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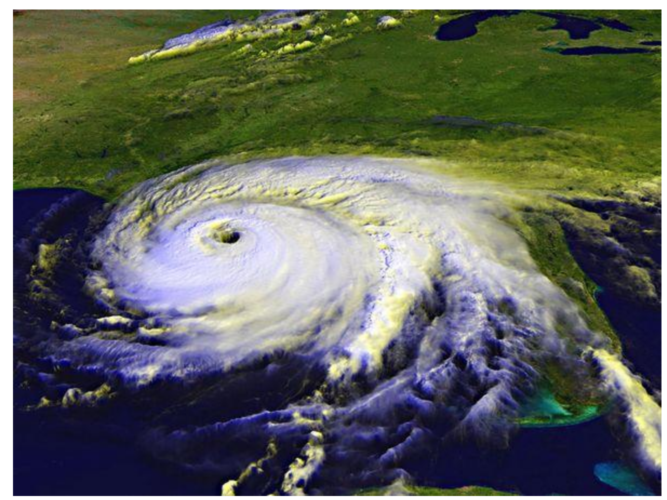

Reliability Characterization of Wide-Bandgap Semiconductor Switches

September 18, 2014

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U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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Project Overview

- ***Wide-bandgap semiconductors have material properties that make them theoretically superior to Silicon for power device applications***
  - Lower power loss and reduced cooling requirements would increase the efficiency and reduce the size and complexity of power conversion systems linking energy storage to the grid, *thus reducing overall system cost*
  - However, wide-bandgap materials and devices are far less mature than their Si counterparts; many questions remain regarding their reliability, *limiting their implementation in systems*
- ***Goal: Understand the performance and reliability of SiC and GaN wide-bandgap power switches and how it impacts circuit- and system-level performance***

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

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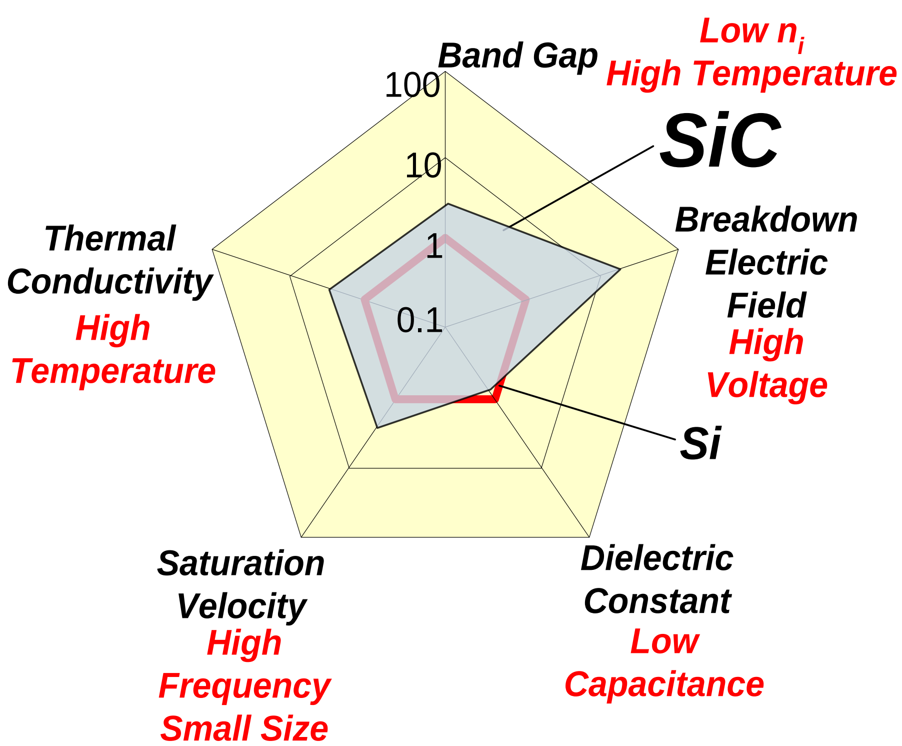
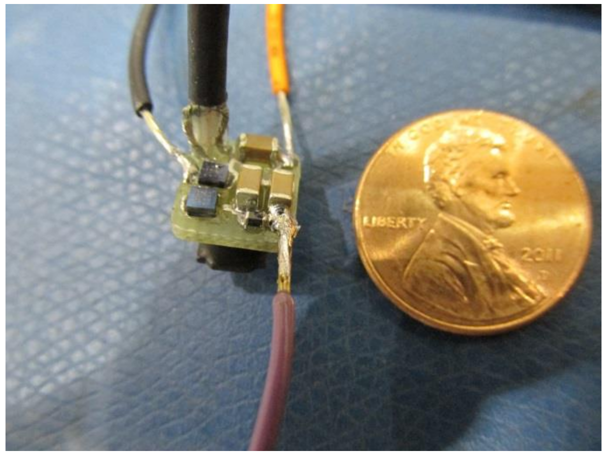
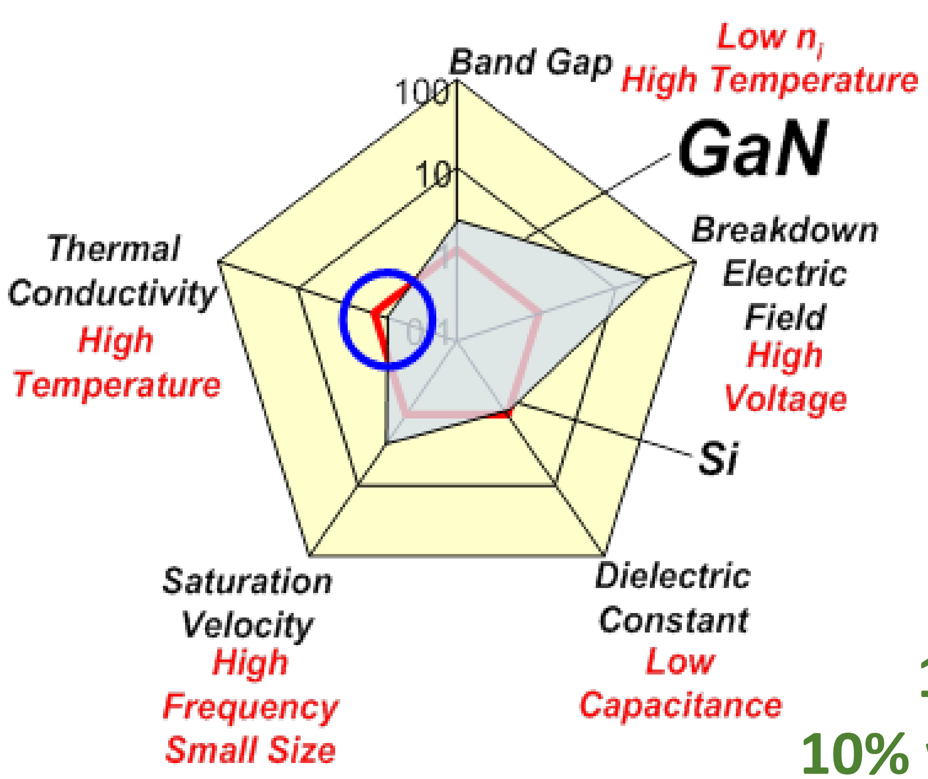


