SAND2015-0154C

Low-dislocation-density AlGaN templates for UV laser diodes

Veeco D-125 MOCVD system

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Acknowledgements: M. Smith, K. Cross, S. Lee, B. Clark, and L. Alessi

Outline

- Introduction UV-devices and substrates
- Dislocation reduction of $Al_{0.3}Ga_{0.7}N$ grown over etched trenches
  - Processing and growth
  - Effect of mesa & trench geometry on dislocation reduction
  - Improvements in PL and EL
- UV Lasing
  - Optical pumping
  - Electrical injection
- Dislocation reduction of $Al_{0.7}Ga_{0.3}N$ grown over etched trenches
- Summary

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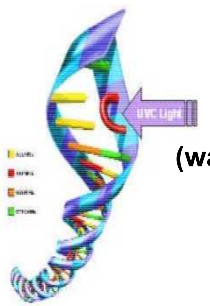
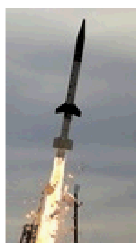
AlGaN Alloys Span UV-A, -B and –C Spectrum

Raman Spectroscopy
225-250 nm
(biological agent identification)

www.hanovia.com

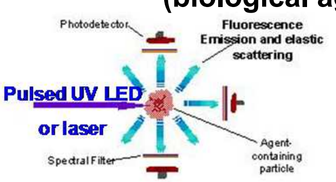


Germicidal
260-275 nm
(water, air, surfaces)

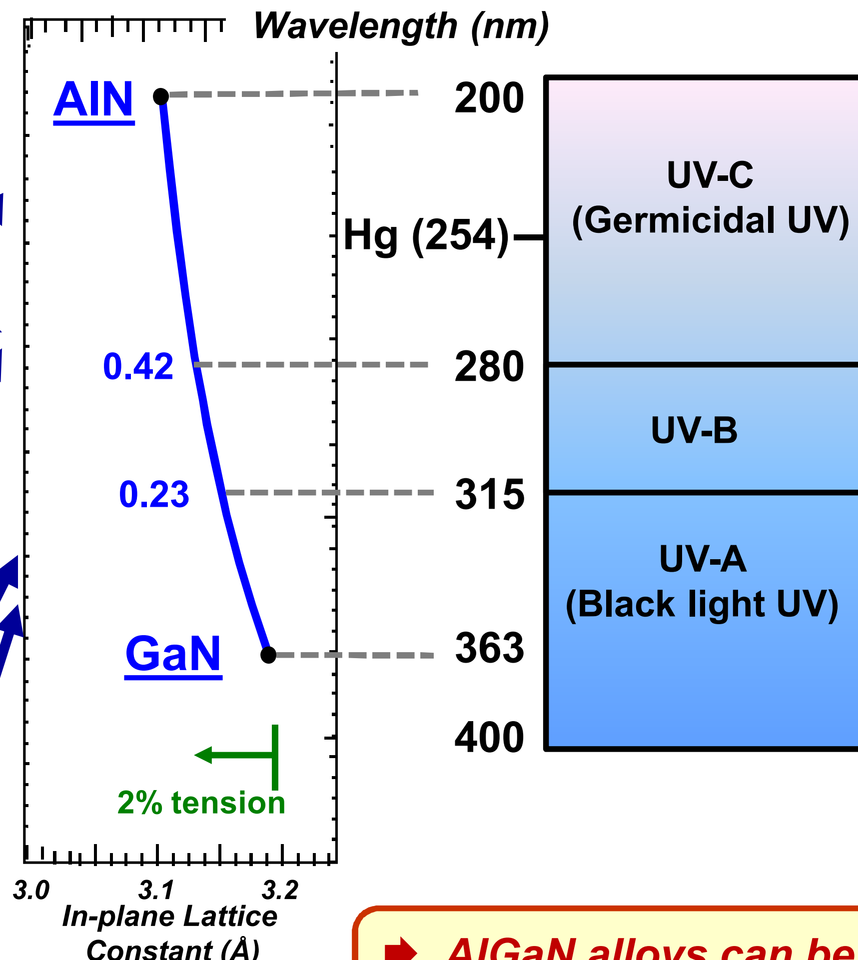


Solar-blind flame detection, λ<280 nm
(launch, fire)

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***

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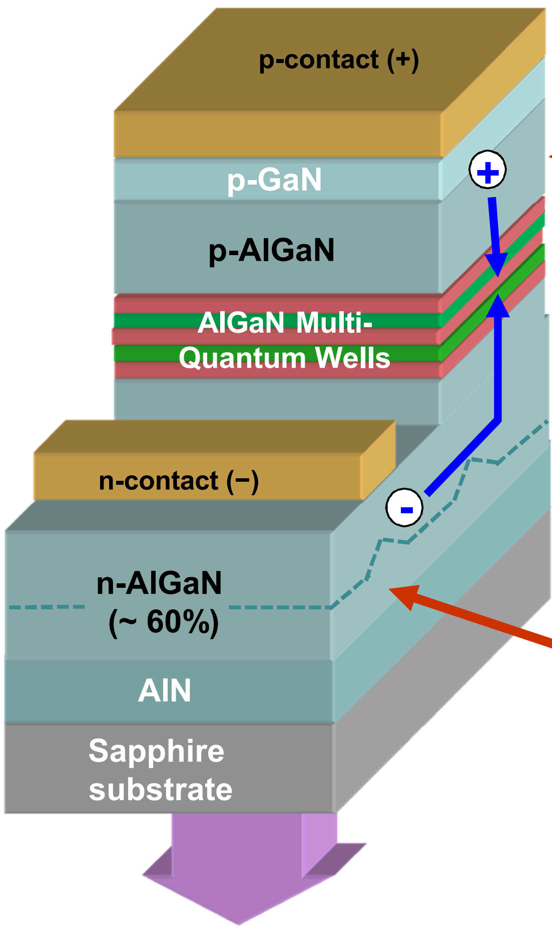
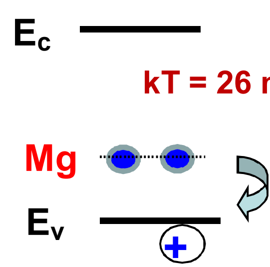
Material challenges in realizing AlGaN based UV optical emitters and detectors

UV (AlGaN) LED / LD



2. *P-type doping of AlGaN is difficult*

- Large acceptor ionization energies
- Thermal ionization ineffective for holes for X > 0.4

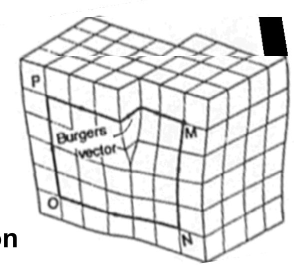


Xal ~ 30%

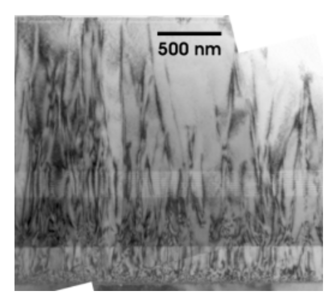
> 300 meV!

1. *Lack of AlGaN Substrates results in crystalline defects*

- High densities of extended defects (threading dislocations)
- Reduced device efficiency and operational lifetime



Screw dislocation



TEM image of AlN, AlGaN on sapphire

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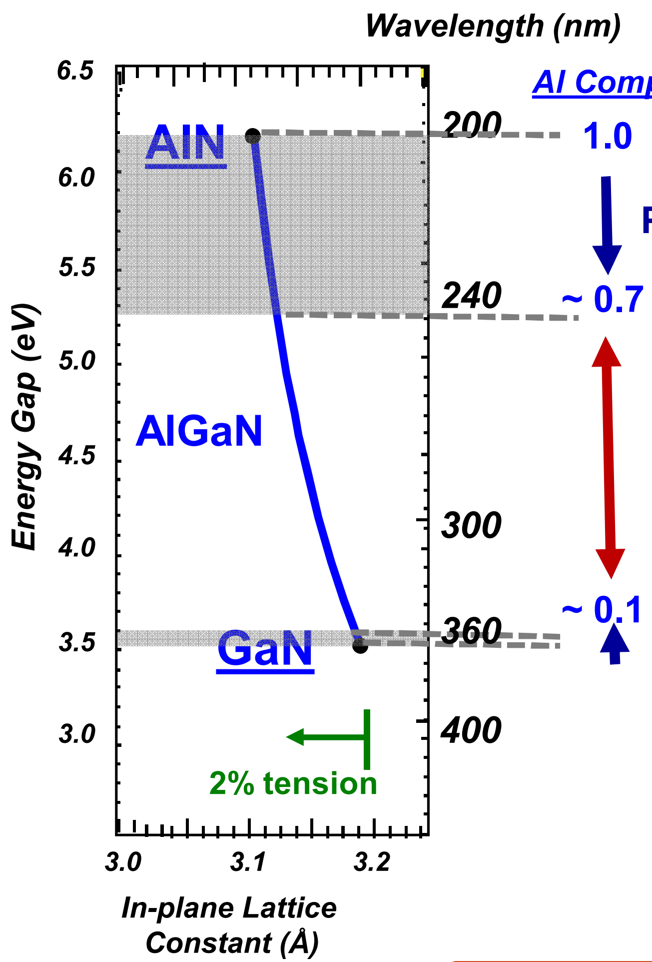
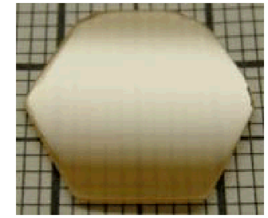
AlGaN Alloys and applications for UV-devices



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 mid-alloy UV-emitters?

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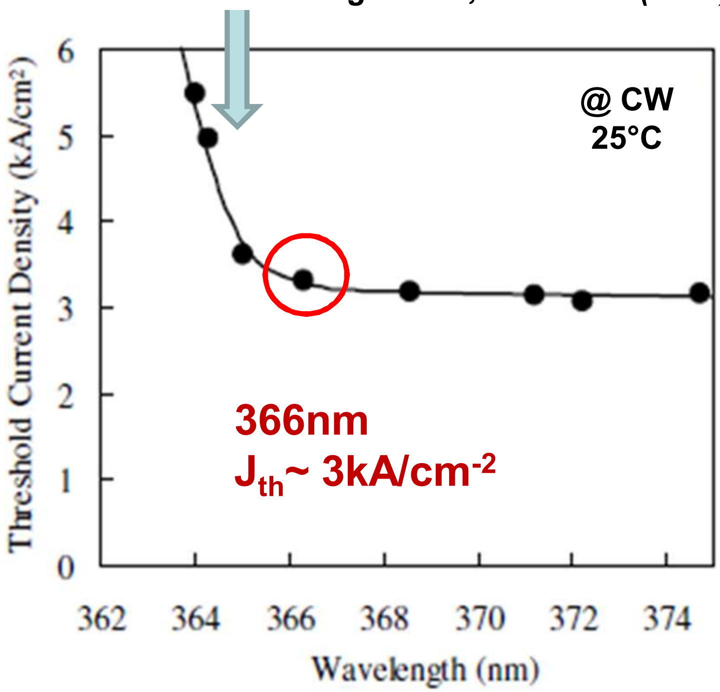
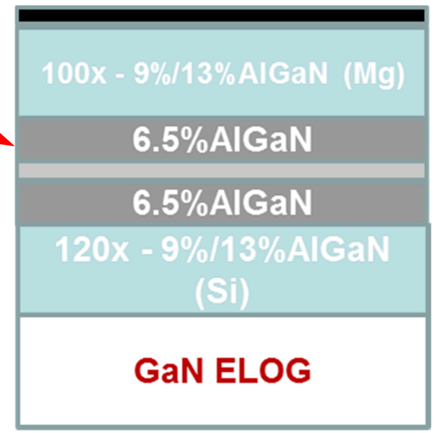
UV-A laser emission on GaN (0001)

Nichia

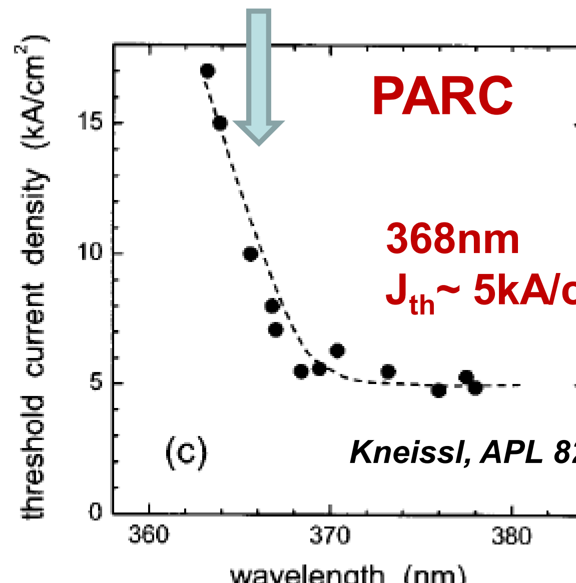
Mukai, PSSA (2004)
Nagahama, SPIE4995 (2003)





