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Hard-switching Reliability Studies of Vertical GaN 1200 V PiN Diodes

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U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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Acknowledgment

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Project Motivation & Goals

- **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 frequencies plus lower conduction and switching losses reduce the size and complexity of power conversion systems, **thus reducing their overall system cost**
  - However, questions remain regarding the reliability of wide-bandgap materials and devices, **limiting their implementation**

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

Program Historical Highlights

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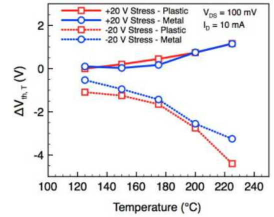
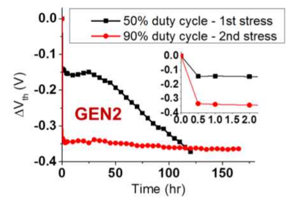
2009

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

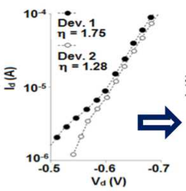
Developed and documented a general process for analyzing the reliability of any power electronics system

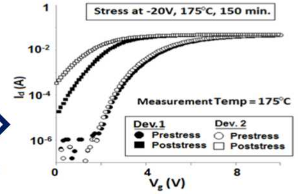
Characterized and evaluated commercial SiC MOSFETs, including the impacts of bias, temperature, packaging, and AC gate stress on reliability



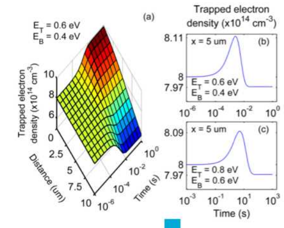


Developed models for SiC threshold voltage instability, and identified the free-wheeling diode ideality factor as a potential screening metric for threshold voltage shifts

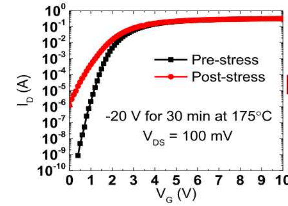


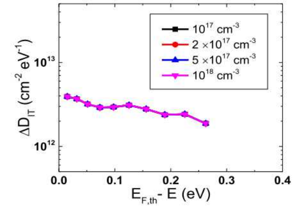


Created a physics-based model for GaN HEMTs linking defect properties to device design



