



Development of High Al-content AlGaN Vertical Diodes for Radiation Studies

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AFOSR Radiation Damage Review 2024

In conjunction with ARO Ultra-wide Bandgap RF Center
(Tom Oder, ARO PM ... OSU lead PI Siddharth Rajan)



Recent work:

Developed high voltage/high electric field diodes

GaN pn junctions

Punch through structures ... average reverse bias field ~ 2.5 MV/cm

→ single event studies

β -Ga₂O₃ Schottky diodes

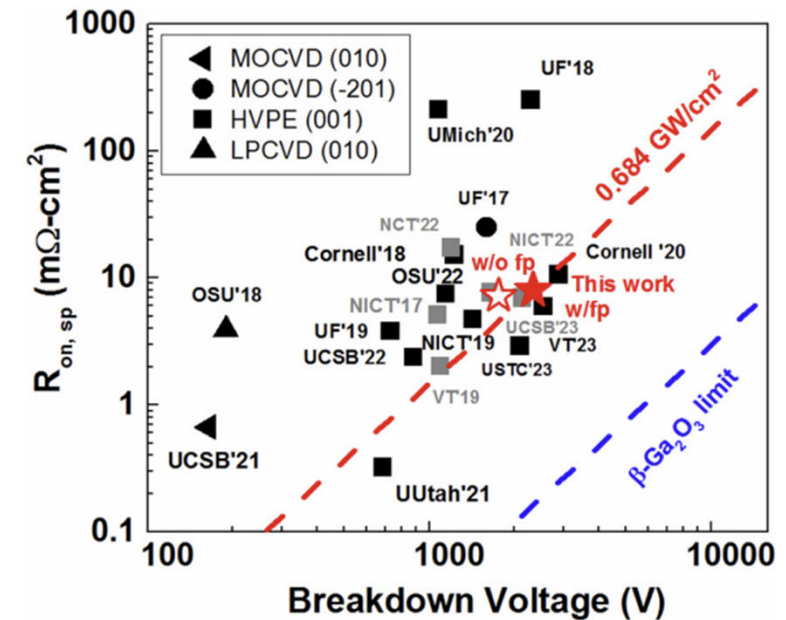
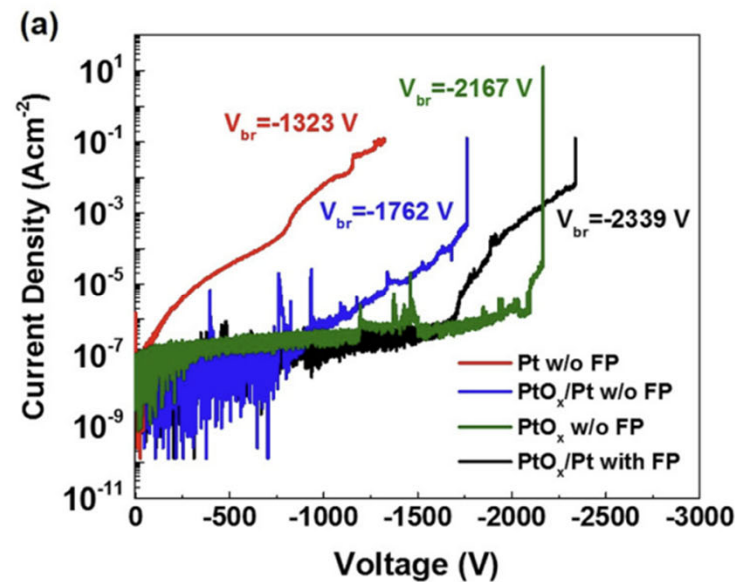
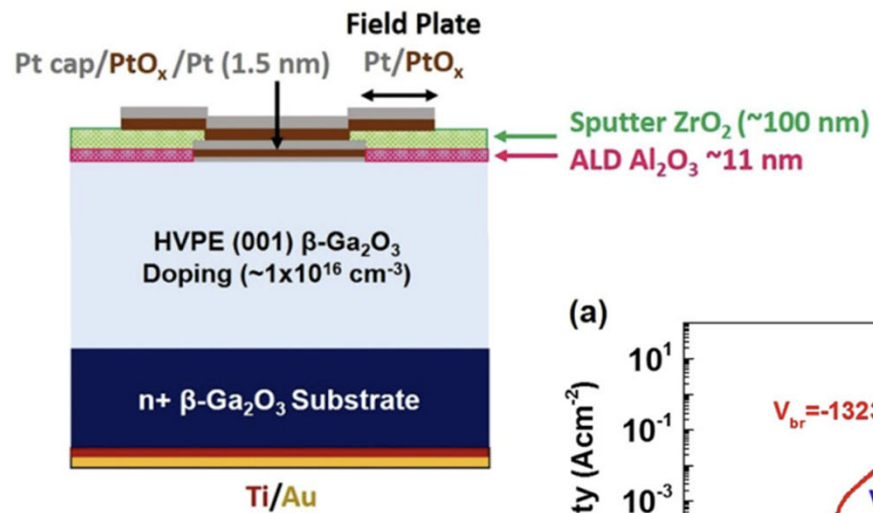
Use of mid and high κ dielectrics for field management/edge termination

→ single event studies

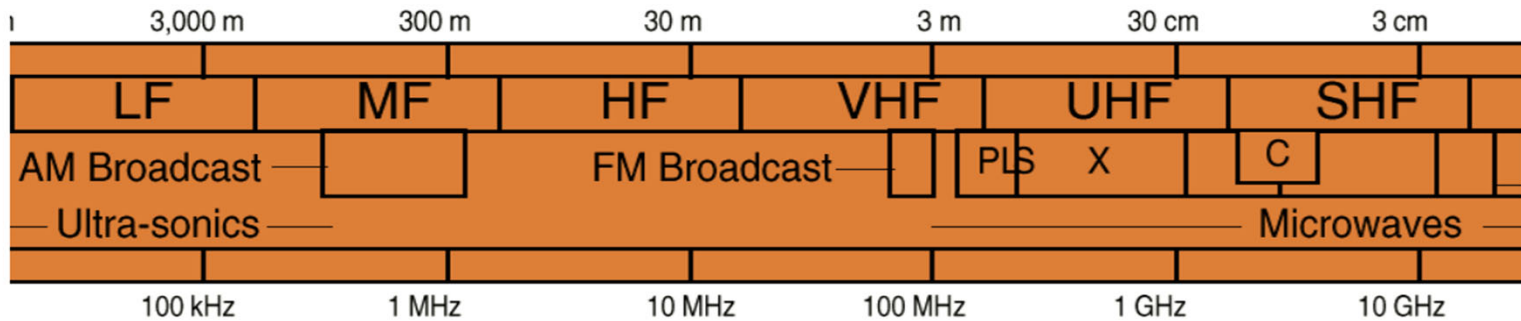
Current work:

Developing high Al content AlGa_N diodes

Low Leakage, High Breakdown Voltage β -Ga₂O₃ Device



- **Introduction**
- Materials Optimization
- Device Design
- Device Fabrication
- Device Measurements
- Conclusions and Future Work



W band
mm wave

THE RADIO SPECTRUM

**New materials for extreme environments and
high frequency electronics**

$\beta\text{-Ga}_2\text{O}_3$

GaN, AlGaN, AlN

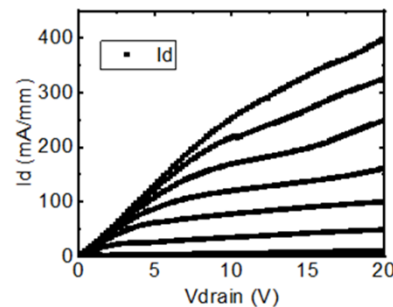
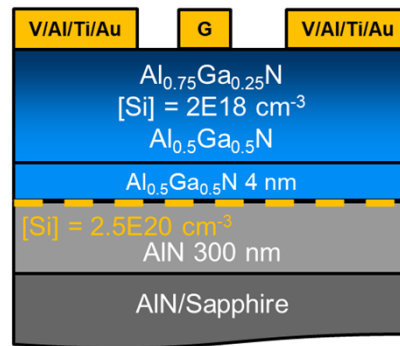
Why AlGaN?

UV-LEDs

(a)	p-GaN	20 nm
	p-Al _{0.8} Ga _{0.2} N/Al _{0.2} Ga _{0.8} N SPSL	20 x (1 nm / 1 nm)
	p-Al _{0.8} Ga _{0.2} N EBL	5 nm
	UID Al _{0.8} Ga _{0.2} N Spacer	14 nm
x6	UID Al _{0.8} Ga _{0.2} N QB	14 nm
	UID Al _{0.5} Ga _{0.5} N QW	1.5 nm
	n-Al _{0.8} Ga _{0.2} N/Al _{0.6} Ga _{0.4} N Smoothing Superlattice	3 x (14 nm / 14 nm)
	n-Al _{0.65} Ga _{0.35} N	400 nm
	UID-Al _{0.85} Ga _{0.15} N	70 nm
	AlN	600 nm
	Sapphire	500 μm

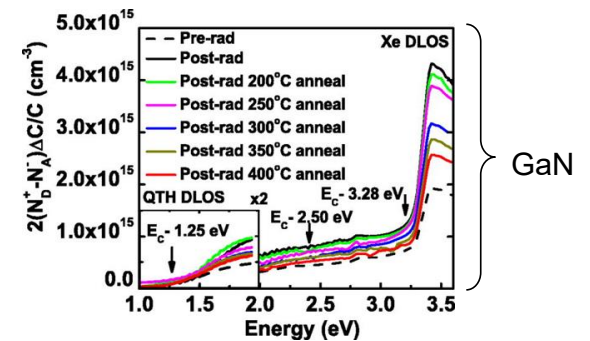
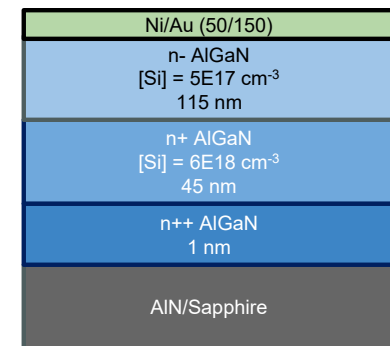


Lateral Power Transistors



Key Applications

DLOS / Radiation Effects

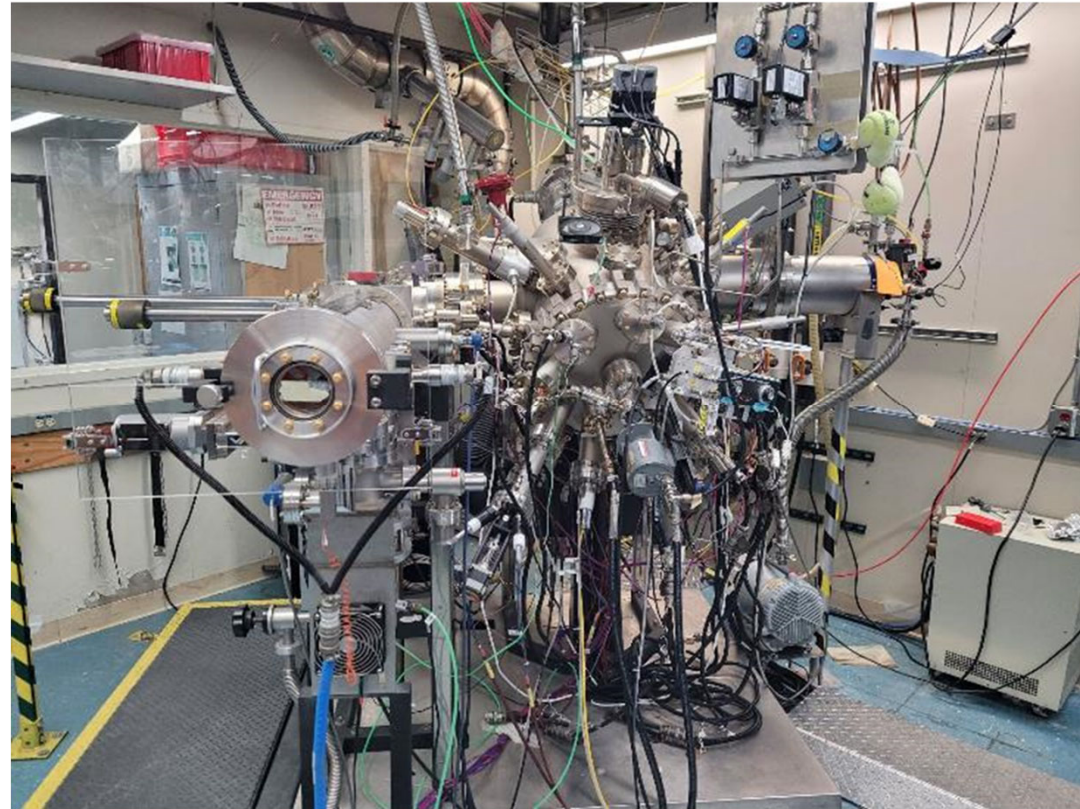


Test Structures

- NH₃-MBE is an ultra-high vacuum thin film growth technique
- Favors N-rich growth regime - better for leakage in vertical devices
- High purity, high mobility, conductive material

