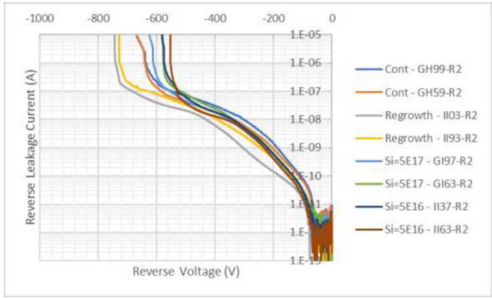
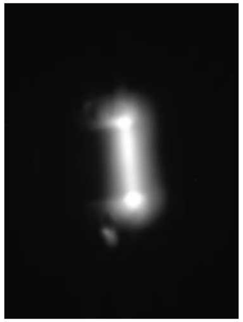
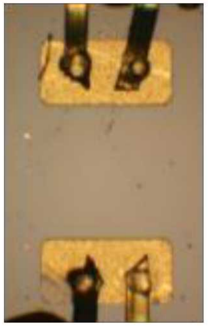
SAND2018-10913C

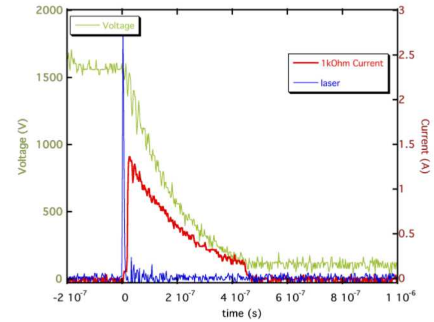
Exceptional service in the national interest

Sandia National Laboratories









Advanced GaN Device Technologies for Power Electronics

G.W. Pickrell, A. M. Armstrong, A. A. Allerman, M. H. Crawford, D. Feezell, M. Monavarian, A. Aragon, F.J. Zutavern, A. Mar, E. Schrock, J.D. Flicker, J. J. Delhotal, J.D. Teague, J.M. Lehr, K.C. Cross, C.E. Glaser, M.S. Van Heukelom, R.J. Gallegos, V.H. Bigman, and R.J. Kaplar

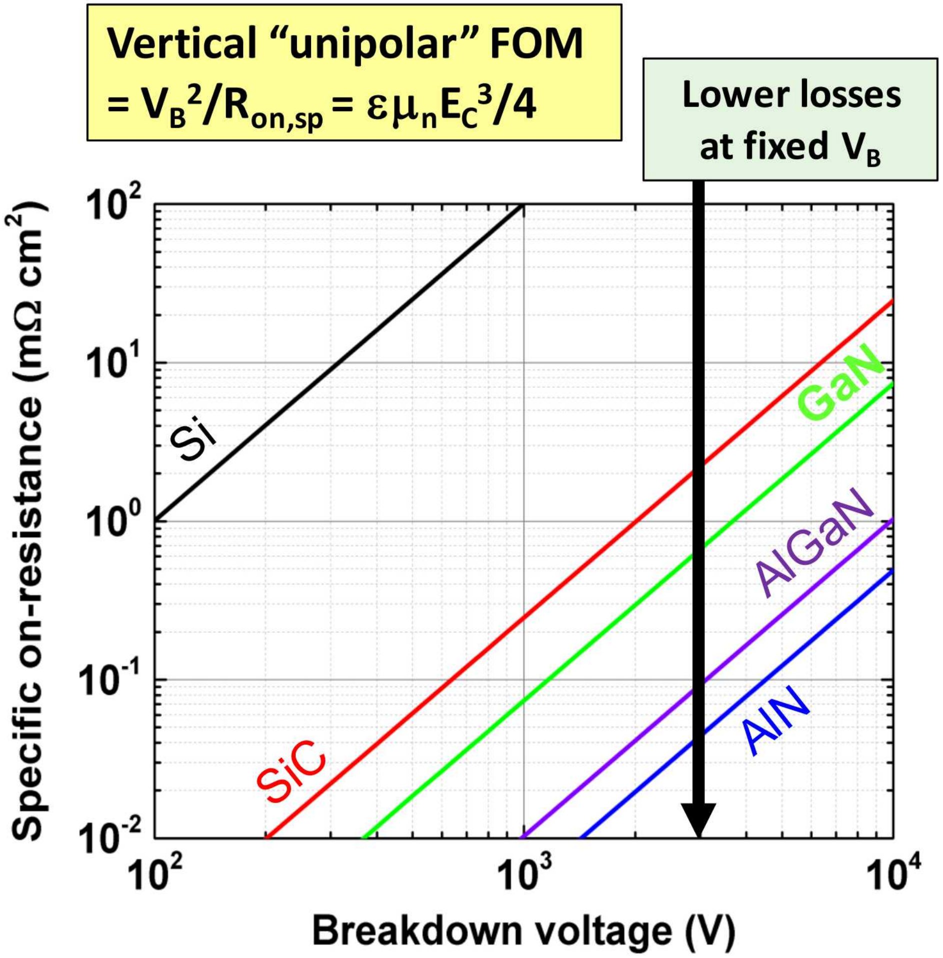
Sandia National Laboratories is a multimission laboratory managed and operated by National Technology and Engineering Solutions of Sandia, LLC., a wholly owned subsidiary of Honeywell International, Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA-0003525.

Outline

- Motivation for GaN in power electronics
- Regrown p-n diodes: selective area doping control for vertical GaN devices
- GaN photoconductive semiconductor switches (PCSS) technology demonstration and characterization

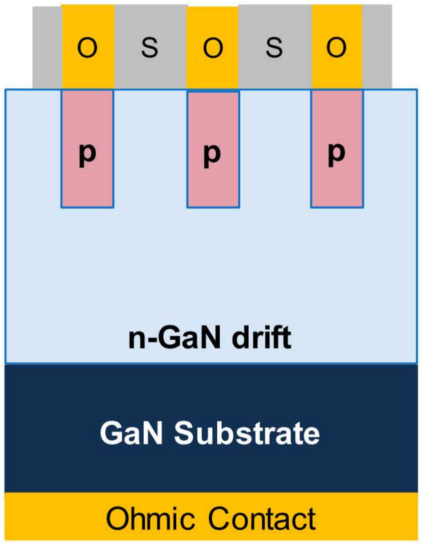
GaN for Power Electronics

- Larger bandgap and critical electric field (E_c).
- Systems with reduced **size, weight, &** increased **power density.**
- $Al_xGa_{1-x}N/GaN$ HEMTs mature in RF applications.
- GaN p-n diodes demonstrated with V_{br} ~ 4-5 kV and R_{sp}~1 mΩ cm^2.
- Vertical GaN transistors demonstrated (MOSFETs, CAVETs, etc.).
- Commercial GaN substrates available.
- New GaN devices are promising
  - Selective Area Doping (enabling technology for vertical transistors)
  - Photoconductive Switches



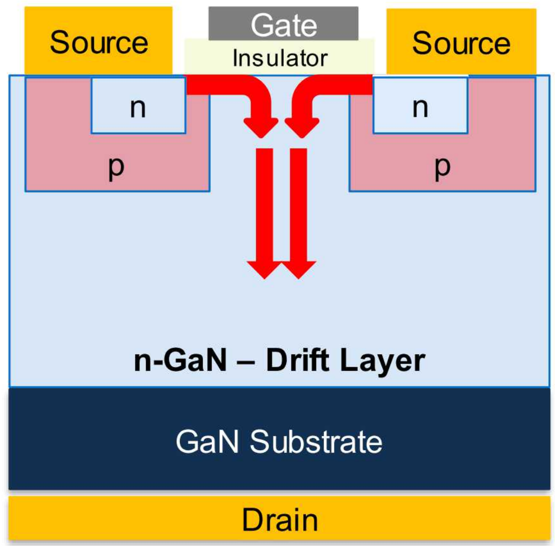
Selective Area Doping Control – Advanced Devices

Merged pin Schottky (MPS) Diode

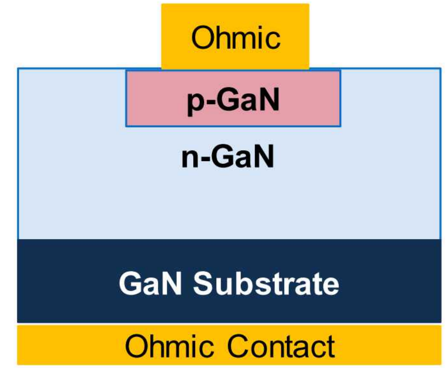


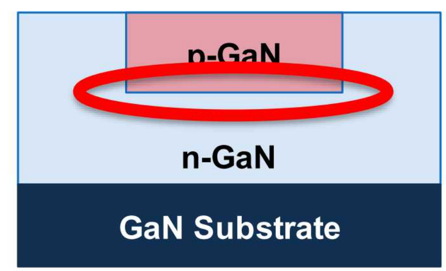
O=Ohmic
S=Schottky

Double-Well, MISFET (D-MISFET)



Basic Building Block Selective Area p-n Junction



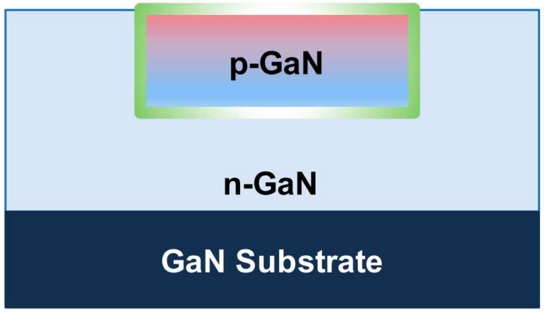


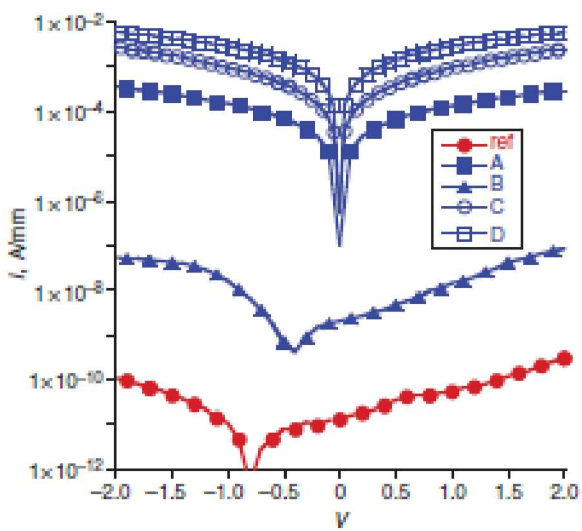
- Interface control of **impurities and crystalline quality** required for high-quality regrowth
- Both polar and non-polar planes involved in epitaxial regrowth
- Merged PIN Schottky (MPS) diodes, and vertical GaN transistors possible

