SAND2015-10179C

Low Dislocation Density AlGaN Epilayers for UV Laser Diodes and Devices for Power Electronics


Veeco D-125 MOCVD system

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Acknowledgements: M. Smith, K. Cross, and L. Alessi

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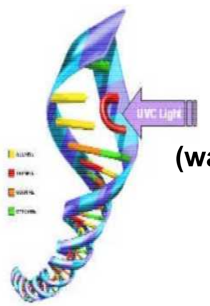
Outline

- $Al_xGa_{1-x}N$ pseudo-substrates for UV-emitters and power devices
- $Al_xGa_{1-x}N$ (x = 0.3, 0.7) and AlN templates on sapphire by overgrowth of patterned $Al_xGa_{1-x}N$ & AlN.
- Devices enabled by patterned AlGaN/AlN templates
  - UV-Laser Diode ($Al_{0.3}Ga_{0.7}N$)
  - PIN diodes ($Al_{0.3}Ga_{0.7}N$)
  - AlGaN HEMTs (on AlN)
- Summary

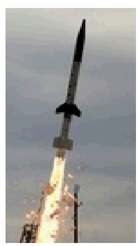
AlGaN Alloys Span UV-A, -B and –C Spectrum

Raman Spectroscopy
225-250 nm
(biological agent identification)

www.hanovia.com

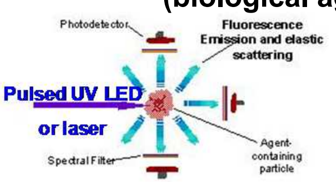


Germicidal
260-275 nm
(water, air, surfaces)

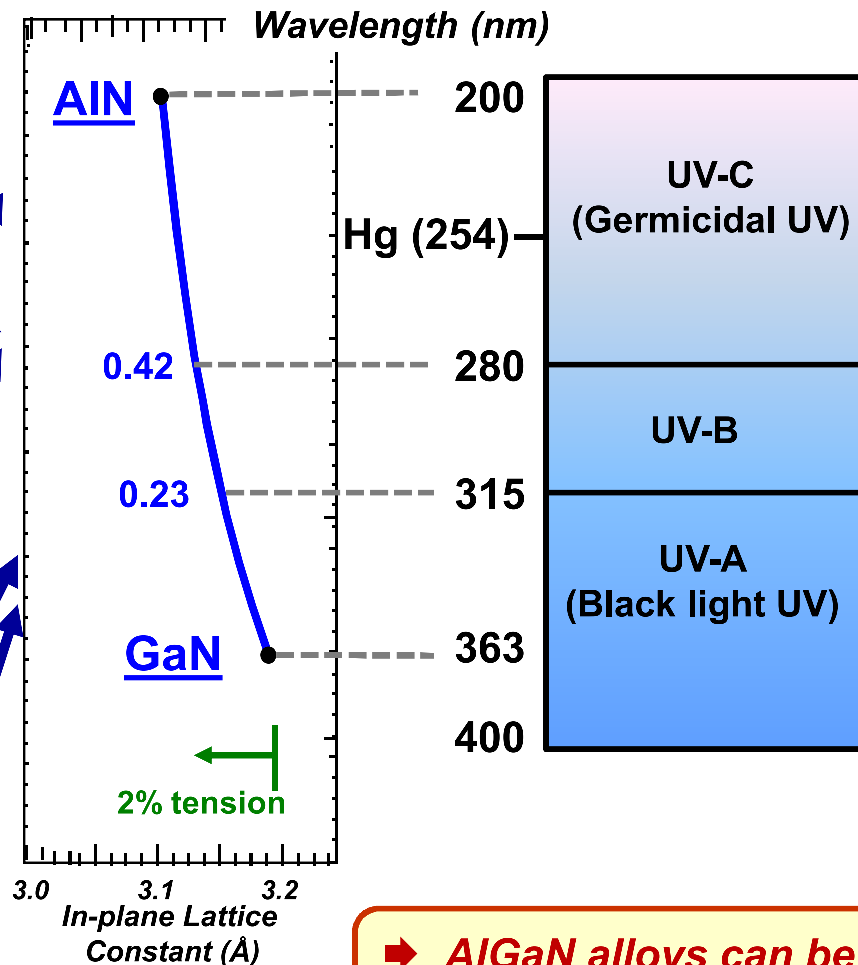


Solar-blind flame detection, λ<280 nm
(launch, fire)

UV-Induced Fluorescence
340, 280 nm
(biological agents)



UV Processing
300-360 nm
(inks, epoxy)



➡ ***AlGaN alloys can be used for UV-emitters and detectors***

Why Wide-Bandgap Semiconductors (WBS) for power electronics

Decreasing TRL ➡

Wide-Bandgap Semiconductors

Property	Si	GaAs	4H-SiC	GaN	AlN
Bandgap (eV)	1.1	1.43	3.3	3.4	**6.2**
Critical Electric Field (MeV/cm)	0.3	0.4	2.0	**3.3**	**11.7**
Saturated electron velocity ($x10^7$ cm/sec)	1.0	1.0	2.0	**2.5**	1.4
Thermal conductivity (W/cm·K)	1.5	0.5	**4.5**	4.0	3.4

Larger bandgap
➡ ***Higher temperature***

Larger critical E field
➡ ***Higher voltage***

Higher sat. electron vel.
➡ ***Higher switching speed***

Higher thermal conductivity
➡ ***High power***

Radiation tolerant
➡ ***Stable devices***

AlGaN alloys & heterostructures
➡ ***Engineered properties***

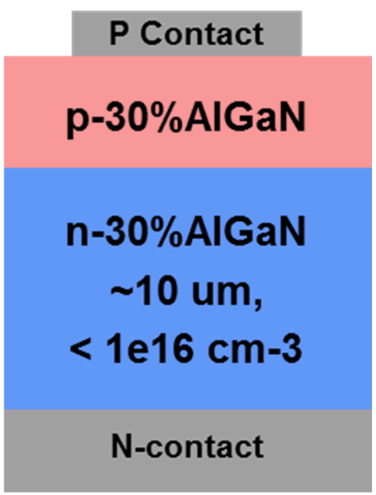
➡ ***WGS enable applications NOT possible in Si and GaAs***

Wide-Bandgap Semiconductors (WBS) for power electronics.

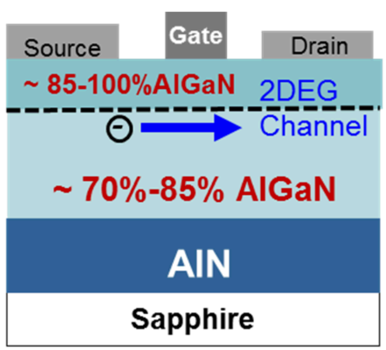
$$R_{sp,on} = \frac{4V_B^{\,2}}{\varepsilon \mu E_C^{\,3}}$$

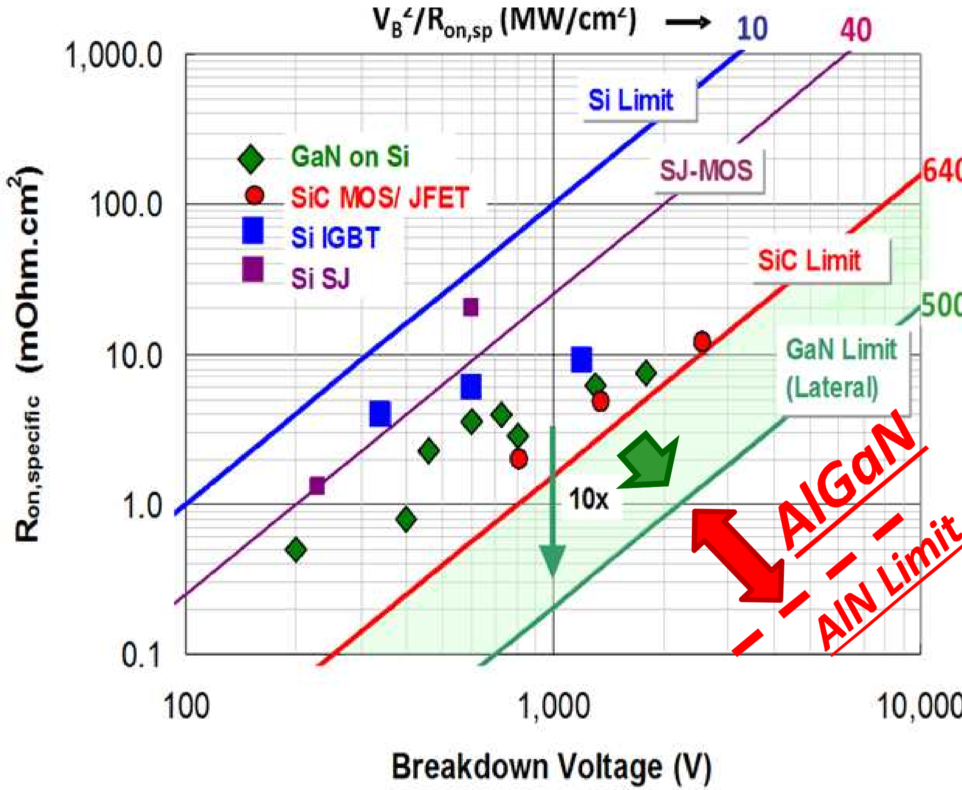
Critical Electric Field (MV/cm)

PIN Diode



Power HEMT





WBS devices:

- ***Higher efficiency***
- ***Higher thermal conductivity***

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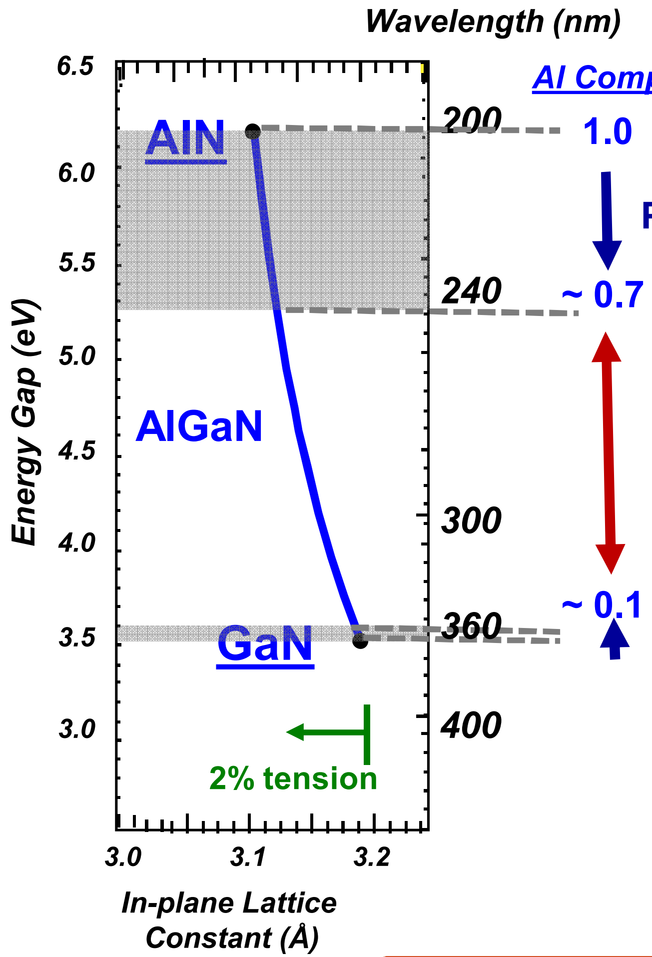
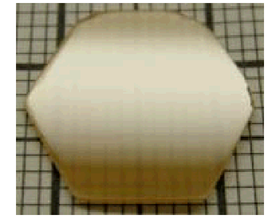
AlGaN Alloys and applications for UV-devices



Pseudomorphic limit
(relaxation by dislocation generation)

- Ternary (AlGaN) "substrate" needed for emitters at many UV wavelengths

Excess tensile strain leads to cracking



AlN
(Hexatech)

(Ammono)
GaN

➡ How to fabricate a low dislocation template for UV-emitters and power devices?

