SAND2021-15818C

ELECTRICAL & COMPUTER ENGINEERING

APERIODIC

APPLIED PULSED ENERGY, IONIZATION, AND DISCHARGE CENTER

Investigating Lock On in Gallium Nitride Photoconductive Solid-State Switches

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Abstract

- As switching requirements for speed, power, and efficiency become more stringent, advances in wide-bandgap (WBG) materials have enabled their use in high power switching devices. One such device, the photoconductive semiconductor switch (PCSS), while previously constructed from GaAs, shows promise using WBG Mn-doped GaN. Lateral and vertical geometries of PCSS have been produced and evaluated for operation using sub-mJ/ns regime pulsed laser incidence. At fields below 25 kV/cm, the lateral switch operates in the linear regime where modest photocurrent fitting the laser envelope is observed. Above this threshold, the switches demonstrate circuit-limited persistent conductivity (PC) current, in what is presumed to be an avalanche process. Switch operation was tested immersed in both a liquid and a gaseous dielectric, where only the linear switching behavior is observed. Lateral GaN PCSS testing has shown indications of lock-on at a bias above 1500 V using a 532 nm pulsed (<10 ns FWHM) laser.”

TABLE 1: COMPARISON OF SEMICONDUCTOR TECHNOLOGIES

Properties	Si	GaAs	4H SiC	GaN
Bandgap (eV)	1.11	1.43	3.26	3.42
Dielectric constant	11.8	12.8	9.7	9
Breakdown field (MV/cm)	0.25	0.35	3.5	3.5
Thermal conductivity (W/cm°K)	1.5	0.46	4.9	1.7

From ELECTRONIC DESIGN,
Stephen Oliver, Sep 30, 2014

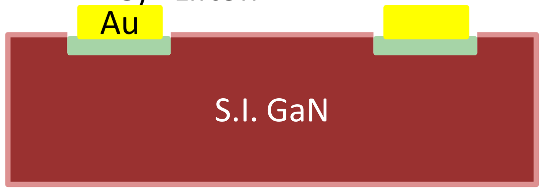
- GaN WBG properties for PCSS could be key enabler for high-voltage, high power applications
- Order of magnitude breakdown greater strength compared to GaAs
- Greater than 3x thermal conductivity compared to GaAs

GaN PCSS Device Fabrication - Process Flow

1) Contact Area Etch
    1) Litho
    2) Etch GaN (selected areas)
    3) Clean

2) Contact Metal Deposition
    1) Litho
    2) Deposit Metals (Ti/Al/Ni/Au)
    3) Liftoff

3) Bondpad Metal Deposition
    1) Litho
    2) Deposit Metals (Ti/Au)
    3) Liftoff



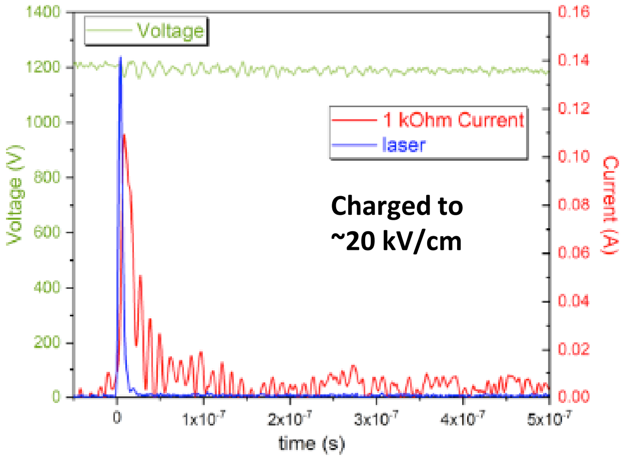
4) Dielectric Passivation
    1) Deposit 500 nm SiN

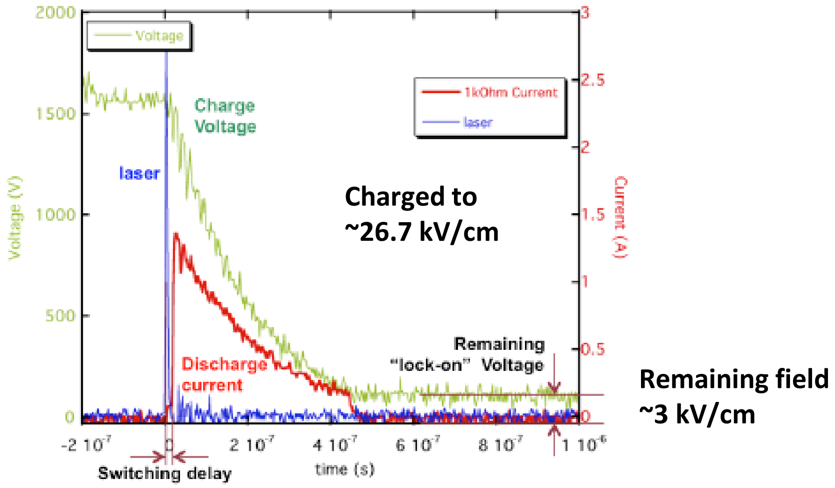
5) Window Etch
    1) Litho
    2) Etch dielectric
    3) Clean

(optional)

6) Test and Singulate
    1) Wafer level testing
    2) Singulate die (dicing saw)
    3) Die level testing

GaAs PCSS Characteristics



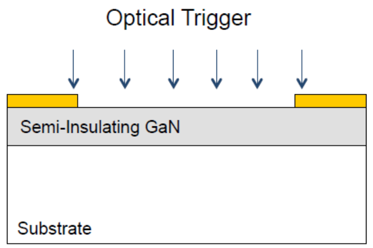


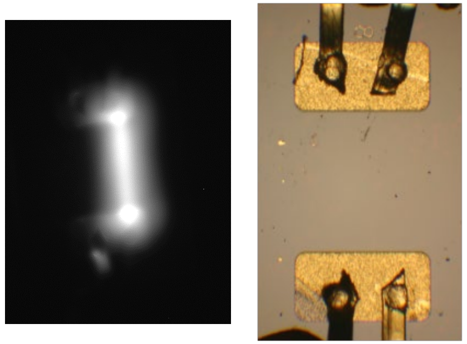
Lock-On Characteristics Observed in GaAs:

- Lock-on *field* is independent of charge voltage/switch length (it is material dependent)
- Lock-on (high gain mode) is achieved when charged voltage is greater than lock-on voltage device settles to after triggering
- Current is continued as long as the external circuit can maintain lock-on field

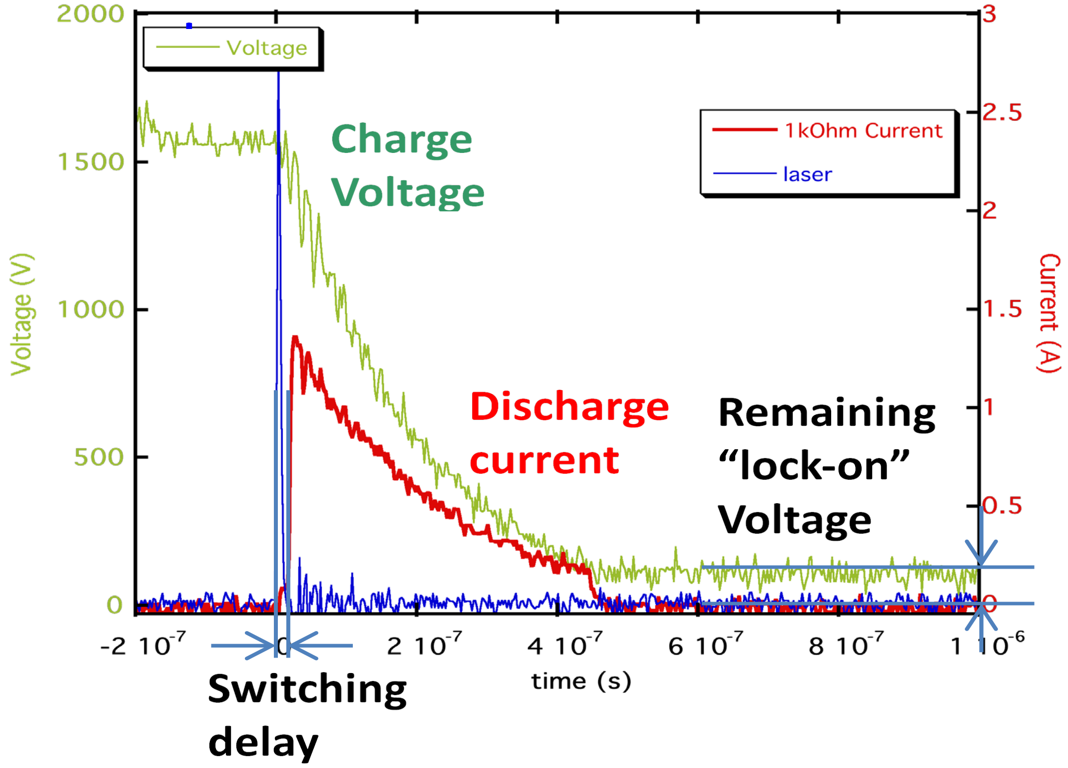
E. A. Hirsch, A. Mar, F. J. Zutavern, G. Pickrell, R. Gallegos, and V. Bigman, "High-Gain Persistent Nonlinear Conductivity in High- Voltage Gallium Nitride Photoconductive Switches," *2018 IEEE Int. Power Modul. High Volt. Conf.*, pp. 45–50, 2018

Lock on Mode in lateral GaN PCSS





Filamentary Conduction
35 uJ trigger at 532 nm

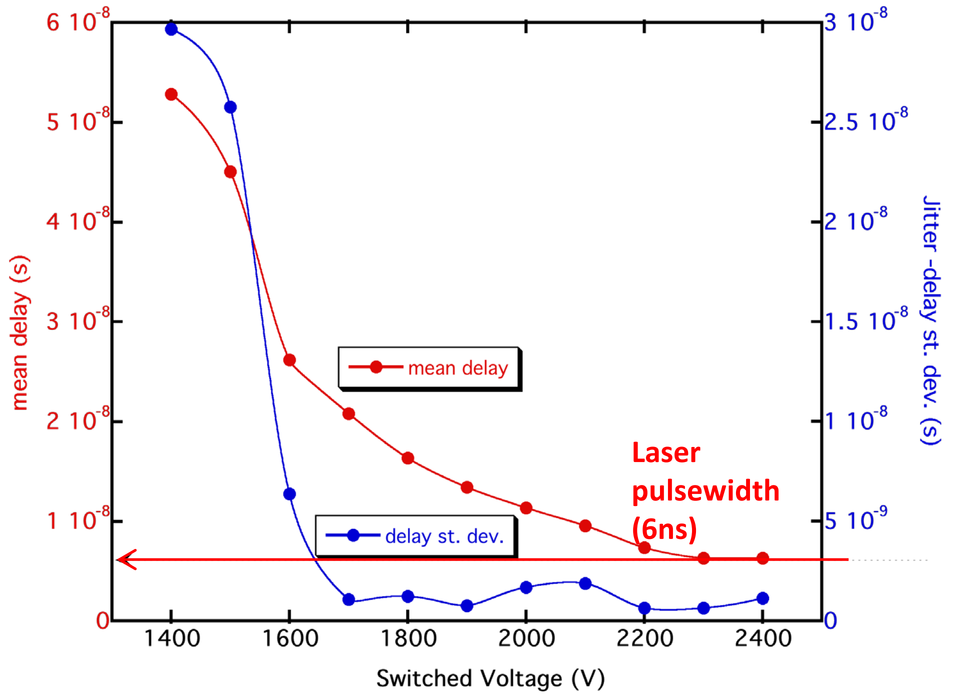


- Long history at SNL for PCSS in other materials (GaAs)
- Demonstrated "high-gain" mode in IDEAS program[1]
- GaN material properties promise high voltage/power switches
- Optical gate control provides isolation