Selective-Area P-Type Doping – Previous Work

Sandia National Laboratories

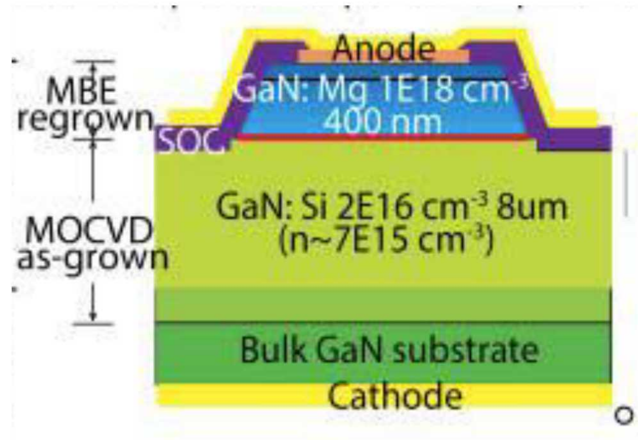
Mg Implant and Multicycle RTA

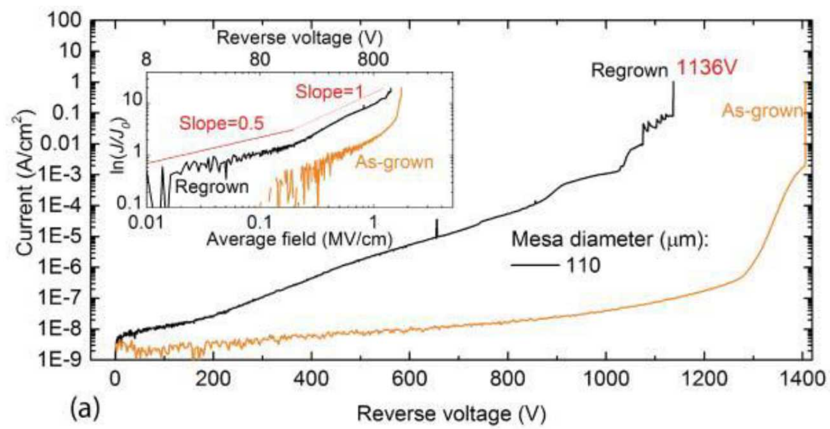




T.J. Anderson, B.N. Feigelson, F.J. Kub, M.J. Tadjier, K.D. Hobart, M.A. Mastro, J.K. Hite, and C.R. Eddy Jr., *Elec. Lett*, 50(3), 2014.

Regrowth by MBE

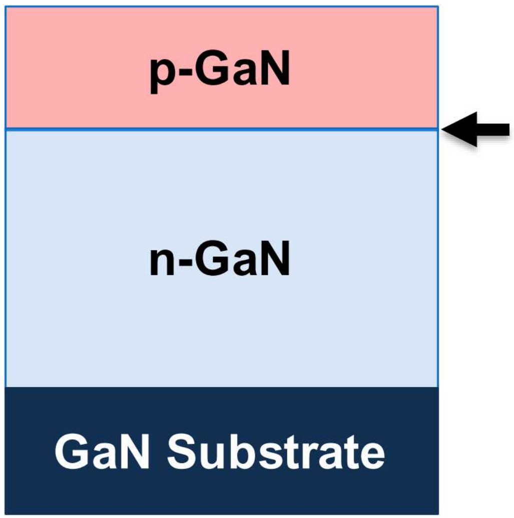




Z. Hu, K. Nomoto, M. Qi, W. Li, M. Zhu, X. Gao, D. Jena, and H.G. Xing, *IEEE Elec. Dev. Lett*, 38(8), 2017.

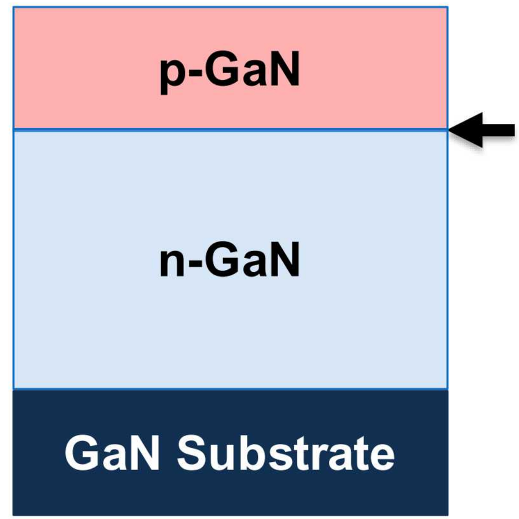
GaN P-N Diodes Under Study

1) Continuously Grown P-N Diodes



a) Traditional
b) Intentional Si-doped at interface

2) Regrown P-N Diodes

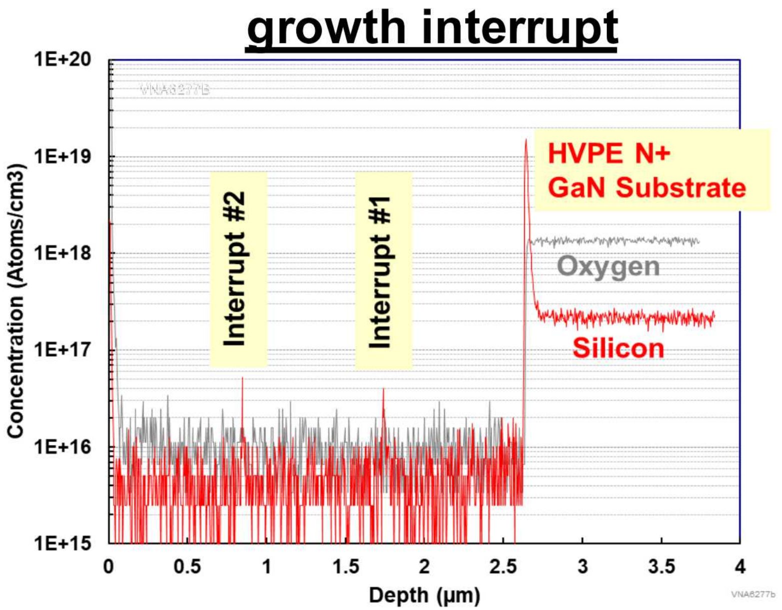


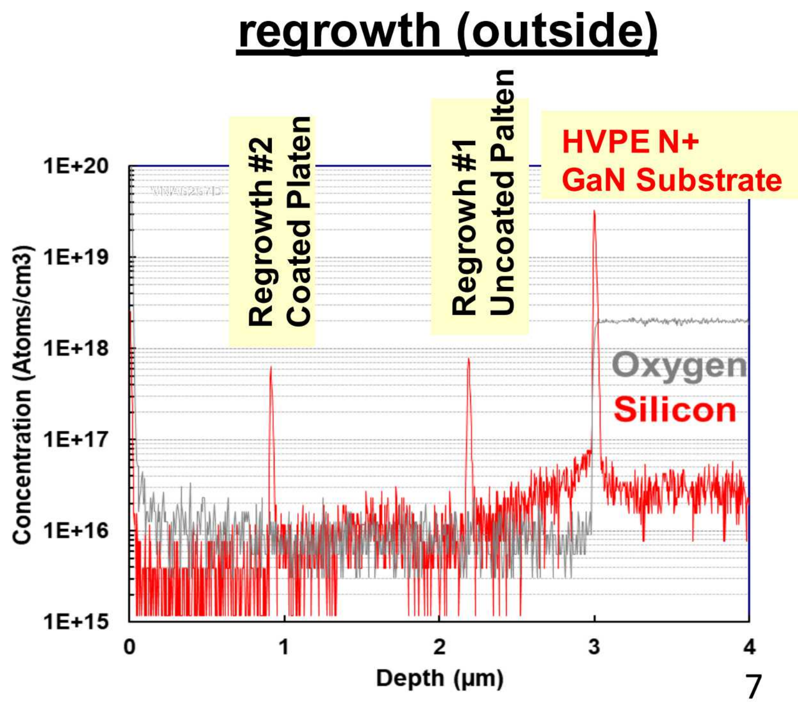
a) *In-situ* interrupt
b) Remove from chamber before regrowth
c) Dry-etched before regrowth

- Epitaxial growth by MOCVD (Veeco D-125 reactor)
  - Commercially available HVPE GaN substrates
  - N-drift layer, 10 µm thickness, ~ 2e16 cm^{-3} carrier concentration
  - p-GaN layer, 0.4 µm thickness, [Mg] = 3e19 $cm^{-3,}$ p+ GaN contact layer

SIMS

- **Question:** Is primary Si contamination coming from inside the reactor?
- **Answer:** Not for this hardware.
- Secondary ion mass spectrometry (SIMS) done by EAG Laboratories
- Growth interrupts (sample inside reactor) shows Si ≤ 3-4E10 cm^{-2} (5E16 cm^{-3})
- Regrowths (sample outside reactor) shows Si ~3-8E11 cm^{-2} (2-7E17 cm^{-3})

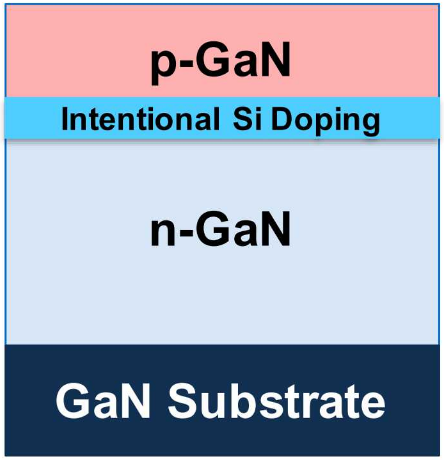




G.W. Pickrell, et al., EMC Presentation, Santa Barbara, CA, June 2018.

