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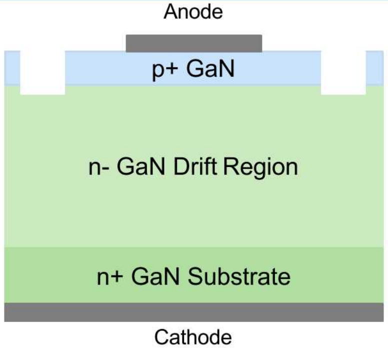

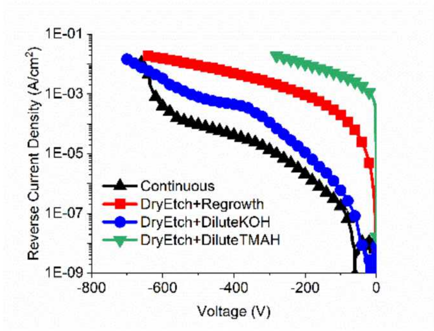

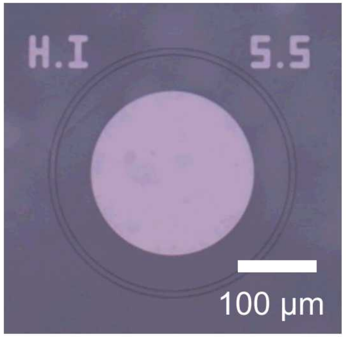

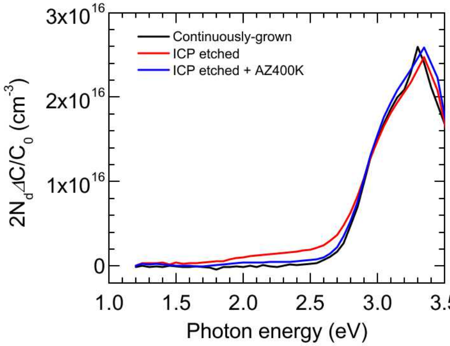

Defect Investigation of Regrown, Vertical GaN P-N Diodes Using Deep-Level Optical Spectroscopy

G.W. Pickrell, A.M. Armstrong, A.A. Allerman, M.H. Crawford, D. Feezell, M. Monavarian, A.A. Aragon, A.A. Talin, F. Leonard, K.C. Celio, C.E. Glaser, J. Kempisty, and V.M. Abate

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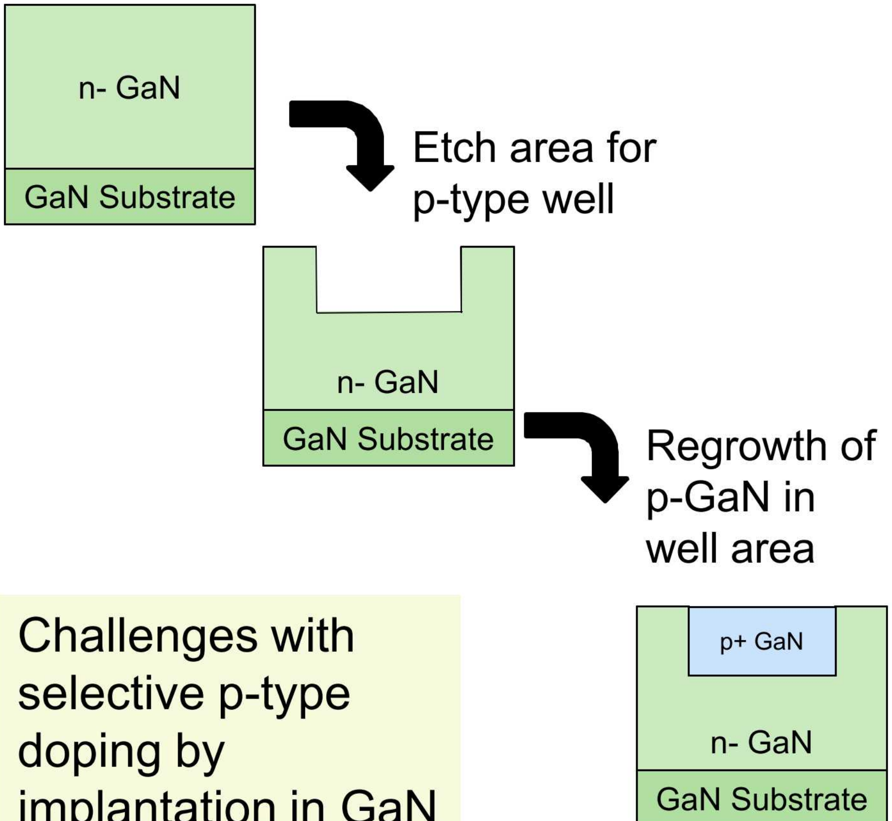
Outline

- Motivation for Epitaxial Regrowth in Power Electronics
- Experimental Details
- Etched and Regrown GaN P-N Diode Performance
  - IV Curves
  - DLOS technique and characterization data
- Summary

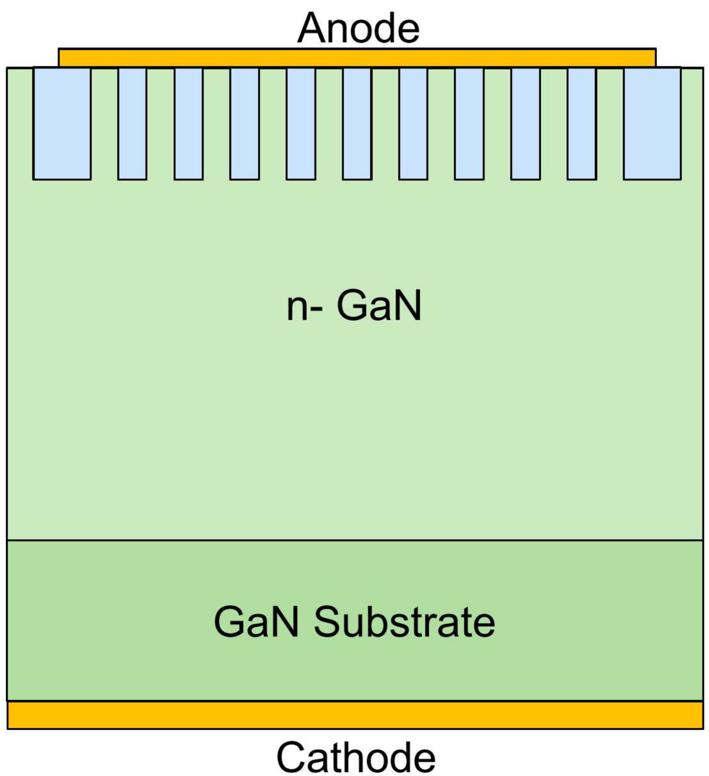
Funded by the Advanced Research Projects Agency – Energy (ARPA-E), U.S. Department of Energy under the PNDIODES program directed by Dr. Isik Kizilyalli.