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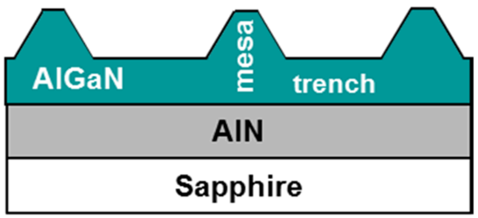
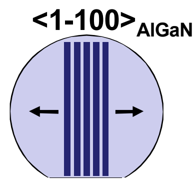
Dislocation reduction with $Al_{0.32}Ga_{0.68}N$ overgrowth of etched trenches

1. Pattern & etch trenches

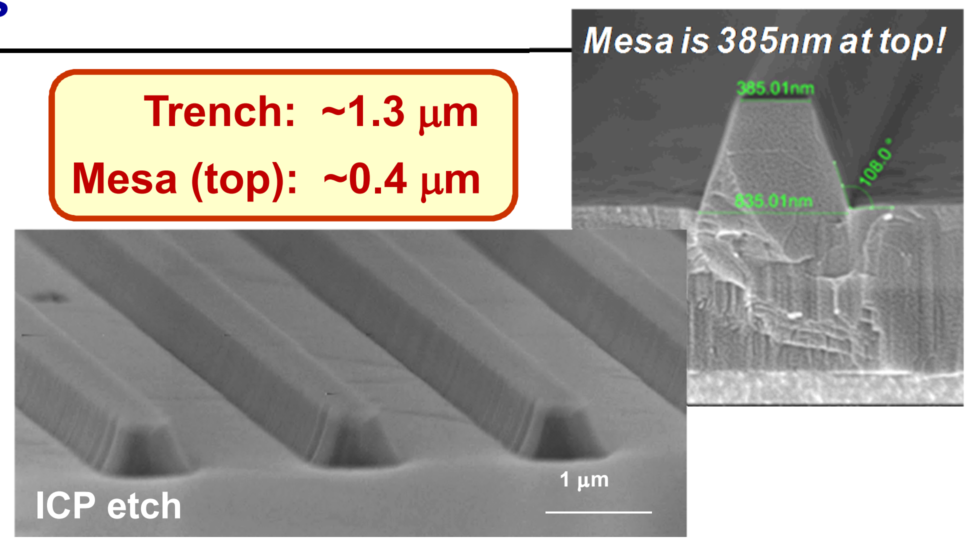
Mesa width: 1 μm
Trench width: 1 μm
Etch Depth: 0.4 – 0.7 μm





Trench Alignment

Trench: ~1.3 μm
Mesa (top): ~0.4 μm

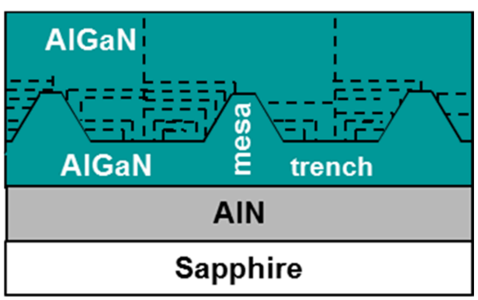


➡ ***Sub-micron features are key for uniform reduction of dislocations***

2. Overgrow with AlGaN

*Allerman JCG **76** 388 (2014)*

$Al_{0.3}Ga_{0.7}N$ Overgrowth: 6-10 μm



Reactor:	Veeco D-125
Chamber:	75 torr, 1060 °C
Al/III & V/III Ratio:	0.32, 1040
Group-III:	34 μmoles/min
Growth rate:	0.6 μm/hr

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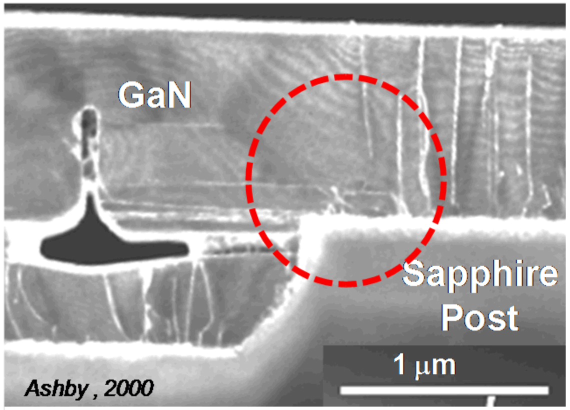
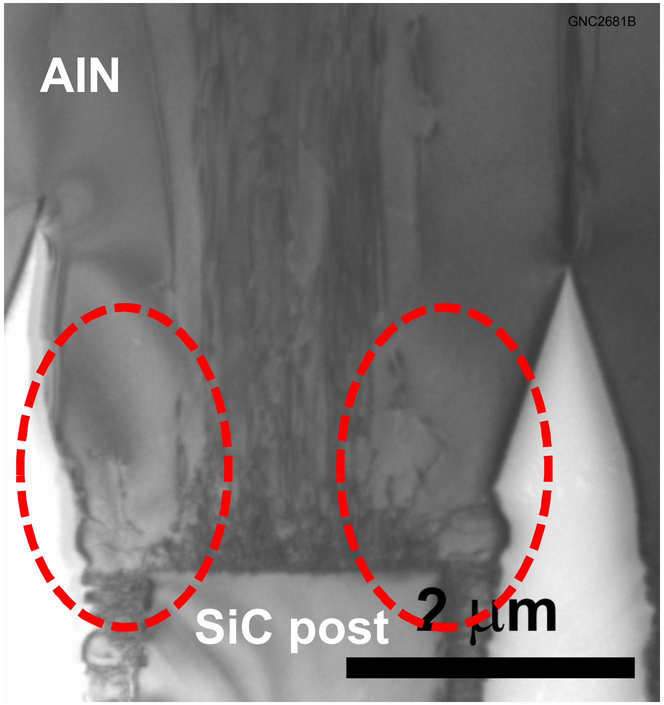
Dislocation Bending Near Edges of Posts

- Not necessary to form complete pyramids (11-22) to turn dislocations
- Dislocations will bend when near a free surface (image force)

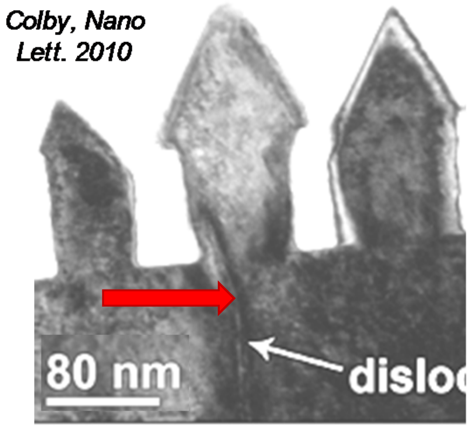
Cantilever Epitaxy: GaN on sapphire



Cantilever Epitaxy: AlN on SiC



Nanowires



➡ Expect dislocations emerging from sub-micron wide mesas to bend.

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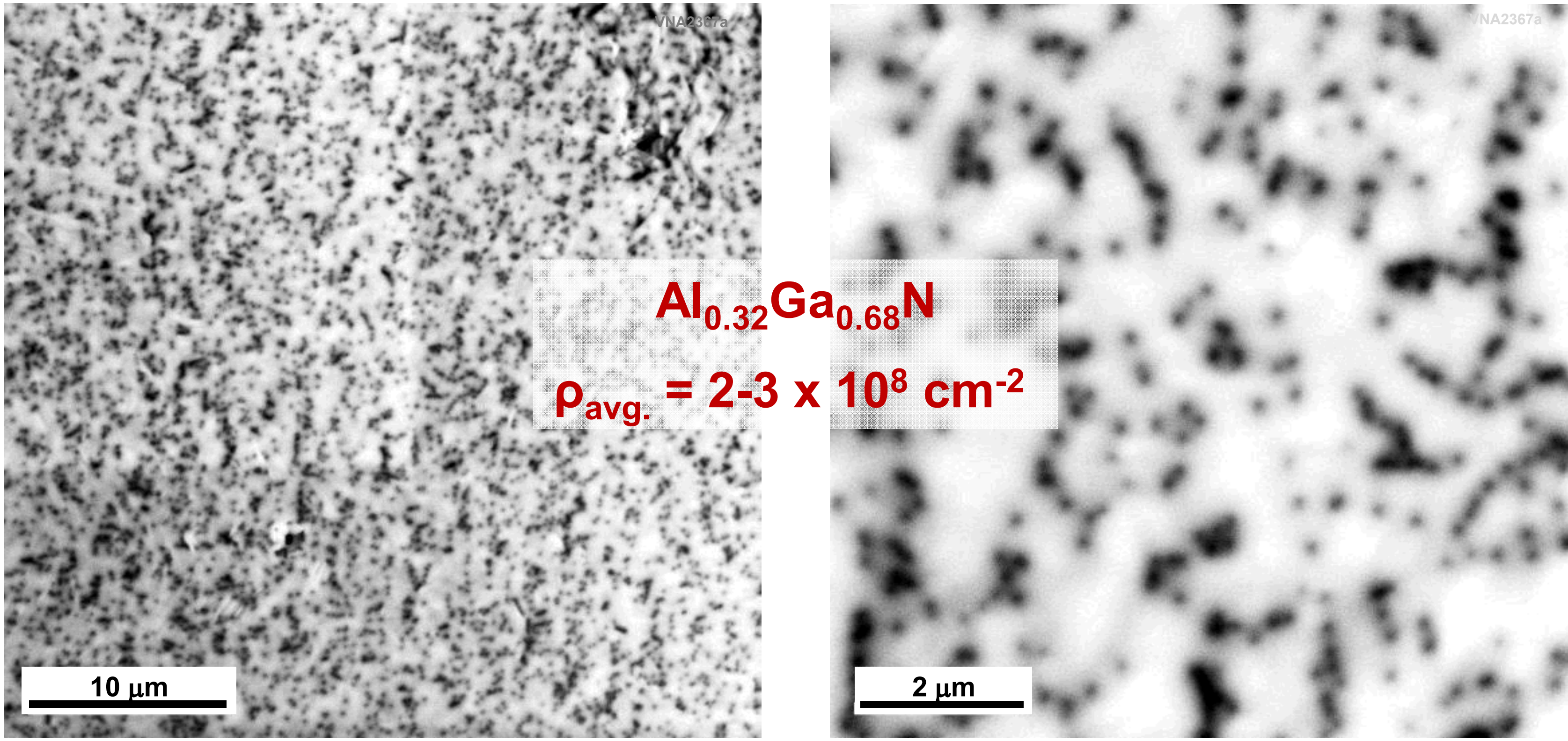
Cathodoluminescence of $Al_{0.32}Ga_{0.68}N$ Overgrowth of Patterned $Al_{0.32}Ga_{0.68}N$