Key NH₃-MBE research highlight

- High conductivity n-Al_{0.6}Ga_{0.4}N
- Ohmic contact achieved with V-based stack
- **$n = 4 \times 10^{19} \text{ cm}^{-3}$,**
- **$R = 3 \text{ m}\Omega \cdot \text{cm}$,**
- **$\mu = 48 \text{ cm}^2/(\text{V} \cdot \text{s})^*$**

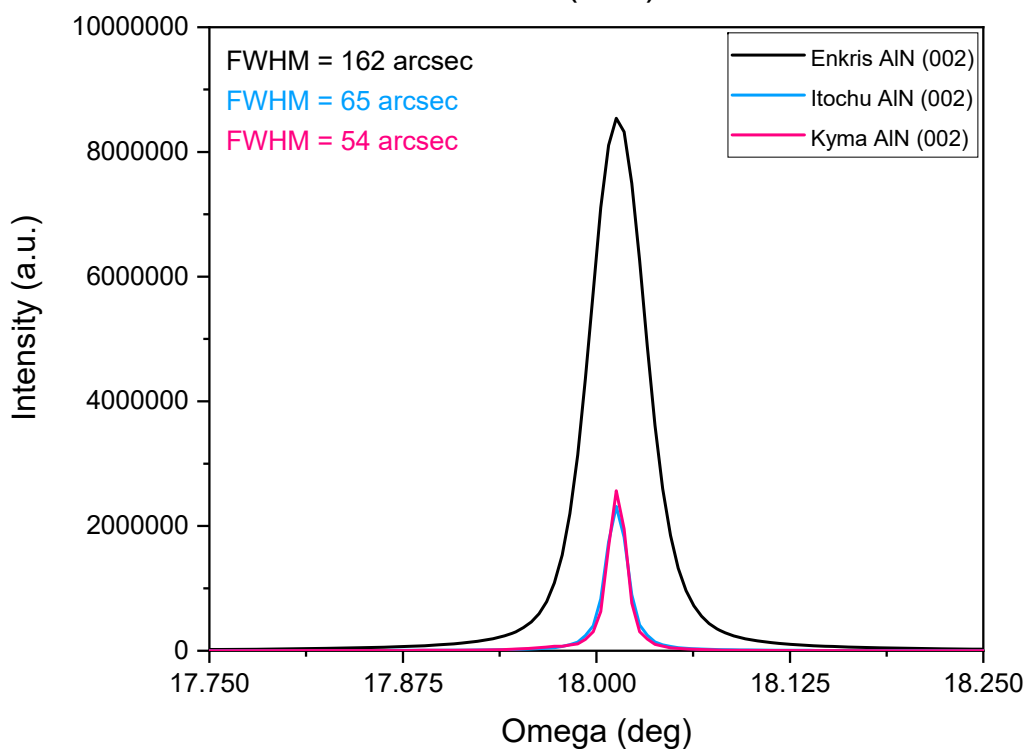


*J. Wang et al, Optics Express **29**, 40781 (2021)

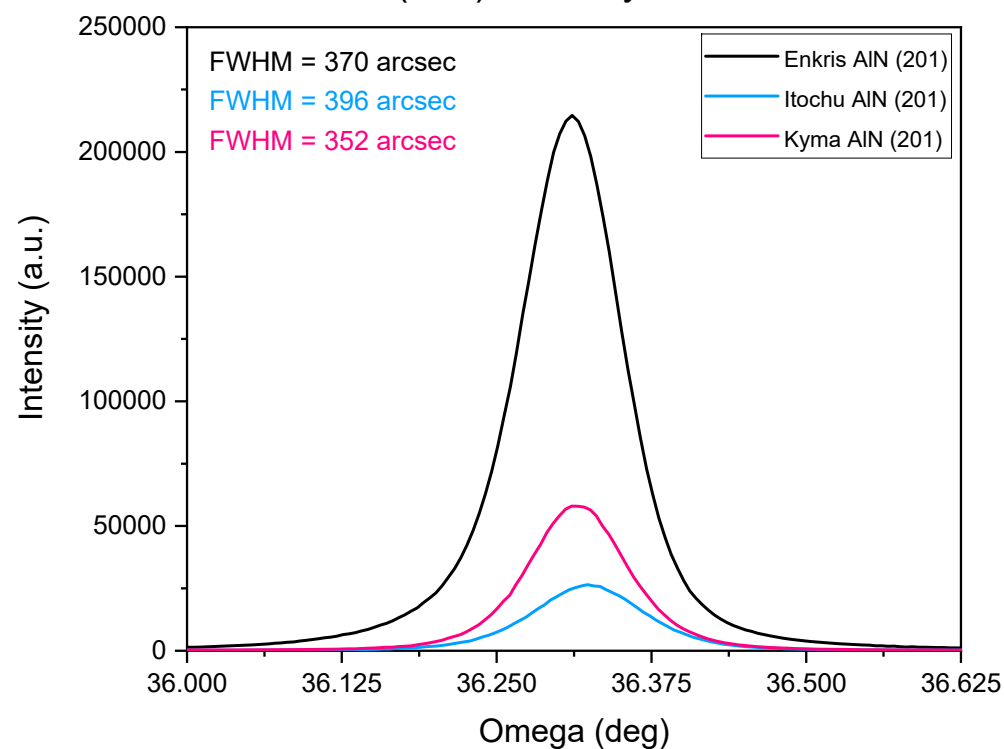
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MOCVD: Enkris Semiconductor Sputtered and Annealed: Itochu and Kyma Technologies

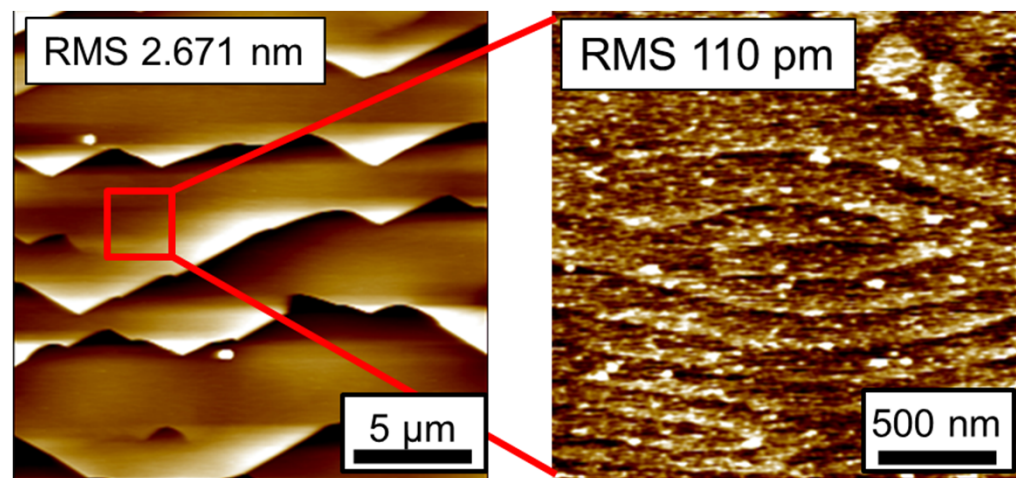
AlN (002)



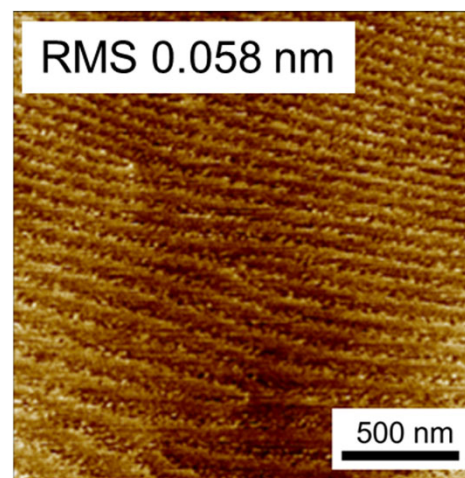
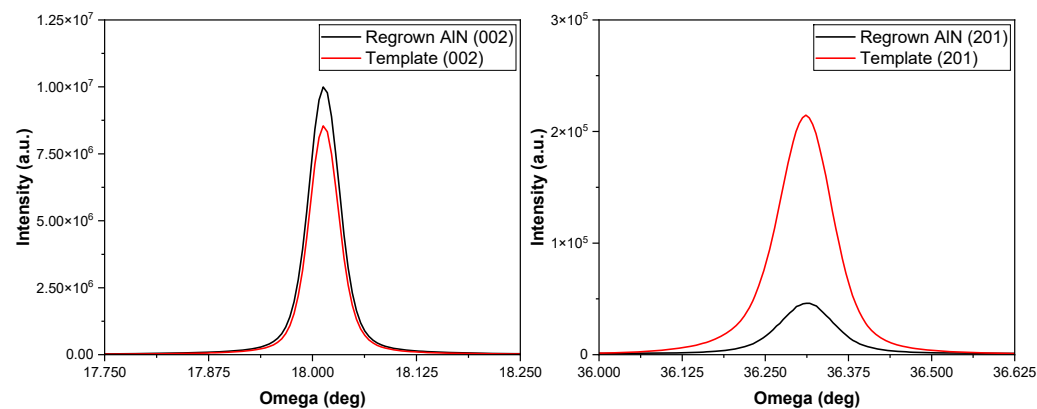
AlN (201) skew-symmetric



AlN Templates vs Regrown AlN

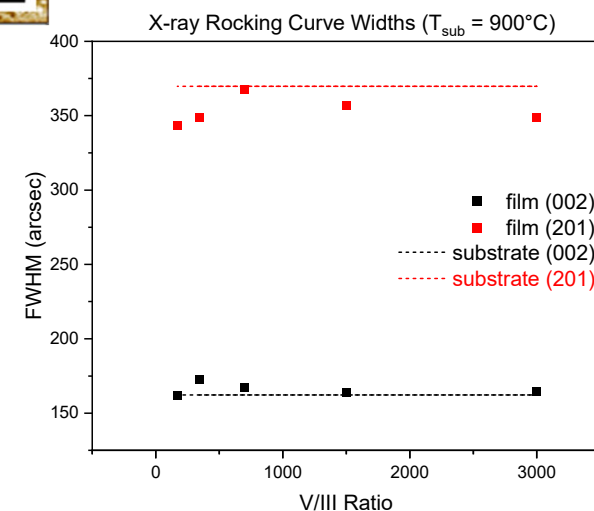
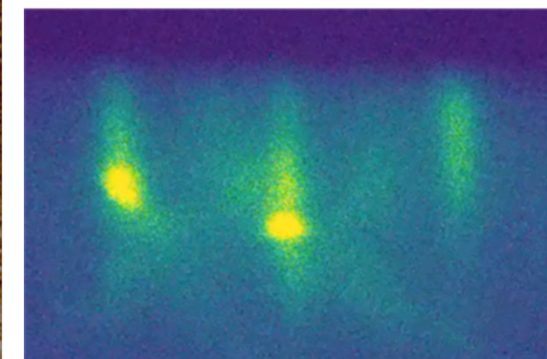