Intentionally Si-Doped c-Plane Diodes

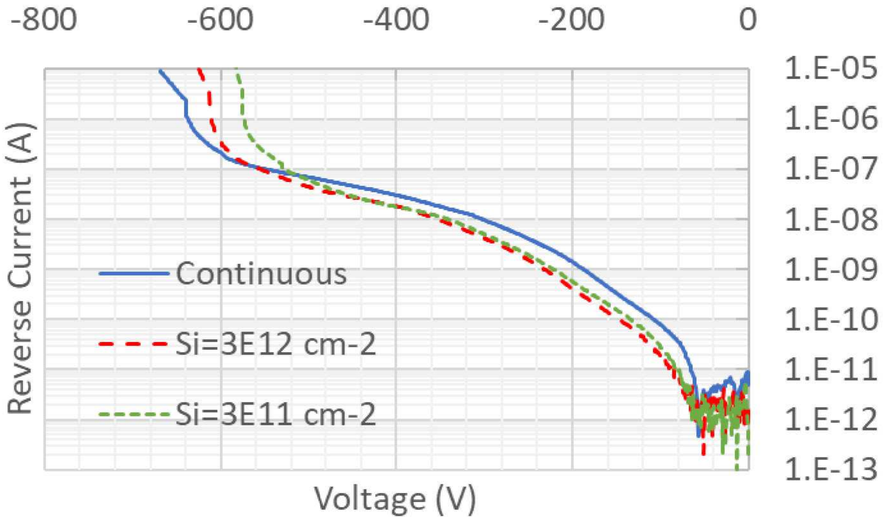
Sandia National Laboratories



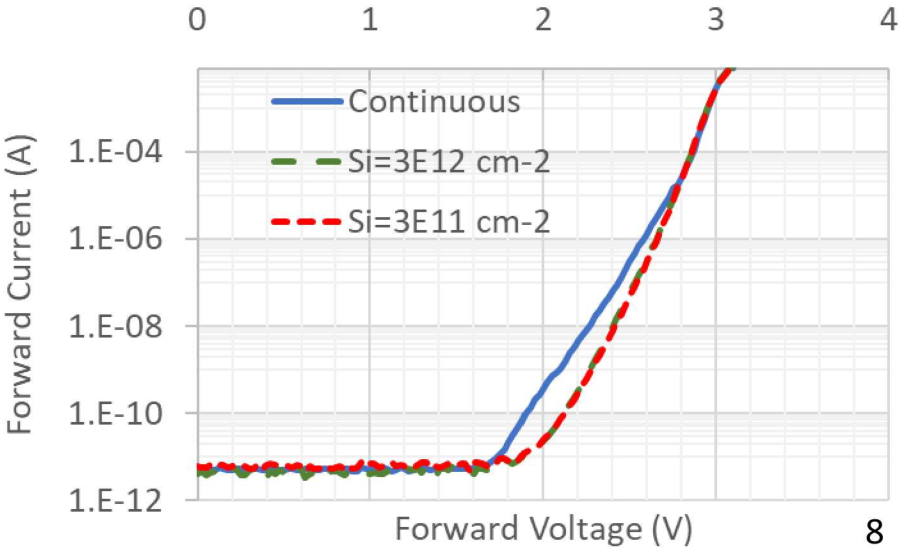
- [Si] ~ 3E11 cm^{-2} and 3E12 cm^{-2} in continuously grown diodes
  - 5 nm with [Si] ~5E16 cm^{-3} or 5E17 cm^{-3}

- [Si]<= 3E11 cm^{-2} does not degrade electrical performance of continuously grown diodes
- >600 V reverse breakdown voltage with no field management

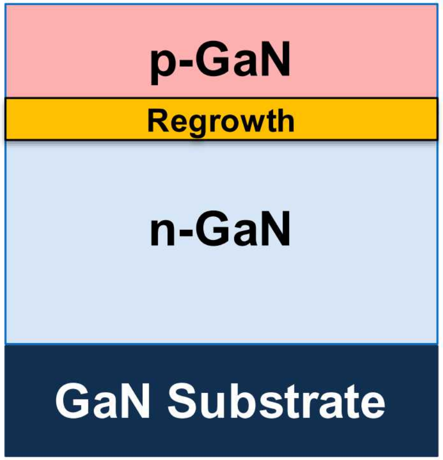
Reverse Bias



Forward Bias



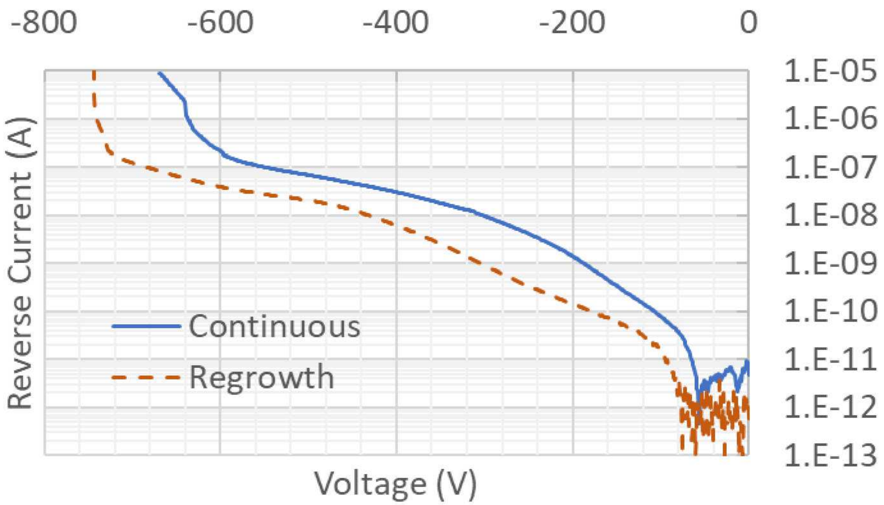
Regrown c-Plane Diodes by MOCVD



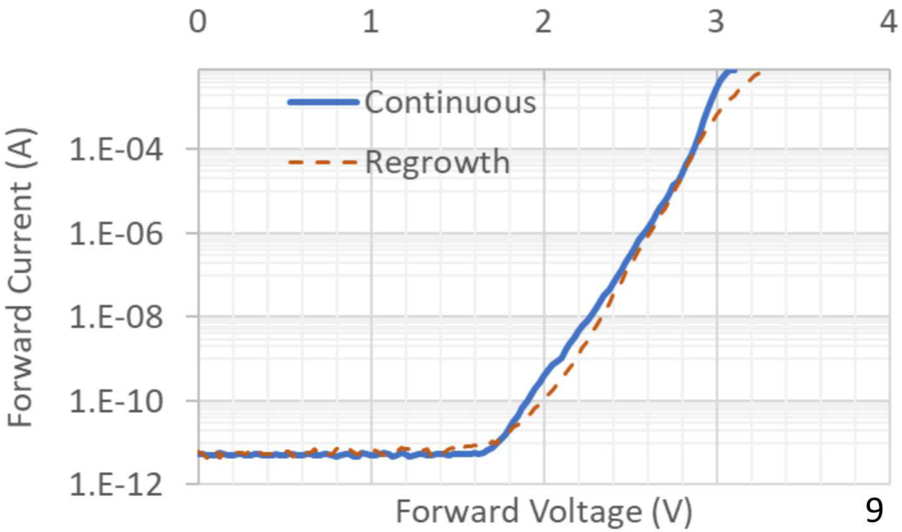
- Growth of p-GaN on drift layer after taking out of growth chamber
  - Characterization and HCl cleaning prior to regrowth

- ***MOCVD regrowth process itself*** does not degrade electrical performance of continuously grown diodes
- >700 V reverse breakdown voltage with regrown diodes with no field management