Optical absorption in WGL

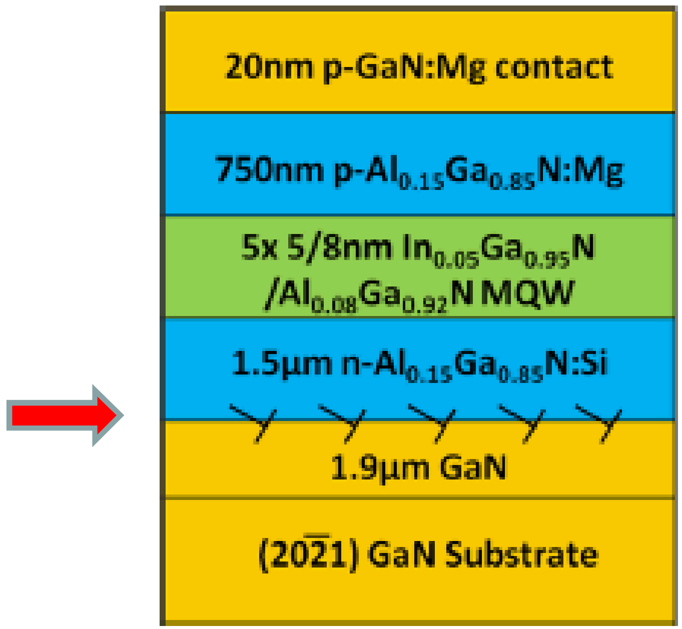
Higher Xal ➡ Cracking!

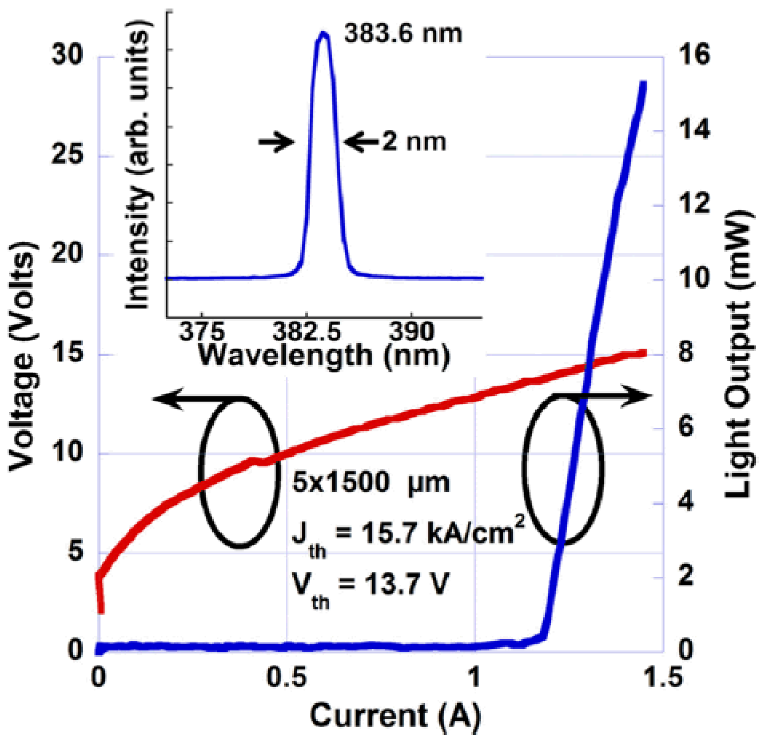


Kneissl, APL 82 (2003)

Solutions to substrate and strain challenges

"Metamorphic" Approach





UCSB: Haeger et al. APL 100 161107 (2012)

- **Relax strain, defects confined below active layers**
- **Utilize dislocation glide not possible in c-plane orientation**
- **AlGaN on semi-polar GaN substrate**
- **Laser at 384nm, Jth = 15.7 kA/cm2**

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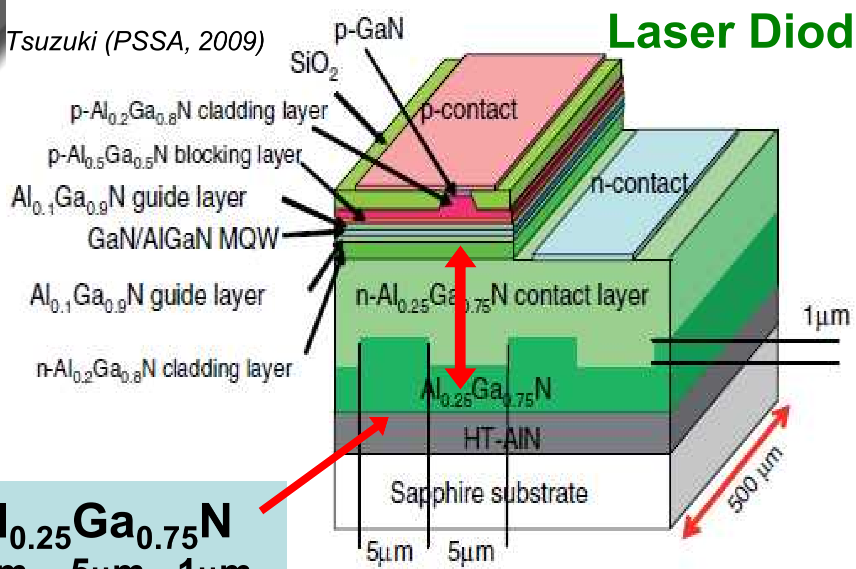
Previous Work (H. Amano)

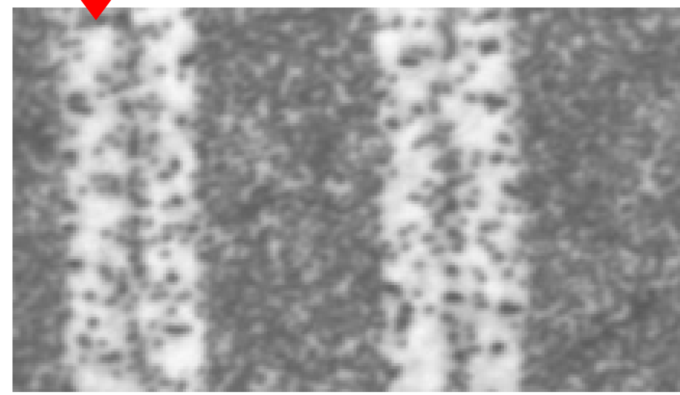
Tsuzuki (PSSA, 2009)



$Al_{0.25}Ga_{0.75}N$
5 µm, 5µm, 1µm

Laser Diode on grooved $Al_{0.25}Ga_{0.75}N$

Align laser bar *Iida (PSSC, 2008)*



Cathodoluminescence of MQWs on grooved $Al_{0.25}Ga_{0.75}N$

- **Template layers are transparent (necessary for bottom emitting LEDs)**

- **Dislocations reduced only over trench**
  - ➡ **50% of LED area has high dislocations**
  - ➡ **Laser ridge aligned to trench**

- **Grooves in $Al_{0.25}Ga_{0.75}N$:** *Tsuzuki (PSSA, 2009)*
  - **356 nm, 13.9 kA/cm^2, (w/o mirrors)**
  - **358 nm, 4.3 kA/cm^2, (w/ mirrors)**
  - **α_i = 4.6 cm^{-1}, α_{mirror} = 7.6 cm^{-1}**

- **Grooves in *GaN*:** *Iida (JCG, 2004)*
  - **350.9 nm, 7.3 kA/cm^2**
  - **Cleaved facets**
  - **18%AlGaN claddings**

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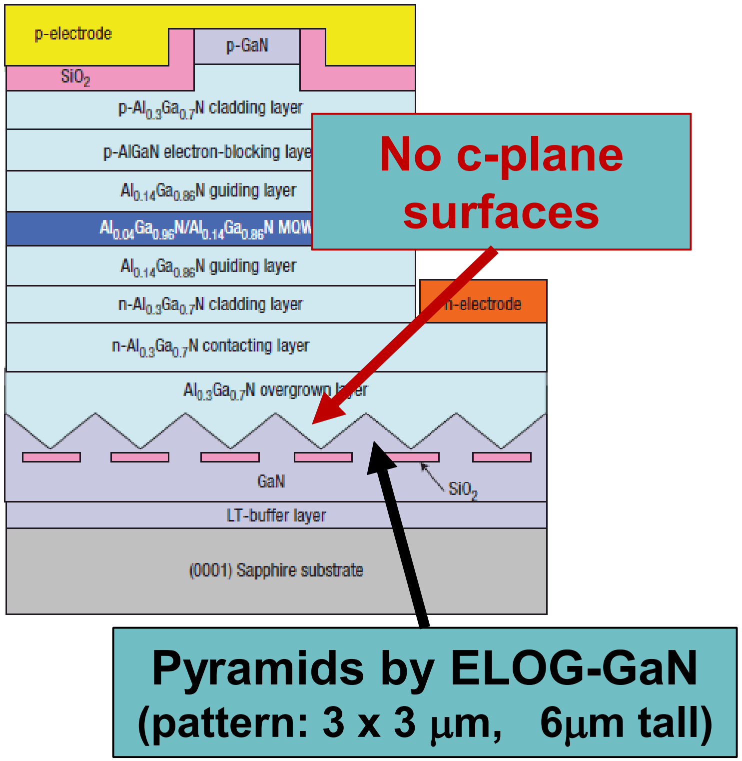
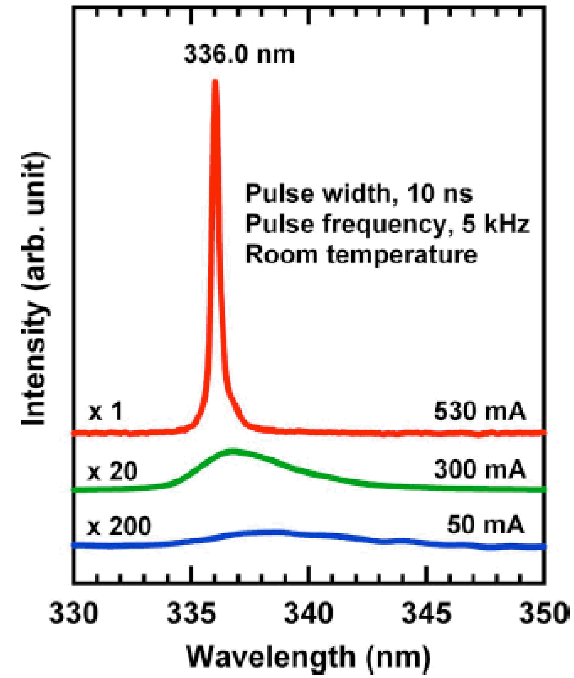
Previous Work (Yoshida)

Yoshida (Nat. Photonics, 2008)



Yoshida (APL, 2008)



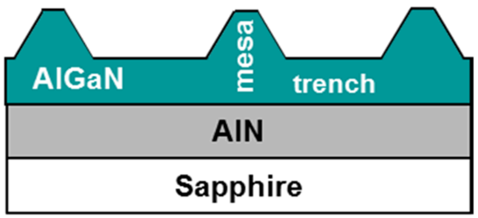
- **Dislocations uniformly reduced over wafer**
- **Utilizes GaN layer**
  - ➡ **Not useful for bottom-emitting UV LEDs**
  - ➡ **Can't use ELOG for AlGaN**

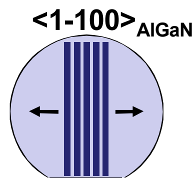
- ***ELOG-GaN with $Al_{0.3}Ga_{0.7}N$ claddings*:**
  - **336 nm, 17.6 kA/cm^2**
  - **342 nm, 8.7k A/cm^2**
  - **Etched facets, 10 ns,**