- Spatially uniform reduction in dislocation density
- Si-doped, $N_o = 2\text{-}4 \times 10^{17} cm^{-2}$ (Vertical diodes following sapphire removal)
- Transparent template for bottom emitting LEDs

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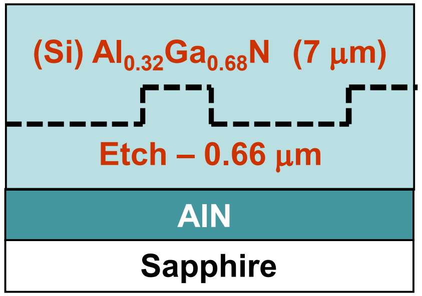
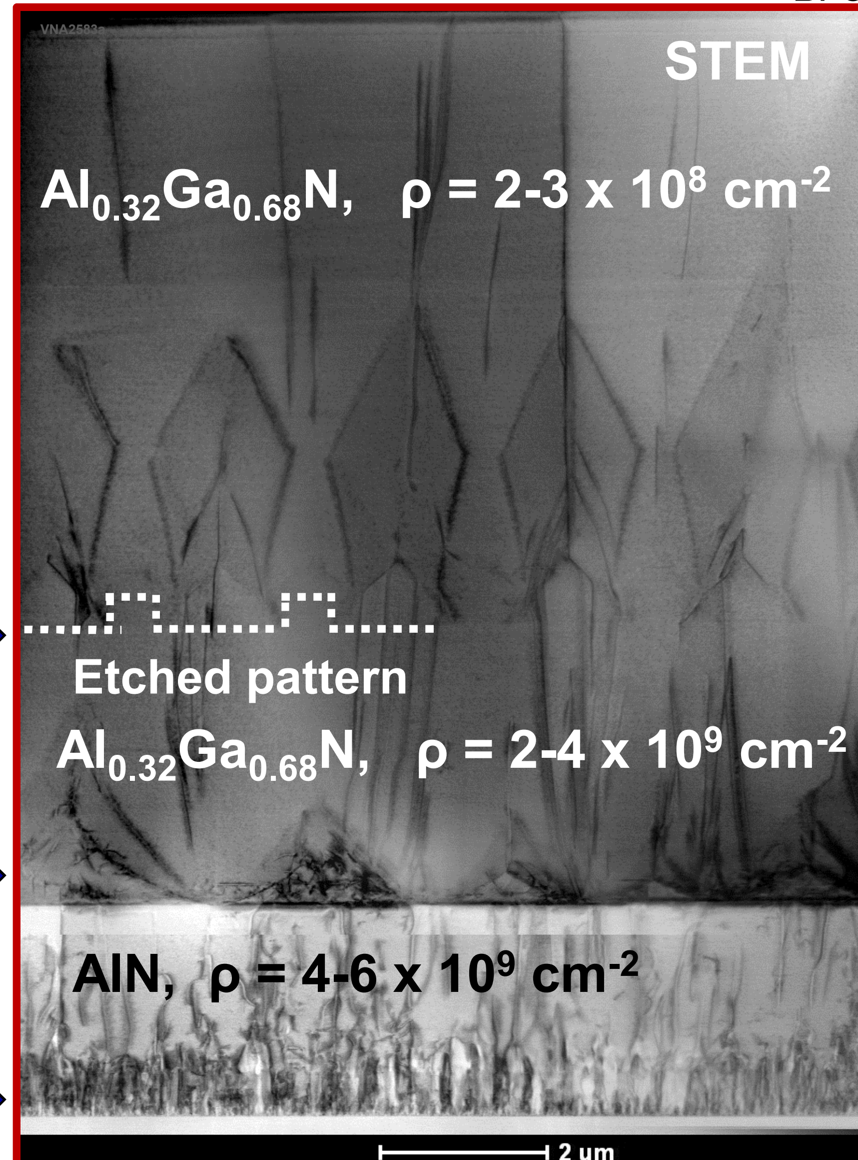
Two-Beam BF-STEM of $Al_{0.32}Ga_{0.68}N$ Overgrowth of Patterned $Al_{032}Ga_{0.68}N$

B. Clarke



Introducing surface roughness drives dislocation reduction

- **Overgrowth of etched trenches**
- **Strain induced 3D islanding**
- **Roughened, transitional layer with voids**



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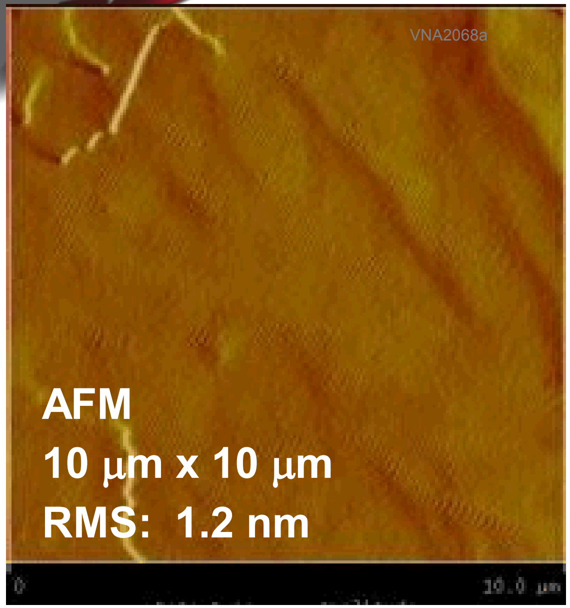
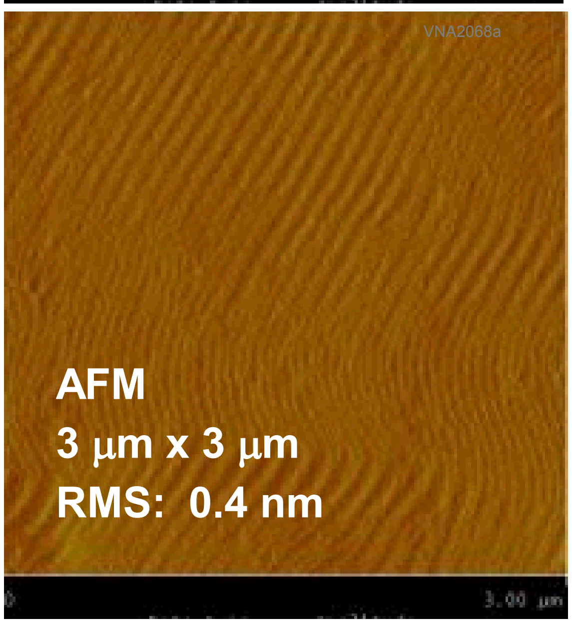
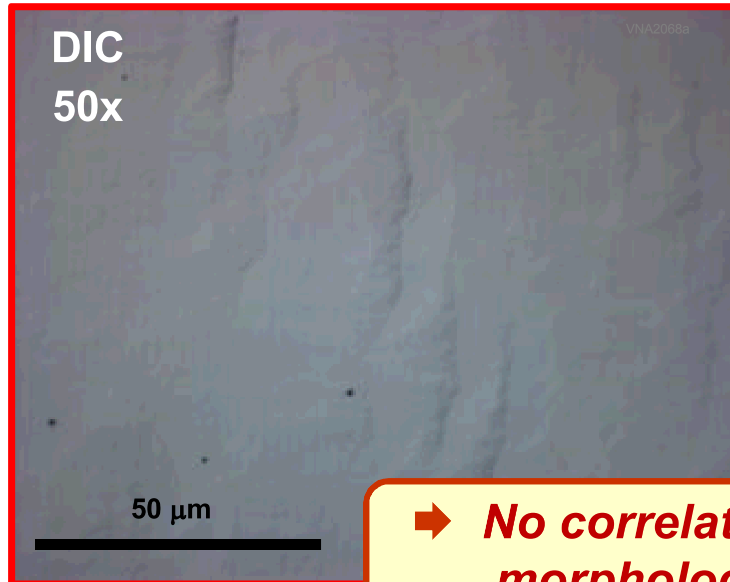
Surface Morphology of $Al_{0.32}Ga_{0.68}N$ Overgrowth of Patterned $Al_{0.32}Ga_{0.68}N$