As-received



AlN homoepitaxy

Dislocation density
 $9 \times 10^8 \text{ cm}^{-2}$

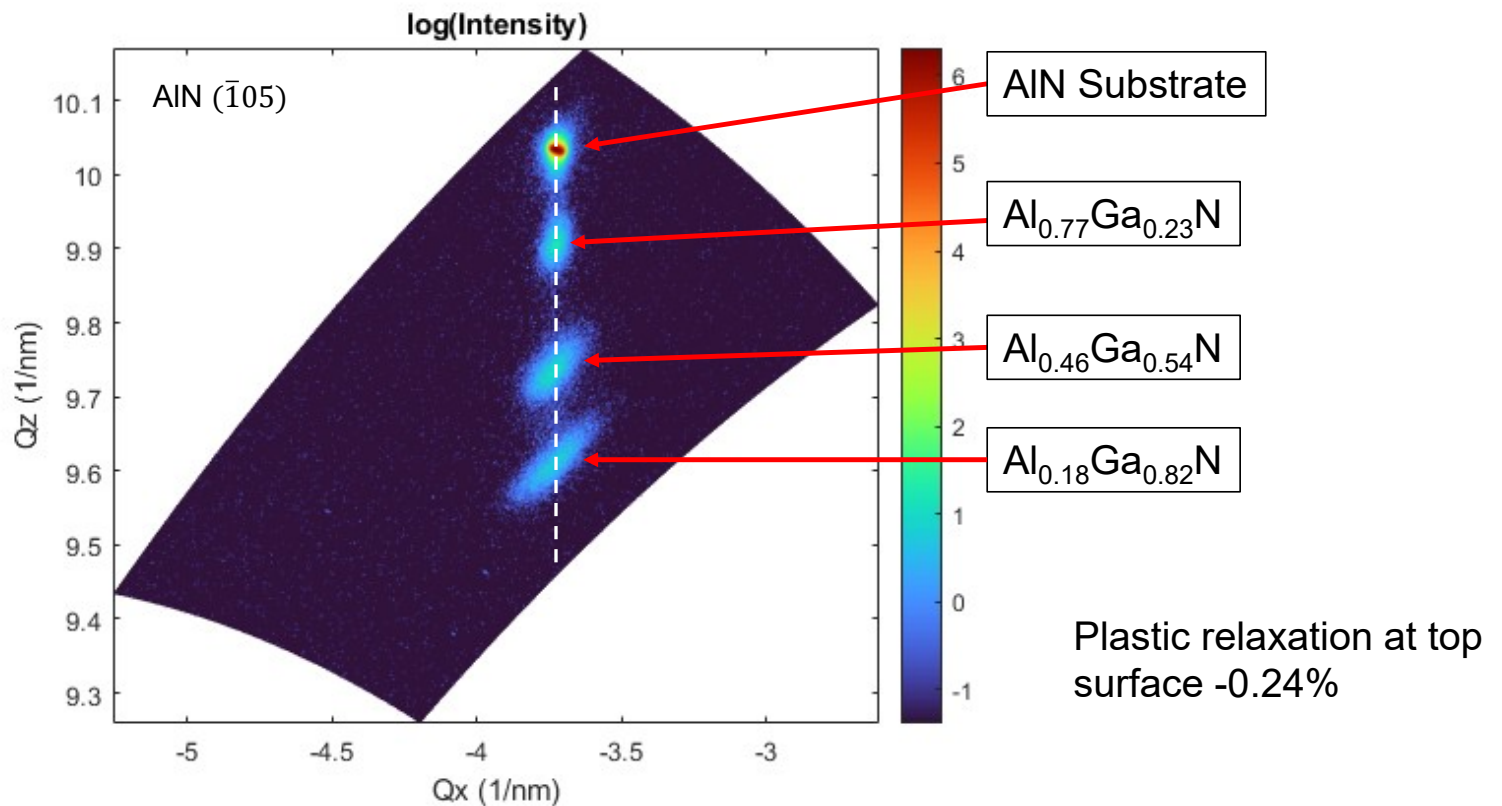


UCSB



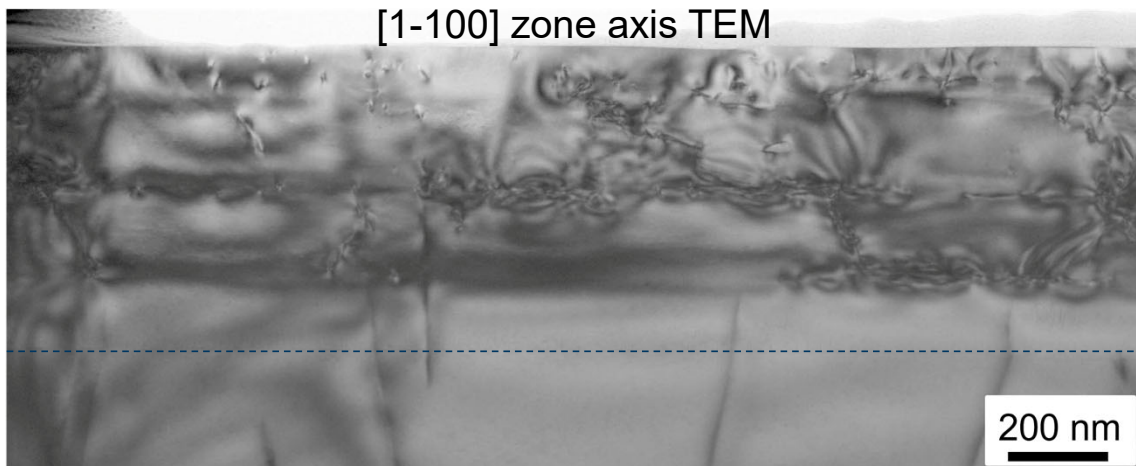
Thick AlGaN Shows Plastic Relaxation

RSM shows mosaic broadening of lower Al-content peaks

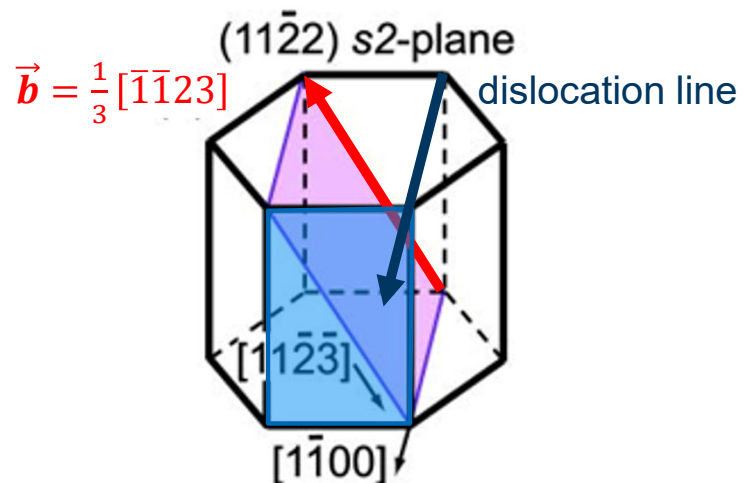
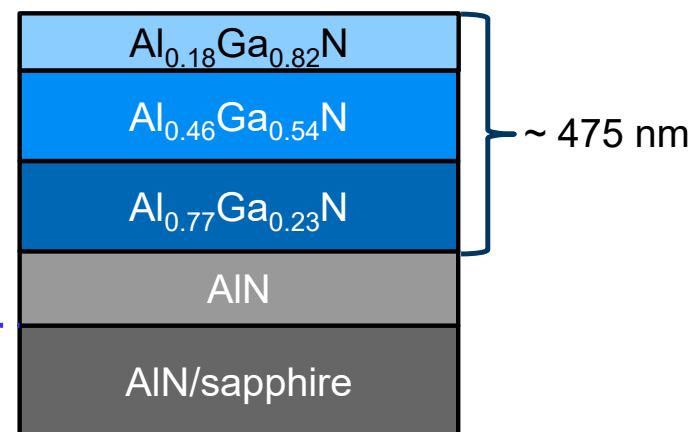


AlGaN Relaxation Mechanism

[1-100] zone axis TEM



regrowth
interface

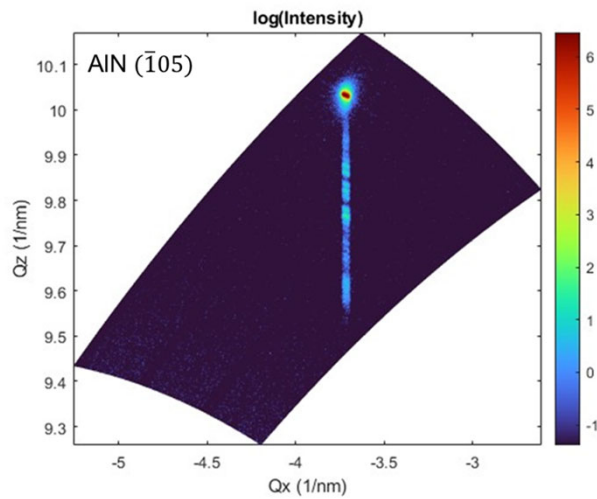
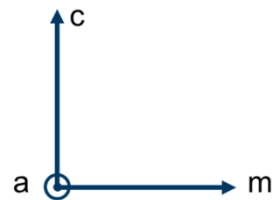
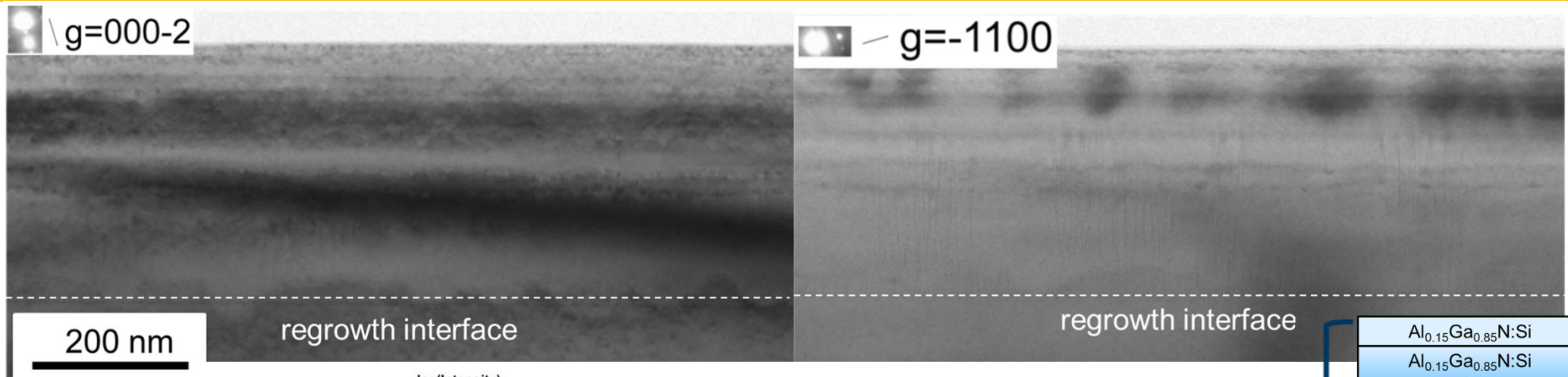


$\frac{1}{3}\langle 11\bar{2}3 \rangle \{11\bar{2}2\}$ slip system

Pure edge dislocations with $\frac{1}{3}\langle 11\bar{2}3 \rangle$ Burger's vector

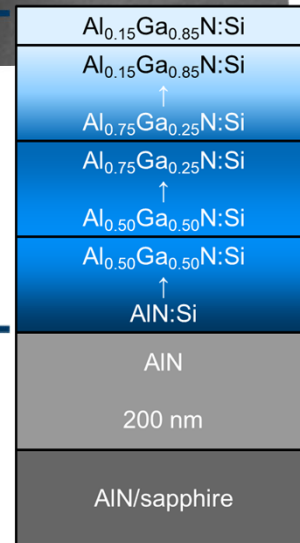
Dislocation lines are $\langle 11\bar{1}00 \rangle$ directions

Thin AlGaN Avoids Relaxation

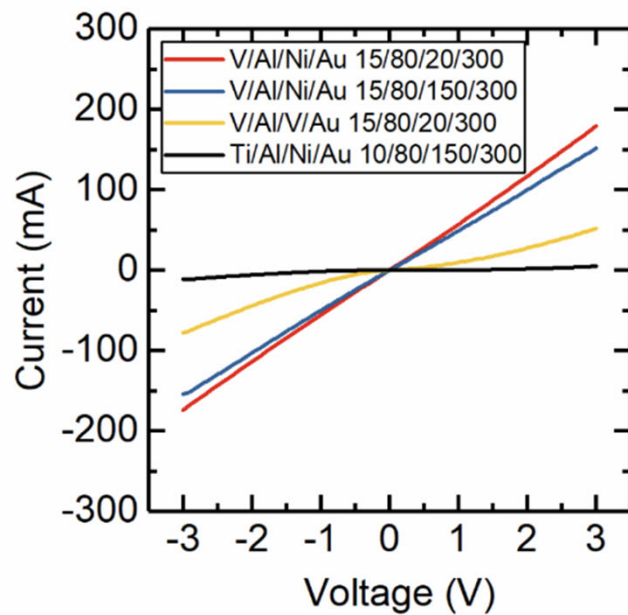


Total AlGaN thickness 145 nm

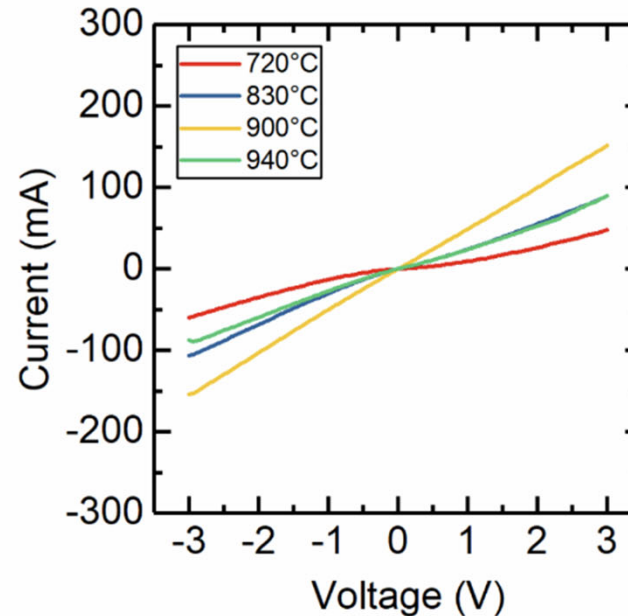
No mosaic broadening in RSM



V-based ohmic contact to n-AlGaIn



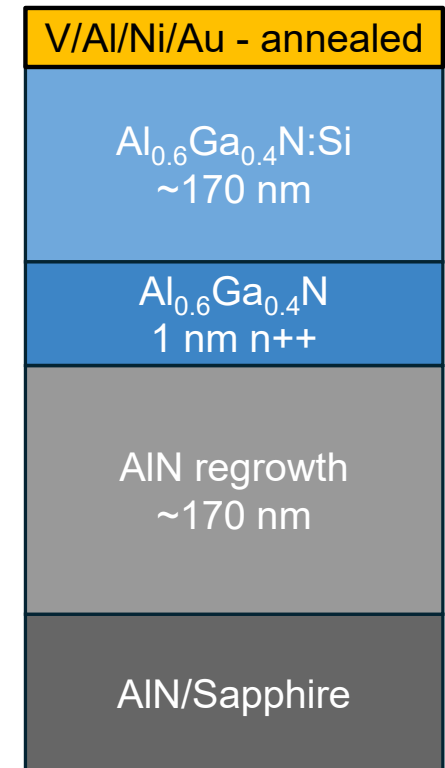
(a)