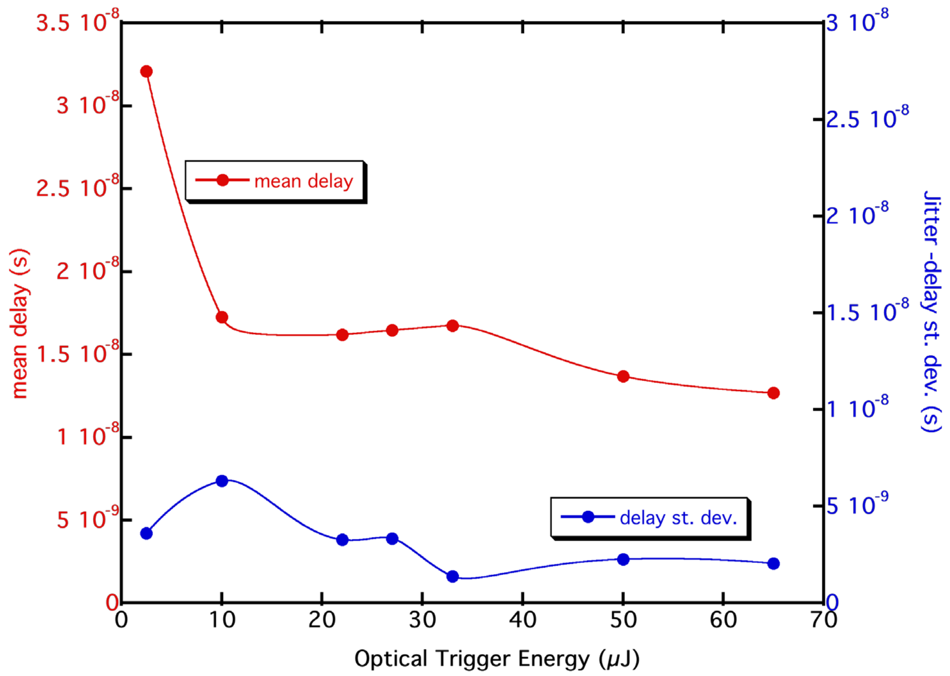
GaN PCSS exhibited the same lock-on characteristics observed in GaAs by SNL personnel & others for many years.

GaN PCSS in Lock-on Characteristics

Switching Delay & Jitter vs. Applied Voltage



Switching Delay, Jitter 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

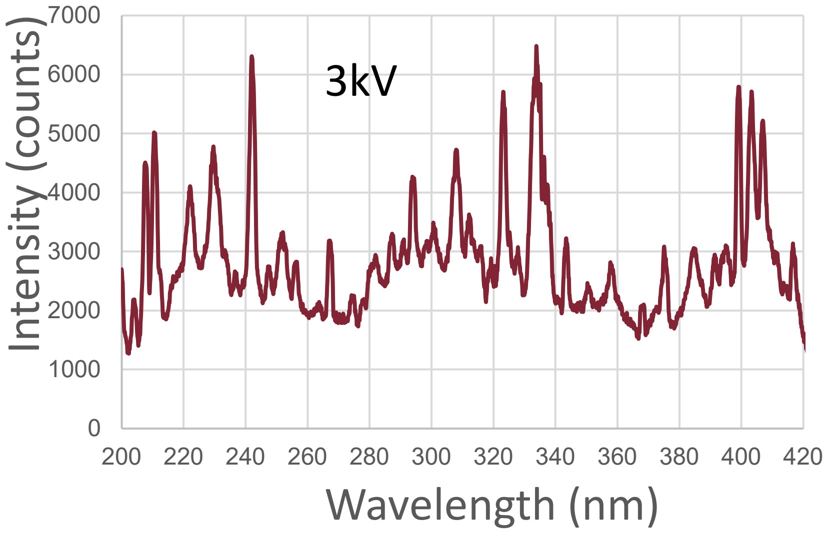
GaN PCSS High-Gain Switching Characteristics

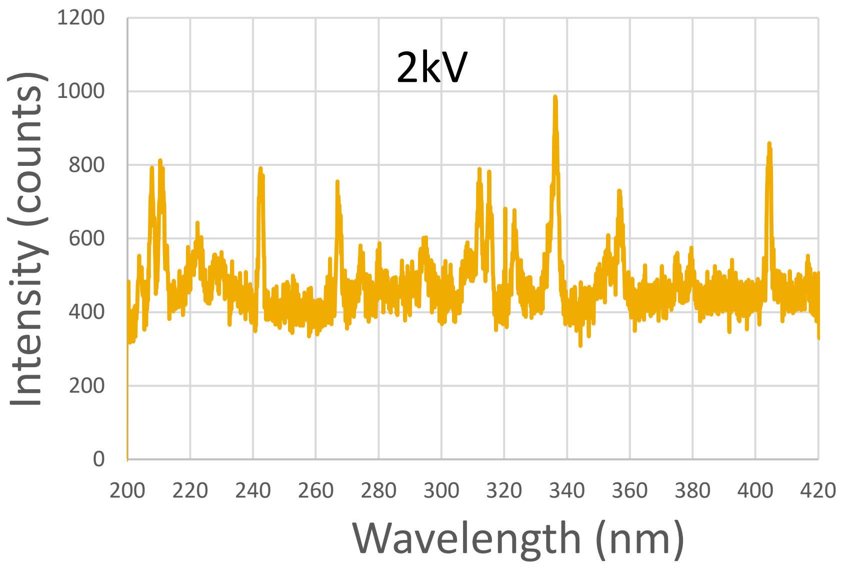
- **Persistent conductivity after laser initiation is removed**
  - Conduction continues until sustaining voltage/charge source is depleted
  - Conduction occurs at lower fields compared to measured breakdown limit
- **Small trigger laser energy requirement, sub-bandgap (532nm)**
  - ~20uJ using a 3mm diameter beam overfilling 600 µm PCSS gap
- **Filamentary current channel imaging**
  - Similar appearance to filaments in GaAs during lock-on switching, non-damaging
- **Maintaining field in on-state ~3kV/cm**
- **Small switching latency, jitter**
  - Field (voltage) dependent, can approach laser pulsewidth limit
  - Some dependence on optical trigger energy
- **Persistent conductivity and filaments do not occur under immersion in FC-70**
  - Strong evidence that high-gain is a surface effect
  - **Switching is laser-initiated, and well below the surface breakdown threshold**

Why is this?

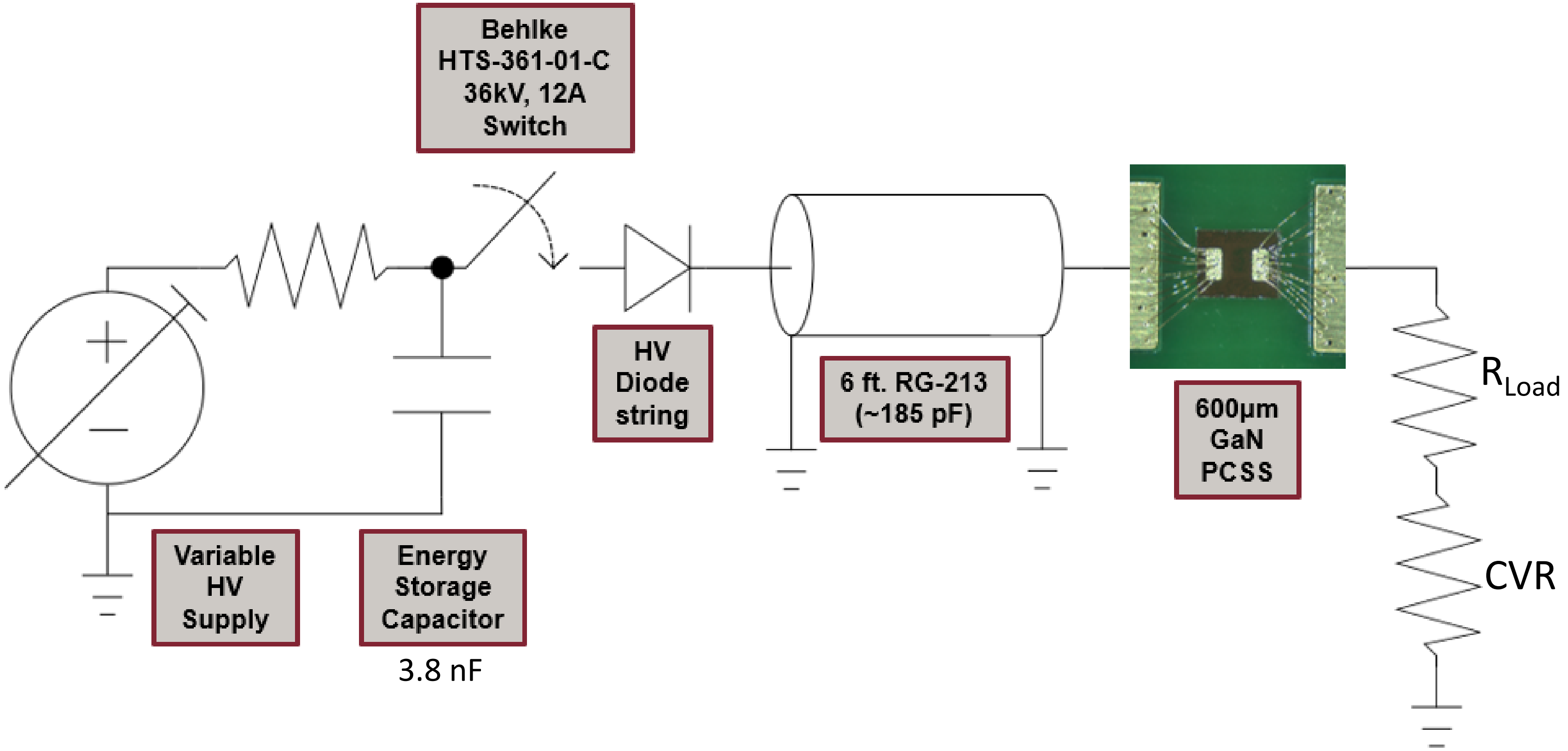
Laser-induced High-gain Switching @ 2kV + Flashover @ 3kV

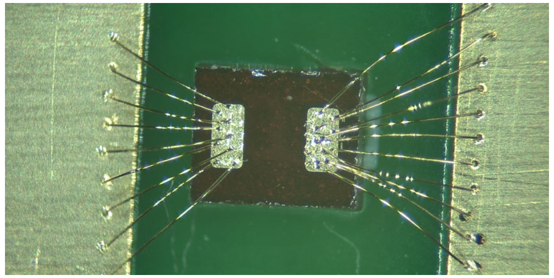
- Measurement is difficult, fiber coupling of spectrometer to capture emission from filaments
- Many features (peaks) similar between high-gain (laser induced) and high-voltage breakdown
- fine structure is reproducible
- Notably: No peak at bandgap wavelength 365nm(!?!)





Why is High-gain switching not observed under FC-70?