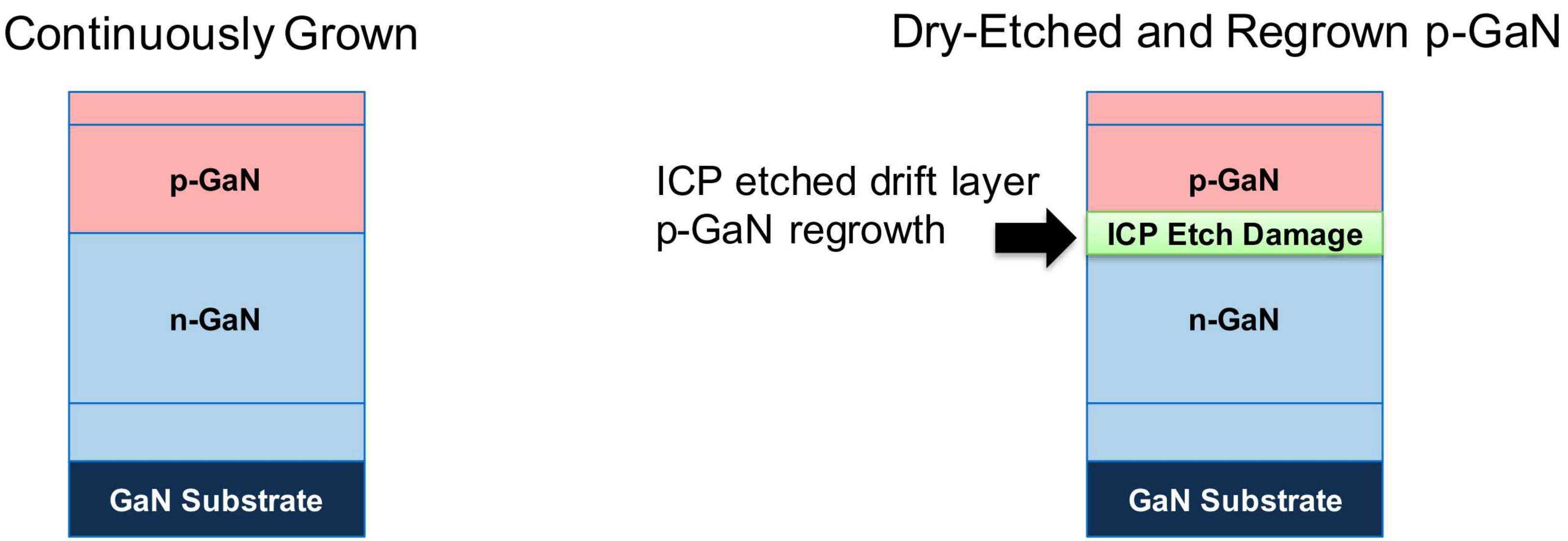
Reverse Bias



Forward Bias

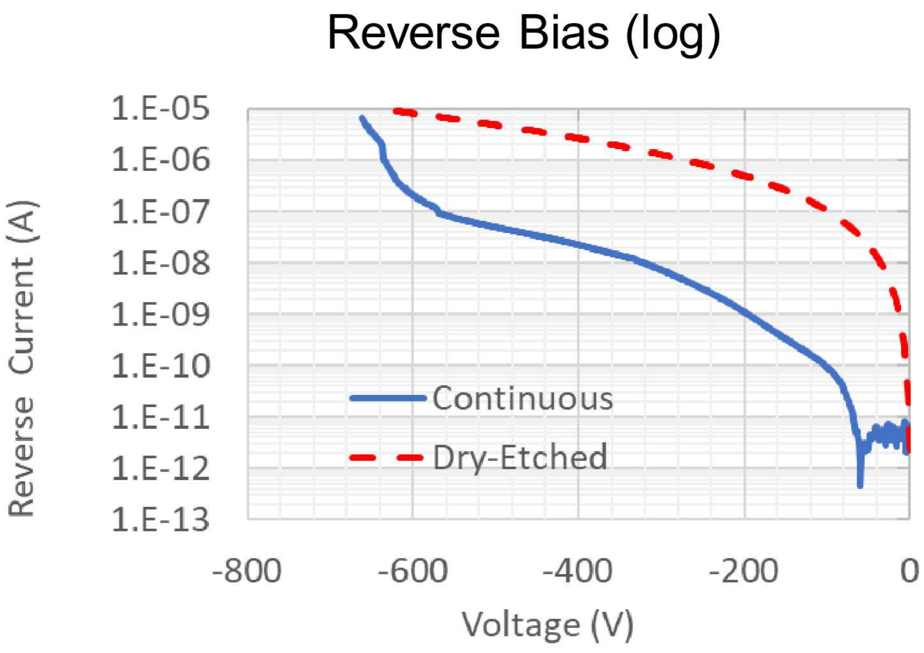


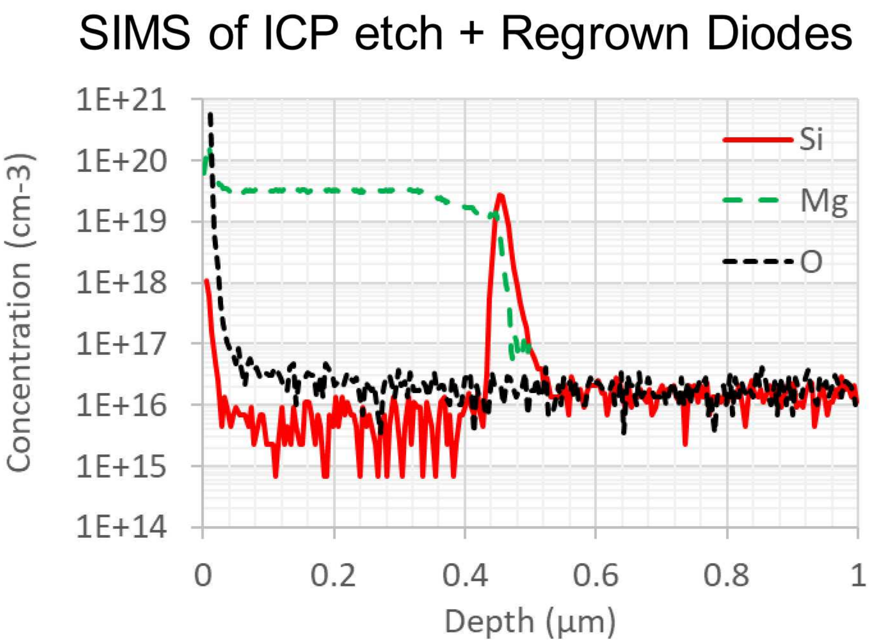
P-Regrowth on ICP etched c-Plane Drift Layers



- Compare electrical performance of regrown and ICP Etched/Regrown PN Diodes
- ICP etched ~400 nm using $BCl_3/Cl_2/Ar$, low-damage ICP etch (10 W)
  - Optimized for improved ohmic contacts to etched AlGaN surfaces (Al > 0.6)
- Regrow on ICP etched surface using same temperature ramp/regrowth process
  - No attempt to treat etched surface prior to p-GaN regrowth
  - Worst case scenario

P-Regrowth on ICP Etched Drift Layer



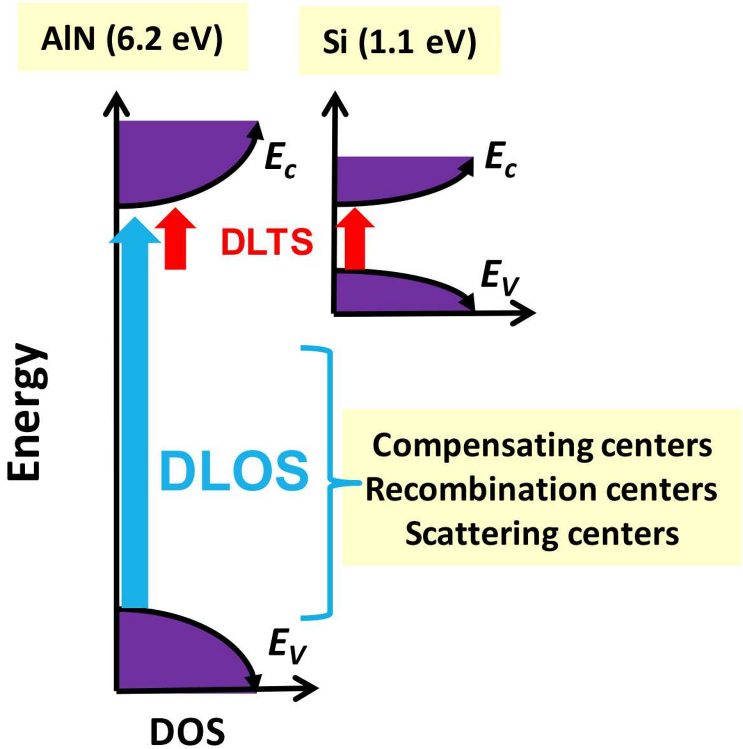


- Drives understanding of expected performance degradation effects
- Reverse bias performance significantly degraded for etched/regrown diode
  - 2-3 orders of magnitude increase in reverse leakage currents, especially at lower voltages
  - SIMS shows significantly higher Si spike contamination (5E13 cm^{-2}/3E19 cm^{-3})
- Possible causes: defects induced by dry-etch damage and interface contamination

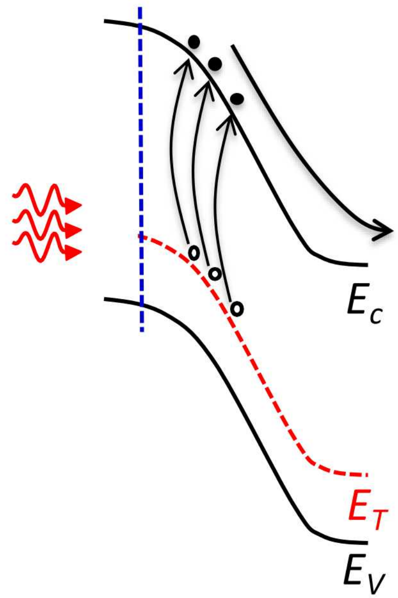
Deep Level Optical Spectroscopy (DLOS)

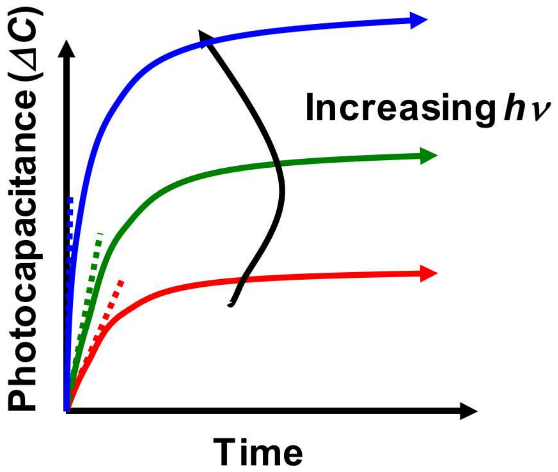
Sandia National Laboratories

Wide Bandgap semiconductors require DLOS (mid-gap)



Photoemission from electron traps



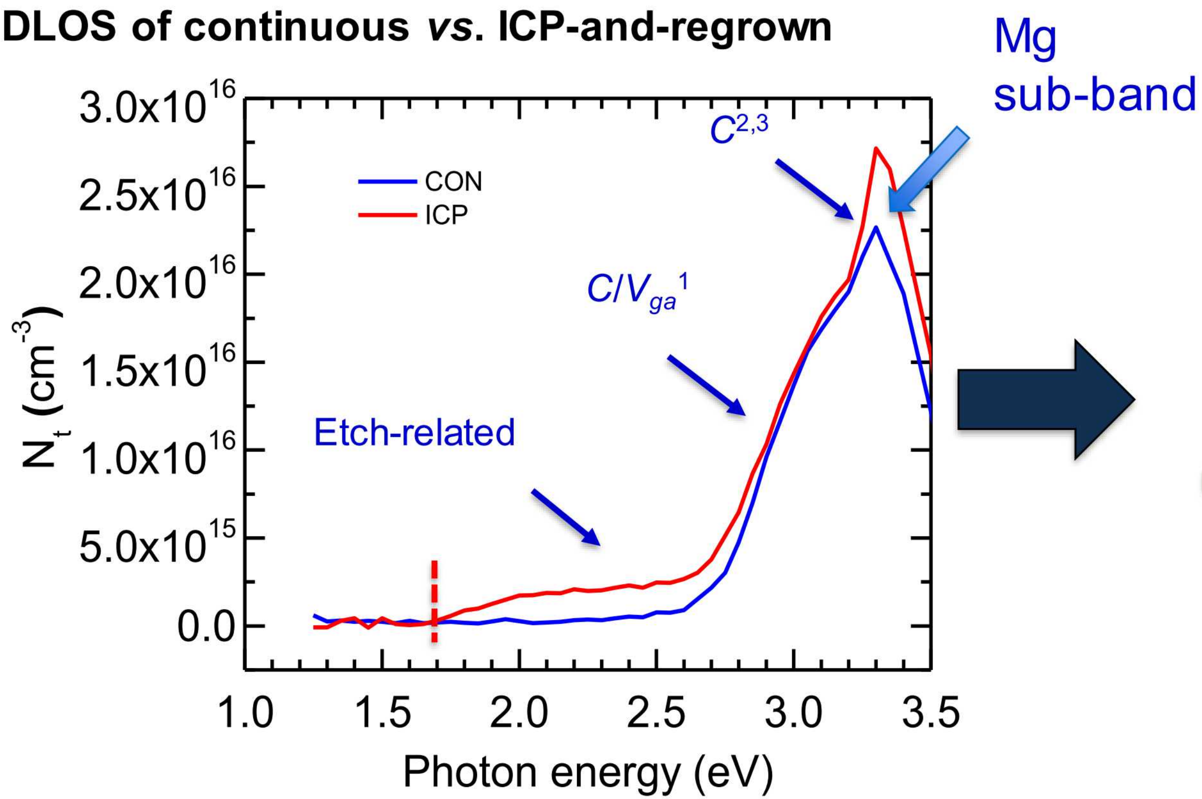


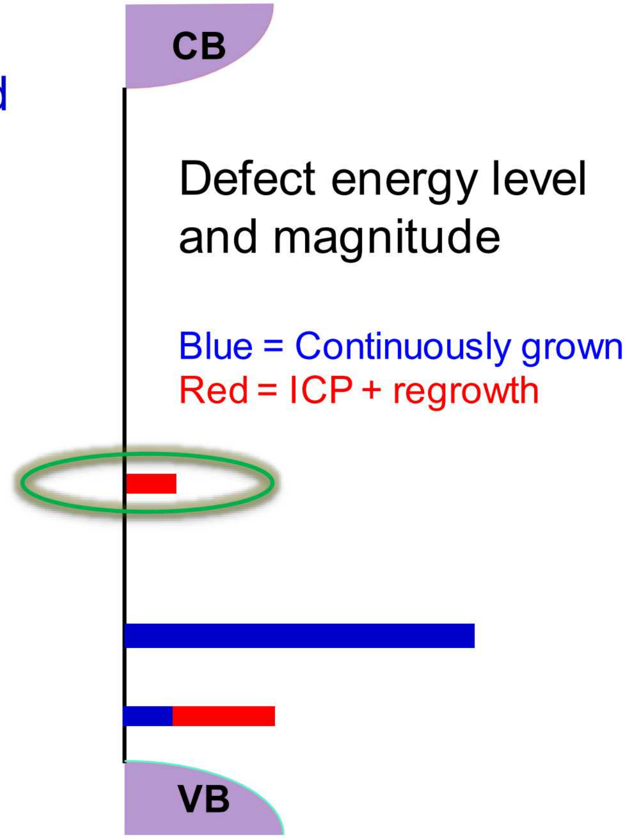
- DLOS required to probe mid-band gap and near-E_v defect levels in GaN
- Majority carrier photoemission from defect levels increases capacitance
- Magnitude of photo-capacitance (ΔC) proportional to $N_t = 2N_d\Delta C/C_0$

