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Demonstration of High-Voltage Regrown Nonpolar *m*-Plane *p-n* Diodes for Selective-Area-Doped Power Electronics

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Outline

- Applications of GaN for power electronics
- Vertical GaN *p-n* diodes as building blocks for power electronics
- Selective-area doped geometries and nonpolar *p-n* diodes
- Impurity incorporations at the regrowth interfaces
- Comparison of nonpolar *p-n* diodes with continuous, interrupted, and regrown junctions
- Demonstration of a high-voltage regrown nonpolar *m*-plane *p-n* diode
- Summary and conclusion

Applications

Wind Turbines

Ship Propulsion Systems

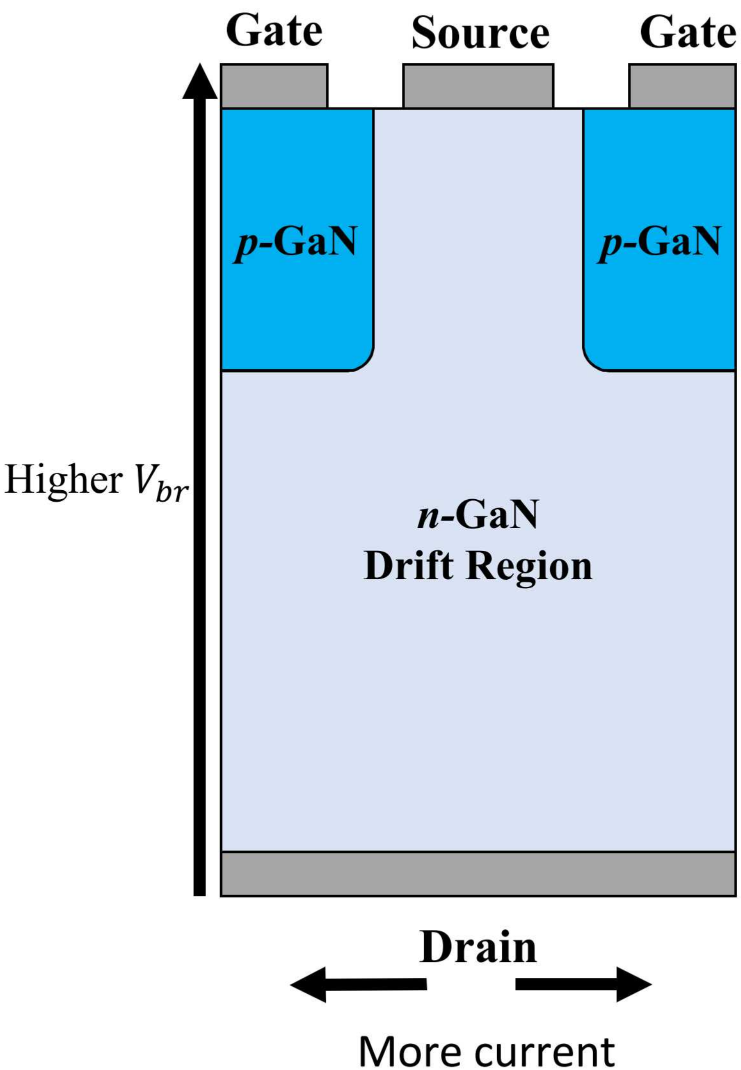
Electric Grid

Solar Inverters

Consumer Electronics

Data Centers

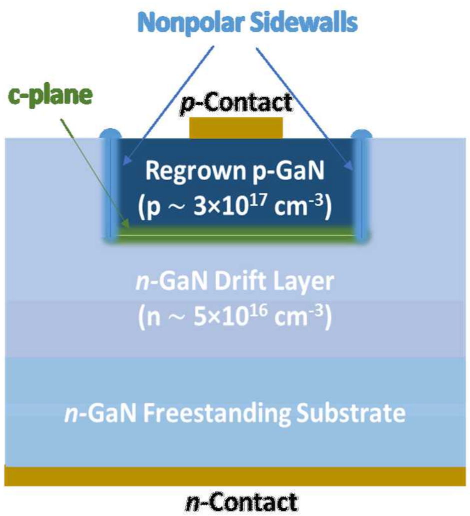
GaN Power Device Architectures

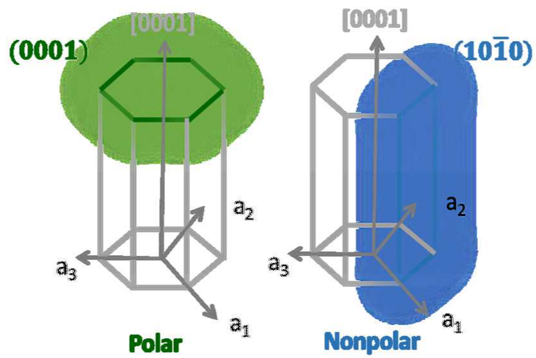


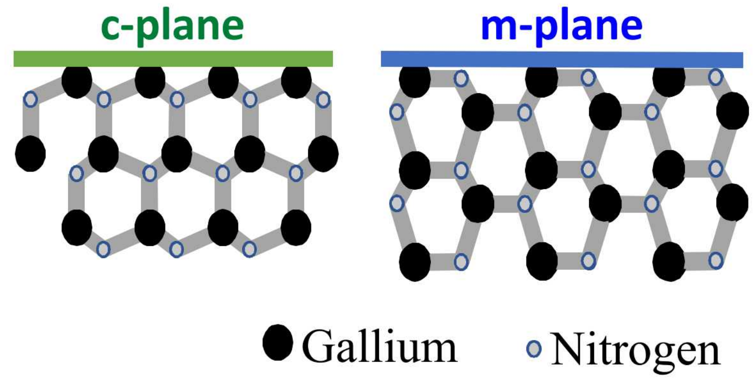
- ✓ Vertical geometries are preferred over lateral geometries for power devices for two reasons
  - ✓ Increase the breakdown voltage V_{br} by growing a thicker drift region
  - ✓ Increase current handling by designing devices with wider lateral dimensions
- ✓ Vertical Junction Field Effect Transistor (VJFET)
  - ✓ Applying a bias to the gate terminals modifies the depletion region between the *p*-GaN regions allowing the modulation of current flowing through the source and drain
  - ✓ Simulations by researchers from Arizona State University demonstrated a Vertical Cavity JFET achieving $V_{br} = 1260\ V$ and R_{on}=5.2m$\Omega \cdot \mathrm{cm}^2$ for a drift region of 11 μm

Ji and Chowdhury, IEEE Transactions on Electron Devices **62**(8), 2571–2578 (2015)