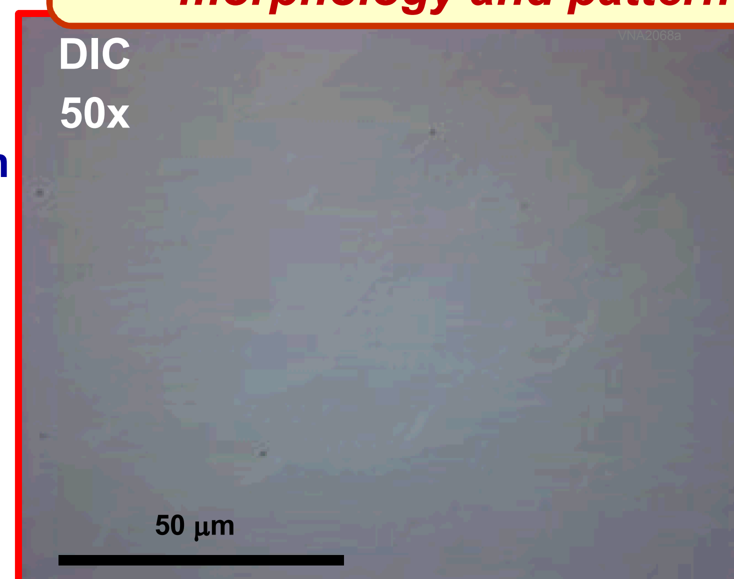




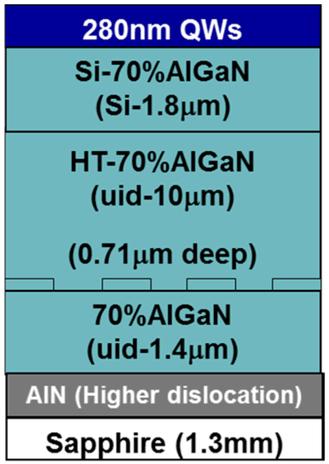


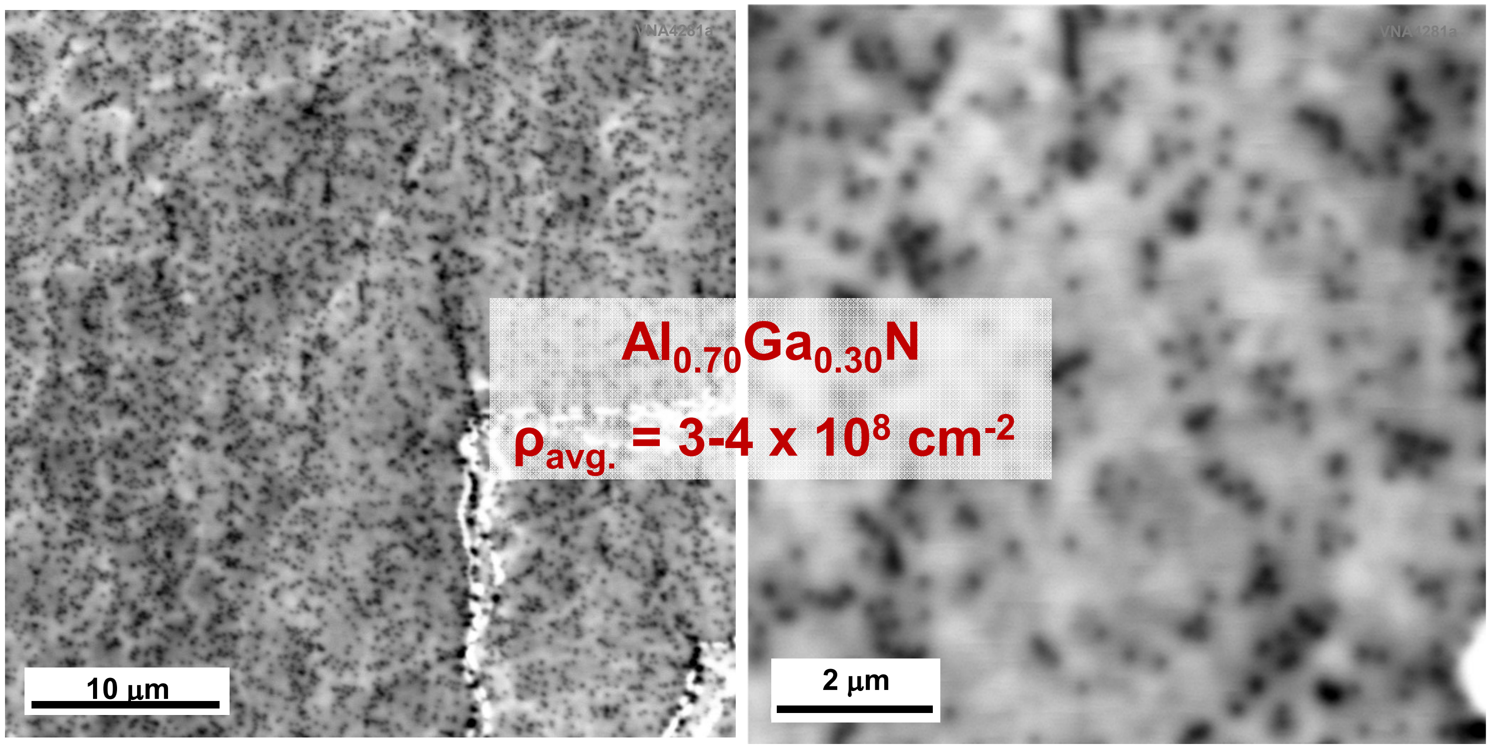
➡ *No correlation between morphology and pattern*

Overgrowth: 6 µm
Mask: (1 / 1) µm
Etch Depth: 0.56 µm



Cathodoluminescence of $Al_{0.7}Ga_{0.3}N$ overgrowth of patterned $Al_{0.7}Ga_{0.3}N$





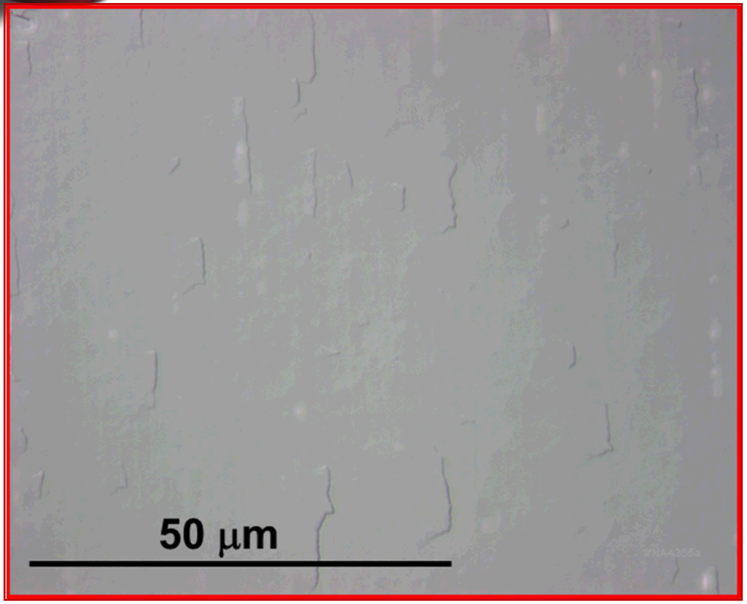
- 0.7 μm etch
- ~12 μm overgrowth

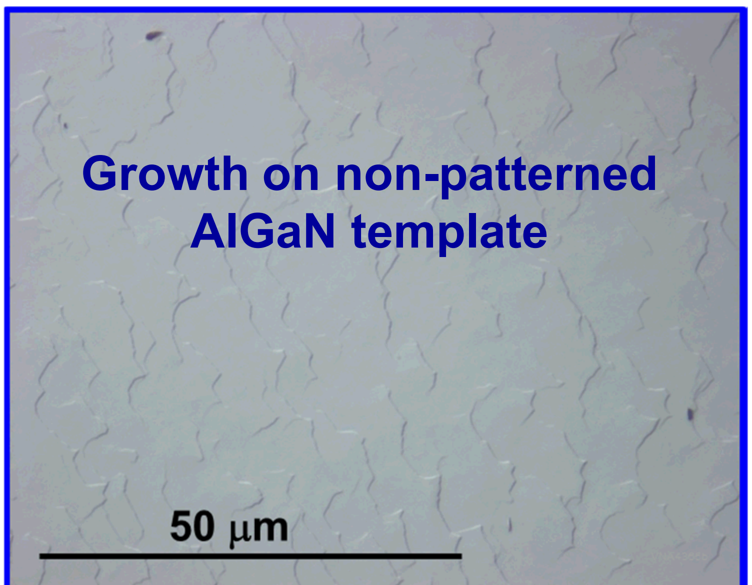
➡ Spatially uniform reduction in dislocation density

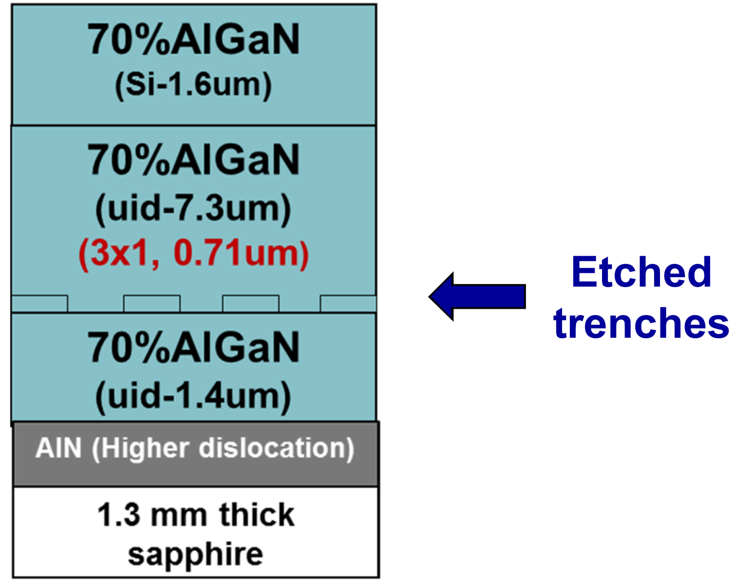
➡ Transparent template for bottom emitting LEDs