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

1. Pattern & etch trenches

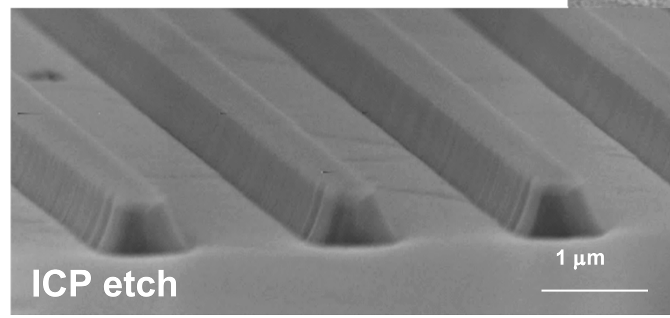
Mesa width: 1, 2 μm
Trench width: 1, 6 μm
Etch Depth: 0.4 – 0.7 μm

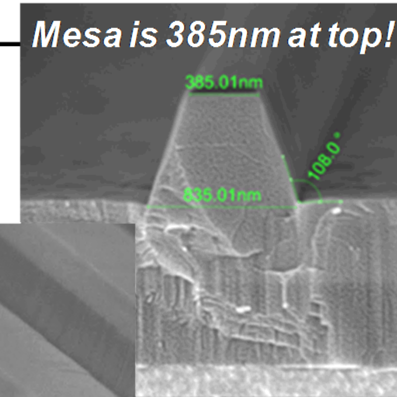




Trench Alignment

Trench: ~1.3 μm
Mesa (top): ~0.4 μm



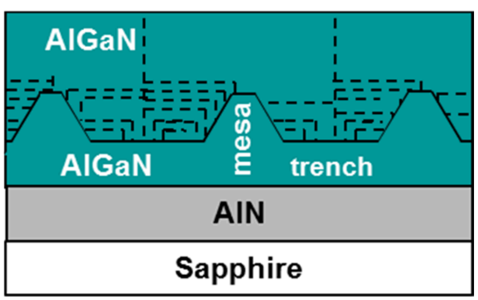


➡ *Sub-micron features are key for uniform reduction of dislocations*

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

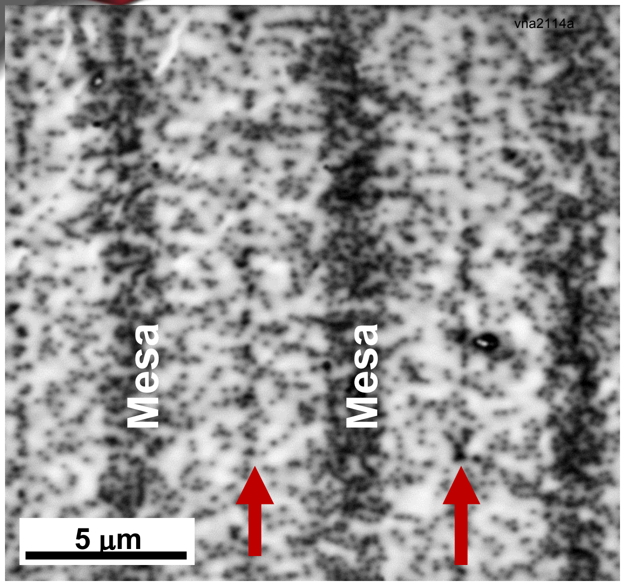
2. Overgrow with AlGaN

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

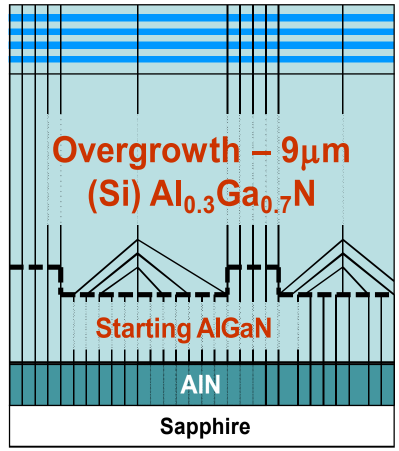


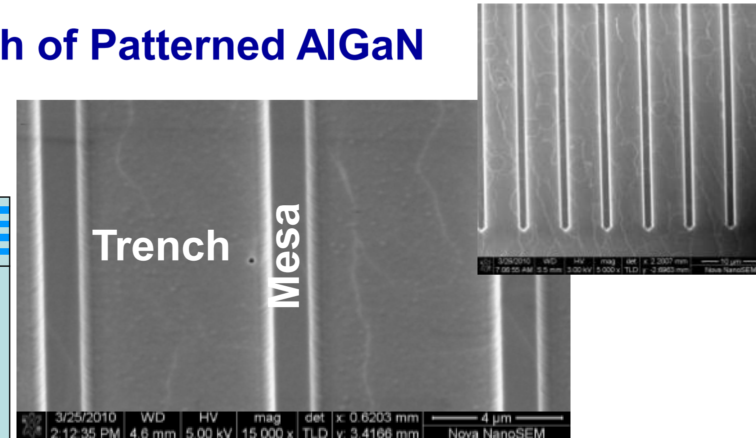
Reactor:	Veeco D-125
Chamber:	75 torr, 1060 °C
Al/III & V/III Ratio:	0.32, 1040
Group-III:	34 μmoles/min
Growth rate:	0.6 μm/hr

Cathodoluminescence of AlGaN Overgrowth of Patterned AlGaN (2/5)



AlGaN Overgrowth of Patterned AlGaN

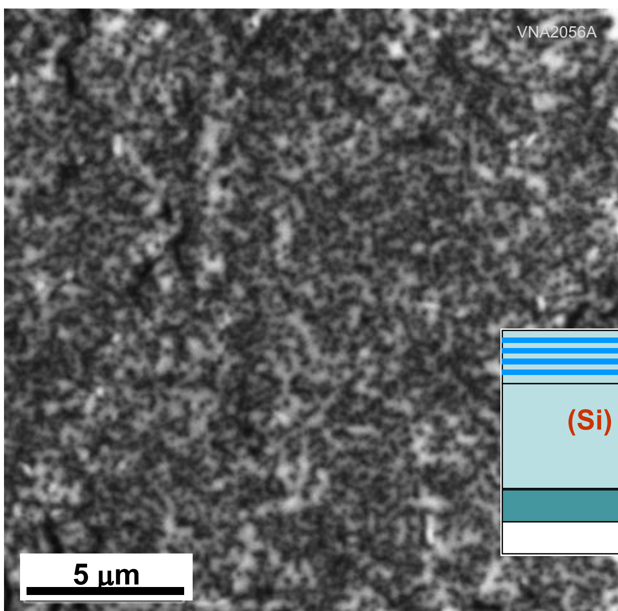




Overgrowth: 9 µm

Mask: 2(mesa) / 5(trench) µm

Etch Depth: 0.4 µm



- No dislocation reduction over 2 µm mesas
- Dislocation density is reduced over trenches.

$$\rho_{\text{trench avg.}} = 5 \times 10^{8}\ cm^{-2}$$

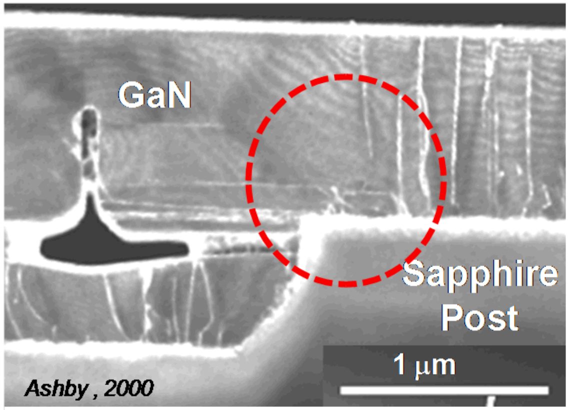
- Dislocations "collect" at center of trenches

Non-patterned AlGaN

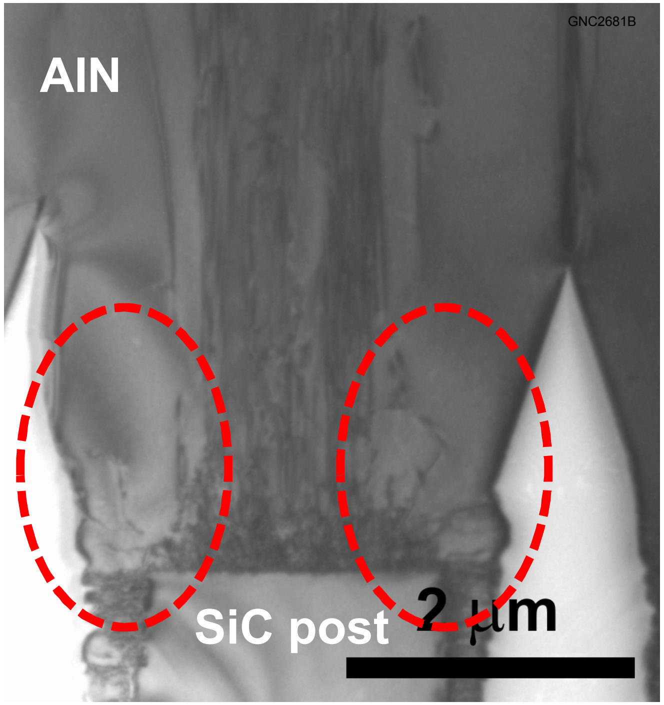
Dislocation Bending Near Edges of Posts

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

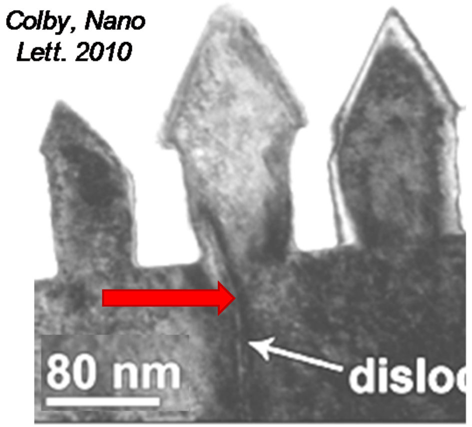
Cantilever Epitaxy: GaN on sapphire



Cantilever Epitaxy: AlN on SiC



Nanowires



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

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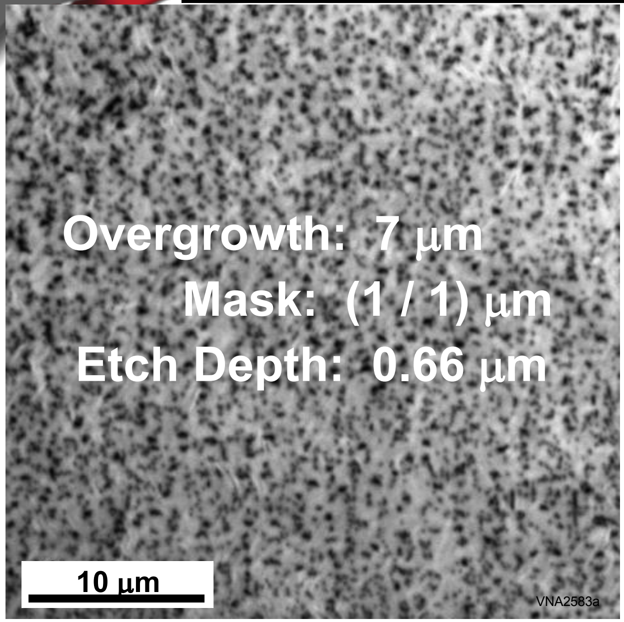
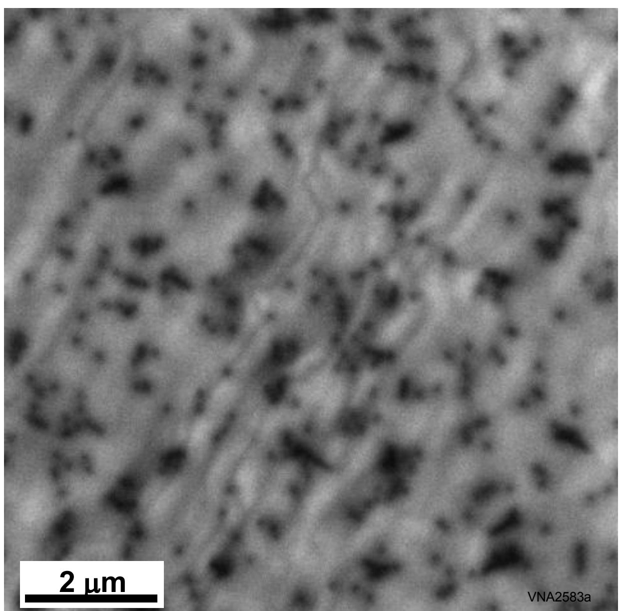
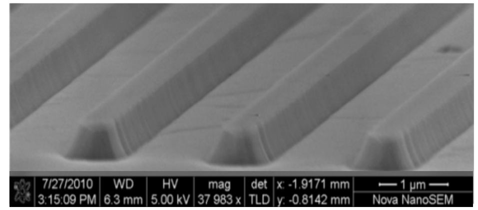
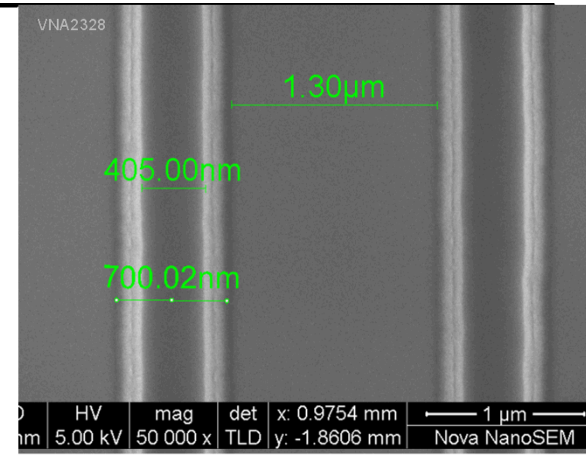
Cathodoluminescence of AlGaN Overgrowth of Patterned AlGaN (1/1)

