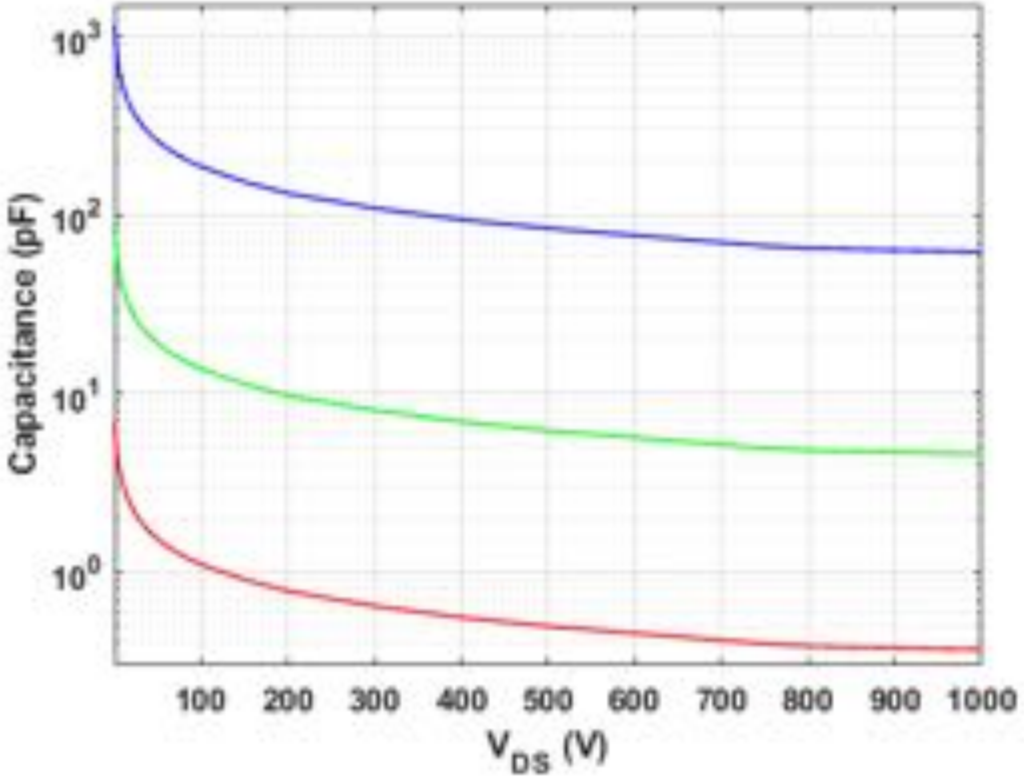
Behavioral Modeling of SiC MOSFETs



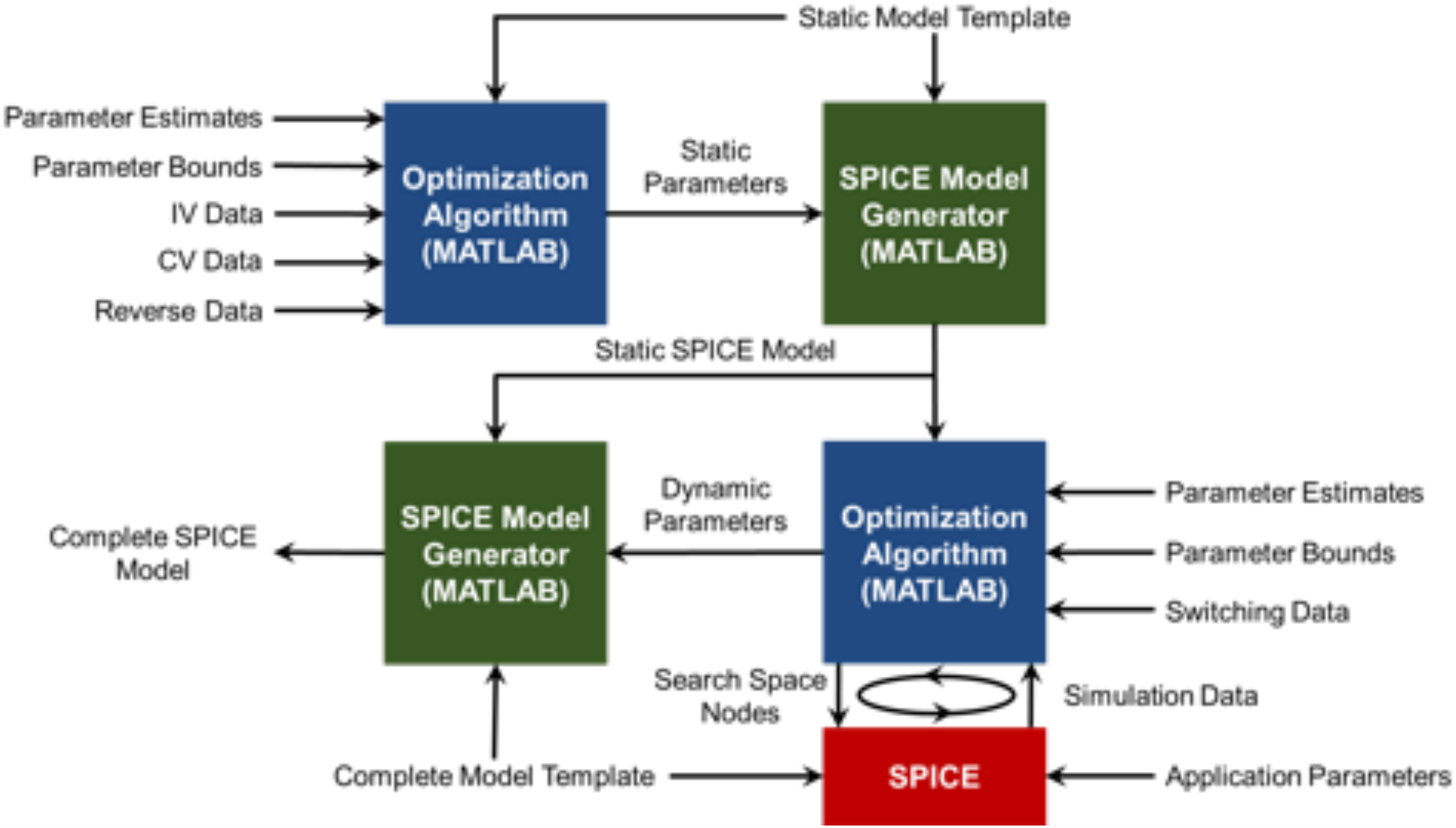


Behavioral Modeling of SiC MOSFETs





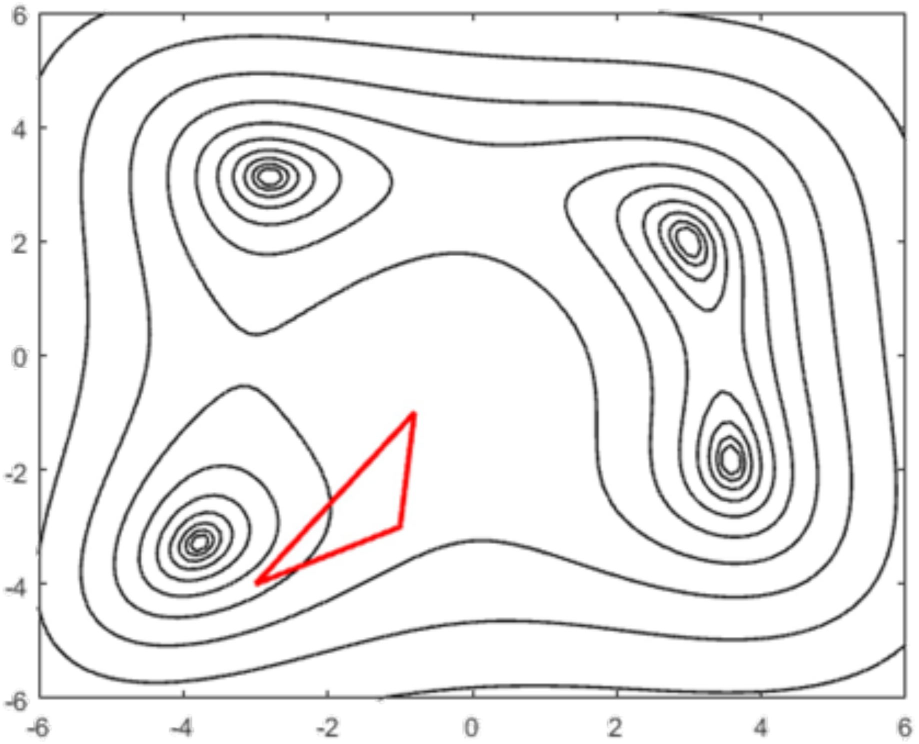
Behavioral Modeling of SiC MOSFETs



A. J. Sellers, M. R. Hontz, **R. Khanna**, A. N. Lemmon, B. T. Deboi, and A. Shahabi, "An automated model tuning procedure for optimizing prediction of dispersive behavior in wide bandgap semiconductor FETs," in *IEEE Transactions on Power Electronics*, vol. 35, no. 11, pp. 12252-12263, November 2020. DOI: 10.1109/TPEL.2020.2986928

Behavioral Modeling of SiC MOSFETs

Algorithm 1: **The Downhill Simplex Algorithm**	
1:	Order the test points in ascending cost order as $f(\mathbf{x}_1) \le f(\mathbf{x}_2) \le \ldots \le f(\mathbf{x}_{n+1})$
2:	Calculate the centroid, $\mathbf{x}_o$, of all test points except $\mathbf{x}_{n+1}$
3:	Calculate a reflected point as $\mathbf{x}_r = \mathbf{x}_o + \alpha(\mathbf{x}_o - \mathbf{x}_{n+1})$ with $\alpha > 0$
	if $f(\mathbf{x}_1) \le f(\mathbf{x}_r) \le f(\mathbf{x}_n)$ i.e. new point is between best and second worst
	then obtain a new simplex by replacing $\mathbf{x}_{n+1}$ with $\mathbf{x}_r$ and go to step 1
4:	**if** the reflected point is the best point so far, that is $f(\mathbf{x}_r) < f(\mathbf{x}_1)$
	then compute an expanded point as $\mathbf{x}_e = \mathbf{x}_o + \gamma(\mathbf{x}_r - \mathbf{x}_o)$ with $\gamma > 1$
	if the expanded point is better than the reflected, i.e. $f(\mathbf{x}_e) < f(\mathbf{x}_r)$
	then obtain a new simplex by replacing $\mathbf{x}_{n+1}$ with $\mathbf{x}_e$ and go to step 1
	else obtain a new simplex by replacing $\mathbf{x}_{n+1}$ with $\mathbf{x}_r$ and go to step 1
5:	It is now certain that $f(\mathbf{x}_r) \ge f(\mathbf{x}_n)$
	then compute a contracted point as $\mathbf{x}_c = \mathbf{x}_o + \rho(\mathbf{x}_{n+1} - \mathbf{x}_o)$ with $0 \le \rho \le 0.5$
	if contracted point is better than the worst point, that is $f(\mathbf{x}_c) < f(\mathbf{x}_{n+1})$
	then obtain a new simplex by replacing $\mathbf{x}_{n+1}$ with $\mathbf{x}_c$ and go to step 1
6:	**else** replace all points except $\mathbf{x}_1$ with $\mathbf{x}_i = \mathbf{x}_1 + \sigma(\mathbf{x}_i - \mathbf{x}_1)$ and go to step 1



