SAND2018-11640C

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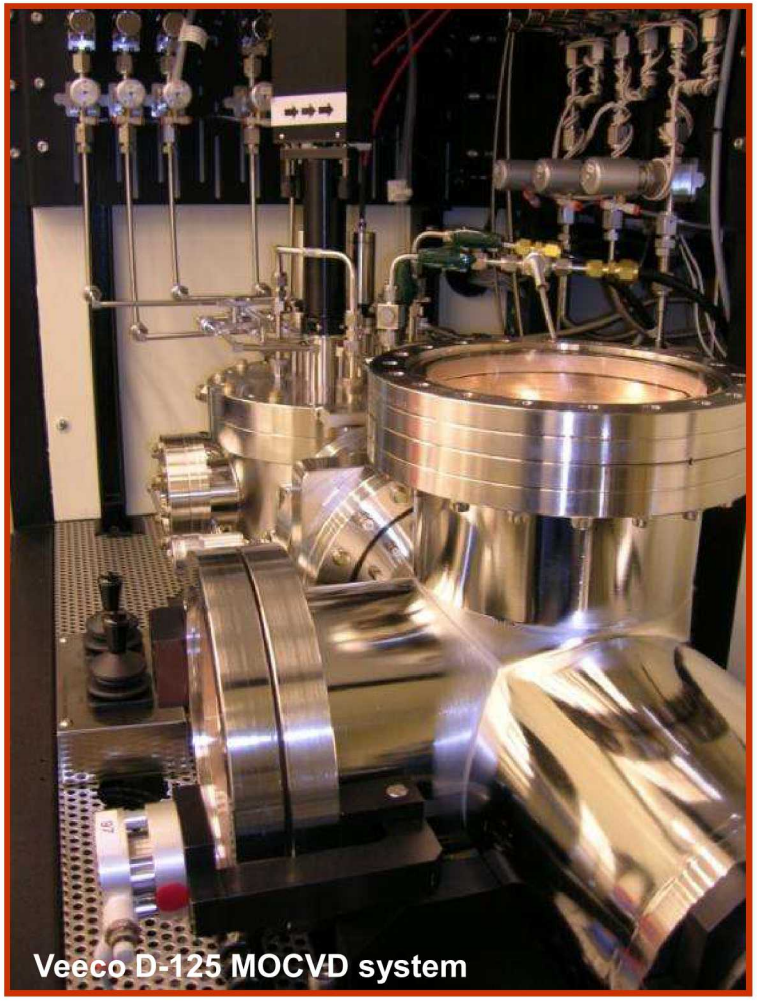
Veeco D-125 MOCVD system

Material advances toward vertically-conducting AlGaN power transistors

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U.S. DEPARTMENT OF ENERGY

Outline

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- **Introduction**
  - AlGaN alloys for power electronics
  - Challenges for vertically conducting power transistors in AlGaN
- **"Quasi-vertical" ($Al_{0.3}Ga_{0.7}N$) PN Diodes on sapphire**
  - Grown continuously and diodes with ***regrown*** p-anode
- **Growth of ($Al_{0.3}Ga_{0.7}N$) on patterned N-GaN substrates**
  - Overgrowth process and pattern geometry
  - Threading dislocation density and morphology
  - Vertically conducting PN AlGaN diode
- **Summary**

Ultra-wide-bandgap semiconductors (UWBS, >4eV) for power electronics

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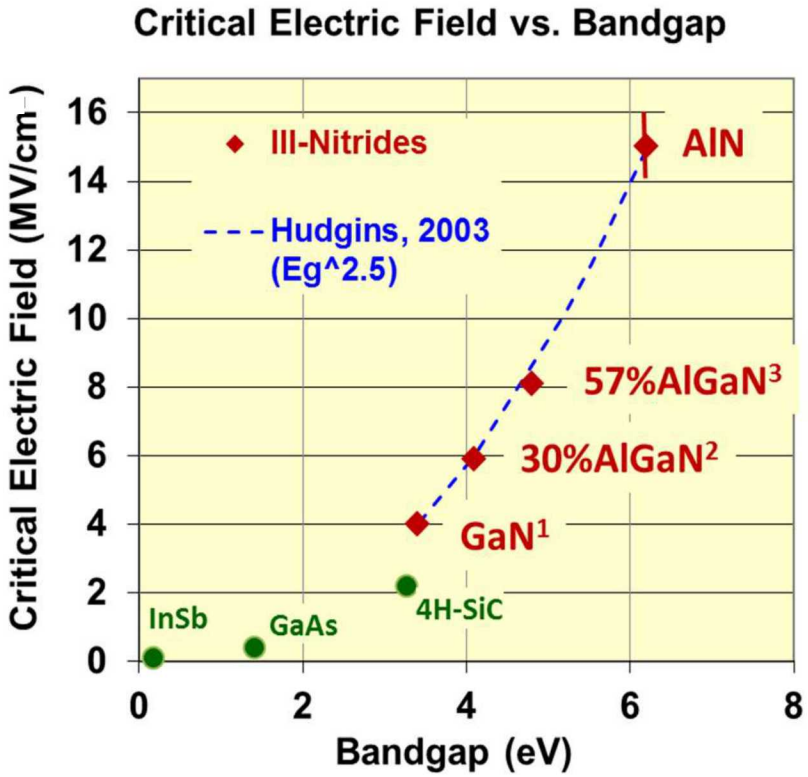
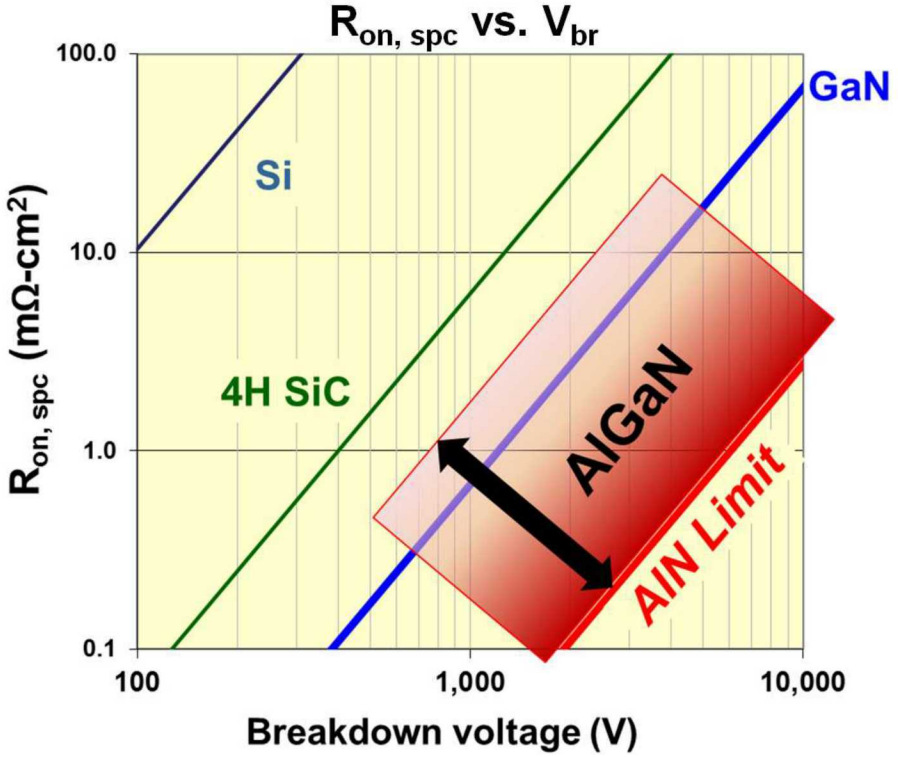
Critical Electric Field (MV/cm)

$$E_C \propto E_g^{2.5}$$ (Direct gap)

Unipolar Figure of Merit (vertical devices)

$$UFOM = \frac{V_{br}^2}{R_{on,sp}} = \frac{1}{4}\varepsilon\mu E_C^3 \propto E_g^{7.5}$$





1-Armstrong, EL 2016, 2-Allerman, EL 2016, 3-Nisikawa, JpnJAP 2007

Why wide-bandgap semiconductors for power electronics?

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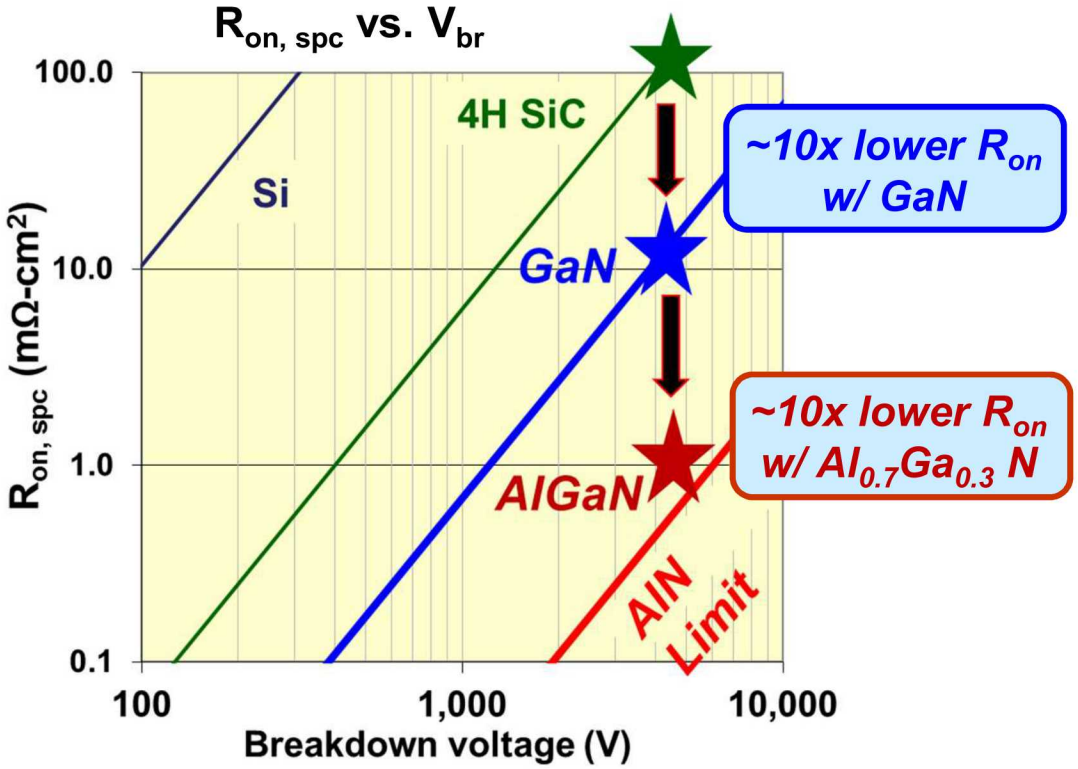
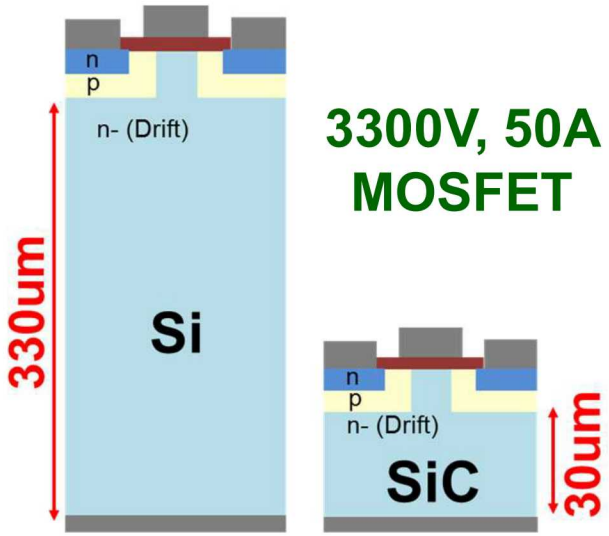
Unipolar Figure of Merit (vertical devices)

$$UFOM = \frac{V_{br}{}^2}{R_{on,sp}} = \frac{1}{4}\varepsilon\mu E_C{}^3 \propto E_g{}^{7.5}$$



