SAND2019-6825PE

ARC-SAFE: Accelerated Response Semiconducting Contactors and Surge Attenuation For DC Electrical Systems

Sandia National Laboratories

G. Pickrell, J. Flicker, J. Neely, A. Mar, E. Schrock, S. Atcitty, H. Hjalmarson, A. Allerman, and R. Kaplar

University of New Mexico

J. Lehr

June 21, 2019

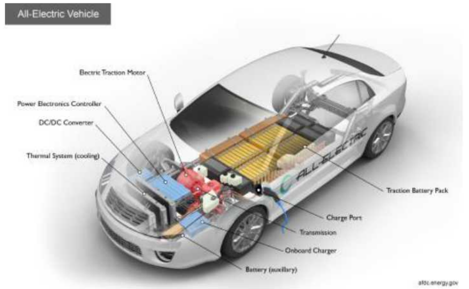
Sandia National Laboratories is a multimission laboratory managed and operated by National Technology and Engineering Solutions of Sandia, LLC., a wholly owned subsidiary of Honeywell International, Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA-0003525.

Opportunity

- Medium Voltage DC systems lack suitable circuit breaker (CB) technologies – limits system performance and adoption
  - Solar and Wind power generation growing rapidly
  - Electric ship and rail power management, electric vehicles

https://www.nrel.gov/wind/grid-integration.html

https://www.navsea.navy.mil/Home/Team-Ships/PEO-Ships/Electric-Ships-Office/



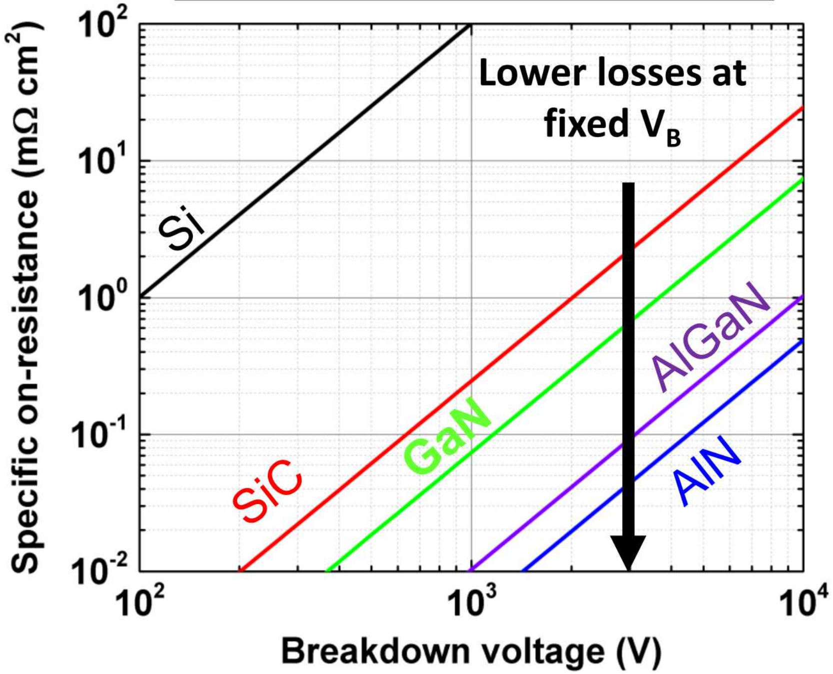
https://afdc.energy.gov/vehicles/electric_basics_ev.html

http://www.industrytap.com/wp-content/uploads/2013/02/US-Electrical-Grid.jpg

- Mechanical CBs are bulky and slow
- Solid State CBs promise <u>faster response times</u>, **smaller form factors**
- Current DC CB available for low voltage and low power applications

Approach

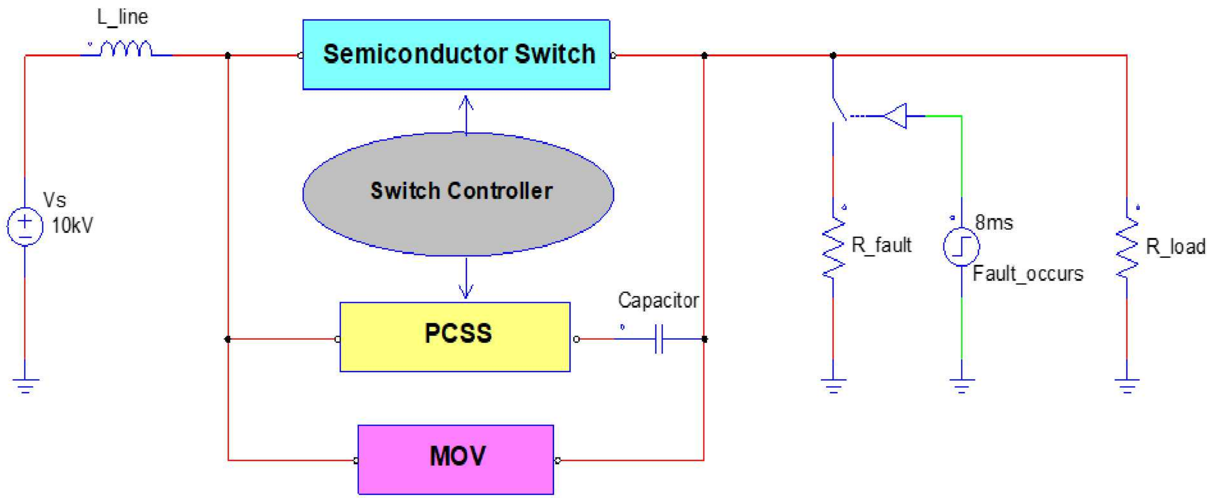
Vertical "unipolar" FOM
= $V_B^2/R_{on,sp} = \varepsilon\mu_n E_C^3/4$