➡ Approach is successful all AlGaN compositions

Nomarski DIC of $Al_{0.7}Ga_{0.3}N$ overgrowth



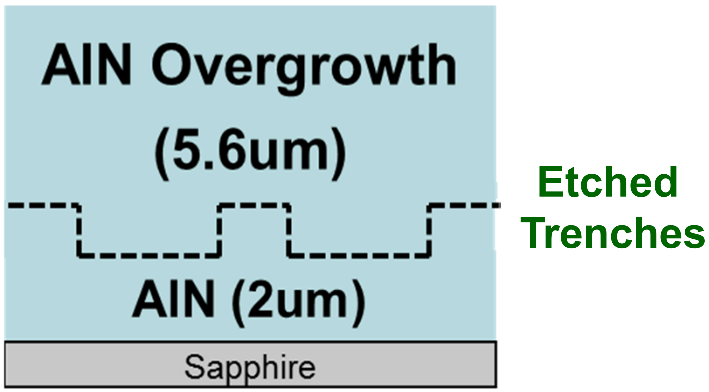




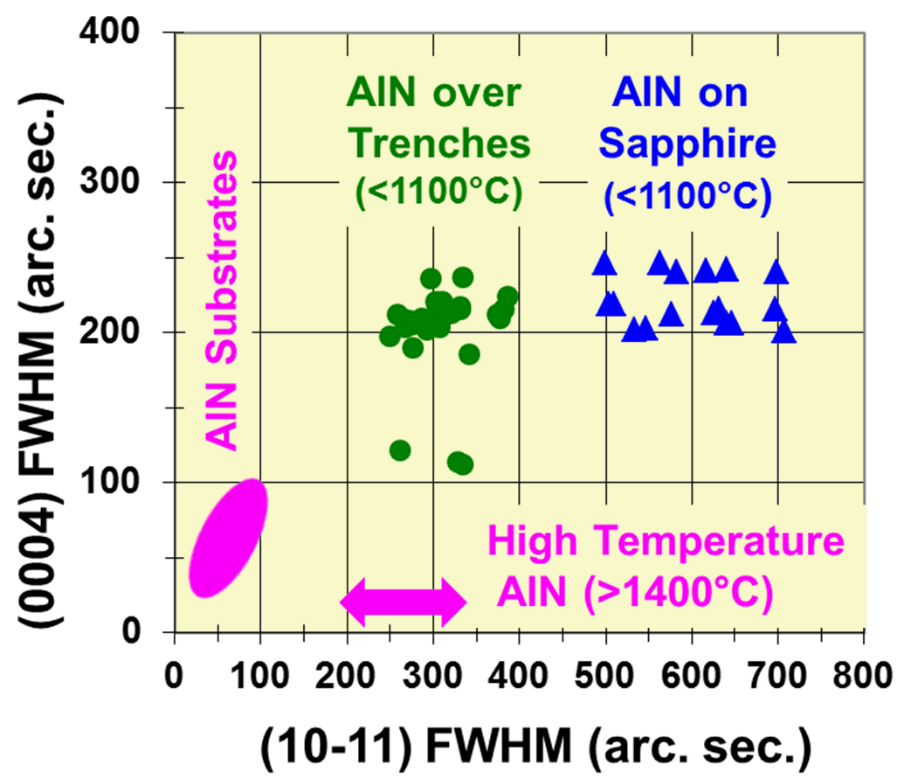
- **Cleaning of patterned template critical for good morphology**

➡ **Morphology of AlGaN overgrowth is similar to regular growth**

AlN overgrowth of patterned AlN



X-ray diffraction peak width of AlN epilayers



Pattern in AlN/sapphire template

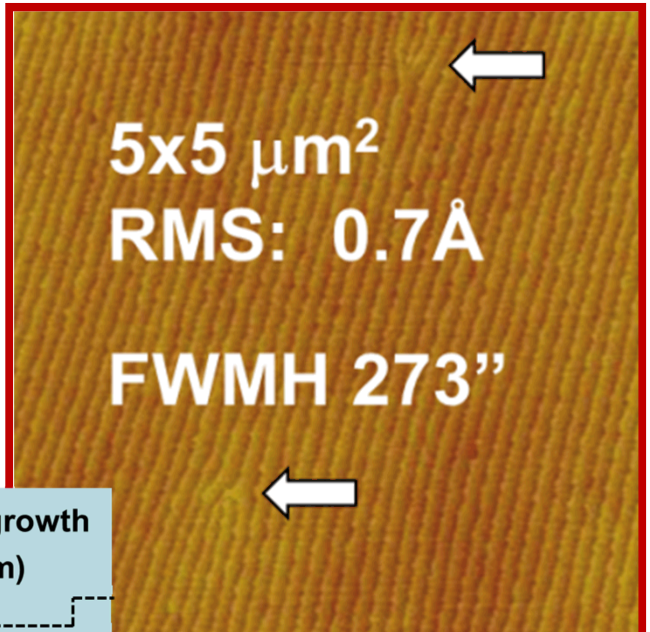
- 1 μm mesa / 1 μm trench
- 0.2 – 0.7 μm etch depth
- 5.6 μm overgrowth

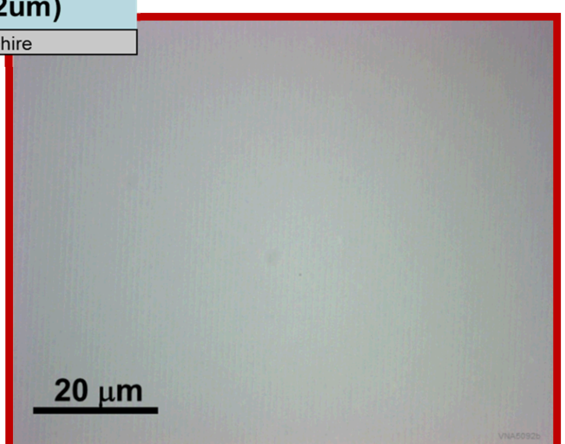
➡ **Significant reduction in edge-type dislocations with AlN overgrowth process**

➡ **TDD ~ 3-5 x10^{8} cm^{-2}**

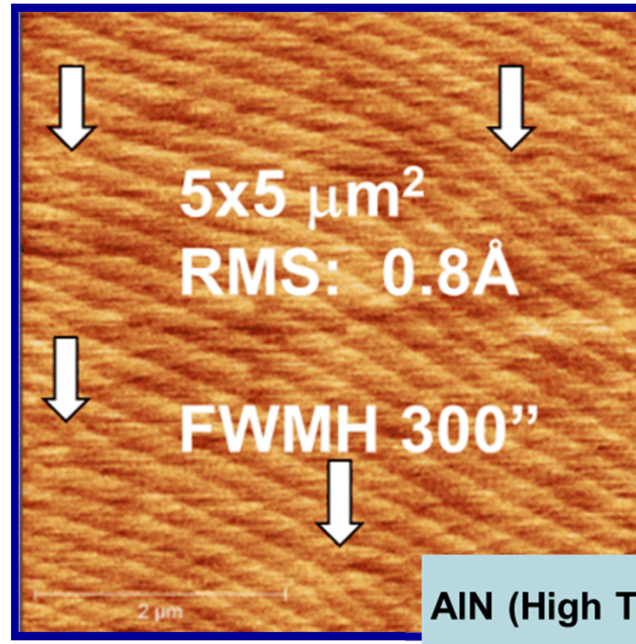
AFM and Nomarksi DIC of AlN overgrowth

SNL overgrowth - 1100°C





High Temperature AlN on sapphire by SET *(Jones 2015)*



- AlN overgrowth produces AlN epilayers similar to high temperature growth

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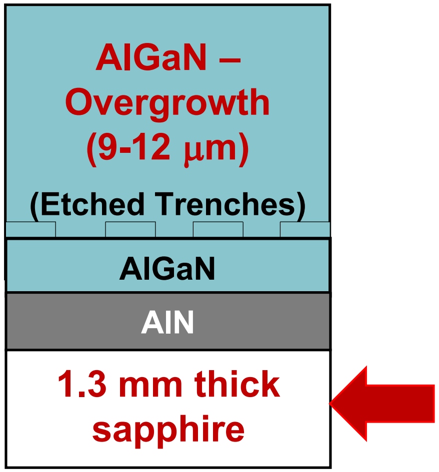
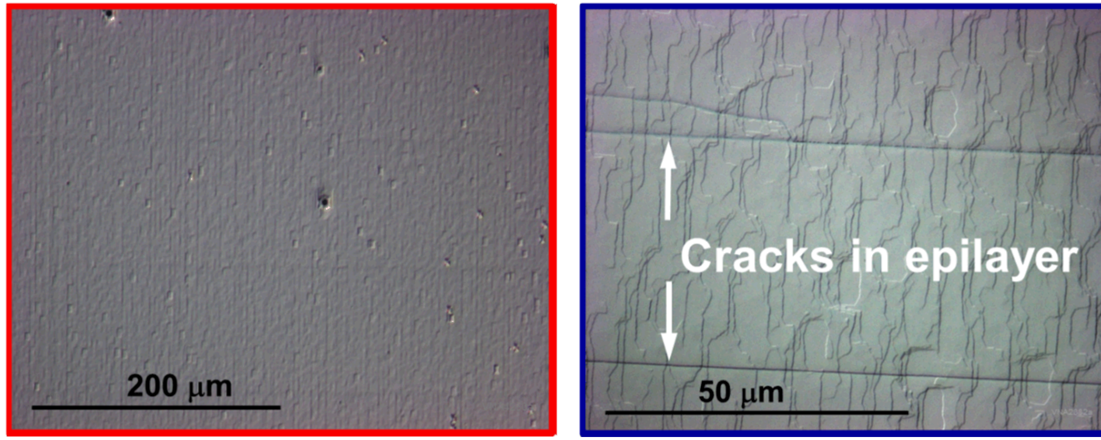
Reduction of wafer bow and cracking using 3x thicker sapphire substrates

AlGaN template



Optical Image of $Al_{0.3}Ga_{0.7}$ N surface

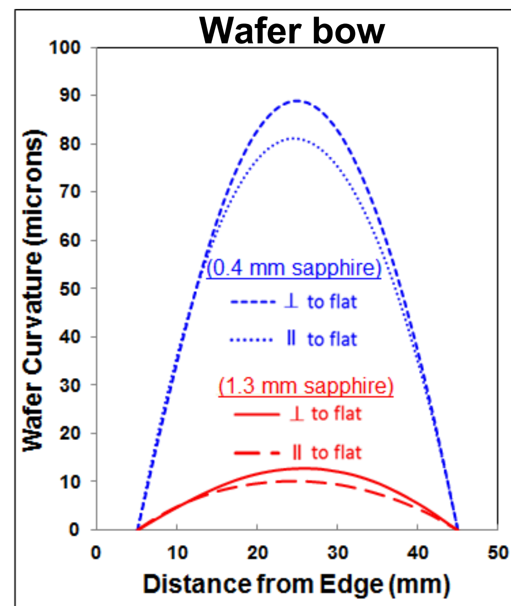


1.3 mm thick sapphire

0.4 mm thick sapphire

- Tensile strain in thick AlGaN overgrowth causes wafer to bow and epilayers to crack.
- 3x thicker sapphire reduces wafer bowing and cracking.
- Photolithography over larger areas is enabled with less bow.

