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High-Gain Persistent Nonlinear Conductivity in High-Voltage Gallium Nitride Photoconductive Switches

Alan Mar, Emily Schrock, Fred Zutavern, Gregory Pickrell, Jarod Delhotal, Richard Gallegos, Verle Bigman

Sandia National Laboratories

Joseph Dana Teague, Jane Lehr, Joshua Atencio

University of New Mexico

Motivation and Background

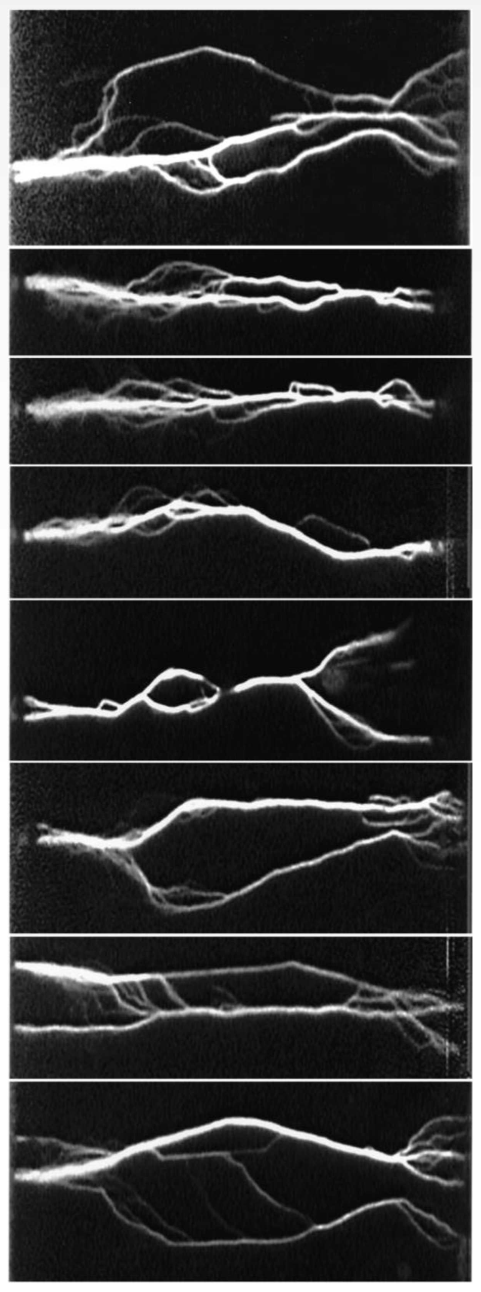
- Photoconductive Semiconductor Switch (PCSS) for high power, high speed, compact switch for power applications.
- Wide bandgap technology using GaN promises significant improvement over other material systems.
    - Increased electric field holdoff (fewer switches)
    - Higher switch efficiency (lower switching losses)
    - Fast turn on/recovery (higher frequency switching)
- Potential System Applications
    - Fault tolerance/mitigation (enhanced grid resiliency)
    - High-performance, lower cost renewables integration
    - Fast charging stations for electric vehicles

Metric	Standard		SOTA	Proposed
Technology	Si IGBT	Si LTT	SiC Thyristor	GaN Optical Switch
Voltage Rating	6.5 kV	10 kV	15 kV	100 kV
Switching Time	400 μs	100s μs	10s μs	0.01 μs
Switching Freq.	20 kHz	60 Hz	1 kHz	100 kHz
Switching Loss (J/switch)	10	100	5	2
Cost ($/MW)	$230k-$500k		>$2,000k	$100k