Epitaxial Regrowth Enables Selective-Area Doping Control (Vertical GaN Transistors)



Challenges with selective p-type doping by implantation in GaN

Junction Barrier Schottky (JBS) Diode



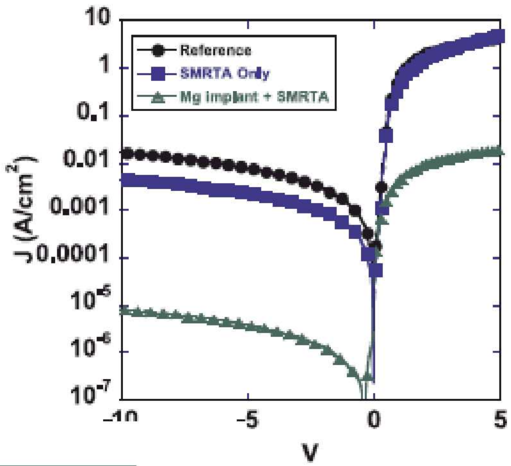
- High-quality processing and epitaxial regrowth enable selective area doping control
- JFETs, Junction Barrier Schottky (JBS) diodes, and vertical GaN transistors could be realized
- Potential to have higher performance than SiC devices (Vbr and current capacity)

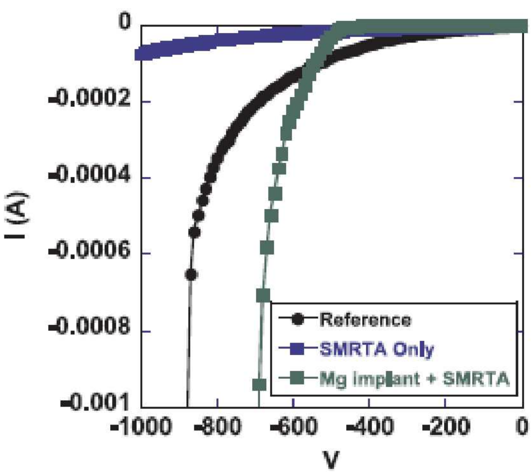
Selective-Area P-Type Doping – Previous Work

CHANGING WHAT'S POSSIBLE

Mg Implant and Symmetric Multicycle RTA (SMRTA)

Schottky barrier diode and Mg-implanted diode IV curves (rectifying behavior)



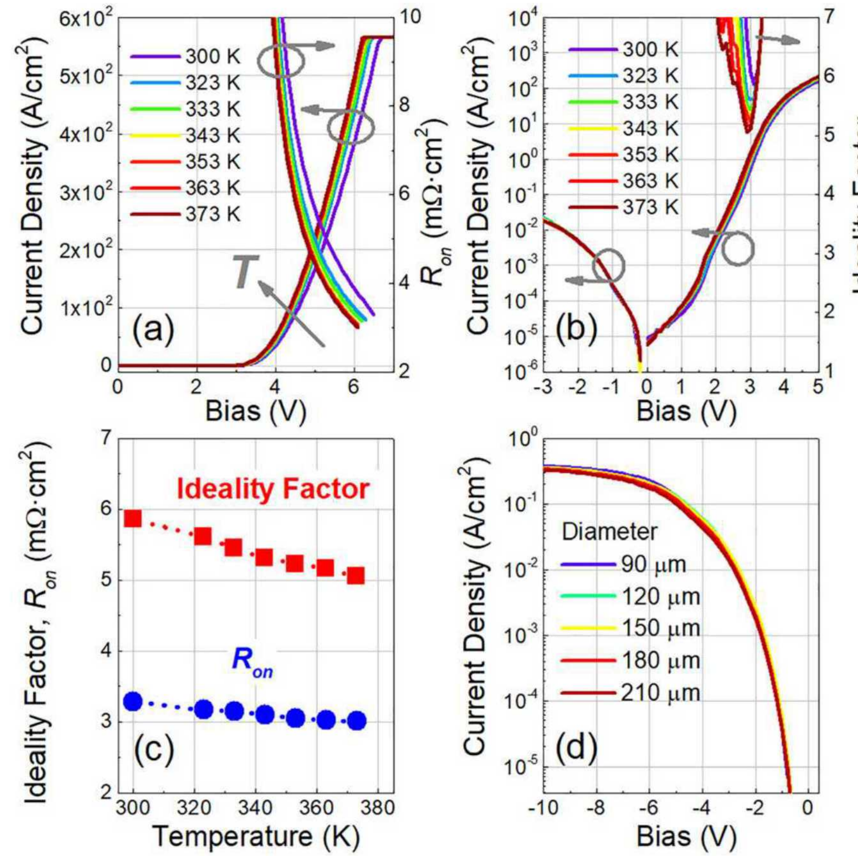


Schottky diode and Mg-implanted diode reverse IV curves

T.J. Anderson, J.C. Gallagher, L.E. Luna, A.D. Koehler, A.G. Jacobs, J. Xie, E. Beam, K.D. Hobart, and B.N. Feigelson., *J. Cryst. Growth*, 499, 35-39, 2018.

Regrowth by MOCVD

Planar, c-plane regrown GaN PN Diodes

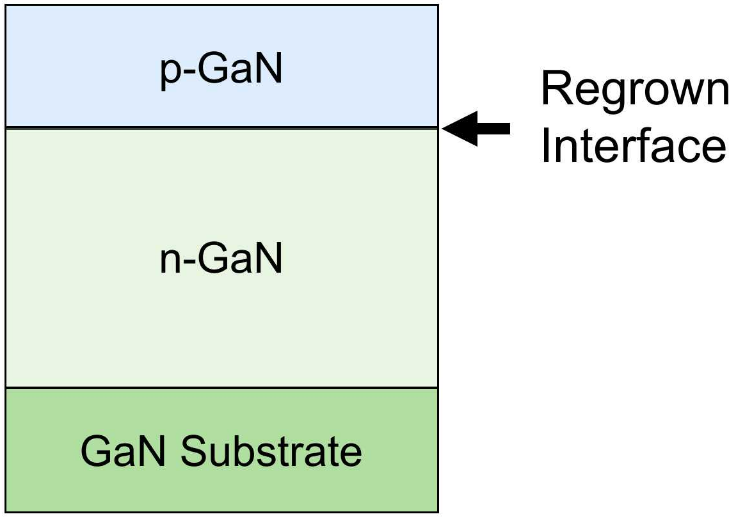


K. Fu, H. Fu, H. Liu, S.R. Alugubelli, T.H. Yang, X. Huang, H. Chen, I. Baranowski, J. Montes, F. Ponce, and Y. Zhao, *Appl. Phys. Lett.*, 113, 233502, 2018.