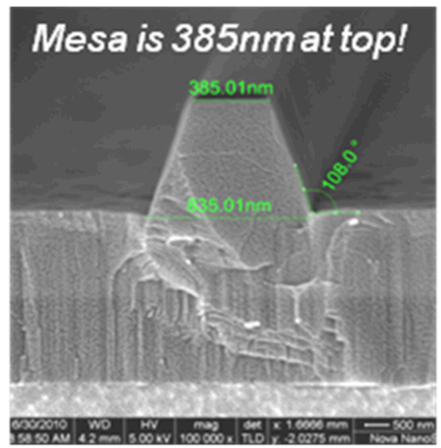






- Narrow Trench to ~1.2 – 1.4 µm





- Narrow Mesa (< 1um)

- Spatially uniform reduction in dislocation density $\rho_{avg.} = 2.5 \times 10^{8}\ cm^{-2}$

- Doped with Si, $2\text{-}4 \times 10^{17} cm^{-2}$

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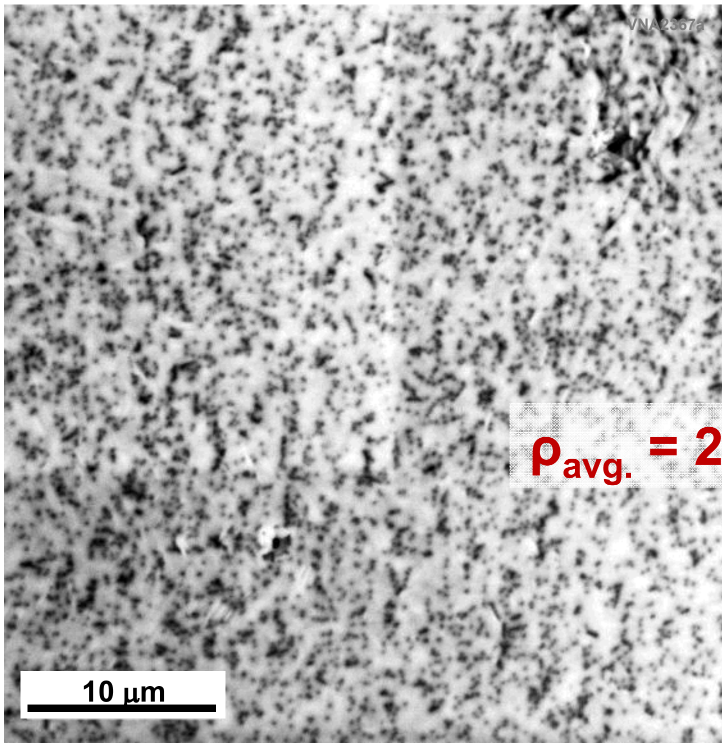
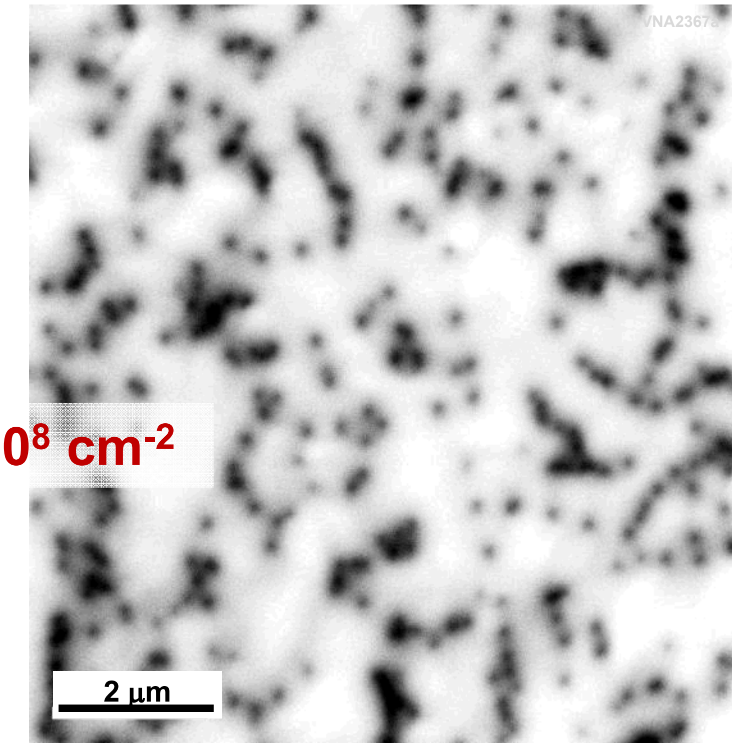
Cathodoluminescence of AlGaN Overgrowth of Patterned AlGaN

$Al_{0.32}Ga_{0.68}N$



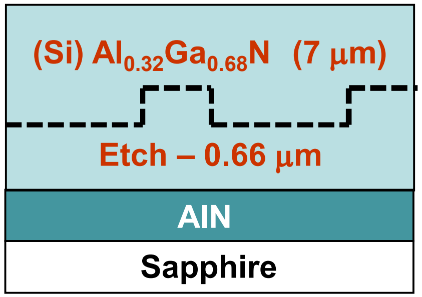


$\rho_{avg.} = 2\text{-}3 \times 10^{8}\ cm^{-2}$

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

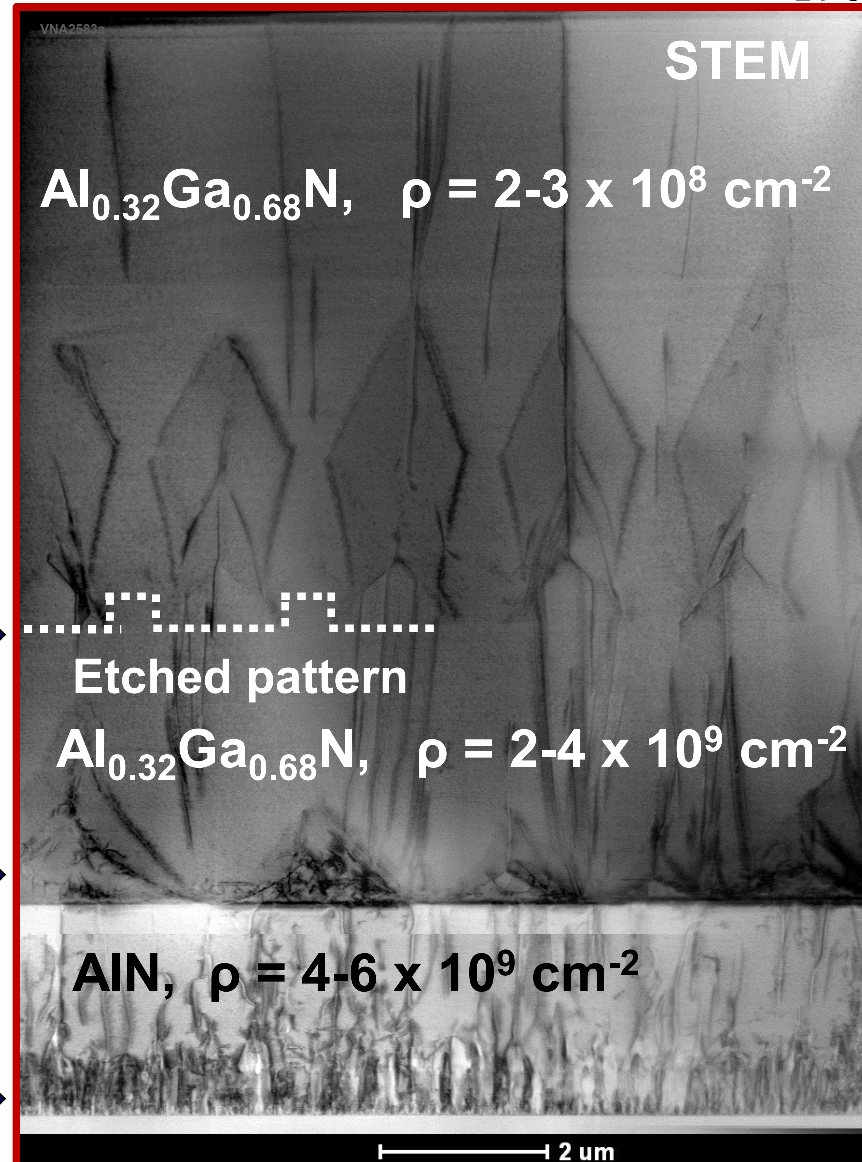
Two-Beam BF-STEM of $Al_{0.32}Ga_{0.68}N$ Overgrowth of Patterned $Al_{032}Ga_{0.68}N$ (1/1)

B. Clarke

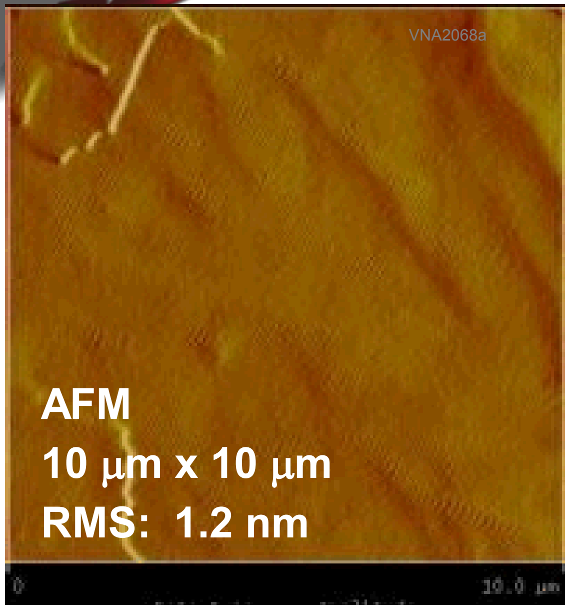


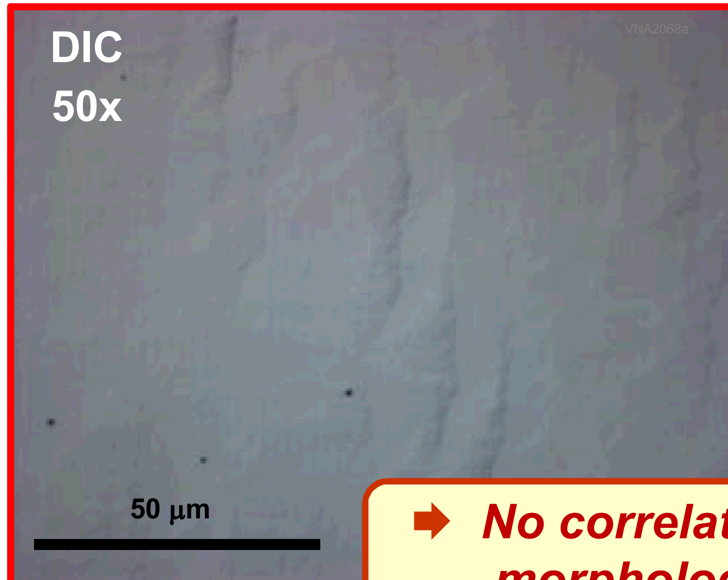
Introducing surface roughness drives dislocation reduction