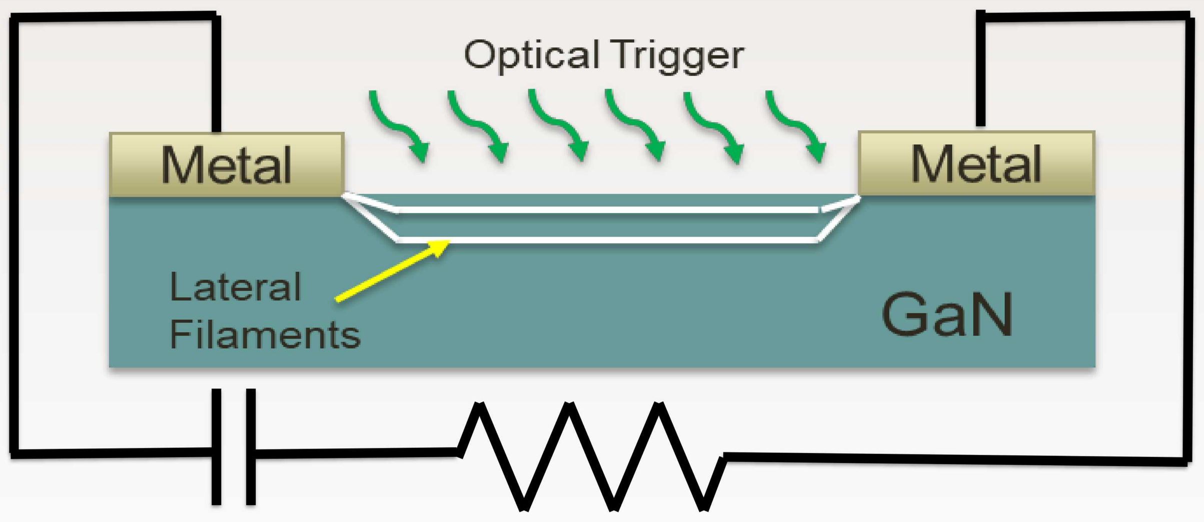
Technology Impact

Enable the progressive adoption of a hybrid AC/DC US grid that will reduce transmission and distribution losses saving $15.4 B over 33 years.

GaAs PCSS Current Filaments



Technical Approach



- GaAs PCSS switches showed "High Gain" behavior - low energy triggering with high current
    - E-field avalanche generation of laser-induced carriers in GaAs forms plasma filaments that close the switch
    - Conduction filament persists after laser light is removed (as long as necessary field is maintained)
- Low energy triggering
    - Avalanche produces up to 100,000 e/h pairs per photon (circuit dependent)
- Current forms in filaments
    - 20 A/filament = 100,000,000 shots
    - 2000 A/filament = 1 shot lifetime