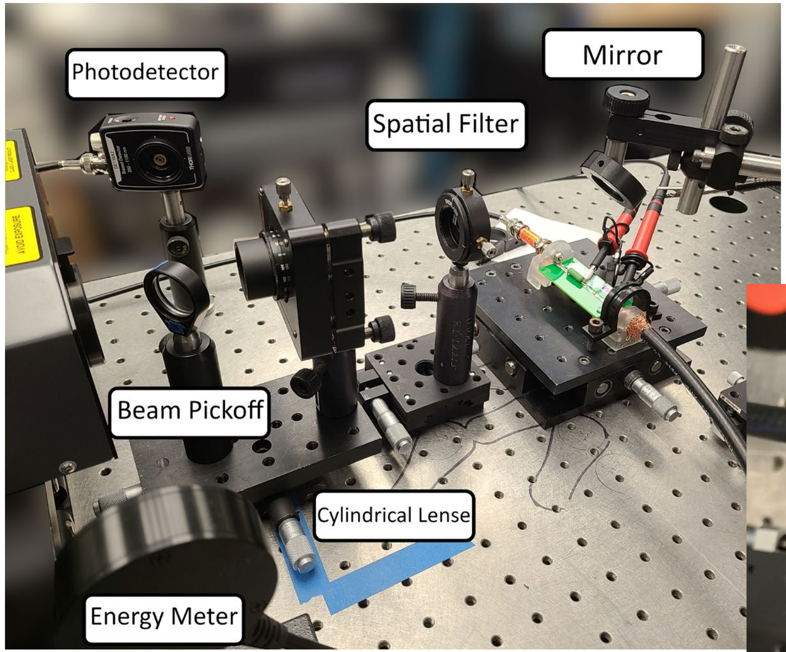




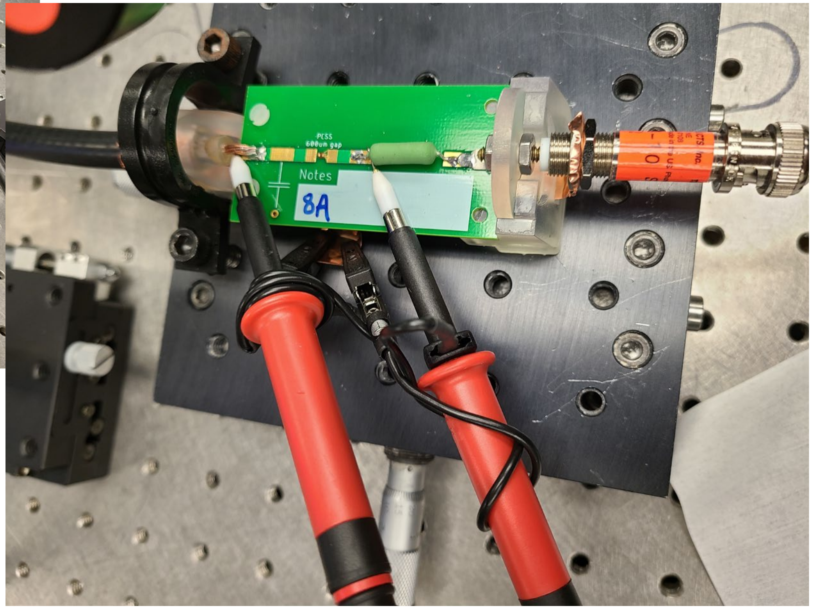
600µm lateral GaN, ball-bonded at UNM using 1µm gold wire

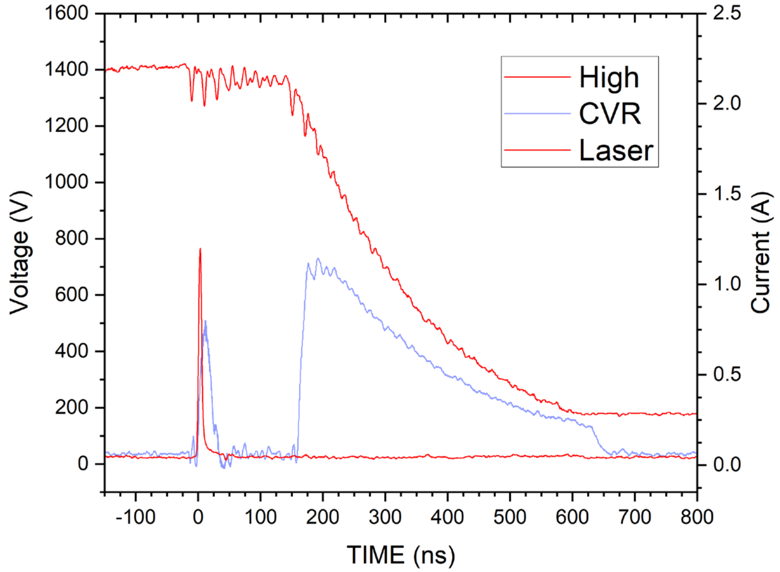
Solid State DPSS Laser at 266 nm

Optics train at 266 nm



- Updated PCBs with soft gold deposition for wire bonding
- Custom circuit interface

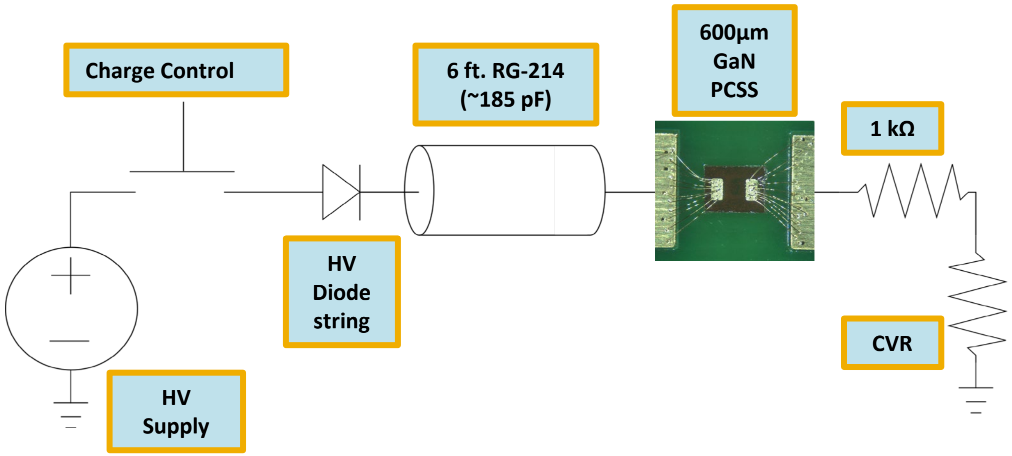


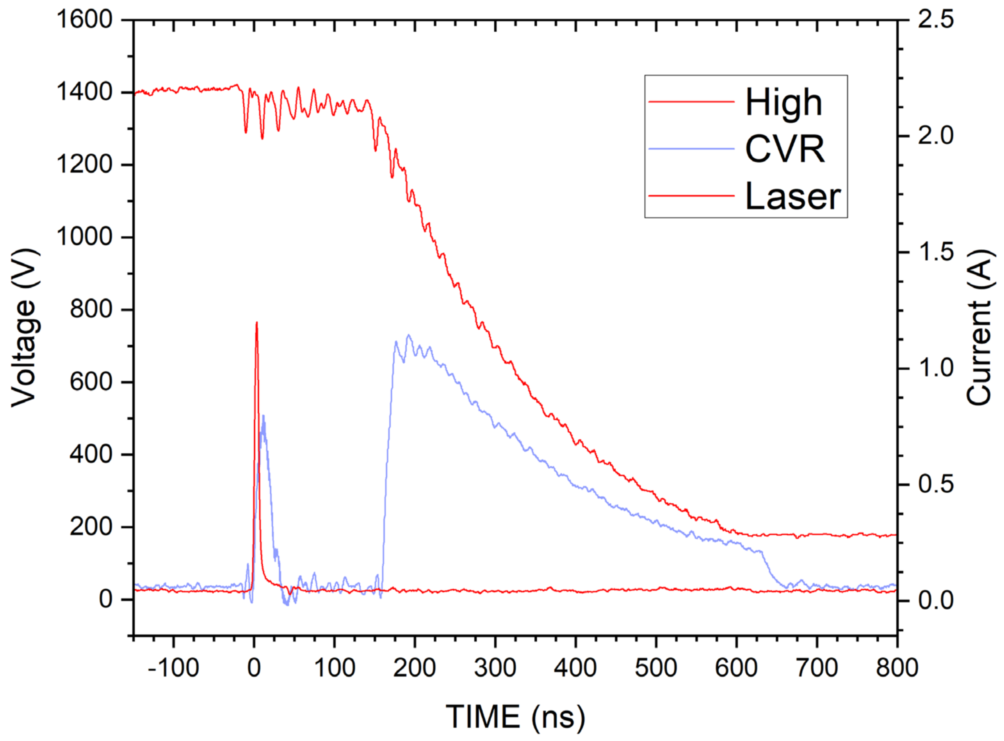


- ~55 µJ of laser energy
- 4 ns pulse width FWHM
- Current limited by 1kΩ resistor
- At 1.0kV charge, device operates in linear mode
- At 1.5kV charge, lock-on phenomenon is observed

Lock-on observed at 266 nm using RC decay circuit config.

- ~55 µJ of laser energy, 4 ns pulse width FWHM
- Current limited by in-series 1kΩ resistor
- At 1.0kV charge, device operates in linear mode
- At 1.5kV charge, lock-on phenomenon is observed