Selective-area doped vertical GaN *p-n* diodes



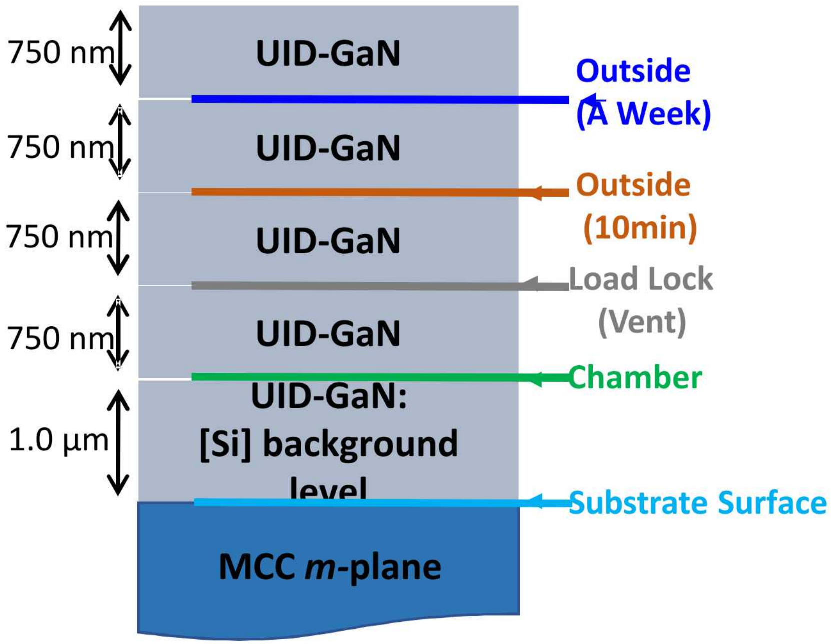


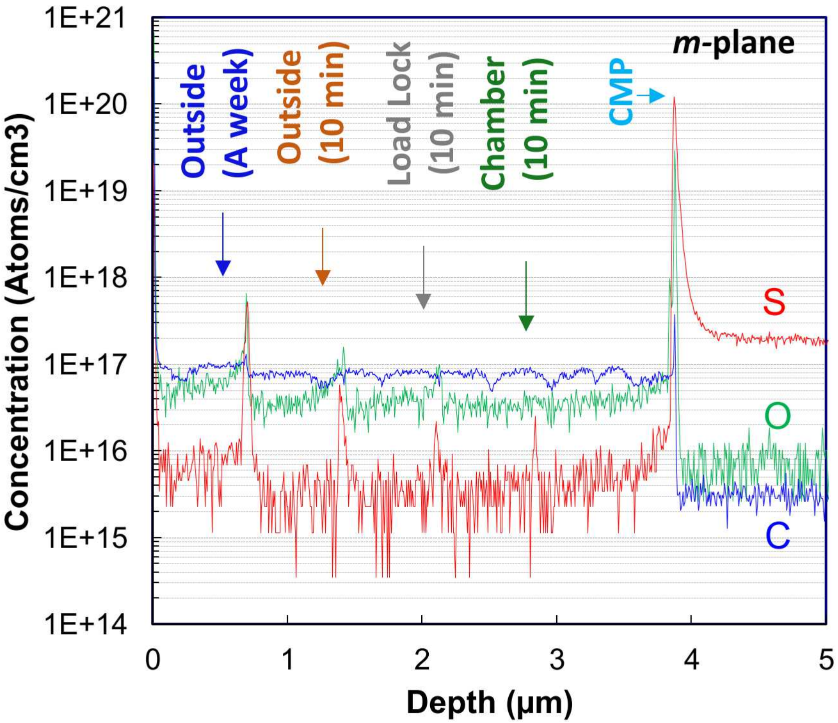


- ✓ GaN devices with complex designs such as JFETs often requires selectively doped regions embedded into the device
  - ✓ Such selectively doped regions are achieved by selective etch then regrowth of the embedded region
  - ✓ *p-n* junctions at these regrowth interfaces show considerable leakage currents
- ✓ Impurity incorporation from shallow dopants oxygen and silicon, or the deep level acceptor carbon at these regrowth interfaces can be a factor in the leakage currents
- ✓ Nonpolar planes construct the sidewalls of these selectively defines geometries. Hence, it is important to demonstrate a high-voltage regrown nonpolar device to realize low leakage operation in selective-area doped vertical GaN power switches

Impurity Evaluations

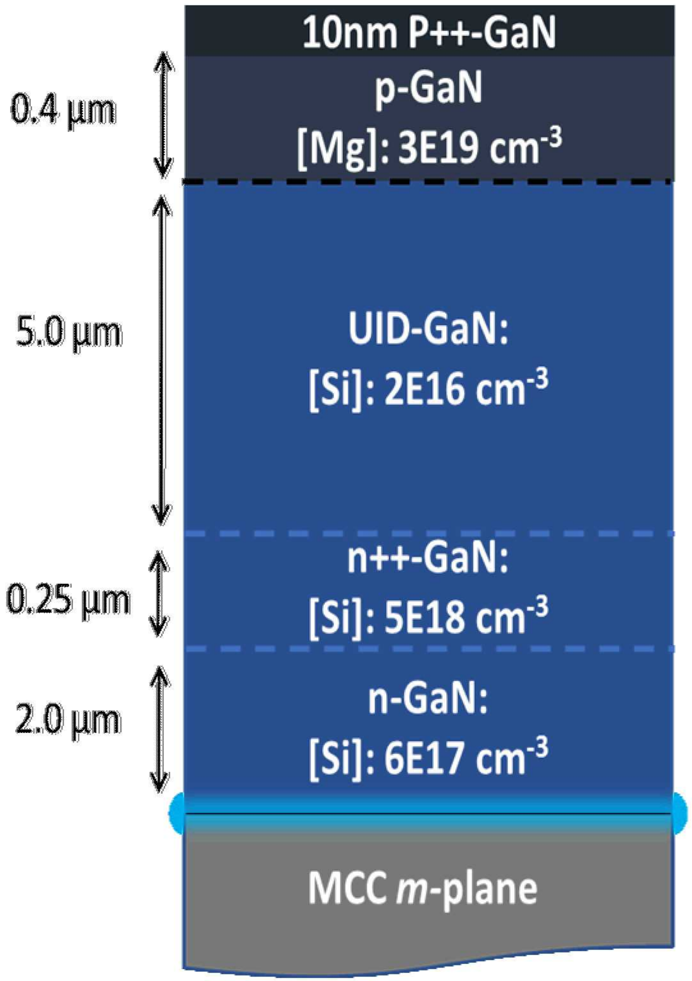
- ✓ The interfacial impurities have been evaluated using secondary-ion mass spectroscopy (SIMS) on an m-plane with embedded multiple interruptions