- **WBG semiconductors can have a strong impact on system size and weight due to higher switching frequency and reduced thermal management requirements**
- ***But their reliability is far less mature than traditional Si devices!***

Achieved: GaN - 8.5 W => 215 W/in^3

92 V, ~92 mA => 8.5W, 215W/in^3, 1 MHz





M. K. Das et al., ICSCRM 2011

13.5 kV, 100 A Si IGBT module

10 kV, 120 A SiC MOSFET module
10% weight and 12% volume of Si module

Figures courtesy of Prof. D. K. Schroder, ASU

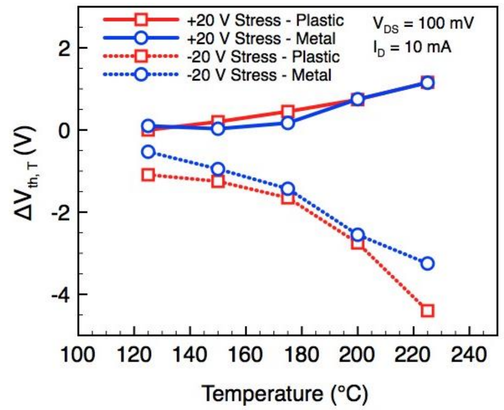
Project Highlights

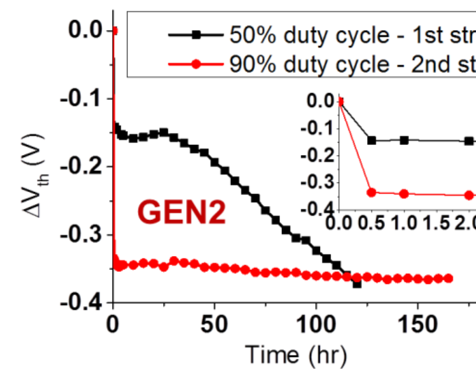
Over 26 Papers and Presentations

Sandia National Laboratories

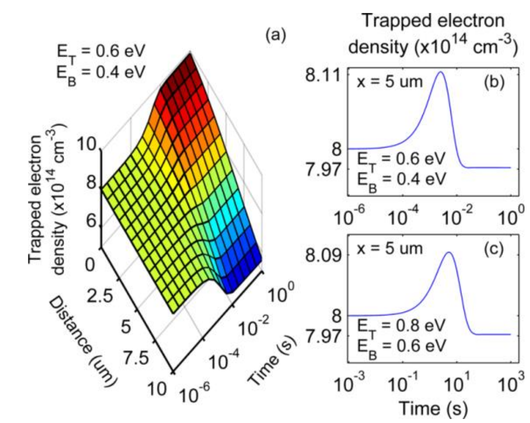
Reliability improvements suggested for components, software, and operation of Silicon Power Corporation's Solid-State Current Limiter.

Commercial SiC MOSFETs characterized and evaluated. Investigated 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.

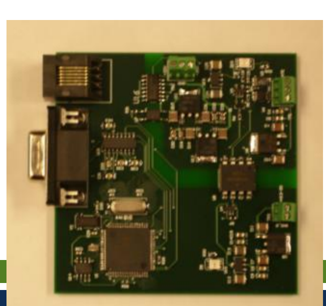


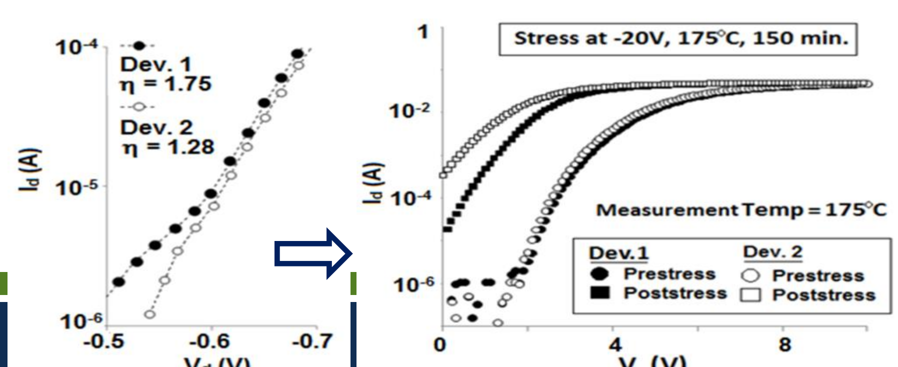
2009 — 2016

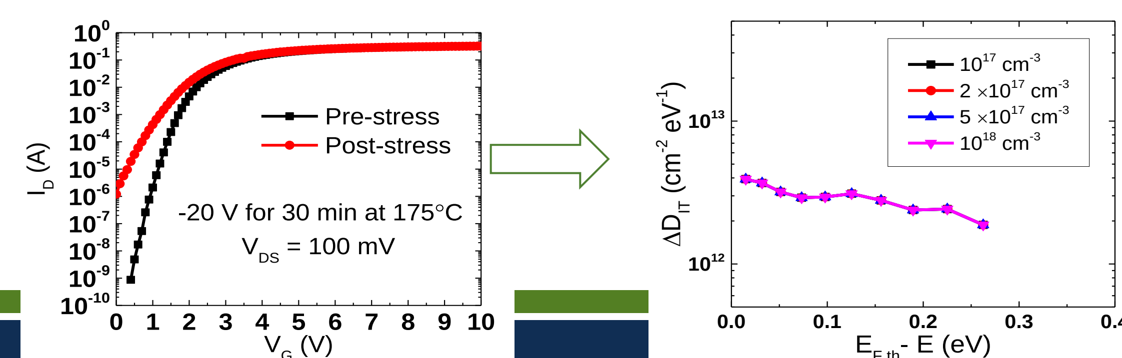
Sandia developed and documented a general process for analyzing the reliability of any power electronics system.

Developed models for SiC threshold voltage instability. Identified the free-wheeling ideality factor as a potential screening metric for threshold voltage shifts.