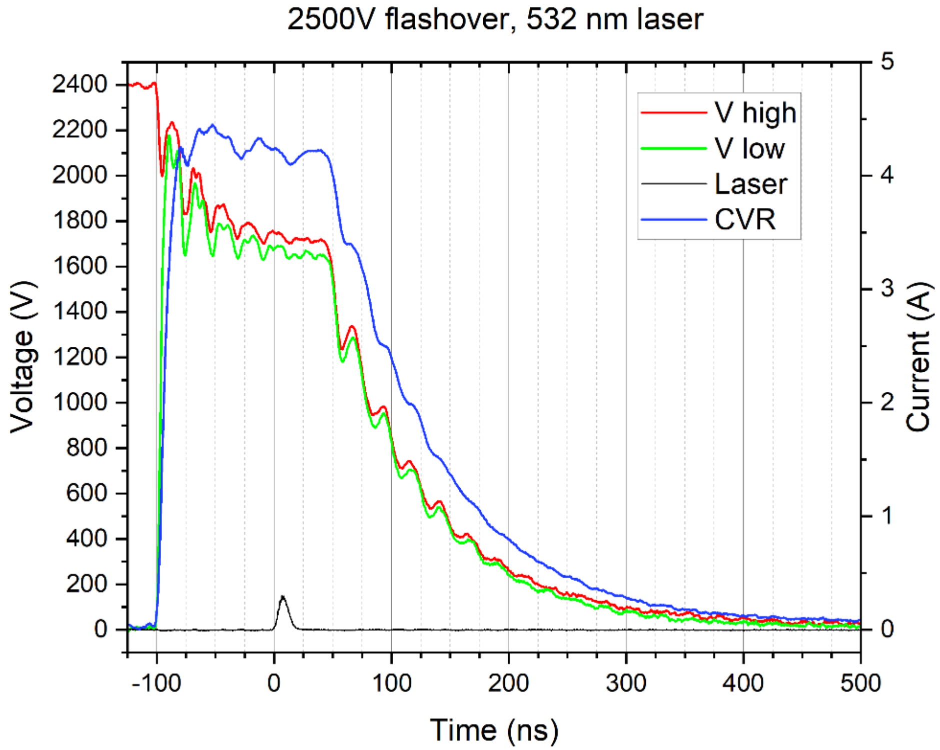


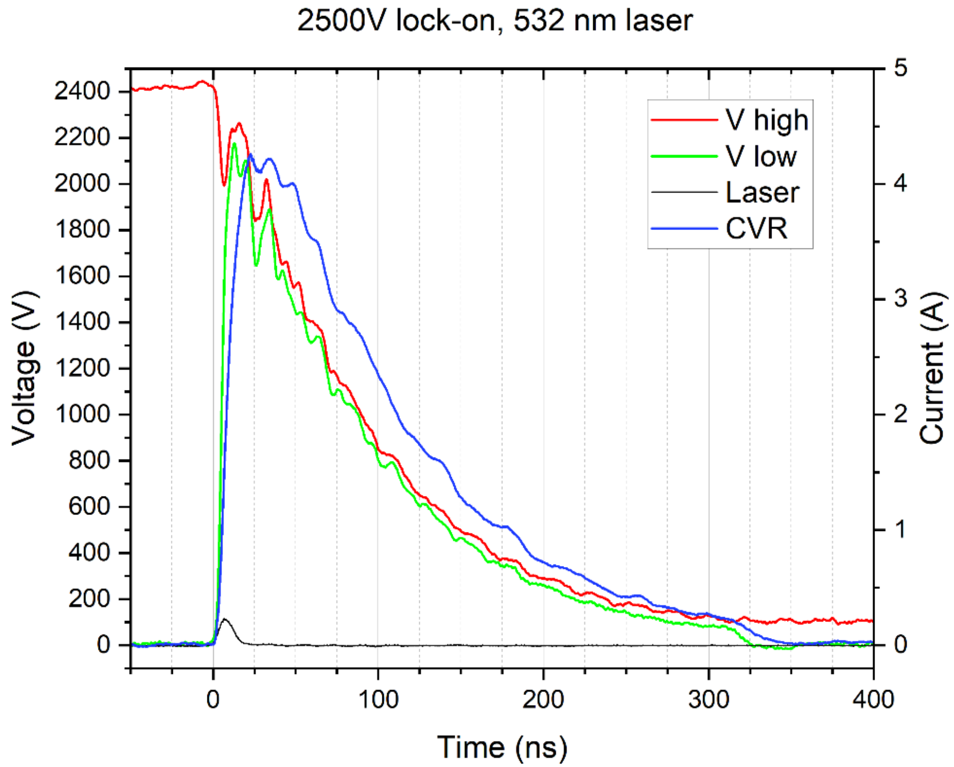


Waveform Differences in Lock-on and Flashover Events

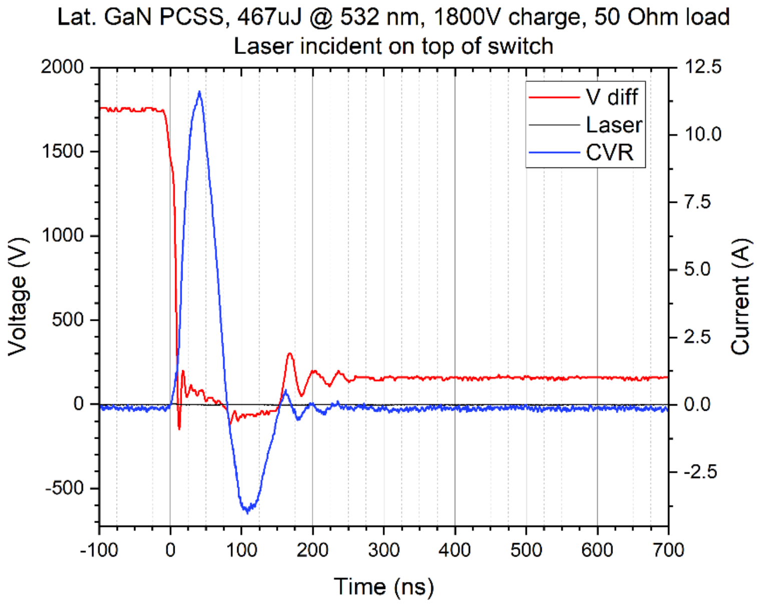
- 1k Ohm load, V high and low refer to the potential across the switch
- Current risetime and magnitude appear equivalent in each event
- Flashover delay time and "Pulse-width" of current flattop varies

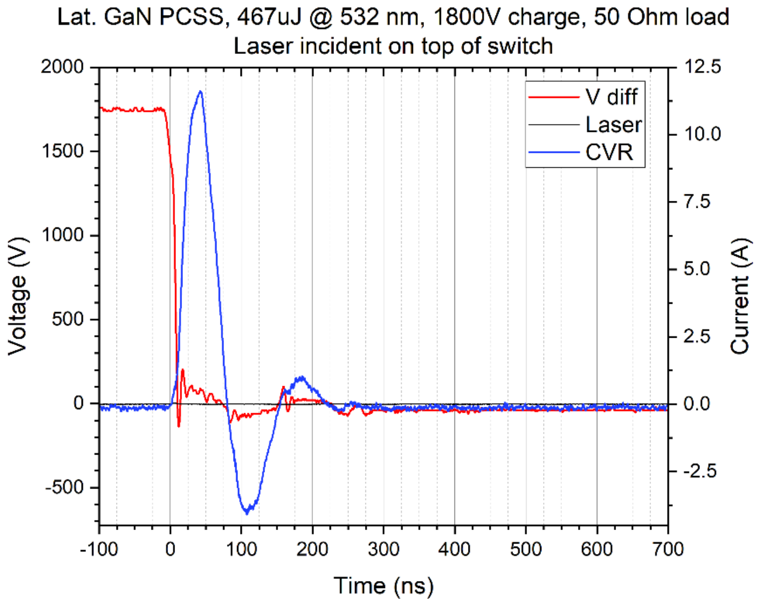
R_L= 1 kΩ





50 Ohm load

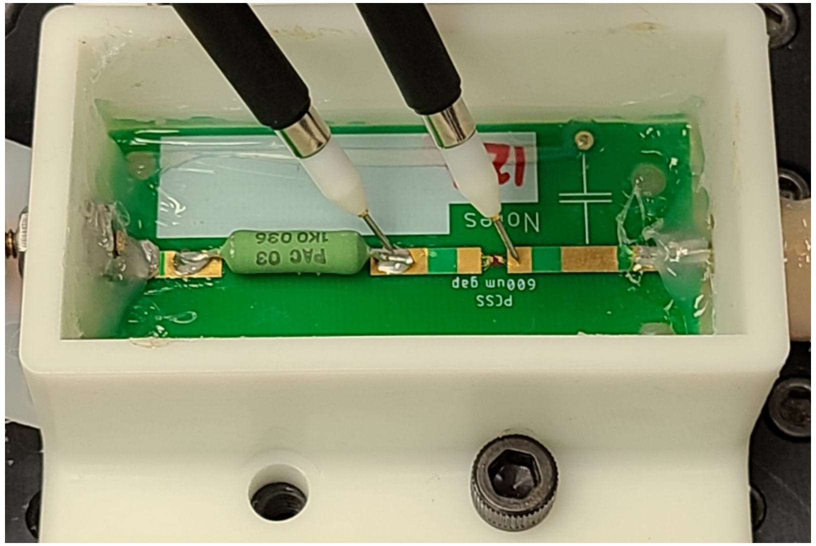


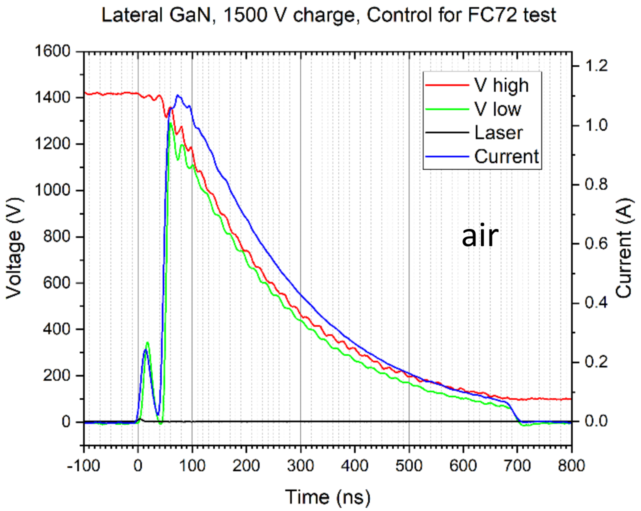


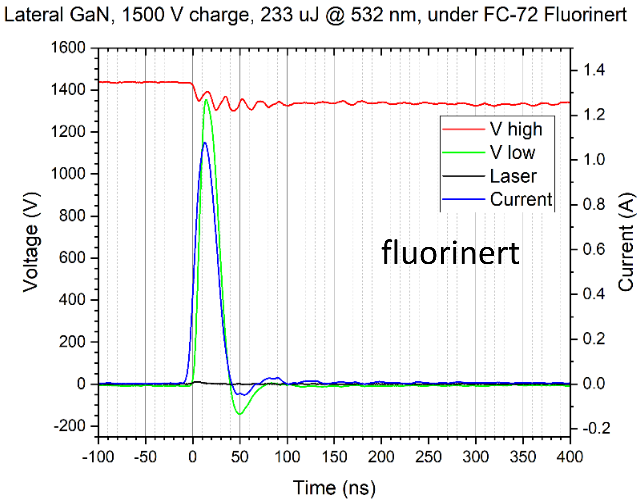
V diff refers to the differential voltage across the switch

Fluorinert FC-

RL=1kΩ



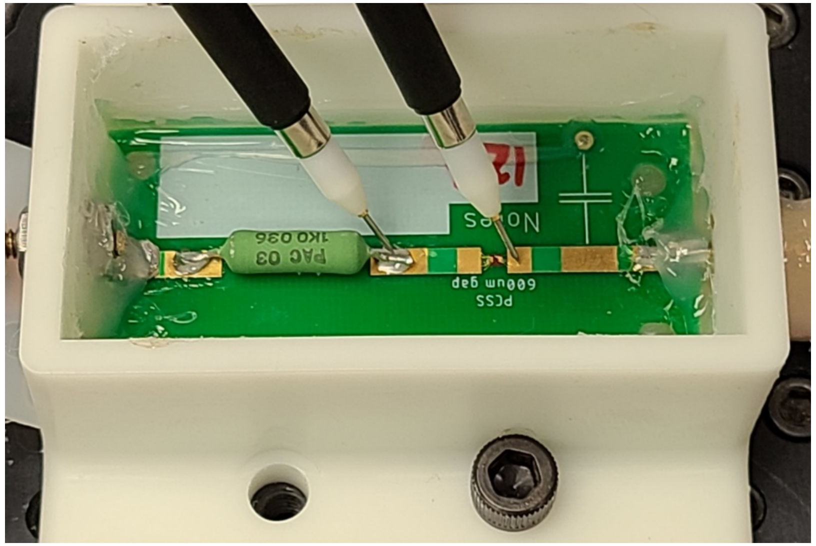


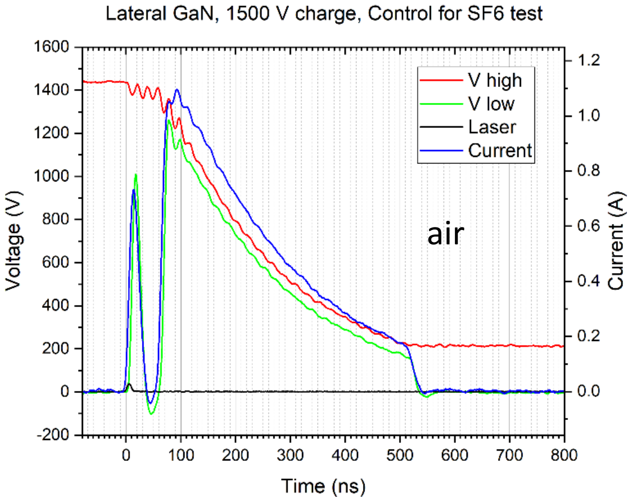


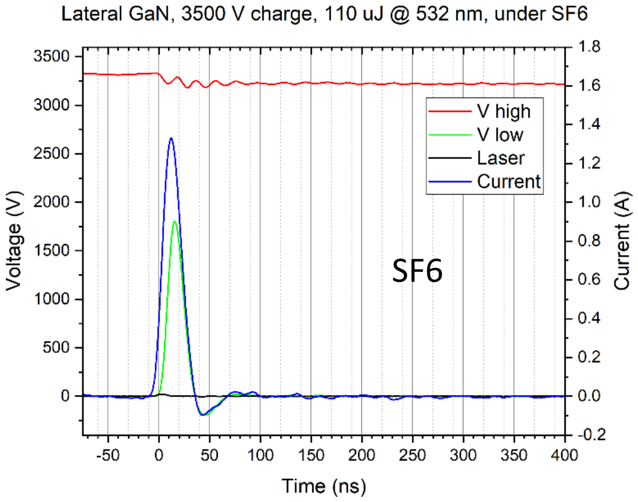
After verification of previous results, the lateral GaN PCSS was blanketed with fluorinert and the prior test results were verified.