(b)

*C.J. Zollner et al, Crystals 11, 8, 1006, (2021)

Van der Pauw Hall Effect Structure

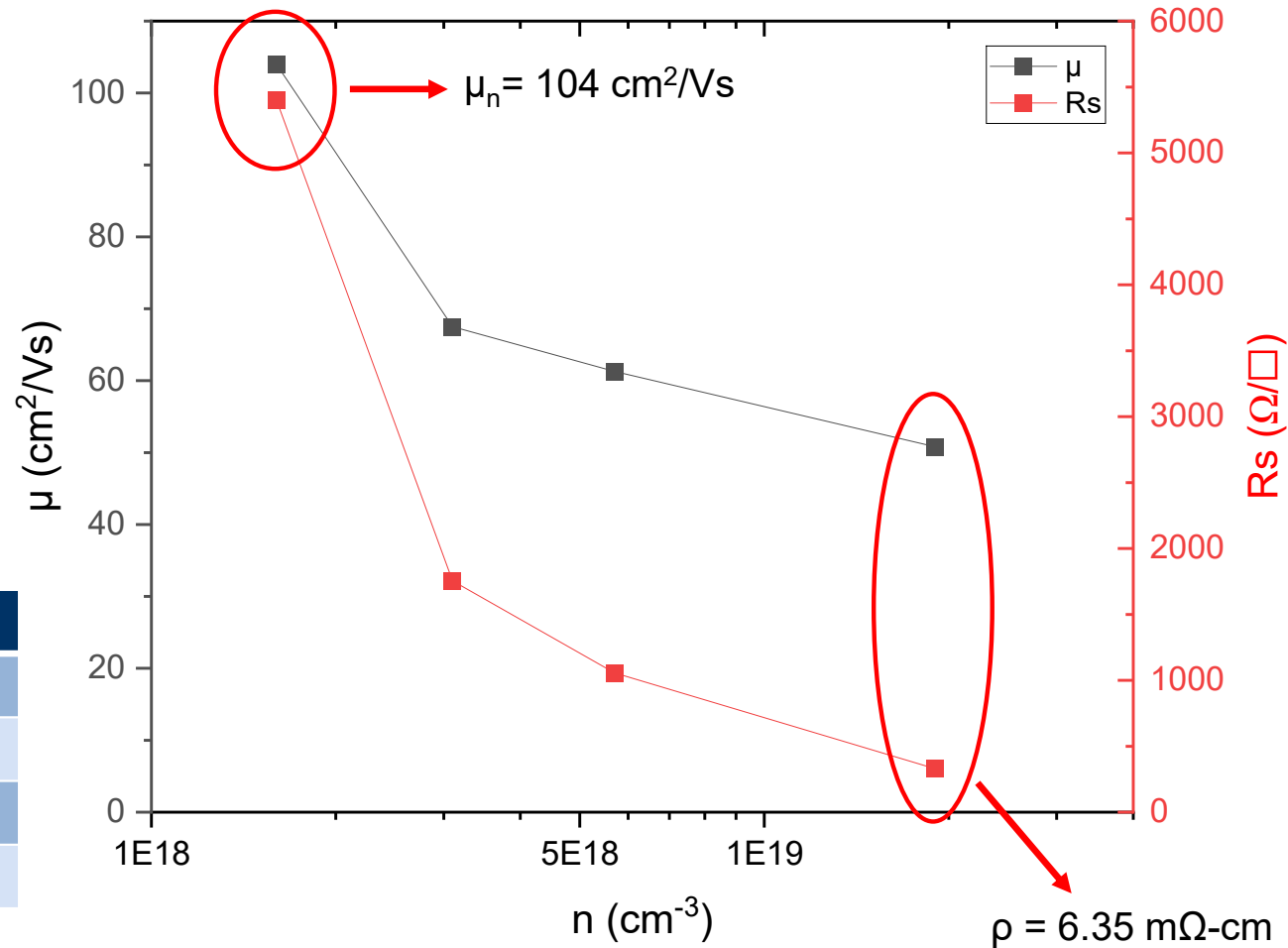


Van der Pauw Hall Data on $\text{Al}_{0.6}\text{Ga}_{0.4}\text{N}$

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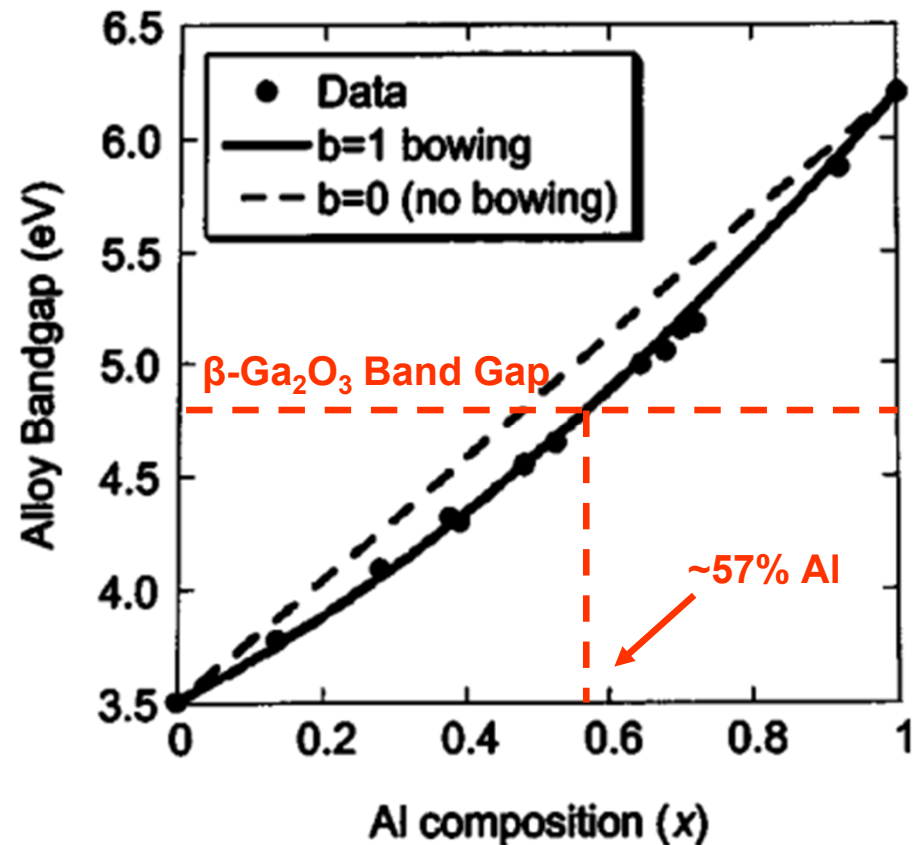
V/Al/Ni/Au - annealed
$\text{Al}_{0.6}\text{Ga}_{0.4}\text{N}:\text{Si}$ ~170 nm
$\text{Al}_{0.6}\text{Ga}_{0.4}\text{N}$ 1 nm n++
AlN regrowth ~170 nm
AlN/Sapphire

[Si] expected (cm^{-3})	n (cm^{-3})
3×10^{18}	1.6×10^{18}
5×10^{18}	3.1×10^{18}
7×10^{18}	5.7×10^{18}
3×10^{19}	1.9×10^{19}



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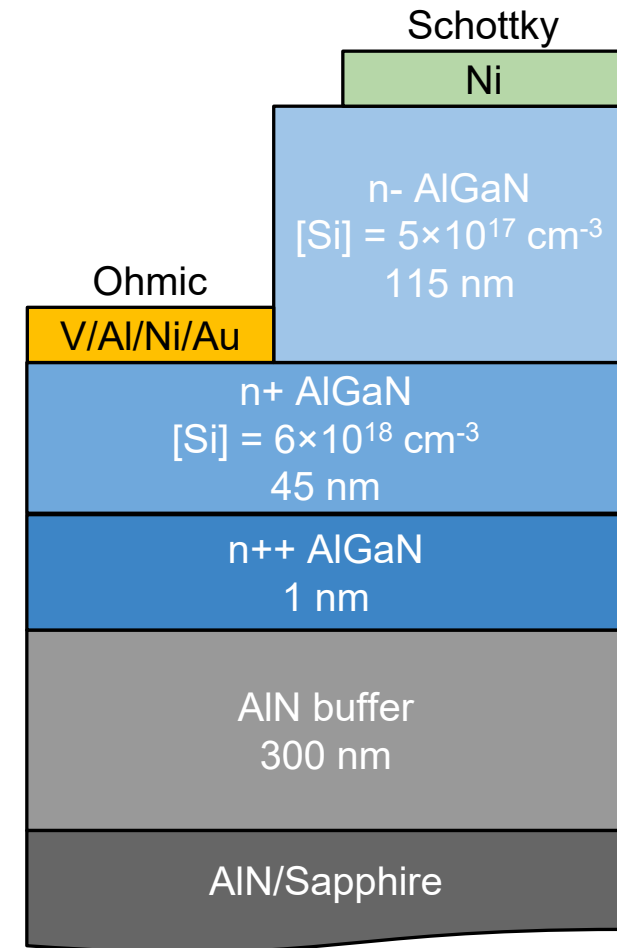
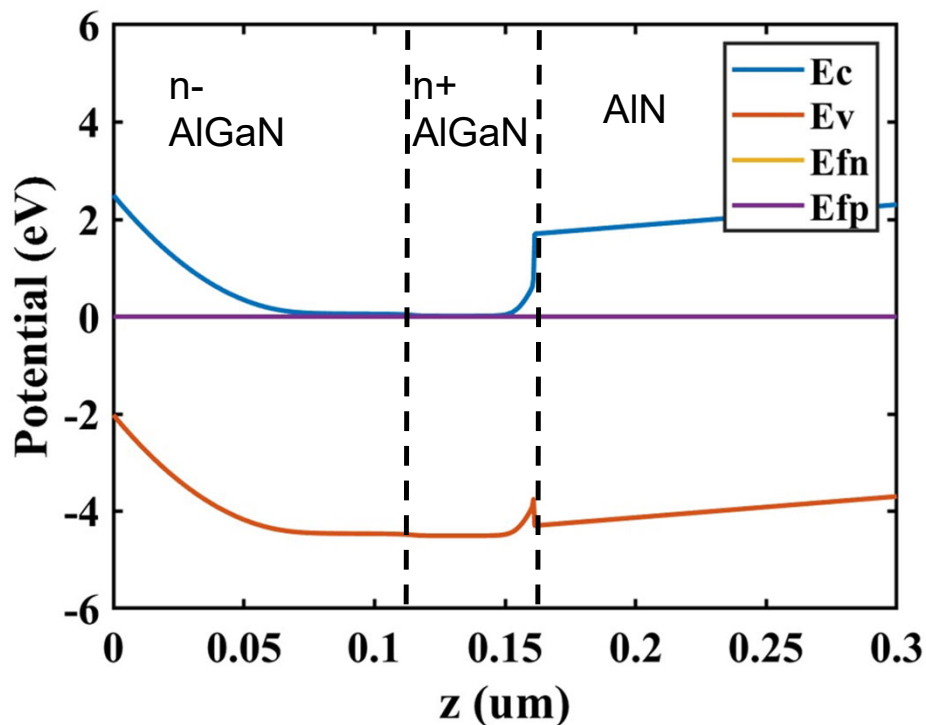
- Study three $\text{Al}_x\text{Ga}_{1-x}\text{N}$ compositions and GaN ($x = 0.5, 0.6, 0.7$)
- Start with unipolar devices (Schottky diodes)
- Radiation testing (collaboration with Ron Schrimpf and Dan Fleetwood, Vanderbilt University)
- DLOS/DLTS before/after radiation (collaboration with Aaron Areheart, The Ohio State University)
- Compare to Ga_2O_3 with equivalent AlGaN band gap