Si, SiC Power Transistors



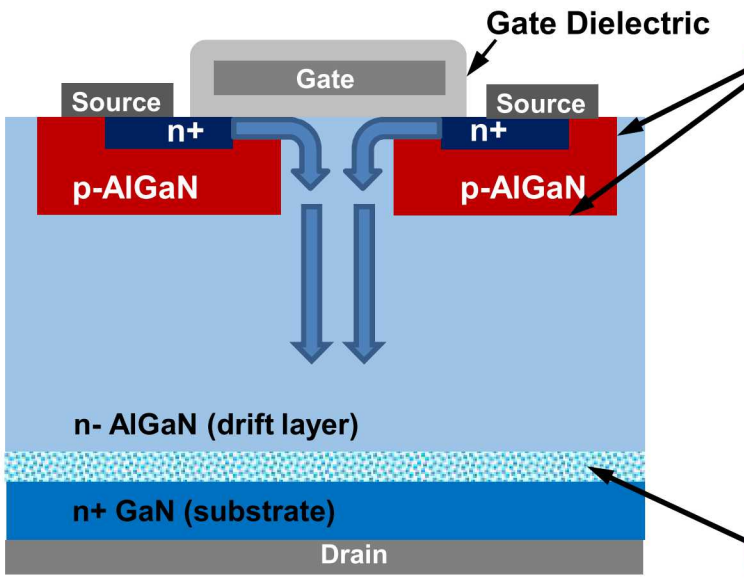
3300V, 50A MOSFET

	Si	SiC
V_{drop}:	250V	1.2V
P_{loss}:	***12,500W***	***60W***

WBS devices:
➡ ***Lower ohmic loss***

Challenges for a AlGaN-based switching transistor

➡ *Double-well Metal-Insulator-Semiconductor Field-Effect-Transistor (D-MISFET)*



AlGaN based vertical D-MISFET

1 **Reverse bias PN junction key to multi-kilovolt blocking voltage (V_{br})**

- ➡ Must have low reverse leakage current
- P-layers formed by ion implantation and annealing for Si and SiC devices
- ➡ P-AlGaN by implantation has not been reported

2 **Vertically conducting device geometry**

- ➡ No AlGaN substrate for vertical conduction
- Substrate removal possible alternative

➡ *Form the p-well by selective-area-growth (SAG) of p-AlGaN*

➡ *Develop growth of AlGaN on conductive GaN or SiC substrates*

Challenges to selective area regrowth of PN junctions

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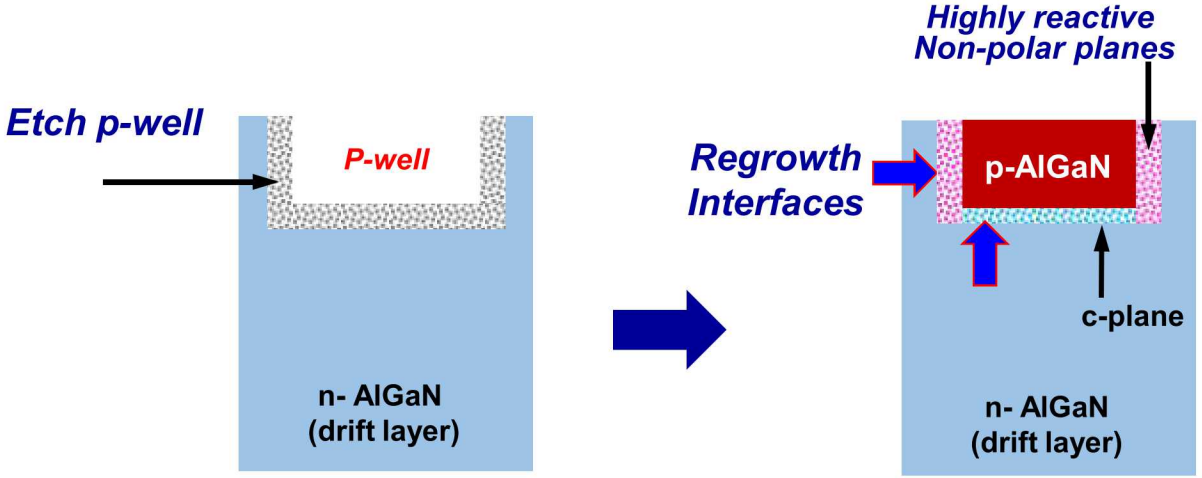
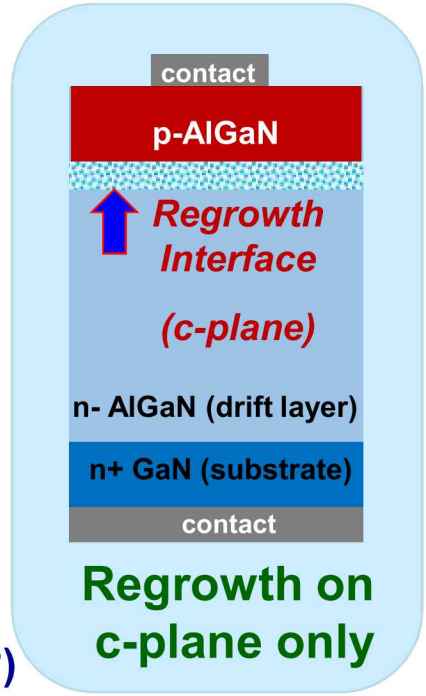
Sources of current leakage at regrown PN interface

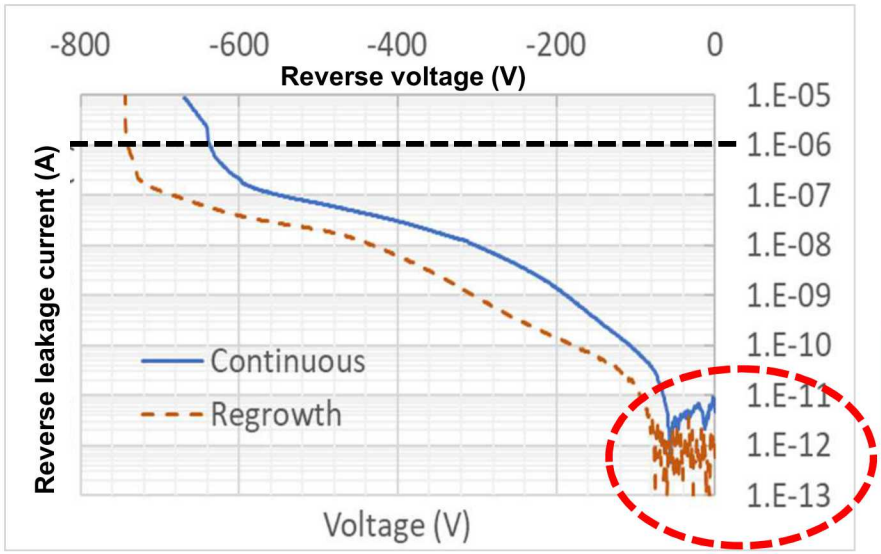


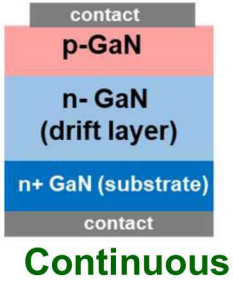


- Electrically active impurities (Si, O, etc.)
- Damage to crystal structure from ICP etch resulting in extended (?) and point defects (e.g. vacancies).
- Incorporation rates of impurities and growth rates depend on crystal plane
- Impact of mask on regrowth and subsequent mask removal

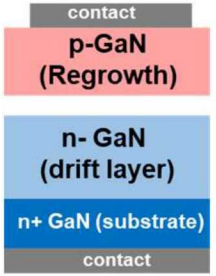
➡ *Start simple, p-AlGaN regrowth only on c-plane drift layers*

GaN PN diodes: Continuous and regrown p-GaN





Continuous

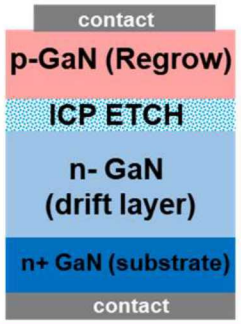


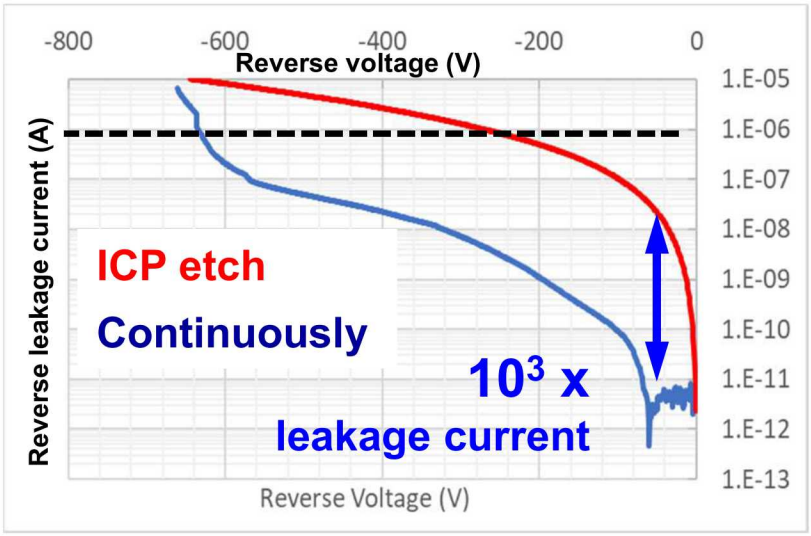
Regrowth on "as-grown" drift layer

➡ Regrown PN diode equal to continuously grown diode

➡ MOCVD regrowth is not a problem

Regrowth on ICP-etched drift layer





➡ Regrown PN diode on an *etched* drift layer has *high reverse leakage current* ➡

$Al_{0.3}Ga_{0.7}N$ "Quasi-Vertical" PN diode on sapphire

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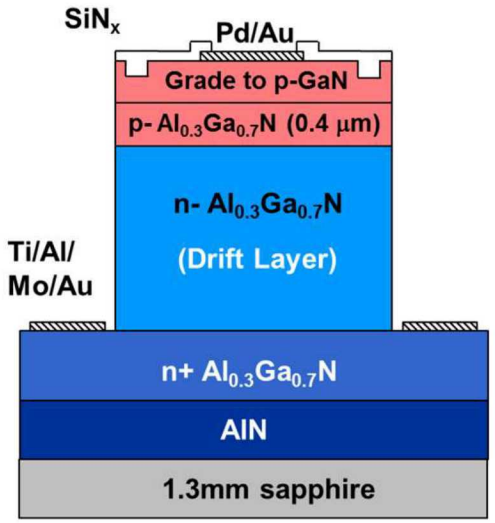
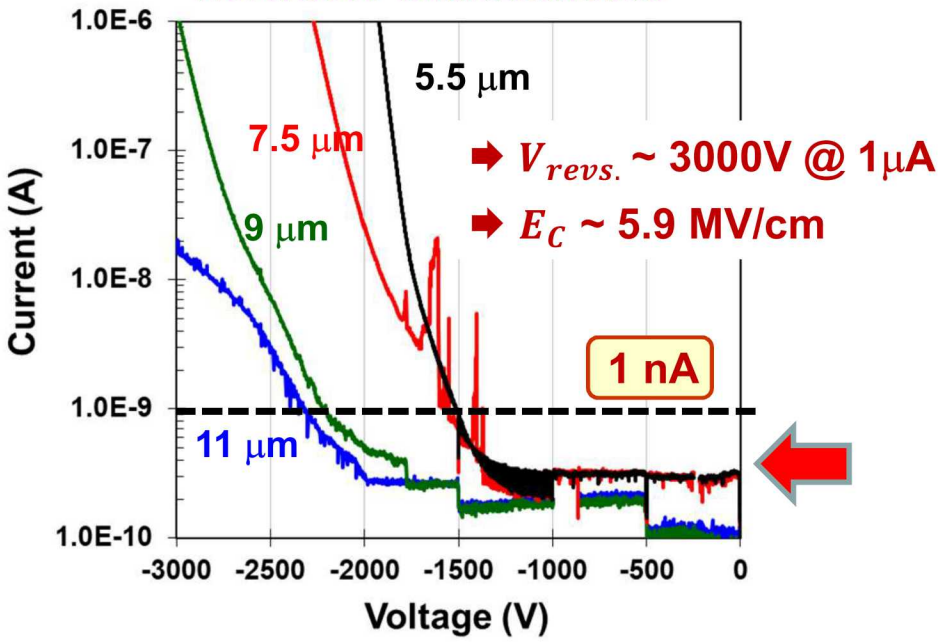
Quasi-Vertical AlGaN PN diode