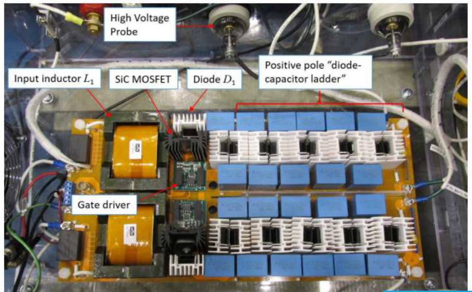
- Wide bandgap semiconductors (SiC, GaN) enable Solid State CB technologies
  - Lower switching losses
  - Higher power density
- Our Approach: SiC power electronics + Optically triggered GaN-based switch to enable DC CB
  - **SiC power devices with novel circuit architectures**
  - **GaN-based Photoconductive Semiconductor Switch (PCSS)**
  - ***Targeting 10 kV/100 A CB performance***

Goals

- Goals of project:
  - Design and model/simulate Solid State CB
  - Develop and analyze 10 kV/100 A GaN PCSS
  - Demonstrate DC CB technology
  - Develop CB commercialization plan

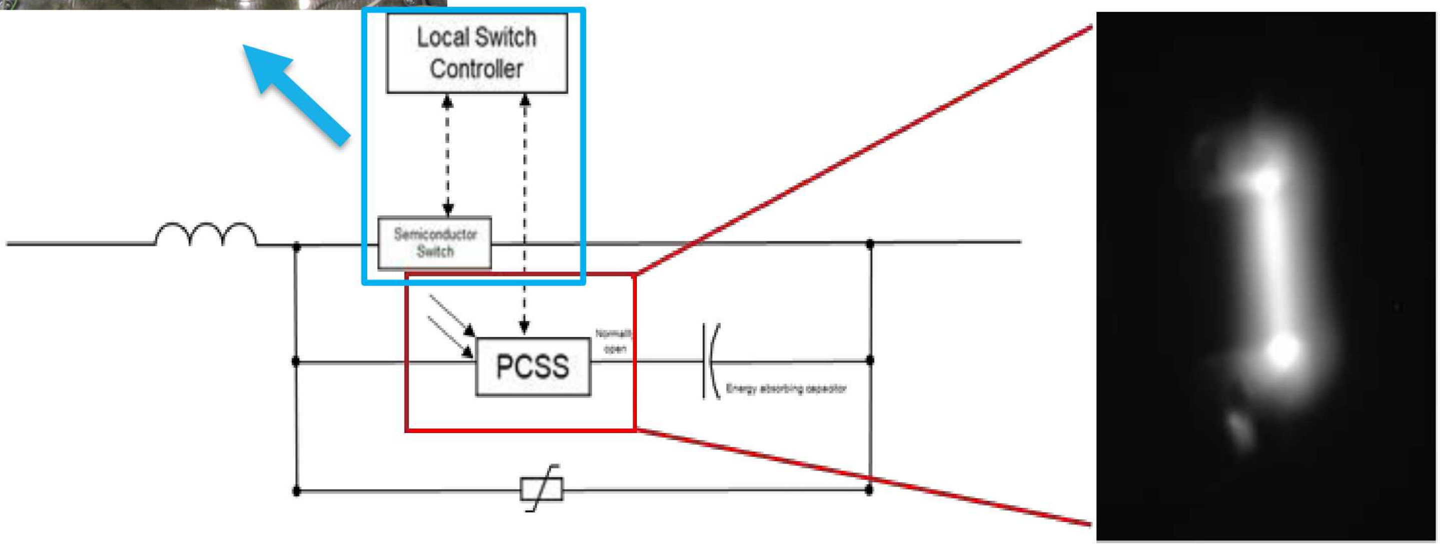


Uniqueness of Approach



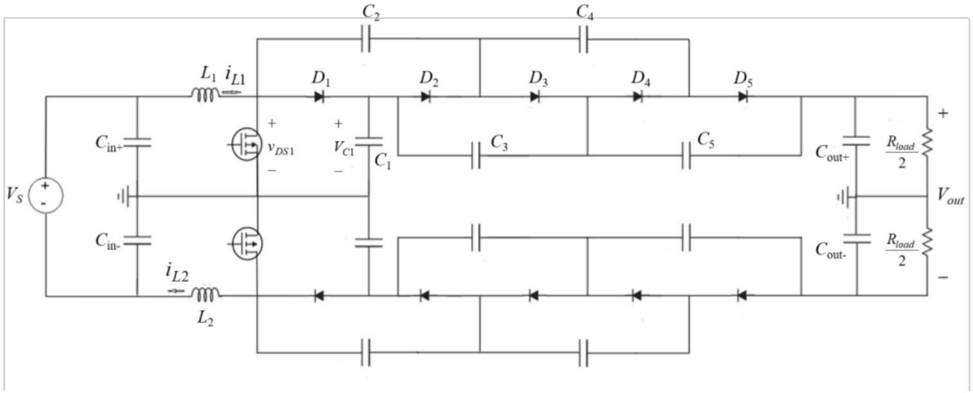
Leverage SNL's experience in novel circuit architecture developed in IDEAS program (Hy-GaiN)

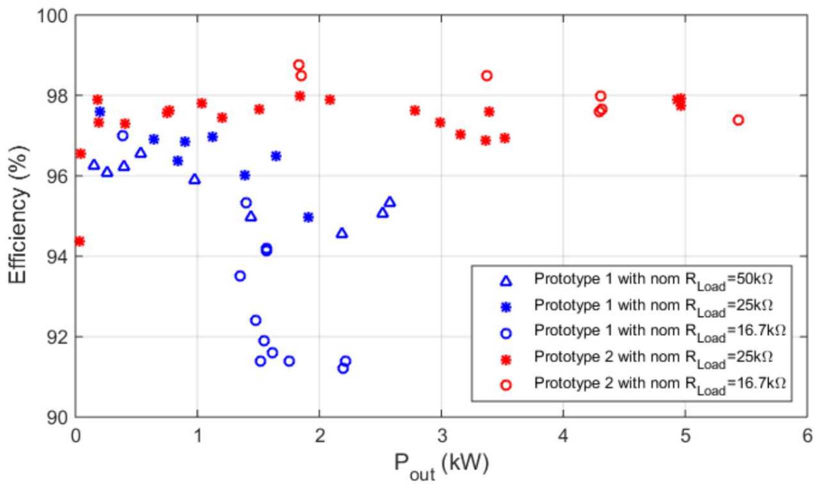
SNL's Lateral GaN PCSS Developed in IDEAS program (GaN PCSS)

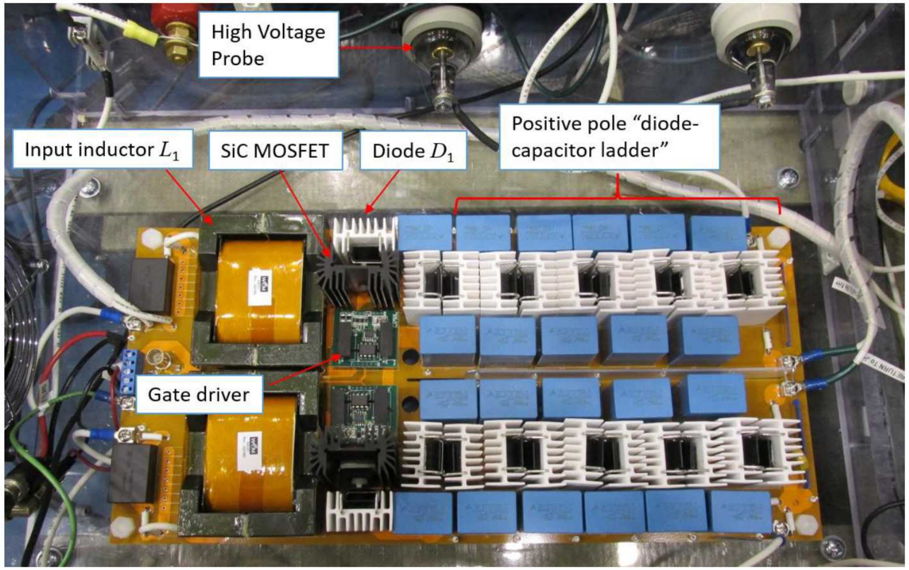


- Normally "On" leg to use SiC MOSFETs with novel circuit architecture
- Normally "Off" leg to use optically-triggered GaN PCSS (good isolation)
- Power Dissipation leg to investigate metal oxide varistors, other technologies