SF6

RL=1kΩ



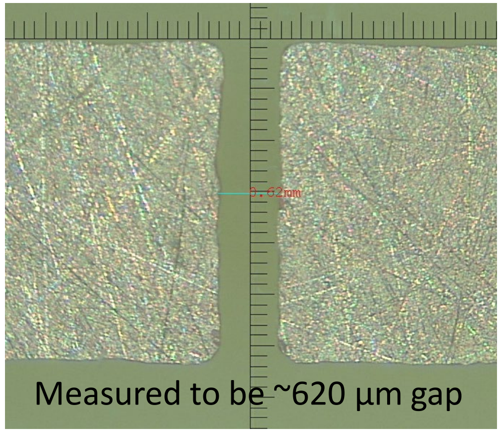


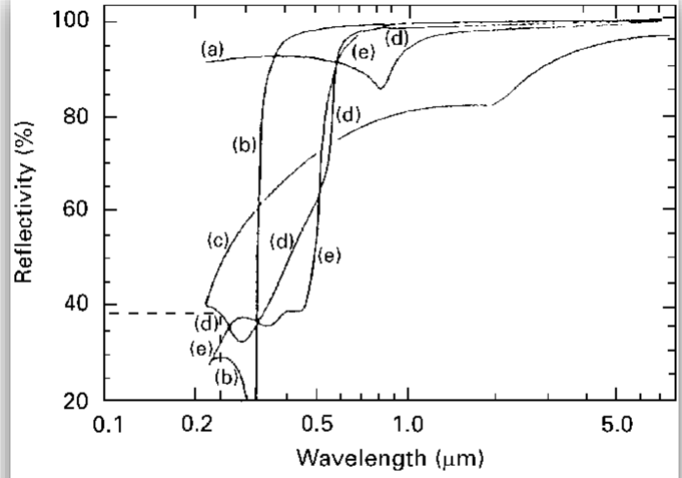


The test was repeated with another discharge surpressing fluid, SF6 to insure that it is a voltage effect. Here, the lateral GaN PCSS was blanketed with SF6 and the prior test results were verified.

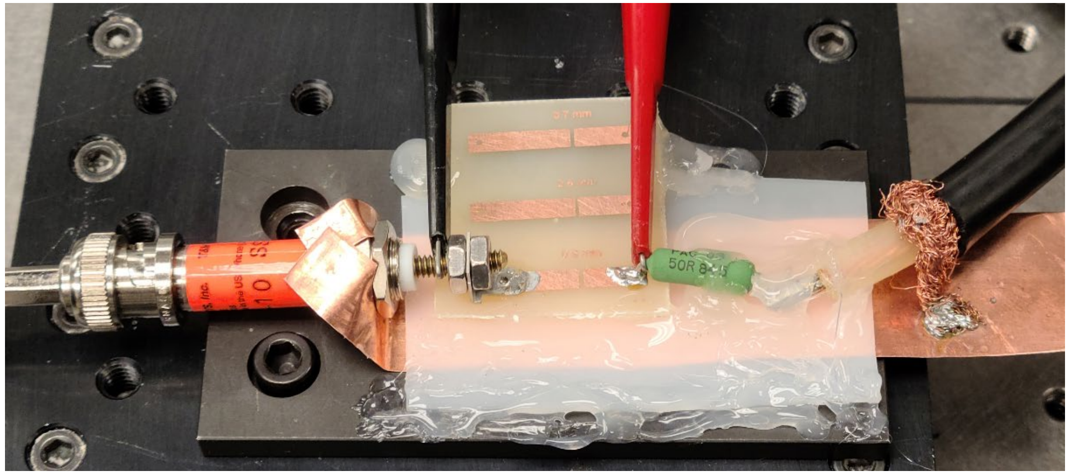
Laser Triggered Airgap Test

- Test to see if a gap of similar size to lateral GaN device can be flashed-over using 532nm
- Standard copper-clad FR4 etched using ferric chloride
- The reflectivity of Cu and Au at 532nm is comparable ~65%



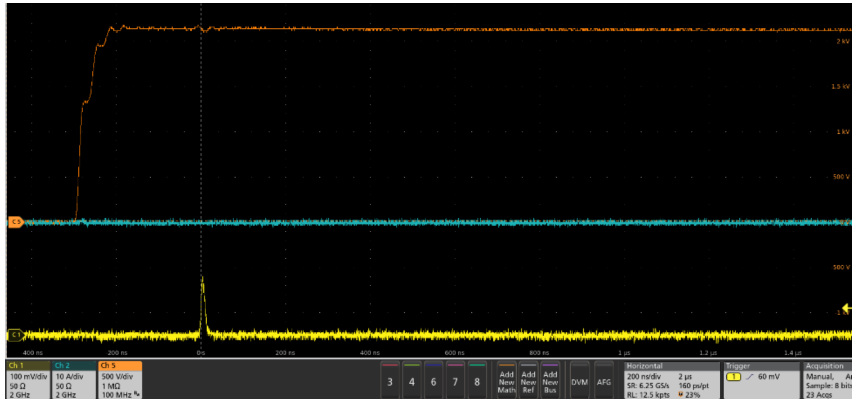


Reflectivity of a number of metals (including copper) as a function of wavelength: (a) Al, (b) Ag, (c) Pt, (d) Cu and (e) Au.



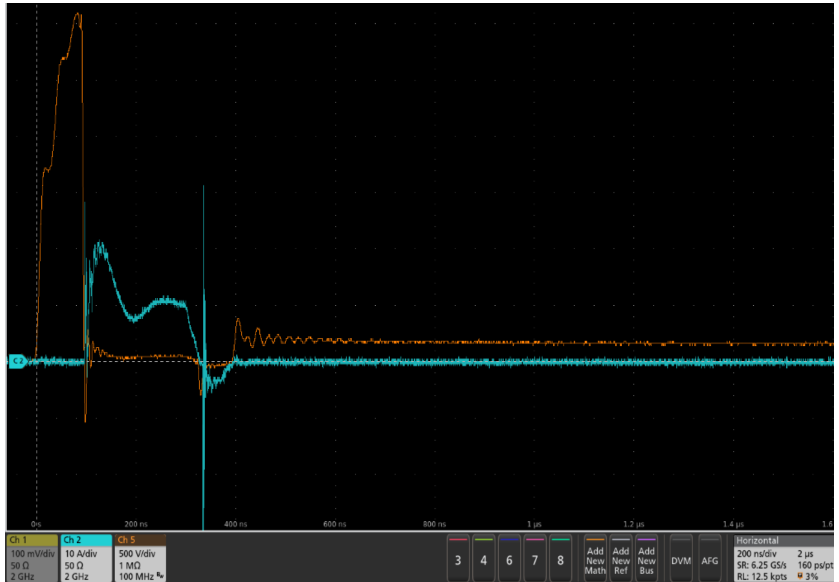
Panagopoulos, C. & Markaki, Athina & Hontzopoulos, Elias. (1997). Excimer laser treatment of copper-coated mild steel. Journal of Materials Science. 32. 1425-1430. 10.1023/A:1018589514262.

Laser Triggered Airgap Test Results

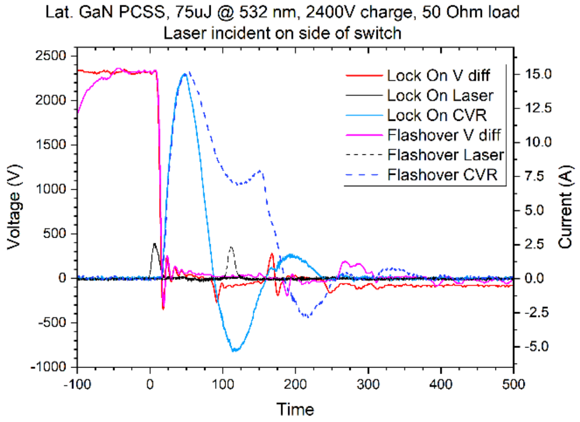


RL=50Ω

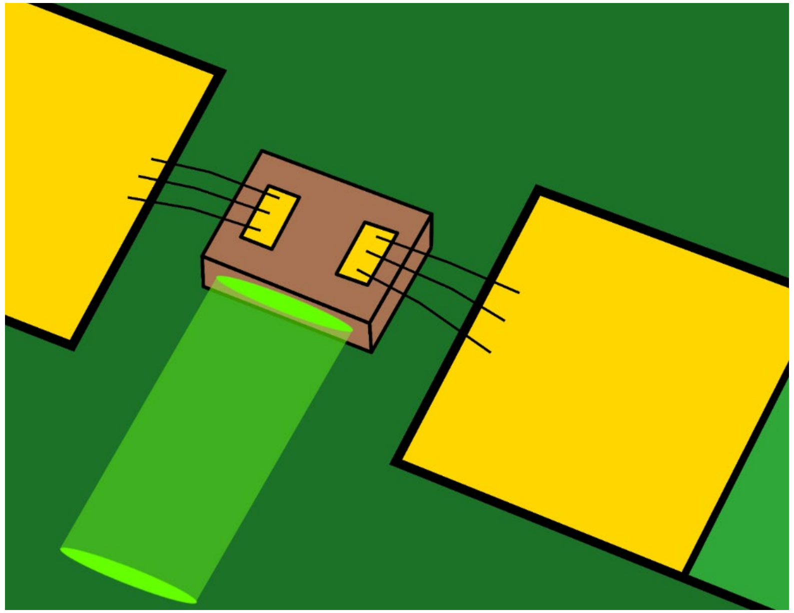
- Unable to induce flashover with laser energies of 40 to 150μJ incident on gap and Cu traces
- Orange: V diff across gap
- Blue: CVR
- Yellow: Laser
- Current limited by 50 Ohm resistor