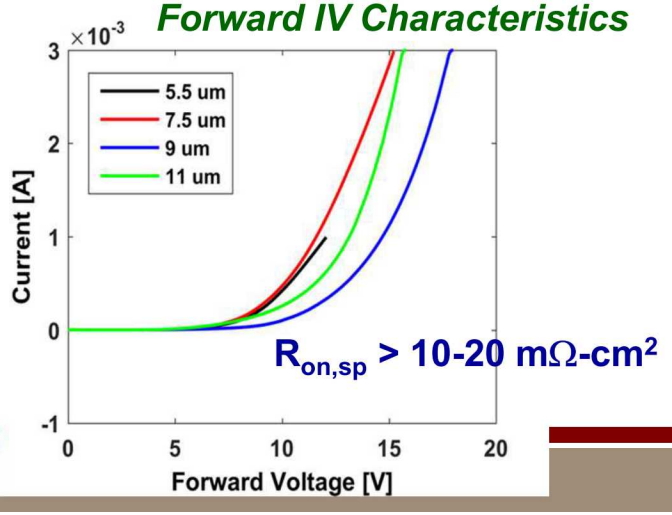


Reverse IV Characteristics



- Implanted junction edge termination
- Mesa & p-metal dia.: 300 - 50 μm
- *Drift Layer: 4.3, 5.5, 7.5, 9, 11 (total to 18 μm)*
- Drift layer doping: mid 10^{15} – mid 10^{16} cm^{-3}
  Mobility: 150 cm^2/Vs
- *Threading dislocation density: 1-3 x 10^9 cm^{-2}*

Forward IV Characteristics



Impurities at regrowth and growth interrupt interface (GaN) — SIMS Studies

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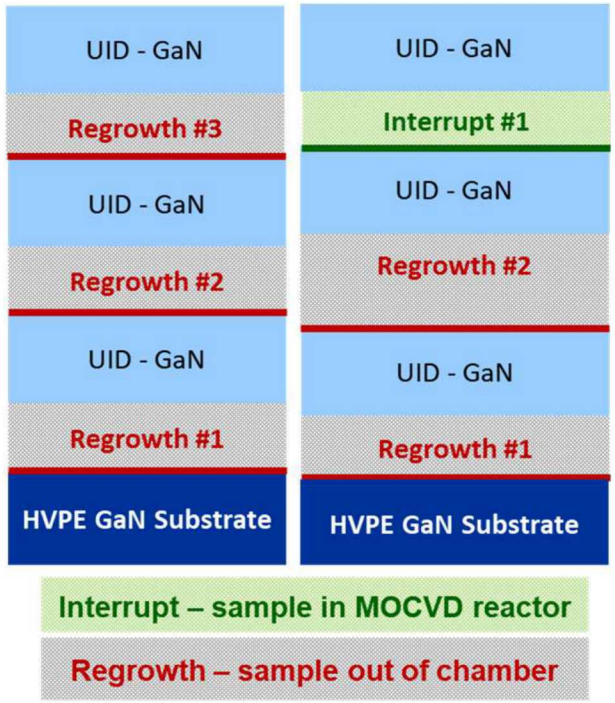
Characterize the extent of impurities (Si, O) at the regrown interface (GaN)

- **Is silicon (oxygen) coming from inside the reactor?**
  - SiC platen
  - Backside of HVPE N+ GaN wafer
  - Si doped N-type GaN epilayer
  - Source material (TMGa, NH3)
  - Reactor parts
- **Studied many regrowth scenarios**
  - In-chamber growth interrupts vs. out of chamber
  - Uid-GaN coated or uncoated SiC platen
  - Uid-GaN vs. Si-GaN surfaces
  - GaN substrate vs GaN/sapphire
  - Temperature & ramp-rate prior to regrowth

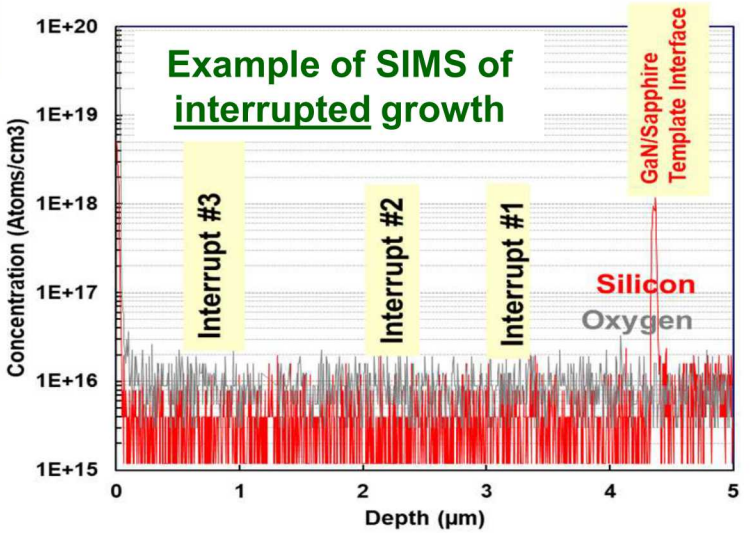
Examples of SIMS interface structures



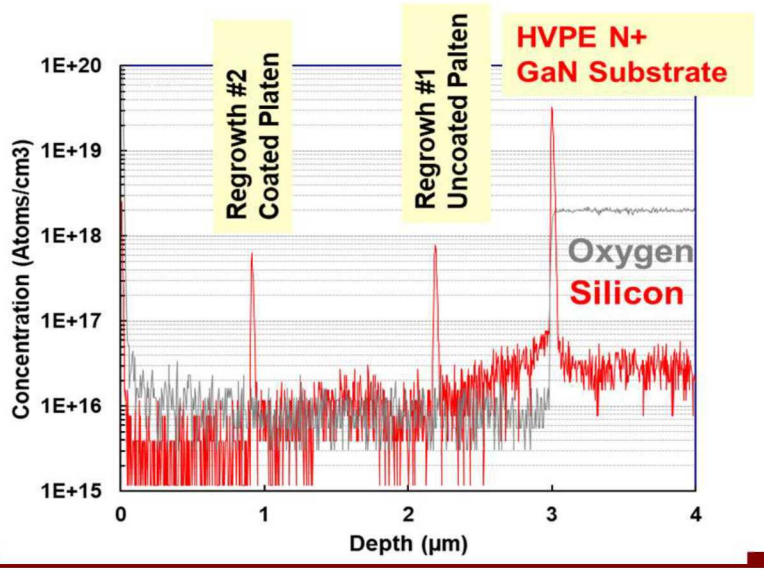
Impurities at regrowth and growth interrupt interface — (GaN)

- **Growth interrupts show MOCVD reactor is *not* a major source of silicon or oxygen**
  - All growth interrupts show:
    - [Si] < 5e16 cm^{-3}
    - [O] ~ at background level
  - Even when moving wafer to load lock and back into the chamber

- **Silicon is from *outside* the chamber but oxygen isn't incorporated**
  - Si is highly variable in concentration and time:
    - [Si] ~ 0.5-5 e18 cm^{-3}
    - [O] ~ at background level
  - HVPE GaN substrate (1st layer)
    - [Si] > 1.5e19 cm^{-3}



Example of SIMS of regrowth interfaces



Impurities at regrowth and interrupt interfaces ($Al_{0.3}Ga_{0.7}N$)

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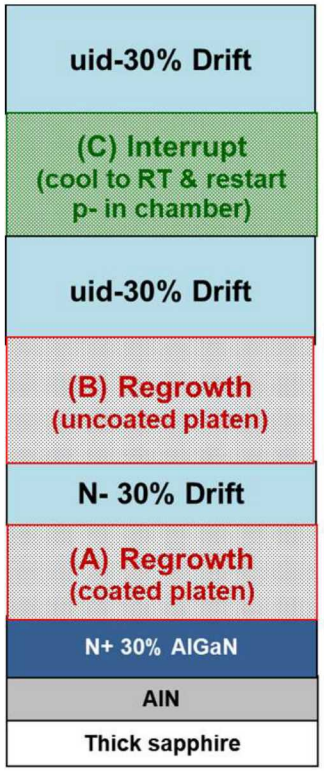
SIMS: $Al_{0.3}Ga_{0.7}N$ regrowth & interrupt interfaces

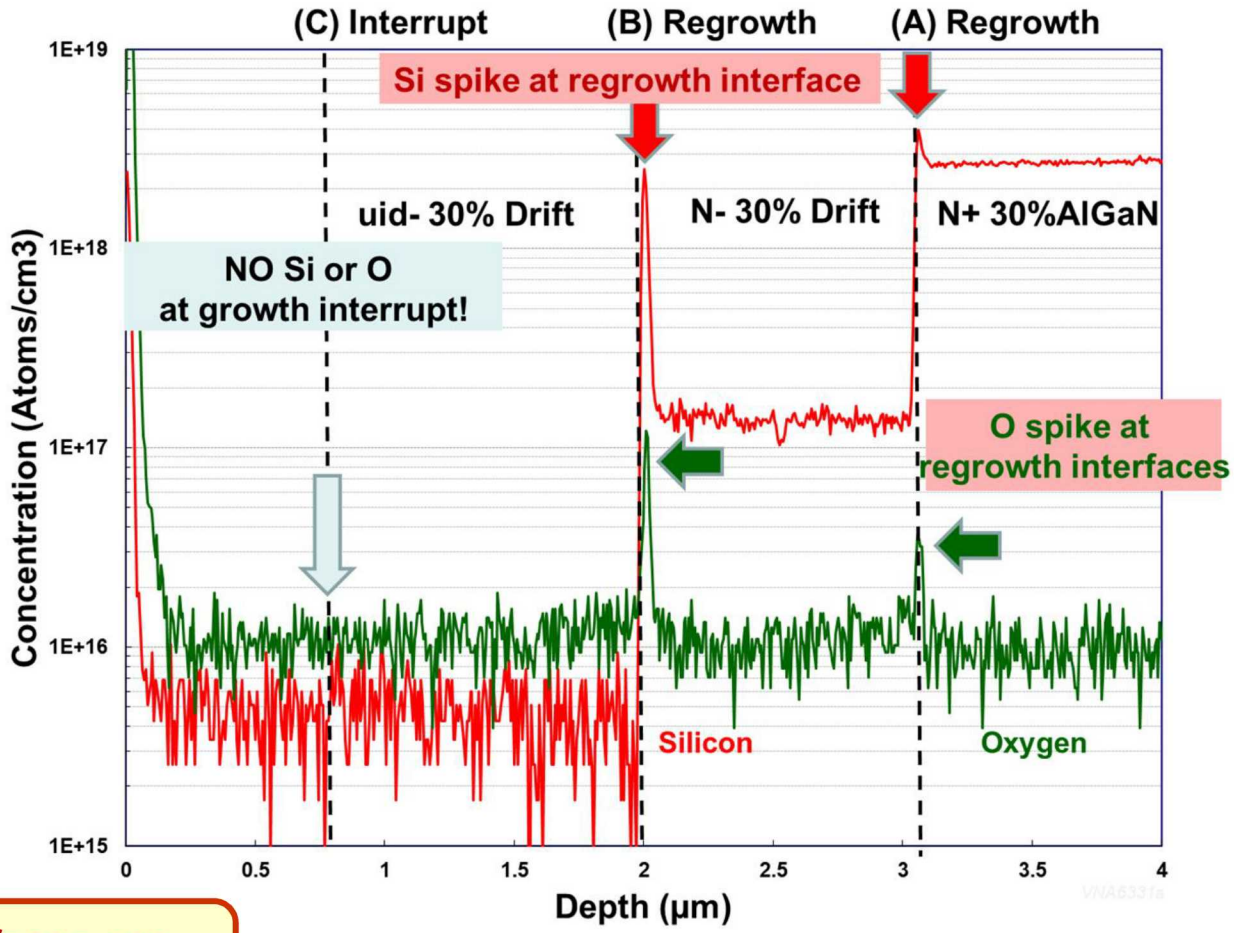
SIMS test structure



[Si] - DL
[O] - Backgnd.