GaN P-N Diodes Under Study

Planar P-N Diodes (c-plane):

1. Continuously Grown
2. Dry Etch + Regrowth
3. Dry Etch + Chemical Treatment + Regrowth



- Quick-Turn Diode Fabrication
- Current-Voltage Characterization
- Deep Level Optical Spectroscopy (DLOS) Characterization on Specifically Designed Structures

- Epitaxial growth by MOCVD
  - 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
- Dry etch process: Low damage ICP etch: Cl_2+BCl_3+Ar, 10 W RF power

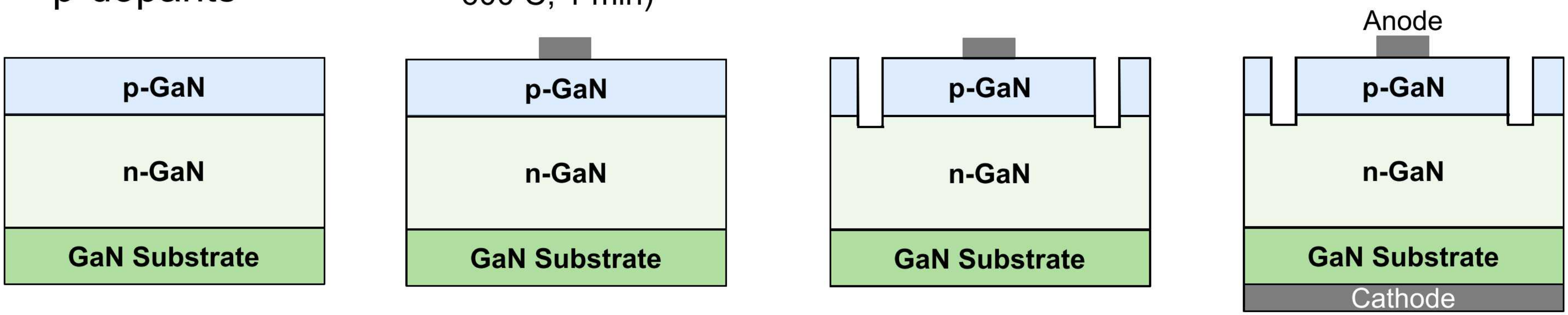
Quick-Turn Fabrication Process

1) Activate p-dopants

2) p-Metals (Pd/Au, RTA 600 C, 1 min)

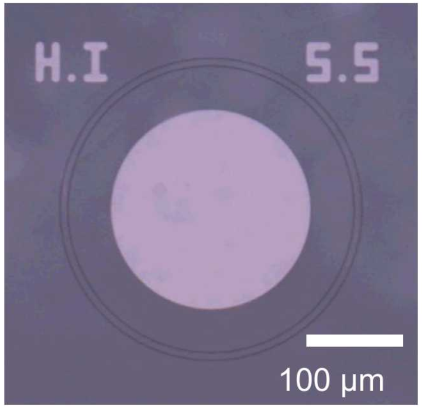
3) Isolation

4) n- Metals

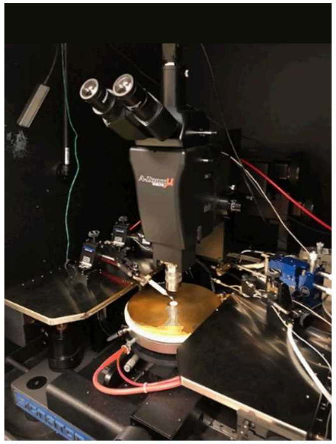


- Simple device structure for rapid-feedback
- No field-management structures to increase reverse breakdown voltages
- Wafer-level current-voltage characterization using HV wafer-probing setup

