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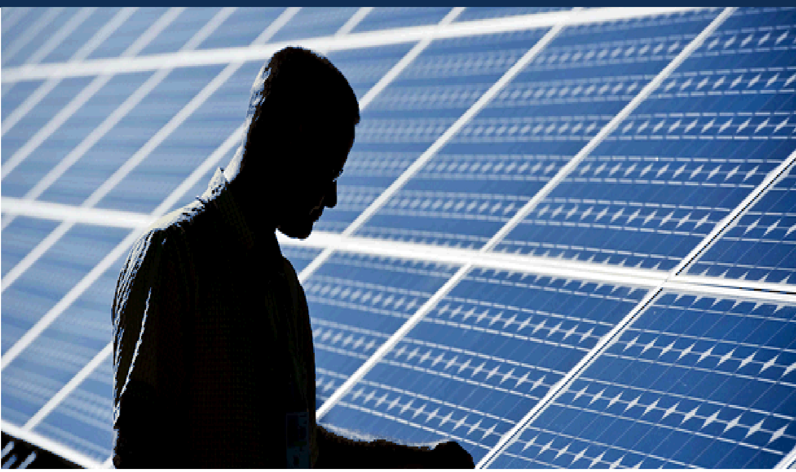

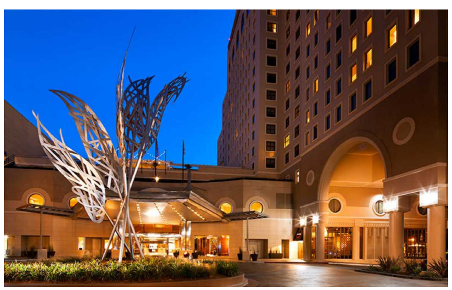

EESAT 2017
San Diego, CA
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Switching Reliability Characterization of Vertical GaN PiN Diodes

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4 – Avogy, Inc. (now at ARPA-E)

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Acknowledgment

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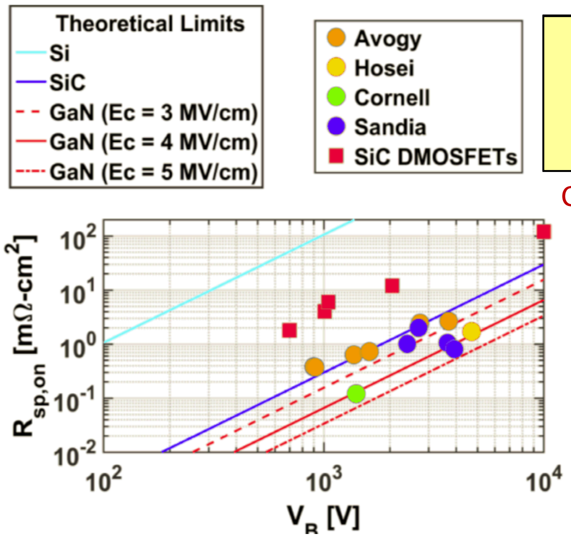
Project Goal

- ***Power electronic systems are a necessary interface between energy storage systems and the electric grid***

- ***Wide-bandgap semiconductors have material properties that make them theoretically superior to silicon for power conversion applications***
  - Higher switching frequency and lower conduction and switching losses reduce the size and complexity of power conversion systems, ***thus reducing overall system cost***
  - However, questions remain regarding the reliability of wide-bandgap materials and devices, ***limiting their implementation in systems***

- ***Program goal: Understand the performance and reliability of wide-bandgap power switches, and how this impacts circuit- and system-level performance and cost***

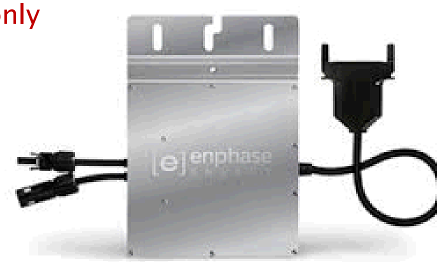
Superior Properties of WBG Materials and their Impact on Power Conversion Systems



Baliga FOM =
$V_B^2/R_{on,sp}$ =
$\varepsilon\mu_n E_C^3/4$

Conduction losses only

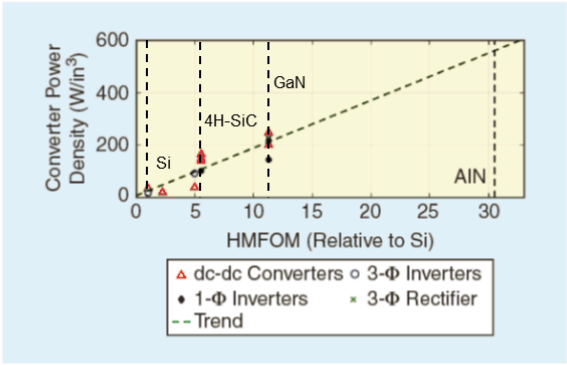
SNL GaN HEMT microinverter
400 W in 2.4 in^3 → 167 W/in^3



SOA commercial microinverter
250 W in 59 in^3 → 4.2 W/in^3

Huang Material FOM = $E_C\mu_n^{1/2}$

Switching and conduction losses



- **WBG semiconductors can have a strong impact on system size and weight due to reduced size of passive components and reduced thermal management requirements**
- ***But their reliability is far less mature than traditional Si devices***

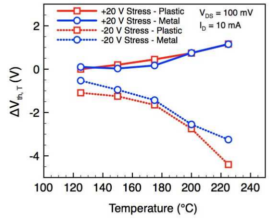
J. Y. Tsao et al., *Adv. Elec. Mat.* (in press); R. J. Kaplar et al., *IEEE Power Elec. Mag. (March 2017)*