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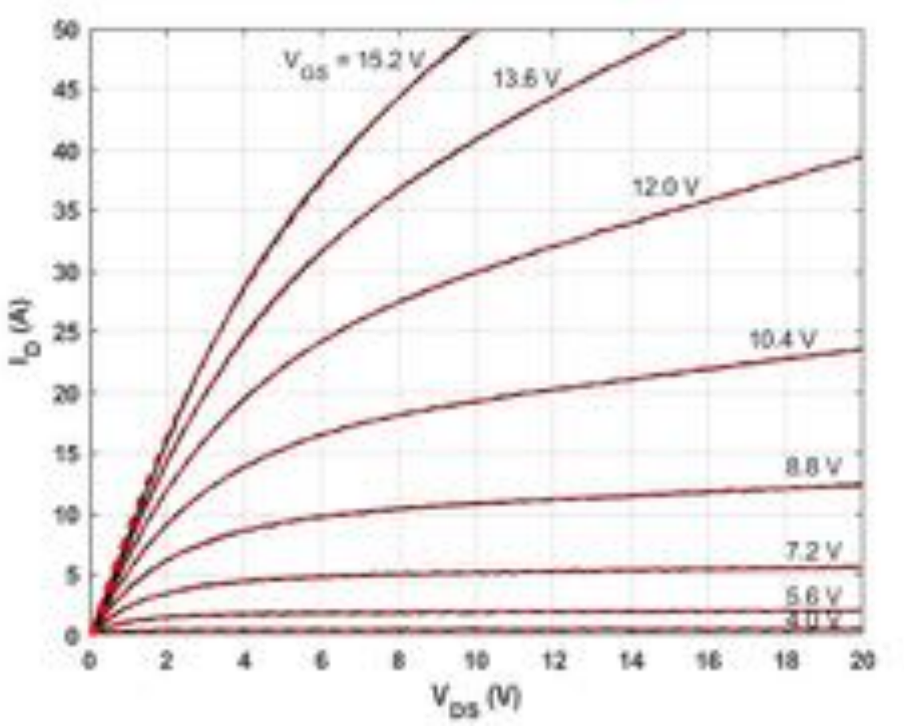
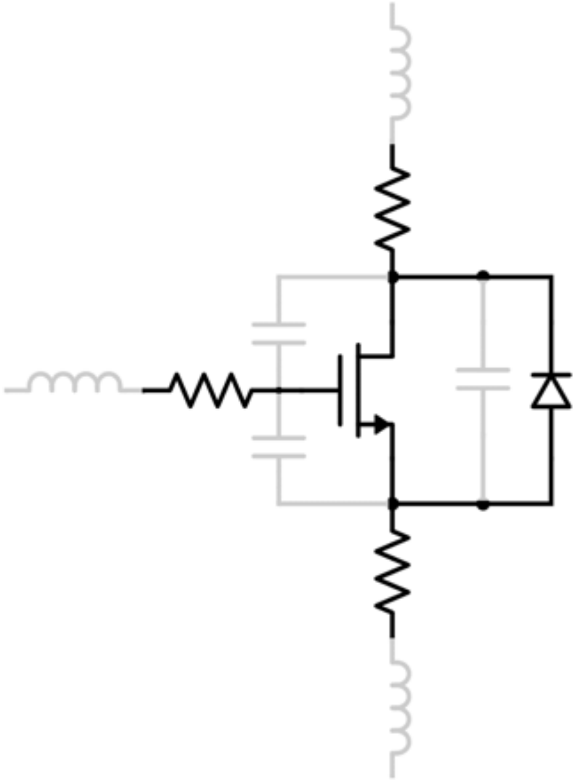
Behavioral Modeling of SiC MOSFETs

- **IV forward/output curves a 1.2 kV SiC MOSFET using conventional model but with Downhill Simplex Algorithm**





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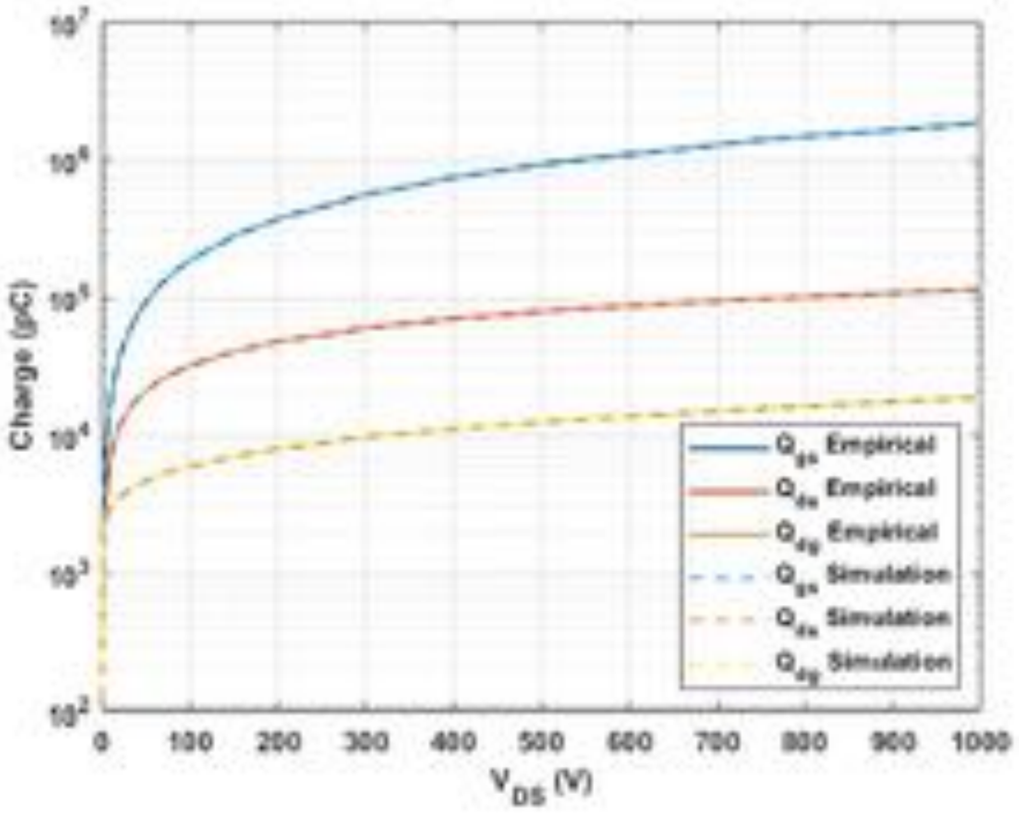
Behavioral Modeling of SiC MOSFETs

- **Using conventional model with Downhill Simplex to simulate capacitance and charge**



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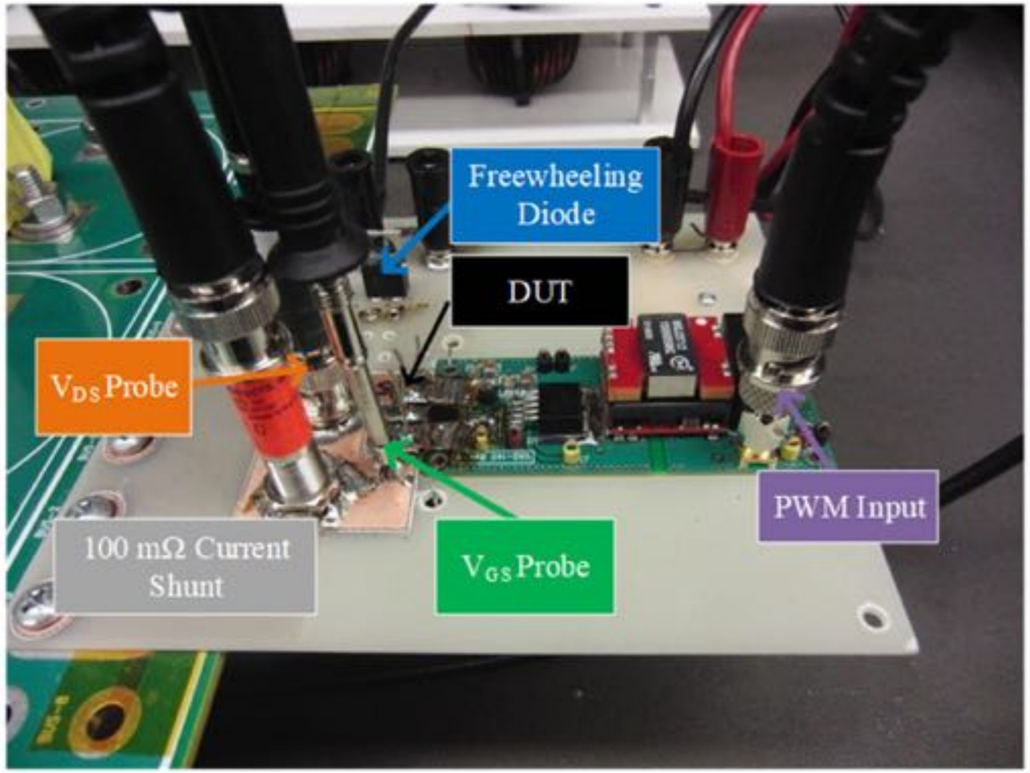
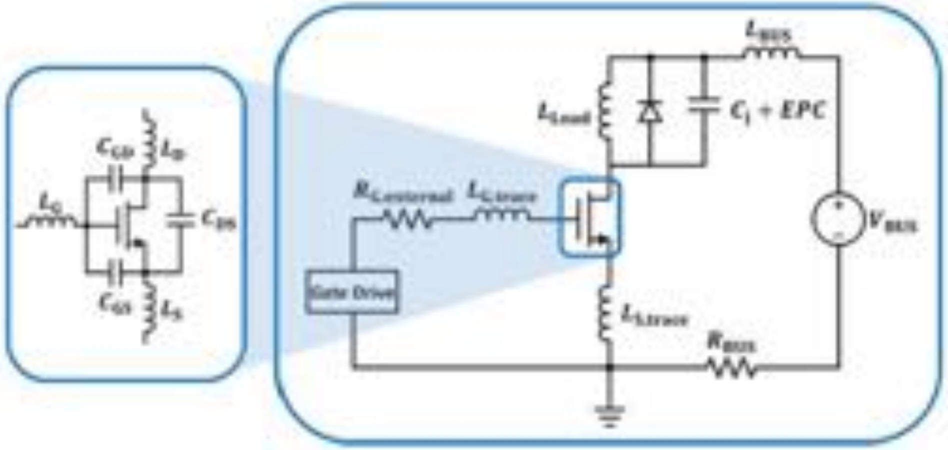
Behavioral Modeling of SiC MOSFETs