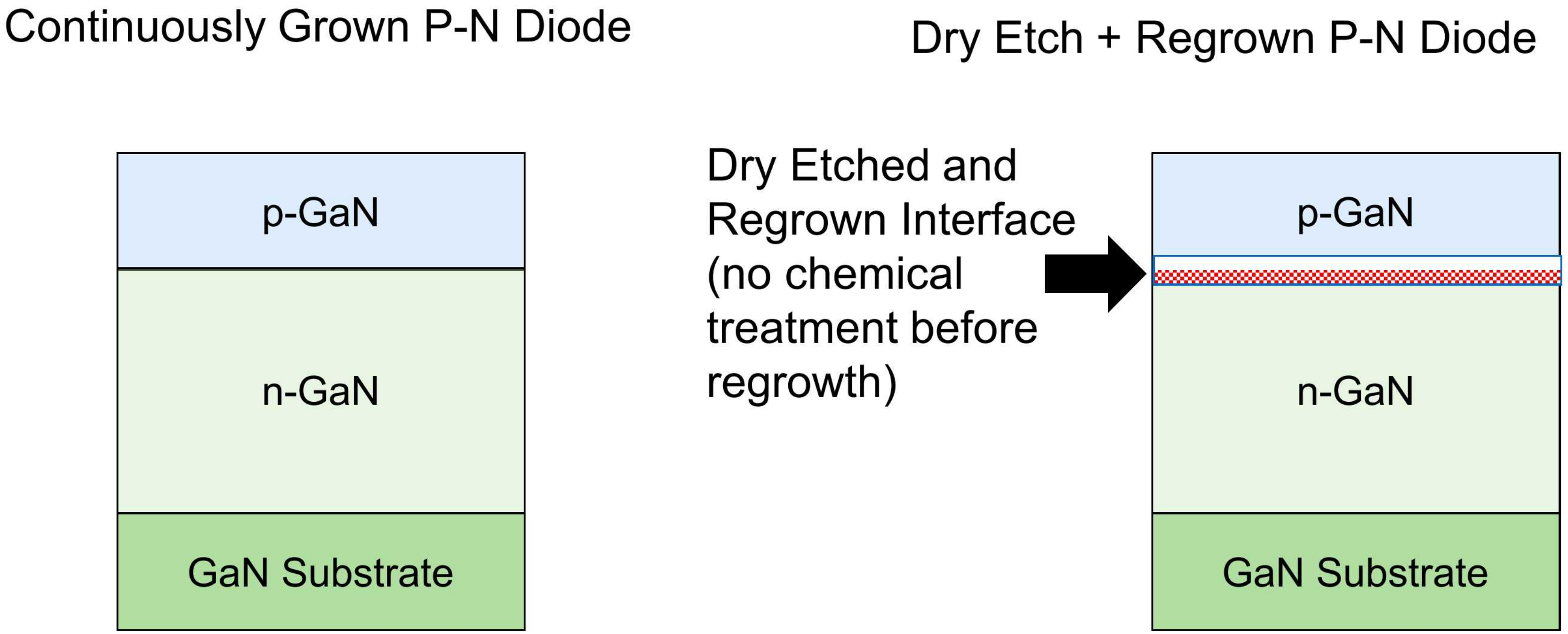
Top View Optical Microscope Image



HV Wafer Prober – Forward and Reverse Current/Voltage Characterization



Continuous vs. Dry Etch + Regrowth

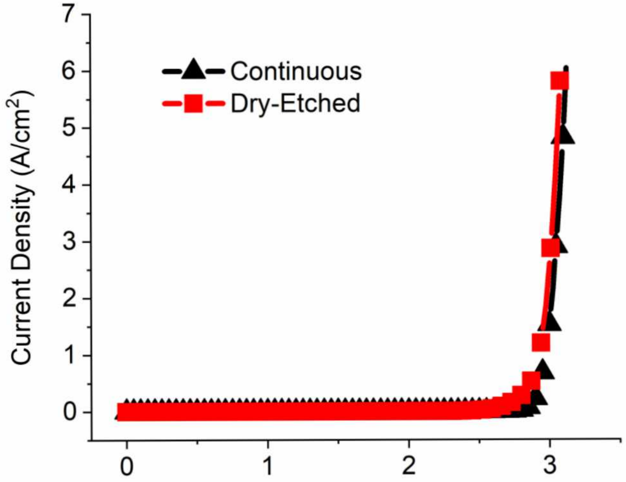


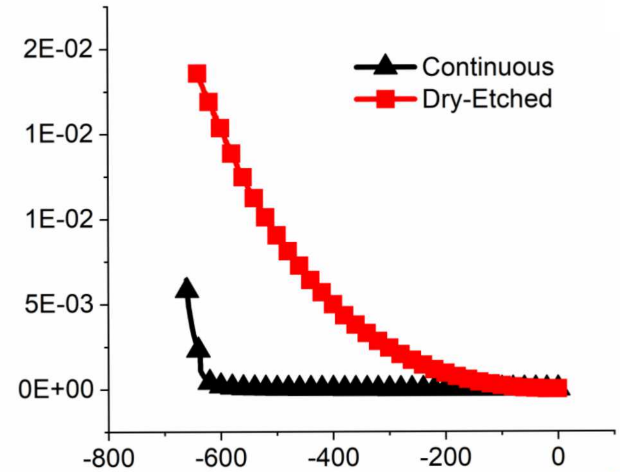
- Worst case scenario to understand effect of dry-etch induced defects in regrown diodes
- Previous study demonstrated no effect on IV behavior for regrown diodes with no dry-etch process (p-GaN regrown on n-GaN)

G.W. Pickrell et al., *J. Elec. Mat.*, 48(3), 3311-3316, 2019.

I-V: Continuous vs. Dry Etch + Regrowth

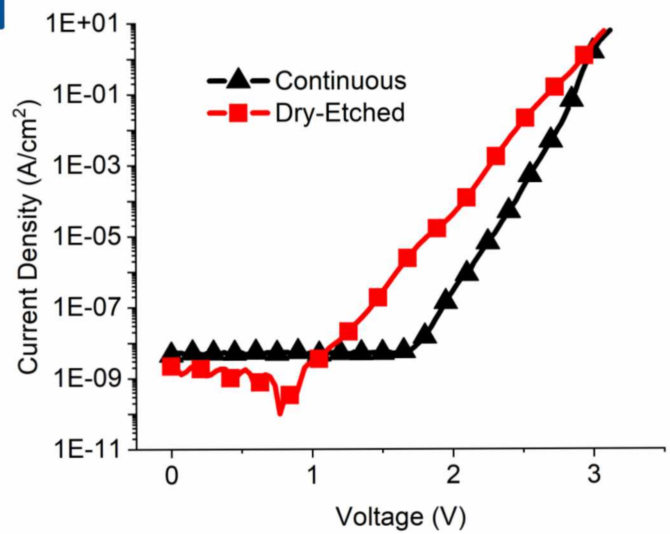
Linear

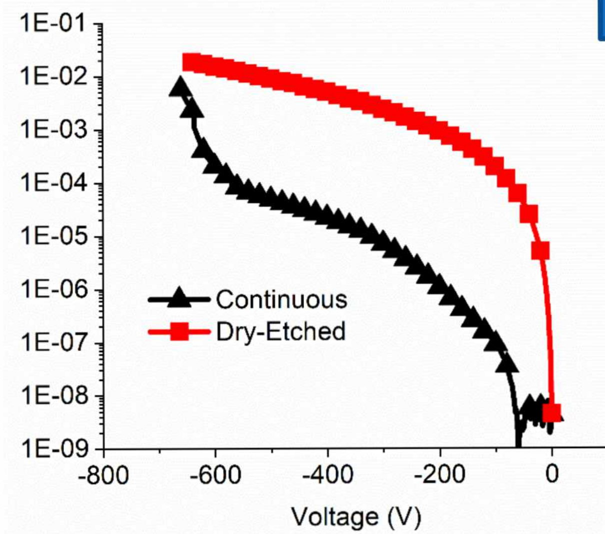




Linear

Semi-Log



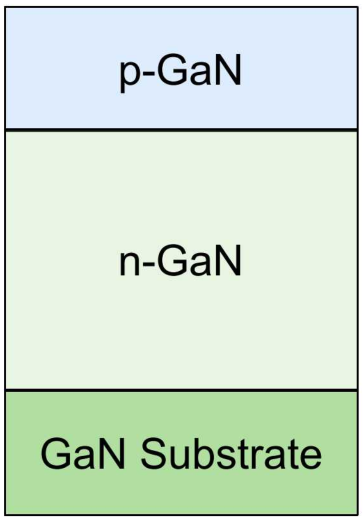


Semi-Log

Dry etch process gives higher forward and reverse leakage currents

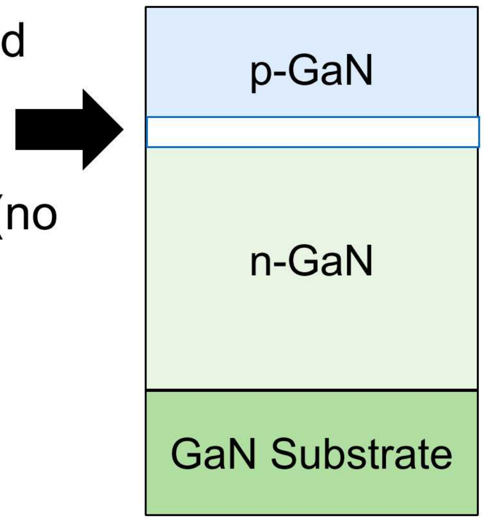
GaN P-N Diodes Under Study

Continuously Grown P-N Diode



Dry Etch + Regrown P-N Diode

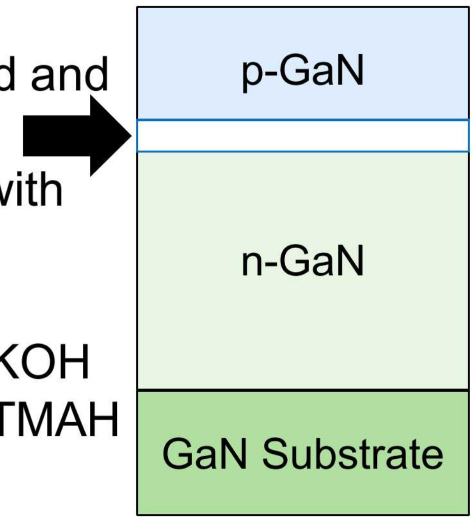
Dry Etched and Regrown Interface (no chemical treatment before regrowth)