- ✓ Background impurities: [Si] ~ $5\times10^{15}cm^{-3}$, [O]< $5\times10^{16}cm^{-3}$, [C]< $1\times10^{17}cm^{-3}$
- ✓ The higher the ambient exposure, the higher the impurity spikes at the interruption interface
- ✓ All the impurity spikes are less than $5\times10^{17}cm^{-3}$

GaN *p-n* diode epitaxial details



→

a. Continuous

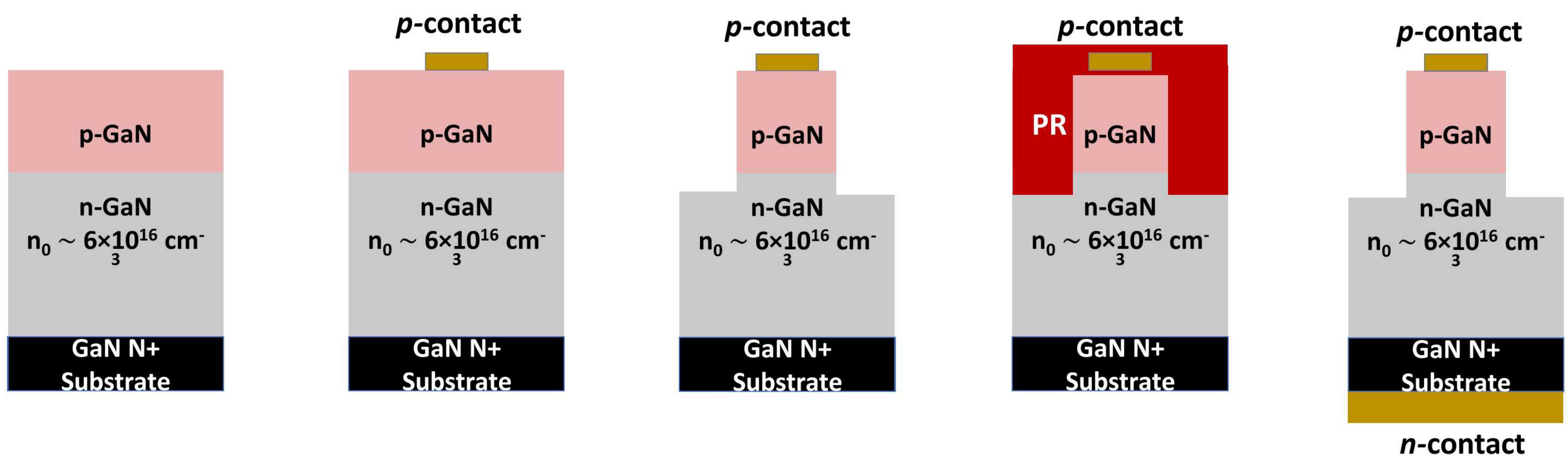
b. Interruption (10 min in chamber)

c. Regrowth (A week outside)