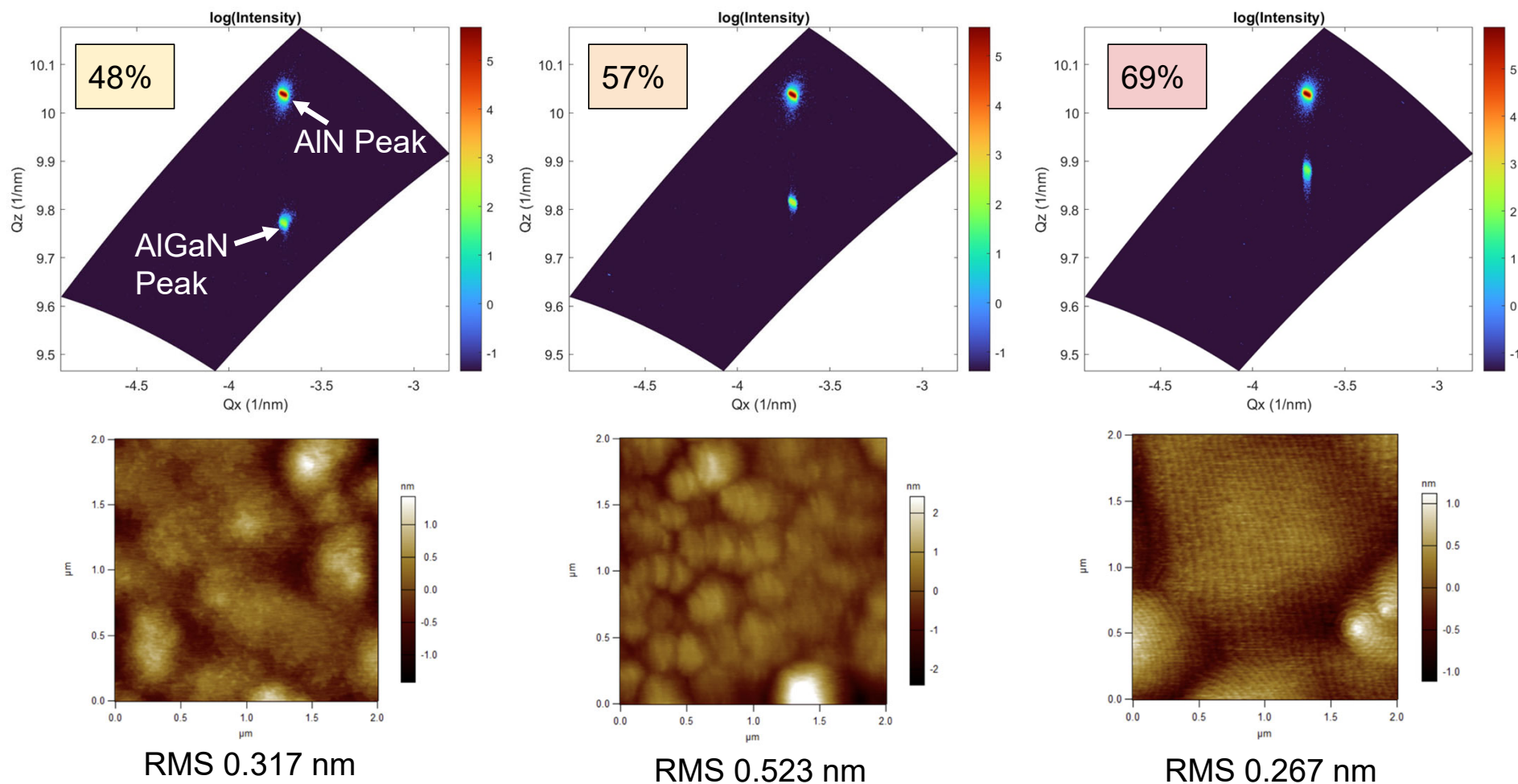
Schottky Diode Design Constraints

- Need to keep total AlGaN thickness low ~160 nm (avoid relaxation)
- Keep depletion depth from M-S junction within n- layer

Band diagram for $\text{Al}_{0.5}\text{Ga}_{0.5}\text{N}$ (zero bias)

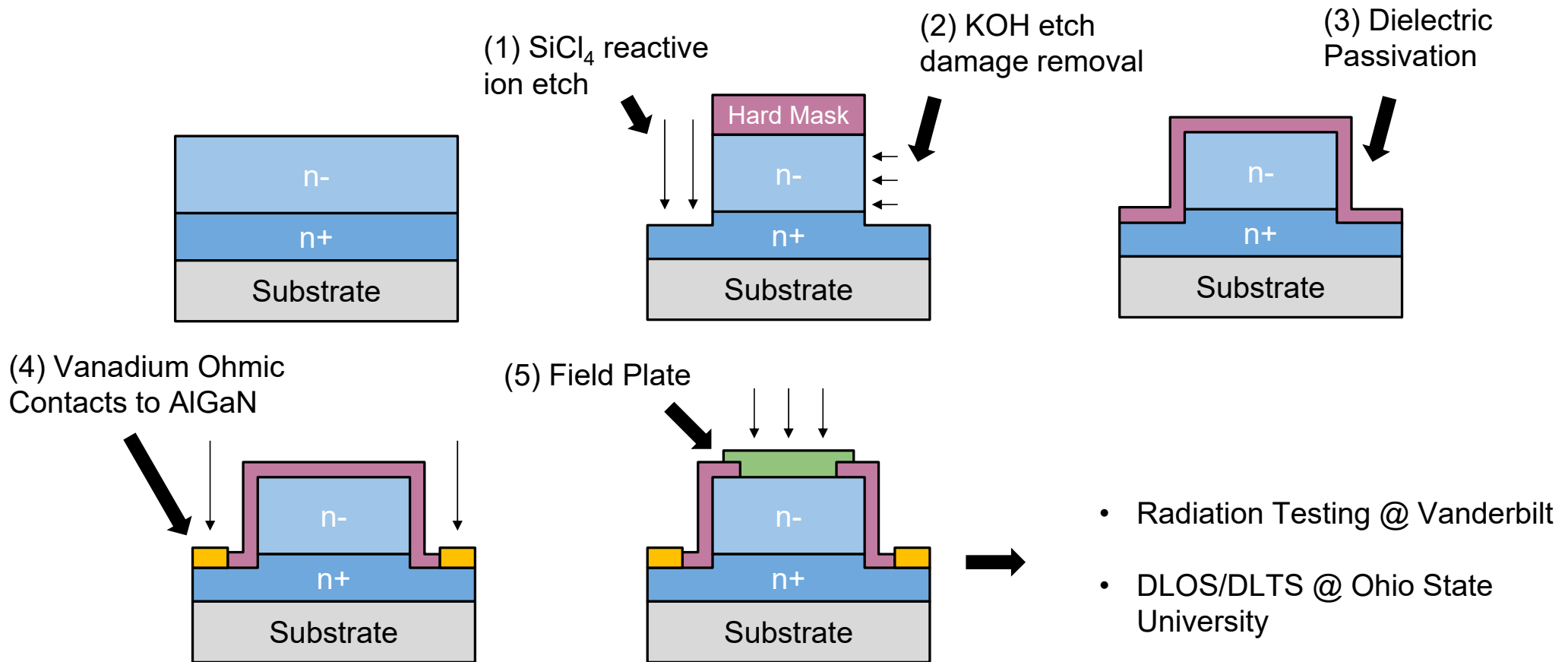


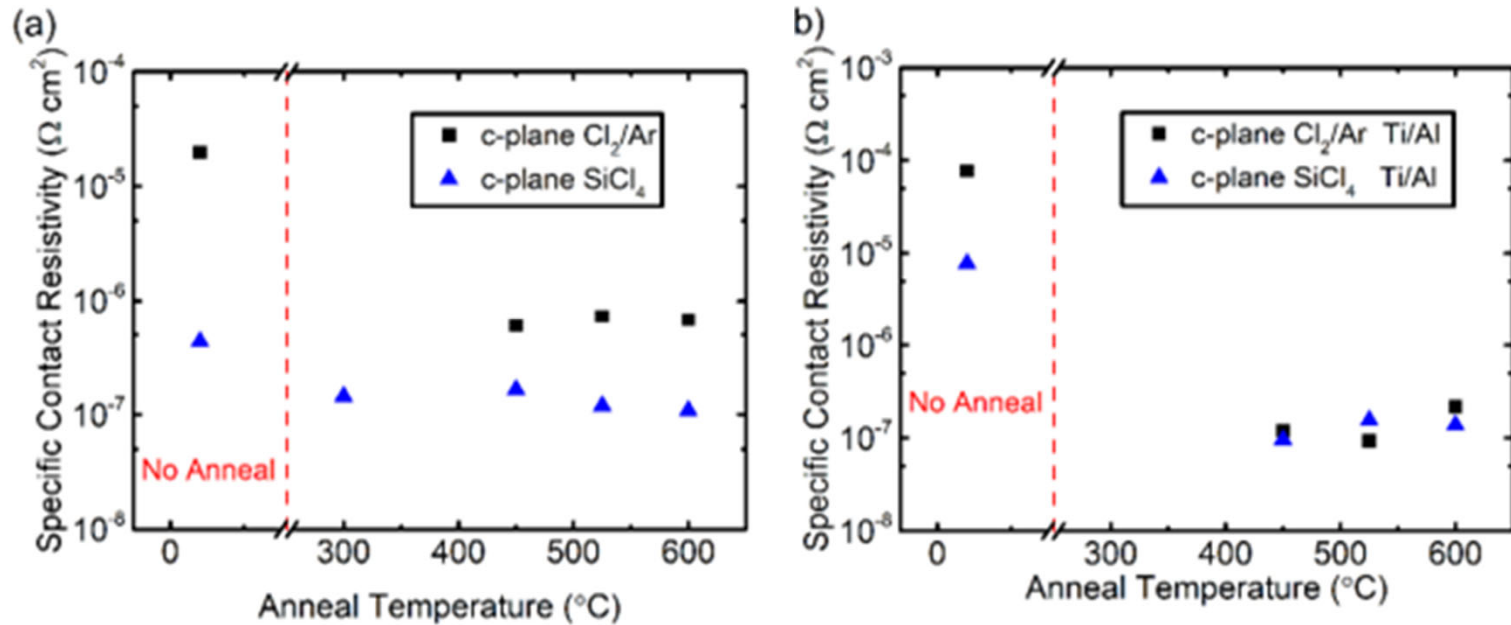
Coherent Films (160 nm thickness)



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Schottky Diode Process Flow



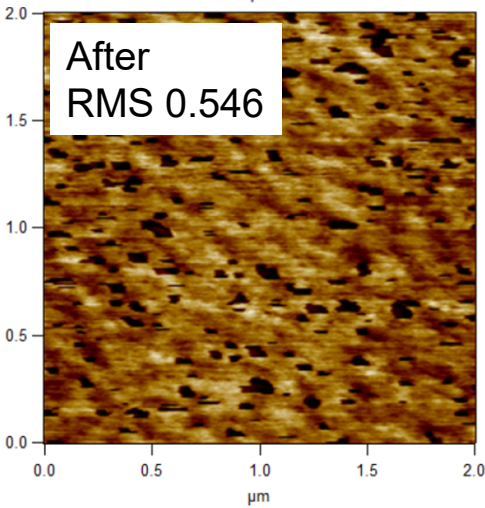
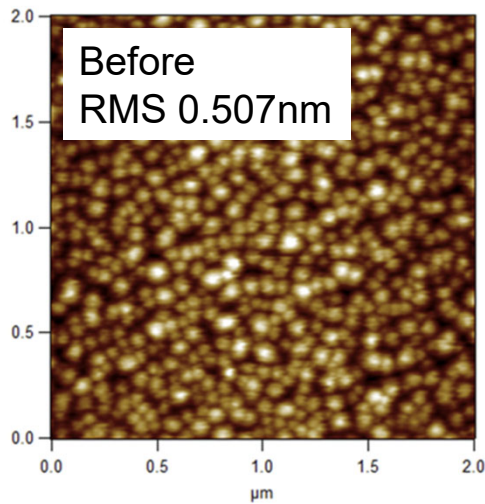


SiCl₄ etchant improves some specific contact resistances in GaN contacts

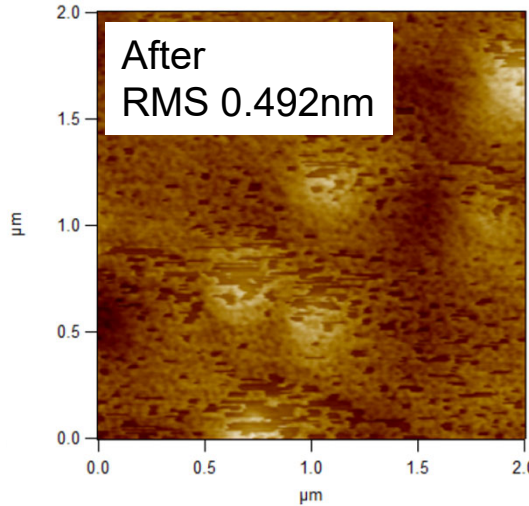
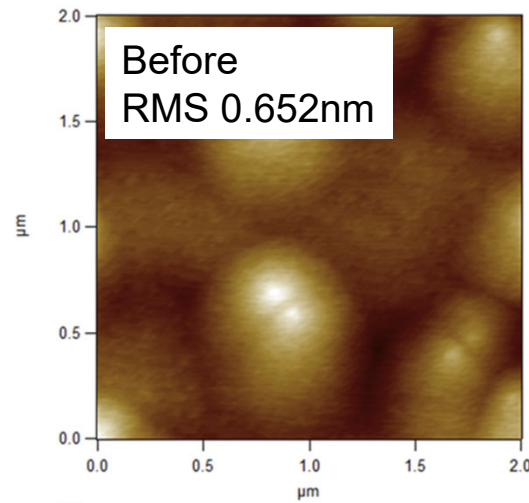
Surface Morphology after Etching – SiCl_4