[Si] - 2e18 cm^{-3}
[O] - 1e17cm^{-3}

[Si] - 4e18 cm^{-3}
[O] - 3e16cm^{-3}



➡ *Si & O at regrowth interfaces are from outside the chamber*

($Al_{0.3}Ga_{0.7}N$) PN Diode: Regrowth on "as-grown" drift layer

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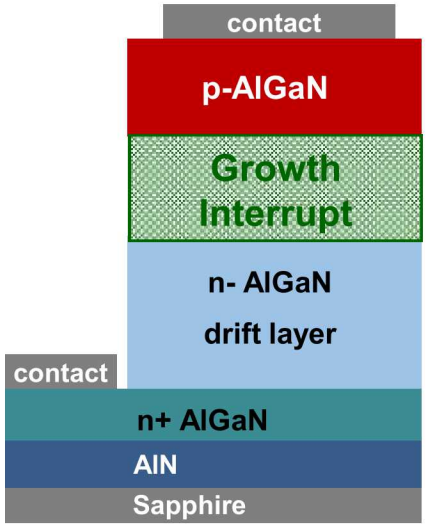
➡ Test p-AlGaN regrowth on *as-grown* drift layer

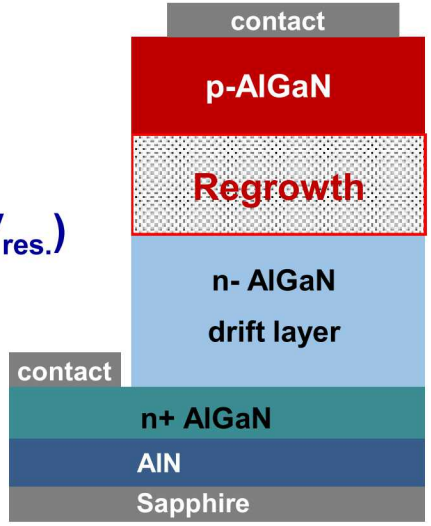
A. *Interrupted growth at junction*



- N_o = 7e16 cm^{-3}
- t = 5.5 μm
- Expect reverse voltage ($V_{res.}$)
  - ➡ 1500 – 1600 V (@ 1uA)

- Cool to room temperature & warm-up for p-AlGaN
- Test temperature ramp
- No Si, O at interface

B. *Regrow junction*



- Remove from reactor
- Same warm-up to p-AlGaN
- Expect Si, O at interface

($Al_{0.3}Ga_{0.7}N$) PN Diode: Regrowth and growth interrupt on "as-grown" drift layer

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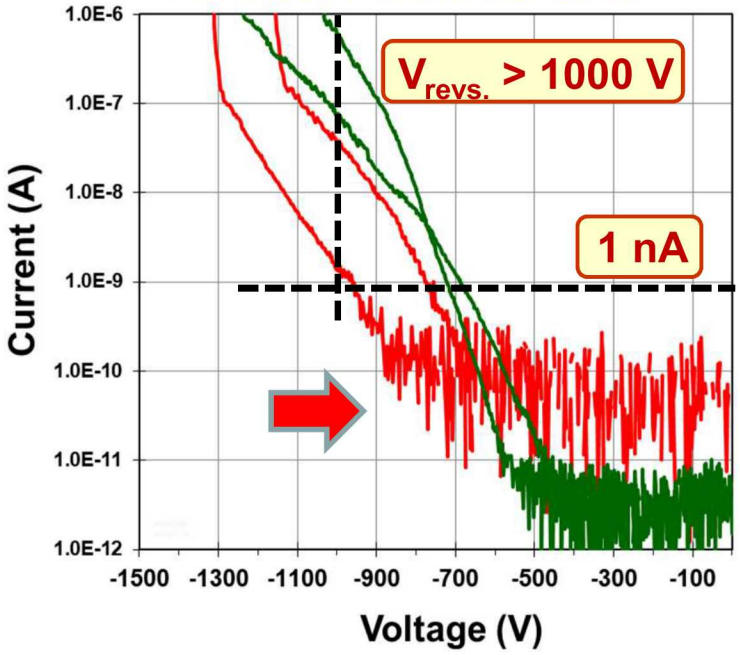
PN Diode IV Characteristics on an "as-grown" drift layer

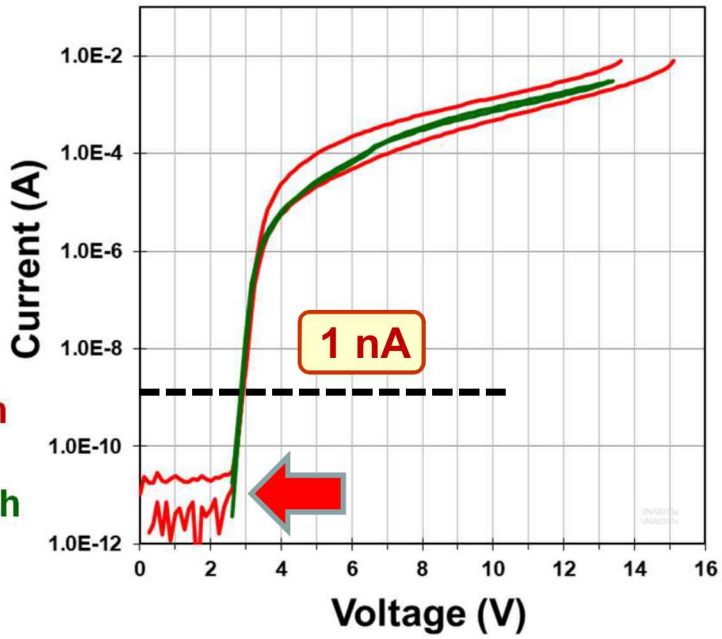
Reverse IV Characteristics



Regrown Junction

Interrupted Growth

Forward IV Characteristics



- Regrown diode has reverse leakage current < 100 pA to 700V
- Very low reverse current leakage indicates a good PN junction (*TDD = low 10^9 cm^{-2}*)

- Very low forward current leakage indicates a good PN junction

➡ Demonstrates regrowth of good PN junctions on "as-grown" drift layers

AFM of $Al_{0.3}Ga_{0.7}N$ drift layers: "As-grown" and ICP etched

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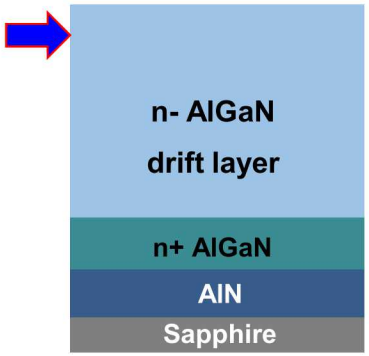
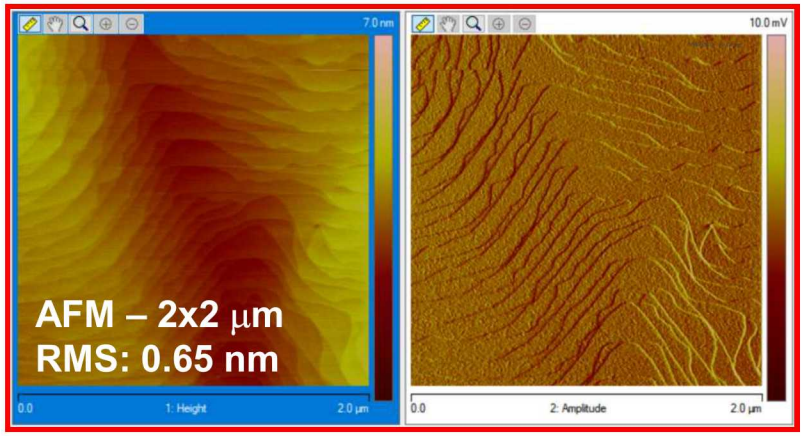
As-Grown drift layer

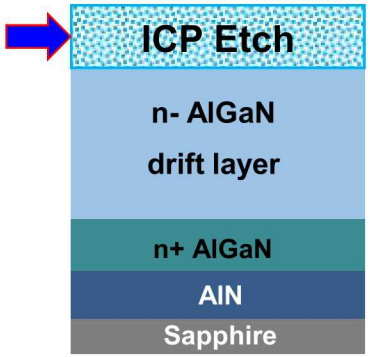


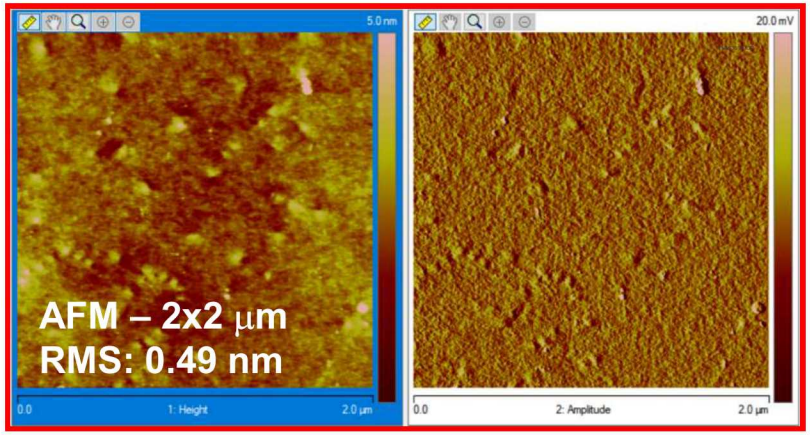
N_o = 7e16 cm^{-3}

t = 5.5 μm



ICP Etched drift layer (0.3 μm)





➡ ICP etching leaves a smooth but damaged surface

AFM of $Al_{0.3}Ga_{0.7}N$ drift layers

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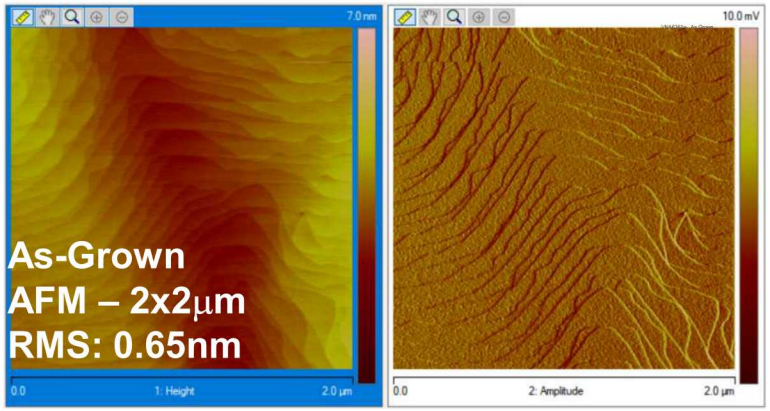
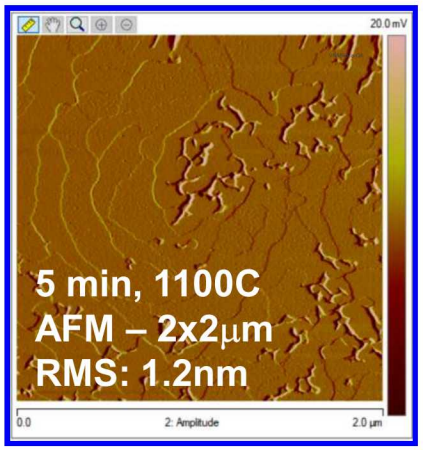
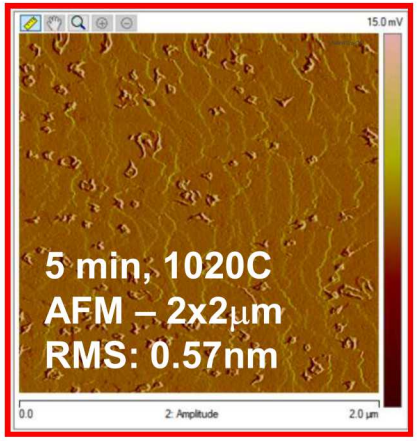
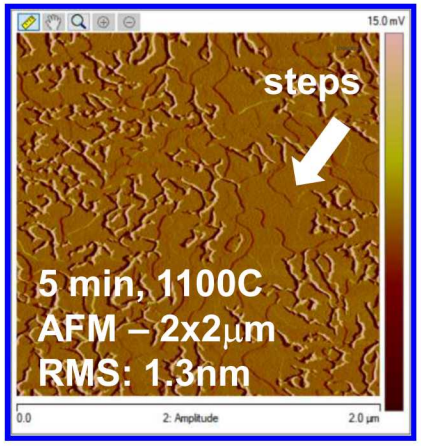
Thermal processing (1100 & 1020 C) on "as-grown" drift layer