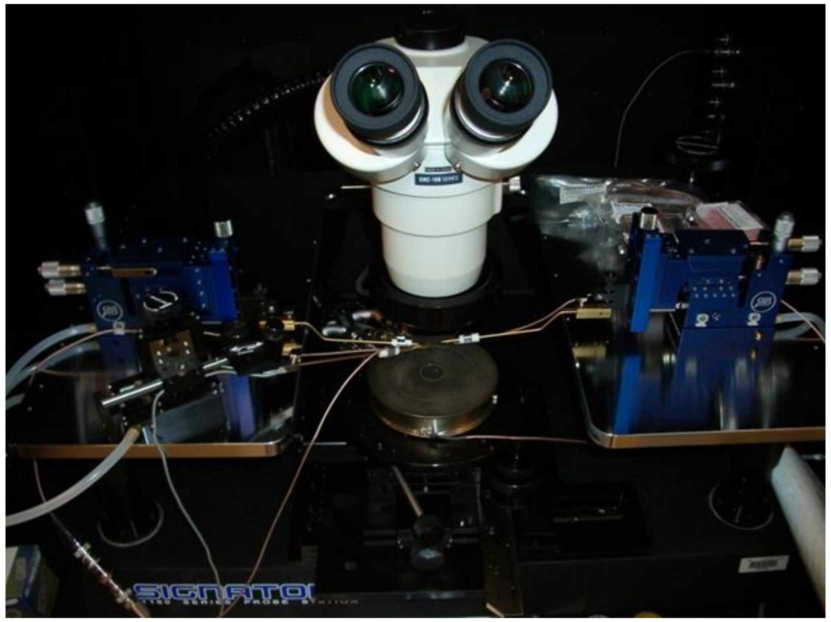
Developed an easy to use method that can be used by circuit designers to evaluate the reliability of commercial SiC MOSFETs.







Power Device Characterization Laboratory



Facilities funded by this program

- **Hot chuck capable of 600˚C operation**
- **High-power test system for evaluation of power semiconductor switches**
  - **10 kV, 50 A**
  - **Packaged parts up to 400˚C**
  - **Wafers and die up to 300˚C**

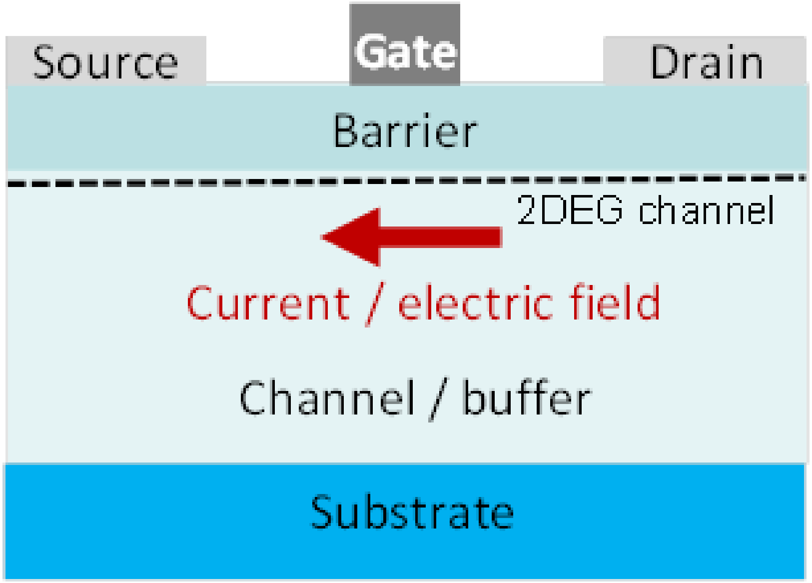
- **High power clamped inductive load switching circuit allows realistic characterization of power losses due to switching as a function of parameters like frequency and duty cycle**

- ***Leverages Sandia's role as the lead DOE lab for electronics, including significant investments in silicon (e.g. ASICs) and compound semiconductors (e.g. solid-state lighting)***

Motivation and Overview for This Year's Work

For mature Si technology, most power device reliability focuses on the packaging and thermal management