Dry Etch + Treatment + Regrown P-N Diode

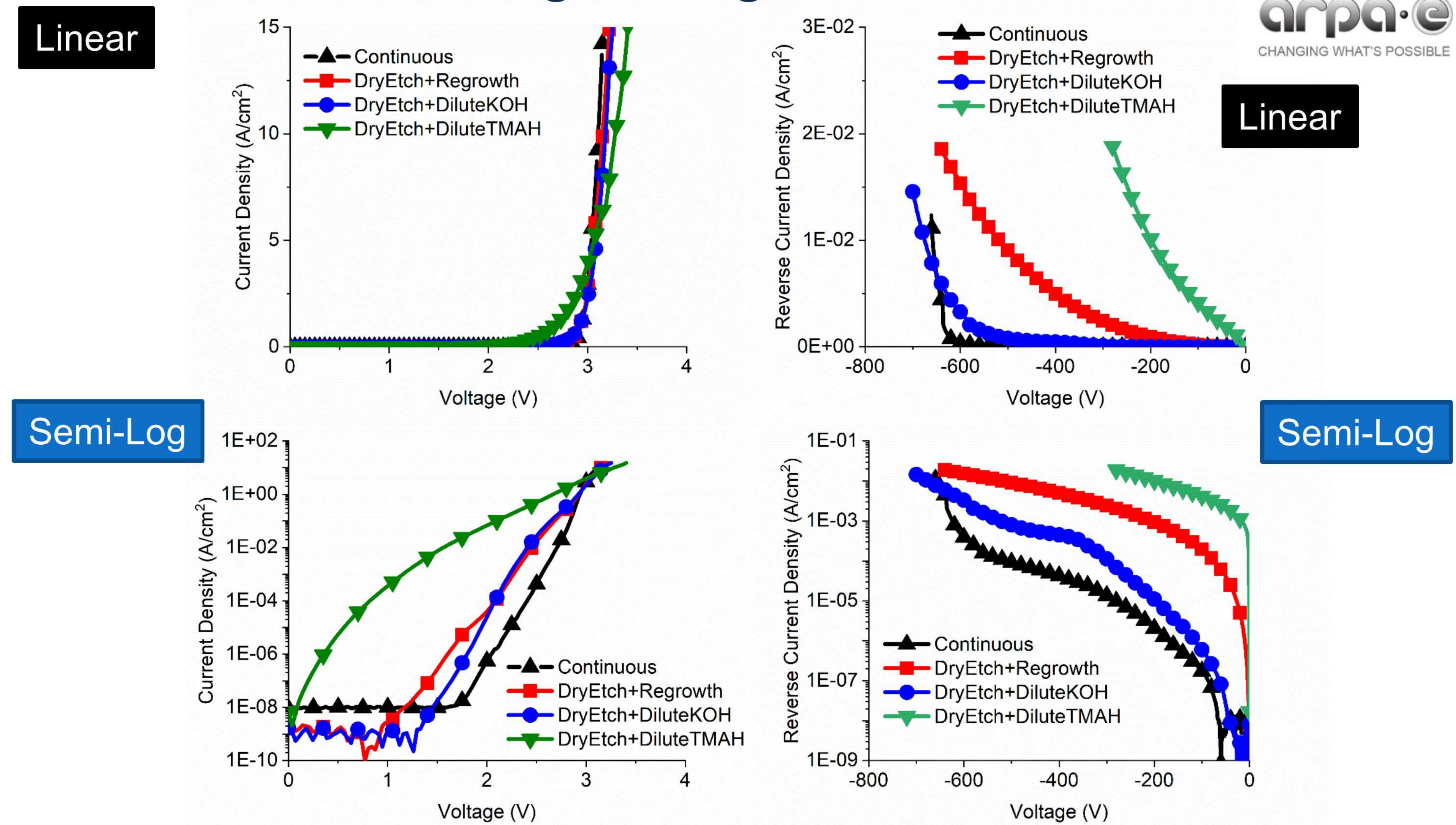
Dry Etched and Regrown Interface with chemical treatment

1) Dilute KOH
2) Dilute TMAH



- KOH-based AZ-400K developer – 2% KOH (by weight) in water
  - 80 ºC, 10 min, followed by DI water rinse and nitrogen dry
- TMAH-based AZ300MIF developer - <3% TMAH (by weight) in water
  - 80 ºC, 20 min, followed by DI water rinse and nitrogen dry
- Samples immediately loaded into MOCVD system for regrowth

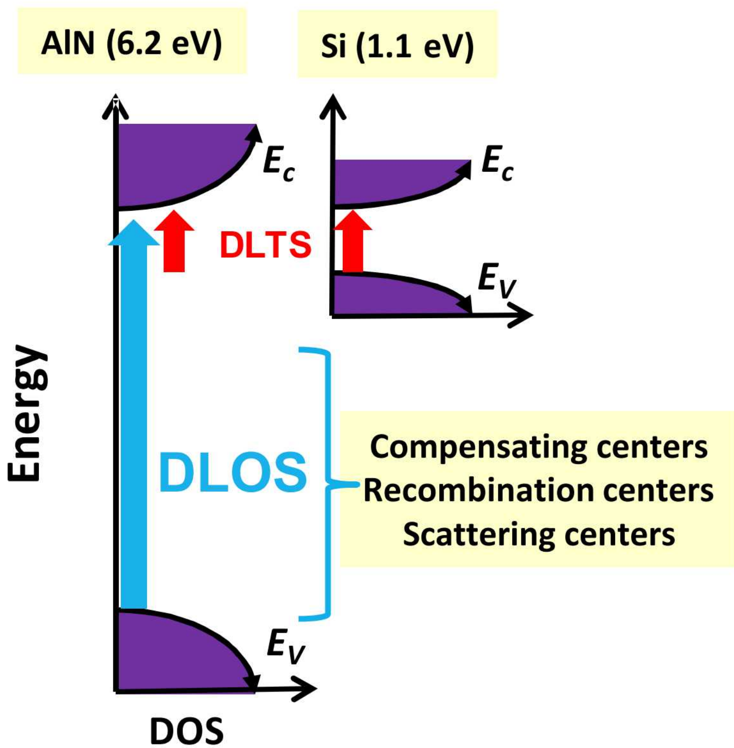
I-V: Etch Damage Mitigation



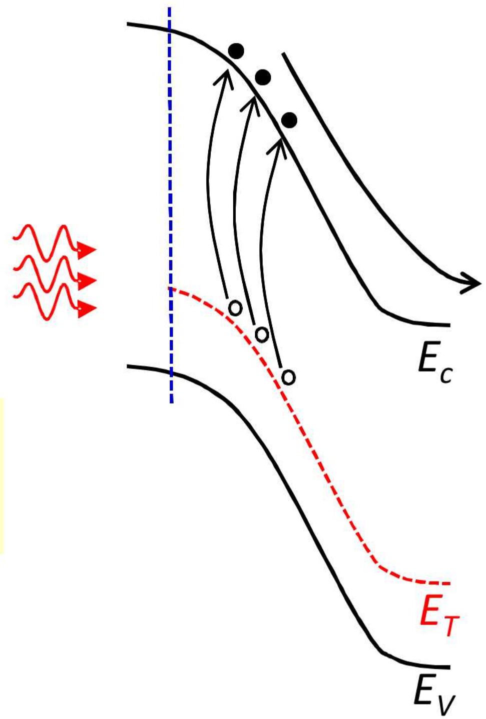
- **AZ400K treatment gives closest results to continuously-grown diodes**
- Significantly worse TMAH results are not well understood.