- ✓ Three *p-n* diode structures were grown
  - a. Continuously grown diode
  - *b.* *p*-GaN grown after 10 min interruption in the main chamber
  - *c.* *p*-GaN grown after sample being kept outside the chamber in a N_2 box for a week
- ✓ All structures were grown on m-plane substrates with -0.95 off toward c-direction -> the selected off-angle shows low impurities based on literature
- ✓ Substrates were obtained from Mitsubishi Chemical Corporations (MCC)
- ✓ 5-µm thick drift layers ([Si]: ~ 2×10^{16}cm^{-3}, corresponding to $n_0\sim$ 5×10^{16}cm^{-3} from C-V measurements) were used for all three structures

Yamada *et al*, Jpn. J. Appl. Phys., 57, 04FG01 (2018)

Fabrication Process



1) p-GaN Activation

- 655 C for 15 min (N_2/O_2 mixed)

2) p-Contact Deposition

- Pd/Au (20/300 nm)
- E-beam evaporation

3) Device Isolation

- Cl_2 ICP mesa etching

4) Protect Front Side

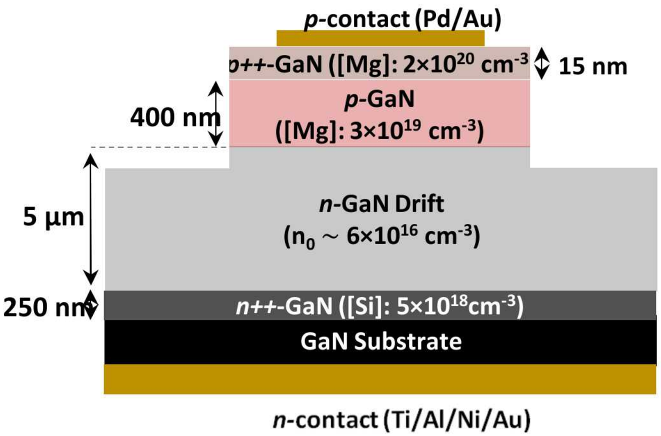
- Use photoresist (PR) to protect top side when backside n-contact deposition