GaN Materials and Devices

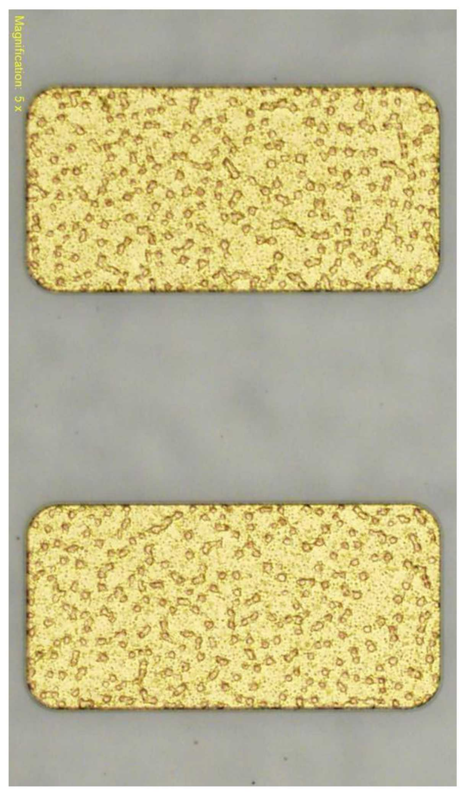
Semi-Insulating (S.I.) GaN Substrates

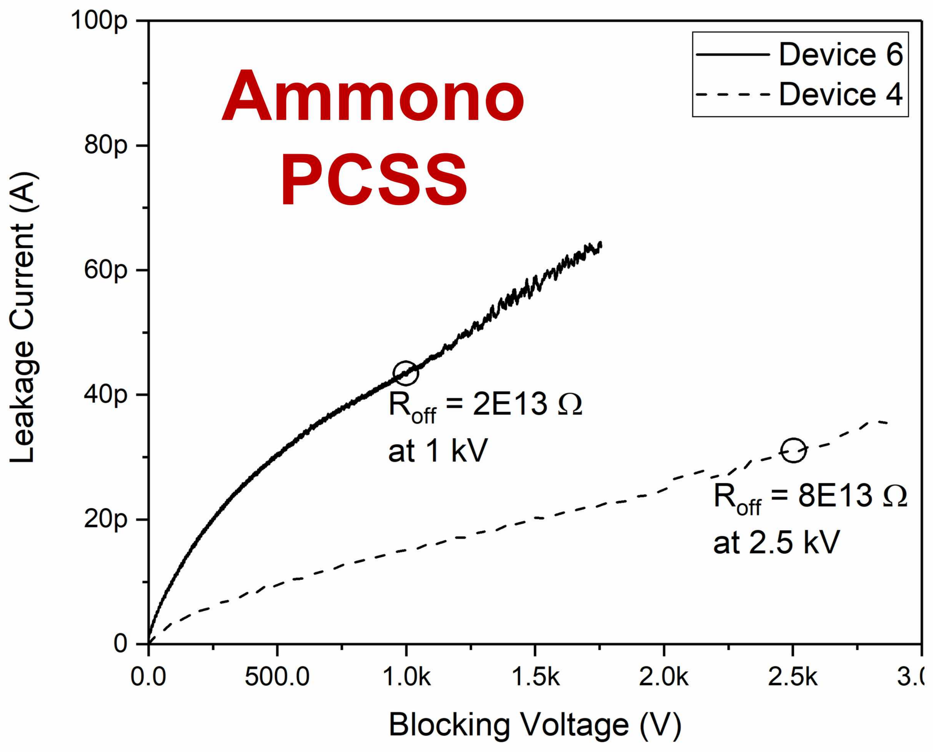
- Kyma S.I. substrates by Hydride Vapor Phase Epitaxy
- Ammono S.I. substrates by Ammonothermal growth (Mn)

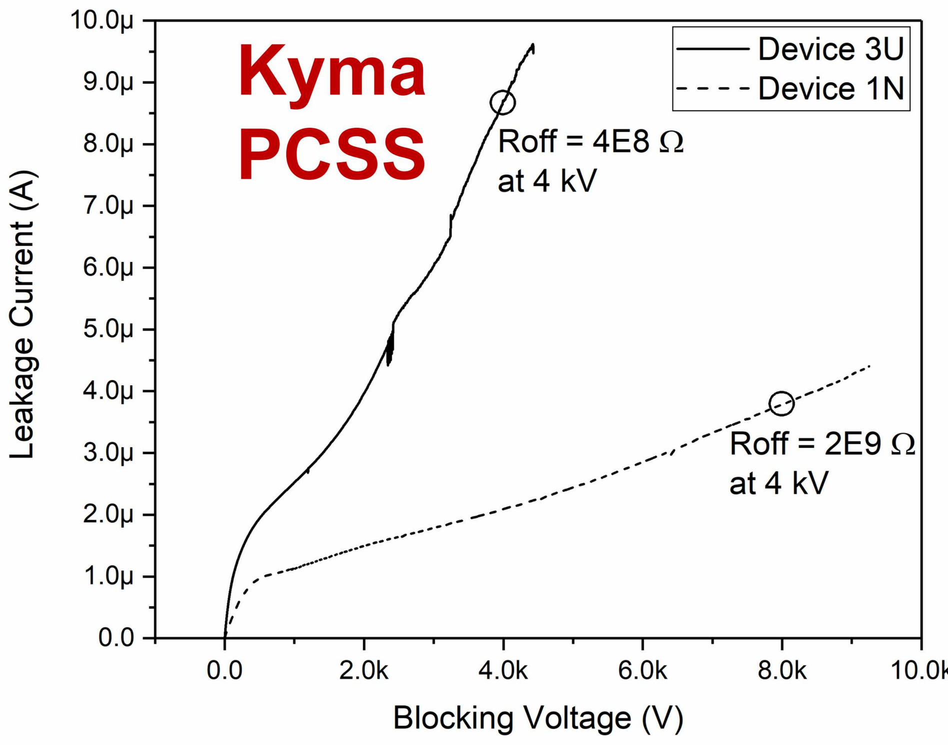
ammono

	Kyma	Ammono
Size	10 mm x 10 mm	37.9 +/- 0.5 mm diameter
Thickness (μm)	475+/- 25	350 +/- 50
Resistivity (Ohm-cm)	$> 1 \times 10^6$	$\geq 1 \times 10^9$
Dislocation Density (cm^{-2})	$\leq 1 \times 10^7$	Etch Pit Density $< 5 \times 10^4$