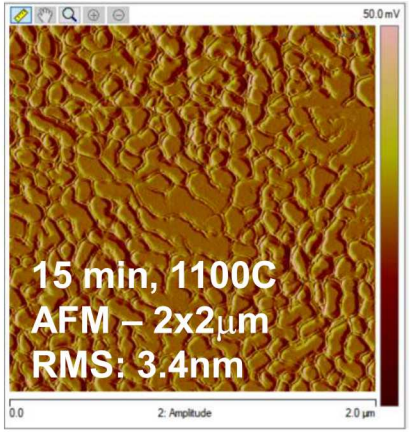


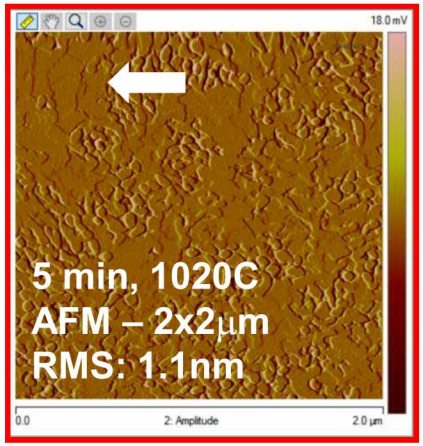


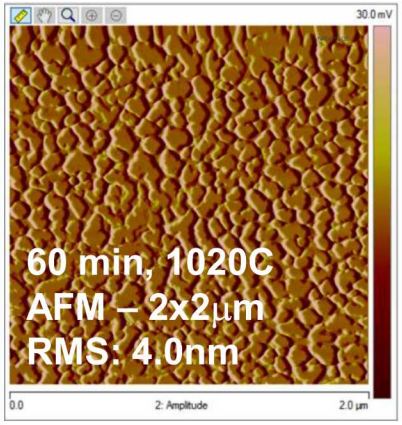


Thermal processing (1100 & 1020 C) on ICP-etched (0.3 μm) drift layer









➡ Little difference in surface of "as-grown" and ICP-etched drift layers after thermal processing

$Al_{0.3}Ga_{0.7}N$ PN Diode: Regrowth on ICP etched drift layer

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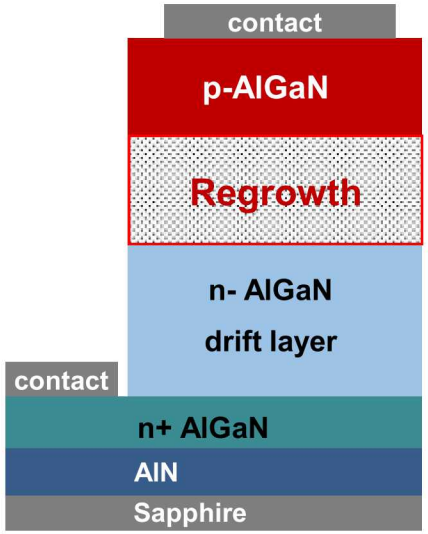
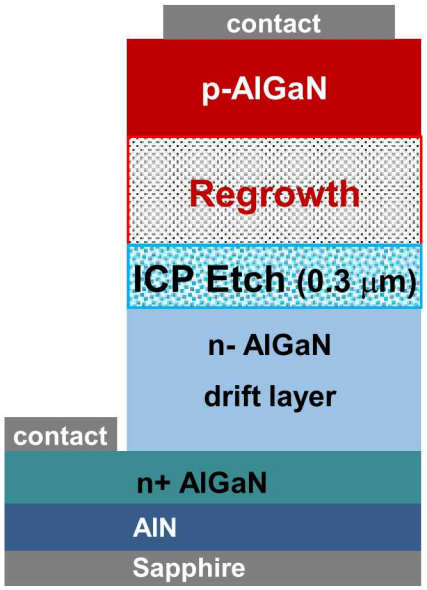
➡ **Test p-AlGaN regrowth on *ICP etched* drift layer**

A. *"As-grown" Drift*



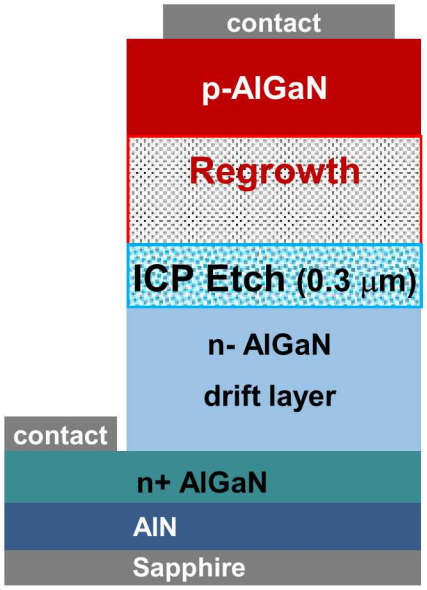
- No ICP etch of drift layer
- Repeat previous regrown diode

B. *ICP-etch ONLY*



- No attempt to remove damage from ICP etch

C. *ICP-etch + Thermal*



- Warm to growth temperature and pause before p-AlGaN

$Al_{0.3}Ga_{0.7}N$ PN Diode: Regrowth on ICP etched drift layer

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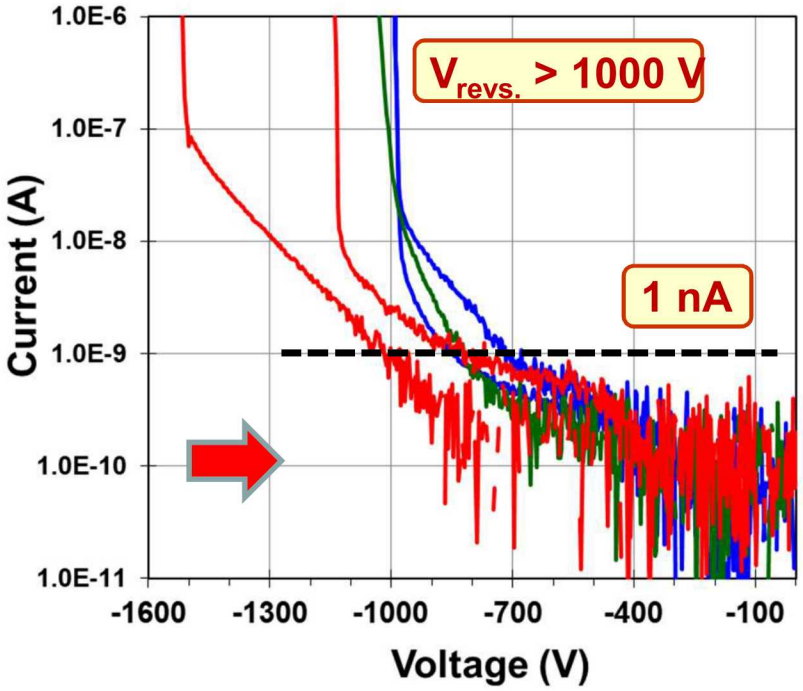
PN Diode IV Characteristics on an ICP-etched drift layer

Reverse IV Characteristics

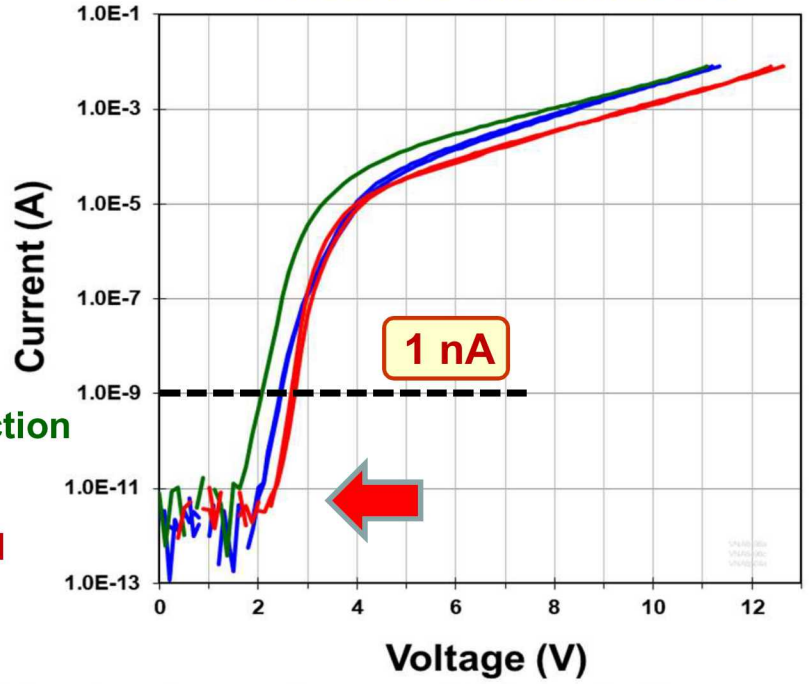


Regrown junction

ICP etch only

ICP + Thermal

Forward IV Characteristics



- Regrowth with thermal treatment reached $V_{revs.}$ > 1500V (@ 1μA)
- Regrowth on "as-grown" diode repeated
- ICP-etched reached $V_{revs.}$ ~1000V (@ 1μA)

- Very low forward current leakage indicates a good PN junction (*TDD = low 10^9 cm^{-2}*)

➡ Regrowth of p-AlGaN on *ICP-etched* AlGaN yields kilo-volt class PN diodes with low leakage!