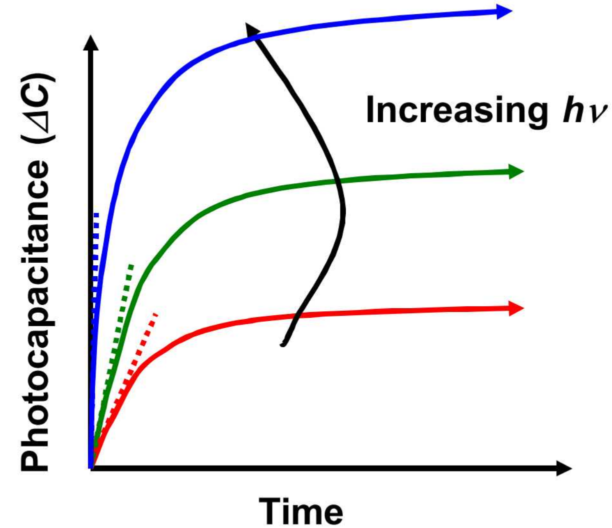
Deep Level Optical Spectroscopy (DLOS)

WBGs require DLOS



Photoemission from electron traps

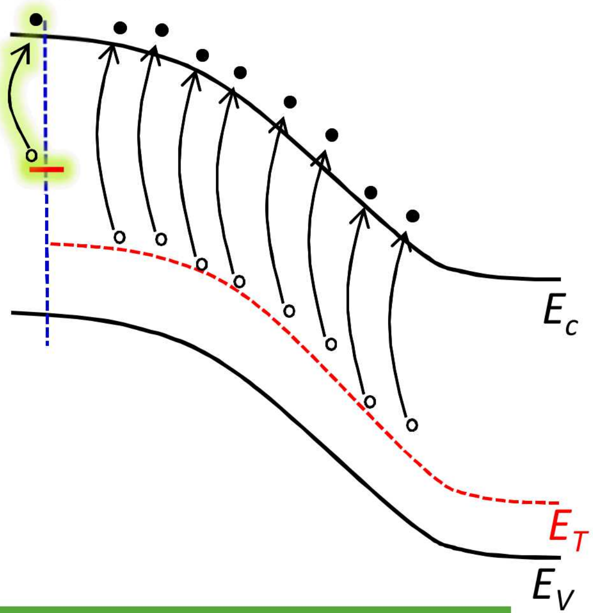




- DLOS required to probe mid-band gap and near-E_v defect levels in GaN
- Majority carrier photoemission from defect levels increases capacitance
- Magnitude of photocapacitance (ΔC) proportional to $N_t = 2N_d \Delta C/C_0$

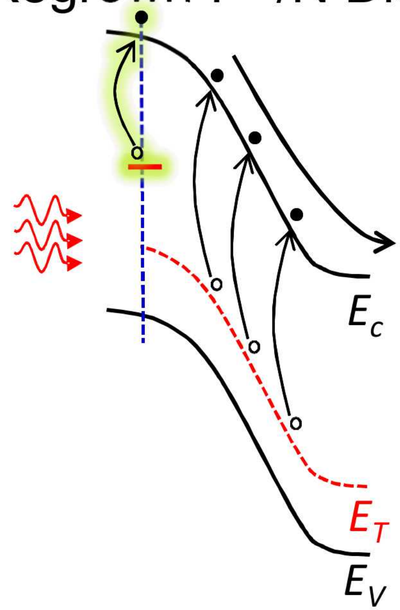
DLOS Consideration for PNDIODES

Regrown P+/n- diodes



Bulk defects overwhelm interface defects

Regrown P+/N Diodes



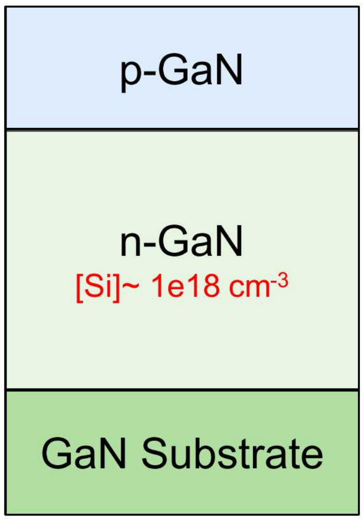
Increased sensitivity to interface defects relative to bulk defects

$$\Delta C_{int} = \frac{N_{t,int}}{2} \frac{C_0}{N_d} \frac{x_{int}^2}{x_d^2} \propto \frac{1}{N_d x_d^3} \propto \sqrt{N_d}$$

- DLOS sensitive to defects the lower-doped drift side of junction…but high doping required for near-junction sensitivity

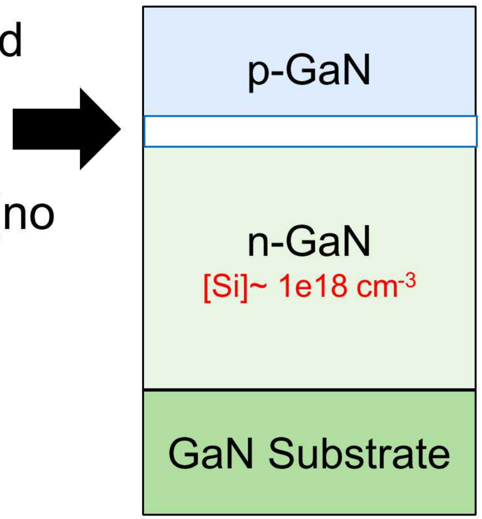
DLOS P-N Diode Structures

Continuously Grown P-N Diode



Dry Etch + Regrown P-N Diode

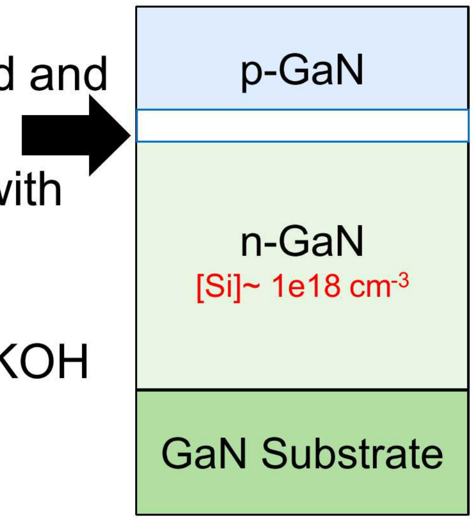
Dry Etched and Regrown Interface (no chemical treatment before regrowth)