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





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

2018

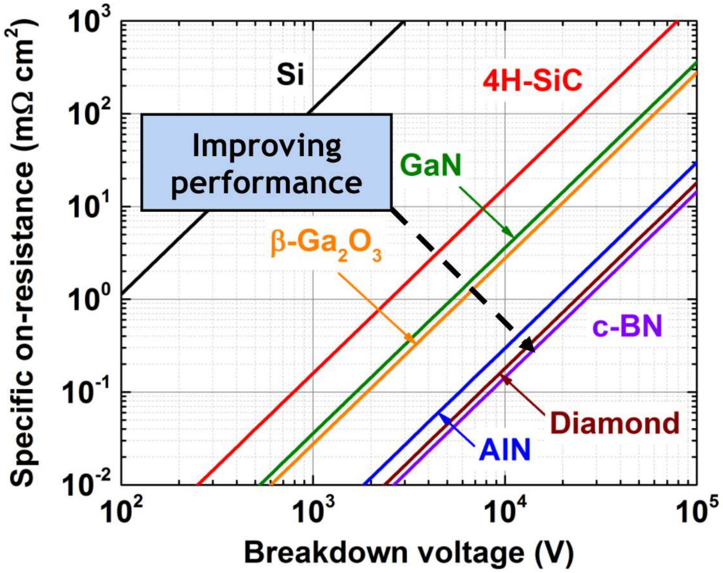
JEDEC

Participating in JEDEC WBG reliability working group

Over 30 papers and presentations through the course of the project

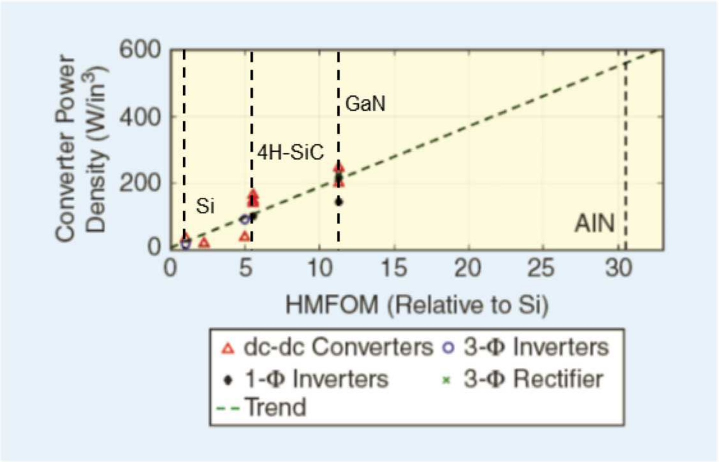
Advantages of GaN in power electronics

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



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

Considers conduction and switching losses



- GaN devices can have a strong impact on system size and weight due to reduced size of passive components and lessened thermal management requirements

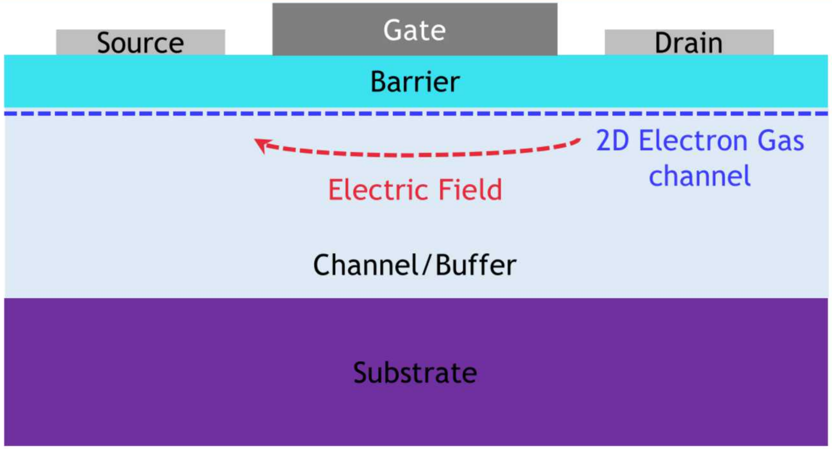
SOA commercial microinverter
250 W in 59 in³ → 4.2 W/in³

SNL GaN HEMT microinverter
400 W in 2.4 in³ → 167 W/in³

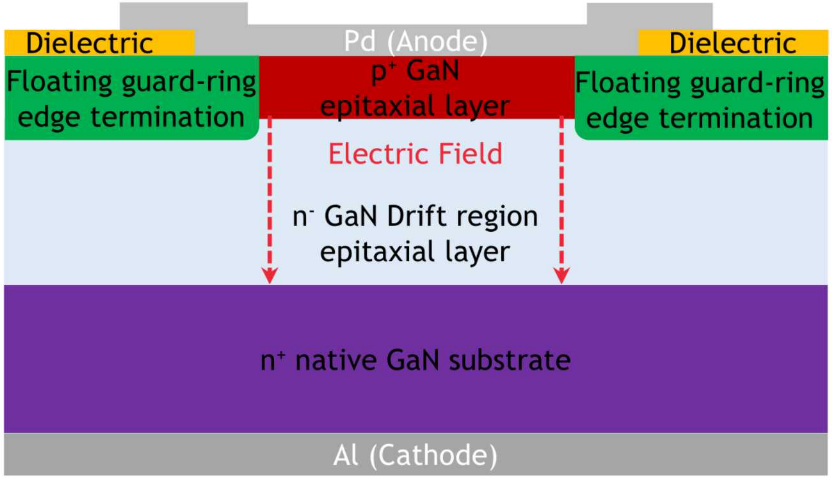
J. Y. Tsao et al., *Adv. Elec. Mat.* 4, 1600501 (2018)
R. J. Kaplar et al., *IEEE Power Elec. Mag.* 4(1), 36 (2017)

Vertical GaN Power Devices

- Historically, GaN devices have had a lateral design
  - Limits hold-off voltage to ≲650 V due to electric-field management
  - High-frequency operation
  - No avalanche ruggedness



- Vertical GaN (v-GaN) devices are now becoming available
  - Greater potential for high-voltage operation ≳1200 V
  - Avalanche capability
  - Greater power density