➡ 3x thicker sapphire reduced wafer bow and epilayer cracking,



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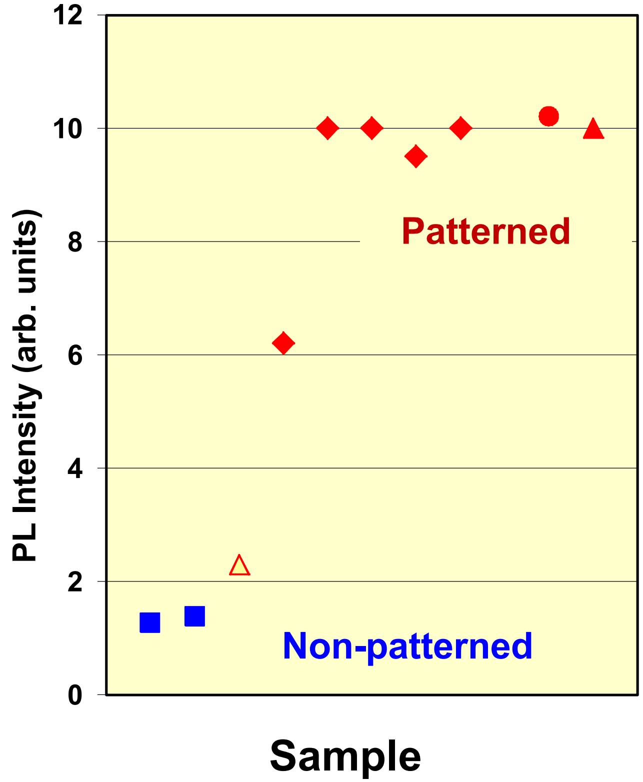
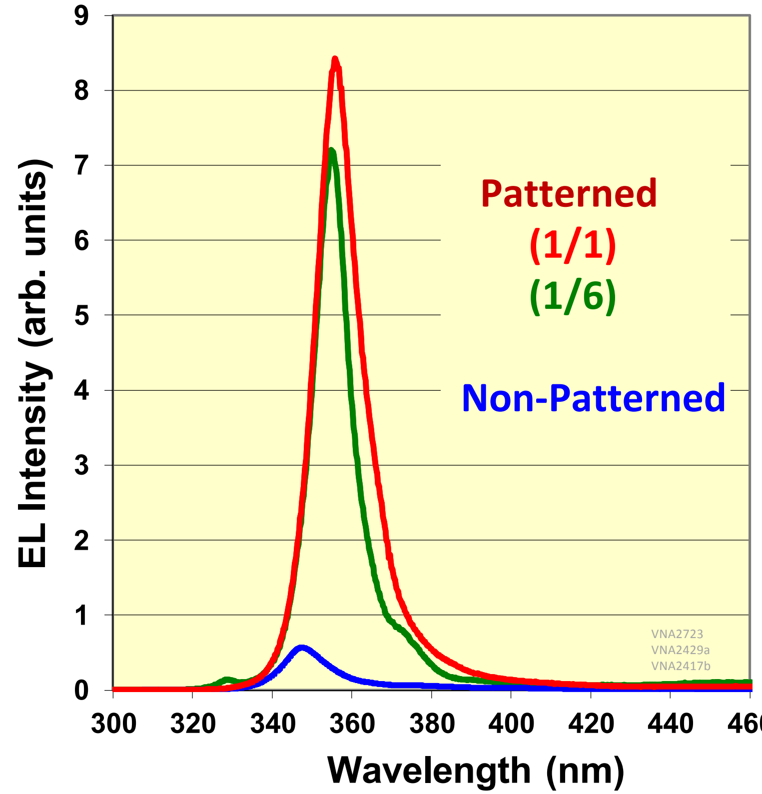
Photoluminescence and electroluminescence of GaN-AlGaN QWs on patterned and non-patterned templates

Photoluminescence (Quantum Wells)



Electroluminescence (LD structure)



With $Al_{0.3}Ga_{0.7}N$ overgrowth of patterned templates:

- ➡ ~7-8x increase in PL
- ➡ ~15x increase in EL

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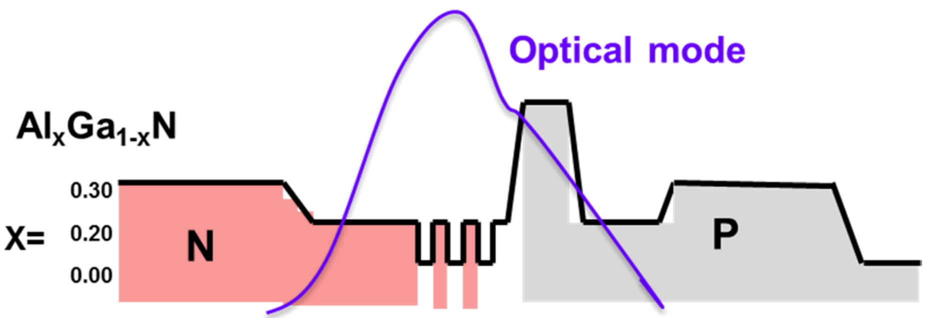
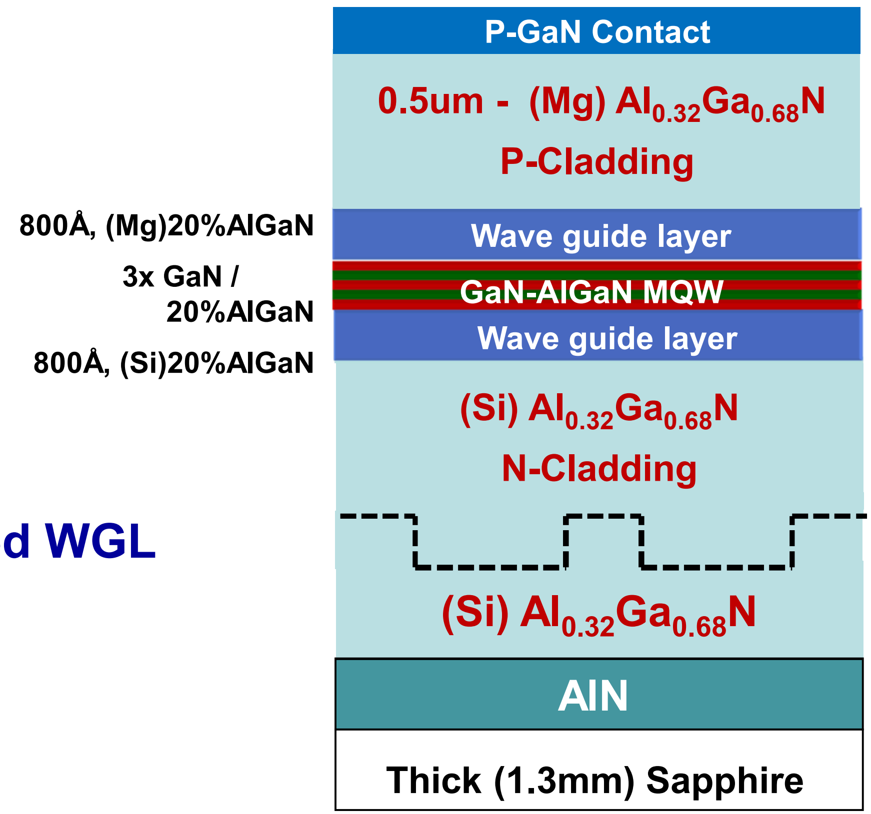
Doped waveguide laser design

Doped Waveguide



Laser Structure



- Improved carrier injection with doped WGL
- Higher optical losses due to doping

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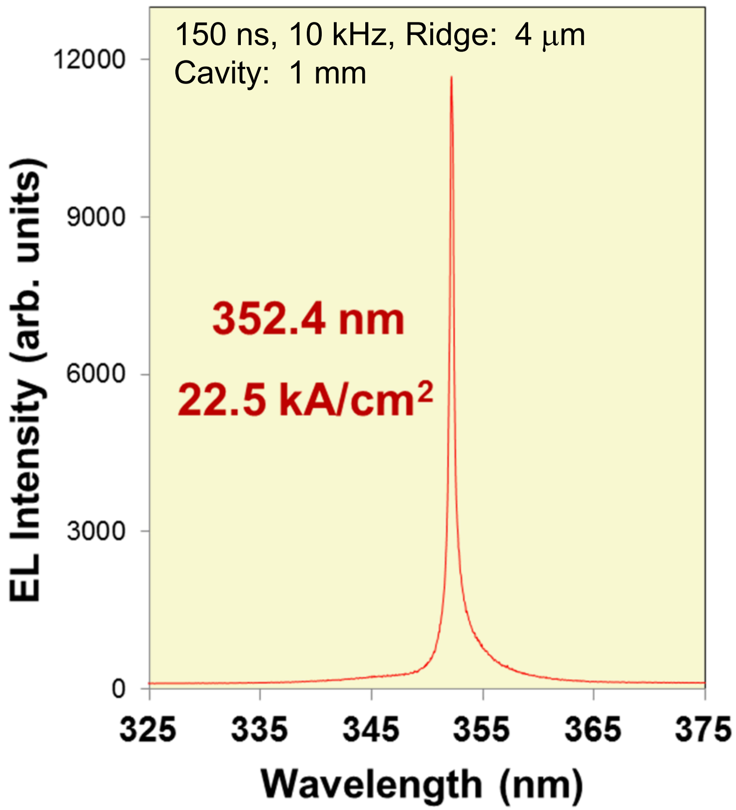
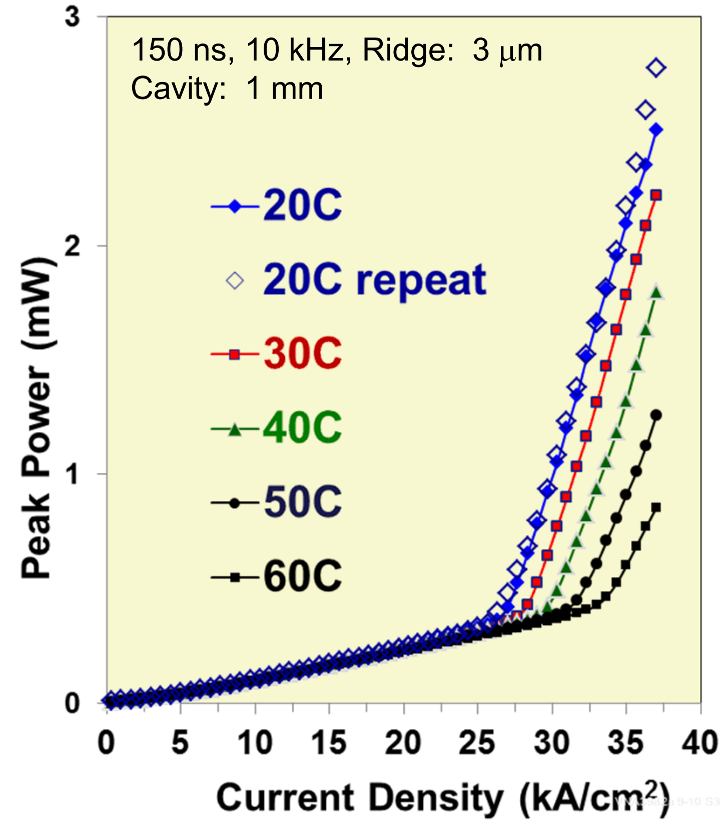
Doped waveguide design: spectra and LI-data (pulsed)

Ridge waveguide process with etched, coated facets





- Lasing from devices with 2-4um ridges, 0.7- 1.3 mm cavities
- Devices are robust to 60°C and 37 kA/cm²
- TE / TM polarization > 100:1