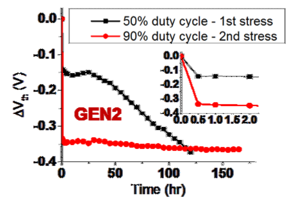
Program Historical Highlights

2009

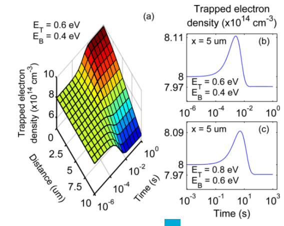
Suggested reliability improvements for components, software, and operation of Silicon Power Corporation's Solid-State Current Limiter

Characterized and evaluated commercial SiC MOSFETs, including the impacts of bias, temperature, packaging, and AC gate stress on reliability





Created a physics-based model for GaN HEMTs linking defect properties to device design



Characterized switching of vertical GaN PiN diodes using double-pulse test circuit

Developed and documented a general process for analyzing the reliability of any power electronics system

Developed models for SiC threshold voltage instability, and identified the free-wheeling diode ideality factor as a potential screening metric for threshold voltage shifts

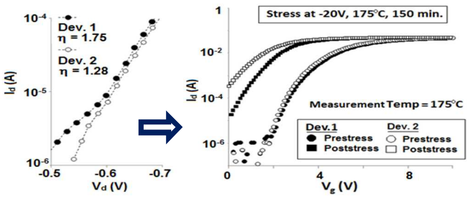
Developed an easy to use method that can be used by circuit designers to evaluate the reliability of commercial SiC MOSFETs

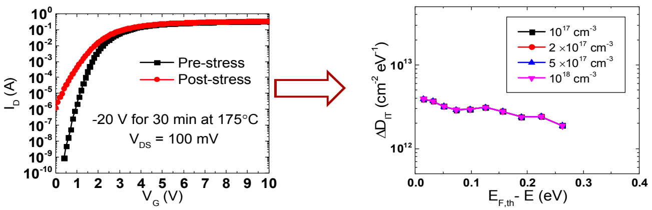
2017

Participating in JEDEC WBG reliability working group

30 papers and presentations over the course of the project

Three this year including EESAT





Motivation and Overview for This Year's Work

- **For Si technology, most power device reliability studies focus on the packaging and thermal management**
  - Devices are mature and well-understood, and manufacturing is well-controlled

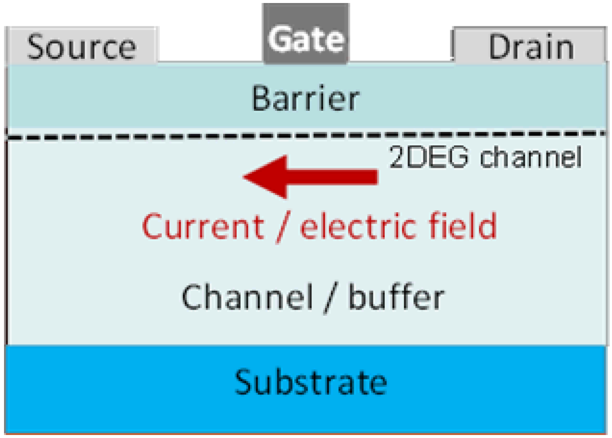
- **For WBG materials, devices are new and (relatively) unproven**
  - Materials are much newer, and manufacturing is not as well-controlled (but this is advancing quickly)
  - SiC is most mature, followed by GaN power HEMTs (cousins of RF HEMTs)
  - Newest type of device is GaN vertical device, which combines the material advantages of GaN with the high-voltage capability of a vertical architecture (>1200 V)

- **Little information on reliability characterization of vertical GaN devices in the literature**
  - **Especially true under realistic switching conditions**

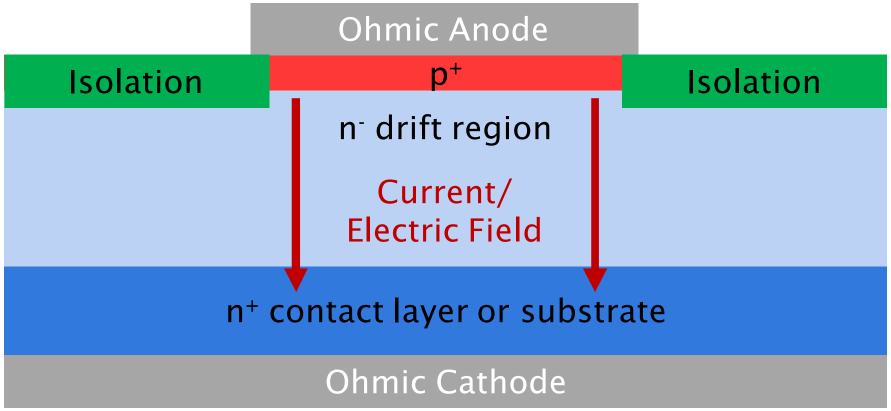
Thus, this year's work focuses on newly developed vertical GaN devices and continuous switching reliability testing

Why Vertical GaN Devices?