Dry Etch + Treatment + Regrown P-N Diode

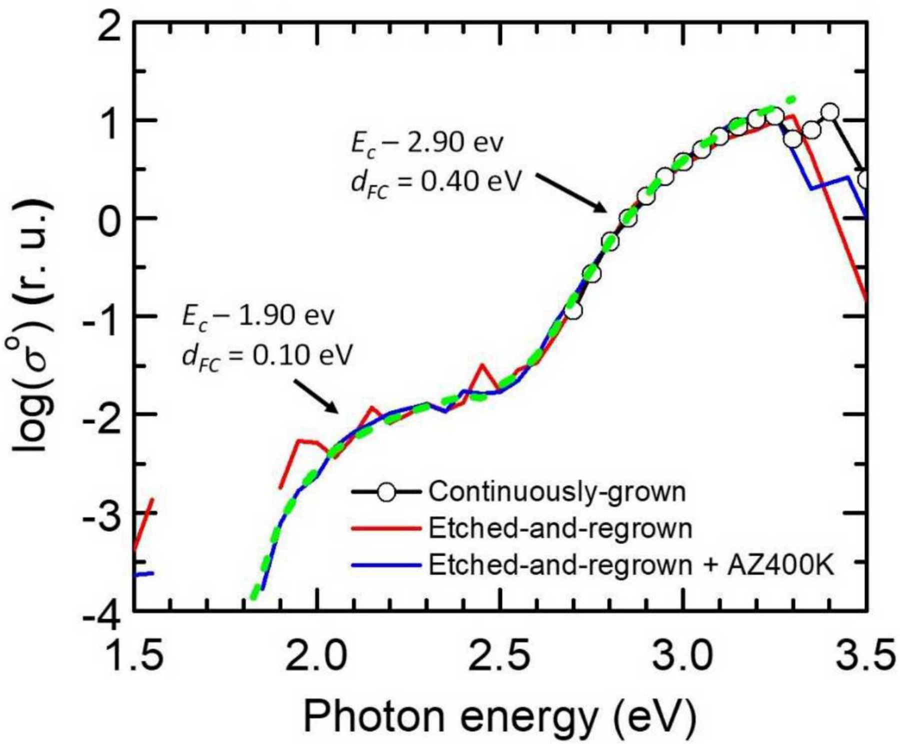
Dry Etched and Regrown Interface with chemical treatment

1) Dilute KOH



- Diodes for DLOS study grown using same growth conditions as other diodes
- Increased Si doping in n-GaN layer to ~ 1e18 cm^{-3} (from ~ 2e16 cm^{-3}) to improve DLOS sensitivity to localized defects near the P-N junction.
- Used KOH-based chemical treatment (AZ400K) for DLOS studies since it had I-V behavior closest to the continuously grown diodes.

DLOS Spectra Results



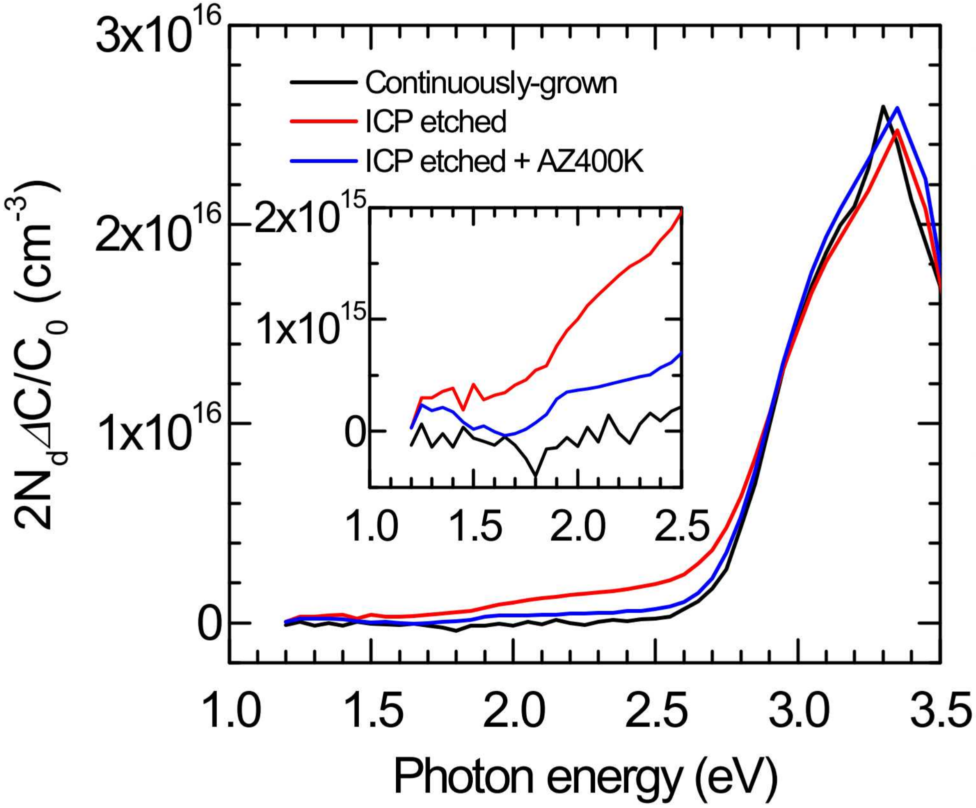
- Optical absorbance per unit defect (σ^0) vs. photon energy
- Single deep level absorption feature with E_C - 2.90 eV relative to E_c (conduction band)
- E_C - 2.90 eV in all three samples
- Spectral features for Photon energy > 3.2 eV obscured by heavy Mg doped layer

- Additional deep level absorption feature seen in both etched + regrowth samples with **E_C - 1.90 eV** relative to E_c (conduction band)
- ***Related to ICP etch damage***

Three samples characterized:

1. Continuously grown (black with circle)
2. Etched + regrown (red)
3. Etched + AZ400K treated + regrown (blue)
4. Model fitting to data (green)

Solid State Photo-Capacitance (SSPC) Results

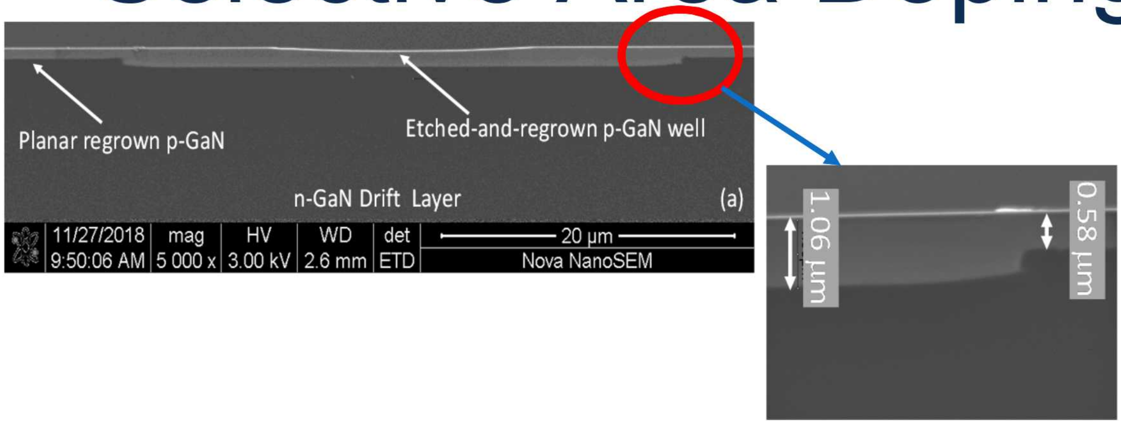


- All structures have similar N_t for E_c - 3.20 eV and E_c - 2.90 eV levels
- E_c - 1.90 eV trap level is increased for Etch + Regrown samples.
  - AZ400K treatment reduced trap density by 3-4X