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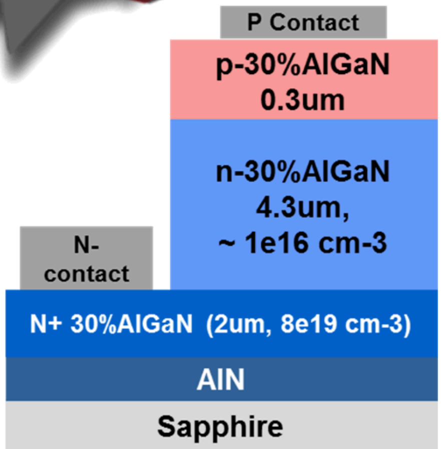
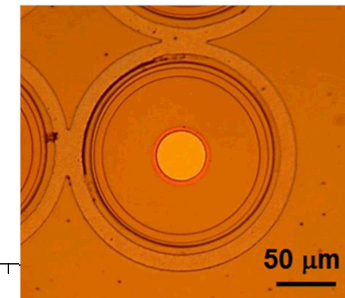
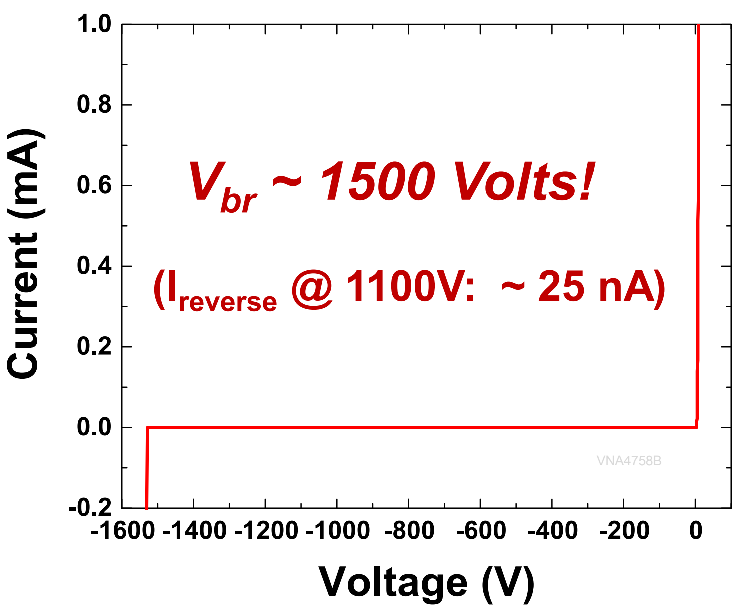
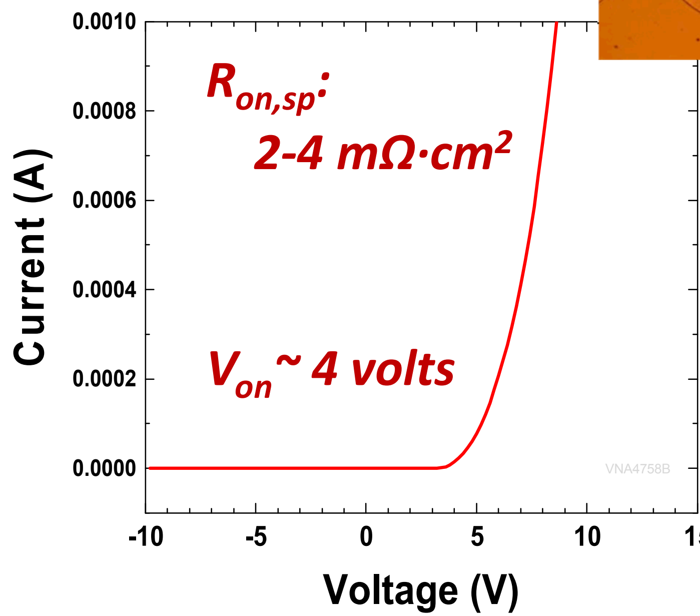
$Al_{0.3}Ga_{1-x}N$ "Quasi-Vertical" Pin diode on sapphire



- Implanted junction edge termination around p-contact
- Drift region: 4.3 μm, N_o~ 1e16 cm^{-2}, μ ~ 150 cm^2/Vs
- Dislocation density: 1-2e9 cm^{-2}
- On wafer testing in Fluorinert (150 μm dia.)







➡ **First report of kilovolt class AlGaN PIN diode**

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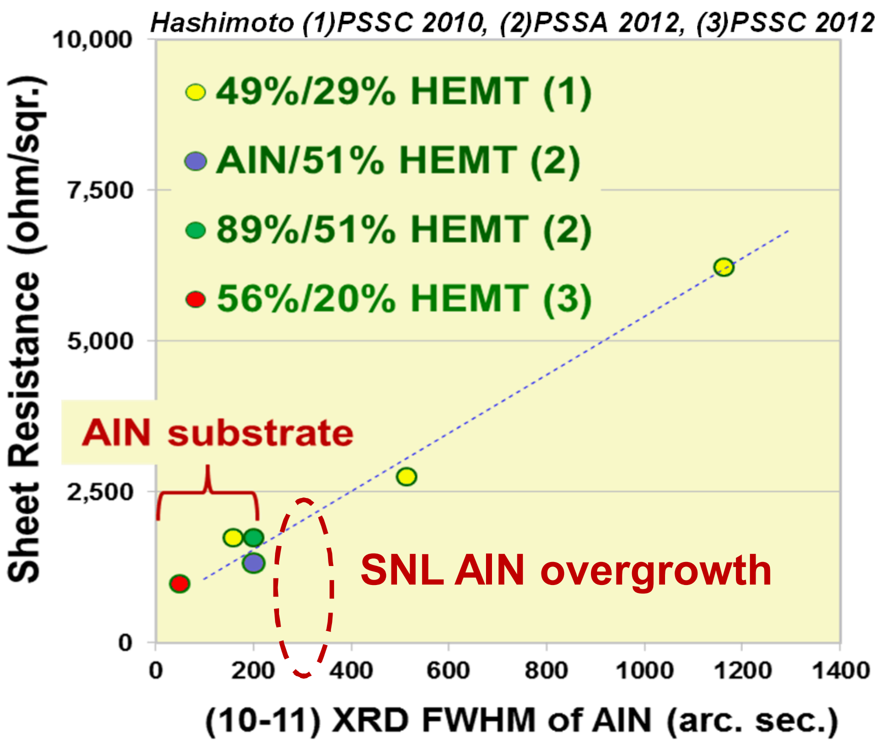
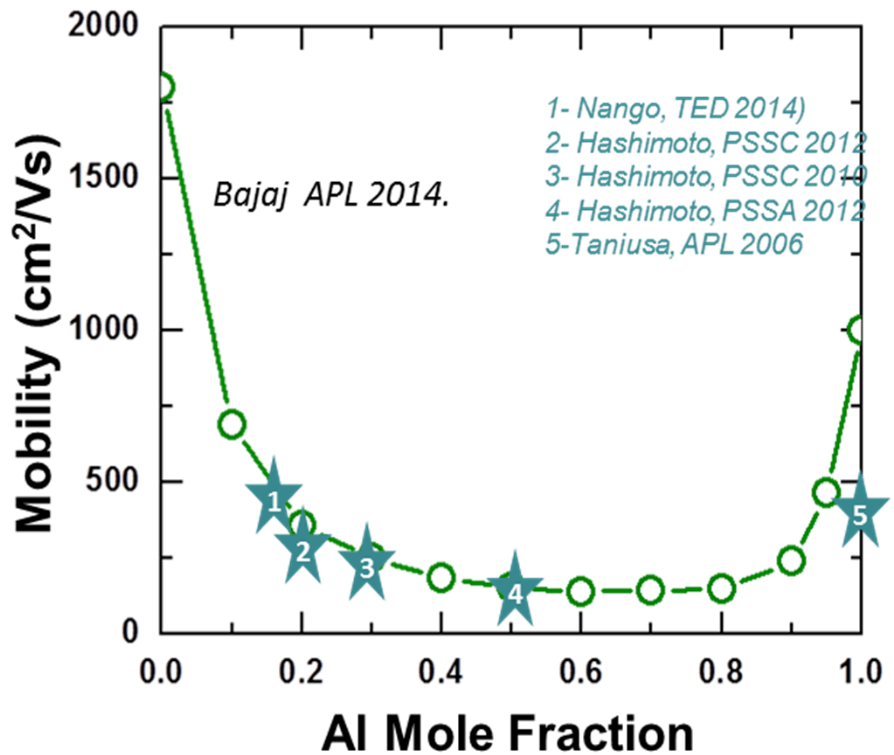
Sheet Resistance and electron mobility of Al-rich AlGaN heterostructures