- **DPT characterization**



Courtesy Professor A. Lemmon Research Group, University of Alabama



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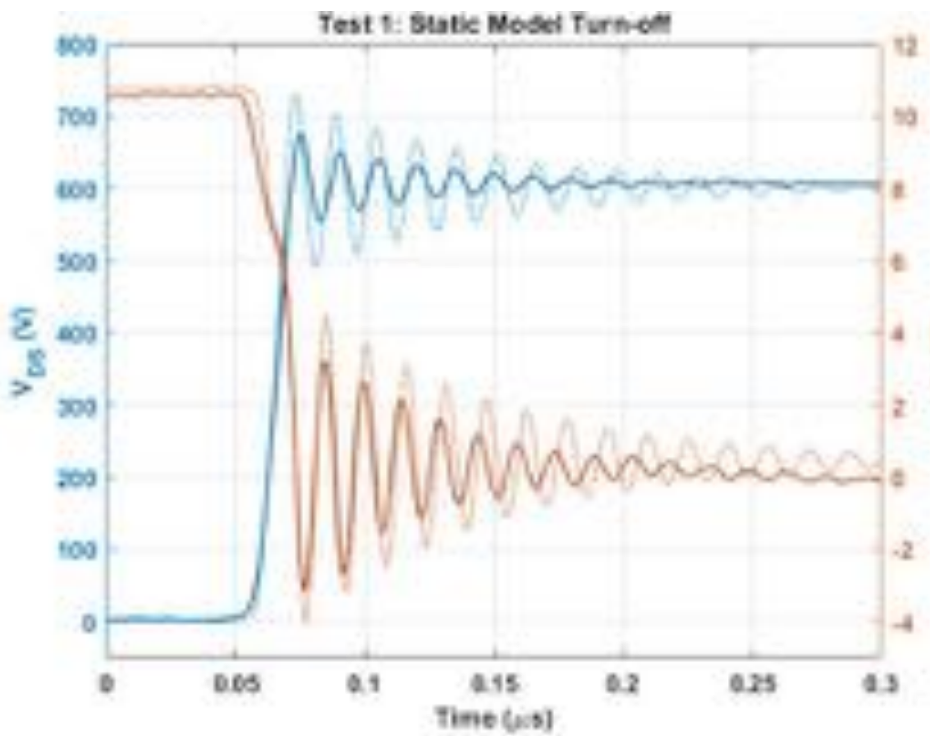
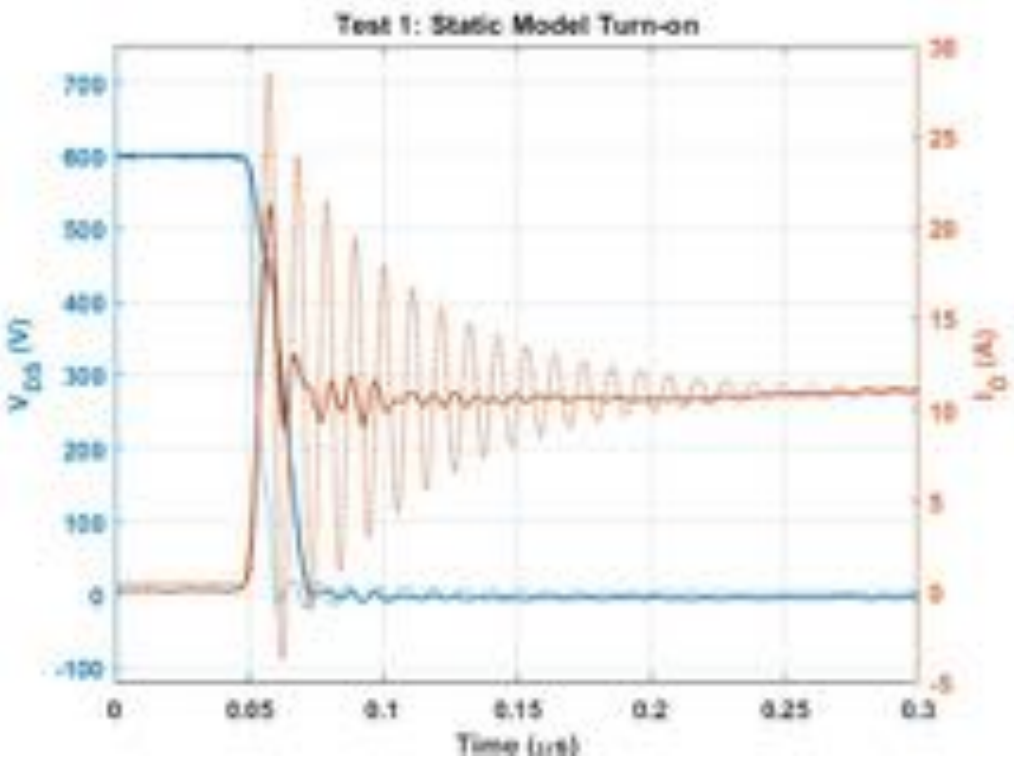
Behavioral Modeling of SiC MOSFETs

- **Static model/experiment overlays at 600 V and 10 A**





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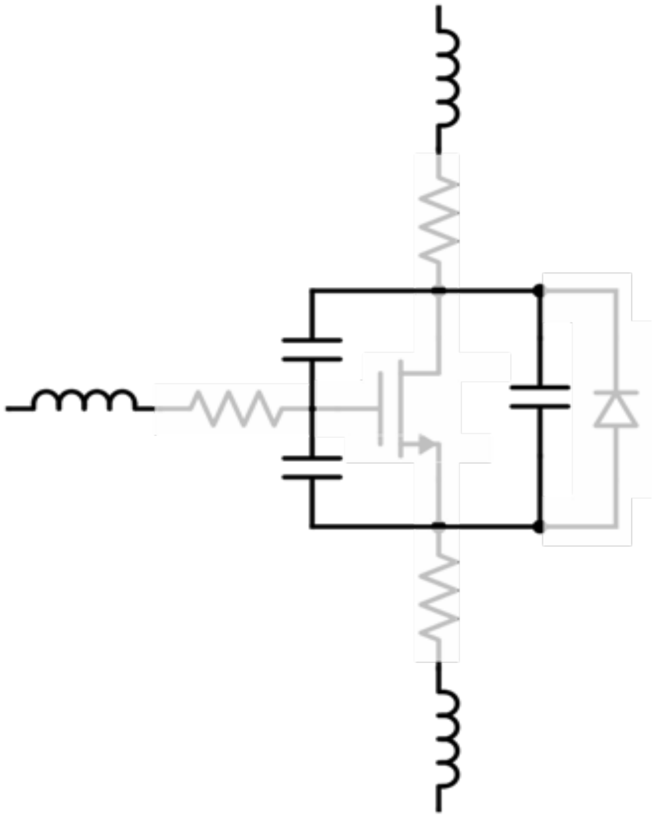
Behavioral Modeling of SiC MOSFETs

- **Dynamic model and parameters**
  - $C_{\mathrm{ISS}} = K_{\mathrm{GS}} C_{\mathrm{GS}} + C_{\mathrm{RSS}}$

    $C_{\mathrm{OSS}} = K_{\mathrm{DS}} C_{\mathrm{DS}} + C_{\mathrm{RSS}}$

    $C_{\mathrm{RSS}} = K_{\mathrm{GD}} C_{\mathrm{GD}}$
  - Inductances allowed to vary within range of uncertainty