Continuously grown vs. ICP etched and regrown diodes

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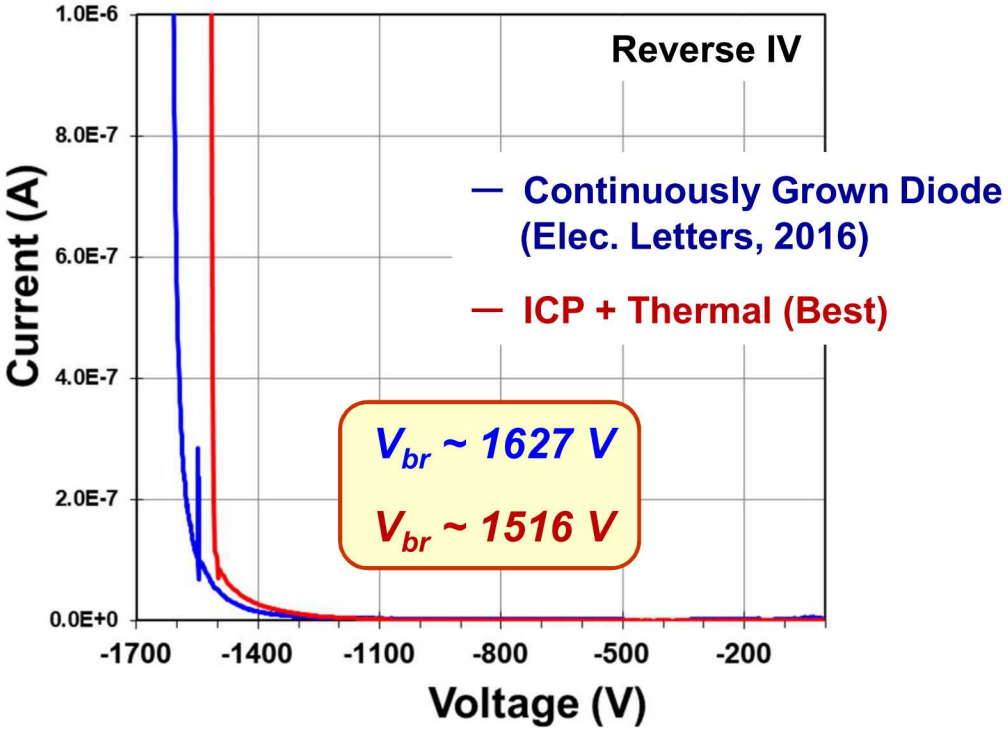
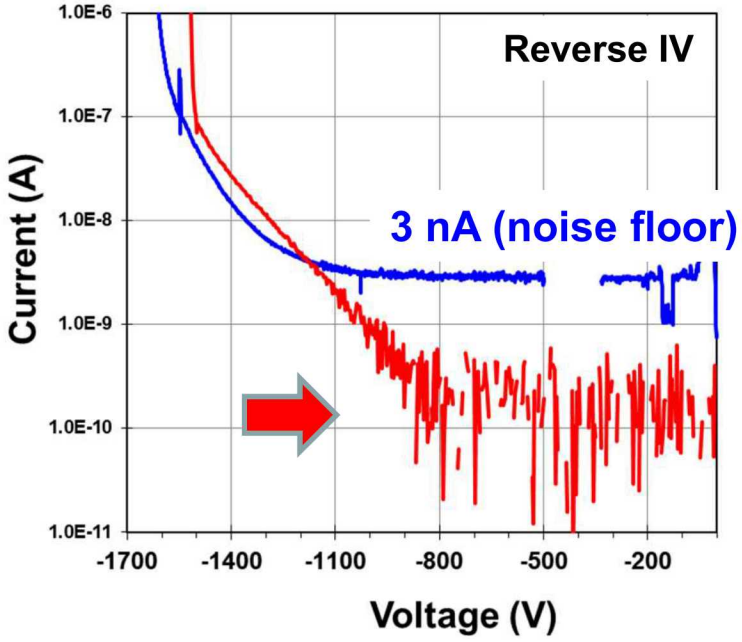
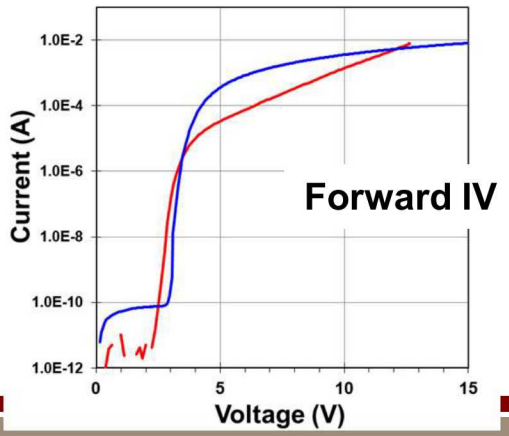
- ***PN Diode IV Characteristics***







➡ **Thermal treatment of ICP-etched drift region can produce AlGaN PN diodes equal to continuously grown diodes (c-plane)**

Outline

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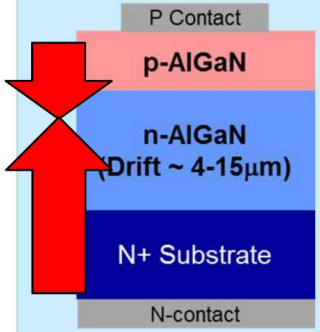
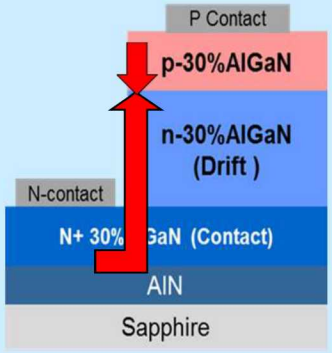
- Introduction
  - AlGaN alloys for power electronics
  - Challenges for vertically conducting power transistors in AlGaN
- "Quasi-vertical" ($Al_{0.3}Ga_{0.7}N$) PN Diodes on sapphire
  - Grown continuously and diodes with *regrown* p-anode
- **Growth of ($Al_{0.3}Ga_{0.7}N$) on patterned N-GaN substrates**
  - **Overgrowth process and pattern geometry**
  - **Threading dislocation density and morphology**
  - **Vertically conducting PN AlGaN diode**
- Summary

Low on-resistance requires vertical geometry diode



Vertical

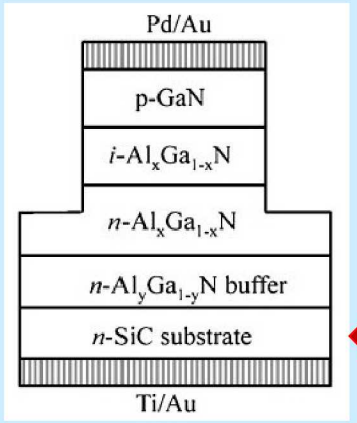


Quasi-vertical

- **Quasi-vertical geometry useful for diode development**
  - **Growth, process & JTE design**
- **Quasi-vertical geometry results on high R_{on} due to current crowding under N-contact**
  - **High resistive losses, low currents**

➡ ***Develop vertically conducting AlGaN diodes***

57%-AlGaN PN diode on n-SiC



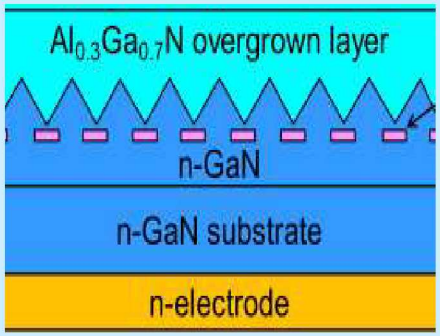
- **0.2 μm drift**
- **V_{br} < 200V**

R_{on}: 1.5 mΩ-cm²

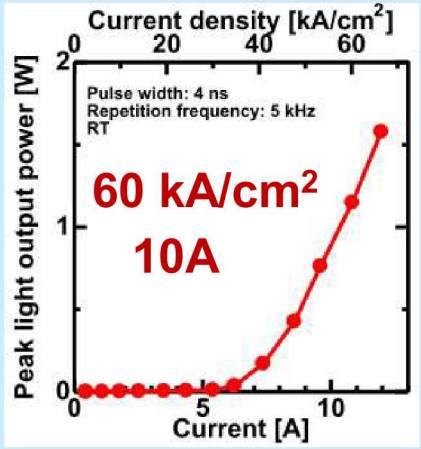
⬅ **n-SiC**

Nishikawa Jpn J. App. Phys. 2007

338 nm laser diode on n-GaN Substrates



Taketomi, Jpn J Appl Phys 2016



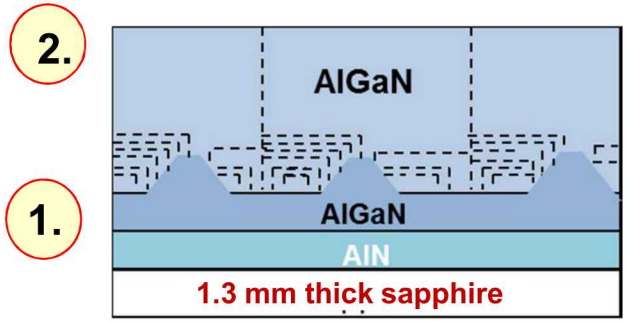
Sandia's AlGaN overgrowth of patterned templates

Sandia National Laboratories

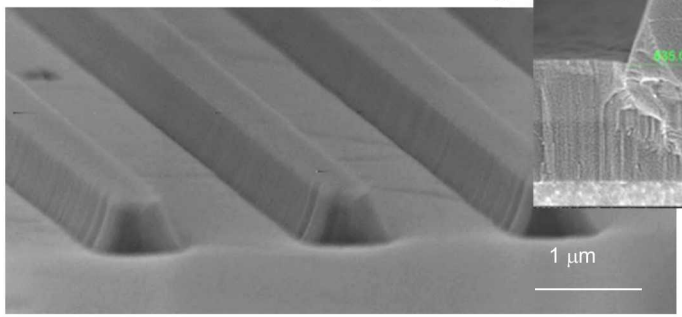
AlGaN Growth on Patterned Templates

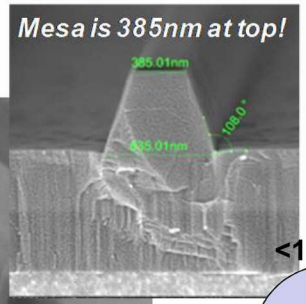
Allerman et. al., JCG 2014

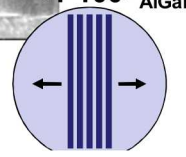
AlGaN with reduced dislocations



Trenches formed by etching

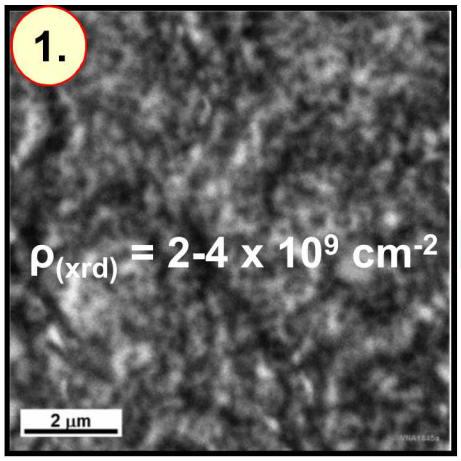


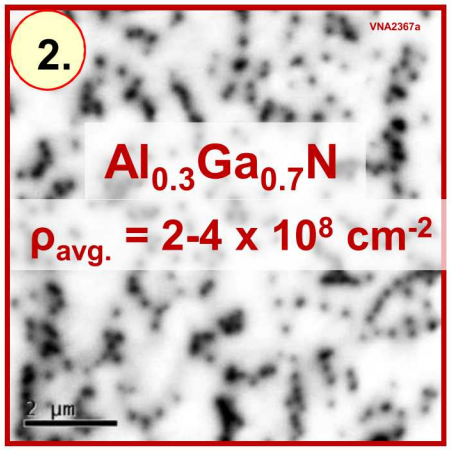




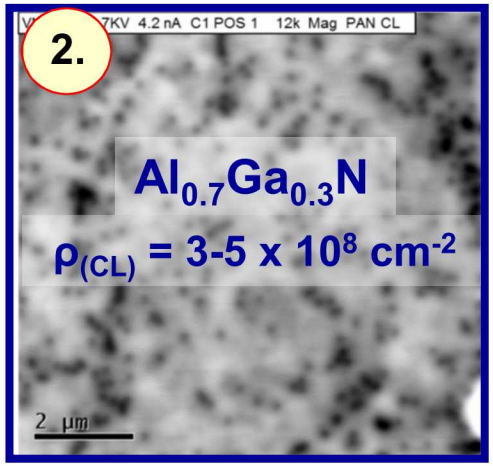
➡ *Sub-micron features are key for uniform reduction of dislocations*