GaN PCSS Device (600 μm gap)







- GaN PCSS devices (600 μm gap) tested for "dark" leakage current
    - Ammono devices measured up to 3 kV in air (50 kV/cm)
    - Kyma devices measured up to 10 kV in Fluorinert (FC-70)
    - Lower leakage currents in Ammono material with higher resistivity

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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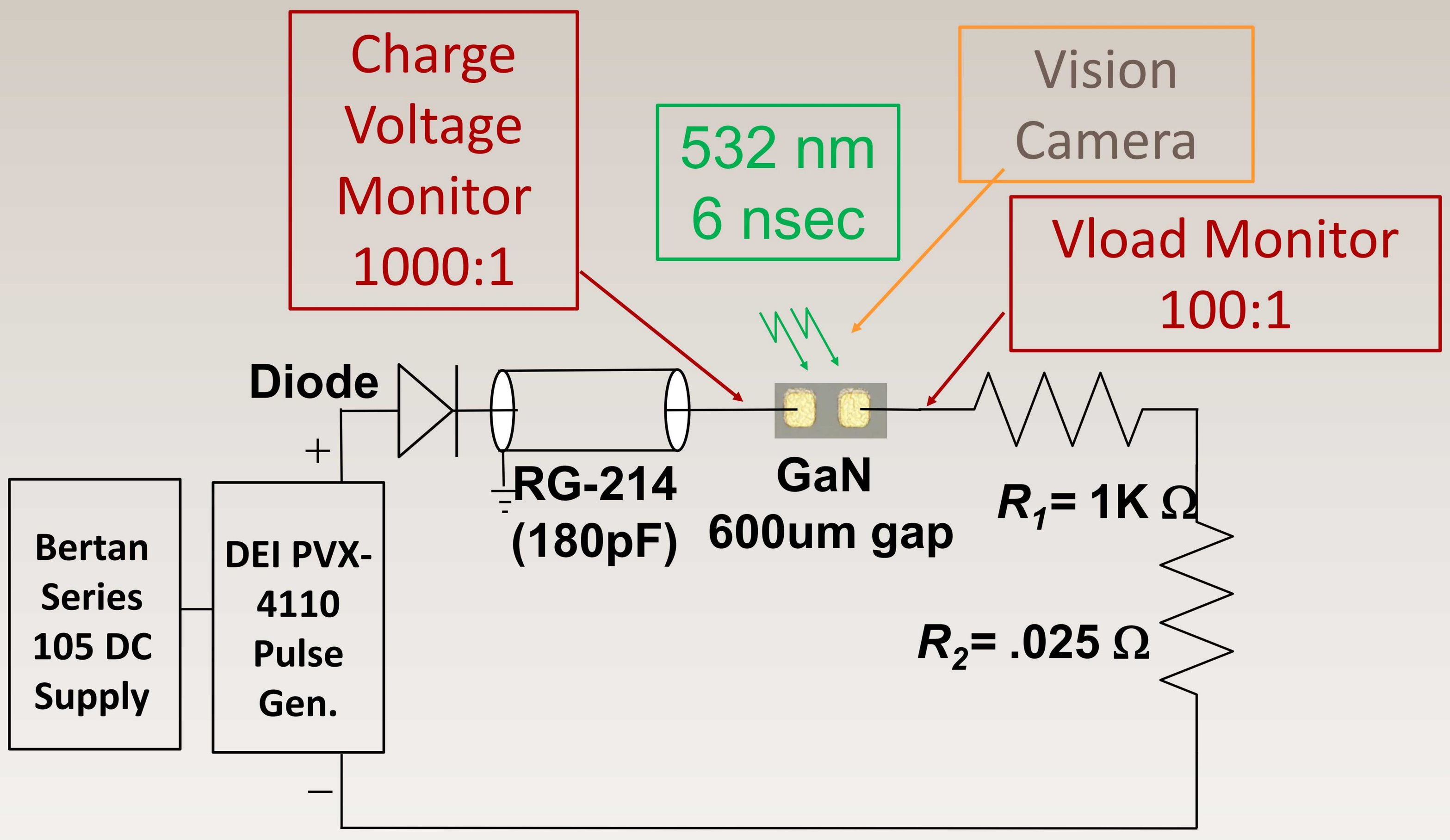
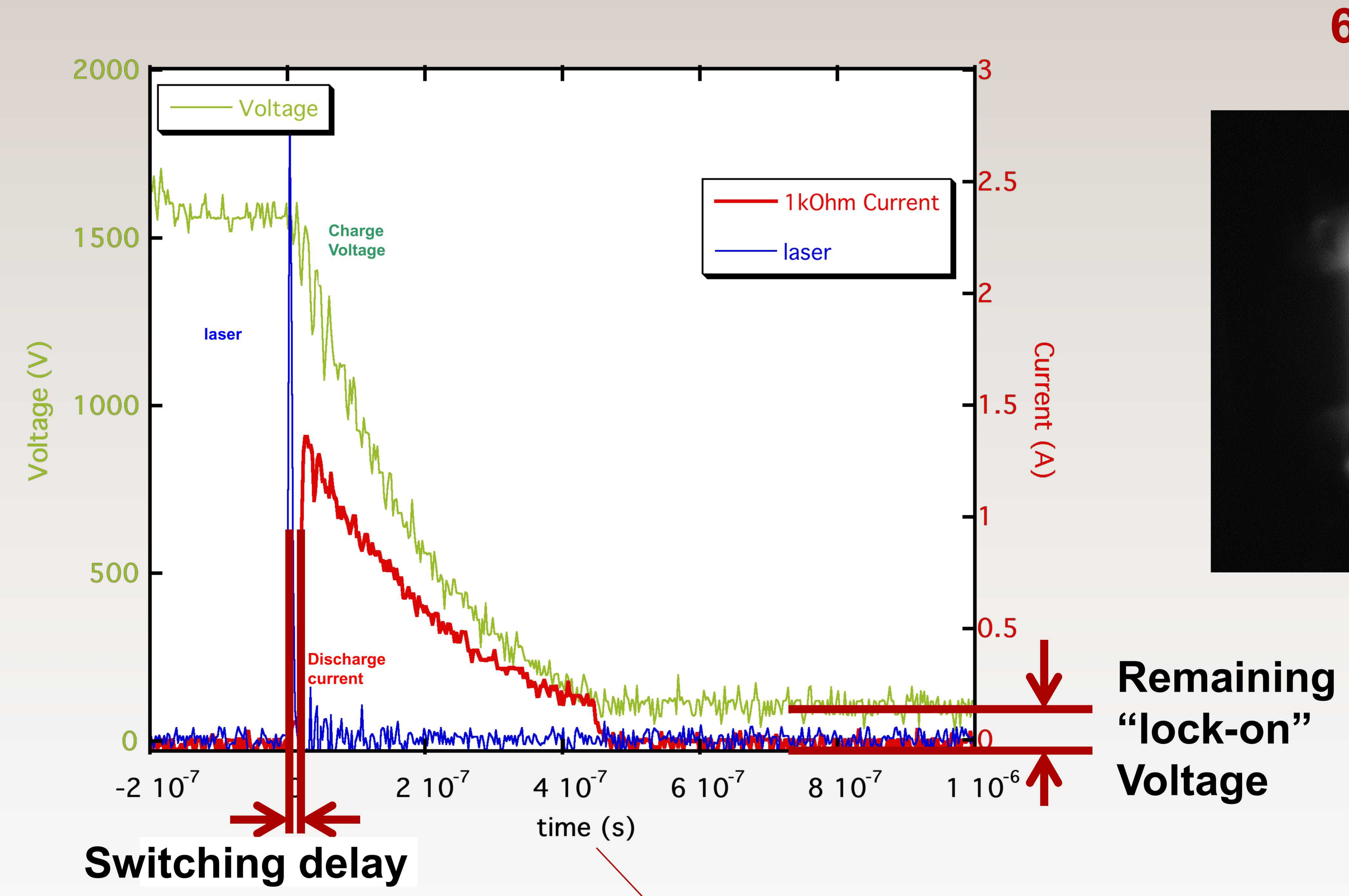
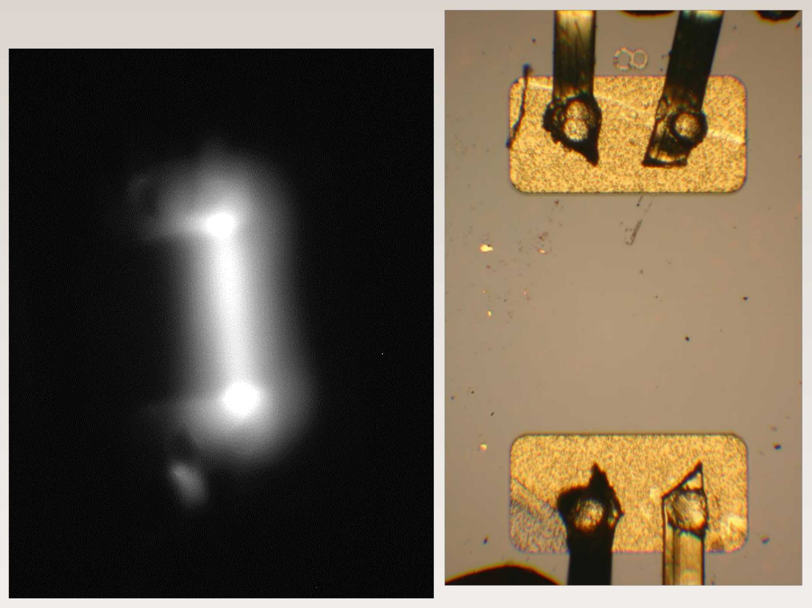
GaN PCSS Switching Behavior Characterization