➢ Reliability and switching performance of v-GaN devices is largely uncharacterized in literature

Area Advantage of Vertical GaN

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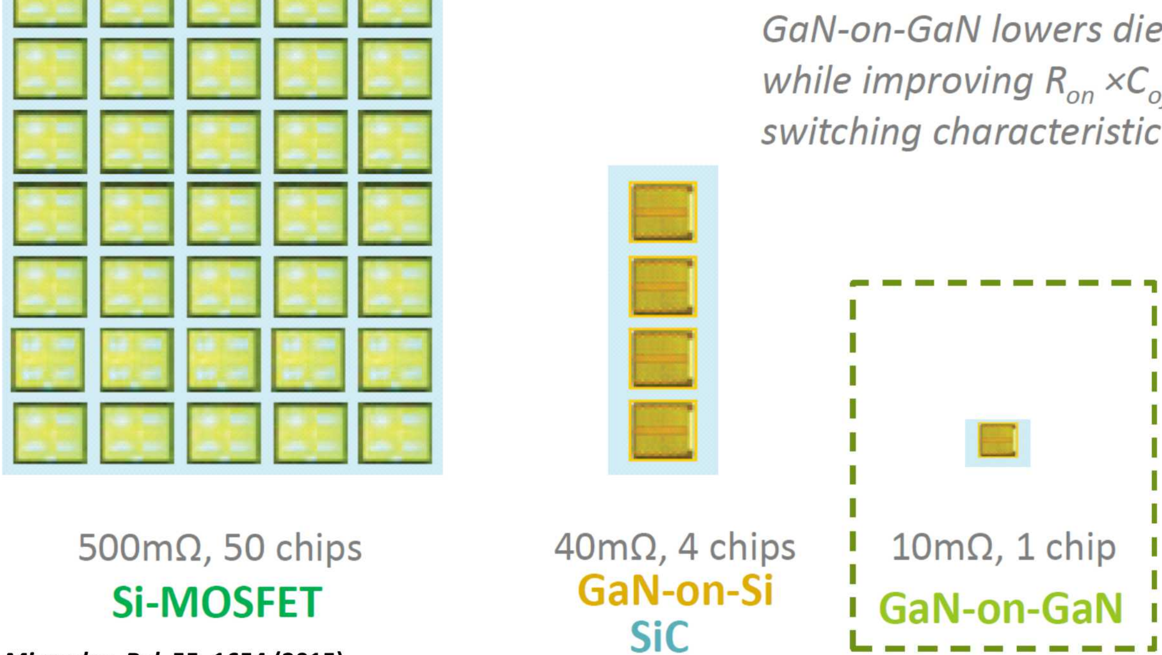
For a given on-resistance (R_{on}) of 10mΩ:

➢ **Tested Avogy vertical GaN PiN diodes:**
- 0.72 mm^2 area
- Rated at 1200 V hold-off voltage, 15 A peak forward current