DLOS

1. Hierro *et al*., APL **80** 805 (2002).
2. Armstrong et al., JAP **106** 053712 (2009).
3. Zhang et al., APL 103 042102 (2013).

DLOS of continuous *vs.* ICP-and-regrown



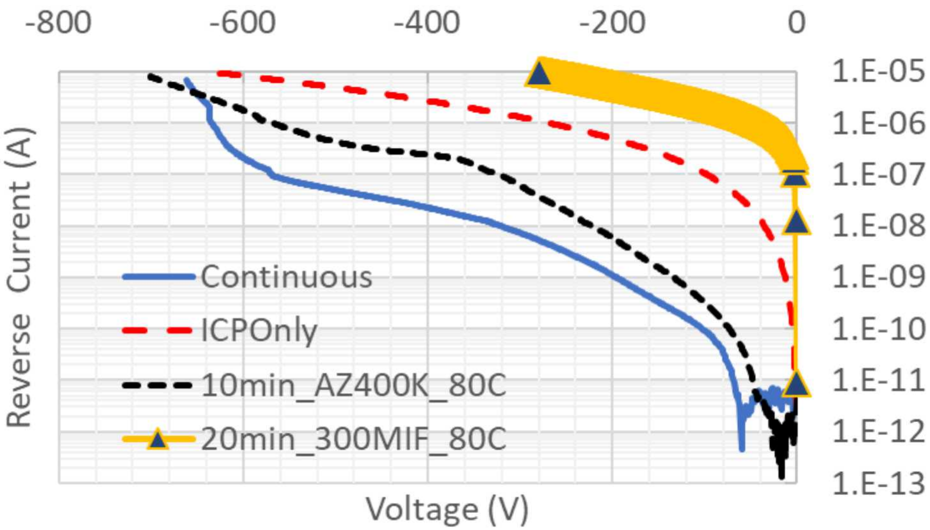


- Asymmetrically- doped structures used for DLOS to probe p- or n-side
- Compared continuously grown and ICP etched + regrowth (no wet etch)
- **New defect is seen in ICP sample at Ec – 1.7 eV (possible mid-gap tunneling state)**
- Higher defect density seen in p-GaN regrown on etched n-GaN

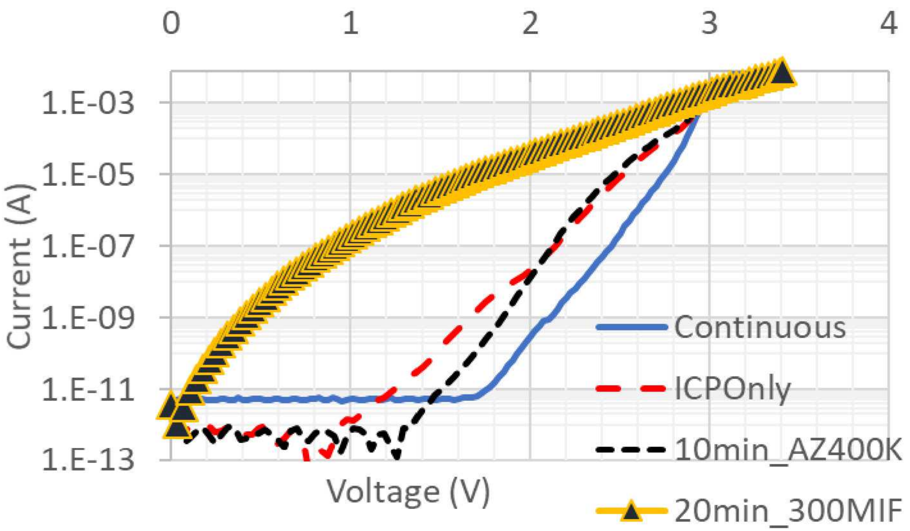
Defect Mitigation – Wet Etching

- Used different wet etch chemistry to attempt to remove damaged layer from ICP
- Four diode designs fabricated and tested
  - Continuously grown p-n diode
  - ICP etch only and regrown p-GaN
  - ICP etch + 10 min AZ400K (KOH based) + regrown p-GaN
  - ICP etch + 20 min 300MIF (TMAH based) + regrown p-GaN
- KOH-based developer reduced reverse leakage currents to near cont. grown

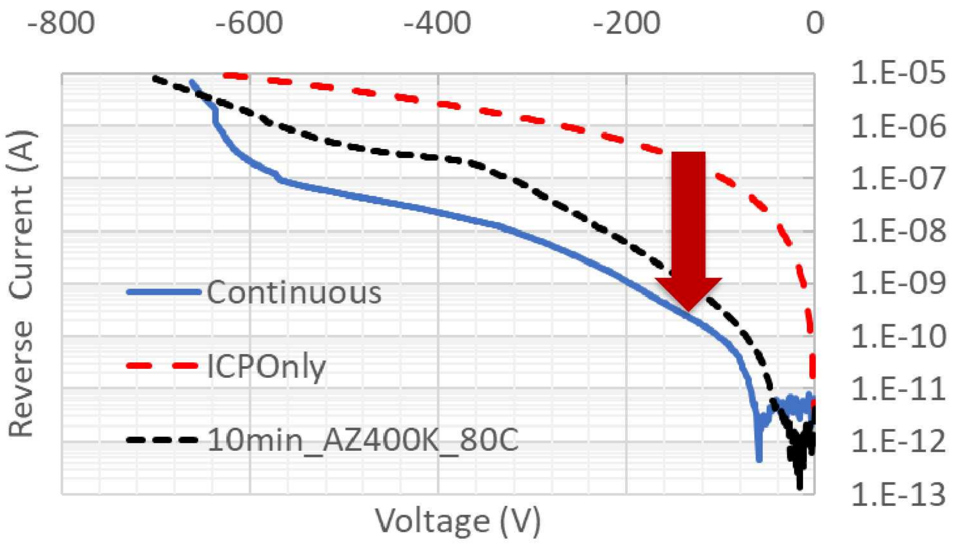
Reverse Bias

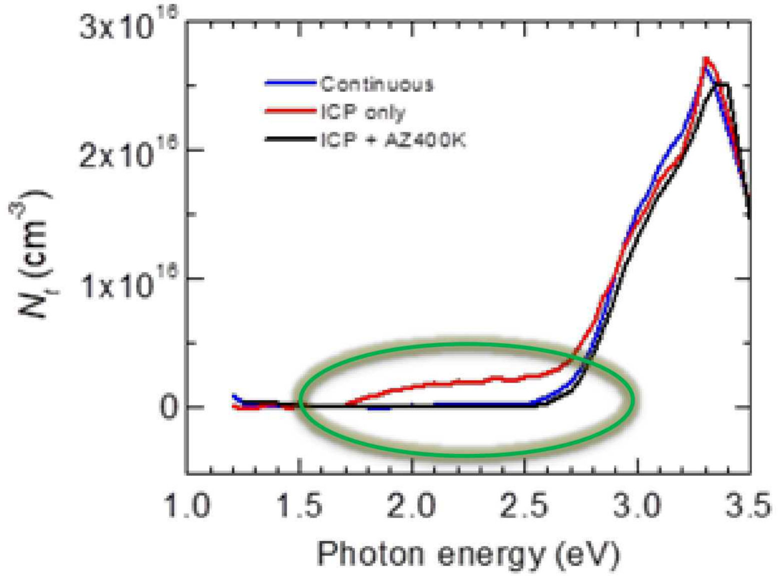


Forward Bias



Defect Mitigation – Wet Etching





- DLOS shows ~ 15x reduction in Ec-1.7eV trap density for (ICP etch + AZ400K + p-GaN regrowth) vs. (ICP etch + p-GaN regrowth).
  - Similar to continuously-grown.
- Correlated to reduction in reverse leakage current.
- Trap density near valence band is similar for all samples.

Energy (eV)	CONT N_t (cm^{-3})	ICP N_t (cm^{-3})	ICP+AZ N_t (cm^{-3})
1.7	4.9e14	2.5e15	1.7e14
3.00	1.9e16	1.7e16	1.9e16
3.30	3.3e15	7.5e15	5.9e15

Summary

- MOCVD System is ***not the primary source*** of the "Si spike" (for our hardware)

- MOCVD regrown, c-plane and m-plane p-n junctions studied
  - **c-plane regrown diodes - same performance as continuously grown**
  - **c-plane electrical performance not degraded by**
    - **[Si] ≤ 3E12 cm^{-2} or the regrowth process itself**

- **Dry etch before regrowth degrades performance significantly in c-plane**
  - DLOS identified new defect at E_c-1.7 eV (possible mid-gap tunneling state)
  - Wet etch treatments can reduce defect density by > 15 x
  - Higher Si contamination levels seen in processed interfaces

Funded by the Advanced Research Projects Agency – Energy (ARPA-E), U.S. Department of Energy under the PNDIODES program directed by Dr. Isik Kizilyalli.