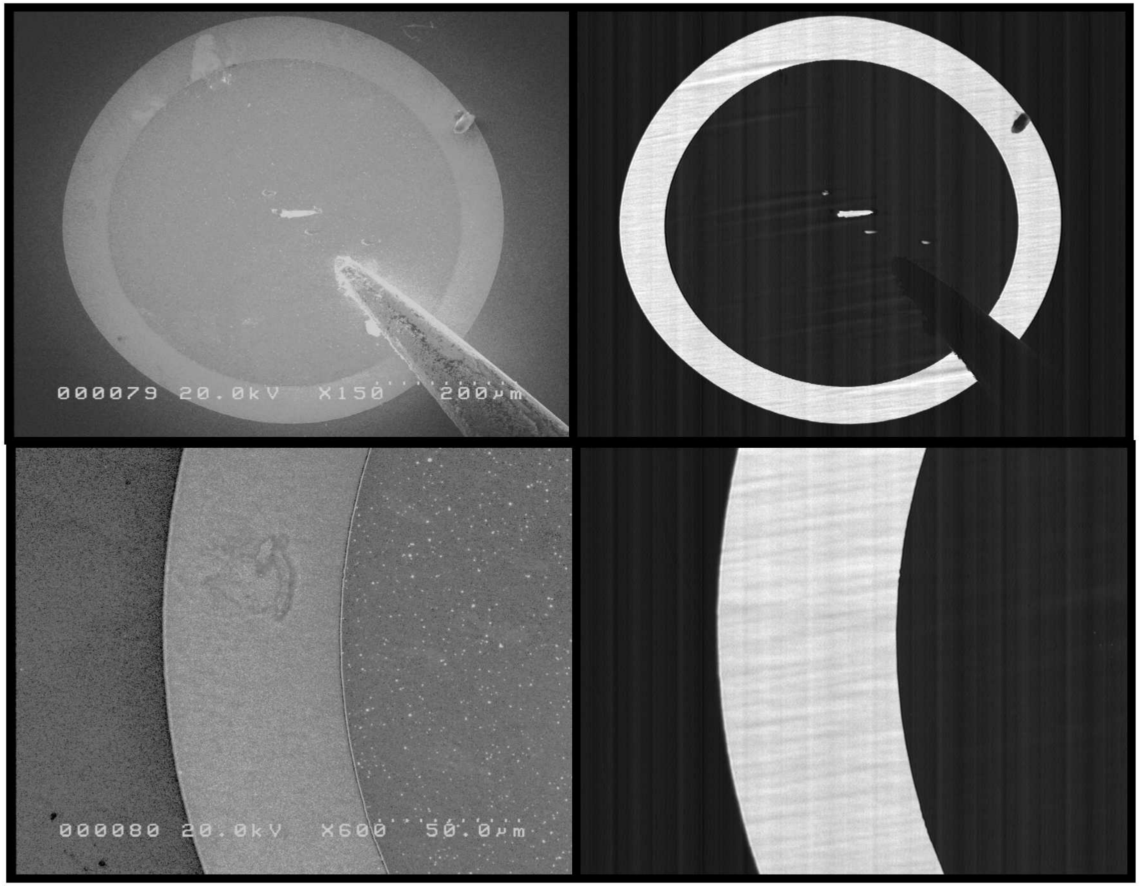
5) Backside n-Metal & Clean Front Side

- Ti/Al/Ni/Au (20/100/50/300 nm)
- E-beam evaporation
- Photoresist removed from top side

✓ A standard simple quick-turn fabrication process was used without applying any edge termination or field management techniques

Injection and current uniformity





✓ A uniform current injection across the mesa was observed using an electron-beam induced current (EBIOC) in conjunction with scanning-electron microscopy (SEM)