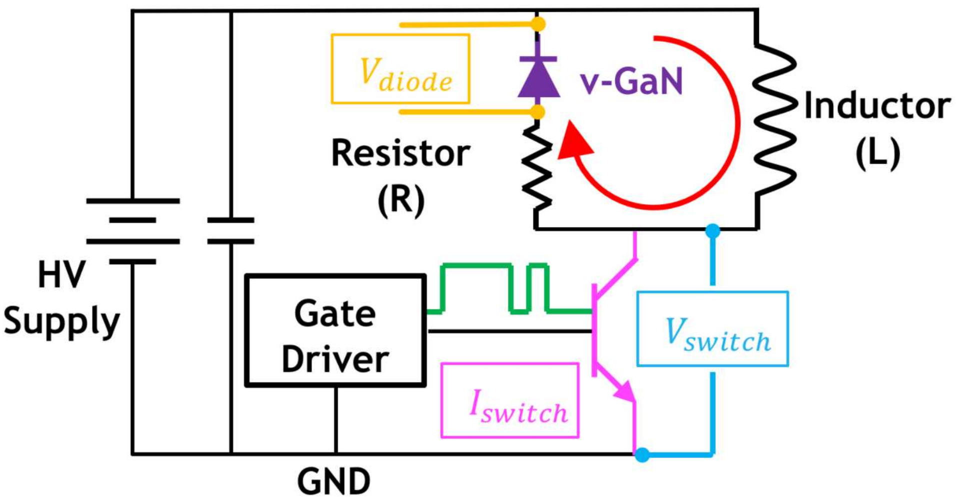


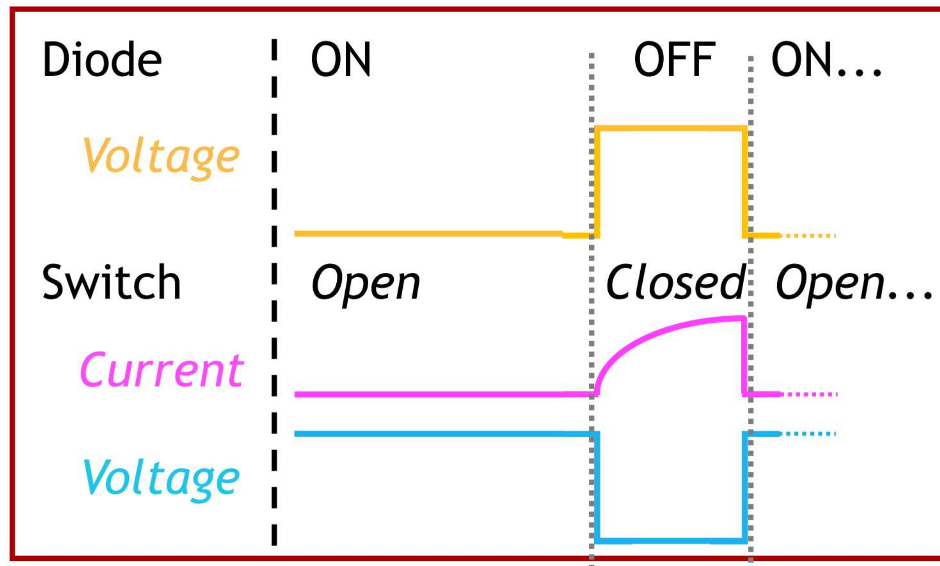
The devices tested were obtained from I. Kizilyalli and O. Aktas at Avogy, and were fabricated under the ARPA-E SWITCHES program managed by Dr. Tim Heidel

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

Stress Testing with the DPTC

- Double-pulse test circuit (DPTC) is usually used to characterize switching of inductively-loaded power transistors
  - But can use a known good switch & characterize the diode
- Transient (double-pulse) operation:
  - Characterize reverse recovery & switching behavior
- Steady-state (continuous) characterization:
  - New use for **reliability testing**
  - **Realistic evaluation of device behavior in switching power circuit**