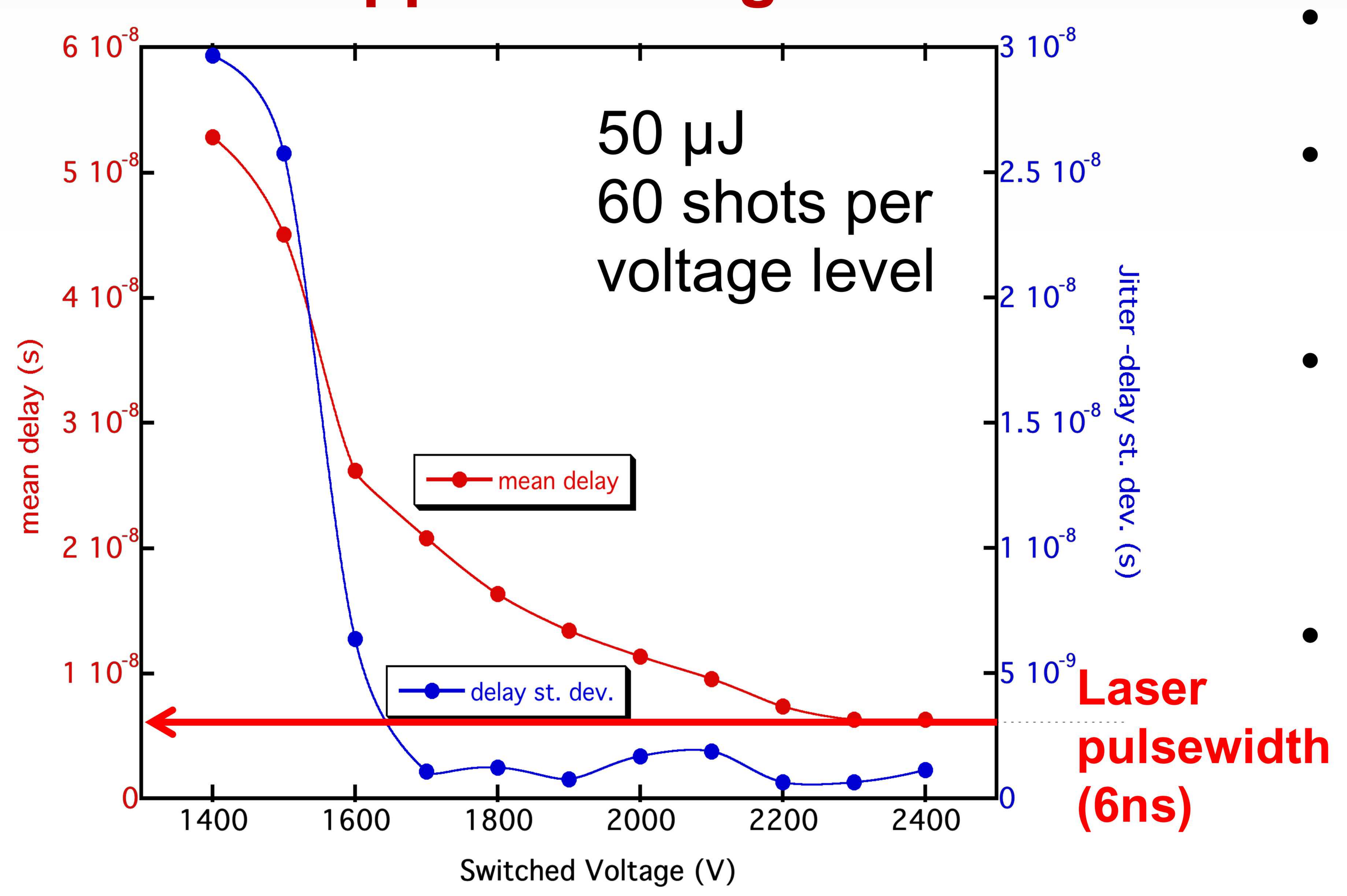


Filamentary Conduction
35 uJ trigger at 532 nm
600 µm gap device



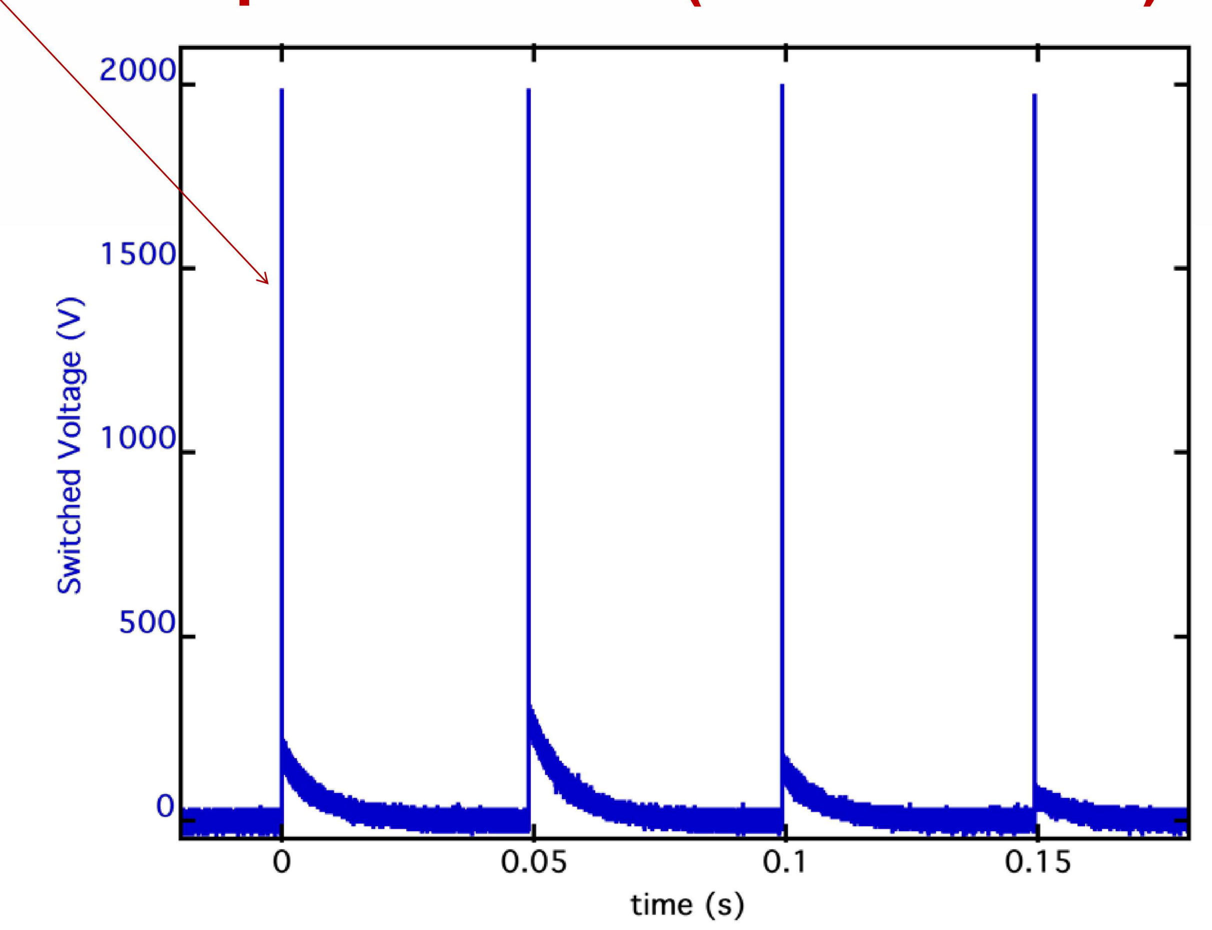
- Frequency-doubled Nd:YAG (532 nm) Q-switched laser used as optical trigger (sub-bandgap)
- RG-214 charge storage line pulse charged with ~60 ns rise/fall time (diode hold-up configuration)
- 1 kΩ current limiting/sensing resistive load (~1.5 A)