- Devices are mature and well-understood
- Manufacturing is well-controlled

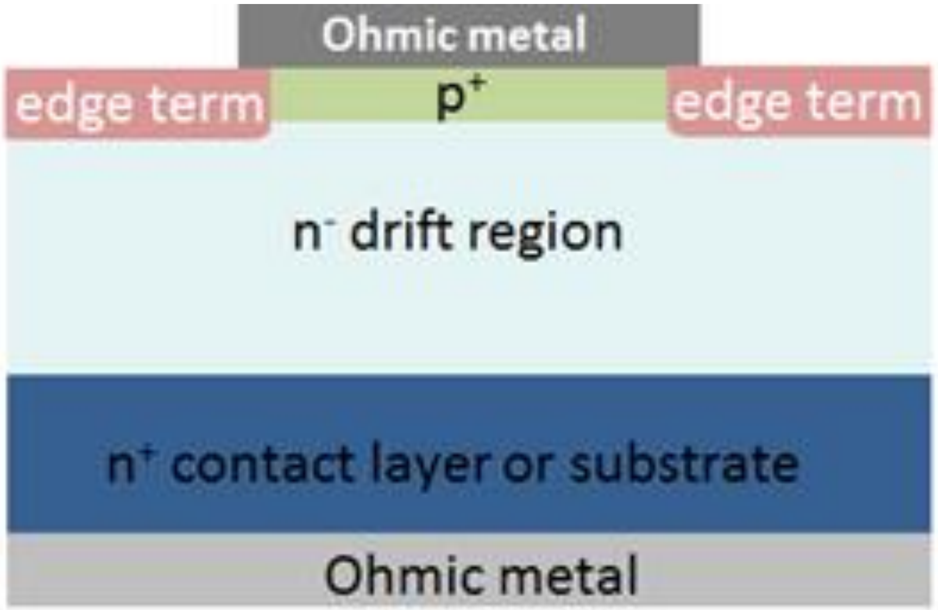


For WBG materials, devices are new and unproven

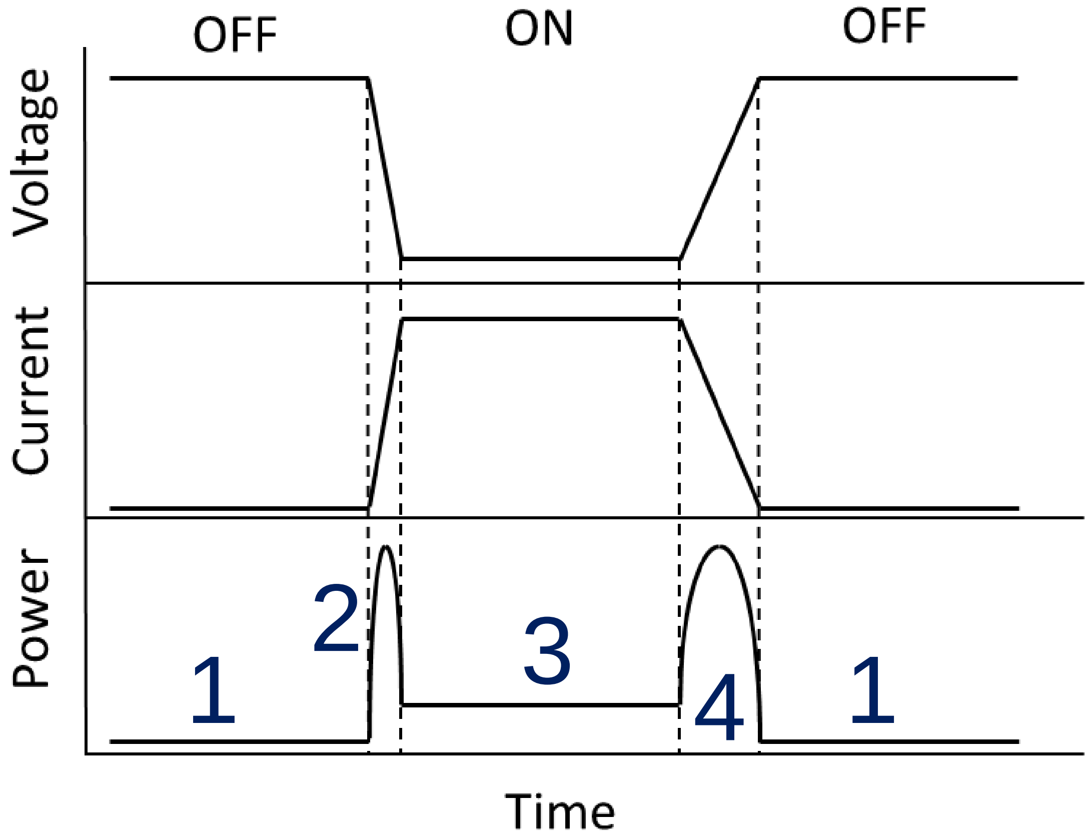
- Materials are much newer
- Manufacturing is not as well-controlled
- True for both SiC and GaN, but SiC is more mature
  - Previous work focused on SiC performance/reliability

Our work has focused on newly developed vertical GaN devices

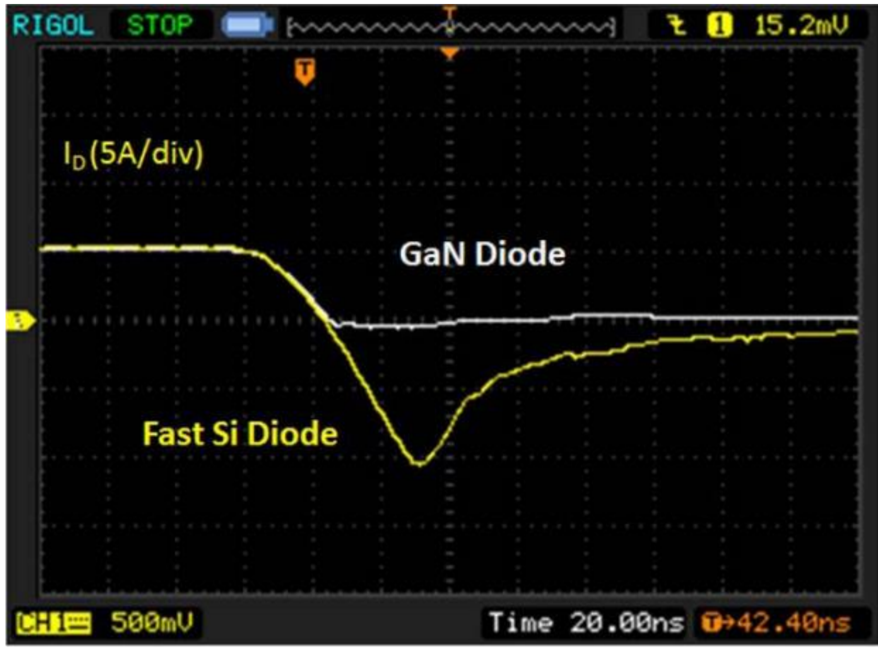
- Historically, GaN devices in lateral orientation
  - Limits voltage hold-off (<600 V) due to E-field management
- Vertical GaN (v-GaN) devices are now becoming available
  - Reliability and switching performance are ***uncharacterized*** in literature
    - Samples from startup company Avogy
      - True vertical device
      - Rated for 1200V and 100 A_{pulse}



Why Switching Characterization?