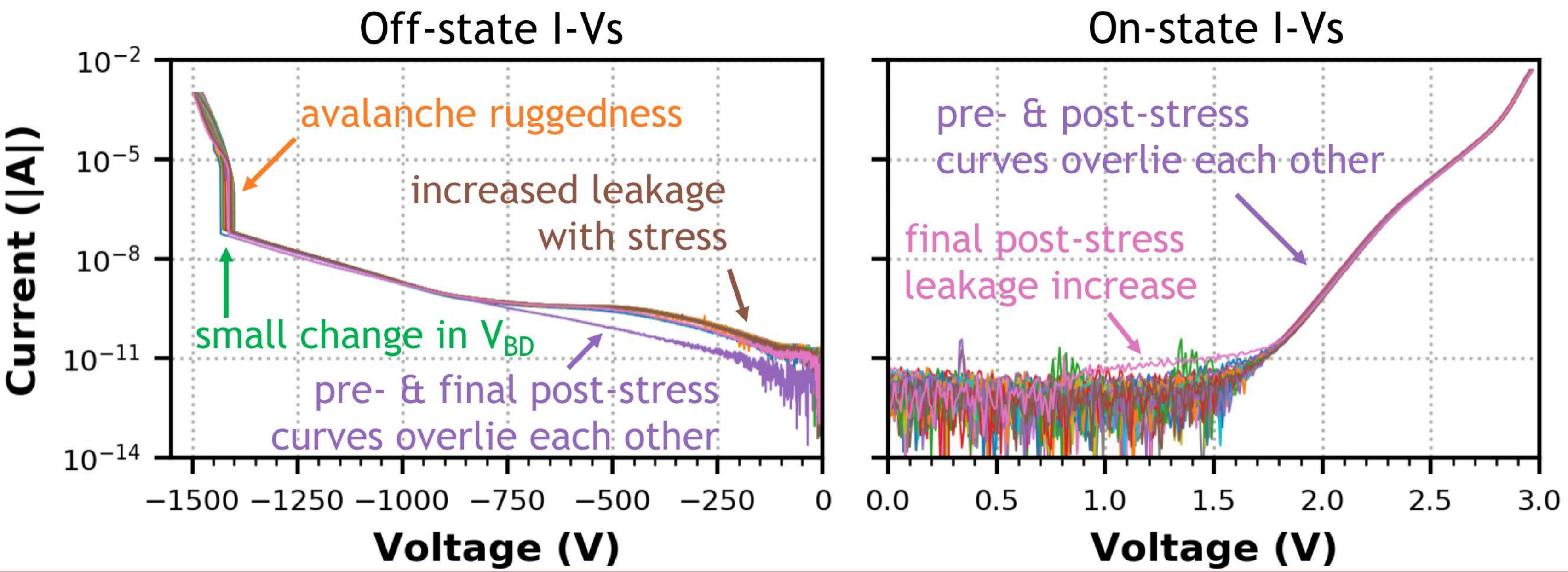




Hard-switching Reliability Studies

- Stress applied over 720 minutes at different supply voltages:
  - 500, 750, 1000, 1170 V
  - To monitor degradation, collected current-voltage curves every 20 minutes
  - Collected oscilloscope traces of double-pulse and stress pulse
- Gate drive conditions:
  - Switching frequency = 1 kHz, pulse length= 2 μsec (0.02 % duty cycle)