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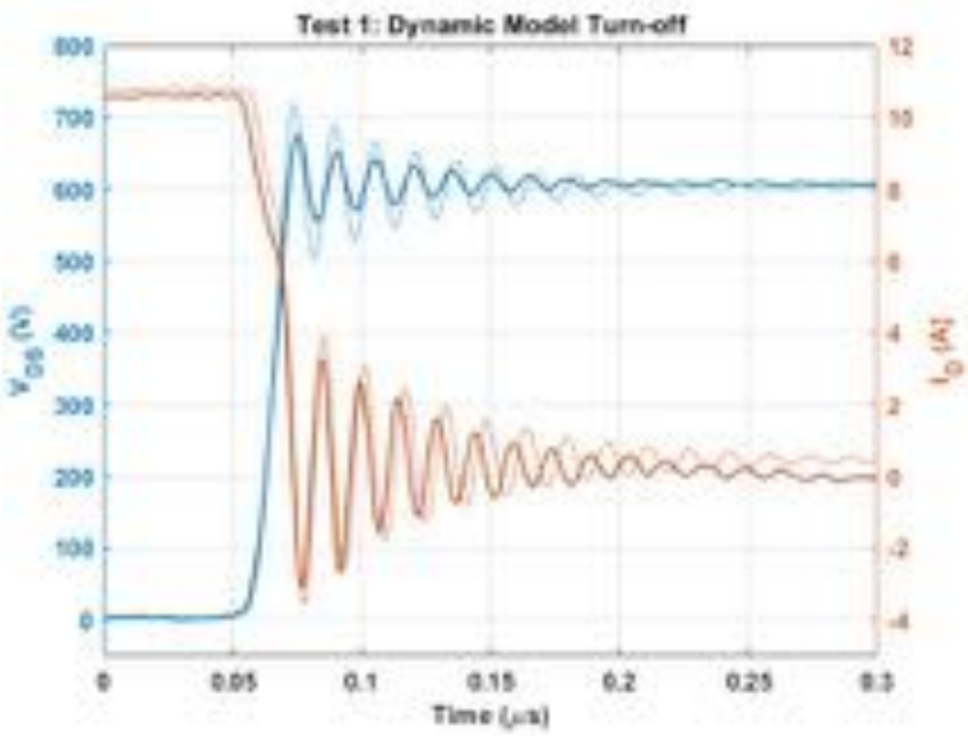
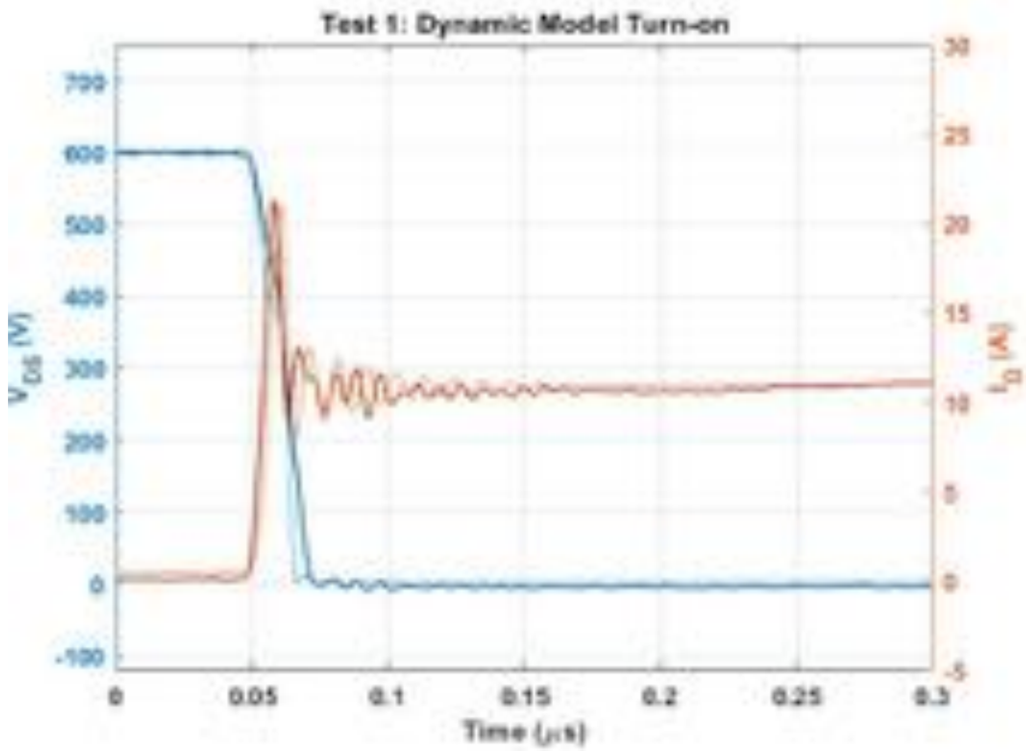
Behavioral Modeling of SiC MOSFETs

- **Dynamic model/experiment overlays at 600 V and 10 A**





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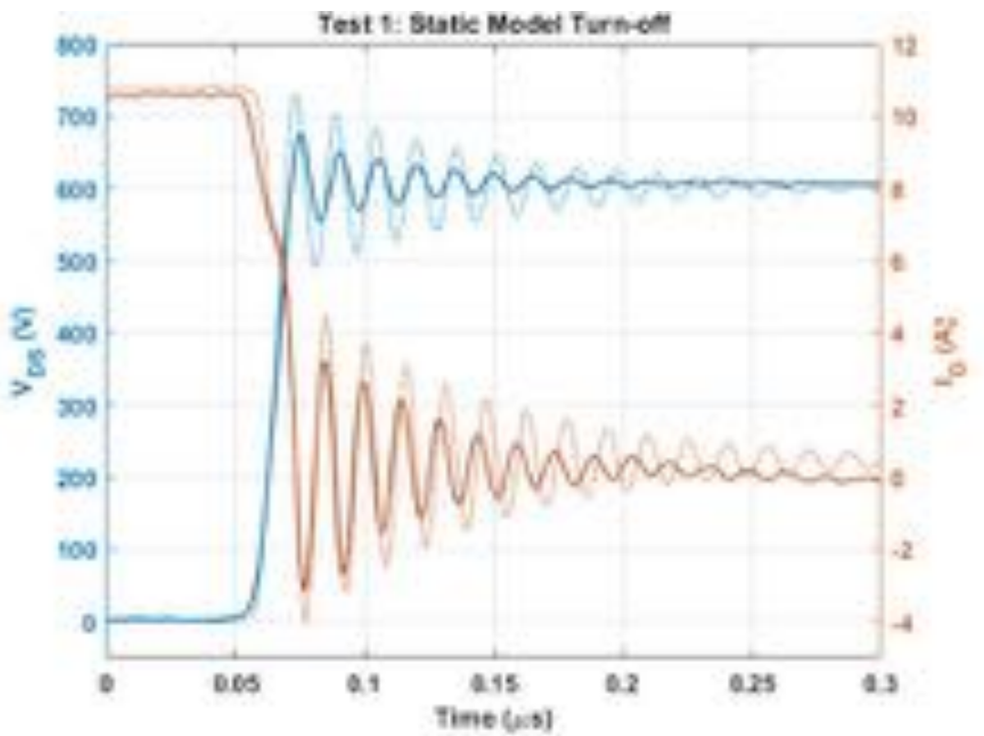
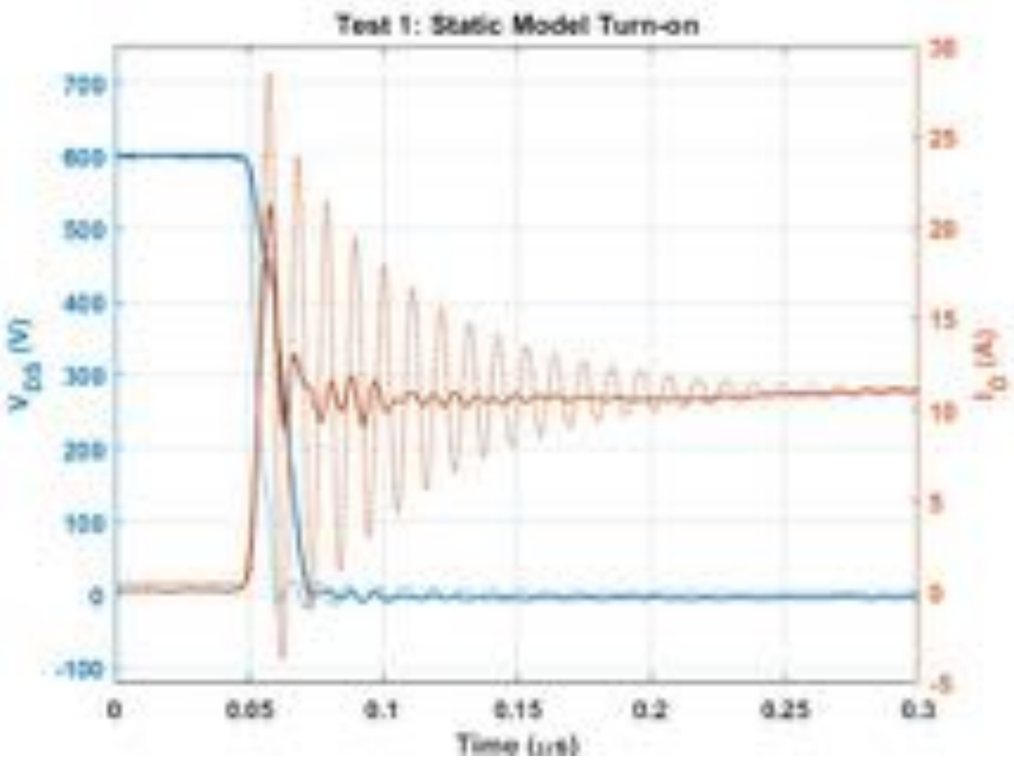
- **Static model/experiment overlays at 600 V and 10 A**





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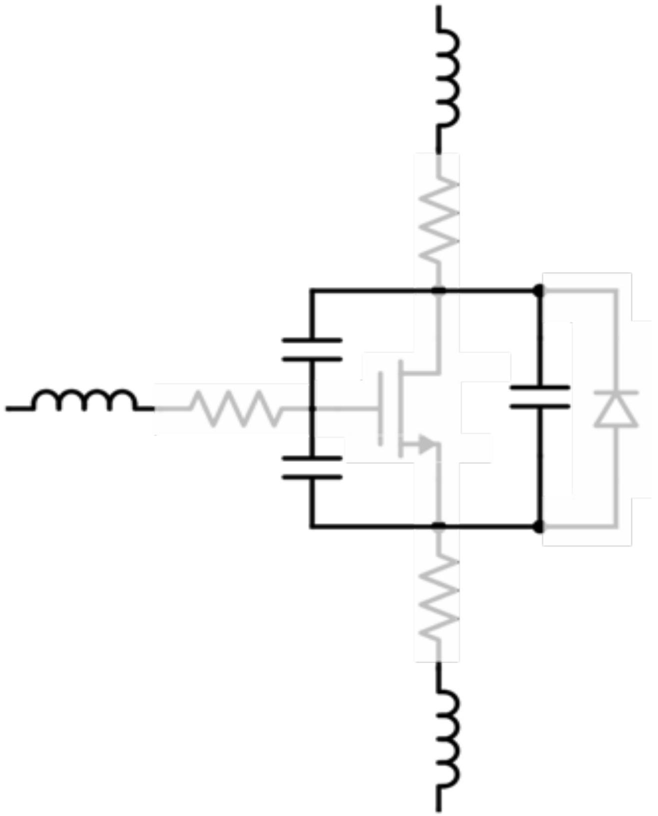
Behavioral Modeling of SiC MOSFETs

- **Extracted dynamic parameters**

TABLE I
MODEL PARAMETER VALUES

	L_d (nH)	L_g (nH)	L_s (nH)	k_{ds}	k_{gs}	k_{dg}
Stat.	0.100	4.895	2.600	1.00	1.00	1.00
Dyn.	0.104	5.895	3.600	0.97	0.87	0.90