- N_t likely *severely underestimated* with this technique
  - Averages value over entire depletion region
  - If defects within 5 nm of surface in 150 nm depletion (CV data), **N_t underestimated by ~900X**

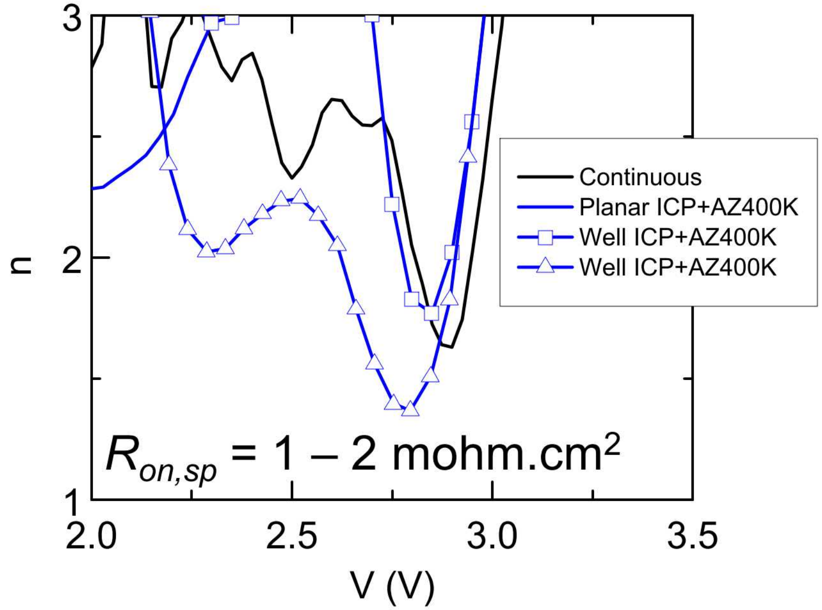
	$[E_c - 1.90\text{ eV}]$ (cm^{-3})	$[E_c - 2.90\text{ eV}]$ (cm^{-3})	$[E_c - 3.20\text{ eV}]$ (cm^{-3})
Continuously-grown	-	2.0×10^{16}	6.0×10^{15}
Etched-and-regrown	1.8×10^{15}	1.7×10^{16}	5.3×10^{15}
Etched-and-regrown + AZ400K	5.0×10^{14}	2.1×10^{16}	5.0×10^{15}

Selective Area Doping (p-well)

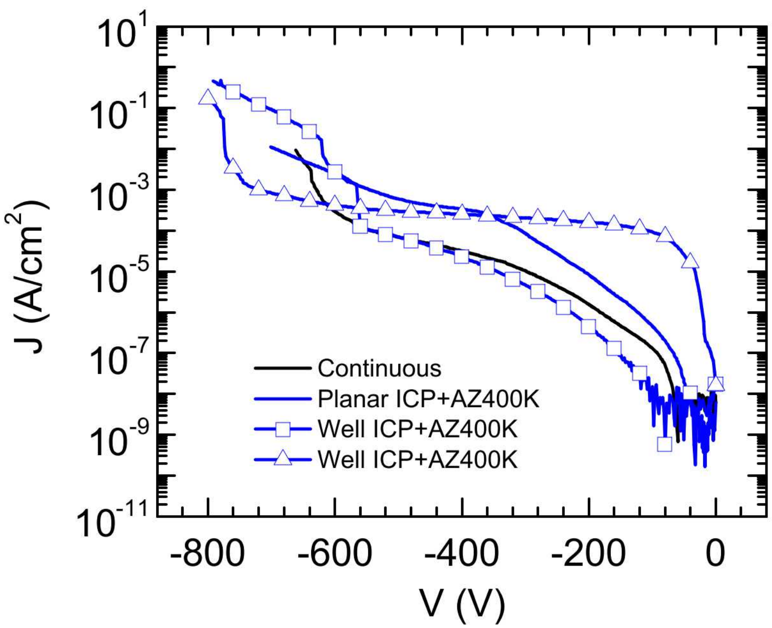


- Demonstration of etch + AZ400K treatment + p-GaN regrowth in an etched well (400 nm deep)
- Includes effect of etched sidewalls
- Quick Turn fabrication process

Forward IV



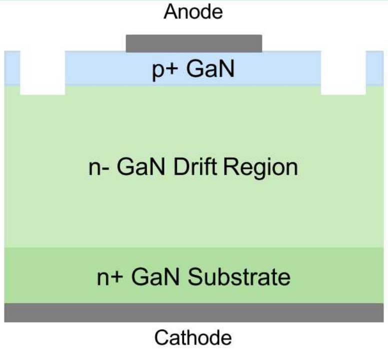
Reverse IV

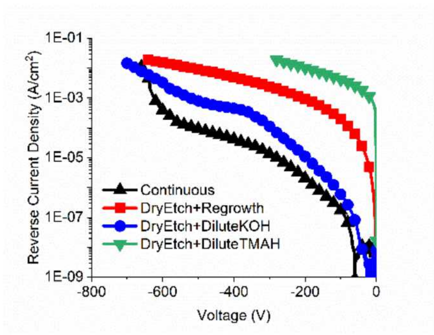


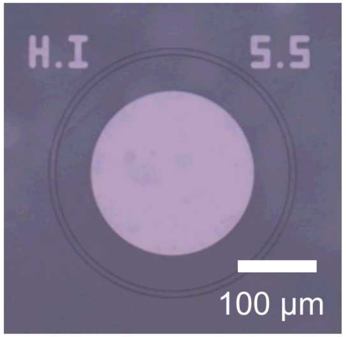
Demonstrated similar forward and reverse IV behavior in sample with well

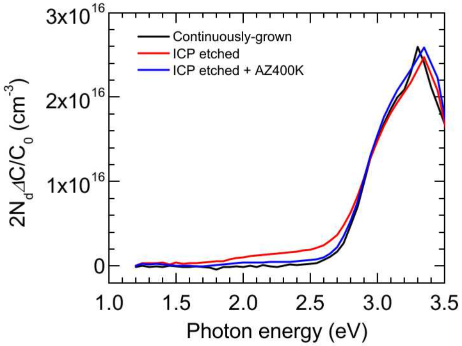
Summary

- Investigated etch/MOCVD regrowth defect behavior in GaN for future selective area doping control in power electronics
- Used forward/reverse IV characterization to study etch damage and chemical surface treatment effects on planar, c-plane GaN diodes
  - Dilute KOH (AZ400K) treatments showed significant reduction of forward/reverse leakage currents vs. etch/regrowth
- Used DLOS and SSPC techniques to identify defects in planar etched/regrown GaN P-N diodes
  - Defect at E_c - 1.90 eV related to ICP etch damage
  - Correlation in reduction of this defect density and reduction in leakage current in etch + treated + regrown diodes
  - SSPS technique likely under-estimating density for defect related to ICP etch damage
- Demonstrated etched and regrown p-well in etched n-type GaN with similar forward and reverse IV characteristics as continuously grown device.









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