Cumulative v-GaN I-Vs over 720 minutes of 1000 V hard switching stress

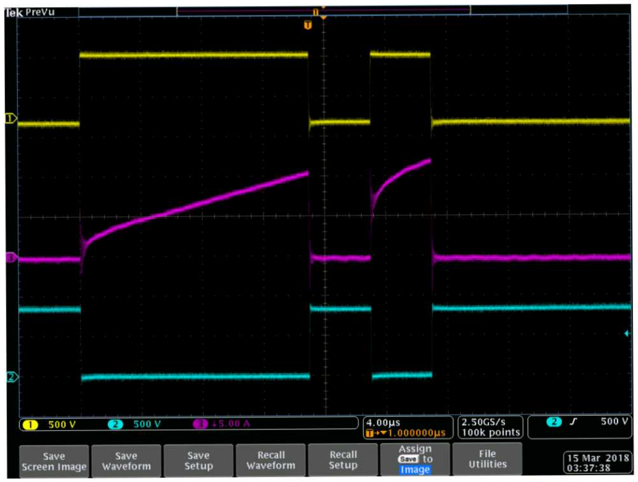


Pre- vs. Post- Stress Traces

Double-pulse

Stress Pulse

Pre-
stress

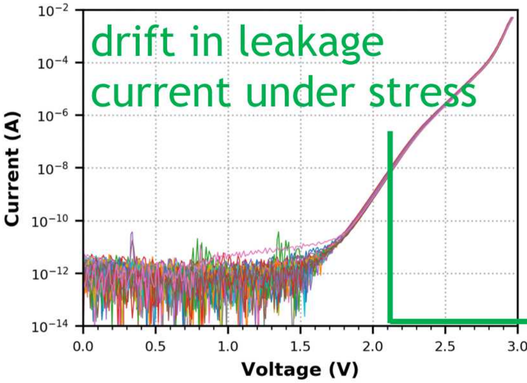


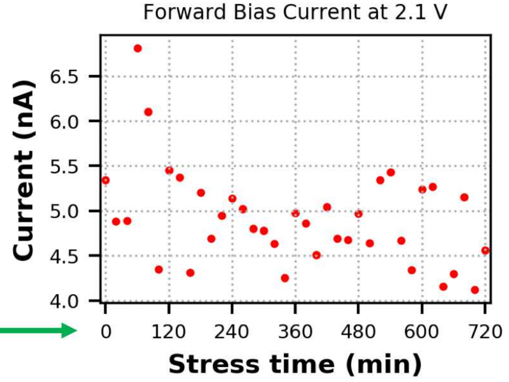
Post-
stress

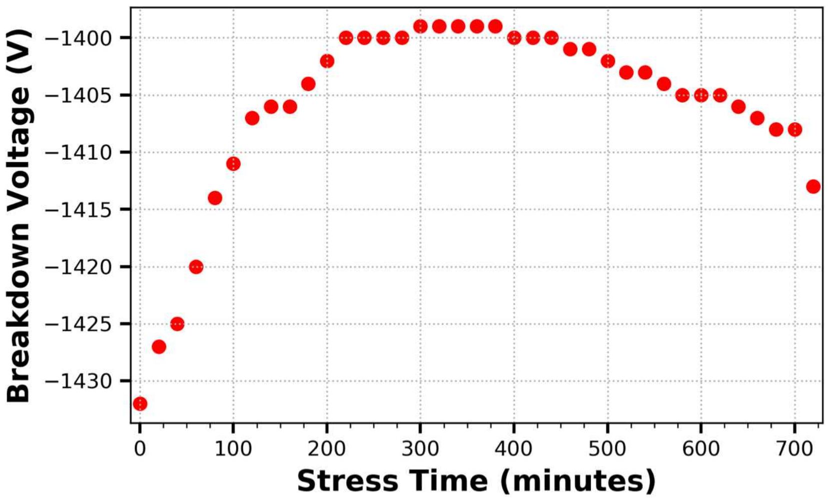
➢ Negligible difference between pre- & post-stress traces

Parametric Drift at 1000 V Stress

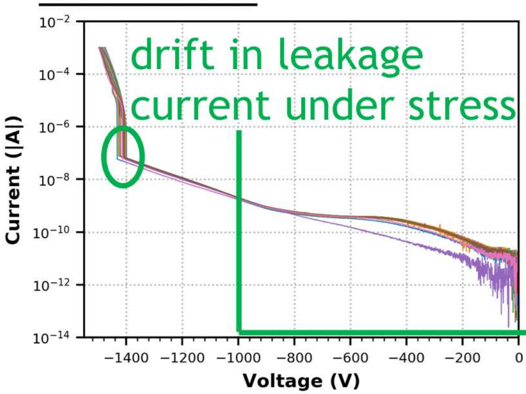
ON-state

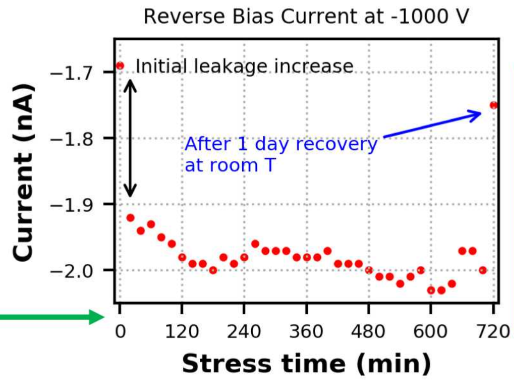






OFF-state





- ➢ Shape of breakdown voltage with stress suggests complex physical mechanisms behind the behavior

- ➢ Thermal recovery suggests degradation mechanism involves carrier trapping

Concluding Thoughts

- Vertical GaN offers a number of advantages over, Si, SiC and lateral GaN
  - Improved device power density
  - Reduced power system cost
  - But... in early research stage with many outstanding questions including their reliability
- Used double-pulse test circuit to evaluate switching reliability of 1200 V-rated Avogy PiN vertical GaN diodes
  - Stressed at 500, 750, 1000, 1170 V in continuous-pulse mode
  - Small increase in OFF-state leakage with stress
  - Devices recover with rest – suggesting trapping mechanism is responsible for the degradation
  - Complex behavior of breakdown voltage with stress

➢ Overall, devices are robust over the range of conditions tested

and What is Next?

- Improved Double-Pulse Test Circuit
  - better temperature control & monitoring
- Further testing
- Development of a physical model of degradation mechanisms

With further questions, contact:

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For more information, also see:

MRS Spring 2018 Talk (invited)

MRS Spring 2018 Research Letter:

Hard-Switching Reliability Studies of Vertical 1200 V GaN PiN Diodes

Thank You

The characterization work at Sandia was supported by the Energy Storage Program managed by Dr. Imre Gyuk of the DOE Office of Electricity.

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