Novel Circuit Architectures

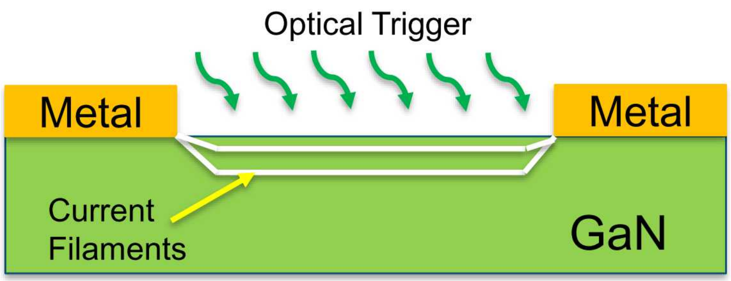


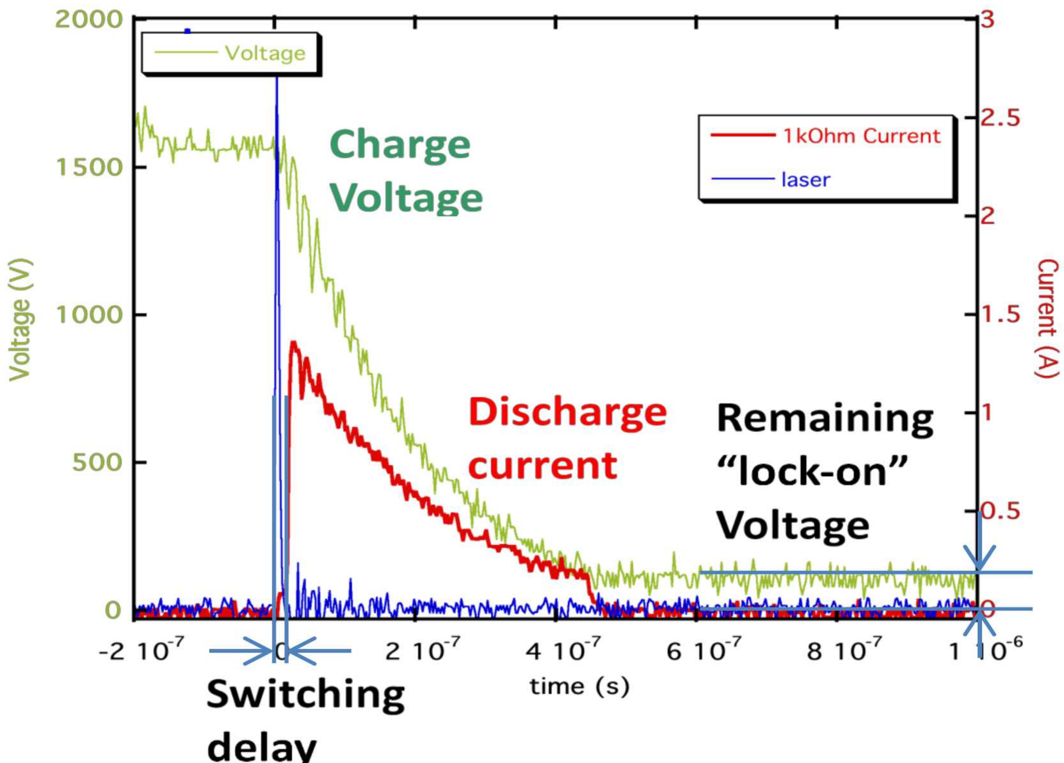


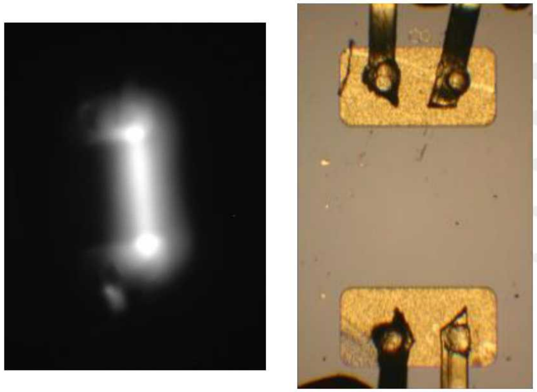


- Advanced circuit architecture capabilities at SNL
- Demonstrated capability in "Hybrid Switched Capacitor Circuit Development for Use of GaN Diodes in High Gain Step-Up Converters (Hy-GaiN) IDEAS program
- Use circuit design and package capabilities toward MVDC CB design