Cathodoluminescence





10-20X reduction



10-15x reduction

$Al_xGa_{1-x}N$ (X = 0.3) overgrowth on n-type GaN substrates

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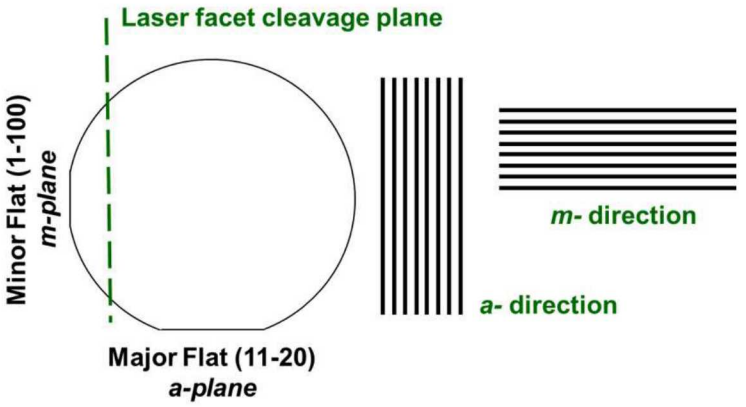
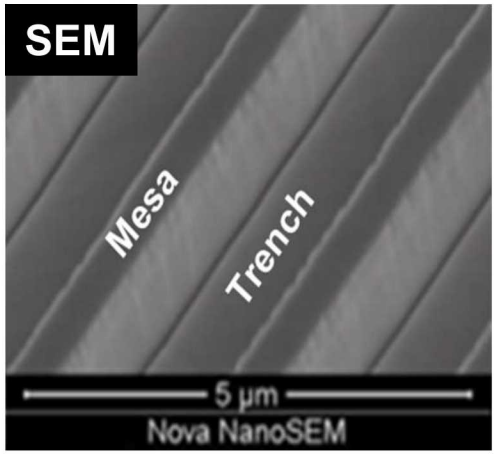
Patterned and etched GaN substrates

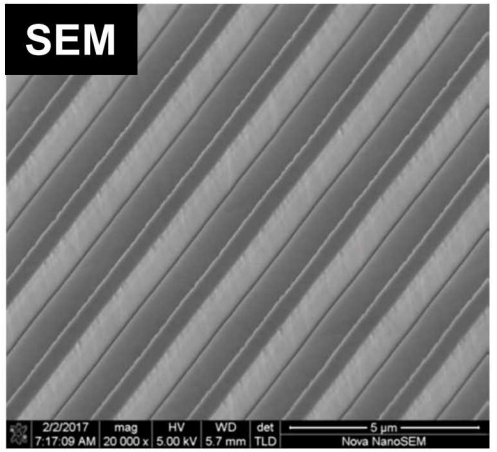
- Geometry: 1, 3 μm (mesa width)
  x 3, 1 μm (trench depth)
- Etch depth: 0.7 and 1.2 μm
- Trench alignment: <1-100> & <11-20>



Growth conditions (27-32%AlGaN)

- Veeco D-125
- V/III ratio: 720 - 1761
- Group-III flux: 44 – 81 μmoles/min
- Growth rate: 0.5 – 0.75 μm/hr
- Temperature: 1050 – 1070°C
- Pressure: 75 torr





$Al_xGa_{1-x}N$ (X = 0.3) overgrowth of patterned GaN — trench orientation

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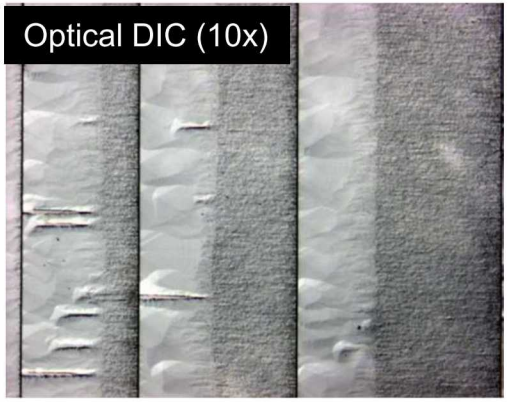
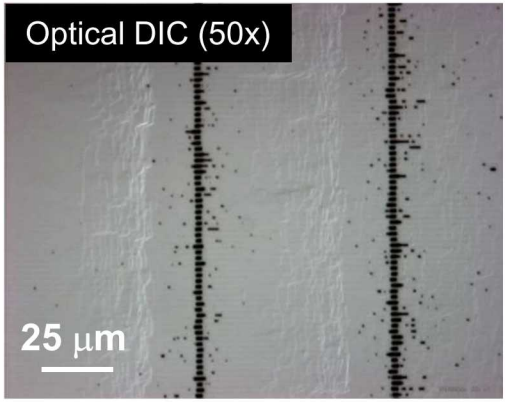
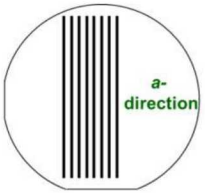
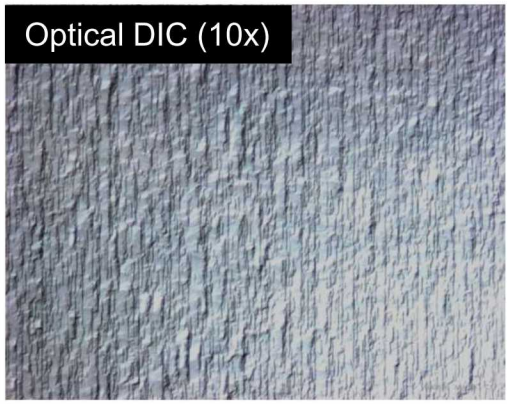
30%-AlGaN overgrowth of patterned GaN — trench orientation

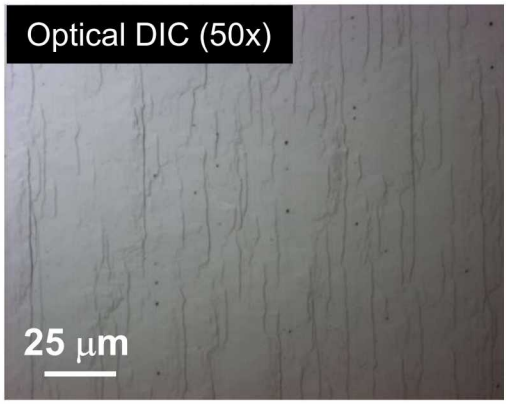




- Cracking perpendicular to trench (m-plane)
- Step bunching due to cracks
- Observed in all growth conditions tested







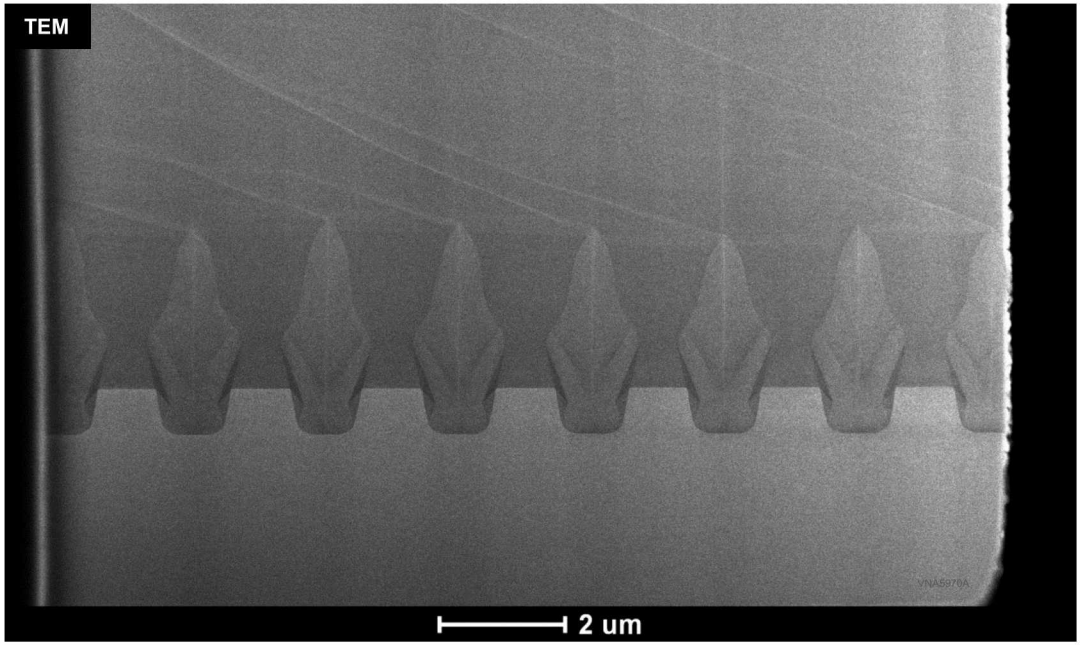
- Cracking perpendicular to trench (a-plane) most common
- Step bunching randomly distributed
- Large wafer bow

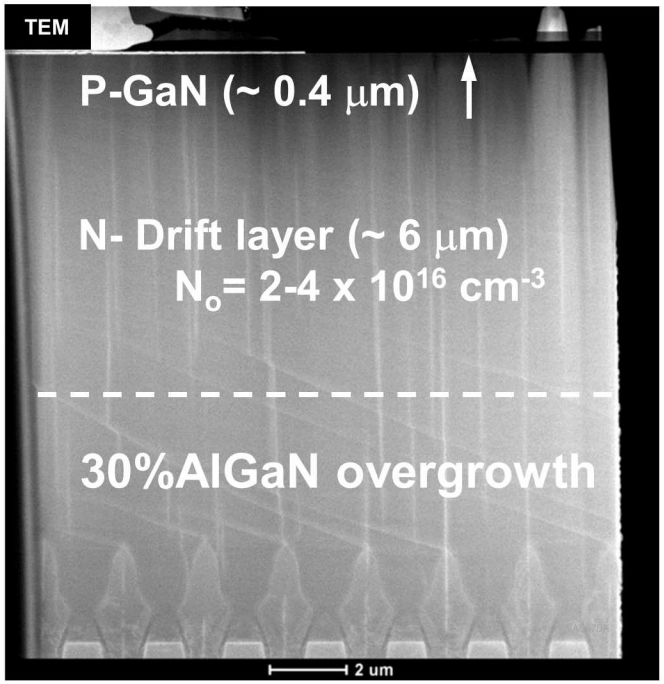
Vertical $Al_{0.3}Ga_{0.7}N$ PN diode on a conducting GaN substrate

Sandia National Laboratories

STEM - Vertical PN in 30%AlGaN

- Large variation in Al composition during film coalescence
- Composition is uniform once coalescence is complete





30%AlGaN overgrowth of patterned GaN

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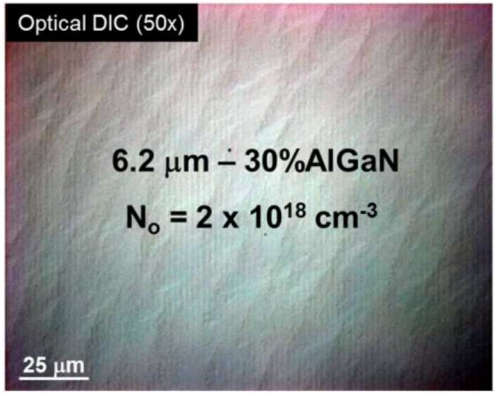
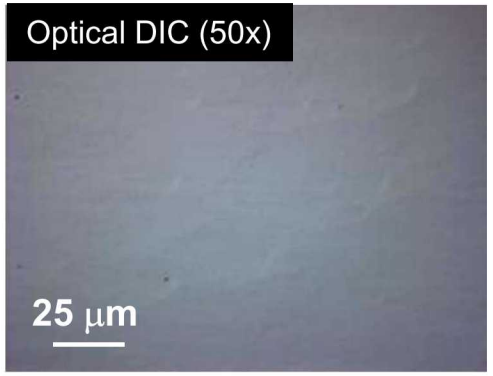
30%AlGaN overgrowth on patterned GaN