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

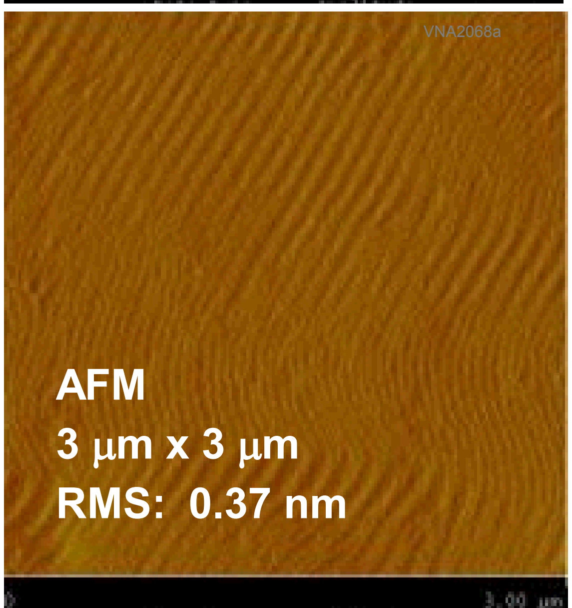


Surface Morphology of $Al_{0.32}Ga_{0.68}N$ Overgrowth of Patterned $Al_{0.32}Ga_{0.68}N$ - (1/1)

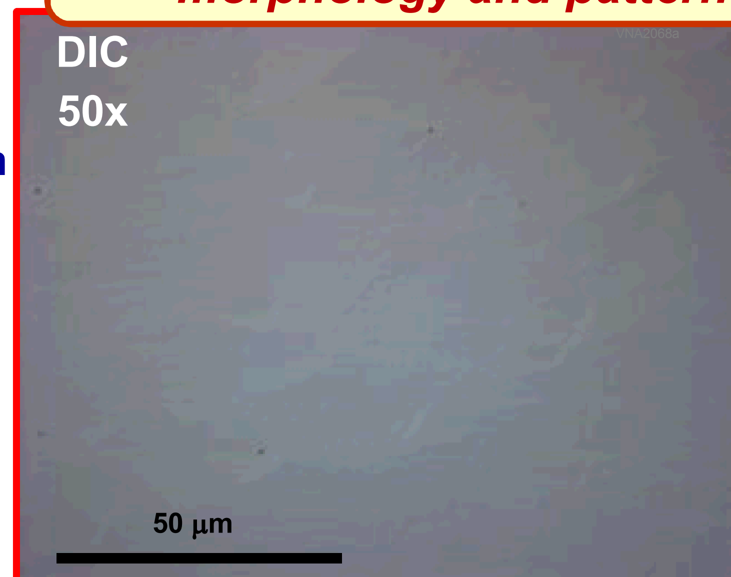




➡ ***No correlation between morphology and pattern***

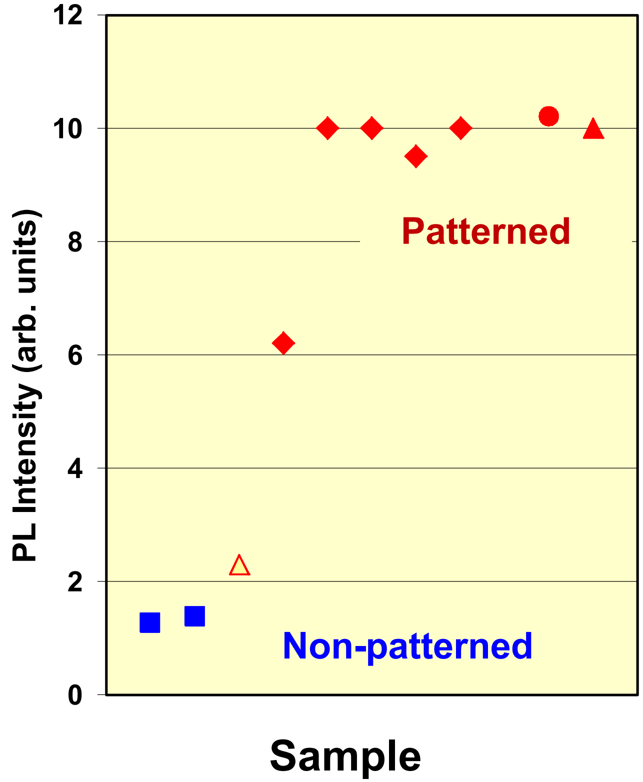


Overgrowth: 6 µm
Mask: (1 / 1) µm
Etch Depth: 0.56 µm

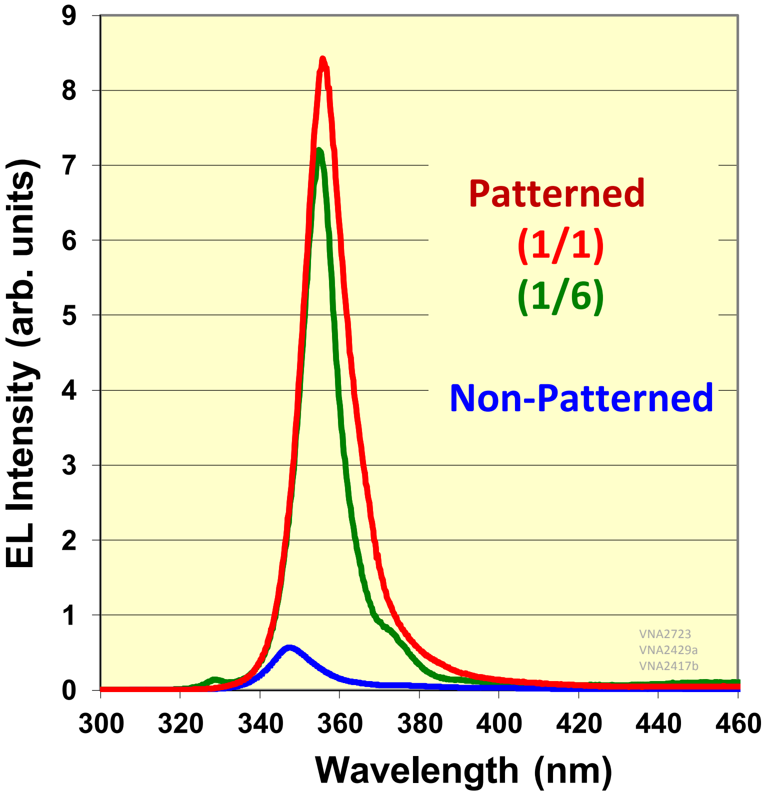


Photoluminescence and electroluminescence of GaN-AlGaN QWs on patterned and non-patterned templates

Photoluminescence (Quantum Wells)



Electroluminescence (LD structure, ~13 A/cm^2)



With AlGaN overgrowth of patterned templates:

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

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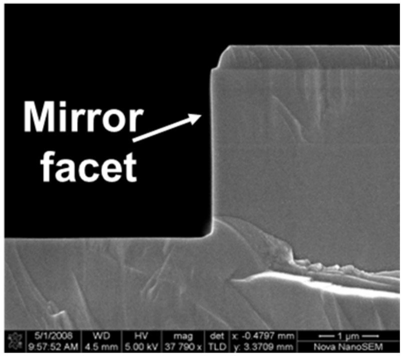
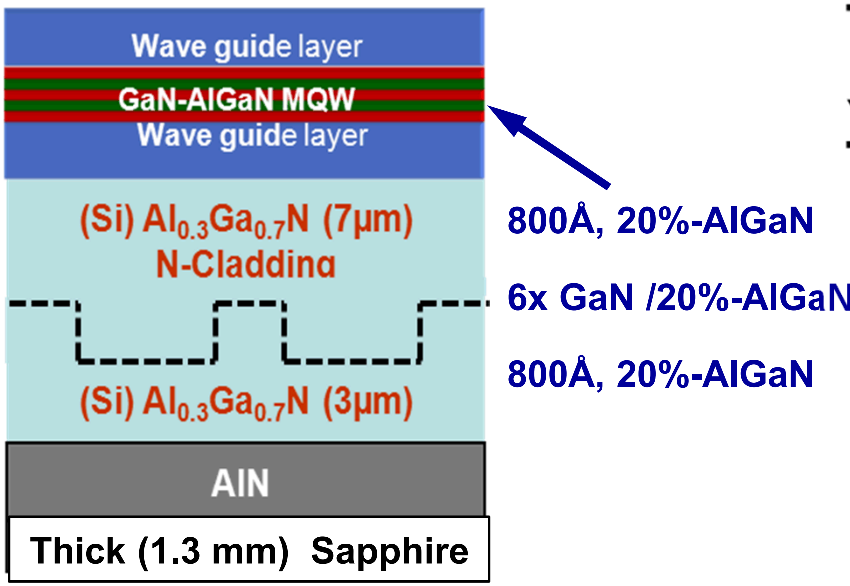
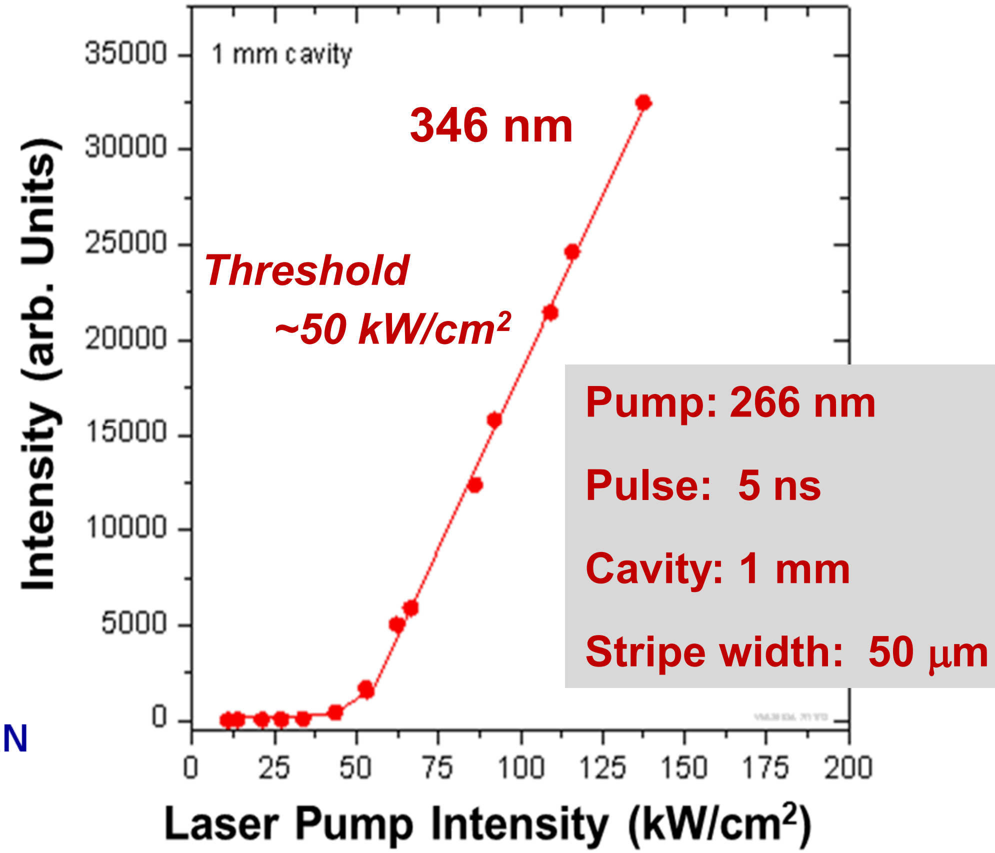
Optically pumped lasing at 346nm



Etched Facets



OP laser structure



➡ *Low lasing threshold*
~50 - 150 kW/cm^2

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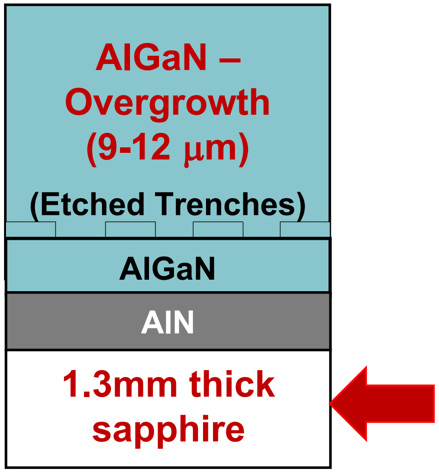
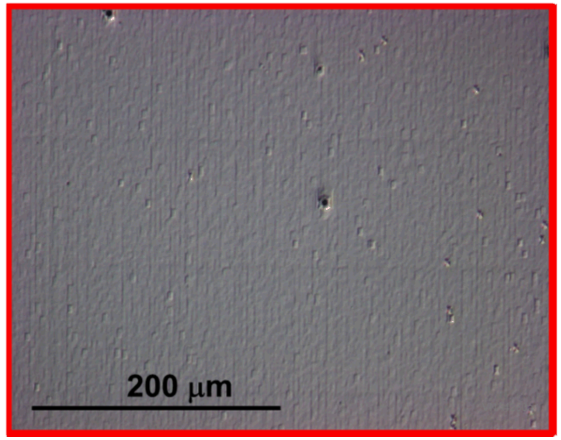
Reduction of wafer bow and cracking using 3x thicker sapphire substrates