Forward current-voltage characteristics

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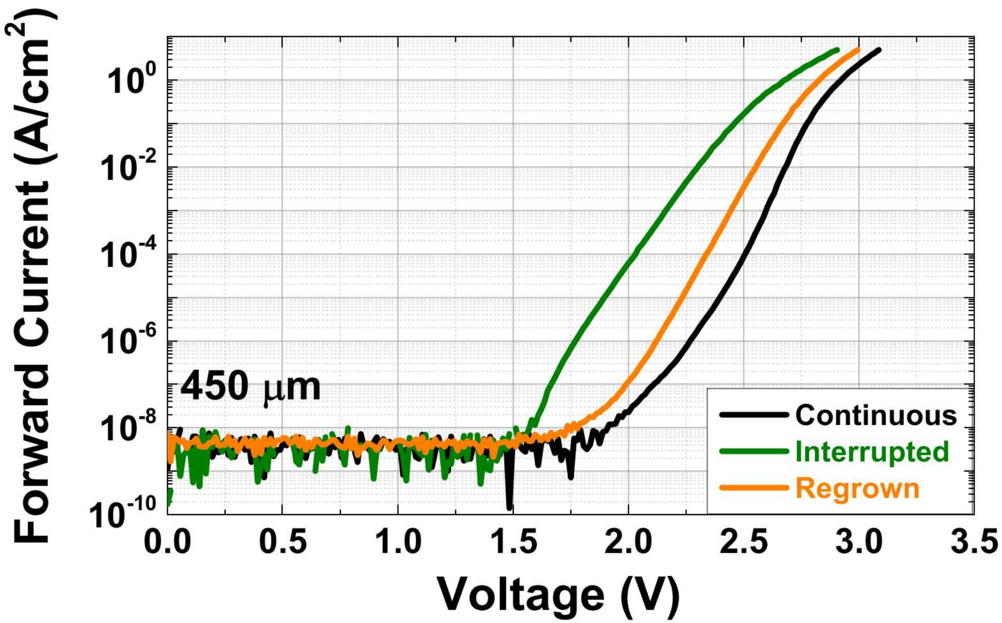