- **Historically, GaN power devices have lateral architecture**
  - Limits voltage hold-off to ≈<650 V due to electric field management
  - High frequency, but no avalanche



- **Vertical GaN (v-GaN) devices are now becoming available**
  - Better potential for high-voltage operation (≈>1200 V)
  - Avalanche capability
  - Reliability and switching performance are largely ***uncharacterized*** in literature

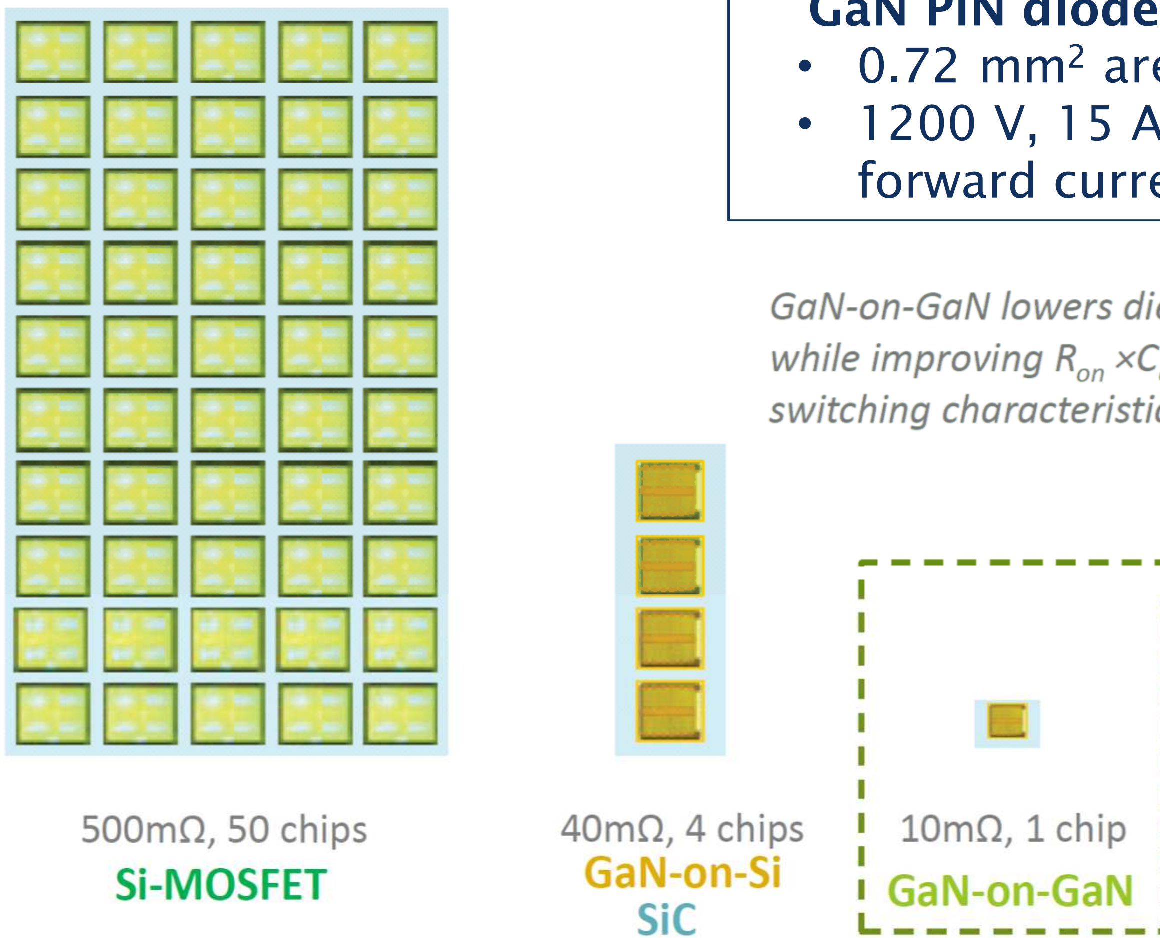


Area Advantage of Vertical GaN

For a given on-resistance (R_{on}) of 10mΩ:

- **Tested Avogy vertical GaN PiN diodes**
  - 0.72 mm^2 area
  - 1200 V, 15 A peak forward current

GaN-on-GaN lowers die cost while improving $R_{on} \times C_{off}$ switching characteristic

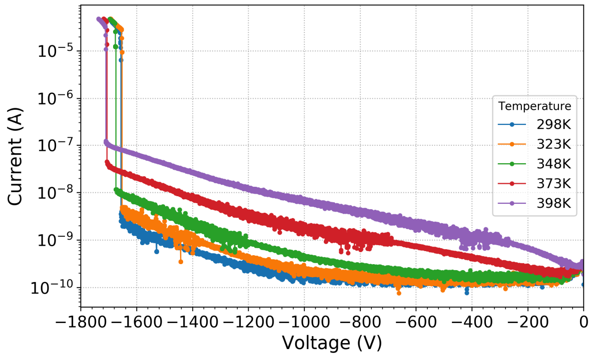


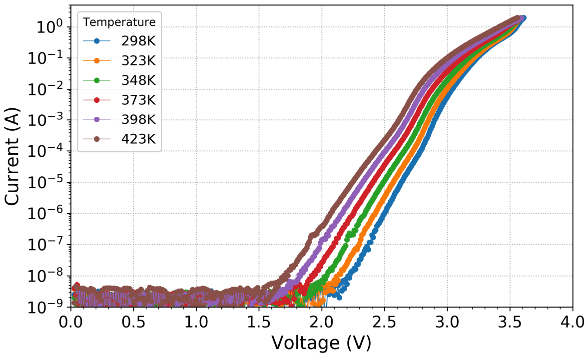
The devices tested were fabricated at Avogy under the **ARPA-E SWITCHES** program managed by **Dr. Tim Heidel**