Loss mechanisms:
1. Leakage
2. Turn-on
3. Conduction (R_{ON})
4. Turn-off



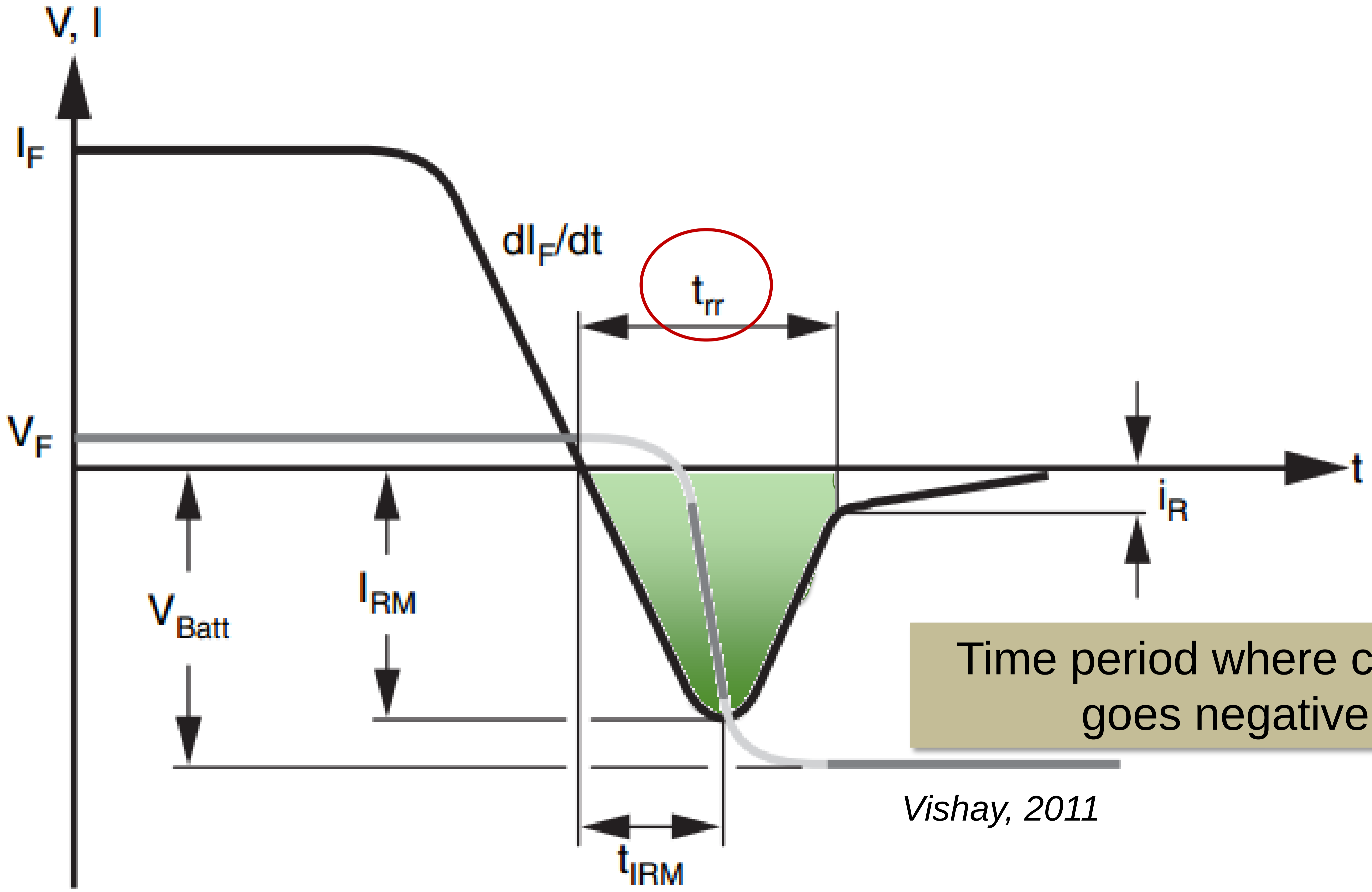
Kizilyalli et al., 2013

- Switching energy (speed) is the highest loss mechanism in power converters
- Potential high speed, high power density power electronics
  - Higher efficiency
  - Less cooling requirements
  - Reduction in system size/cost

	Current		Proposed
Technology	Si IGBT	Si Thyristor	WBG
Voltage Rating	6.5 kV	10 kV	100 kV
Switching Time	400 µs	100's µs	0.1 µs
Switching Frequency	20 kHz	60 Hz	10 kHz
Switching Loss (J/switch)	10	100	2
System Cost ($/MW)	$230,000-$500,000		$100,000

The Reverse Recovery Period

- For diodes, energy loss during switch transitions due to **reverse recovery**
- As diode goes from **conducting** to **blocking** state
  - Current goes negative for period of time



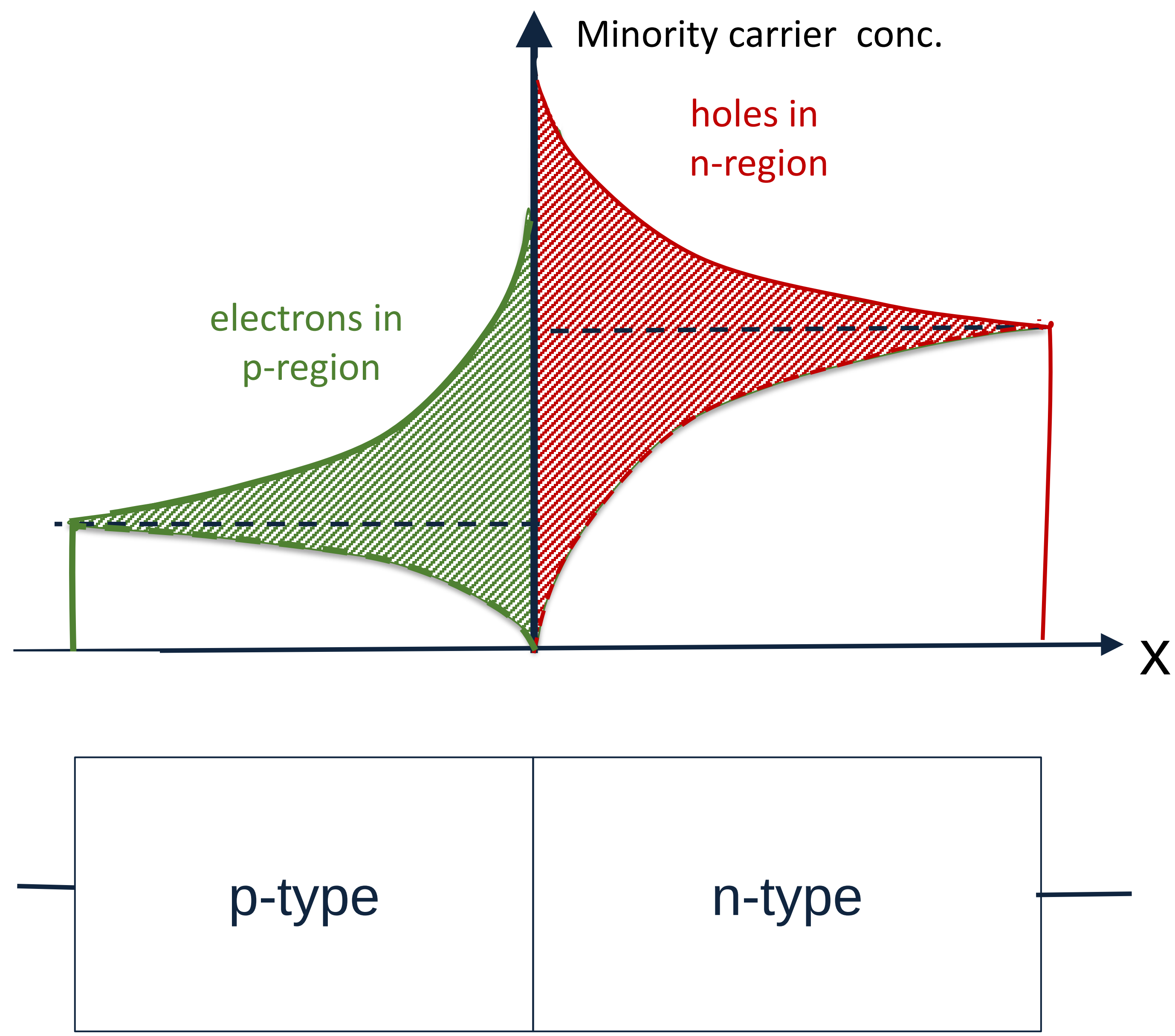
Time period where current goes negative

Vishay, 2011

The Reverse Recovery Period

- For diodes, energy loss during switch transitions due to reverse recovery
- As diode goes from **conducting** to **blocking** state