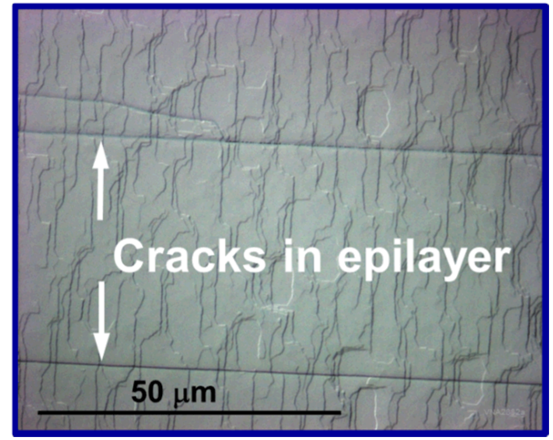
AlGaN template



Optical Image of AlGaN surface



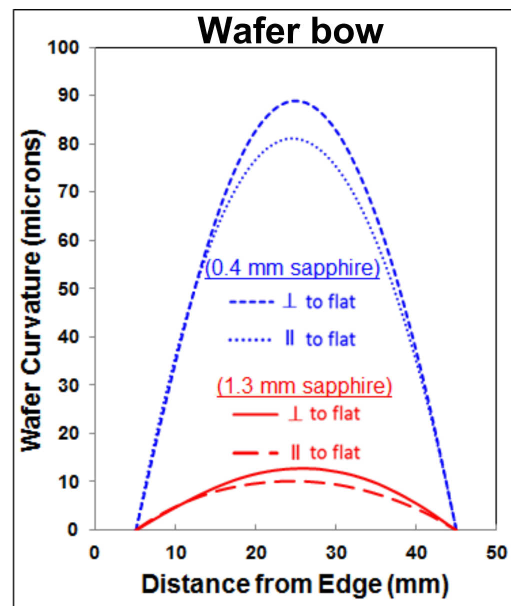
1.3mm thick sapphire



0.4mm 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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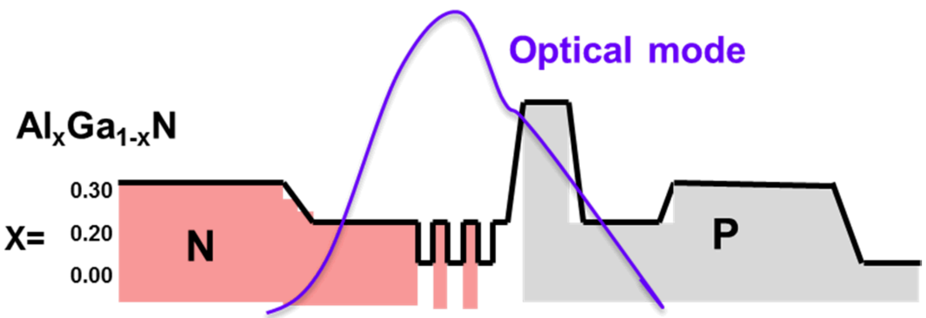
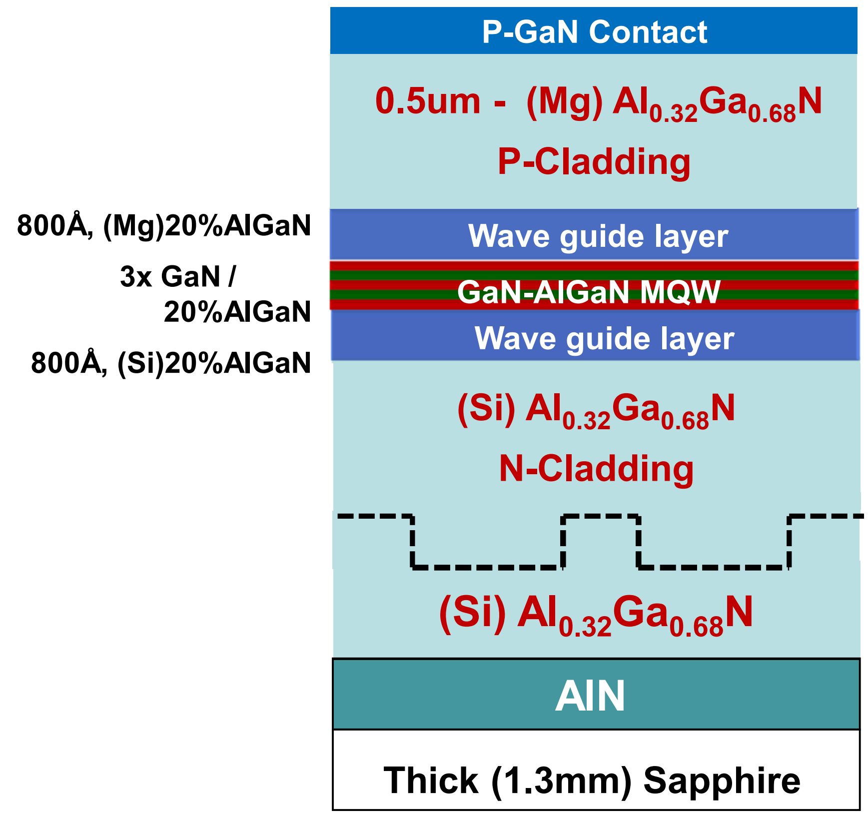
Doped waveguide laser design

Doped Waveguide



- Improved carrier injection
- Higher optical losses due to doping

Laser Structure



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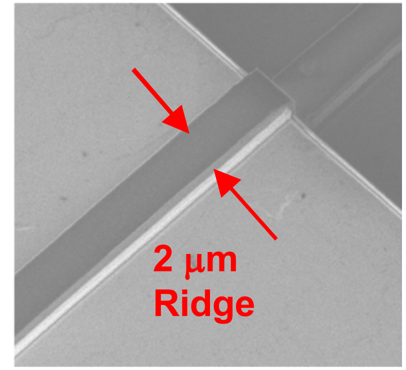
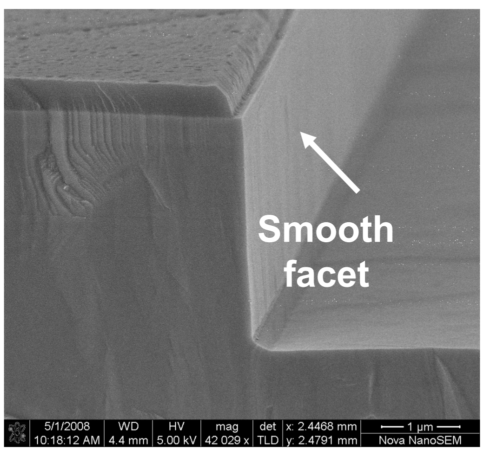
Ridge waveguide laser processing

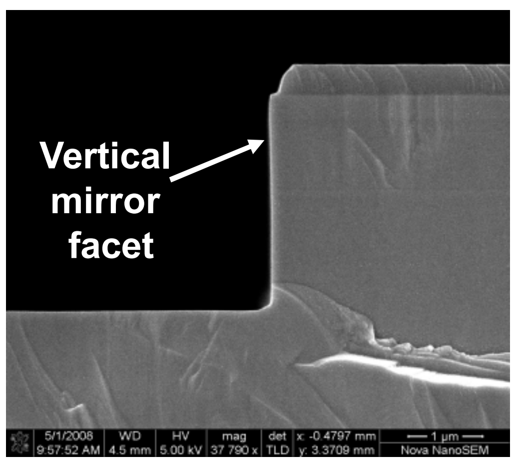
Ridge waveguide laser process ➡



Etched Facet

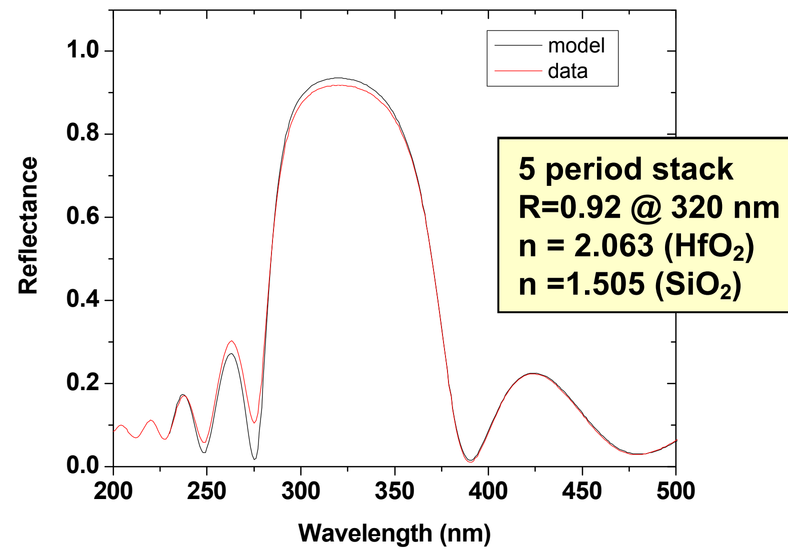
- Combine Cl_2-based plasma etch and crystallographic wet etch





HfO_2 /SiO_2 Facet Coating

- E-beam evaporation at elevated temp.



➡ **Demonstrated R > 0.90 @ 320nm**

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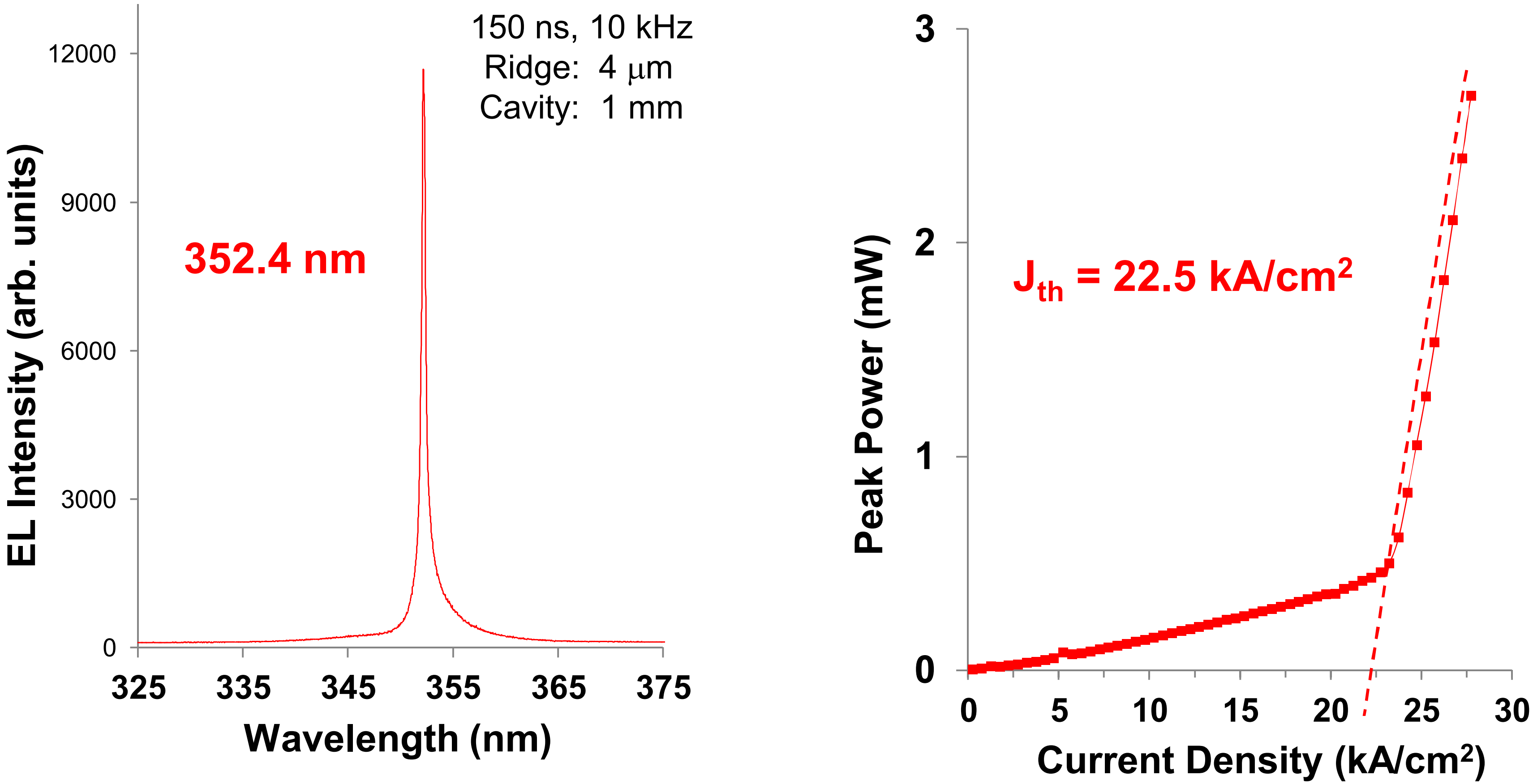
Doped waveguide design: spectra and LI-data (pulsed)