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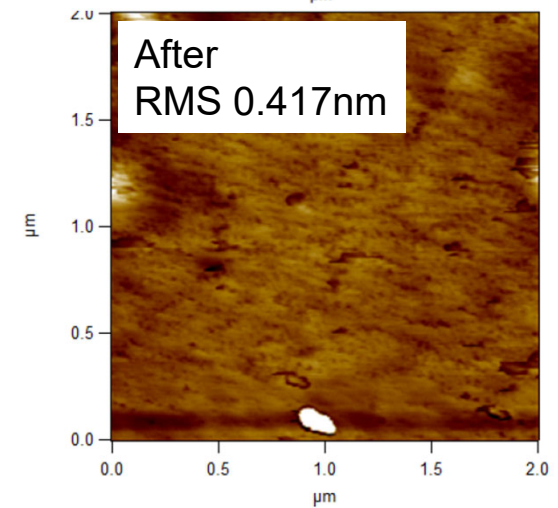
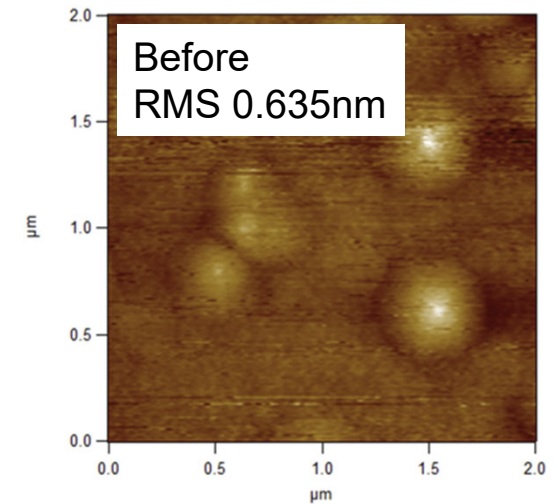
81%

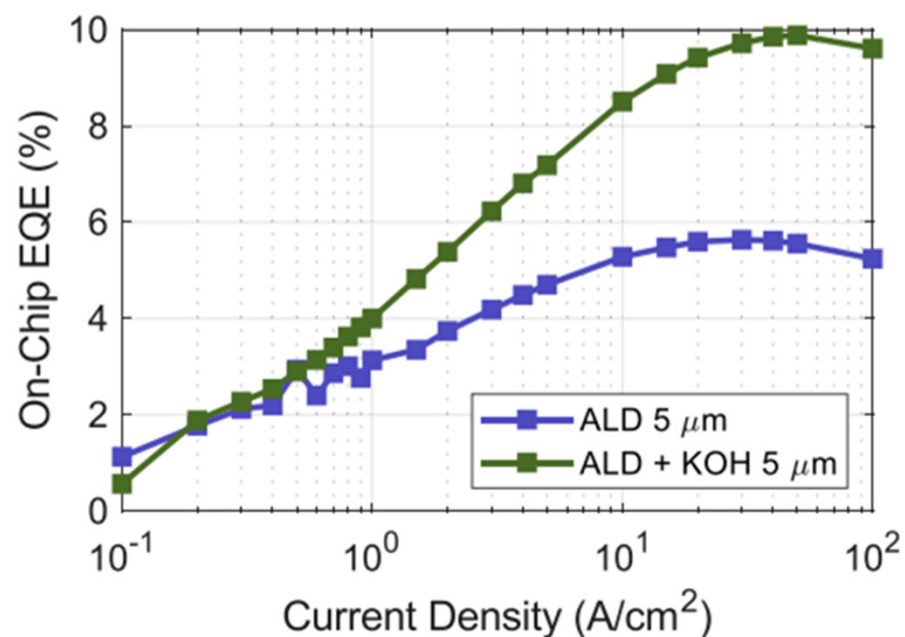
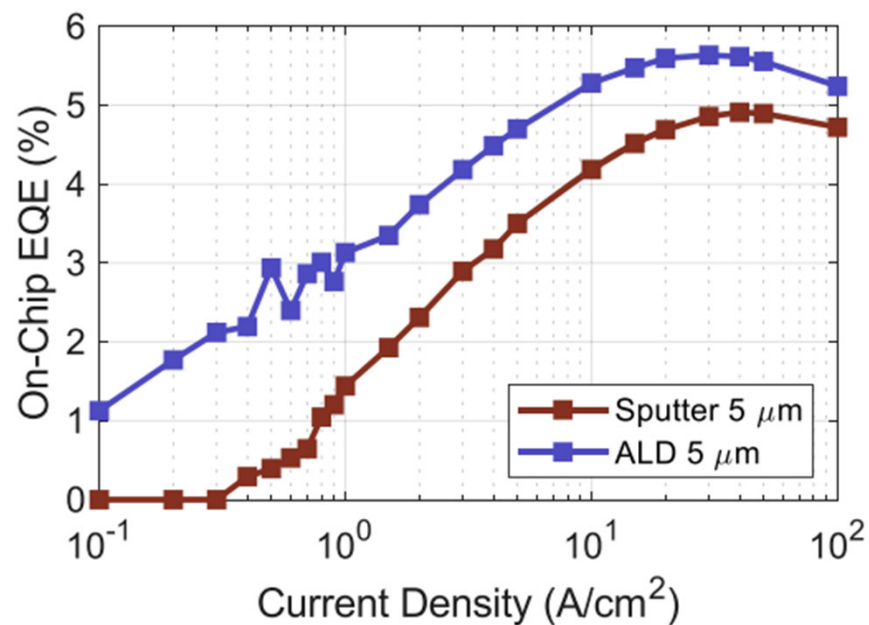


66%



49%

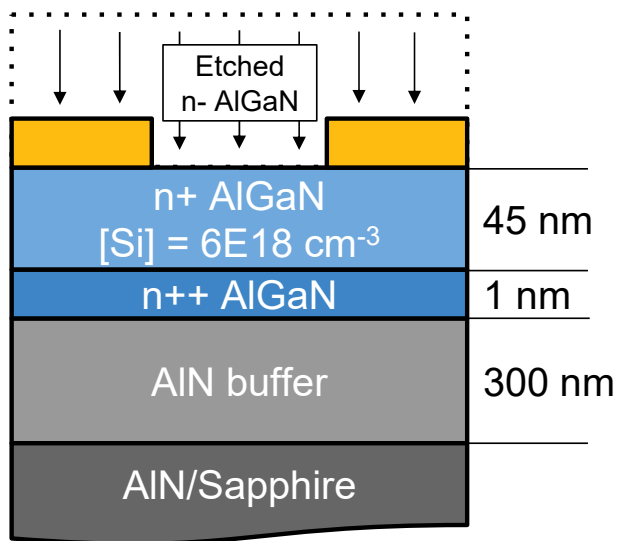




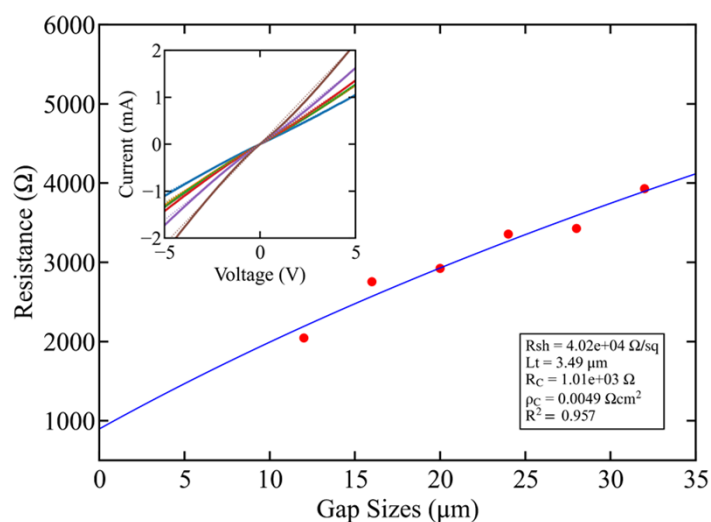
Etch damage removal and sidewall passivation of etched mesas improves device performance

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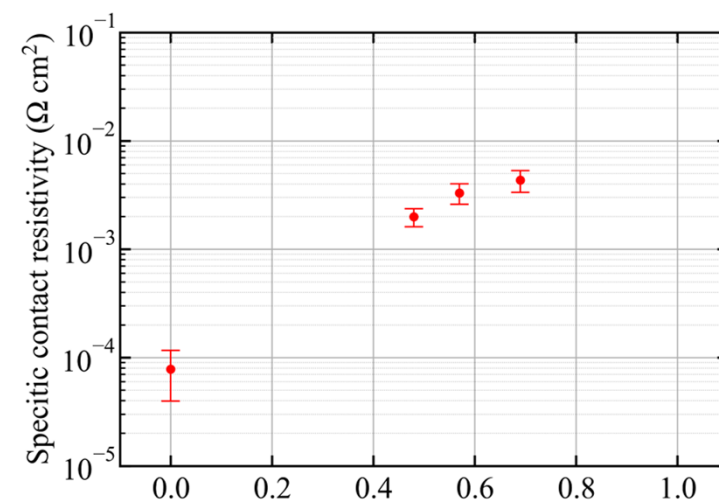
V/Al/Ni/Au Ohmic Contacts
(15/80/20/300 nm)
30s 900°C Anneal



Circular Transmission Line
Measurements (CTLM)

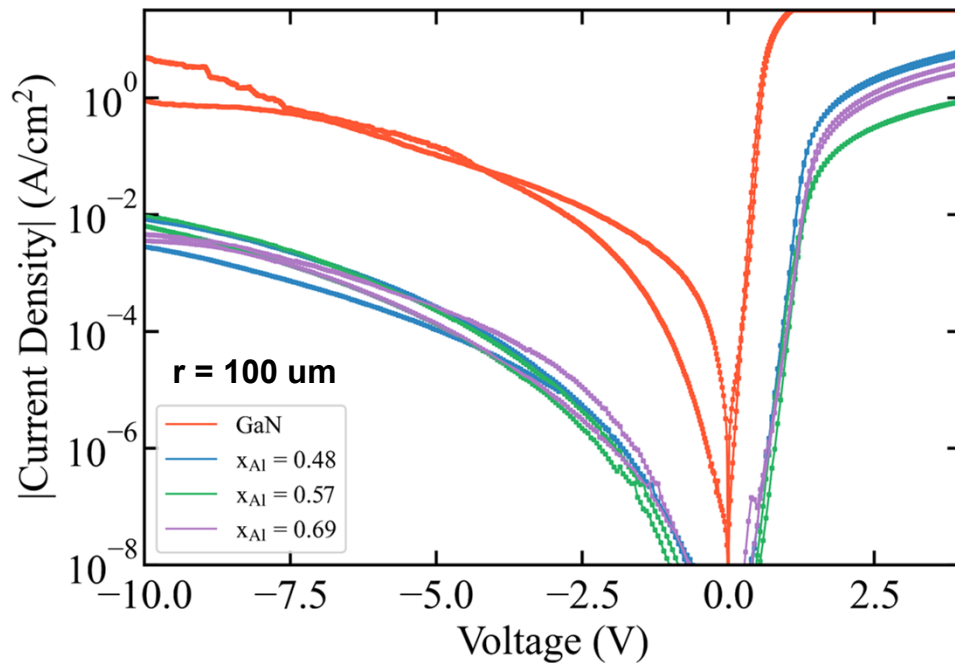


Composition vs.
Specific Contact Resistivity

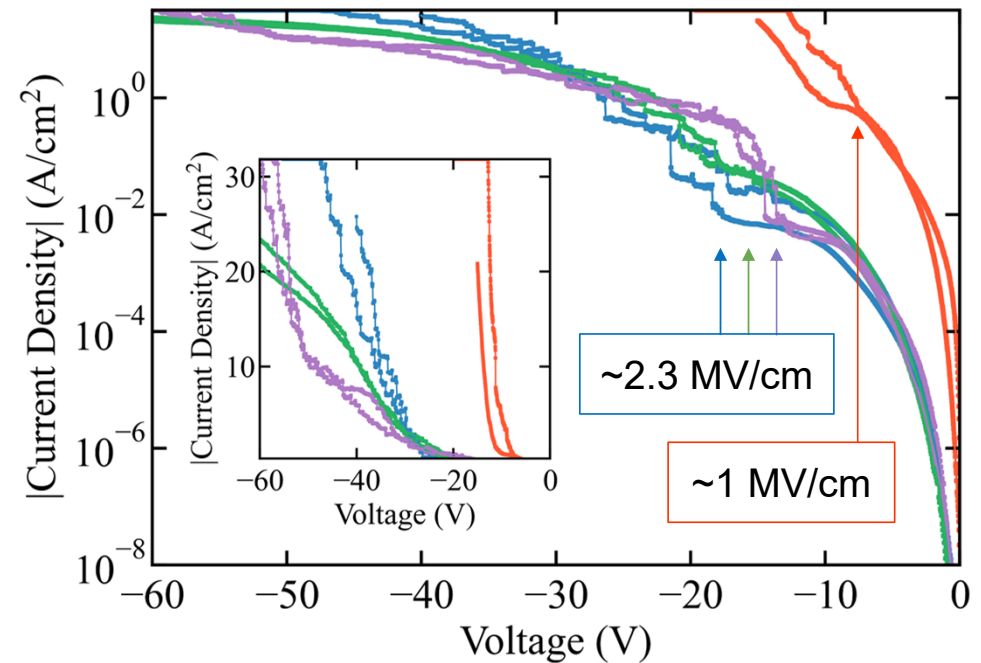


- $10^3 \Omega\text{cm}^2$ contact resistivities achieved
- Improvements with different metal contacts, etch chemistries, and annealing conditions