GaN PCSS Technology





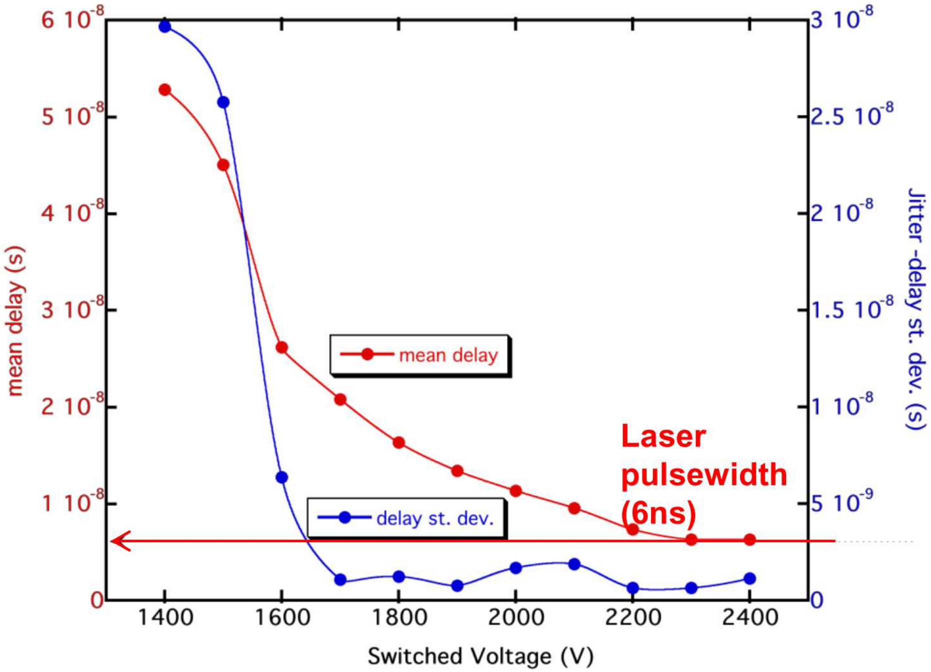


Filamentary Conduction
35 uJ trigger at 532 nm

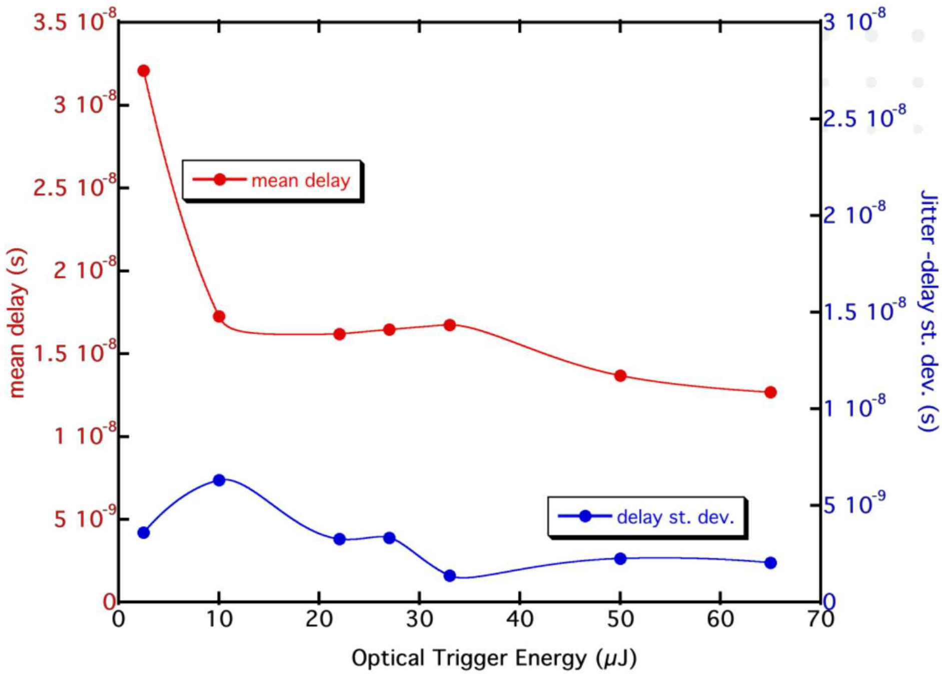
- Long history at SNL for PCSS in other materials (GaAs)
- Demonstrated "high-gain" mode in IDEAS program
- GaN material properties promise high voltage/power switches
- Optical gate control provides isolation

GaN PCSS Technology

Switching Delay, Jitter Characteristics vs. Applied Voltage



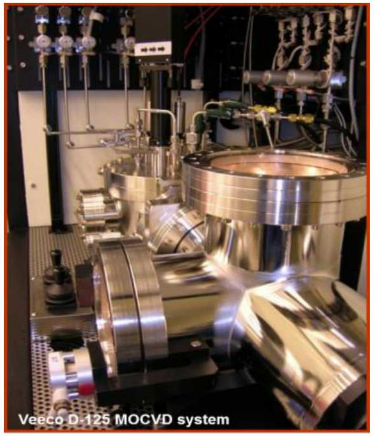
Switching Delay, Jitter Characteristics vs. Optical Trigger Energy