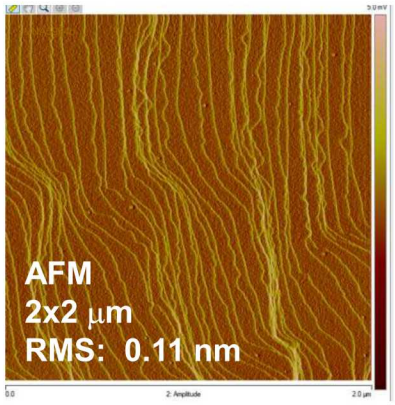


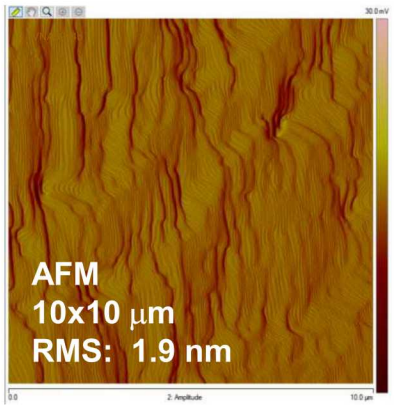
- N-type doping during overgrowth
  - N_o to 2 x 10^{18} cm^{-3}
- X_{al} 0.18 – 0.32 similar morphology
- Planar surface up to X_{al} = 0.45
- More step bunching on GaN (conditions and wafer miscut)



30%AlGaN on patterned GaN

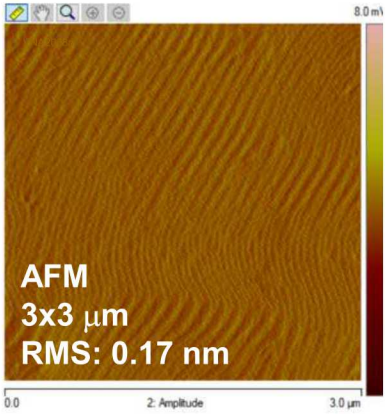
Overgrowth: 6.2 μm
Pattern: 0.67 μm, (1x1)

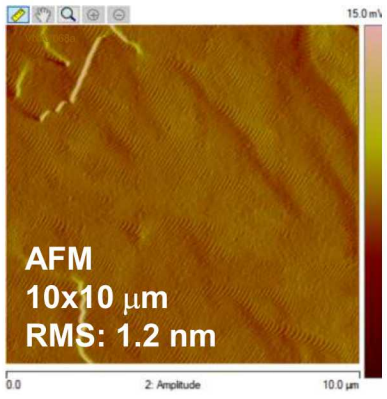




30%AlGaN on patterned AlGaN/sapphire

Overgrowth: 6 μm
Pattern: 0.56 μm, (1x1)





30%AlGaN overgrowth of patterned GaN

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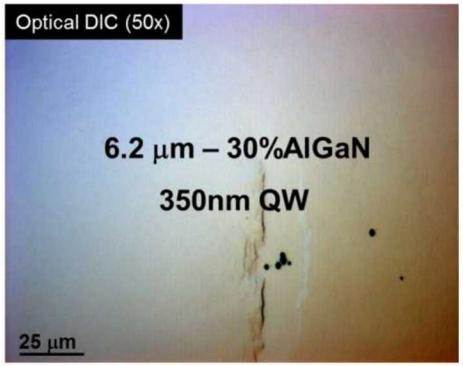
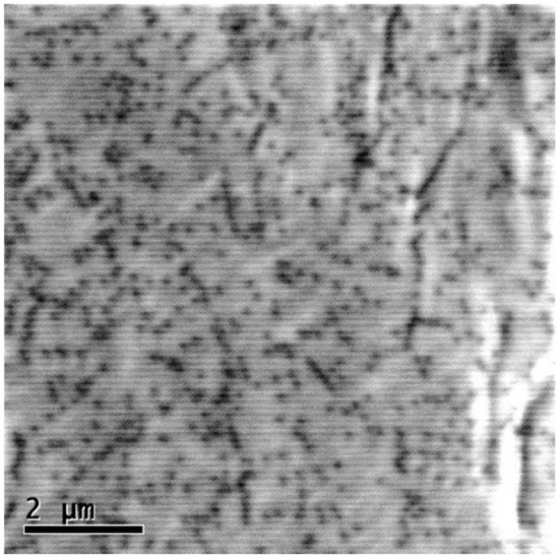
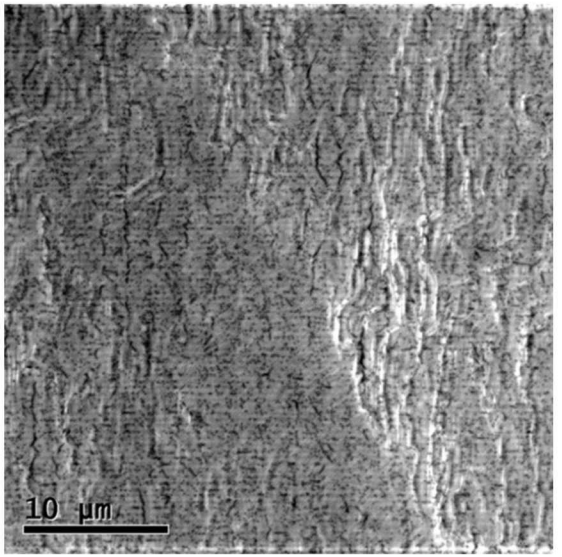
AlGaN on patterned GaN

Overgrowth: 8.3 μm

Pattern: 1.3 μm, (1x1)



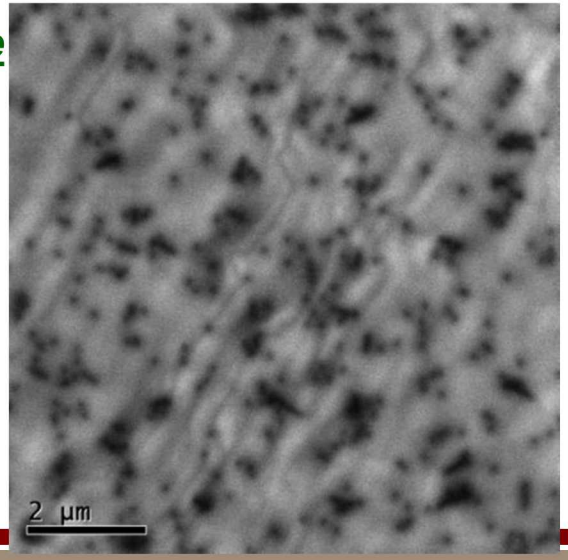


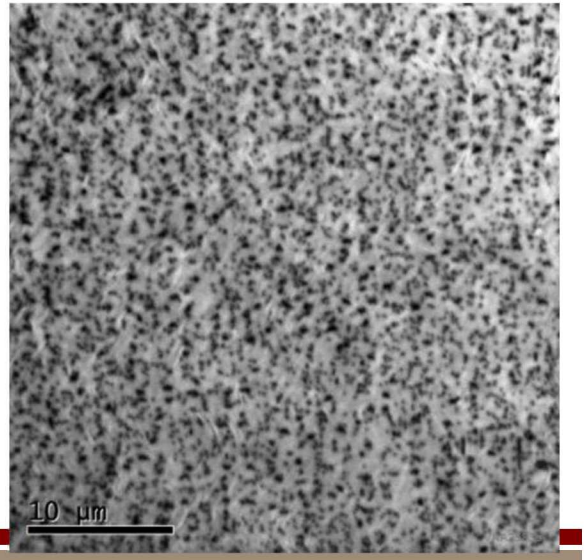


AlGaN on patterned AlGaN/sapphire

Overgrowth: 7 μm

Pattern: 0.66 μm, (1x1)





TTD = 2-5 x 10^8 cm^{-2}

➡ **Similar TTD as AlGaN on sapphire**

Vertical $Al_{0.3}Ga_{0.7}N$ PN diode on conducting GaN substrates

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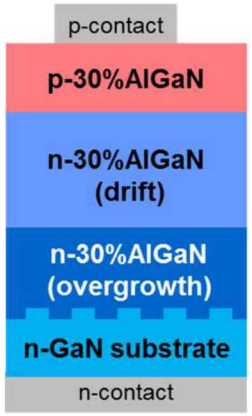
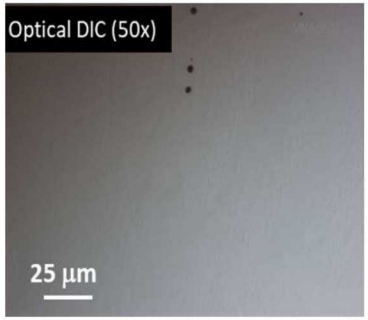
Vertical PN diode in 30%AlGaN



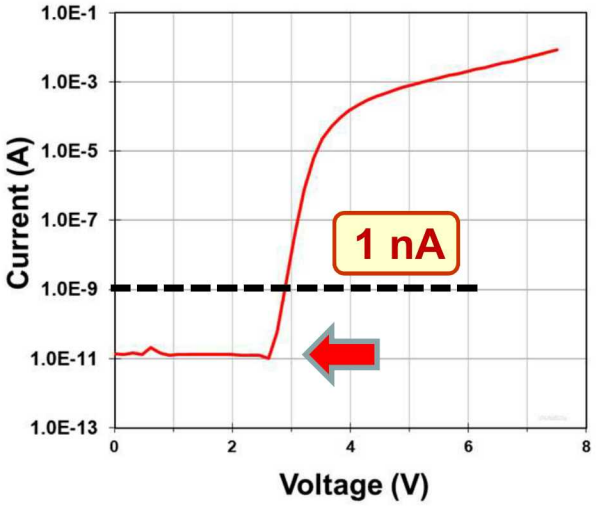
- Drift: t = 5.3 μm
  N_o = 2-4 x 10^{16} cm^{-3}
- Overgrowth:
  t = 6.2 μm

Total : 11.8 μm

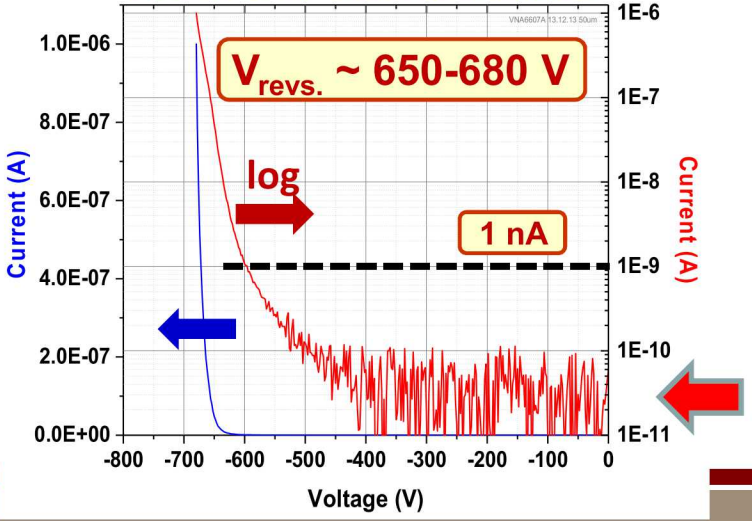


$R_{sp\text{-}on}$ = 1 mΩ-cm²

Forward IV Characteristics



Reverse IV Characteristics



- Much cracking on wafer
- Reverse voltage reached 650-680 V (@ 1μA)
- Low forward. and reverse current leakage

$I_{revs.}$ < 100 pA to 500V

Summary

Sandia National Laboratories

- **Quasi-vertical $Al_{0.3}Ga_{0.7}$ N PIN diodes with regrown PN junction on etched drift layer**
  - **Reverse voltages to 1500 V (@ 1 μA) with n-type drift layer of 6 μm**
  - **Reverse leakage < 3 nA to V_{res} = 1000 V**

    ➡ ***IV characteristics equal to continuously grown PN diodes***

- **Growth of $Al_{0.3}Ga_{0.7}$ on patterned N-GaN substrates**
  - **Threading dislocation density of 3-5 x 10^8 cm^{-2}**
  - **Coalesced - $Al_xGa_{1-x}N$ up to X = 0.45**
  - **$Al_{0.3}Ga_{0.7}N$ overgrowth > 12 μm achieved for vertical PN diodes**
  - **Vertical PN diodes in $Al_{0.3}Ga_{0.7}N$, V_{revs} = 650-680 V (@1 μA)**

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

AlGaN work funded by the Laboratory Directed Research & Development program, Sandia National Laboratories