Current-Voltage

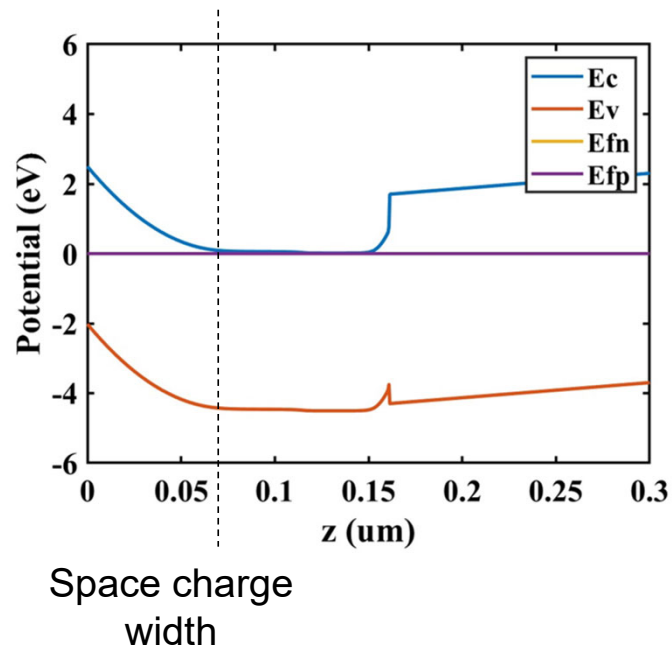


Breakdown

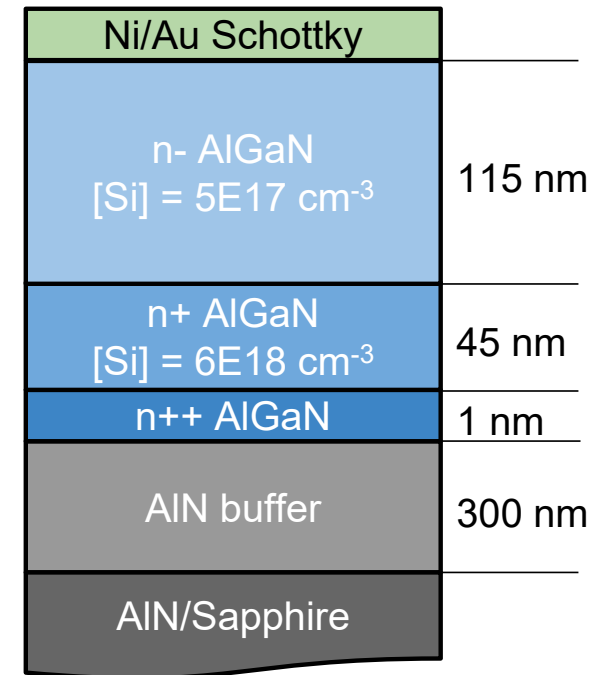
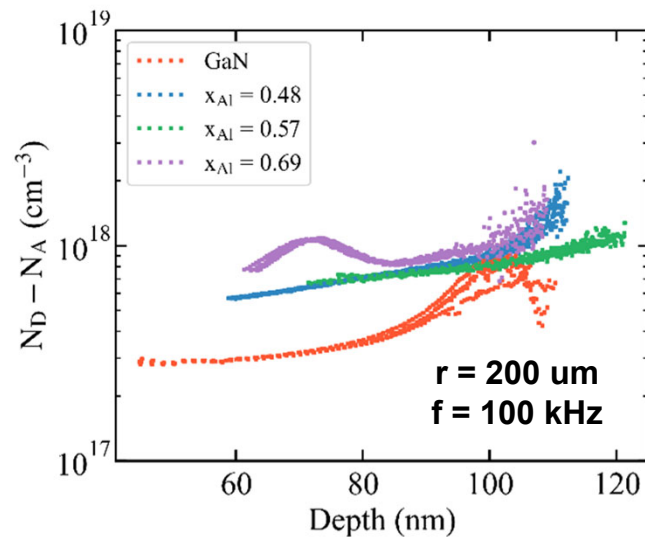


Devices can withstand high field conditions ($\sim\text{MV/cm}$), although not designed to!

Band Diagram



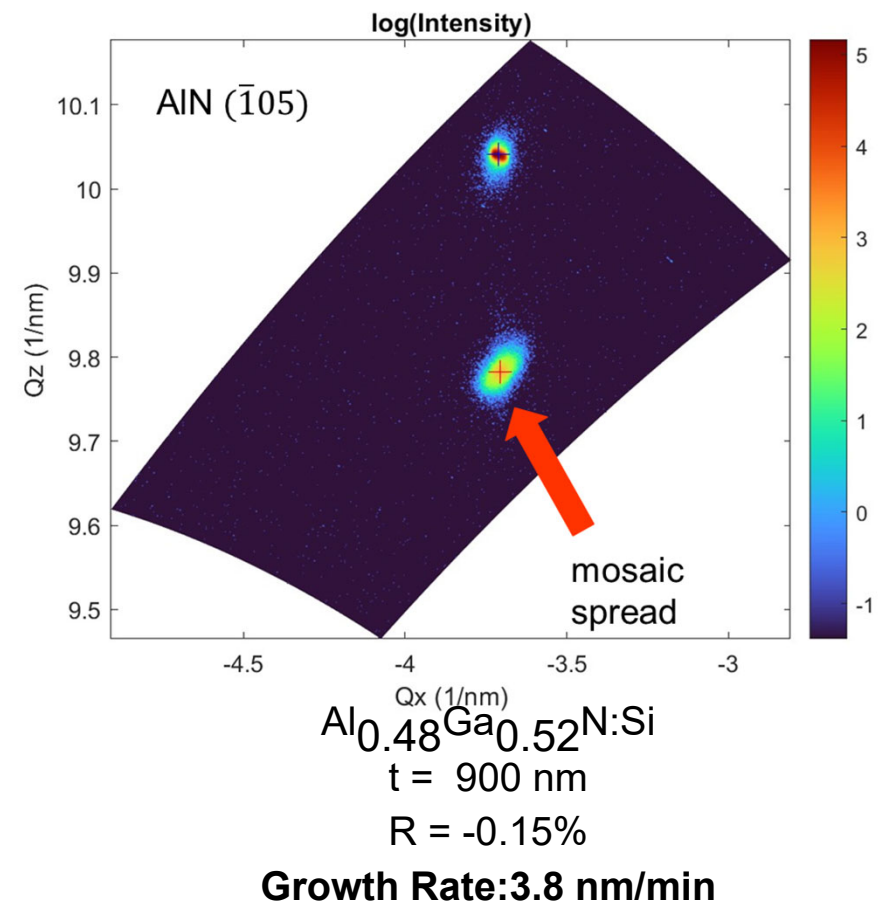
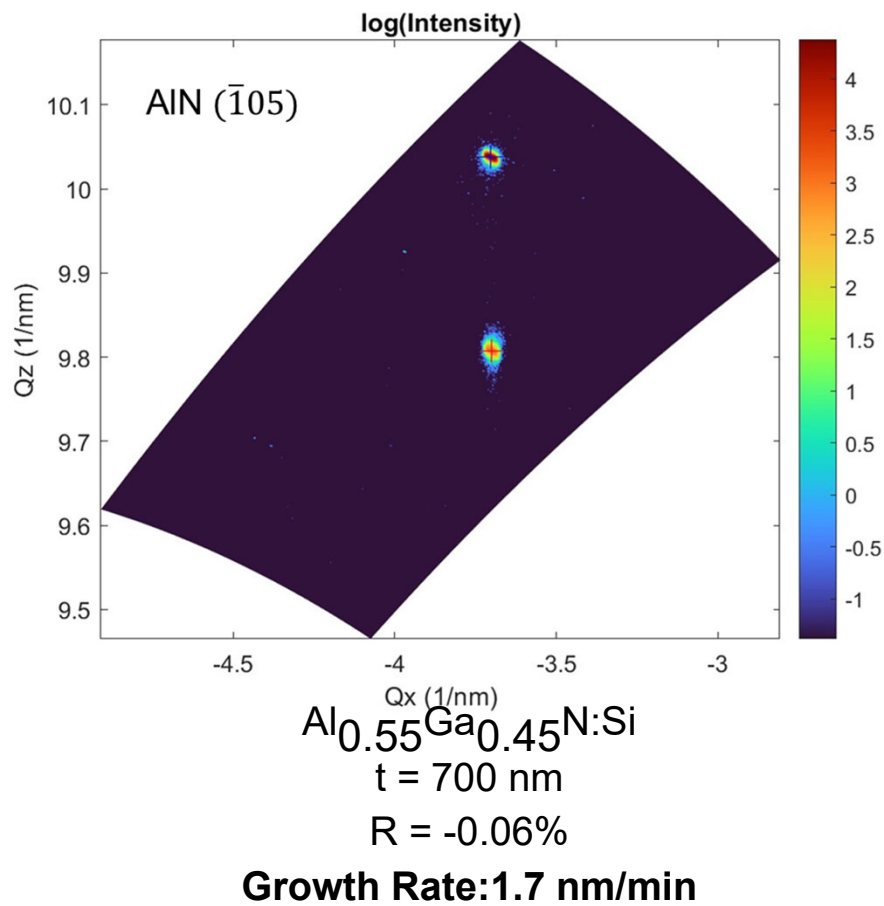
Capacitance-Voltage



- Test structures grown and fabricated on the same wafer at UCSB
- Sent to OSU and Vanderbilt for DLOS and radiation testing

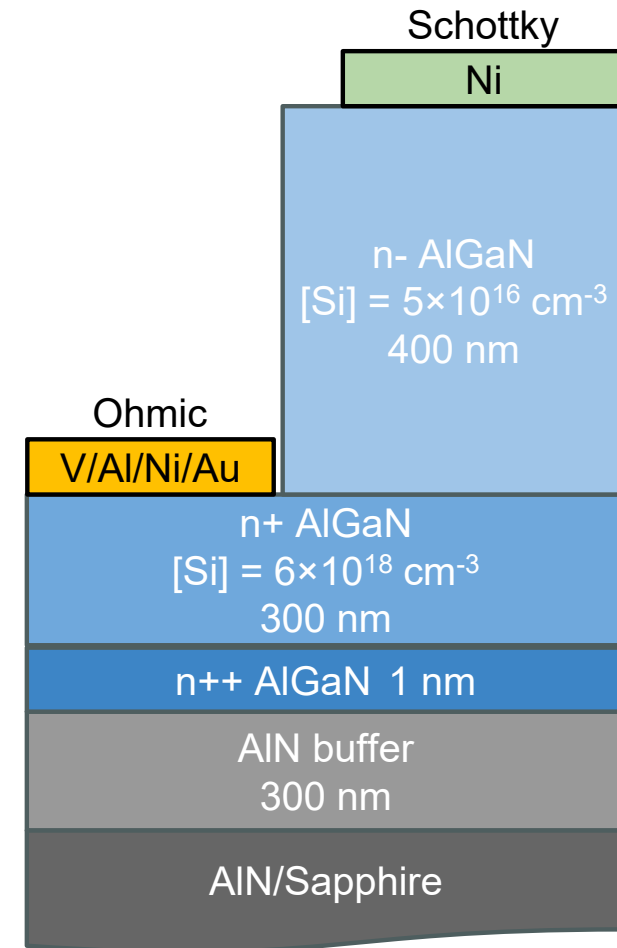
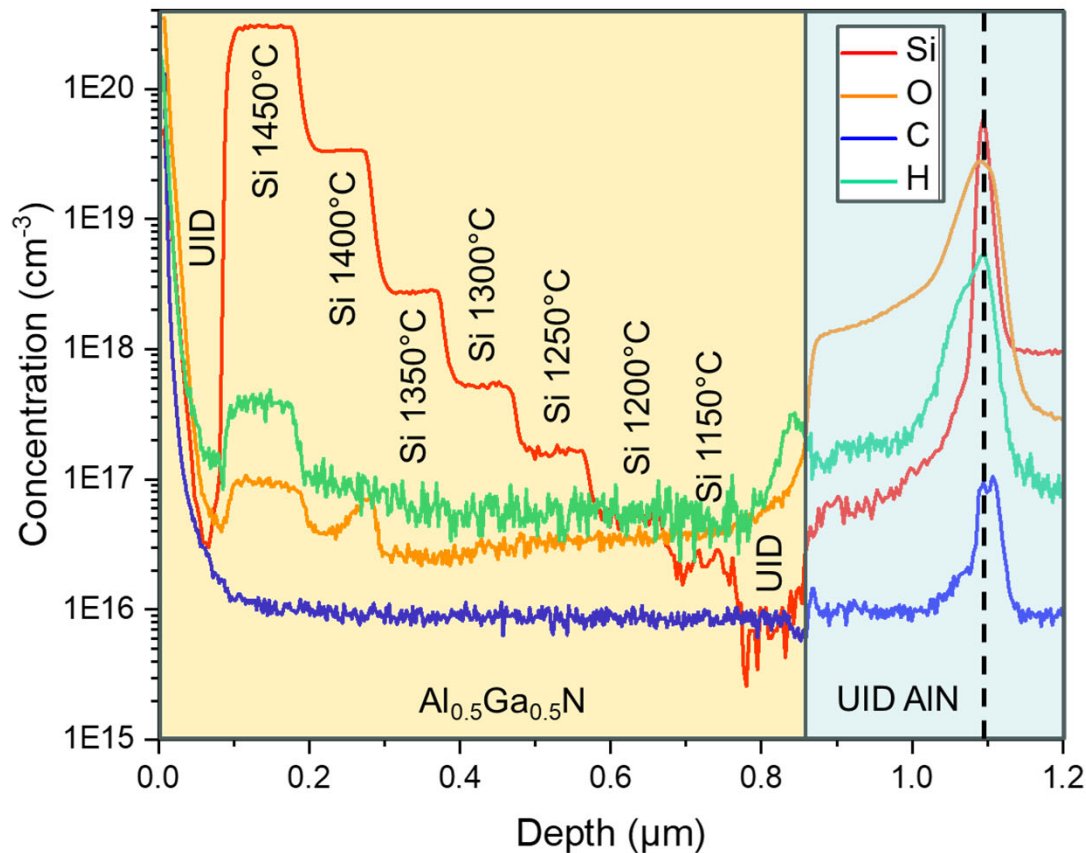
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Slow Growth Rate = Thicker AlGaN?