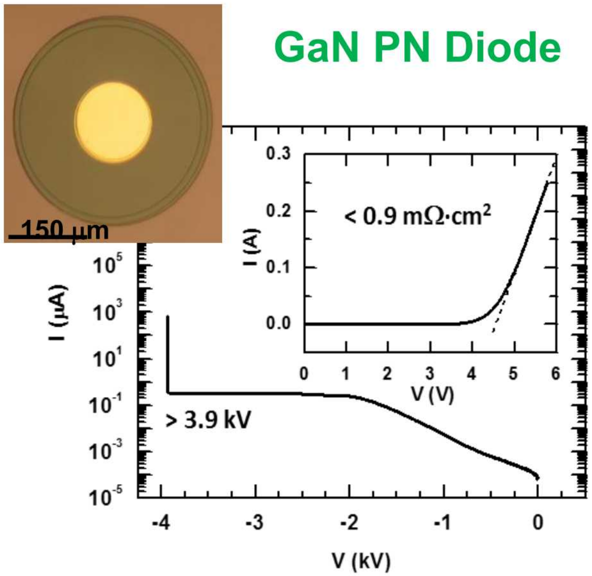
- All data use 50 μJ optical trigger energy, 60 shots per voltage level
- Timing jitter approaches minimum (~650ps) at relatively low voltage (1700V)

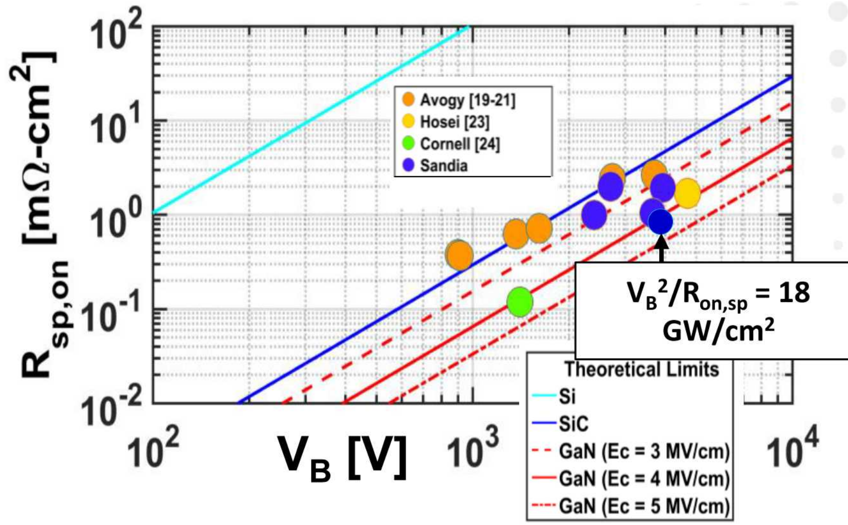
- All data using 2000V applied voltage, 30 shots per optical energy level
- Switching delay and jitter decrease with optical trigger energy

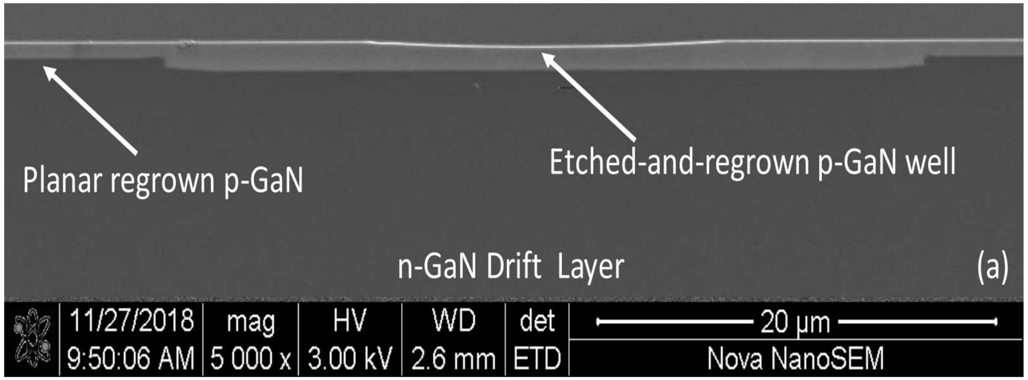
GaN MOCVD Capability



15+ years in wide band gap materials and device R&D







Developed high-quality etch/regrowth GaN process for selective-area doping.

Etch/regrowth process needed for GaN PCSS devices.

Key Metrics/Outcomes

Project Objectives

Category	Key CB Metrics
Rated Voltage	10 kV DC
Power	1 MW (100 A at 10 kV)
Efficiency	99.97%
Response Time	< 500 μs
Lifetime	30,000 cycles, TBC
Nuisance Trips	< 0.1% TBC
Power Density	60 MW/m^3, TBC
Cooling	Passive

GaN PCSS:

- Evaluate lateral vs. vertical device design/performance
- Develop mechanistic understanding of GaN PCSS device operation
- Evaluate compact optical triggering solutions
- Demonstrate high voltage/high current GaN PCSS