Ridge waveguide process with etched, coated facets



- Lasing from devices with 2-4um ridges, 0.7- 1.3 mm cavities
- Similar thresholds from lasers without facet coating

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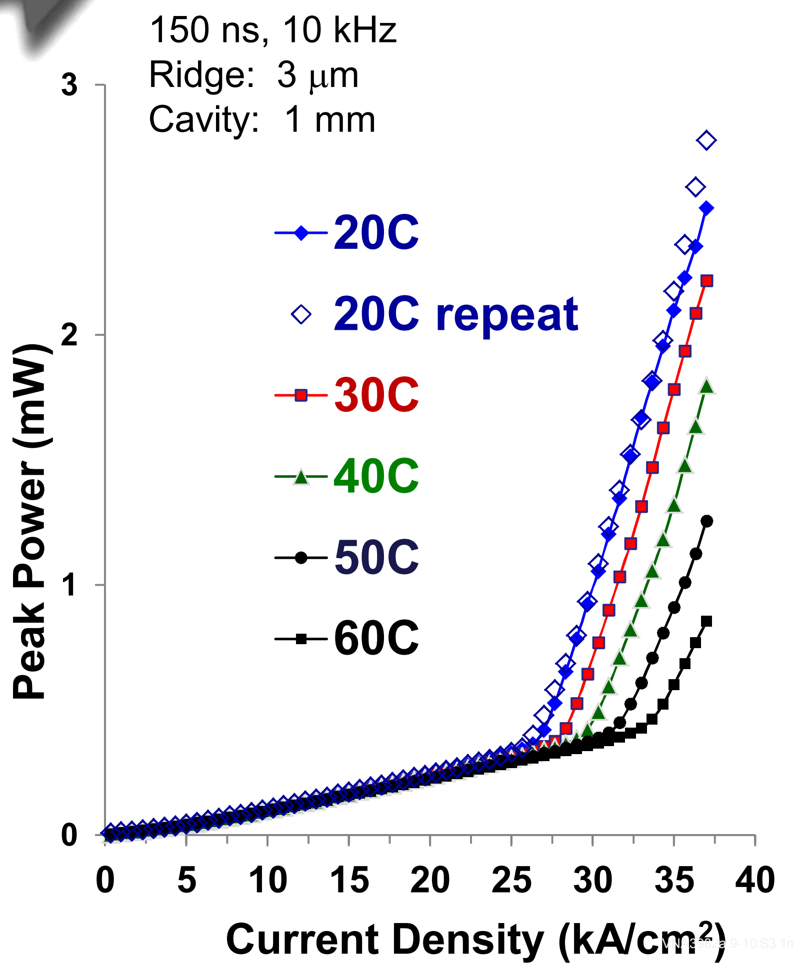
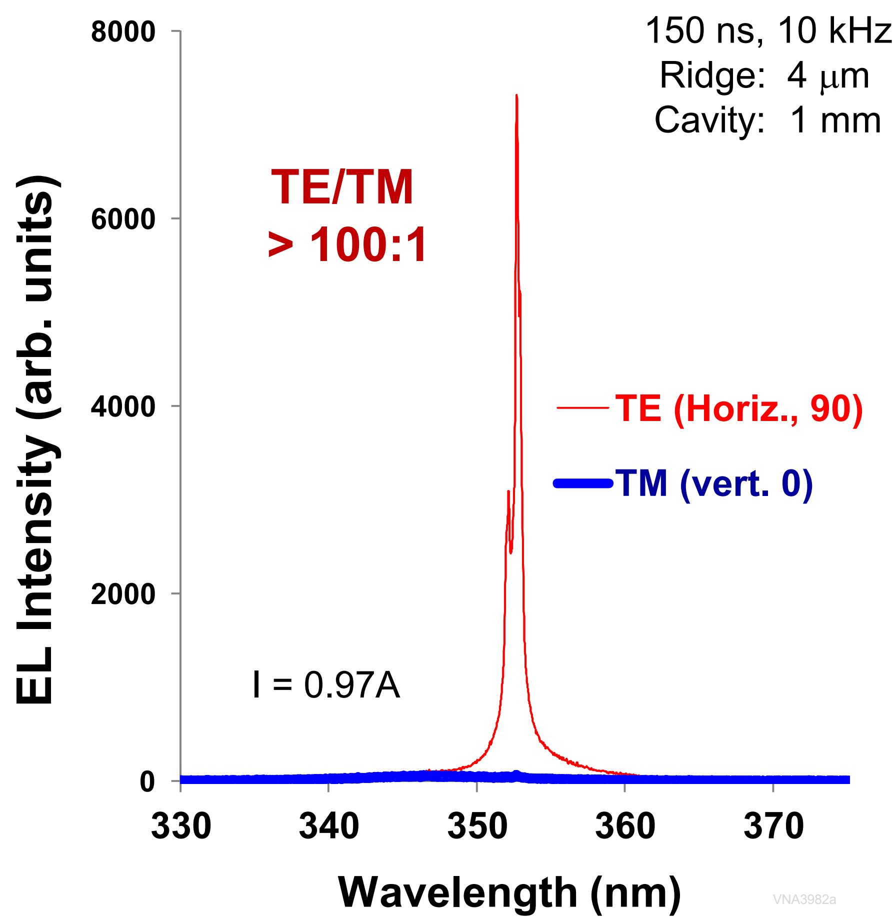
Doped waveguide design: Temperature dependent LI and polarization ratio





- ➡ **Devices are robust to 60°C and 37 kA/cm^2**
- ➡ **TE / TM polarization > 100:1**

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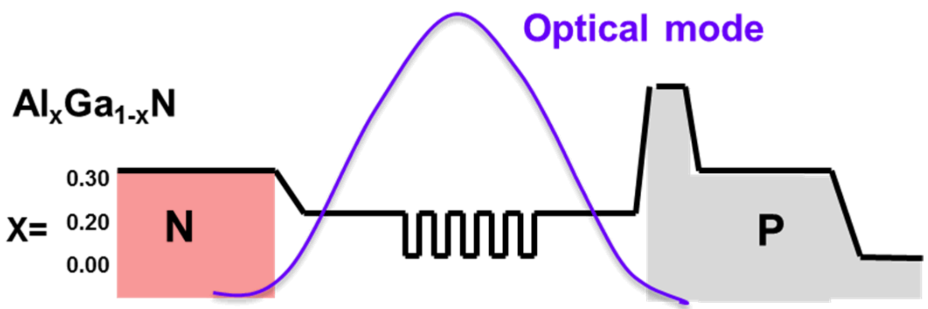
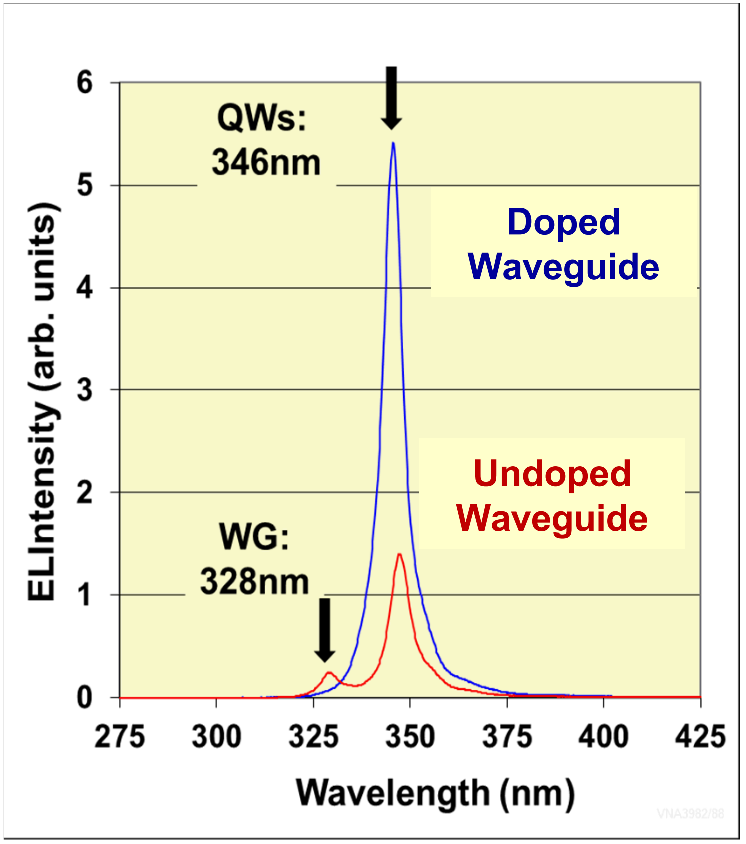
Doped and undoped waveguide laser designs and electroluminescence

Undoped Waveguide (Amano)



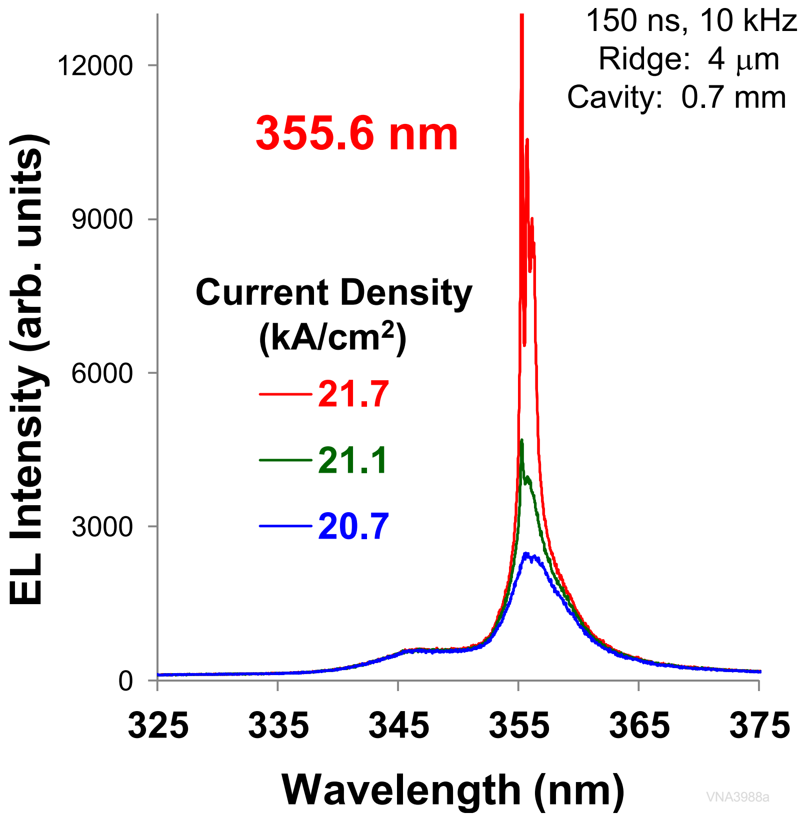
- Lower optical losses
- Reduced carrier injection efficiency