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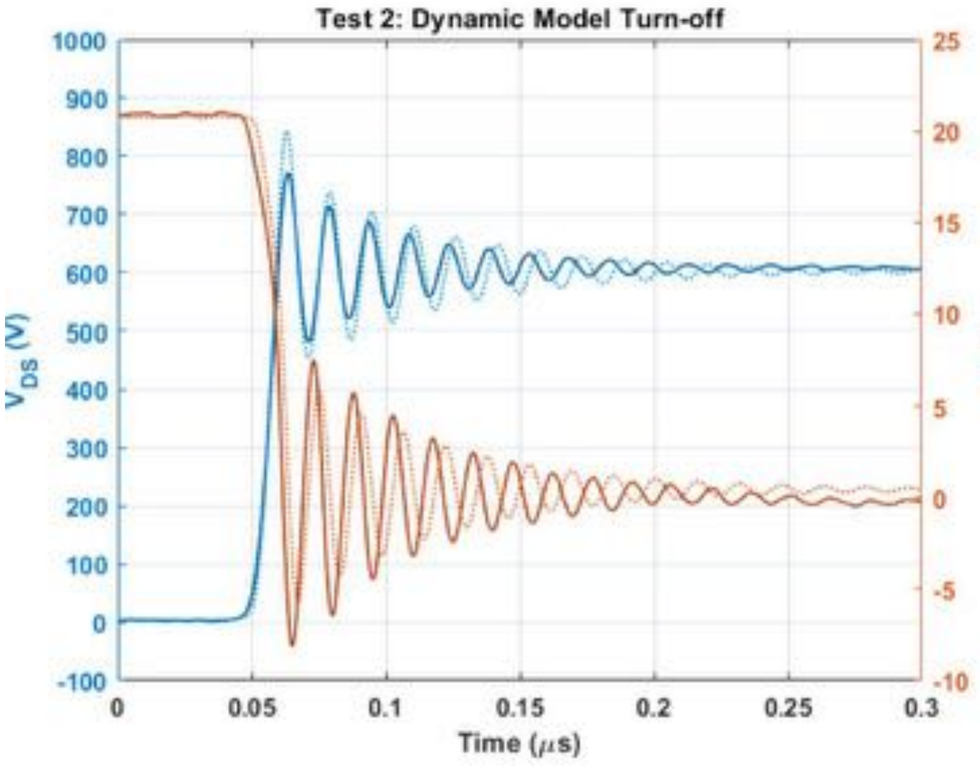
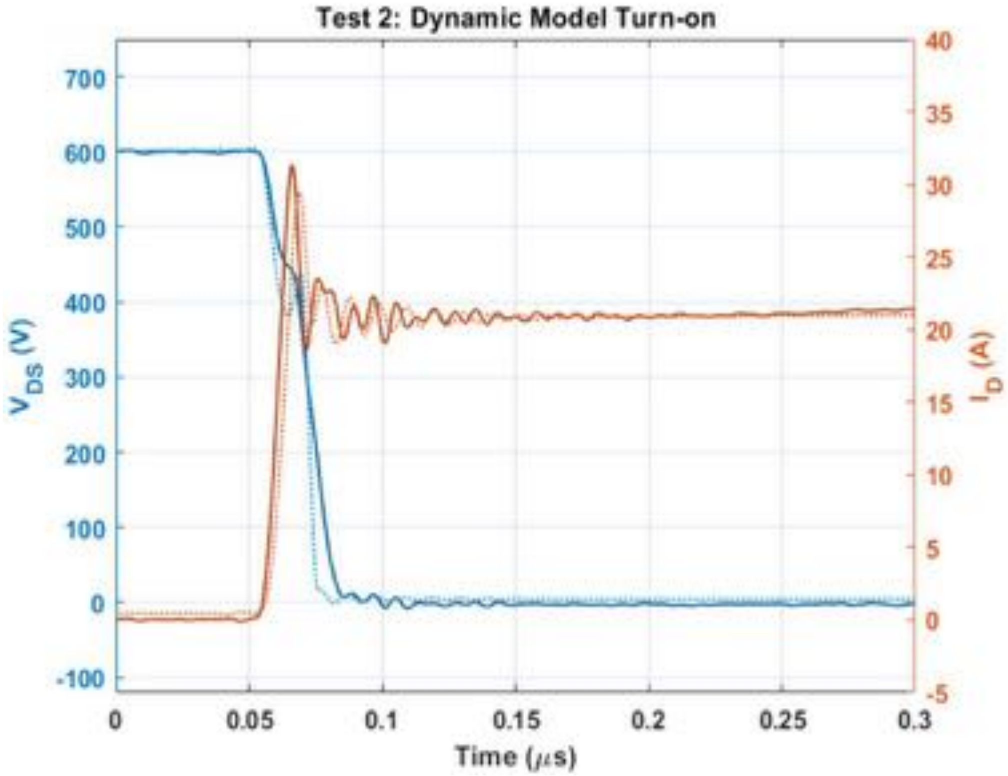
Behavioral Modeling of SiC MOSFETs

- **Orthogonal Dataset at 600 V, and 20 A**





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Outline

- **Introduction: The Need for WBGs and Models**
- **Physics and Behavioral Modeling**
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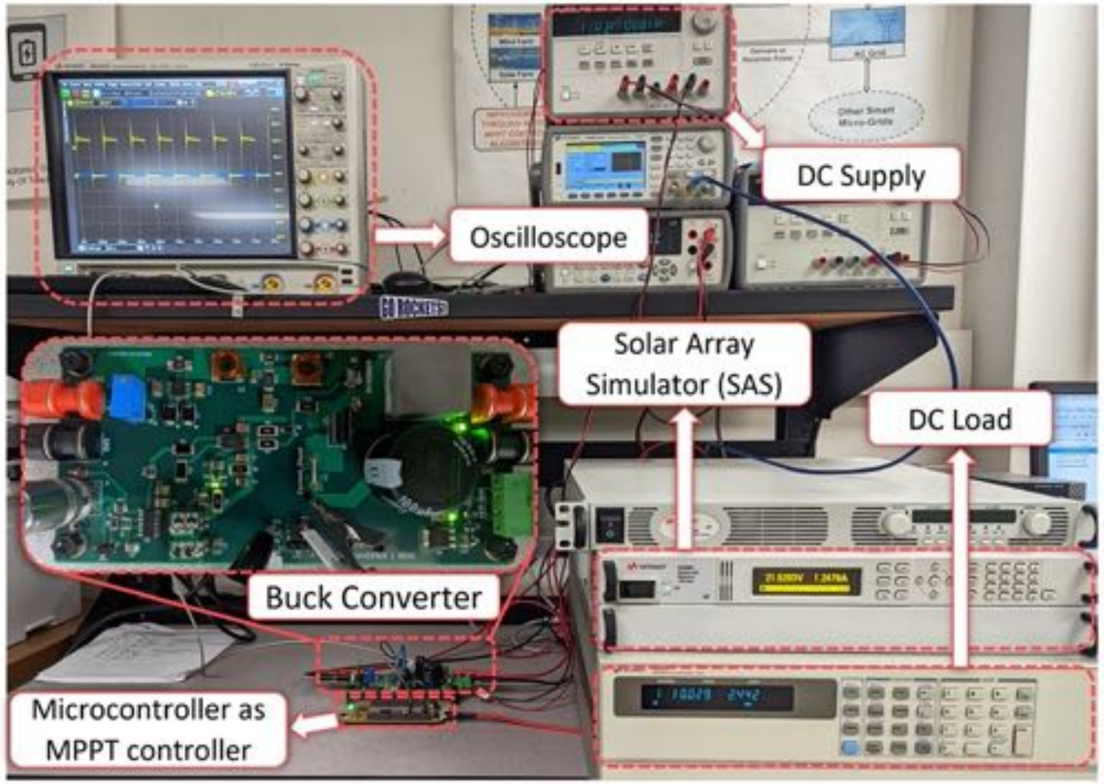
  - MPPT
  - Radiation Intense Environments
- **Future Work**