Year 1 Focus

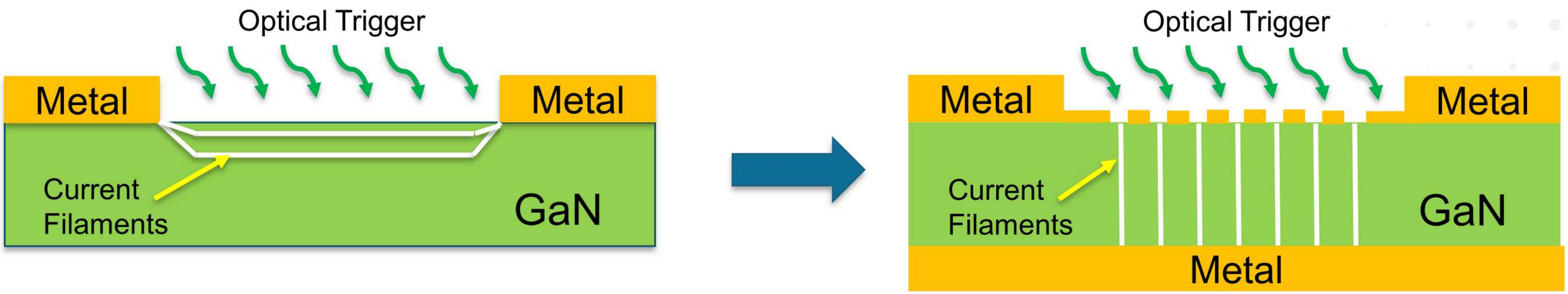
WBS	Description	Year 1			
		Q1	Q2	Q3	Q4
M2.1	Design of normally-on leg of CB.	X			
M2.2	Design of shunt leg of CB.		X		
M2.3	Design of normally-off leg of CB.			X	
M2.4	Demonstration of low-voltage CB operation. 1.2 kV, 10 A, operating speed < 500 μs.				X
M2.5	Develop mechanistic understanding of GaN PCSS devices (model/simulation)				X
M3.1	Evaluate vertical GaN PCSS prototypes for high-gain mode operation.			X	

Biggest challenges revolve around GaN PCSS: Demonstration (Vertical design) and Mechanistic Understanding

Year 1 Focus

Lateral Device Design

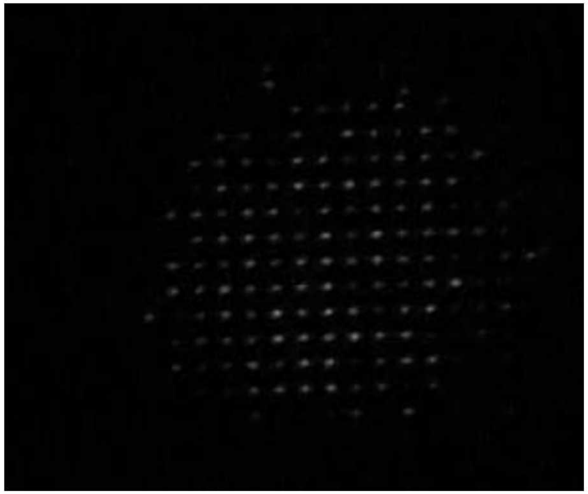
Vertical Device Design



GaAs Vertical PCSS (right)

- ~120 current-sharing filaments visible per shot, changing positions each shot
- Current sharing greatly improves total current-handling and device lifetime
- Vertical design needs to be proven/characterized for GaN materials

Top Image GaAs PCSS



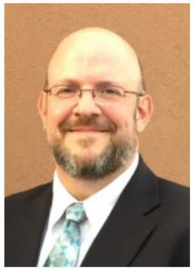
Key Results

- Model of GaN PCSS device in high gain mode
- Evaluation of vertical GaN PCSS device design
- Gen1 designs for three legs of DC CB
- Gen2 designs for three legs of DC CB
- Bench-top Demonstration of low-voltage CB
  - 1.2 kV, 10 A, operating speed < 500 μs

- Will allow for design optimizations and down-select technologies for Gen2 DC CB demonstrations
- Key Results for next meeting: GaN PCSS device results, results from bench-top demonstration

Sandia National Laboratories

Team



Greg Pickrell, Principal Investigator, GaN Power Devices

Alan Mar, PCSS Device design/characterization, pulsed power

Emily Schrock, PCSS Device design/characterization, pulsed power

Andy Allerman, GaN MOCVD growth, power devices

Harry Hjalmarson, PCSS Device theory, modeling/simulation

Sandia National Laboratories

Stan Atcity, Power systems, design optimization

Jason Neely, Power circuit, design optimization, and fabrication

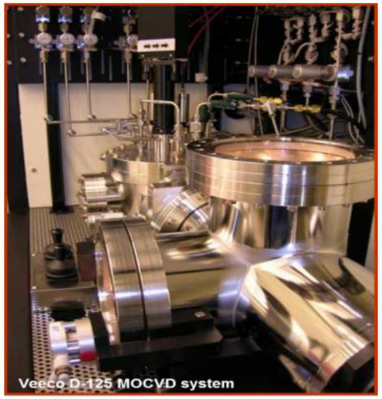
Jack Flicker, Power circuits, simulation, and integration