- Reverse Bias / Forward Bias

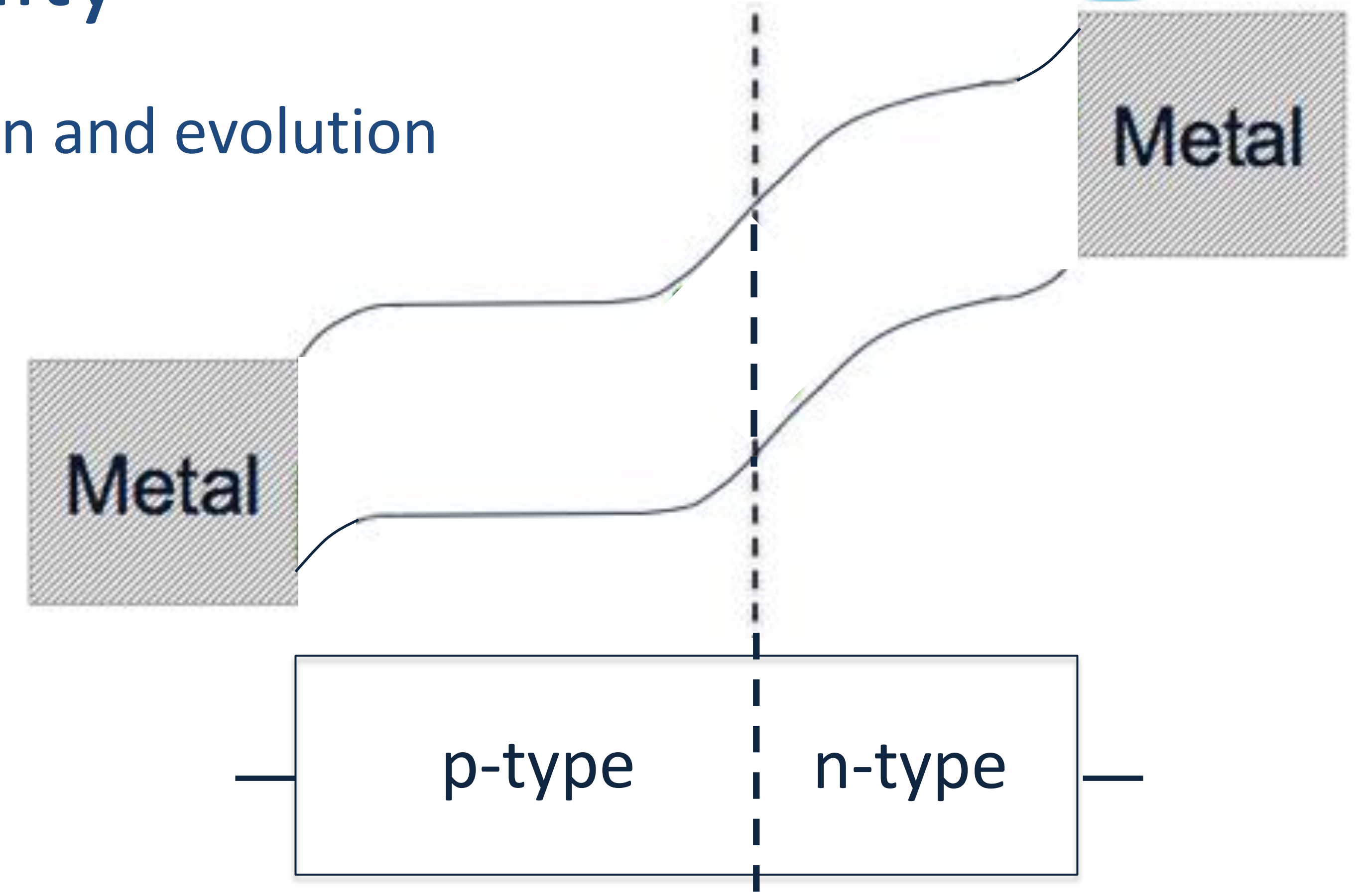


- Change in charge distribution between conducting and blocking states
- Must dissipate extra charge
- Requires reverse current flows until mobile charge in junction is depleted
- Time depends on junction capacitance and carrier lifetime

- Schottky diodes show no reverse recovery
  - Modulating barrier height, not clearing junction junction)

Current Work -- v-GaN Reliability

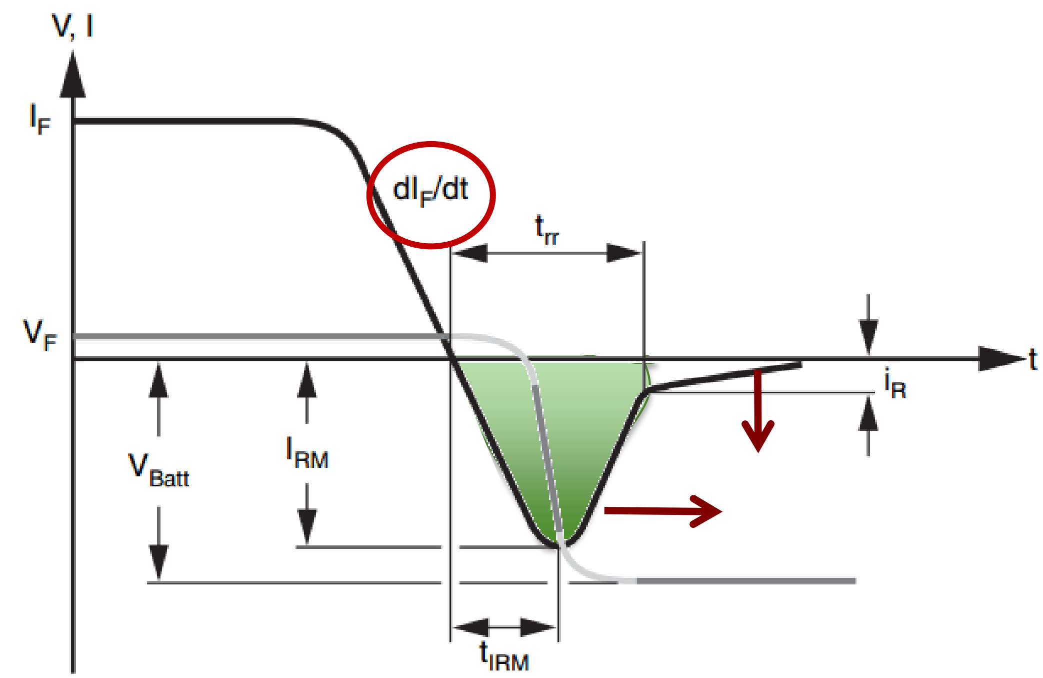
- Switching behavior elucidates trap creation and evolution during long-term device operation



- Introduction of traps in junction will change switching properties
  - Mid-gap traps:
    - I_R Increases
  - Band edge traps:
    - Lifetime Increases
      → t_{rr} increases

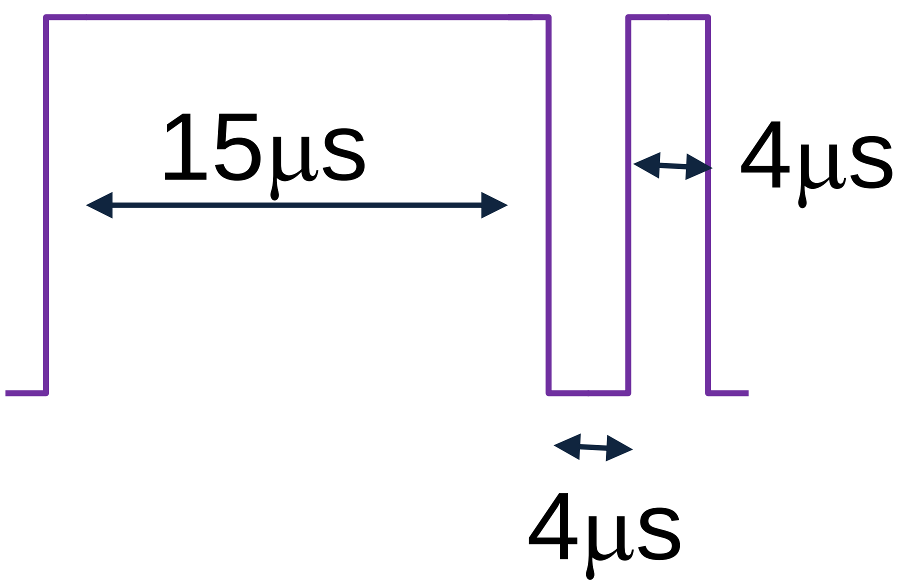
- Introduction of surface traps can change metal/semiconductor interface