Maximum Power Point Tracking w/ GaN HEMTs

- **Experimental Setup w/ GaN-based Buck Converter and PV Simulator**

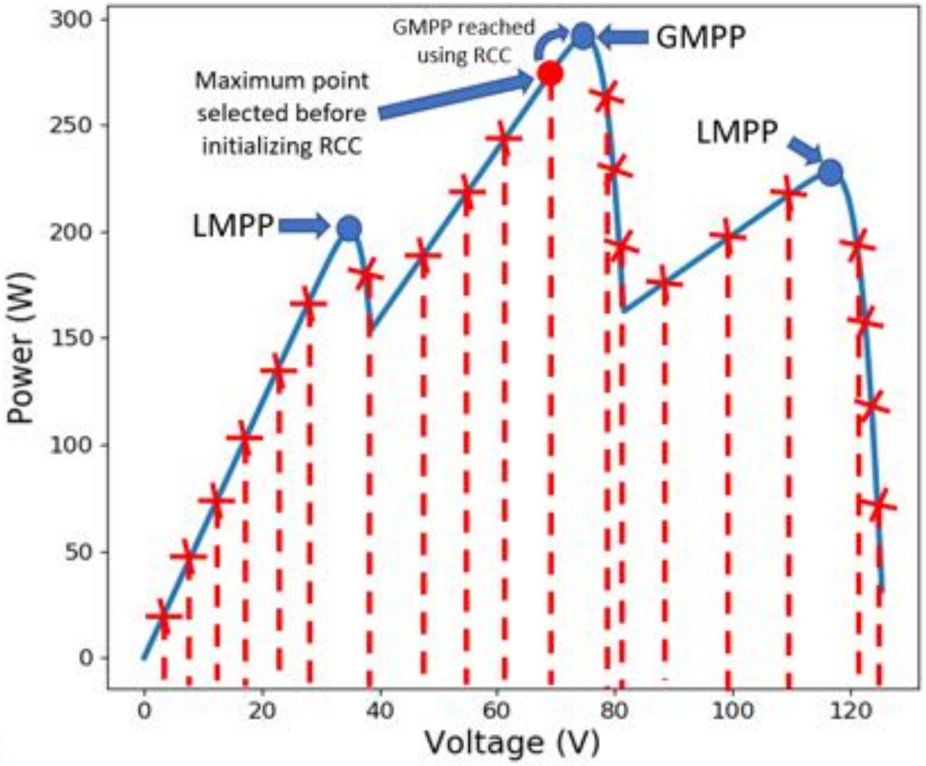


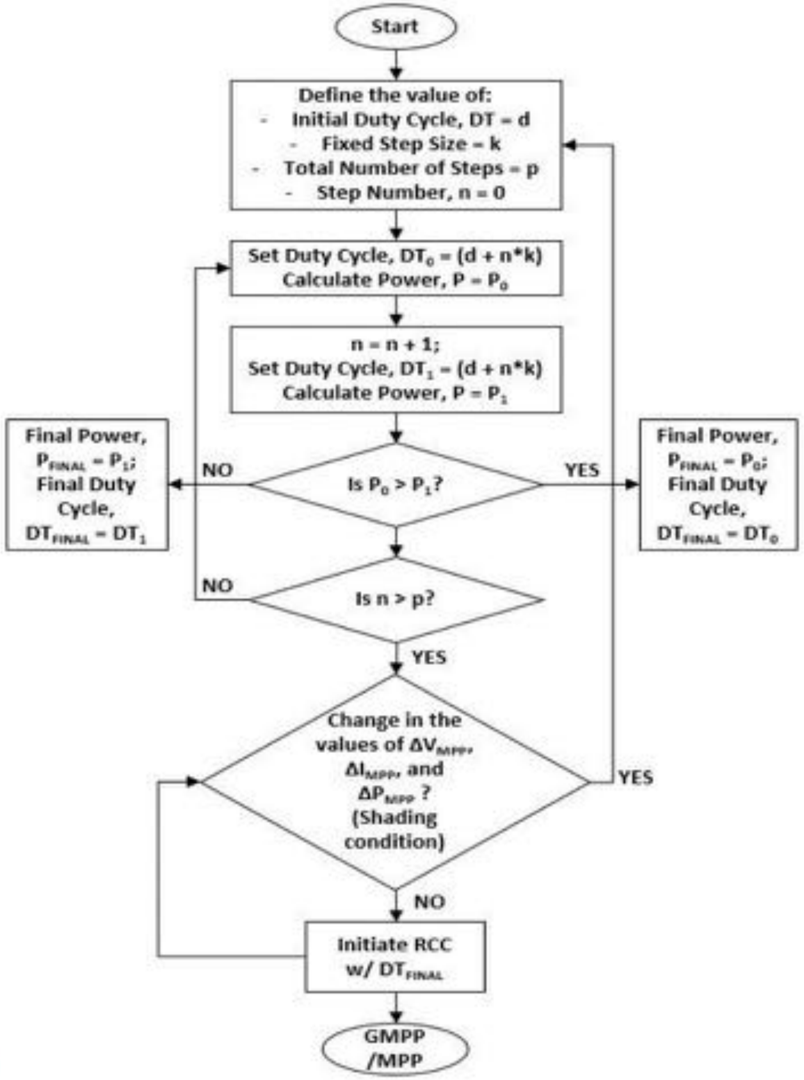
UToledo Power Electronics Research Lab

S. Mahmud, W. M. Collings, A. Barchowsky, A. Y. Javaid, and R. Khanna, "Global maximum power point tracking in dynamic partial shading conditions using ripple correlation control," in *IEEE Transactions on Industry Applications* (in press: accepted for publication), DOI: 10.1109/TIA.2022.3228227

Maximum Power Point Tracking w/ GaN HEMTs

- **Partial Shading Conditions**





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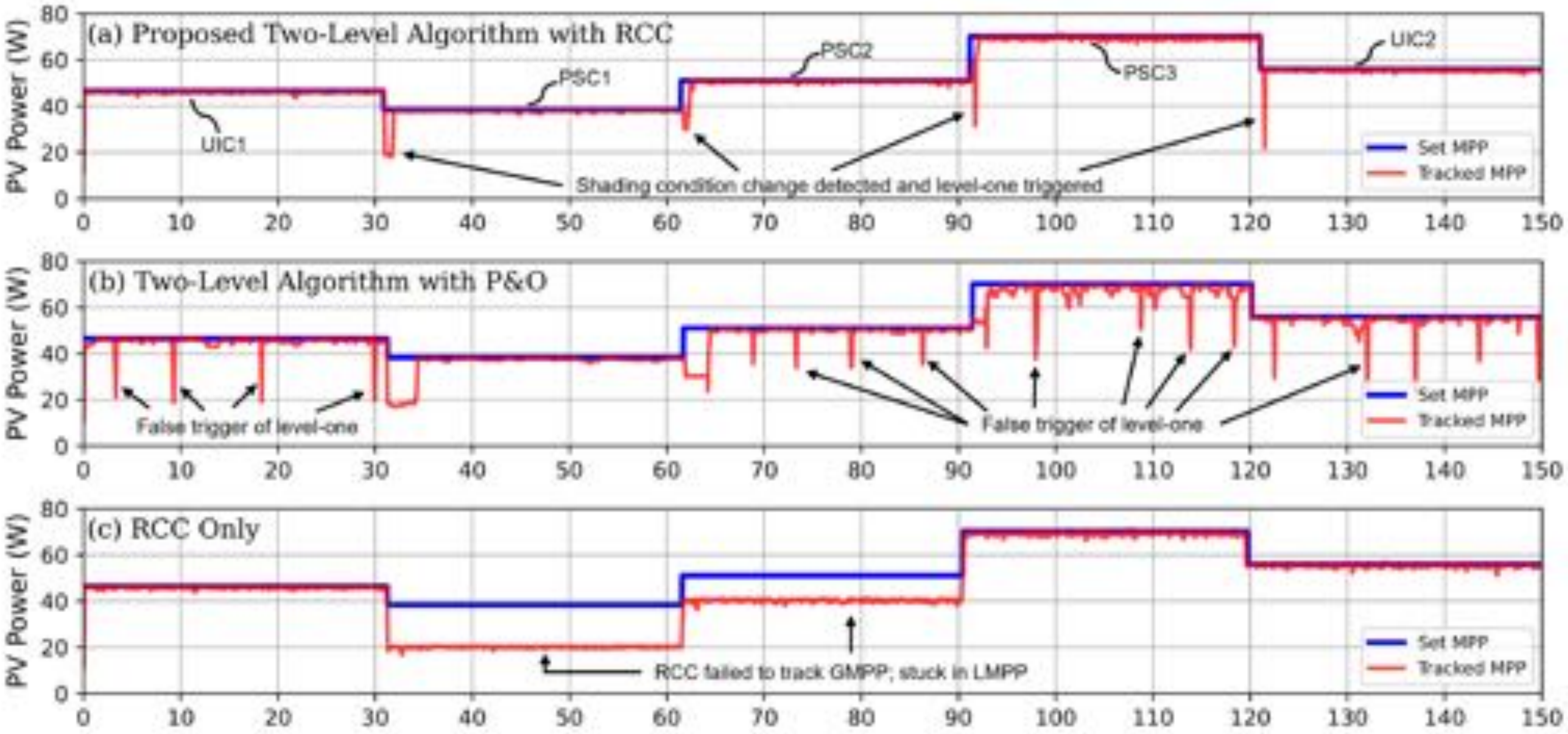
Maximum Power Point Tracking w/ GaN HEMTs

- **Partial Shading Conditions → Utoledo Sampling algorithm in first level of control → RCC used in 2nd level of control**



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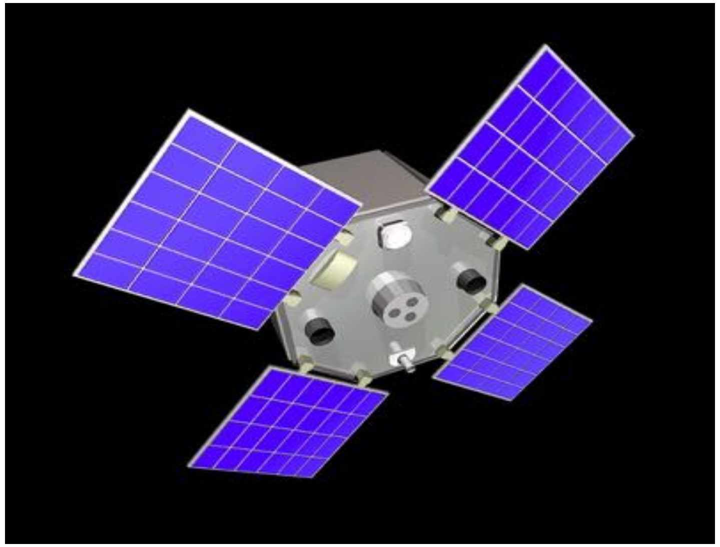
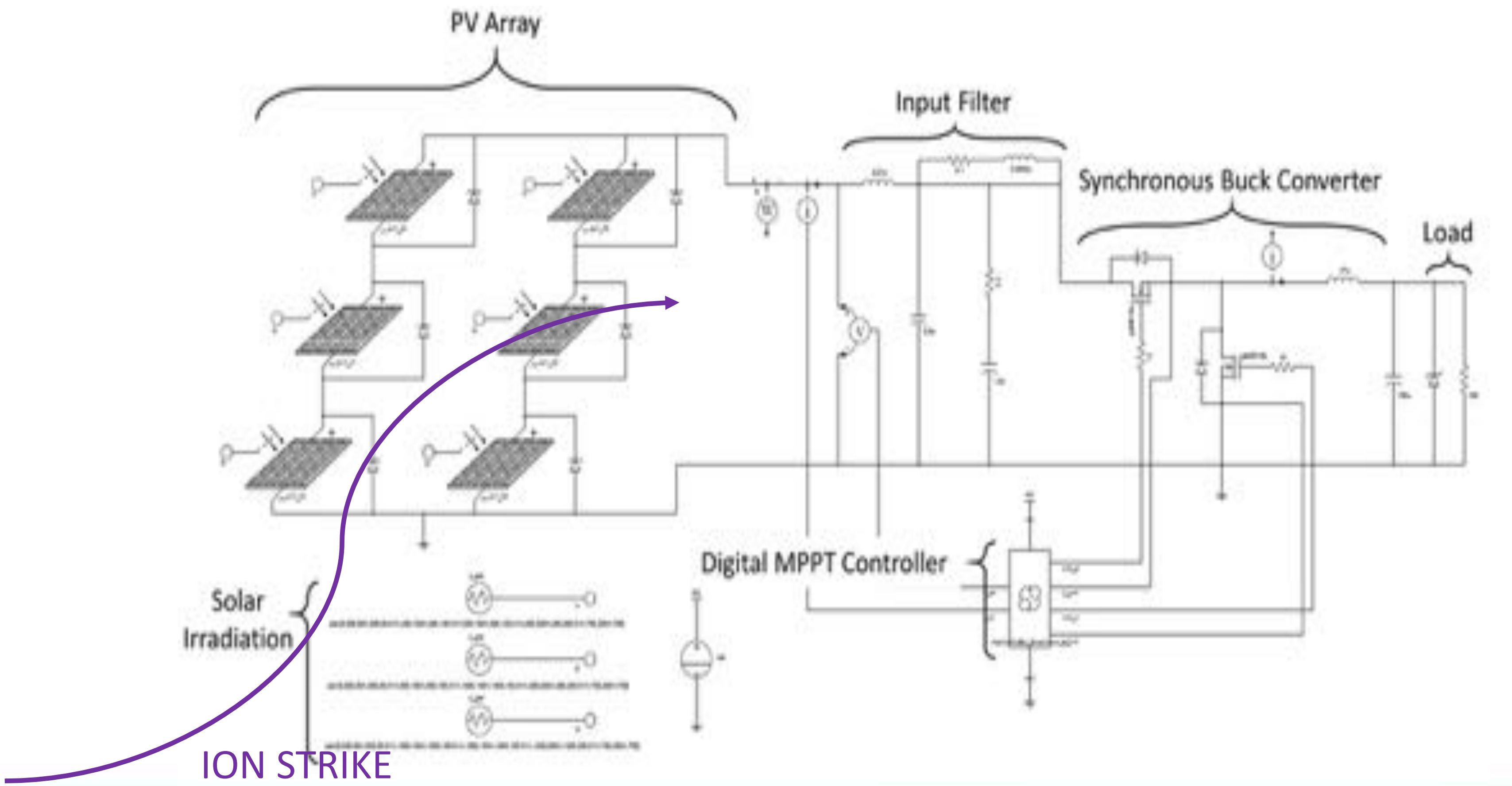
GaN Radiation Tolerance