Outline

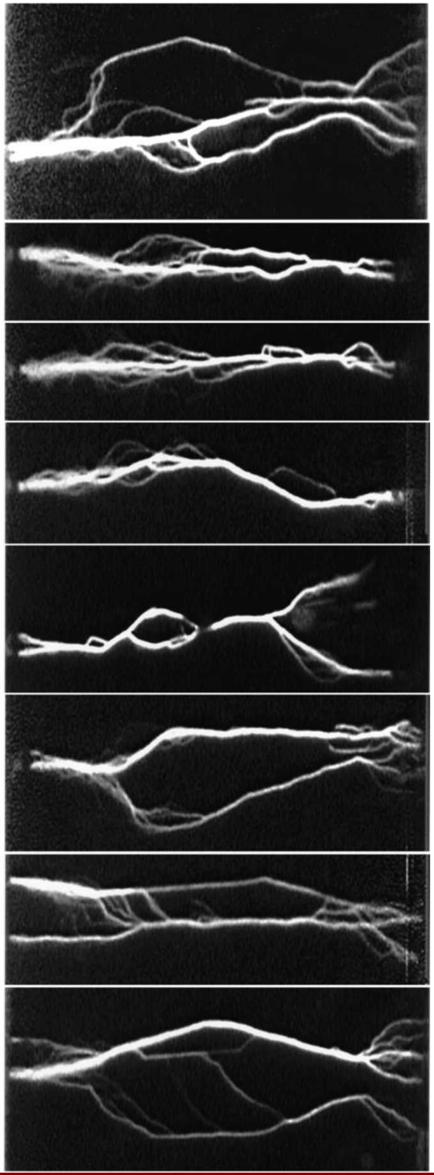
- Motivation for GaN in power electronics
- Regrown p-n diodes: selective area doping control for vertical GaN devices
- GaN photoconductive semiconductor switches (PCSS) technology demonstration and characterization

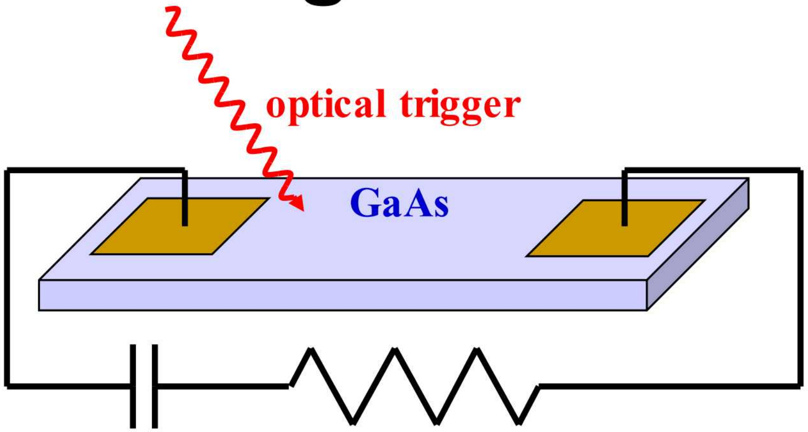
Grid Level Power Converter Devices

	Current Technology		State of the Art	GaN PCSS
Technology	Si Insulated Gate Bipolar Transistor	Si Light Triggered Thyristor	SiC Thyristor	Optical GaN PCSS
Voltage Rating	6.5 kV	10 kV	15 kV	100 kV
Switching Time	400 μs	100s of μs	10s of μs	0.01 μs
Switching Frequency	60 Hz	60 Hz	1 kHz	>10 kHz
Switching Loss (J/switch)	10	100	5	2

- Substantial advantages in switching frequency and voltage rating for GaN PCSS.
- Enables revolutionary HV power converters operating at high frequencies
  - Advanced capabilities for power converters including fault protection/mitigation
  - Fast charging stations for transportation
  - Increased electrification through new builds of high-efficiency, power systems

High Gain Switching in GaAs PCSS

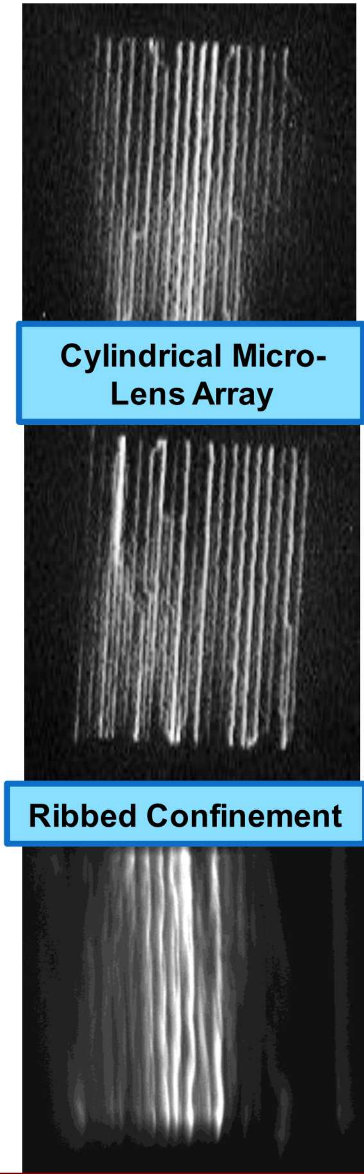




- Avalanche generation of laser-induced carriers in GaAs forms plasma filaments that close the switch
- Conduction filament persists after laser light is removed (as long as field is maintained)
- GaN has potential for higher performance switch
- ***Does GaN work in "High Gain" mode?***

*1) **Low Energy Triggering***
Avalanche carrier generation produces up to 100,000 e/h per photon depending on the circuit

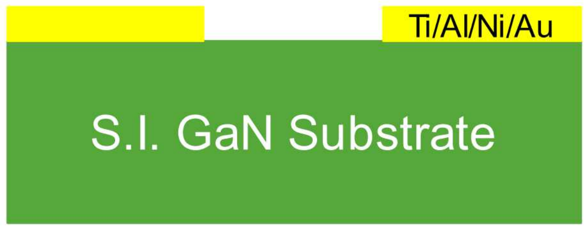
*(2) **Current Forms in Filaments***
20 A /filament ➔ 100,000,000 shot lifetime
2 kA /filament ➔ 1 shot lifetime



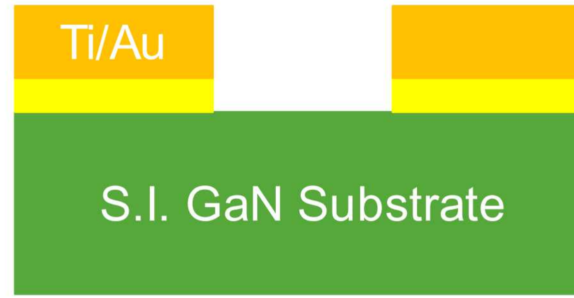
GaN PCSS Device Fabrication - Process Flow

Ammono Semi-Insulating GaN
Ammonothermal growth

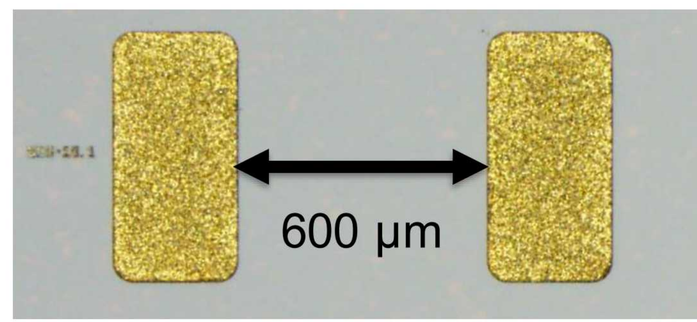
1) Contact Metal Deposition
   1) Ti/Al/Ni/Au by liftoff
   2) RTA 800 C, 30 sec



2) Bondpad Metal Deposition
   1) Ti/Au by liftoff

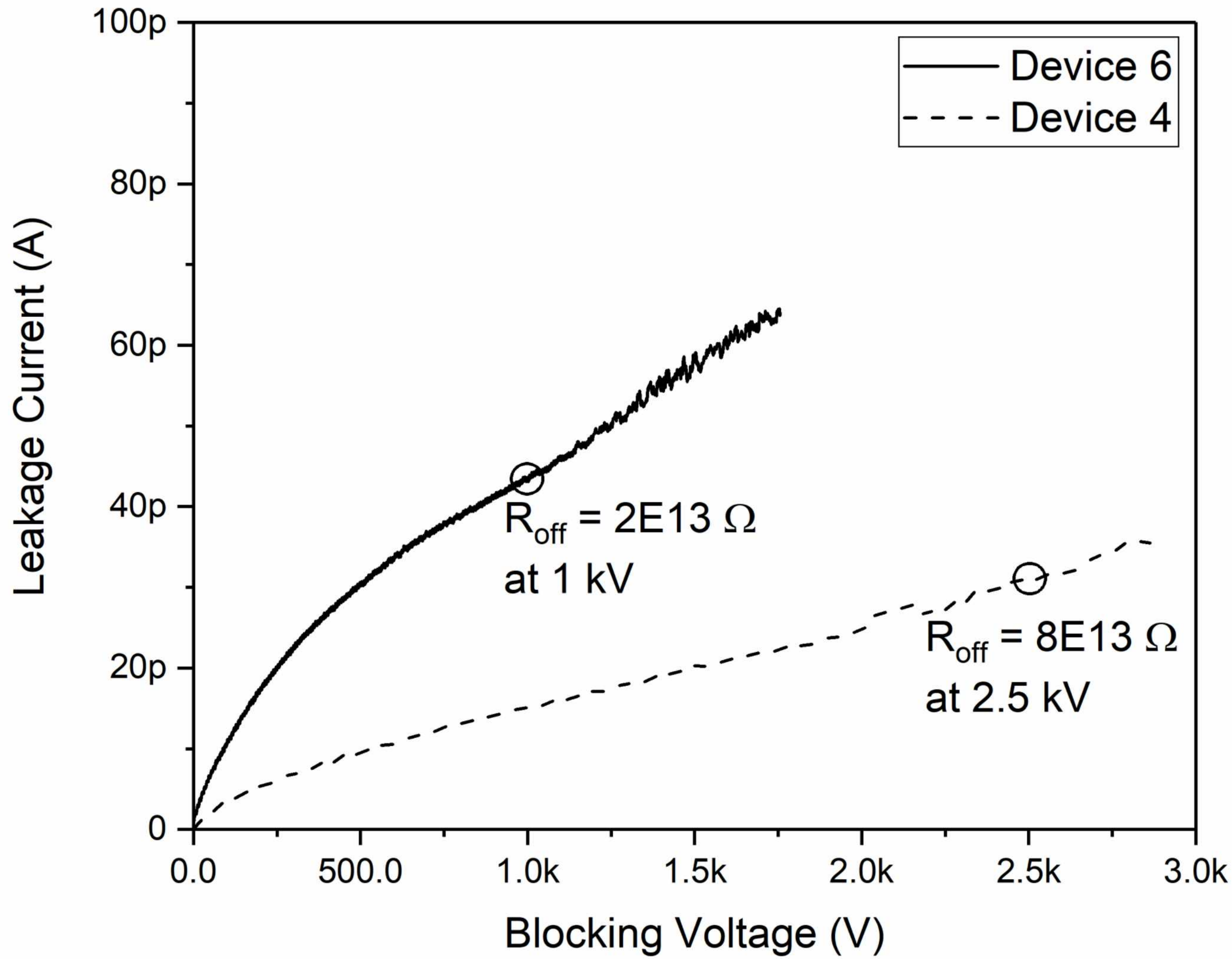


3) Test and Singulate
   1) Wafer level testing
   2) Singulate die (dicing saw)
   3) Wire-bond into circuit for die-level testing



Simple structure used to explore operation of PCSS.
Not optimized for long shot life.