Sheet Resistance vs. Dislocation Density



Calculated Electron Mobility vs. AlGaN Channel Composition

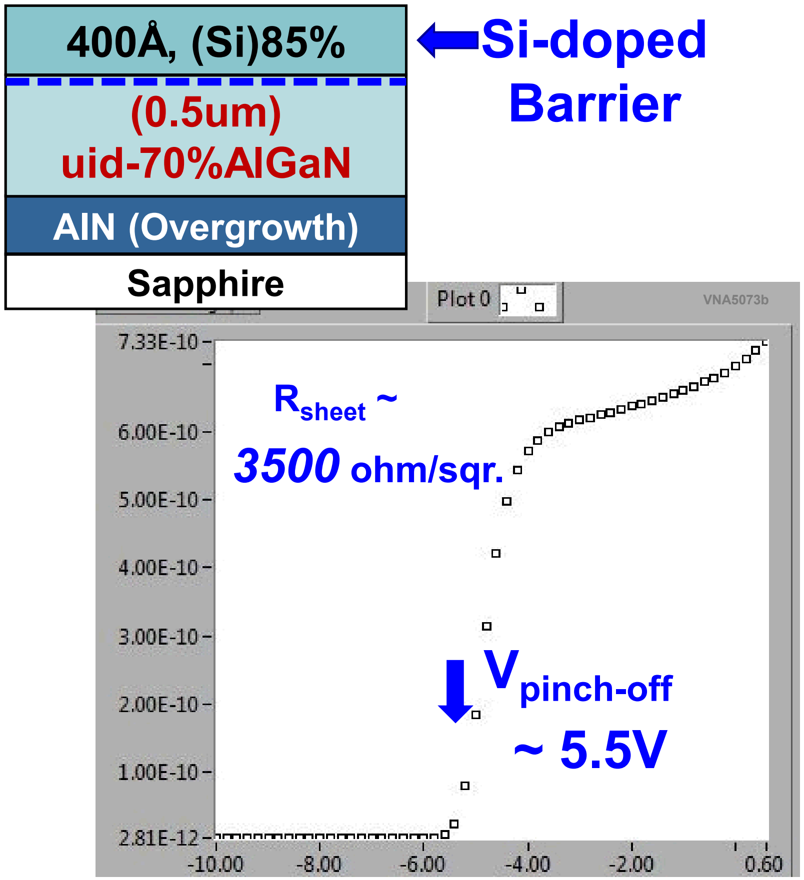


➡ Transport of 2DEG in AlGaN heterostructures improves with lower TDD

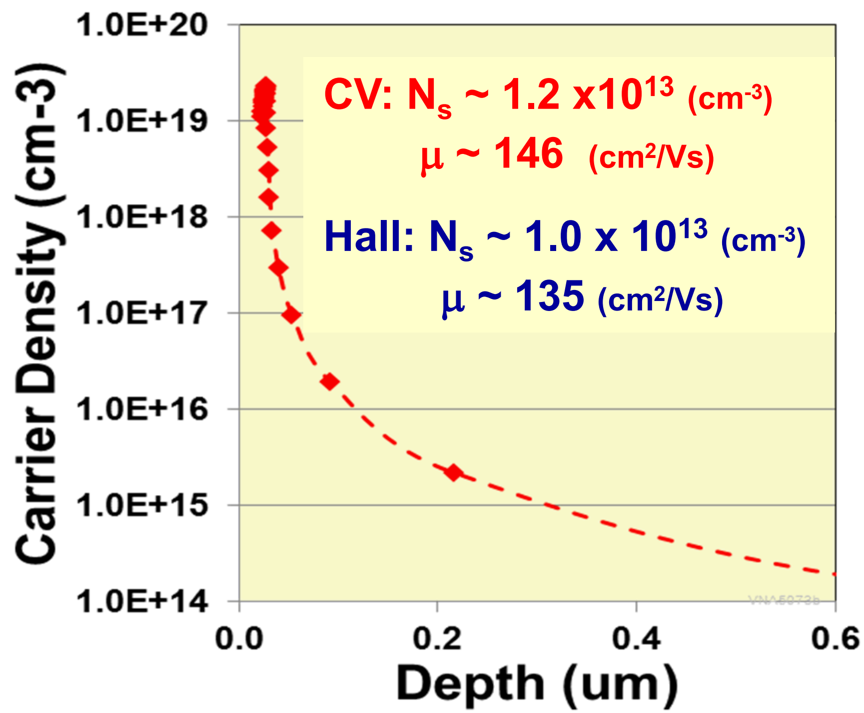
➡ Higher mobility is predicted for higher Al compositions

CV of 85% / 70% AlGaN heterostructure

CV of 85% / 70%AlGaN MODFET



Carrier Density Profile (CV)



- N_s & μ are similar to HEMTs with lower Al channels

➡ First demonstration of 2DEG in $Al_xGa_{1-x}N$ channel for x > 0.5

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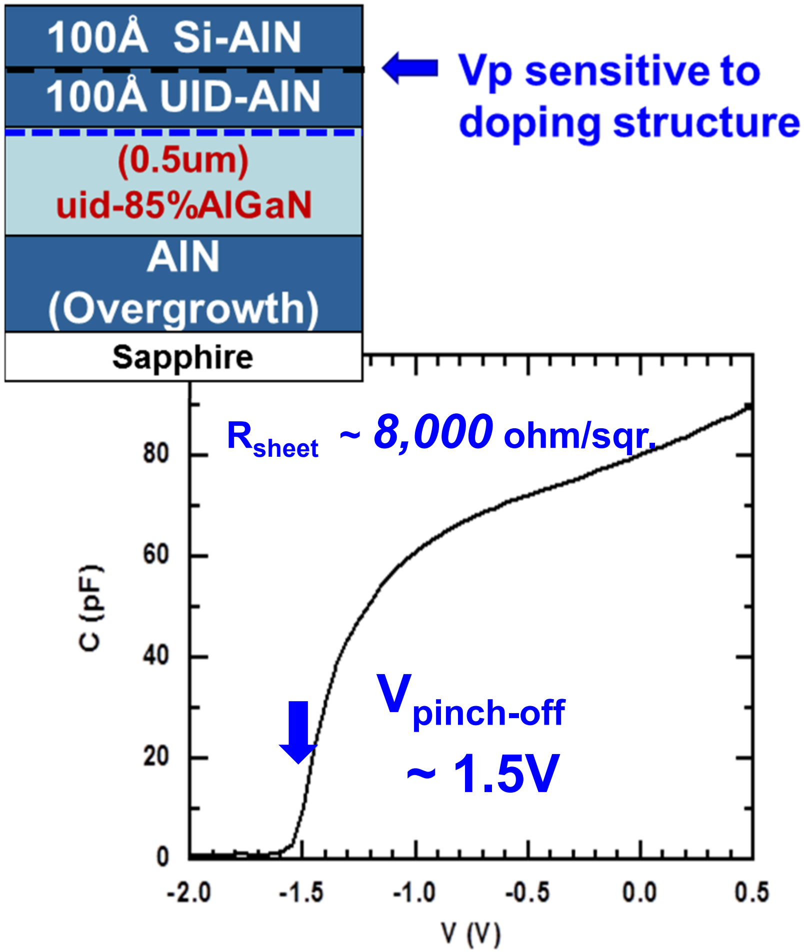
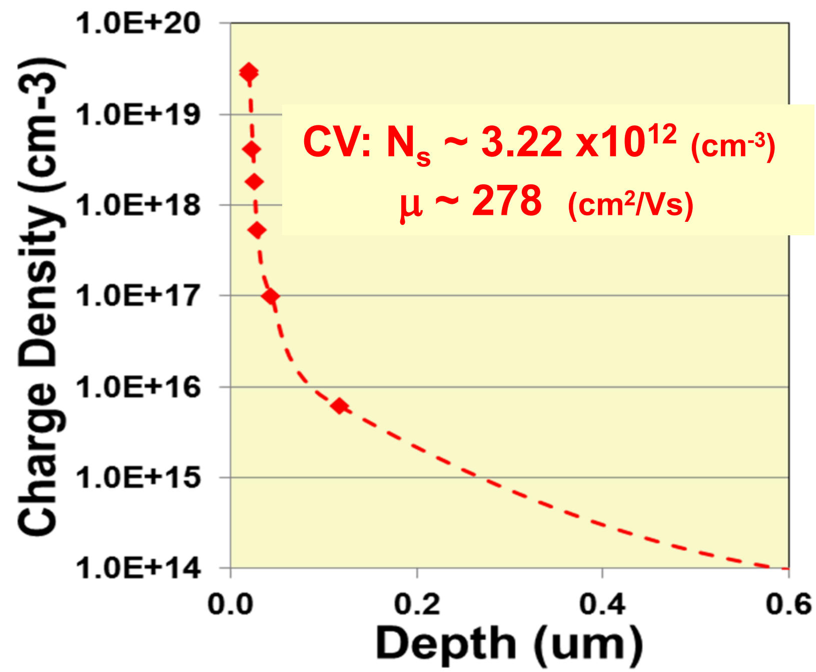
CV of AlN / 85% AlGaN heterostructure

CV of AlN / 85%AlGaN MODFET



Carrier Density Profile (CV)

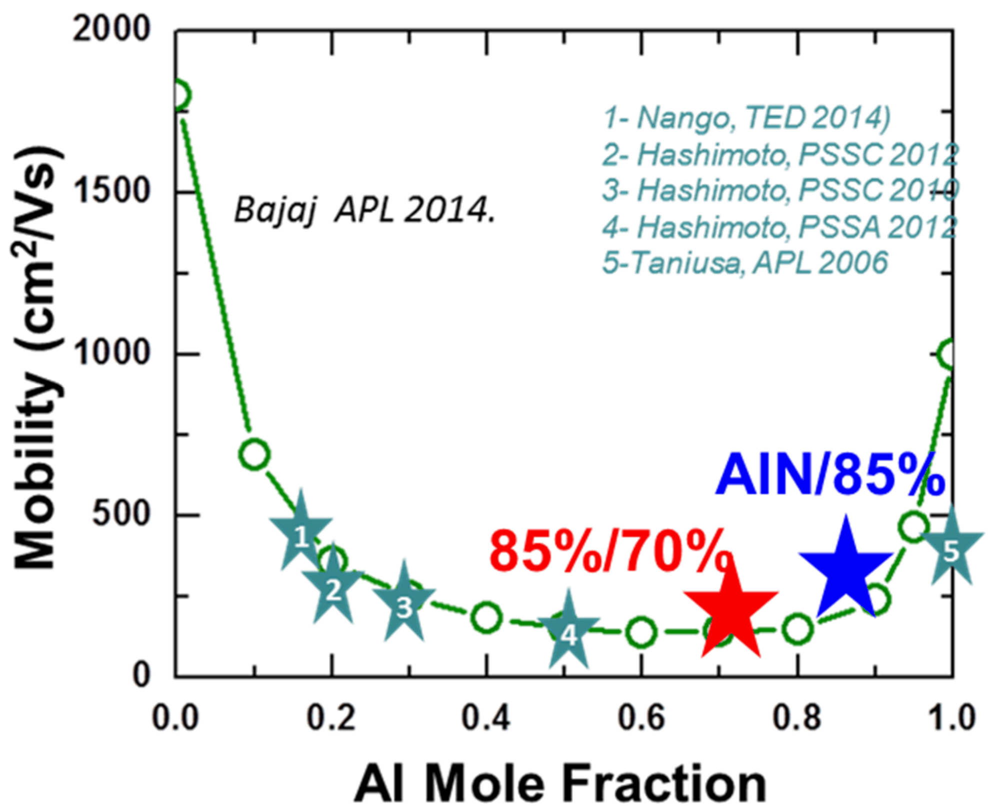


- No indication of parasitic channel
- Mobility is exceptionally high

➡ Largest Al mole fraction exhibiting 2DEG

Electron mobility of Al-rich AlGaN heterostructures

Calculated Electron Mobility vs. AlGaN Channel Composition



➡ *Electron mobility of 2DEG increases with higher Al composition AlGaN heterostructures*

Summary

- Reduced dislocation density of $Al_xGa_{1-x}N$ epilayers by growing over trenches etched in $Al_xGa_{1-x}N/AlN$ on sapphire.

$$\rho = 2\text{-}3 \times 10^8\ cm^{-2} \qquad (x = 0.3,\ 0.7)$$

$$\rho = 4\text{-}5 \times 10^8\ cm^{-2} \qquad (x = 1)$$

  - Spatially uniform reduction ➡ *no device alignment to template*
  - Doped with Si ➡ *simplifies vertical structure, PIN diodes*

- Diode lasing at 352nm from doped waveguide structures.

- $Al_{0.3}Ga_{0.7}N$ PIN diode with breakdown voltage of 1500V

- Observed 2DEG formation and higher mobility in AlGaN heterostructures with Al composition > 0.5 (85%/70%, AlN/85%)