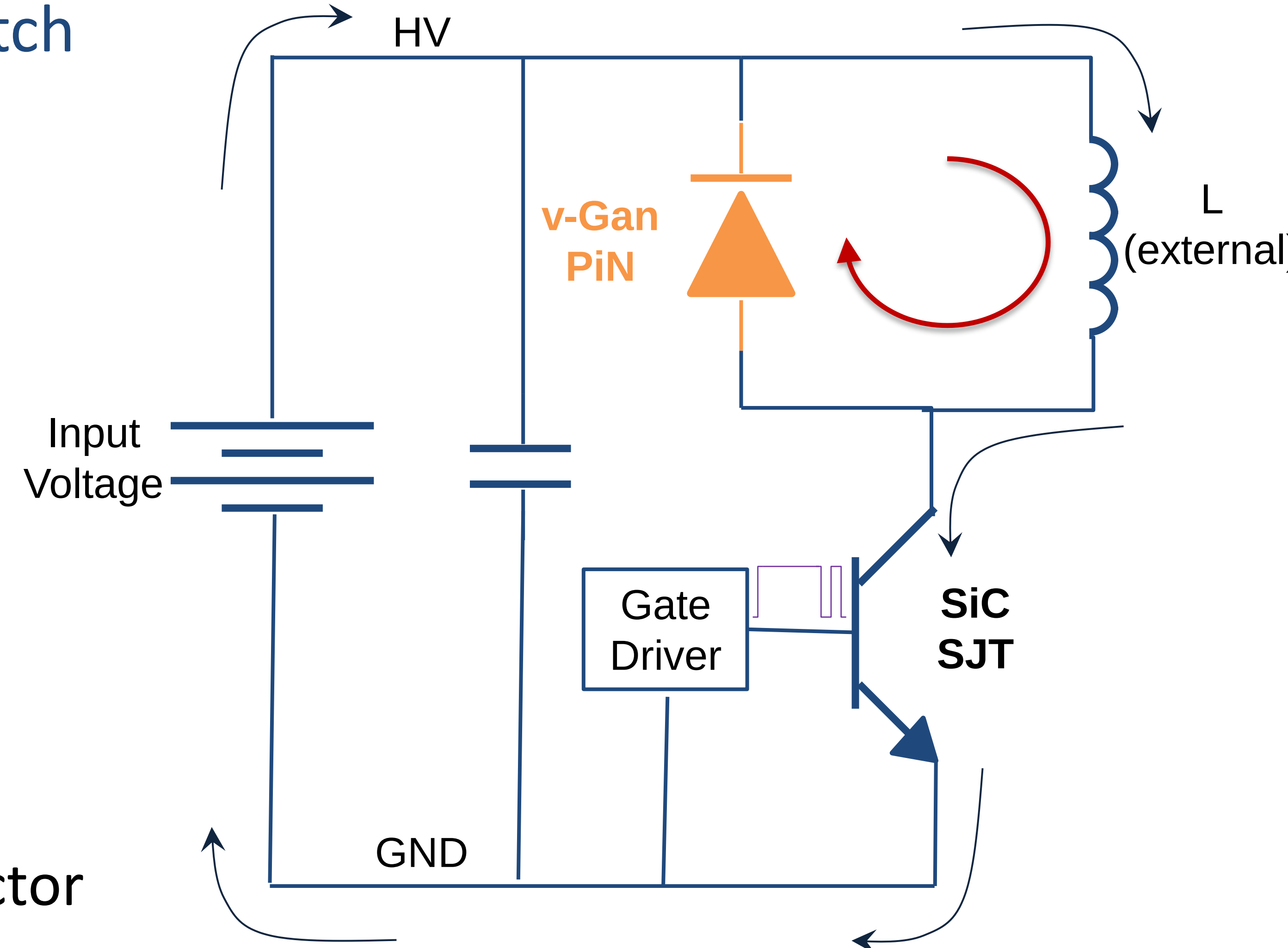
  → Change in switching time (RC time constant)



Test Circuit and Stimulus

- To Test diode reverse recovery used a Double Pulse Test Circuit
- Simple circuit (diode, switch, and inductor)
    - Allows for high voltage, low current power supply to apply high voltage/current to diode and switch
- Gate signal is a double pulse