GaN Material Properties – Leakage Current

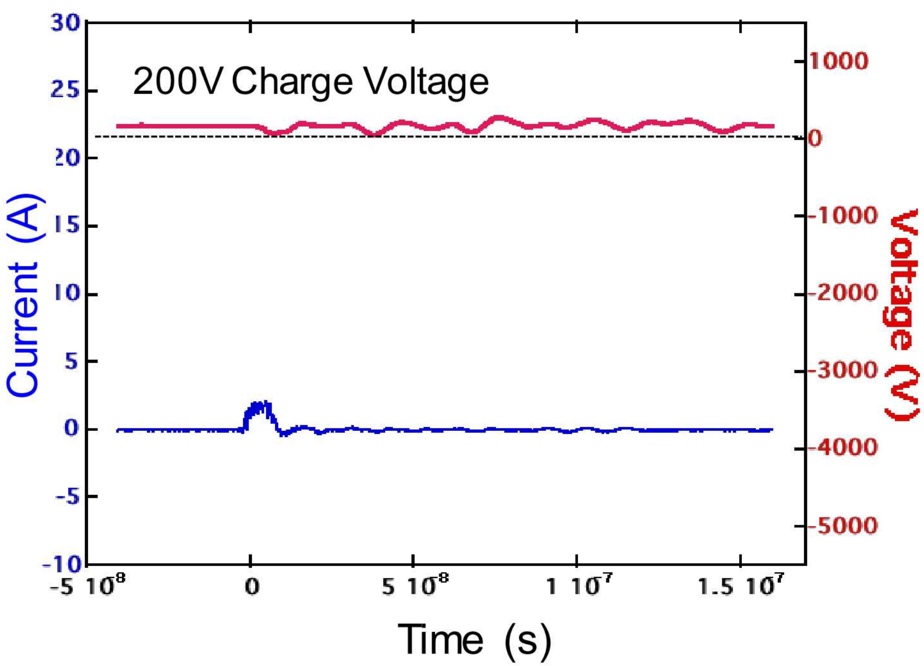


- 600 µm gap devices were tested for their “dark” leakage current
- Some variation between devices

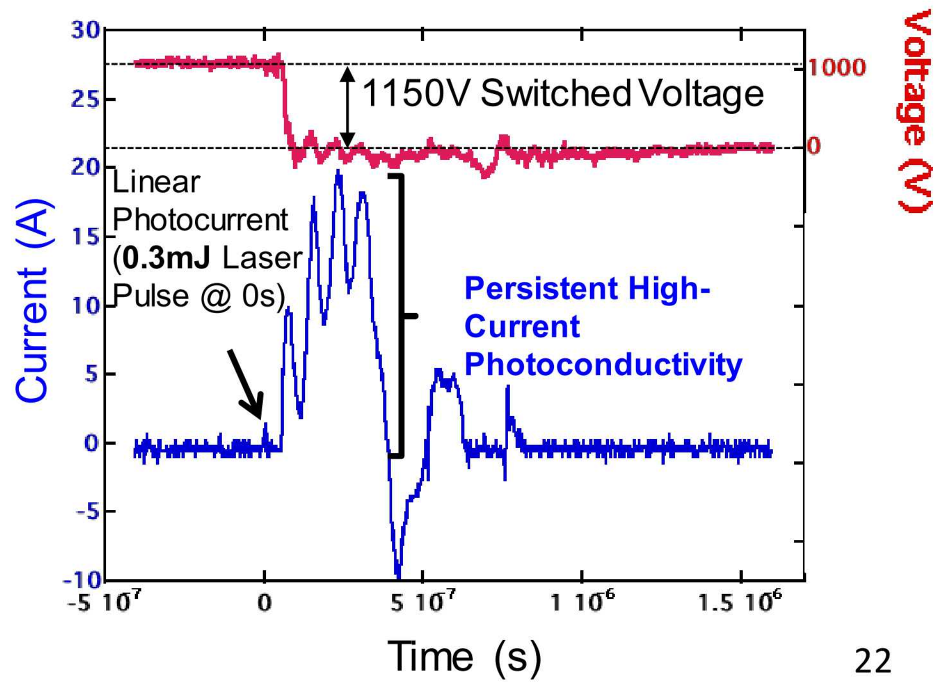
Characterization of Operating Modes

- Frequency doubled Nd:YAG (532 nm) laser (sub-bandgap) for optical trigger
  - Sub-bandgap trigger: deeper absorption, future systems with compact, commercially available source
- Linear photocurrent below 10-15 kV/cm field across device switching powers ≤ 7 kW
- Non-linear "high gain" photocurrent above 10 – 15 kV/cm field across device, with trigger energy as low as 35 uJ switching powers up to 150 kW (> 120 A)
- Under-damped circuit makes PCSS testing difficult