I. C. Kizilyalli et al., Micro. Rel. 55, 1654 (2015)

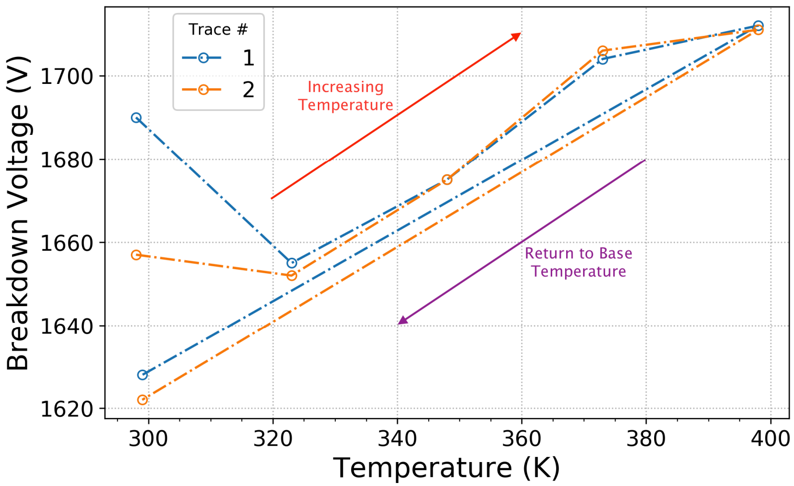
Current-Voltage Characteristics of v-GaN PiN Diodes

- I-V characteristics taken in 25 ℃ steps
  - Reverse to 125 ℃
  - Forward to 150 ℃
- Confirmed datasheets





- **Positive temperature coefficient of breakdown**
  - *Suggests avalanche process*
- Some hysteresis observed for 25℃ breakdown
  - Burn-in effect?



Double-Pulse Test Circuit

- DPTC is usually used to characterize switching of inductively-loaded power transistors
  - But for this work, we use a known good switch and characterize the diode
- Two modes of operation
  - Transient (double-pulse): Traditional use, characterizes switching behavior
  - Steady-state (continuous): New use for reliability testing

Circuit Diagram

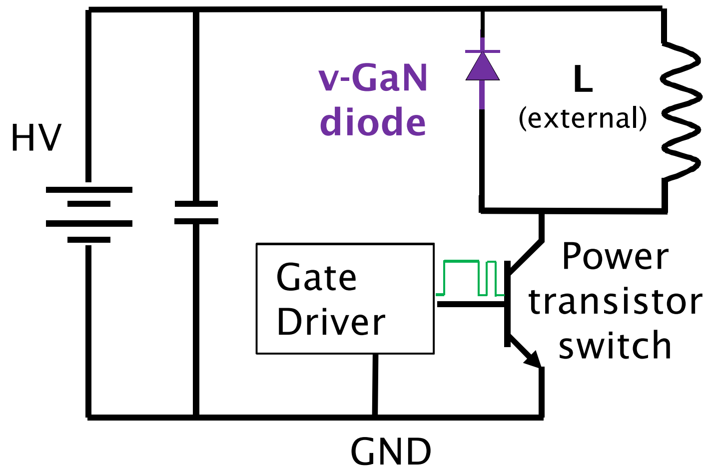
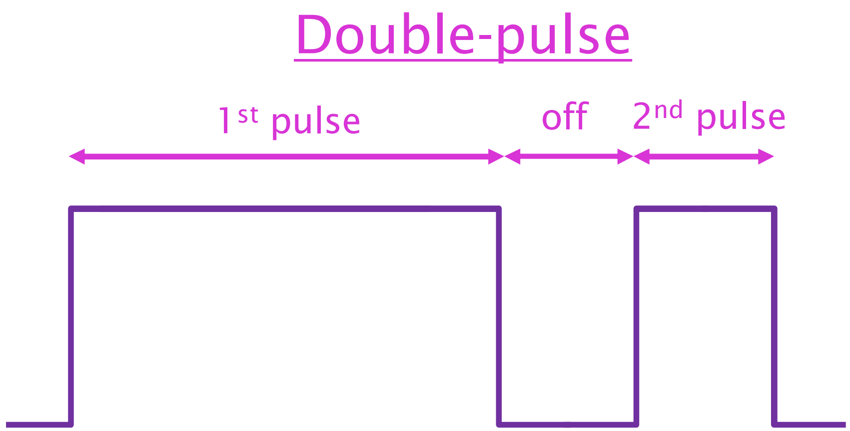