- **Radiation Tolerance of GaN for Space and Nuclear Applications**





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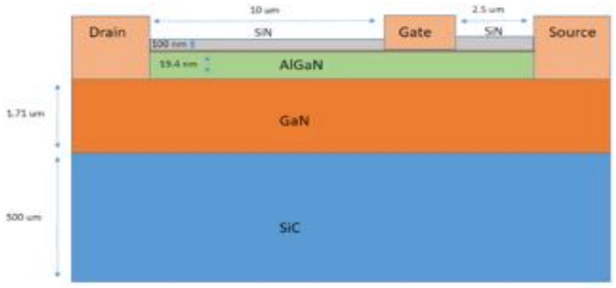
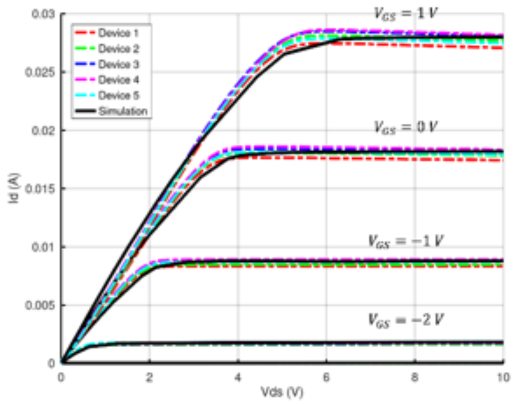
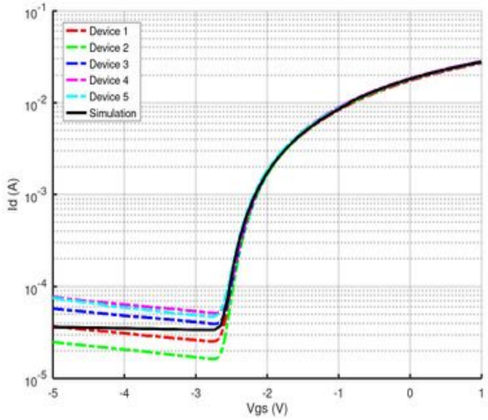
GaN Radiation Tolerance

- **Radiation Tolerance of GaN for Space and Nuclear Applications**
  - **Two Photon Absorption (TPA) used to mimic heavy ion irradiation (Performed at NRL)**
  - **TCAD Model of GaN HEMT Implemented**
  - **Comparisons between experiment and simulation undertaken**
  - **Results to be used to inform design and fabrication of future radiation tolerant GaN devices**

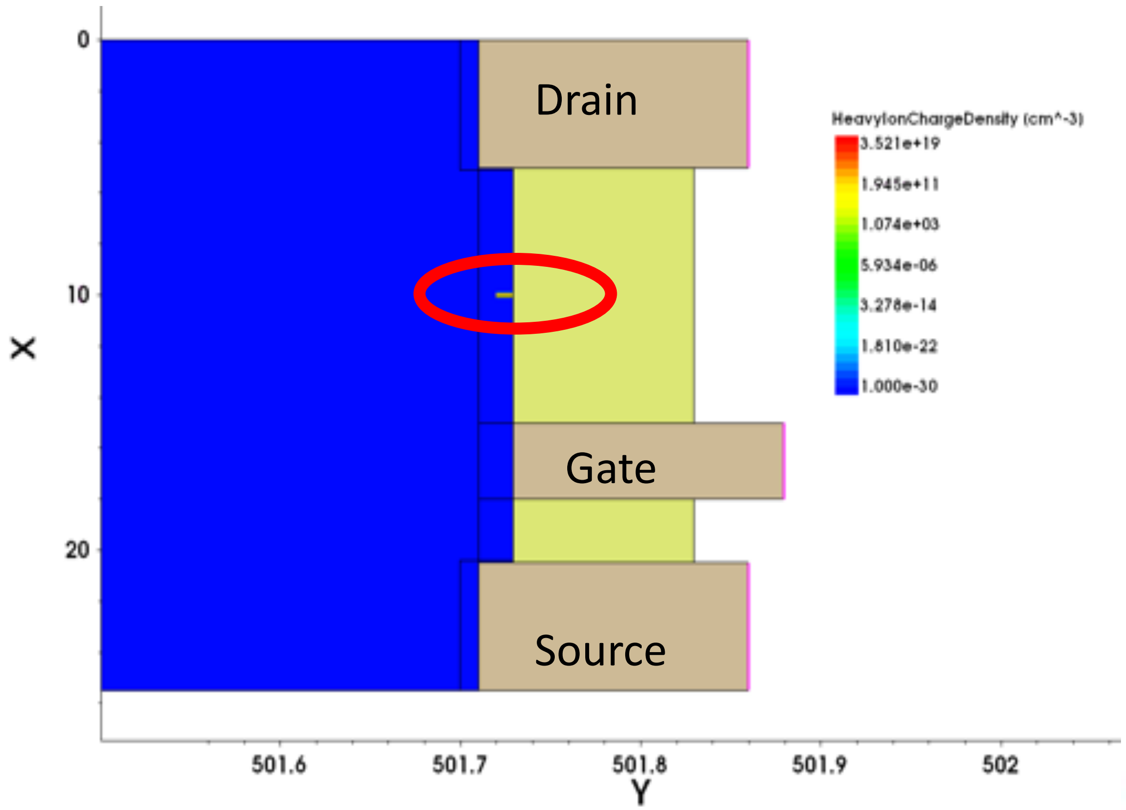


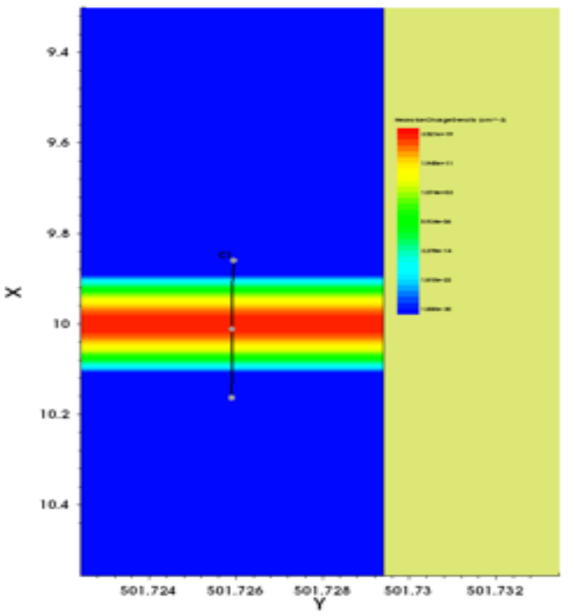


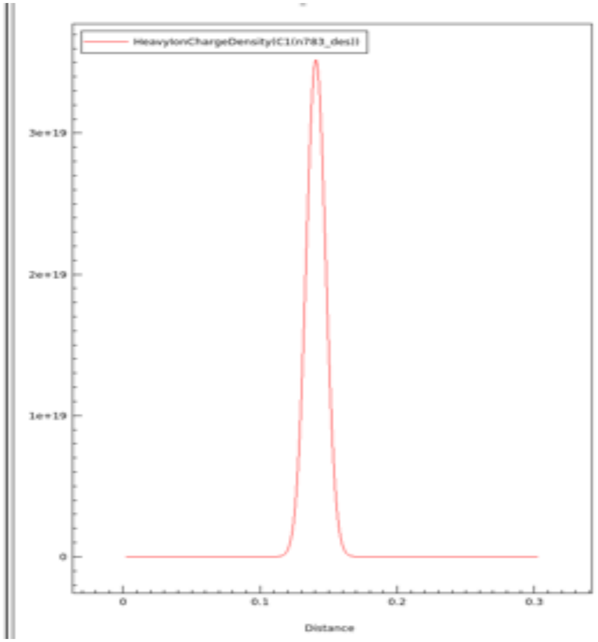


GaN Radiation Tolerance

- **Radiation Tolerance of GaN for Space and Nuclear Applications**
    - **Ion strike only penetrating heterojunction**