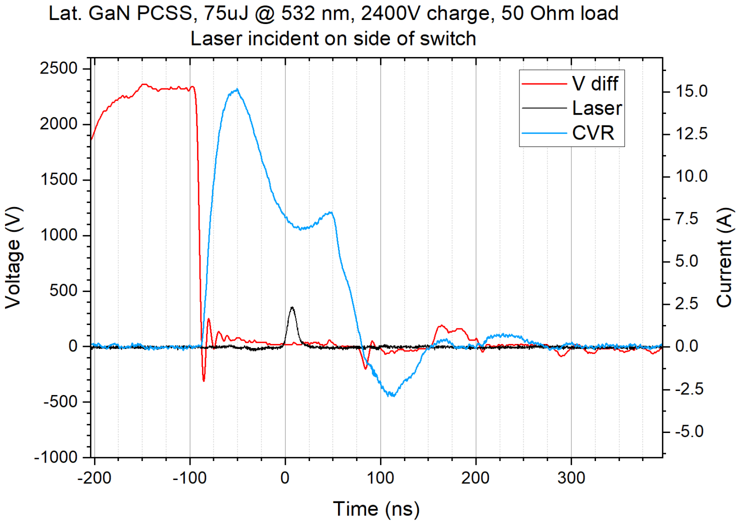


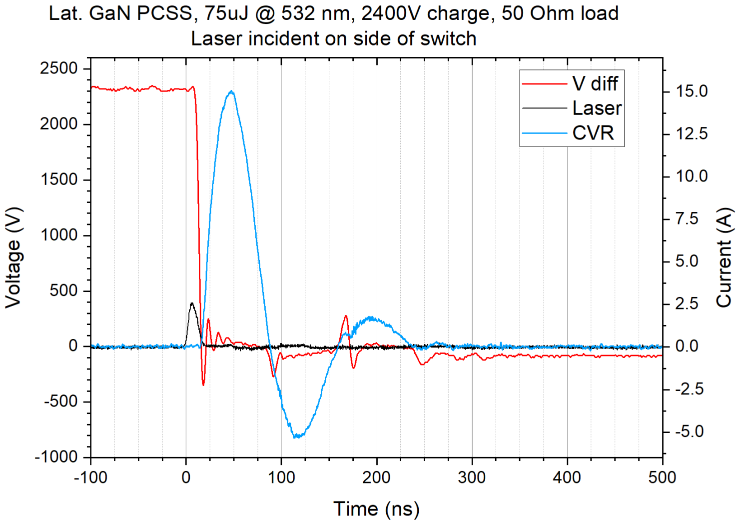
- Gap intentionally overvolted at 3200V to view current and voltage waveforms
- Breakdown current waveform echoes PCSS flashover current

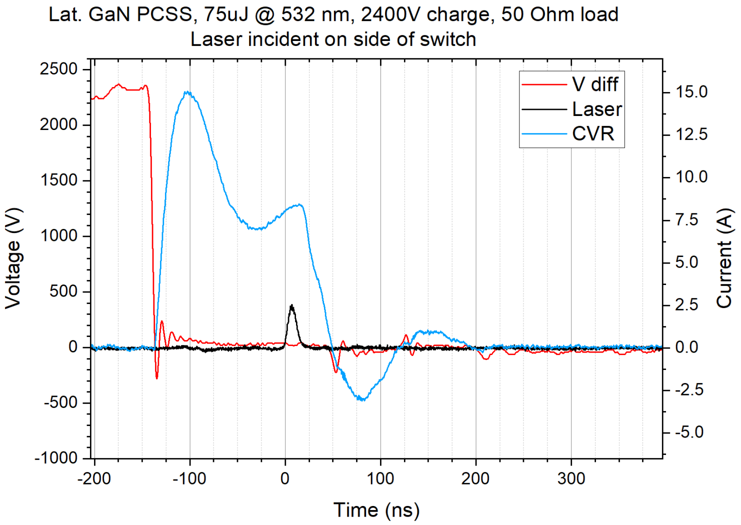


Playing off the Flashover and Lock on Modes with Voltage

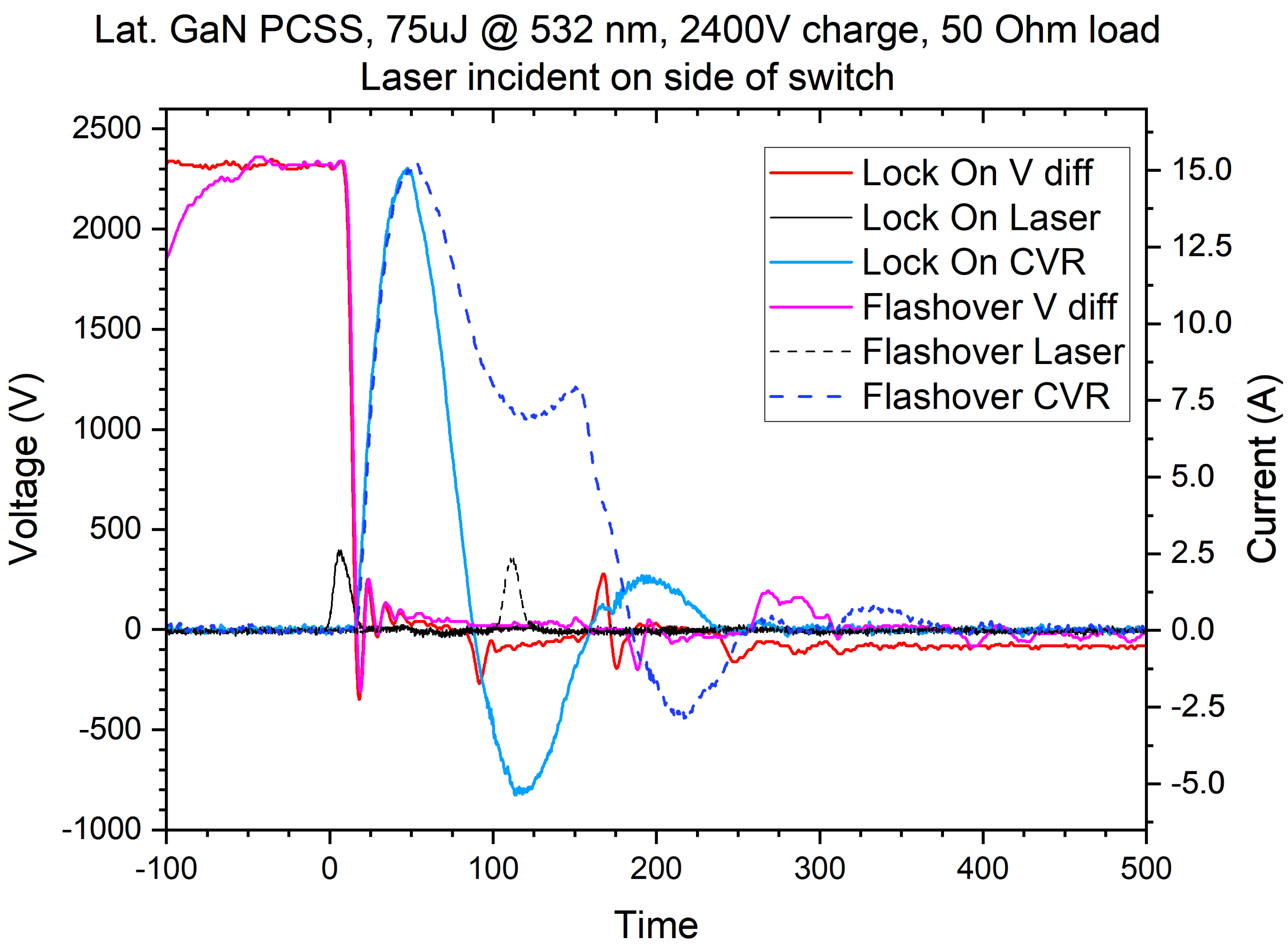




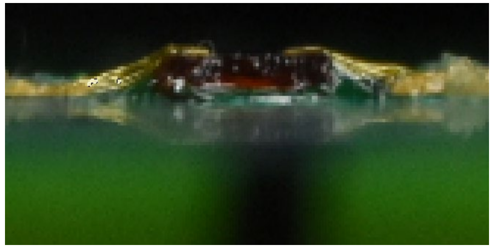
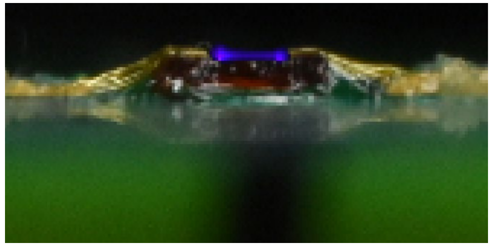




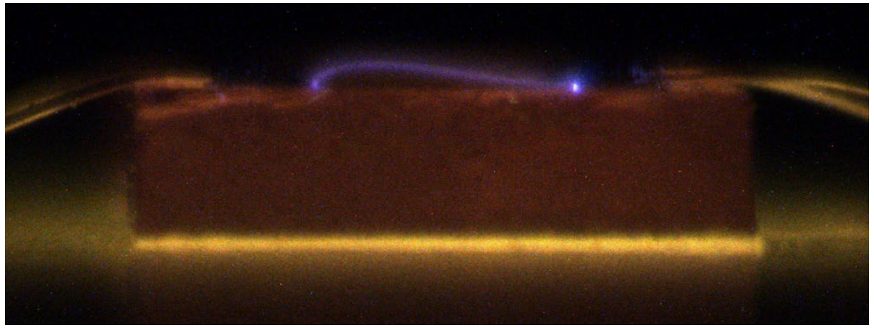
- This is 3 consecutive shots in which we see two flashovers and one “lock-on” event
- This experiment is different in that the laser is incident to the side of the switch
- Previously the laser was incident on the top (switch face with the metallization).


Lat. GaN PCSS, 75uJ @ 532 nm, 2400V charge, 50 Ohm load
Laser incident on side of switch
Voltage (V)
Current (A)
Time
2500
2000
1500
1000
500
0
-500
-1000
15.0
12.5
10.0
7.5
5.0
2.5
0.0
-2.5
-5.0
-100
0
100
200
300
400
500
Lock On V diff
Lock On Laser
Lock On CVR
Flashover V diff
Flashover Laser
Flashover CVR

Flashover or Air Breakdown

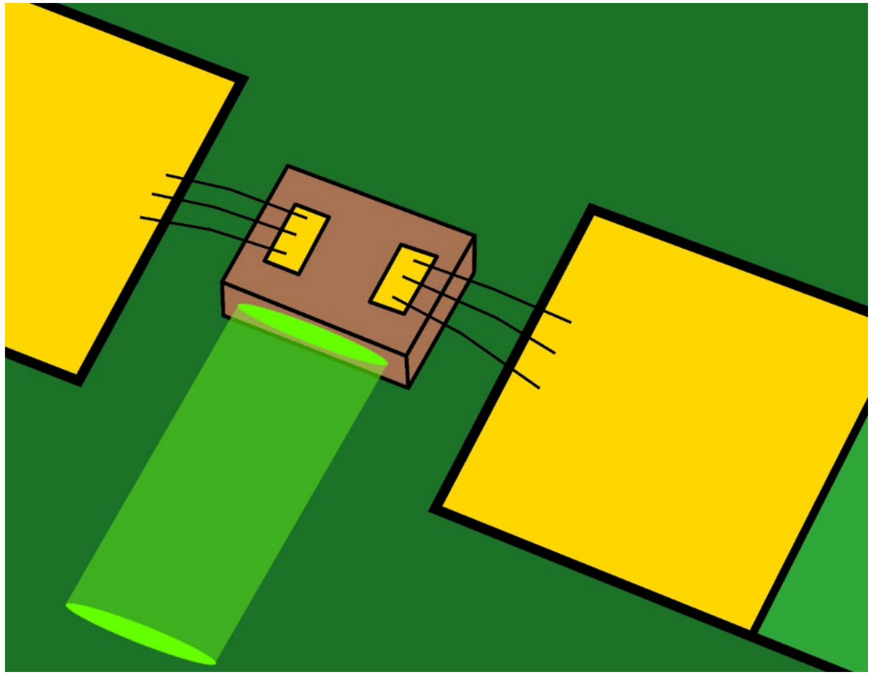
Side view of flashover on lateral switch



Side image of filament on lateral GaN PCSS

A magnified image shows that it is not a flashover but an air Breakdown along an equipotential line.