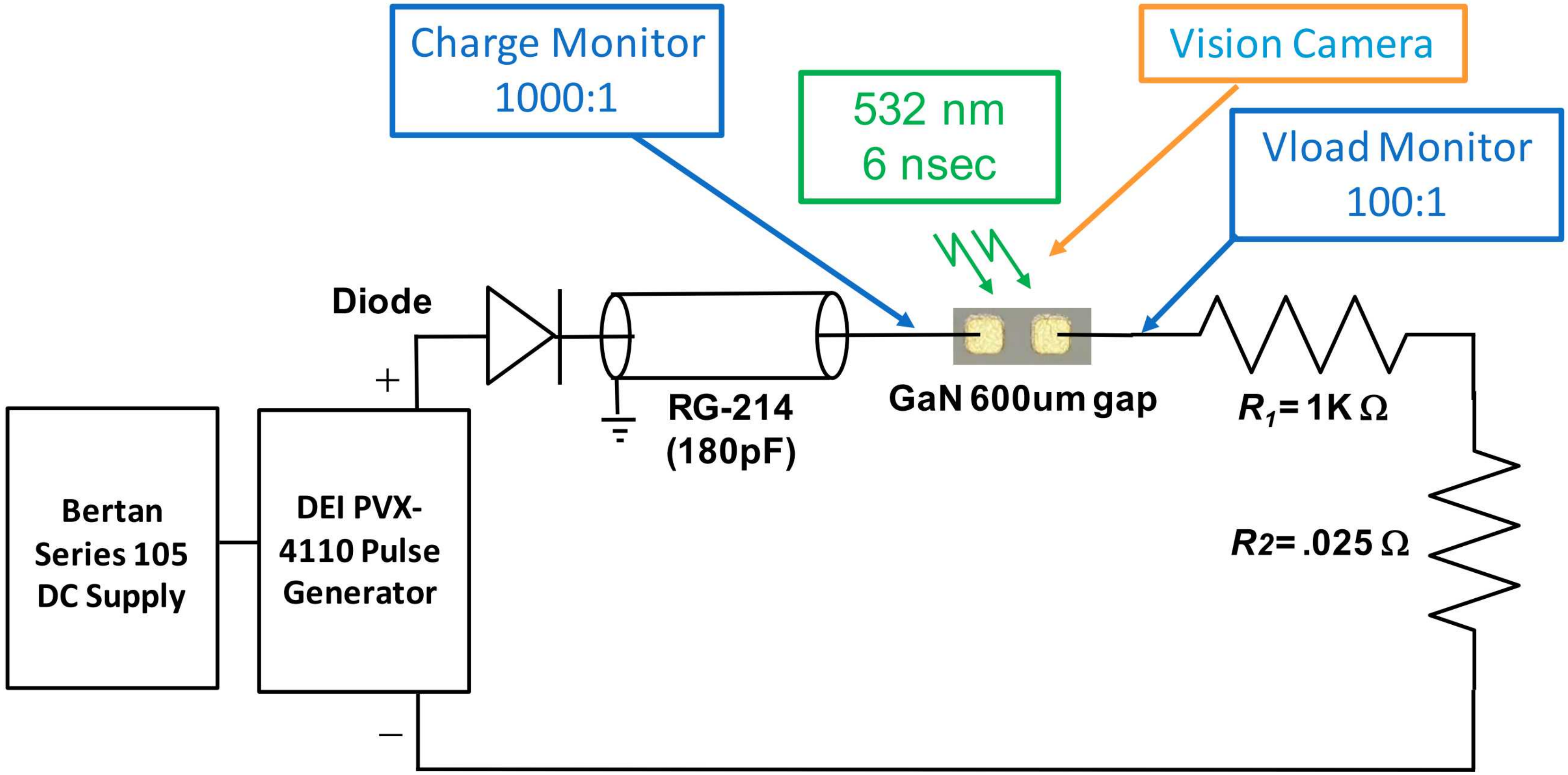
Linear Photocurrent



Non-linear Photocurrent

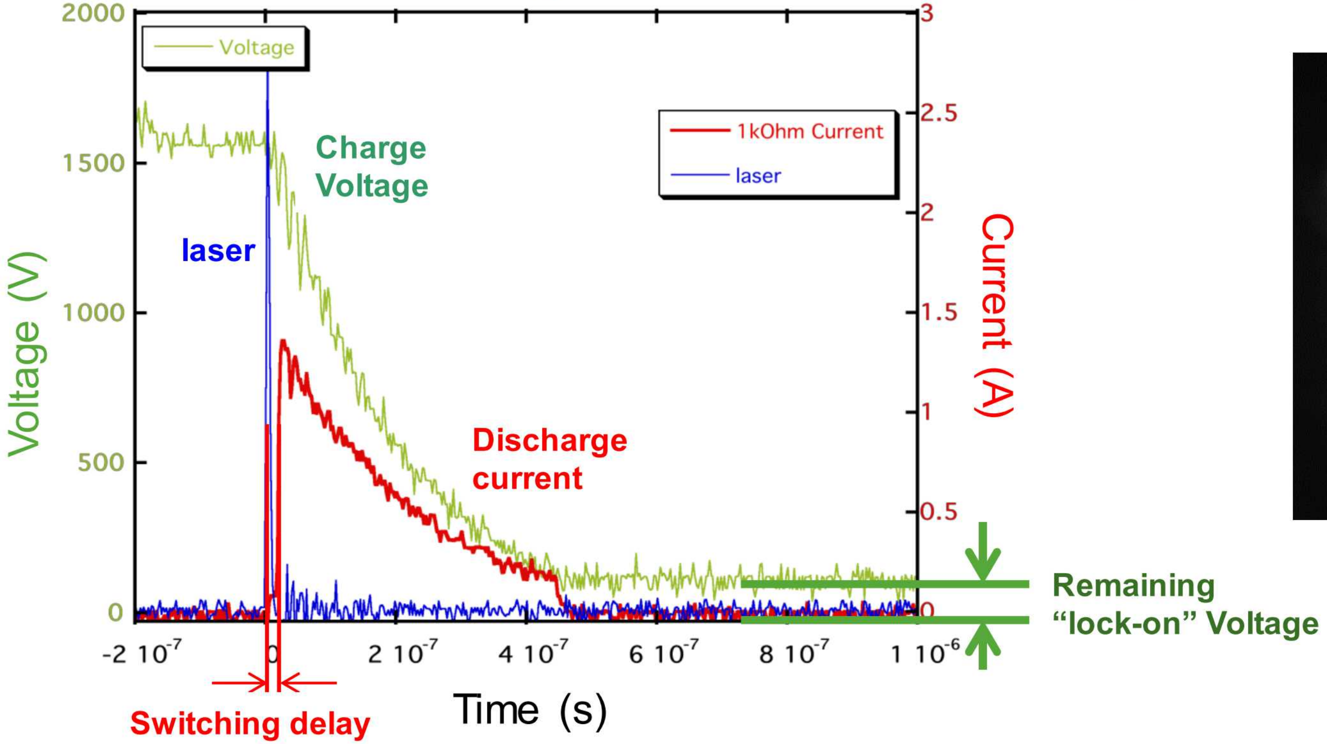


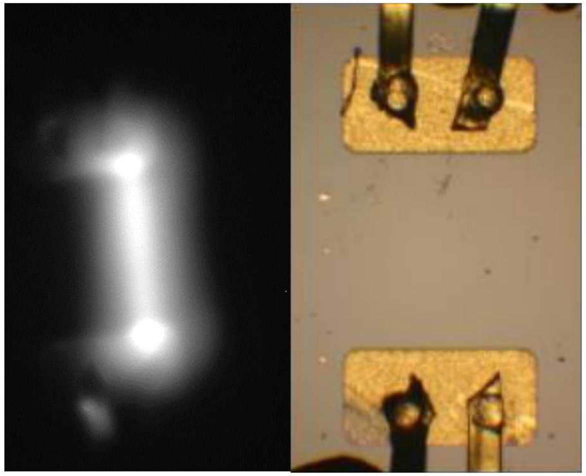
GaN PCSS Switching Testing Configuration



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

GaN PCSS High-Gain Switching Characteristics



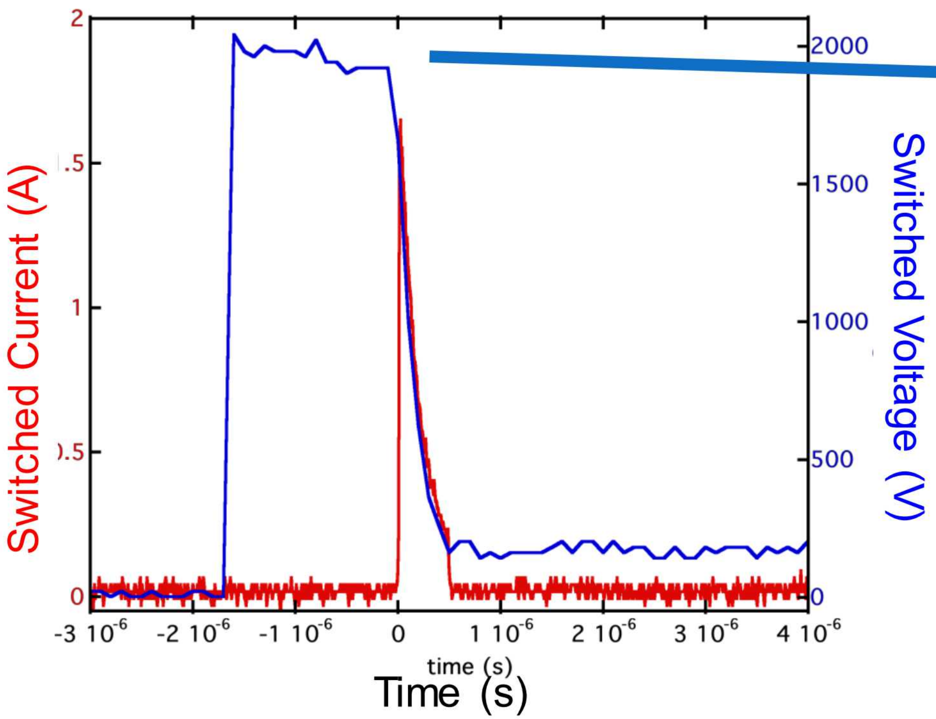


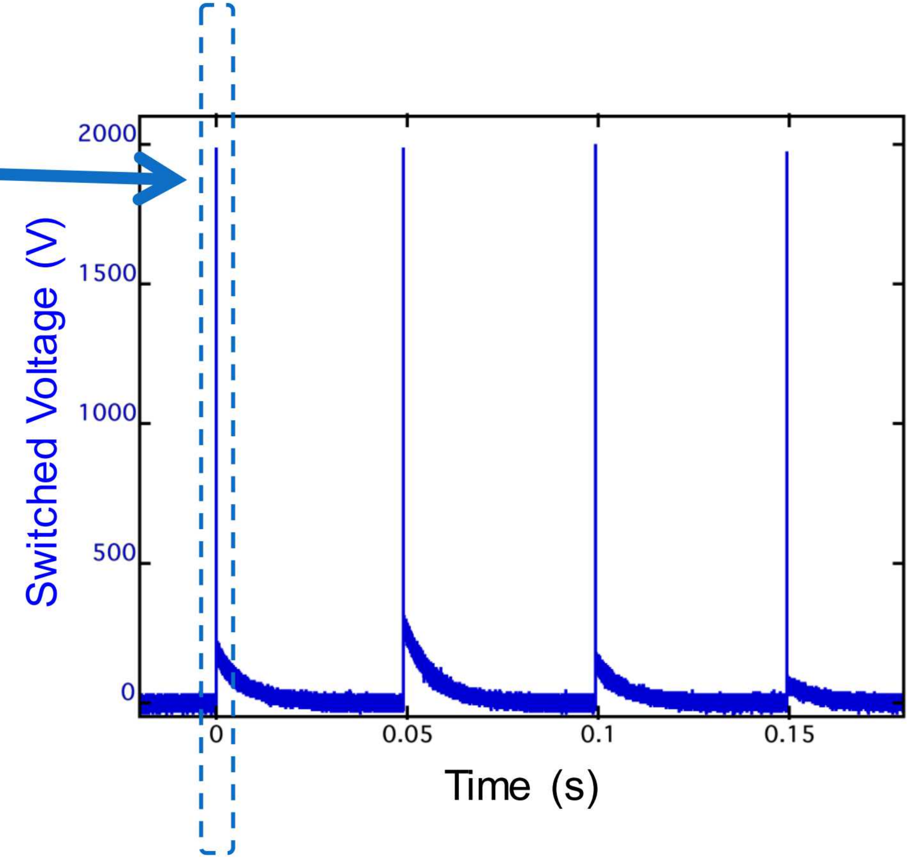
Filamentary Conduction
35 uJ trigger at 532 nm

- Small laser energy (~30µJ, 6ns, gap overfilled) triggers PCSS into "on" state, well below breakdown field
- Highly repeatable on state persists well after laser pulse duration (characteristic of high gain mechanism)
- On state maintained as long as minimum critical ("lock-on") field of ~3kV/cm maintained (200V/0.06 cm)
- Filaments evident in images during high-gain switching, non-damaging to GaN (at limited currents)

GaN High-Gain Switching at 20Hz Repetition Rate

Sandia National Laboratories





- Demonstration of applicability to power conversion circuit
- Limited by repetition rate of Q-switched laser system
- Switched current (power) limited by circuit

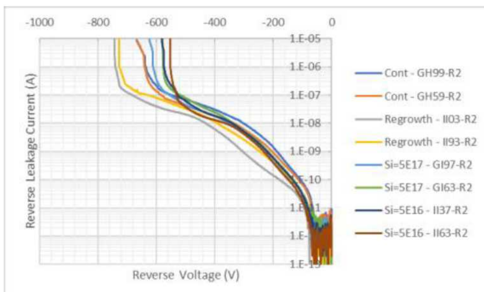
GaN PCSS High-Gain Switching Summary

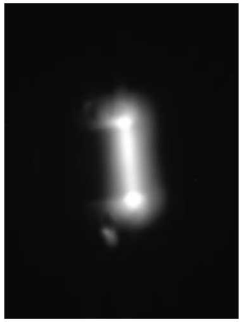
- **Persistent conductivity after laser initiation is removed**
  - Conduction continues until sustaining voltage/charge source is depleted
  - Conduction occurs at lower fields compared to measured breakdown limit
- **Small trigger laser energy requirement, sub-bandgap (532nm)**
  - ~30uJ using a 3mm 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**

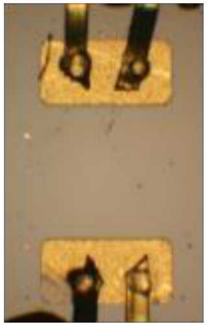
Funded by the Advanced Research Projects Agency – Energy (ARPA-E), U.S. Department of Energy under the IDEAS program directed by Dr. Isik Kizilyalli.

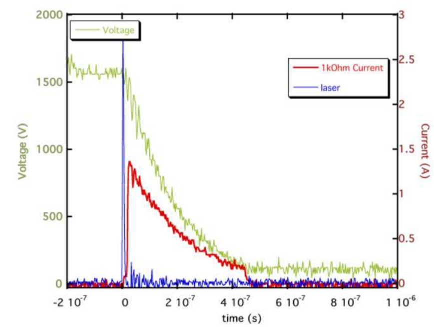
Exceptional service in the national interest

Sandia National Laboratories









Advanced GaN Device Technologies for Power Electronics

G.W. Pickrell, A. M. Armstrong, A. A. Allerman, M. H. Crawford, D. Feezell, M. Monavarian, A. Aragon, F.J. Zutavern, A. Mar, E. Schrock, J.D. Flicker, J. J. Delhotal, J.D. Teague, J.M. Lehr, K.C. Cross, C.E. Glaser, M.S. Van Heukelom, R.J. Gallegos, V.H. Bigman, and R.J. Kaplar

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.