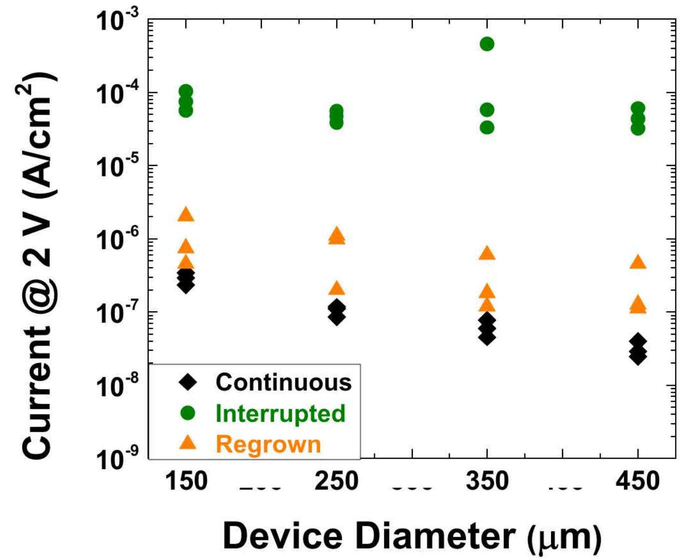
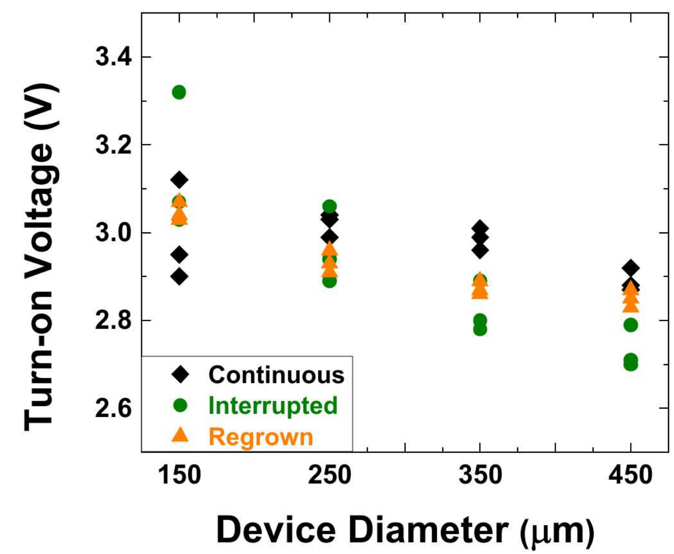
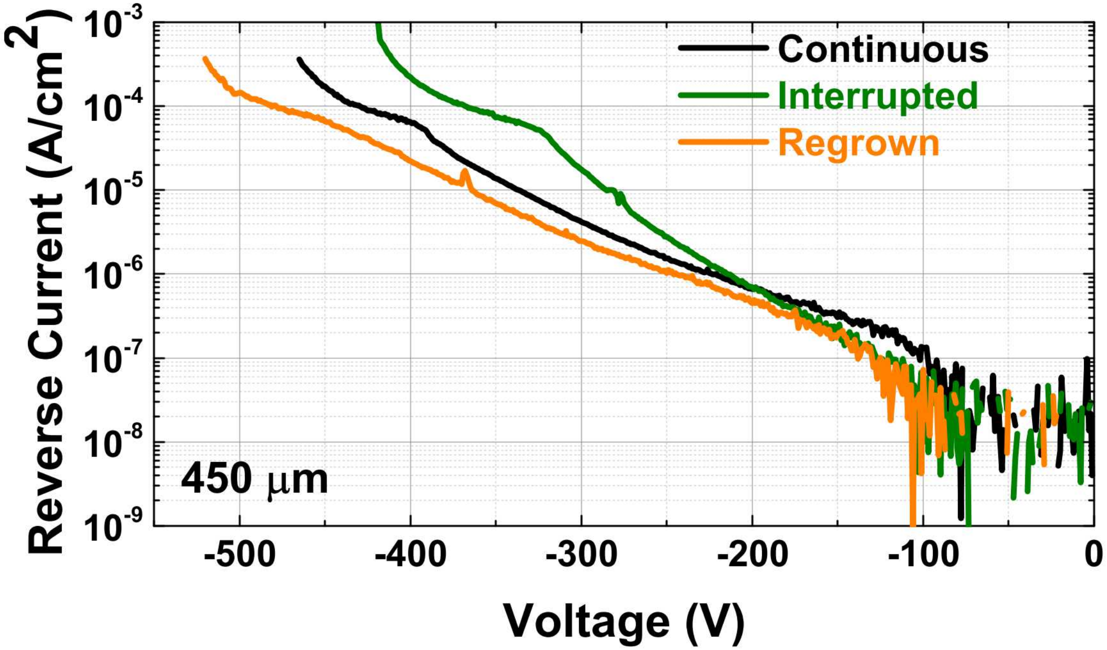