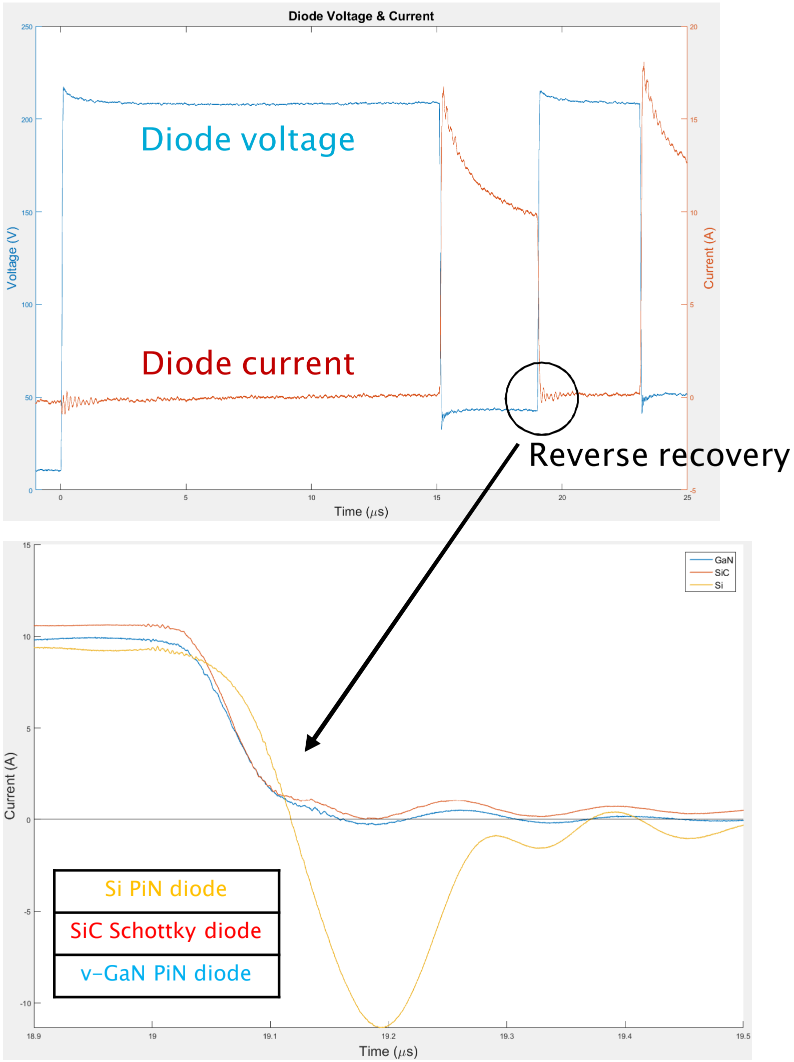
Photo of real circuit

Switching Characterization with DPTC



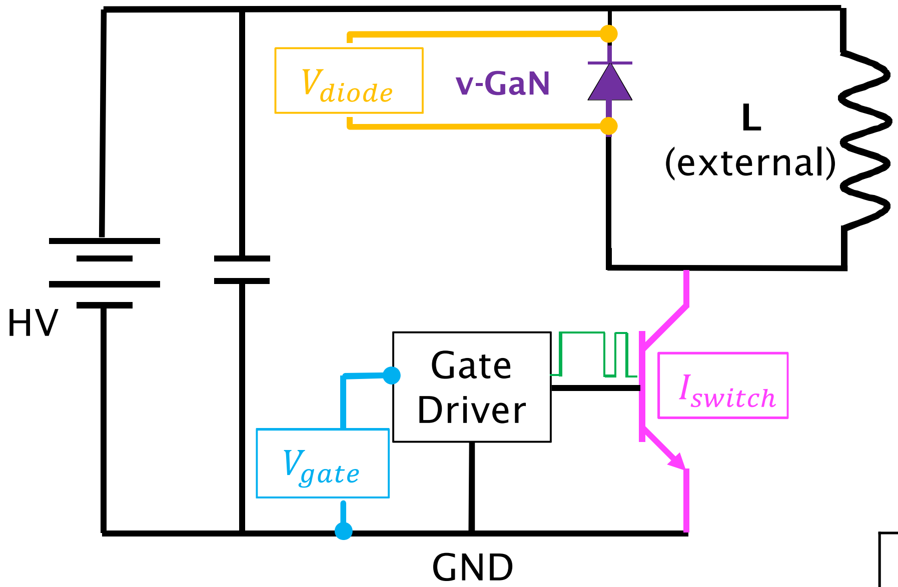
- 1st gate pulse: Increase stored energy in inductor – "charge up" to quasi-steady-state
- Gate off: Current circulates through diode/inductor loop
- 2nd gate pulse: Characterize switching transients