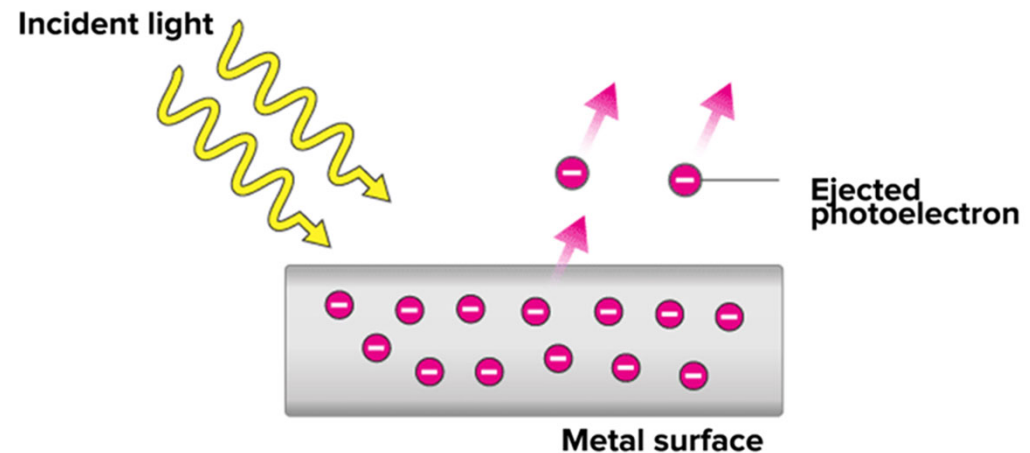
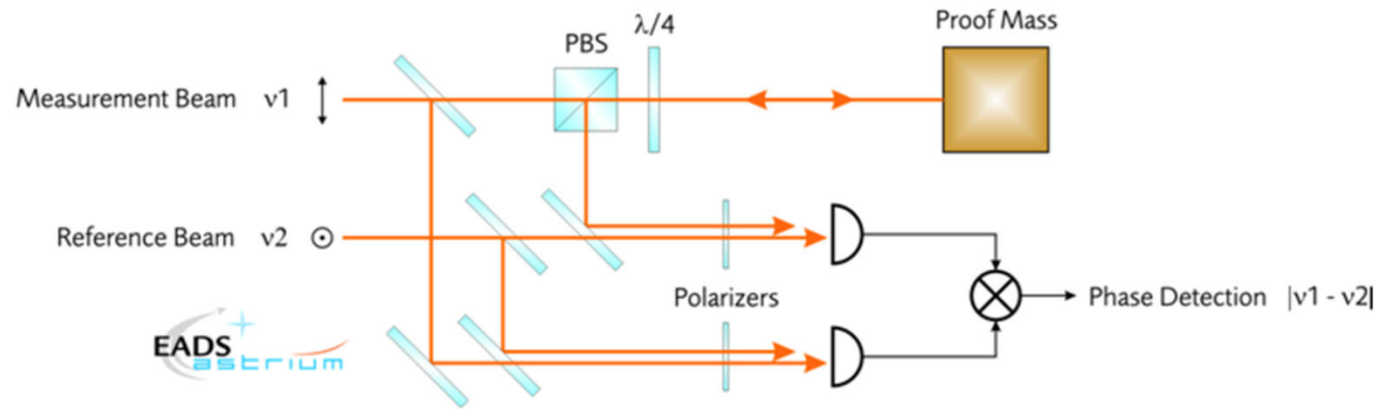


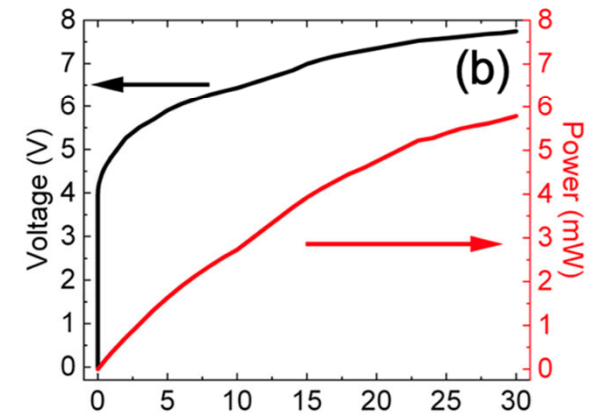
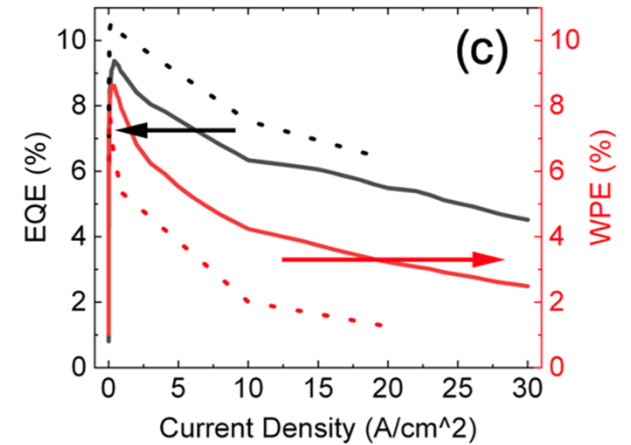
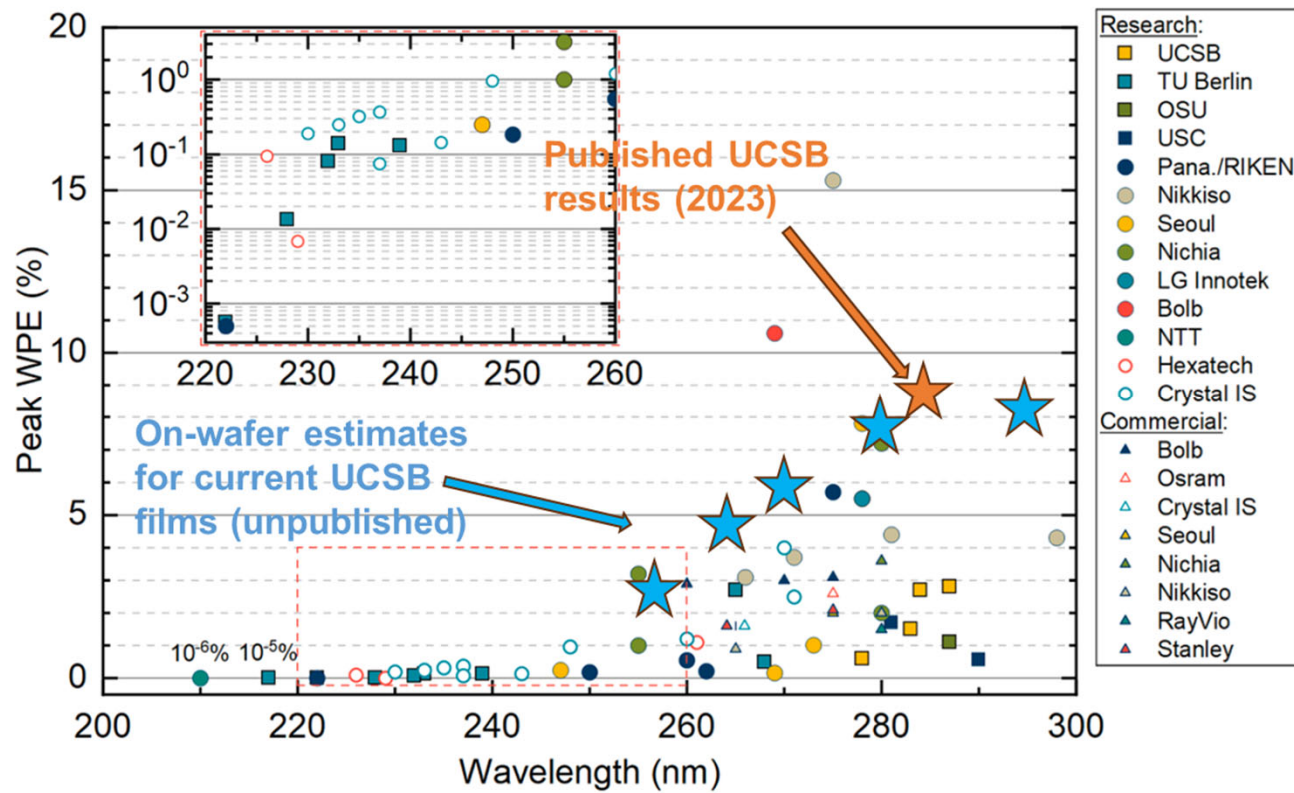
Thicker Coherent AlGaN Diodes

Thicker, low-doped drift region will enable higher breakdown fields



- A free-floating proof mass only affected by gravity provides a reference of a perfect geodesic path for satellites
- Charging due to energetic particles of galactic and solar origin penetrate the spacecraft, leading to charging of the proof mass
- Ultraviolet light enables charging control through photoelectric emission





- Current Schottky diodes withstand relatively high breakdown fields
- DLOS and radiation testing ongoing
- New growth conditions may enable thick, coherent epi → improved device performance
- New device designs, dielectric passivation techniques may improve leakage
- Radiation testing of UV-LEDs

Publications (UCSB and Vanderbilt University)

1. S. Islam, A. Senarath, **E. Farzana**, D. Ball, A. Sengupta, N. Hendricks, A. Bhattacharyya, R. Reed, E. X. Zhang, **J. Speck**, D. Fleetwood, and R. Schrimpf, "Single-Event Burnout in Vertical β -Ga₂O₃ Diodes with Pt/PtOx Schottky Contacts and High-k Field-Plate Dielectrics", *IEEE Trans Nucl Sci.* 71, 515, (2024).
2. S. Islam, A. Senarath, **E. Farzana**, D. Ball, A. Sengupta, A. Sternberg, R. Reed, S. Pantelides, A. Witulski, **J. Speck**, D. Fleetwood, and R. Schrimpf, "Effects of Epitaxial Layer Thickness on Heavy Ion-Induced Single-Event Burnout in Vertical β -Ga₂O₃ Schottky Barrier Diodes", Under review, *IEEE Trans Nucl Sci.* (2024)

Conference Presentations

1. **(Invited) E. Farzana**, N. Hendricks, S. Roy, A. Bhattacharyya, S. Islam, R. Cadena, A. Senarath, A. Sengupta, E. X. Zhang, D. Fleetwood, R. Schrimpf, S. Krishnamoorthy, and **J. Speck**, "Vertical β -Ga₂O₃ Diodes for High-voltage and Harsh Radiation Application," *IWGO*, Berlin, Germany, May (2024).
2. **E. Farzana**, N. Hendricks, S. Islam, A. Senarath, R. Cadena, D. Ball, A. Sengupta, R. Reed, E. X. Zhang, D. Fleetwood, R. Schrimpf, and **J. Speck**, "Radiation-hard Low-loss β -Ga₂O₃ High-Power Diodes," *GOMACTech*, Charleston, SC (2024).
3. S. Islam, A. Senarath, **E. Farzana**, D. Ball, A. Sengupta, R. Reed, S. Pantelides, A. Witulski, **J. Speck**, D. Fleetwood, and R. Schrimpf, "Effects of Epitaxial Layer Thickness on Heavy Ion-Induced Single-Event Burnout in Vertical β -Ga₂O₃ Schottky Barrier Diodes," *RADECS*, Spain (2024).
4. **(Invited, Upcoming) E. Farzana**, N. Hendricks, S. Islam, A. Senarath, A. Sengupta, R. Cadena, D. Ball, E. X. Zhang, D. Fleetwood, R. Schrimpf, and **J. Speck**, "Radiation Effects on Vertical β -Ga₂O₃ High-power Diodes," *MRS Spring Meeting and Exhibit*, Washington, USA (2025).

Thank you!
Questions?