Switching Delay, Jitter vs. Applied Voltage



- Switching delay and jitter decrease with increase in optical trigger energy
- Switching delay and jitter decrease with increasing voltage (field), approaching laser pulsewidth limit
- Timing jitter approaches minimum (~650 ps) at relatively low operating voltage (1700 V)
  - Inherently stochastic filament formation/propagation process
- Average "lock-on" voltage ~ 180 V (3 kV/cm)
  - Low switching loss at high voltage

High-Gain Switching at 20Hz Repetition Rate (Laser-limited)

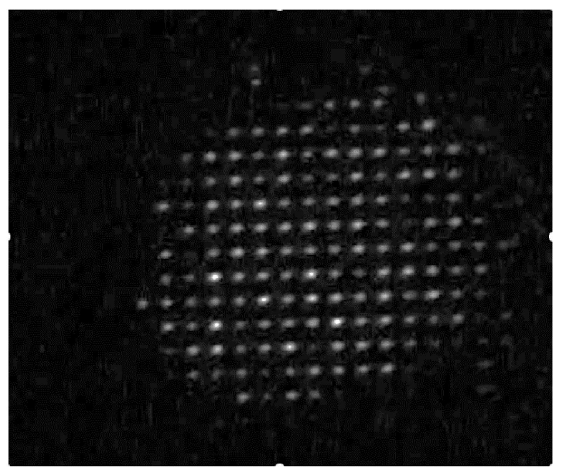


Key Accomplishments

- Persistent conductivity after laser initiation is removed
  - Conduction continues until sustaining voltage/charge source is removed (high-gain operating mode demonstrated)
- Small trigger energy requirement, sub-bandgap (532 nm)
  - **2.5 µJ** using focused beam (cylindrical lens) filling device gap
- Filamentary current channel observed (similar to GaAs PCSS devices)
- Maintaining field ("lock-on" field) in on state ~ 3kV/cm
- Small switching latency and timing jitter
  - Dependent on applied field. Can approach laser pulsewidth limit
  - Some dependence on optical trigger energy
- Persistent conductivity and filaments do not occur under Fluorinert (FC-70)
  - Strong evidence that high-gain is a surface effect
  - **Switching is laser-initiated, and well below the surface breakdown threshold.**

Future Work

- Investigate surface effects in lateral devices.
- Increase operating voltage with larger gap spacings
- Fabricate/characterize vertical devices (higher current with parallel filaments)
- Characterize GaN PCSS behavior in switching circuit



Top Down View of Vertical GaAs PCSS device with parallel current filaments (higher current, longer lifetime)

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