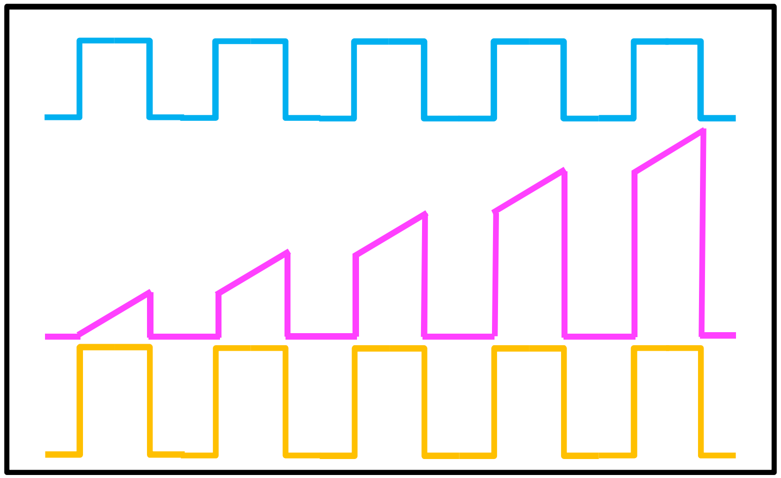
Reported last year



C. Matthews et al., WiPDA 2016

Continuous Waveforms in Ideal DPTC

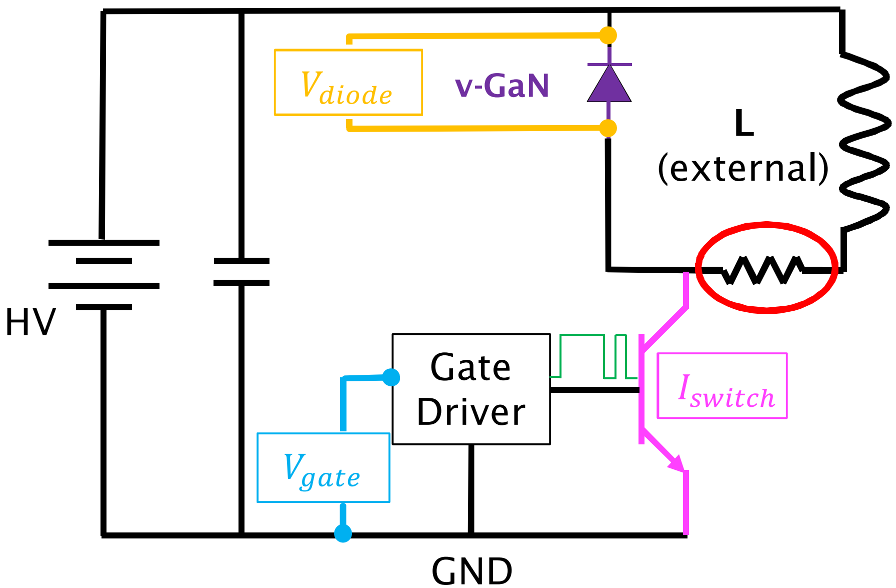


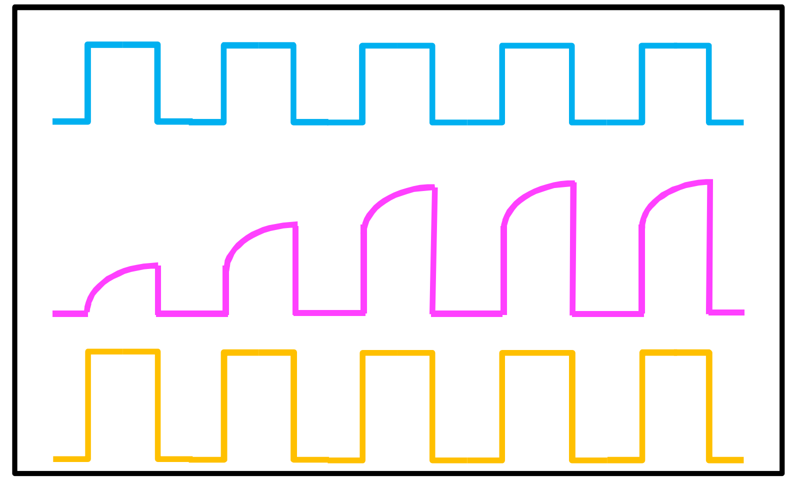


Switch gate voltage	Switch current	Diode voltage

- **Idealized analysis of the double-pulse circuit**
  - All elements are lossless
  - Inductor causes current to increase indefinitely
  - Not realistic!

Continuous Waveforms in Realistic DPTC

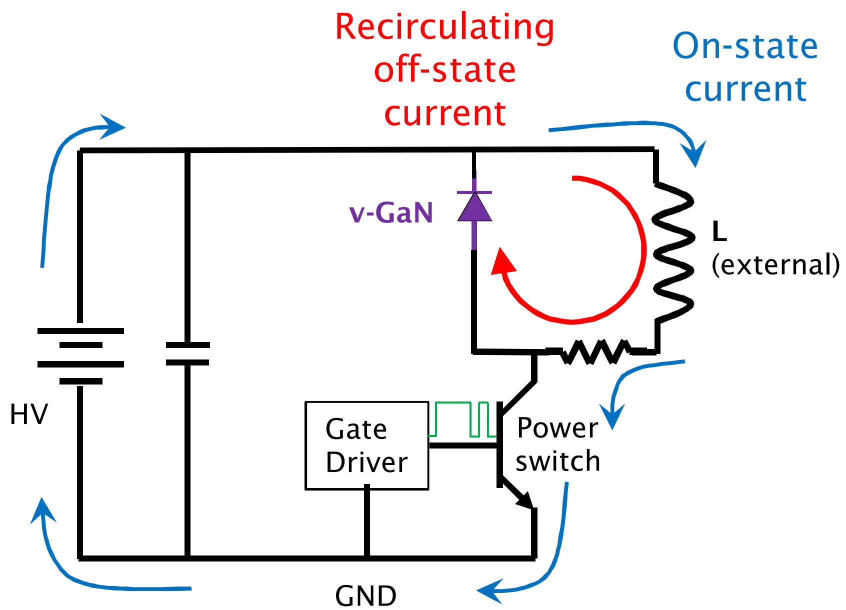




Switch gate voltage	Switch current	Diode voltage

- **Realistic circuit has some lossy elements**
  - Represented by lumped resistance in free-wheeling loop
  - Causes switch (and diode) current to saturate
  - Realistic DPTC is useful for continuous reliability testing!

Parameters for Steady-State Operation of DPTC

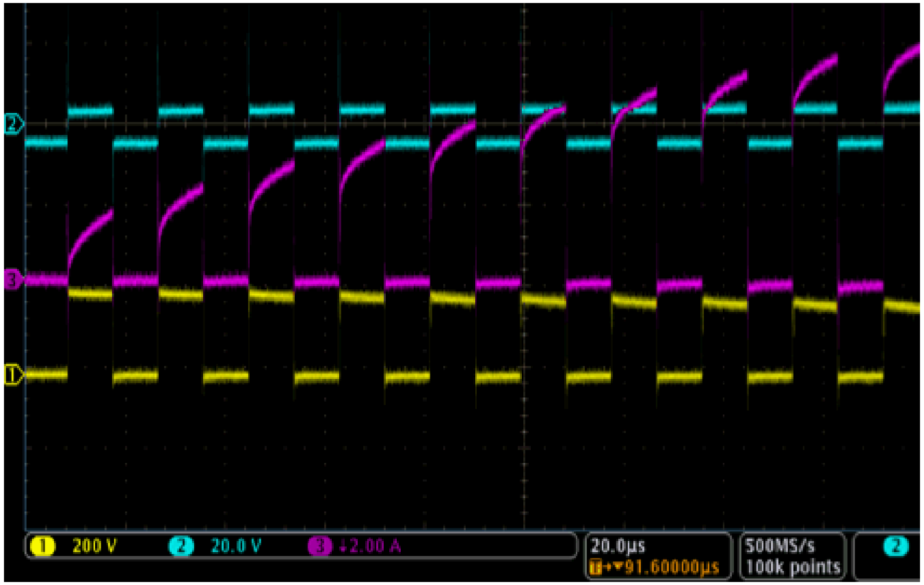


- **Switching duty cycle:**
  - $t_{on} = \frac{\Delta I_L \cdot L}{V_{in}}$
- **Current in loop:**
  - $I_L(t) = I_{max} \cdot e^{-\frac{R}{L}t}$
- **Decay time:**
  - $t_{off} = -\frac{L}{R}\ln\left(1 - \frac{t_{on} \cdot V_{in}}{L \cdot I_{max}}\right)$