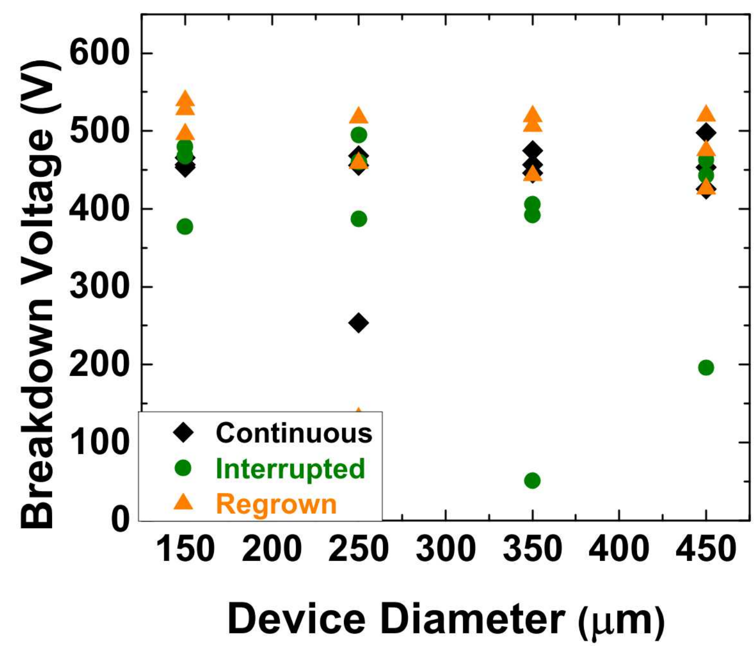


- ✓ At low forward voltages (< 1.5 V), the three structures show similar leakage currents (~ 10^{-9} A/cm^2)
- ✓ At higher voltages but below turn on, the regrown diodes show a little higher leakage currents compared to the continuous diodes. The interrupted diodes show much higher leakage currents compared the other two diodes
- ✓ The trend is verified for a large number of devices with different sizes at 2 V forward bias
- ✓ The turn-on voltages are very similar for all the three structures
- ✓ The regrown diode shows only a little higher leakage currents below the threshold compared to continuous diodes



Reverse current-voltage characteristics





- ✓ Except for some deviations at higher reverse voltages (> 250 V), all three diodes show similar leakage currents (< 10^{-6} A/cm^2)
- ✓ The avalanche breakdown voltages of ~ 450 - 550 V are observed for the three diodes
- ✓ A comparison of breakdown voltages for the regrown, interrupted, and continuously grown diodes with different device diameters across the samples indicate overall similar breakdown characteristics for all three diodes
- ✓ The highest V_{br} of ~ 538 V was obtained for the regrown diode which corresponds to ~ 3.35 MV/cm with the depletion widths of ~ 3.2 μm and ~ 6 nm in *n*- and *p*-side of the junction, respectively

Summary

- The vertical GaN power switches with selective-area doped geometries are of great interests for complex device geometries, including VJFETs
- Realization of a high-voltage regrown junctions on the nonpolar planes which construct the sidewalls of the selective-area doped geometries is desirable
- We presented a high-voltage nonpolar *m*-plane *p-n* diode with regrown junction
- The impurity spikes at the regrowth interfaces below $5\times10^{17}cm^{-3}$ was observed in SIMS
- A comparison of reverse I-V characteristics of nonpolar *m*-plane diodes with continuous, interrupted, and regrown junctions shows similar reverse characteristics
- In the forward bias, however, the interrupted diode shows the highest leakage currents
- The highest V_{br} of $\sim$ 538 V was obtained for the regrown diode which corresponds to $\sim$ 3.35 MV/cm
- The results suggest that an impurity spike level of $\sim$ $5\times10^{17}cm^{-3}$ does not result in a significant change in diode characteristics which supports using nonpolar *m*-plane to obtain high-voltage vertical diodes with selective-area doped geometries for power switching applications

Thank You

III-Nitride Materials and Devices Group
The University of New Mexico