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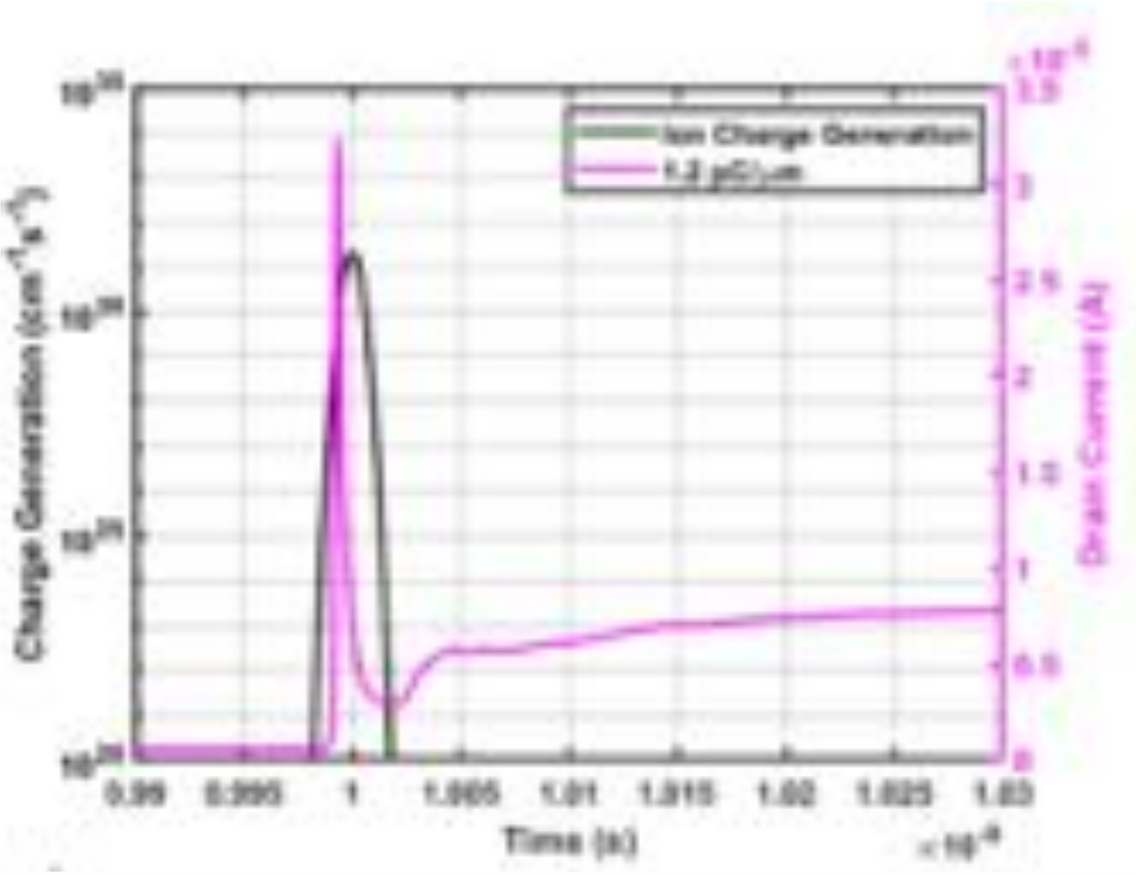
GaN Radiation Tolerance

- **Collected Charge and Current**



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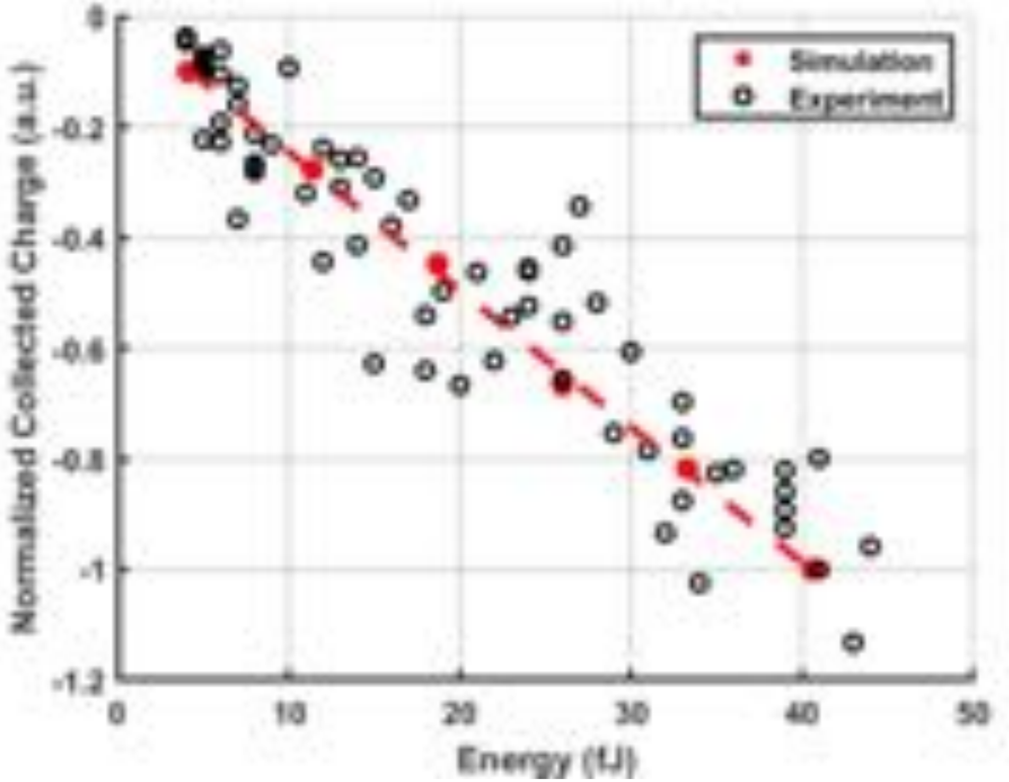
GaN Radiation Tolerance

- **Simulation vs Experiment**



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Conclusions

- **Behavioral Models vs Physics-based Models**
  - Behavioral Models are Generally Faster
  - Physics-based Models are Generally More Accurate
  - Behavioral Models are More Amenable to Model Refinement
  - Physics-based Models are More Amenable to Correlating Observed Behavior with Underlying Physical Device Parameters and *Scaling Rules*
  - *Hybrid models can be explored to settle the tension between the 2*

Conclusions

- **WBGs**
  - Need to continue reducing parasitic inductances so that the value proposition of WBGs can be fully leveraged
  - Need more sophisticated models to account for frequency-dispersion → especially as switching capabilities become faster and faster
  - Need to explore ultra-wide bandgap devices with potential breakdown voltages of 50 kV? Realize Edison's dream!
  - Need to leverage the radiation tolerance of wide and ultra wide bandgap devices to allow deeper space exploration, and to install more resilient power electronics in nuclear energy parks (enable greater Hydrogen production)

Conclusions

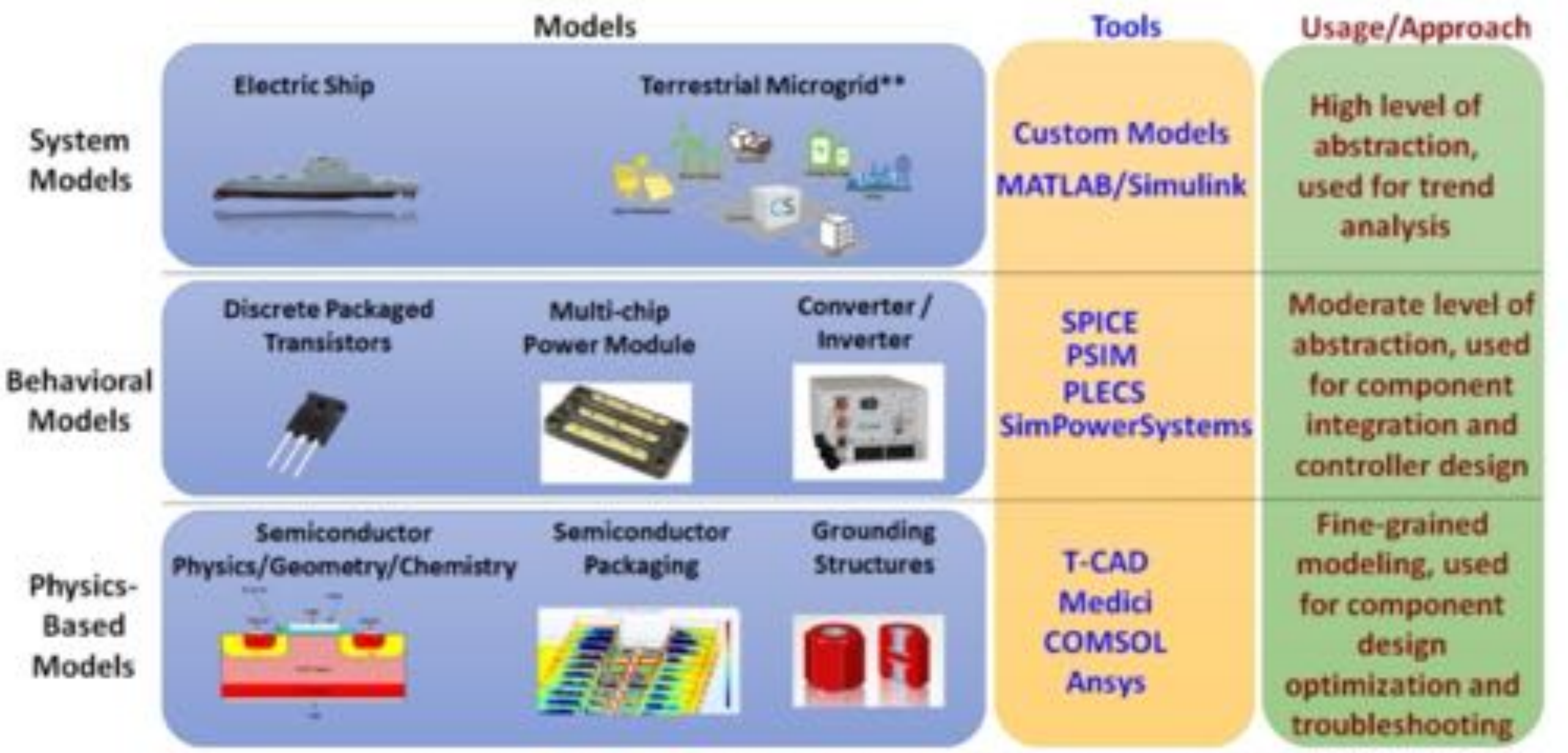

**Image adapted from https://cleantechnica.com/2015/12/10/remote-microgrids-now-dominate-global-microgrid-market/

Acknowledgements

DEPARTMENT OF THE NAVY ONR Science & Technology

U.S. DEPARTMENT OF ENERGY

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THE UNIVERSITY OF ALABAMA
THE CAPSTONE OF HIGHER EDUCATION

HRL LABORATORIES

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Questions?

Raghav Khanna
raghav.Khanna@utoledo.edu