Frequency and duty cycle must be adjusted based on supply voltage and device ratings to achieve desired steady-state operation

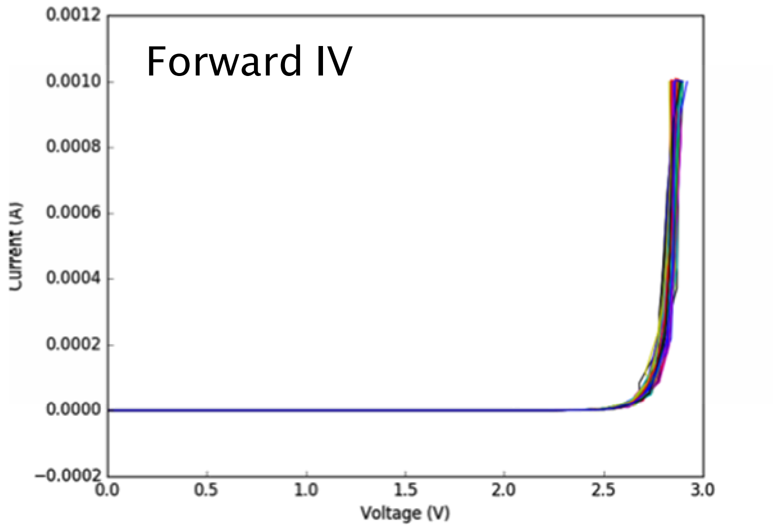
DPTC Testing of v-GaN PiN Diodes

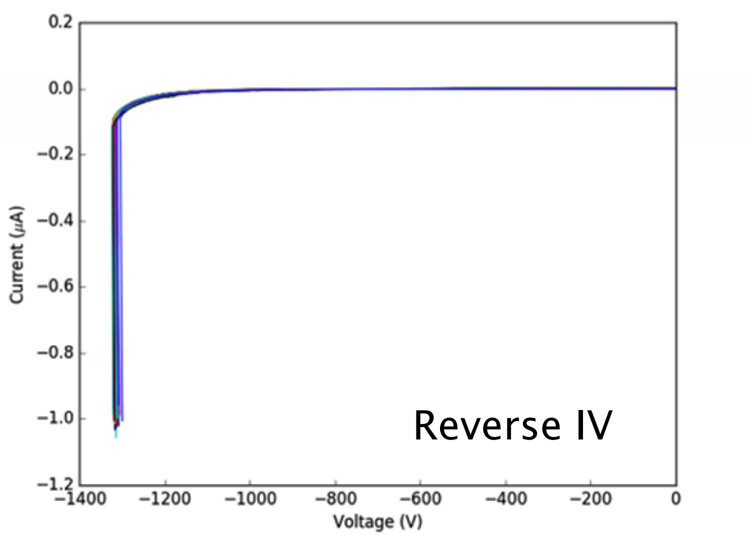
- Operation of circuit was limited by thermal dissipation of package
  - Not adequately heat-sinked
  - Limited voltage to 500 V, current to 2.2 A
- Switching times adjusted to achieve steady-state under these conditions
  - Switching frequency = 1 kHz
  - $t_{on} = 3.5\ \mu s$
  - Duty = 0.35%
  - L = 3 mH implies R ≈ 1 Ω



Switch gate voltage	Switch current	Diode voltage

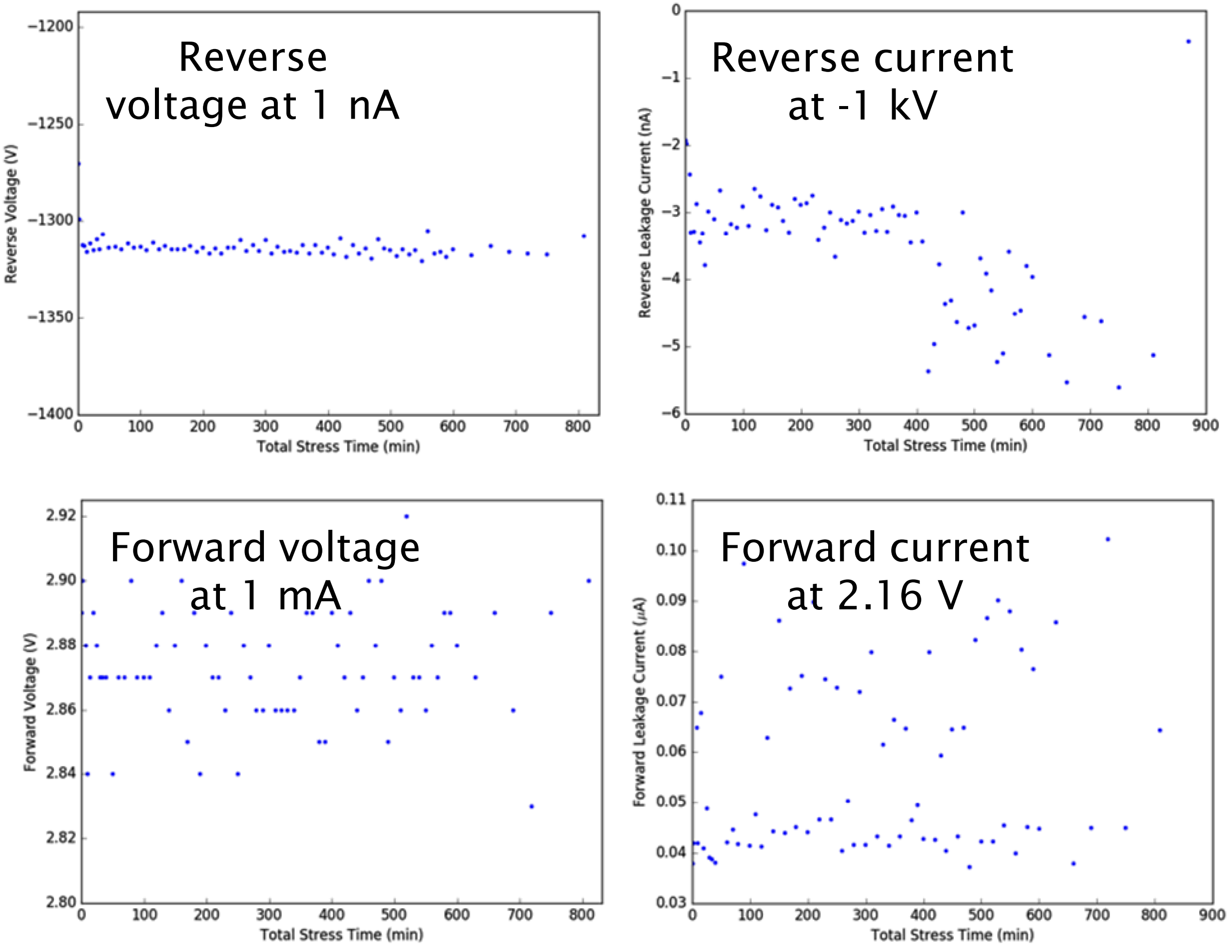
I-V Measured Periodically During Switching Stress