Bob Kaplar, GaN Power Devices, reliability, project management

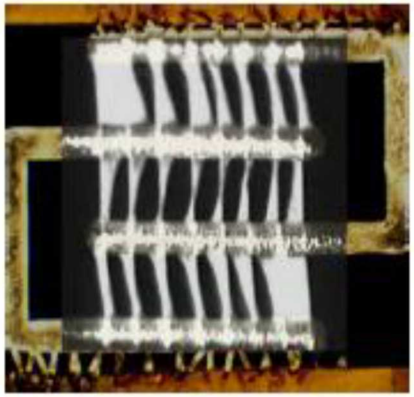
Sandia National Laboratories

- **MESA Facility**
  - GaN Material MOCVD growth and material characterization
  - Semiconductor device fabrication
  - Material and device defect characterization
  - High voltage characterization
- **Pulsed Power Laboratories**
  - PCSS device characterization
- **Power Circuit Laboratories**
  - Design optimization
  - Modeling/simulation
  - Fabrication/integration
  - High voltage characterization

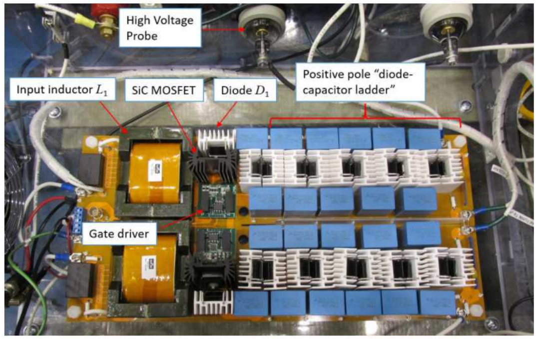
MOCVD Reactor



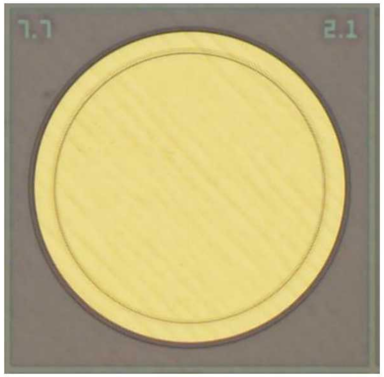
GaAs PCSS



Novel Circuit Design

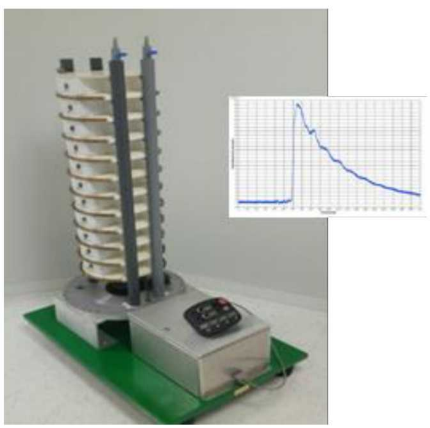


GaN PN Diode



University of New Mexico

Professor Jane Lehr, Director of UNM's Applied Pulsed Energy, Discharge, and Ionization Center (APERIODIC), high power electromagnetics, pulsed power, high voltage engineering, ultra-fast switching.



APERIODIC Laboratory:

- 1500 sq. ft facility on UNM main campus
- Suite of self-contained and modular pulsed sources
- Portable "Harpo" Marx bank pulsed source (300 kV/400 ns) – pictured on left
- Self-matched pulser (0.5-40 kV)
- Portable and shielded LabVIEW data acquisition systems

Commercial Objectives

- As SNL is FFRDC, our primary path for tech to market is licensing
  - Also opportunities for entrepreneurial development
- Applications in DC Electrical Grid (renewables) and electric vehicles (ship, rail, car) are likely opportunities
- First actions are to discuss application requirements in several areas with customers:
  - DC power conversion
  - Renewable energy integration into the grid
  - Electric ships

Critical Path Sourcing

- Semi-Insulating (SI) GaN wafer sourcing is a concern
  - Limited domestic sources of SI GaN wafers
  - Supplier with advanced maturity are overseas (Poland)
  - Varying synthesis methods with small substrate size
  - Will purchase from multiple vendors to minimize risk

Foreign Supplier #1

Domestic Supplier #1

Foreign Supplier #2

Substrate quotation and evaluation underway

Conclusions

- Medium Voltage DC CB approach leverages capabilities of Wide Bandgap semiconductors
  - Critical for power density requirements
  - Commercial/R&D SiC power electronics
  - Novel GaN PCSS (optically triggered, fast acting)
- Team includes expertise and facilities ideal to develop
  - Novel SiC circuit architectures
  - GaN growth by MOCVD
  - Wide bandgap GaN devices
  - High voltage and high speed device/circuit/system characterization