390 ohm load



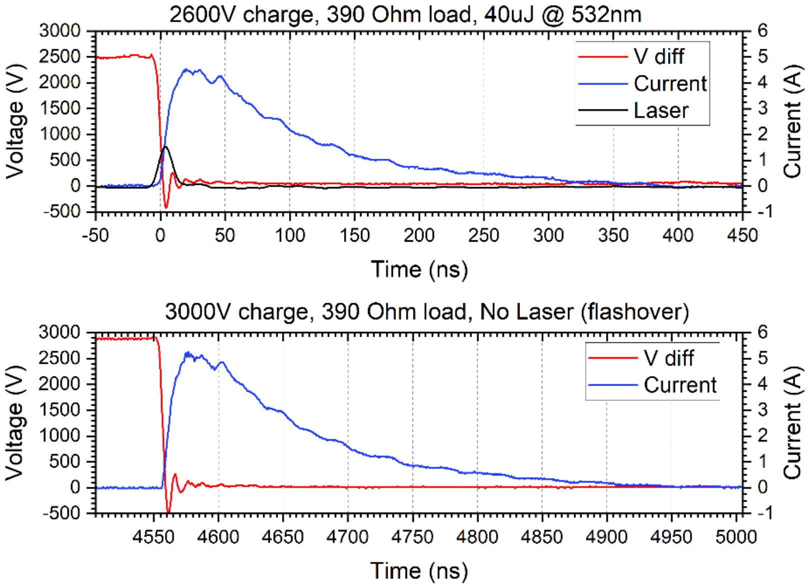
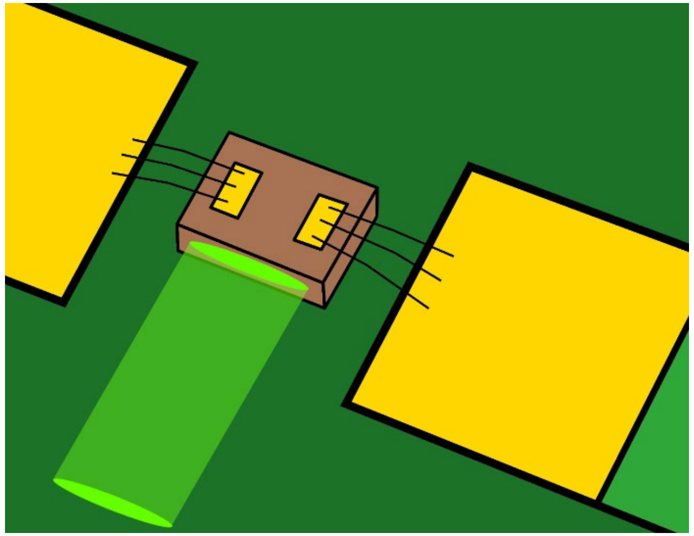
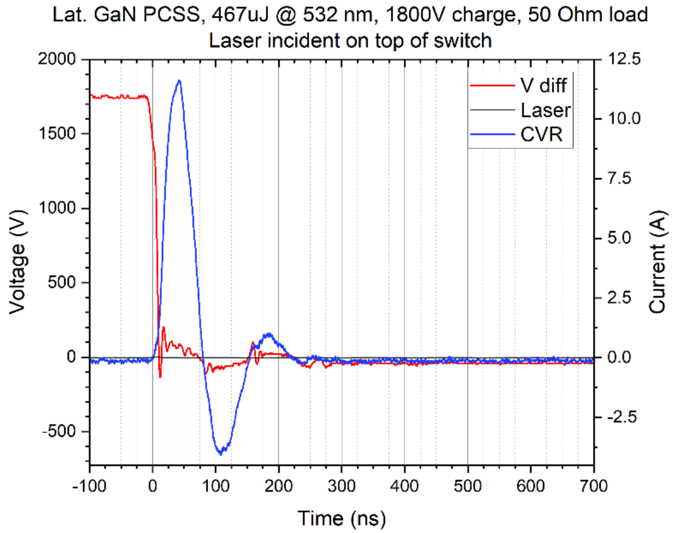


Figure 4.27. Waveforms of a laser initiated switching and an intentional flashover event

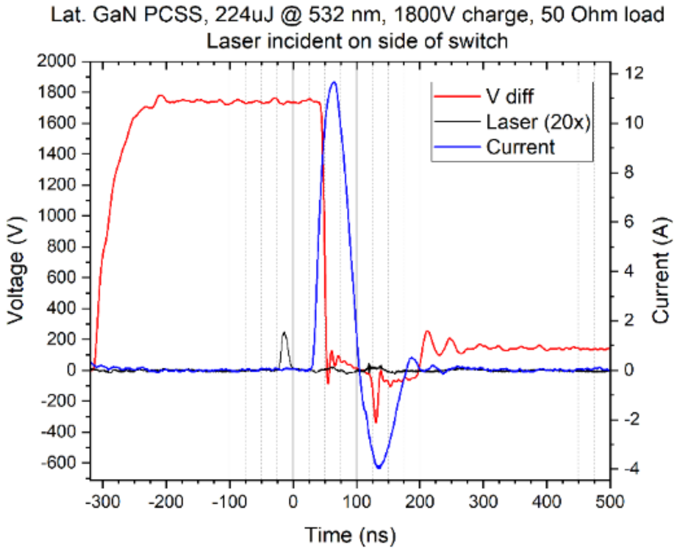
50 ohm load



The adjusted test geometry applies the voltage across the gap but the laser in through the side of the switch

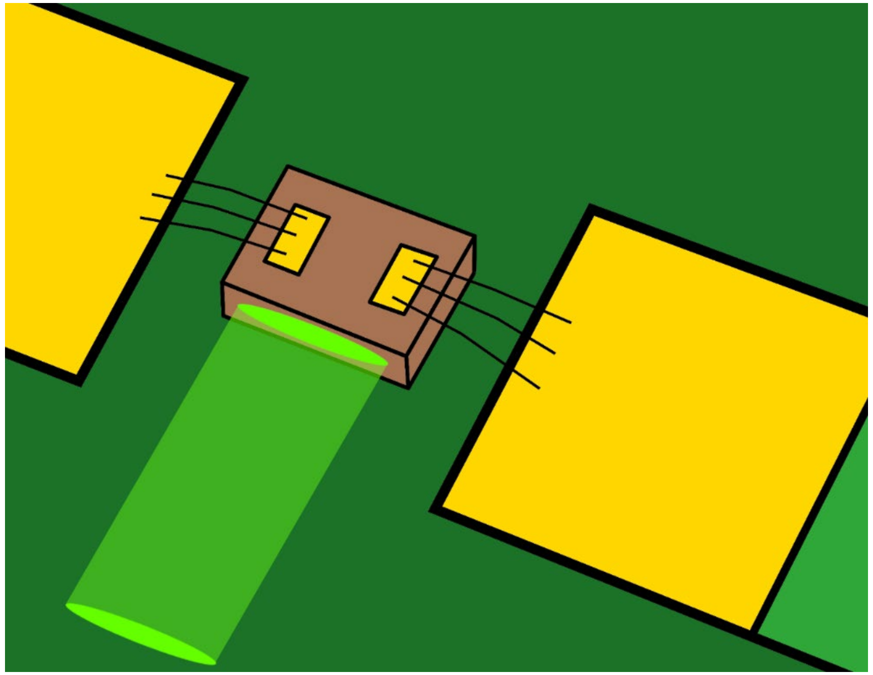


Waveforms from laser incident on top of switch



Waveforms from laser incident on side of switch

Evidence of Lock-On in GaN



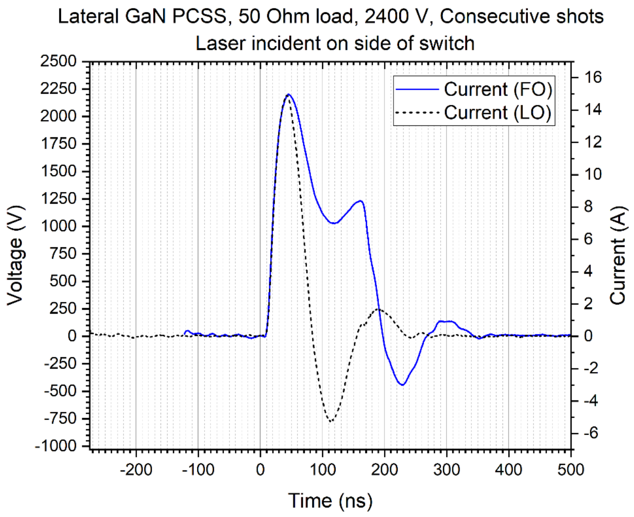
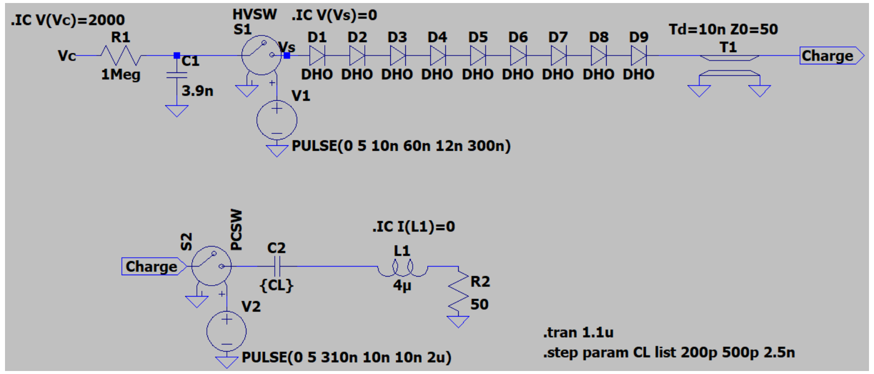


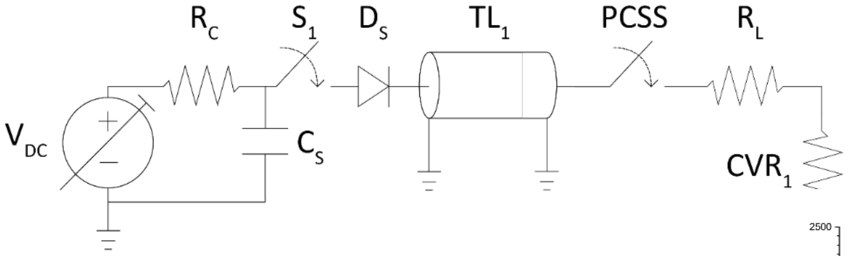
Figure 4.31. Current waveforms for lock on versus flashover

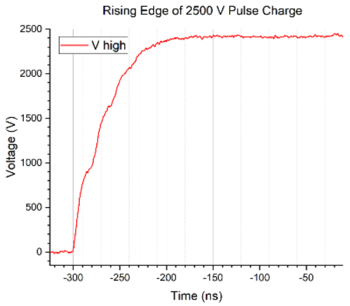
Conclusions

- Previous results (IDEAS) strongly resembled lock-on in GaAs except for its disappearance under a blanket of fluorinert.
- Those results have been replicated and shown to be a voltage effect using the electron attaching gas SF6.
- The "flashover" and lock-on modes could be differentiated using a 50Ω load.
- By aiming the laser through the side, the lock on mode in GaN PCSS was clearly shown. Illumination of the top could result in either lock on, flashover or linear mode operation depending on the voltage level.
- The "flashover" is not along the surface but instead and air breakdown that is electron avalanche dominated at these short gap lengths.