- **Vertical GaN diode subjected to 800 minutes of switching stress**
  - Stress interrupted approximately every 10 minutes
  - Forward and reverse IV curves taken
  - Both curves show minimal change under these stress conditions

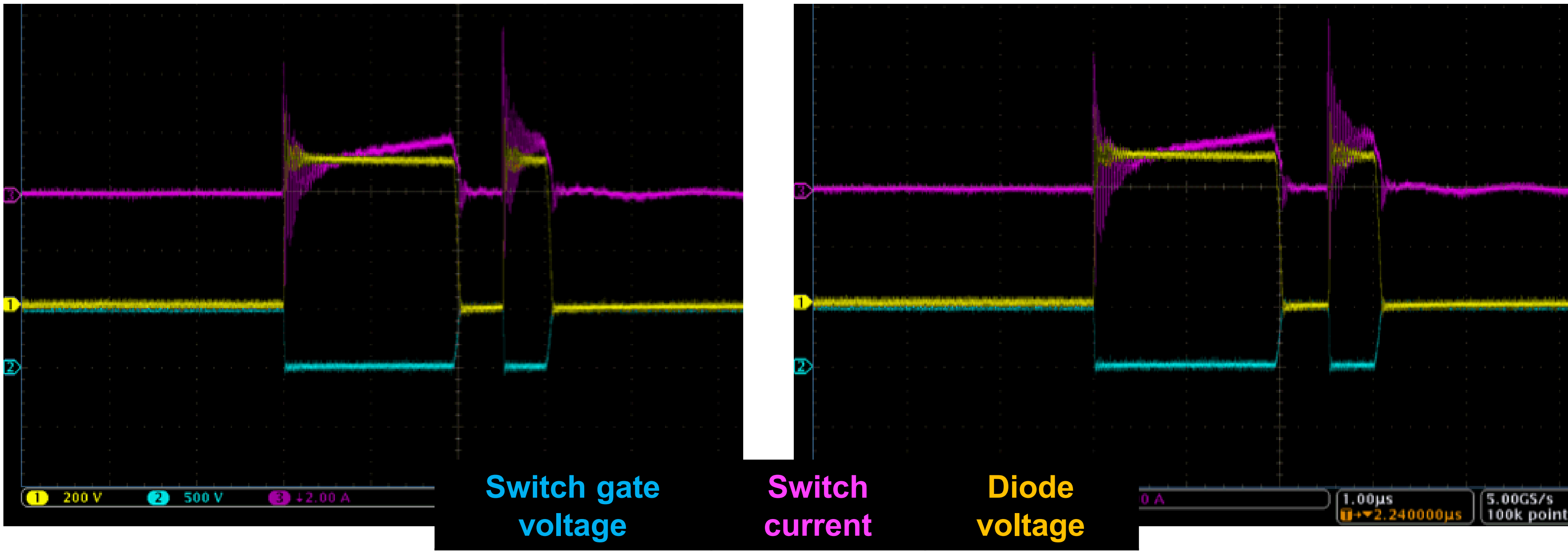
v-GaN Diode Parameters During Switching Stress



- ➢ Electrical parameters extracted from curves on previous slide
- ➢ Negligible parameter degradation observed
  - Drift observed in reverse current at -1 kV is at very low level

Double-Pulse Waveforms Before and After Switching Stress

Initial | **After 800 minutes of switching stress**



Conclusion: Vertical GaN diodes are robust under the switching conditions and total stress time utilized

Summary and Continuing Work

➢ Summary of this year's work:

- Vertical GaN power devices are at the forefront of WBG power semiconductor device technology – great potential to further improve system performance and reduce system cost
- Modified DPTC to perform continuous switching stress of vertical GaN PiN diodes
- Diodes look robust under the stress conditions examined

➢ Work for the coming year:

- Install proper heat-sinking in the DPTC to allow for a wider range of stress conditions (higher current and voltage)
- Install additional voltage and current monitors to record electrical data at more points in the circuit
- Further automate testing to stress more devices, to understand the statistics of vertical GaN device reliability

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