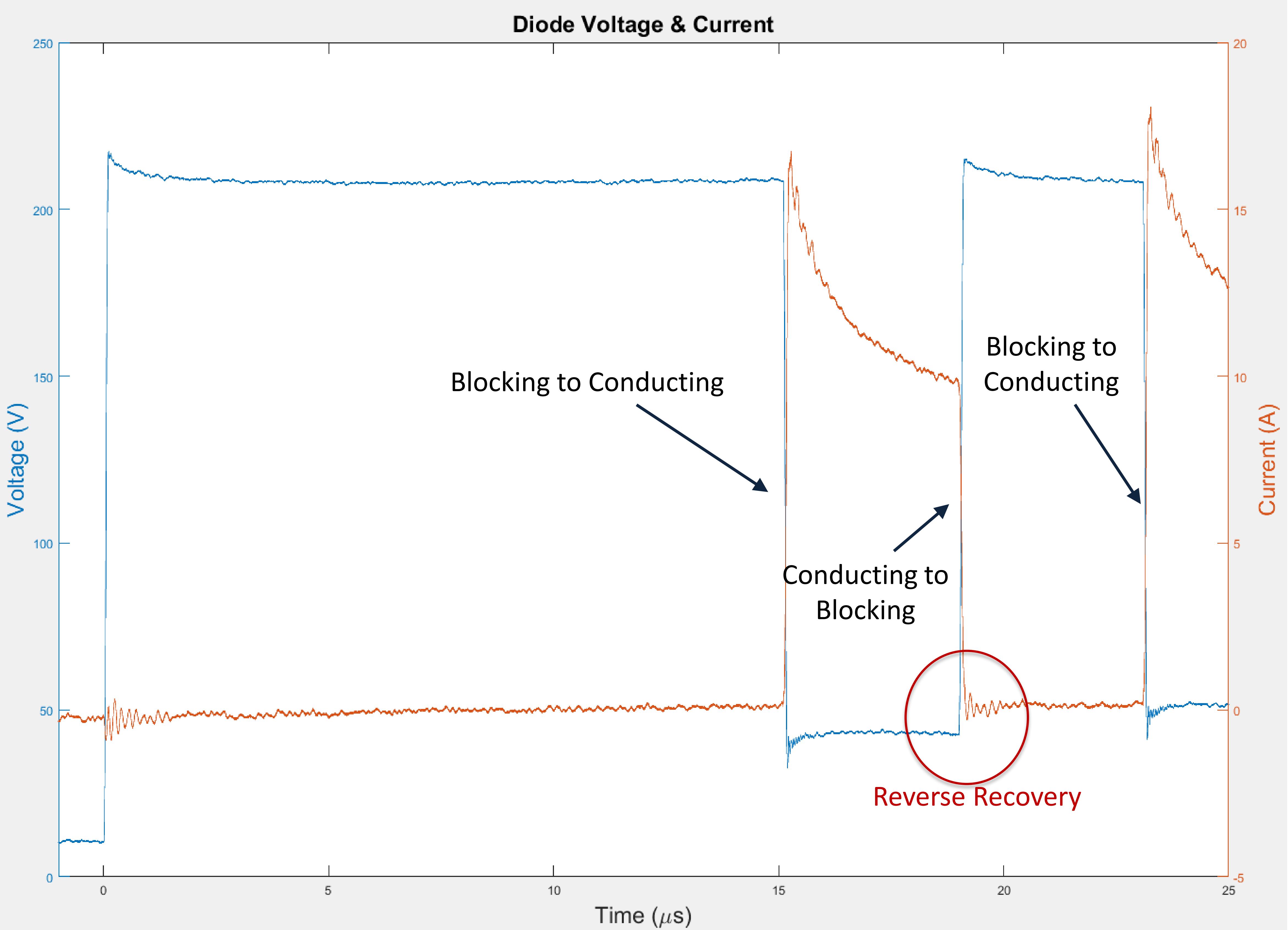


1st pulse: Increased stored energy in inductor

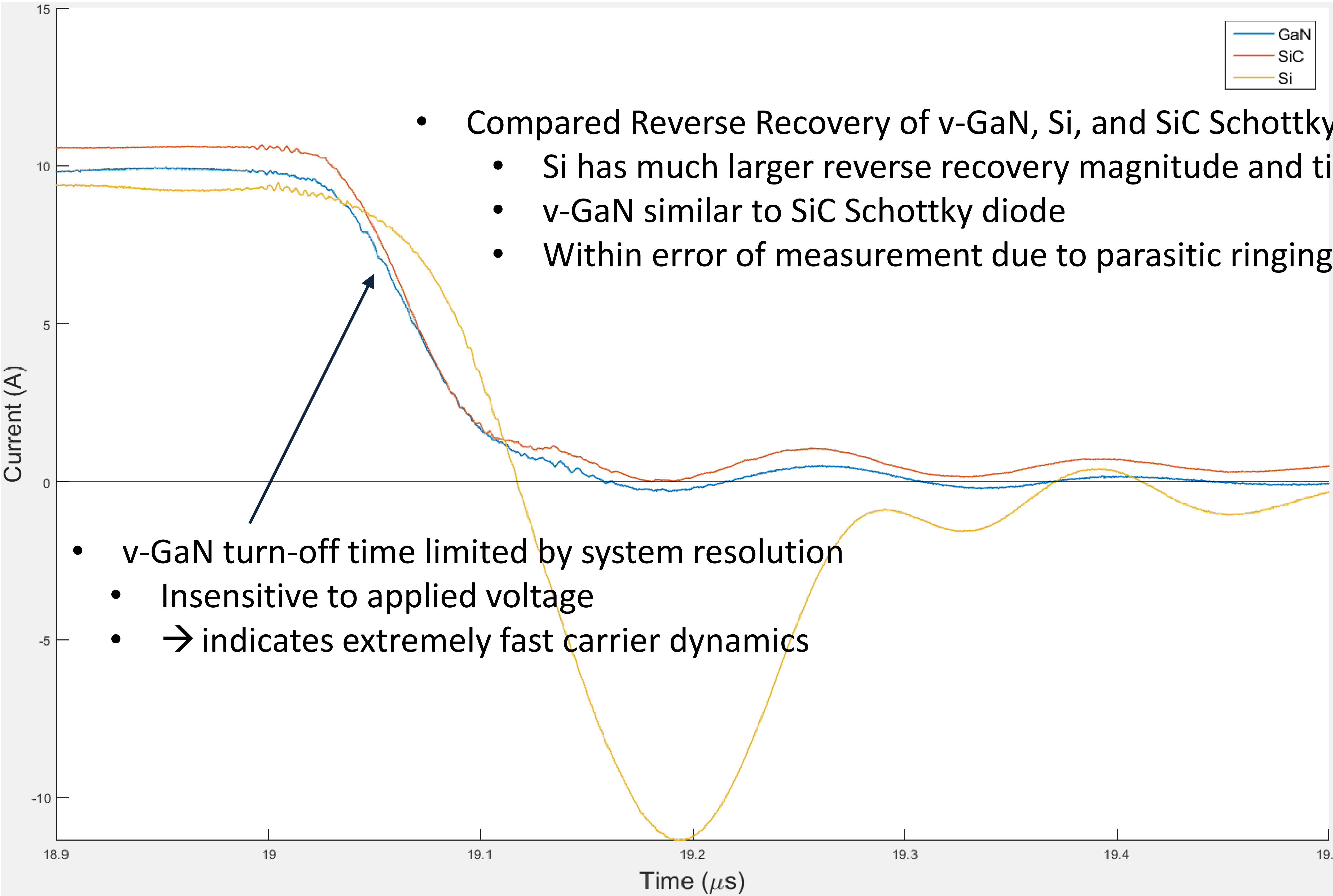
1st off: flow current through diode/inductor loop

2nd pulse: discharge high current/voltage through switch

Double Pulse Test Results -- v-GaN



Material Comparison



- Compared Reverse Recovery of v-GaN, Si, and SiC Schottky
  - Si has much larger reverse recovery magnitude and time
  - v-GaN similar to SiC Schottky diode
  - Within error of measurement due to parasitic ringing

- v-GaN turn-off time limited by system resolution
  - Insensitive to applied voltage
  - → indicates extremely fast carrier dynamics

Summary/Conclusions

- Vertical GaN pin diode performance
  - Analyzed switching characteristics of v-GaN devices under realistic load conditions using Double Pulse Test Circuit
    - Demonstrated short minority carrier lifetime due to insensitivity to applied voltage
    - Showed reverse recovery time smaller than resolution of instrumentation
      - Much smaller than conventional Si diode
      - Commensurate with SiC schottky diode (has no reverse recovery)

- Future Work
  - Long-term evaluation of v-GaN switching under repeated switching stress
  - Higher voltage/current analysis in Double Pulse Test Circuit
  - High Temperature Reverse Bias measurements on die

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Questions?