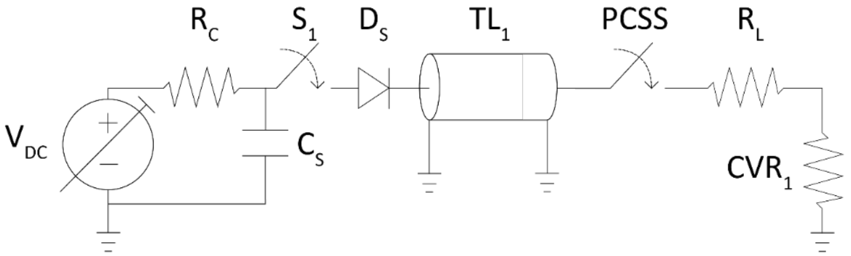
Extra







Ron ~ 95 ohms



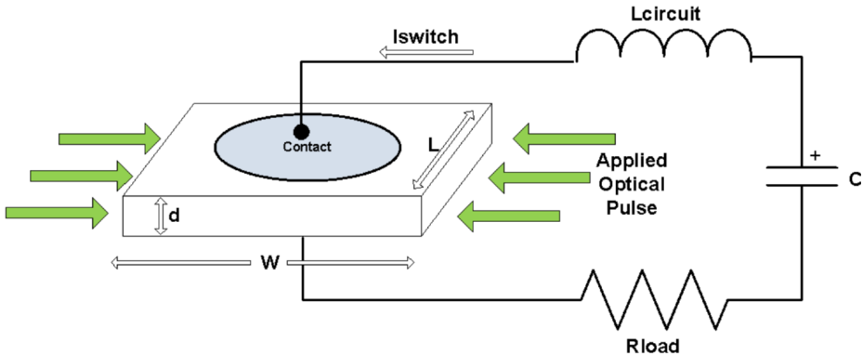
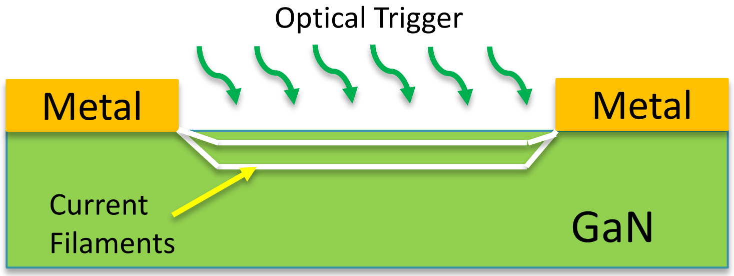
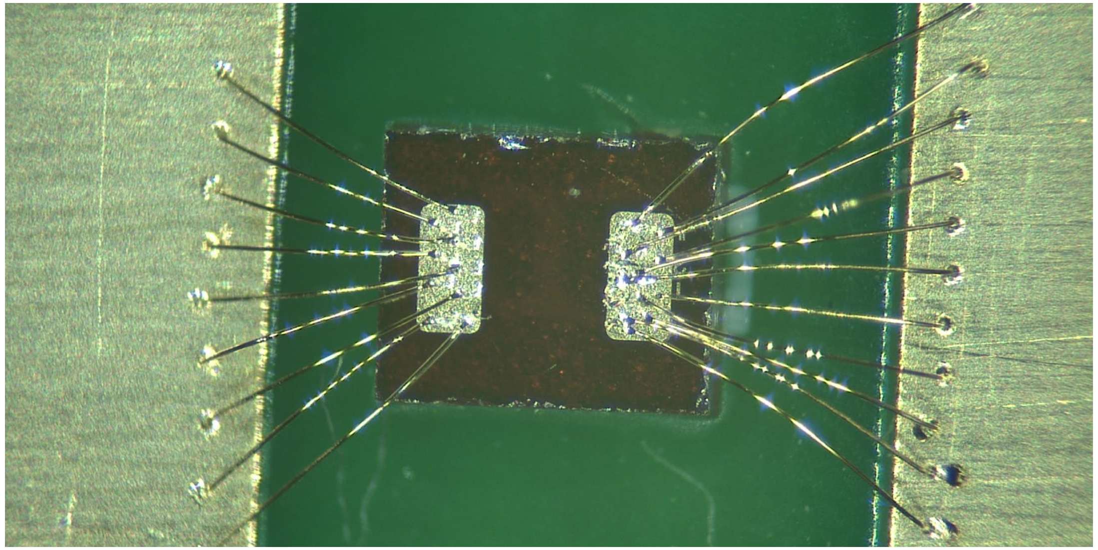


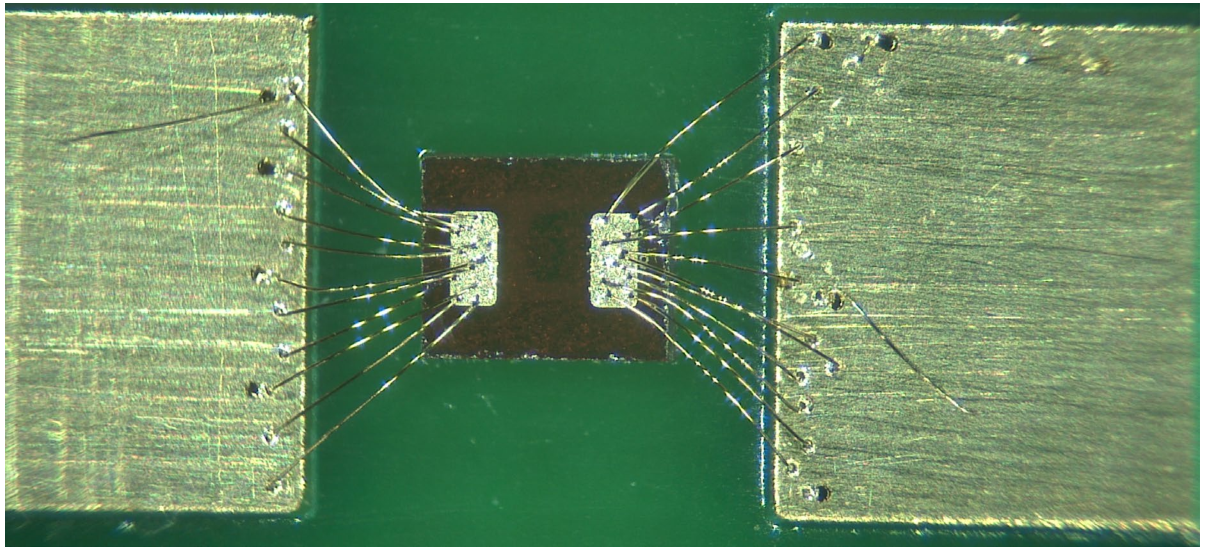
Figure 4.5. Classic vertical PCSS geometry and circuit setup [14]



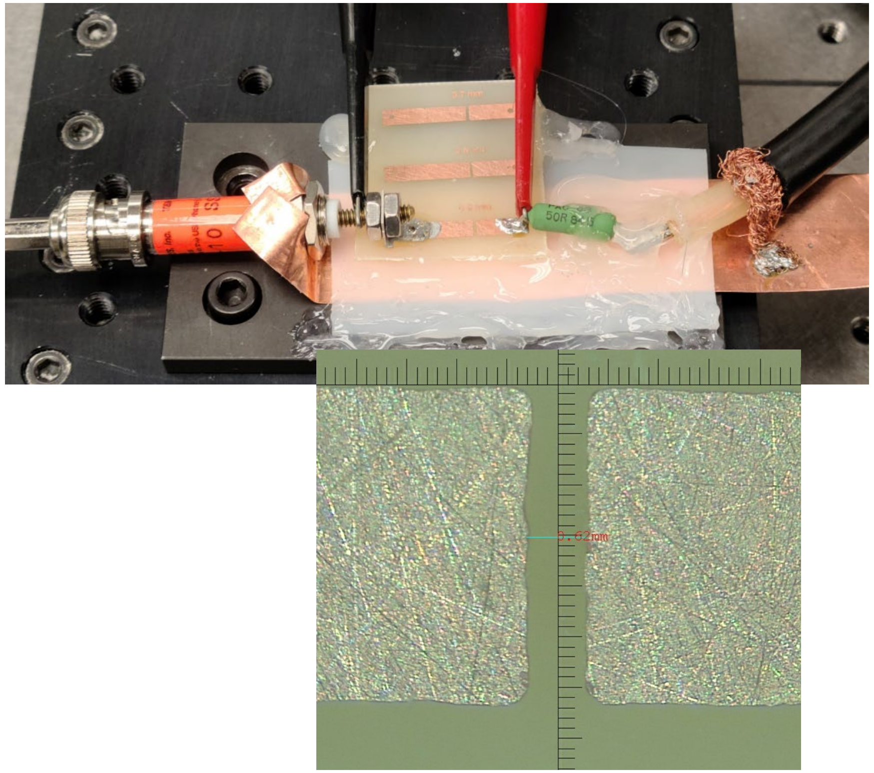
Wire bonded 600µm devices at UNM

- 600µm lateral GaN, ball-bonded at UNM using 1µm gold wire





Intentional Flashover



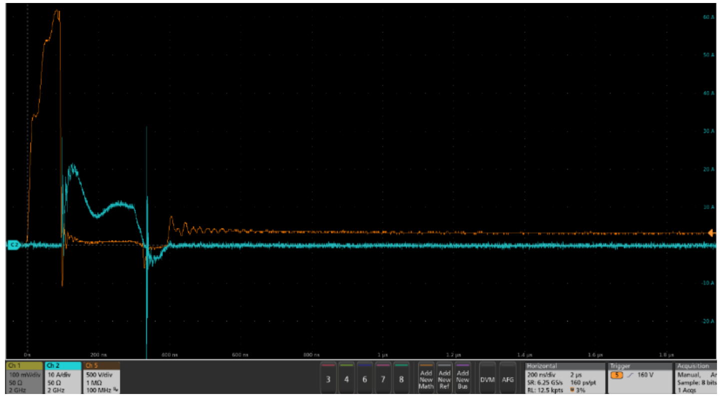


Figure 4.26. Waveforms of intentional air gap flashover of 3200 V (orange = V diff, cyan = CVR)

- **GaN PCSS High-Gain Switching properties**
  - Persistent conductivity
  - Low (<30uJ) laser trigger energy requirement
  - Repeatable low-latency, low jitter laser triggered discharge waveforms
- **GaN photoconductivity properties still being quantified**
  - High-gain switching not observed under FC-70
  - Laser-initiated filament emission spectra different from self-break
  - High-gain may be a surface effect (but potentially useful for applications)
- **On-going / Future development**
  - Devices for higher voltage (lateral with larger gap) and vertical structures
  - Power conversion circuit application demonstration
    - 20Hz (laser-limited) rep rate operation demonstrated