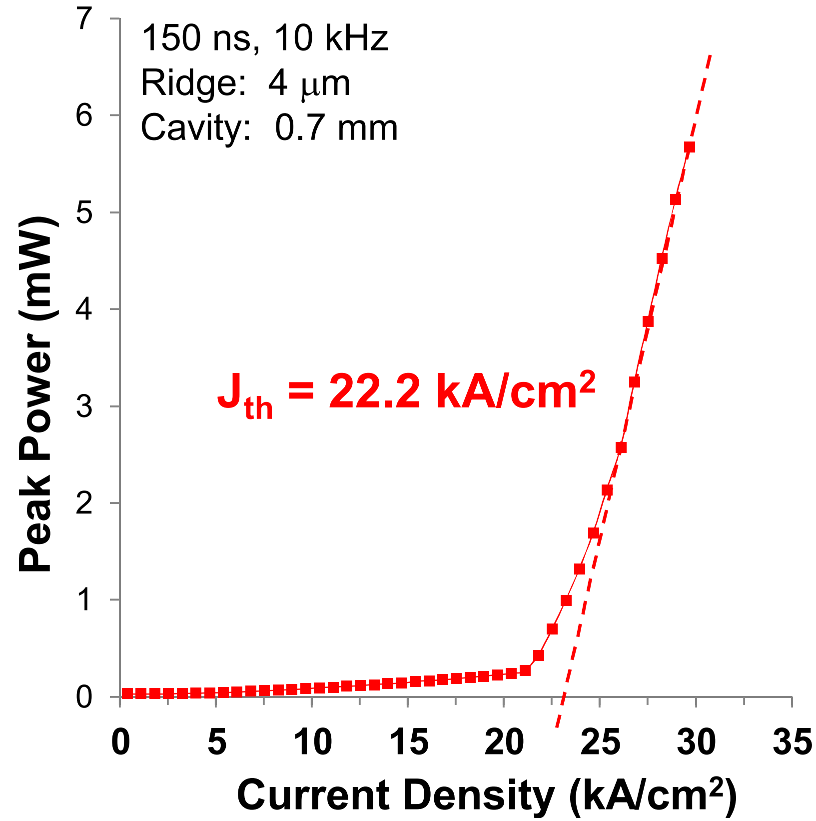
Electroluminescence
(~ 13A/cm^2)



Undoped waveguide design: Spectra and threshold (pulsed)

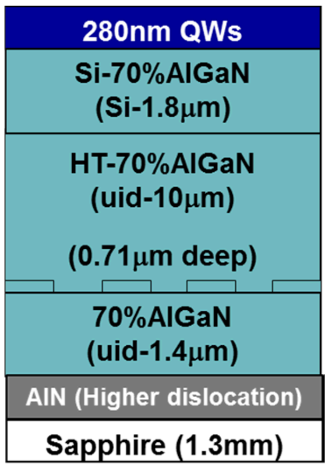
Ridge waveguide process with etched, coated facets



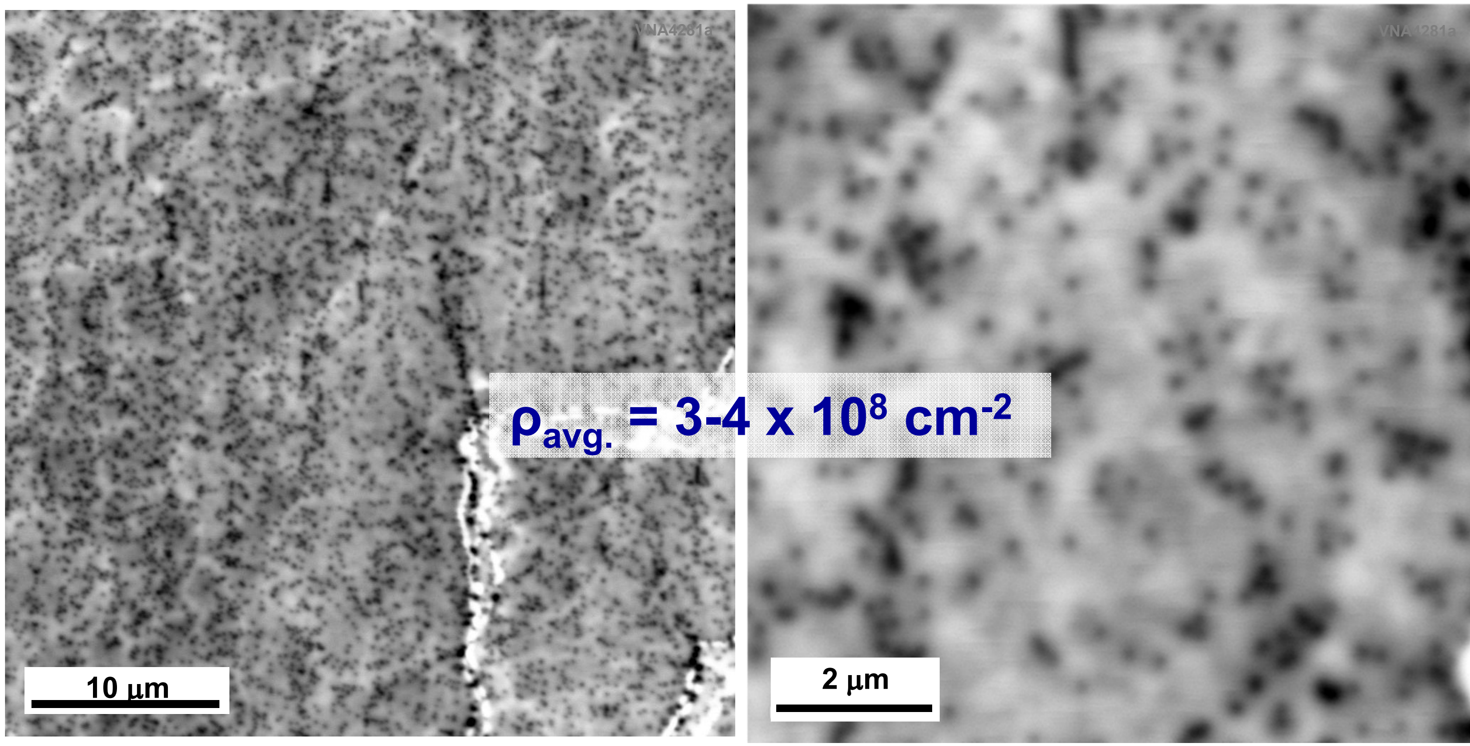


➡ Threshold current densities are similar for both doped and undoped waveguide laser structures.

Cathodoluminescence of AlGaN overgrowth of patterned AlGaN



$Al_{0.70}Ga_{0.30}N$



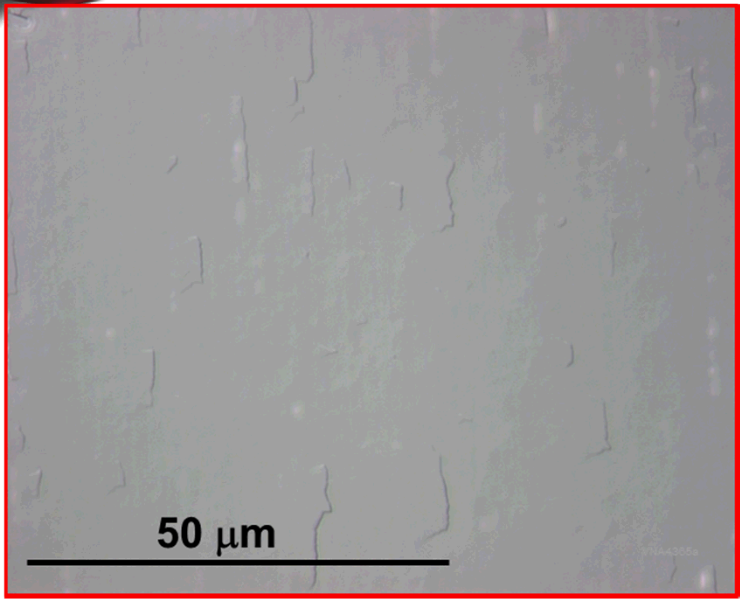
- 0.7μm etch
- ~12 μm overgrowth

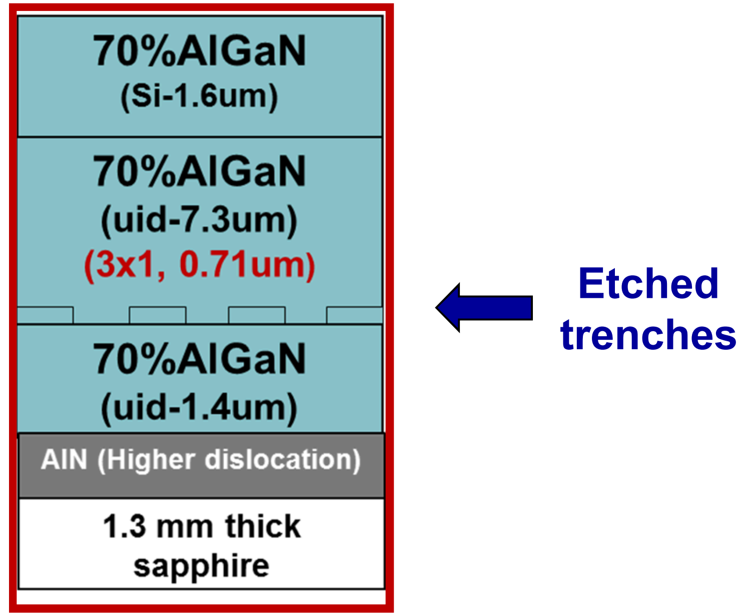
➡ Spatially uniform reduction in dislocation density

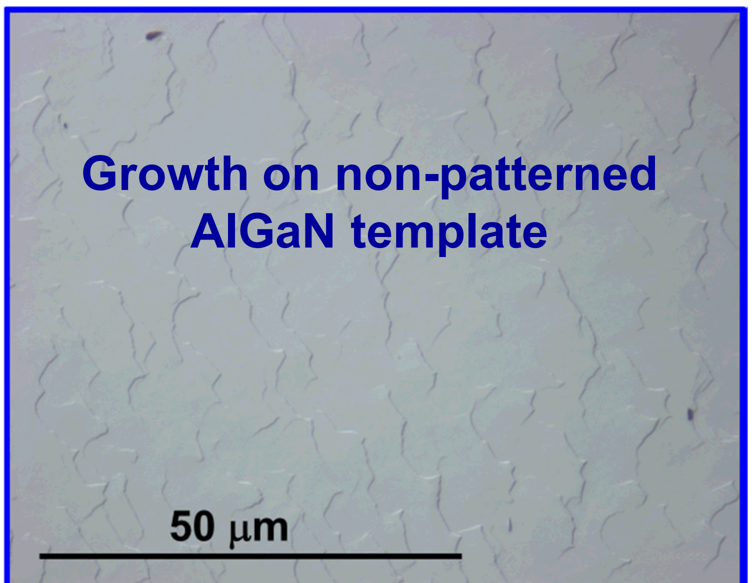
➡ Transparent template for bottom emitting LEDs

➡ Approach is successful all AlGaN compositions

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







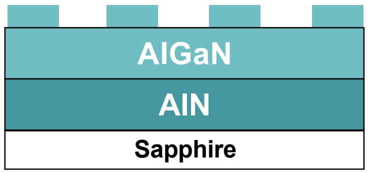
- Cleaning of patterned template critical for good morphology

➡ **Overgrowth of pattern AlGaN is similar to non-patterned growth**

Atomic Force Microscopy of $Al_{0.61}Ga_{0.39}N$ overgrowth

Mask: 1 / 1 (μm)

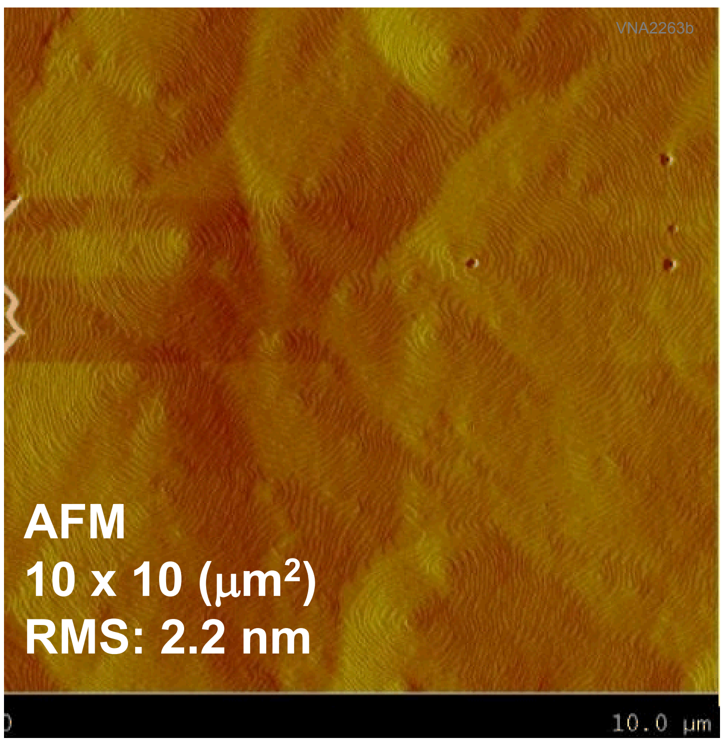
Etch Depth: 0.56 μm

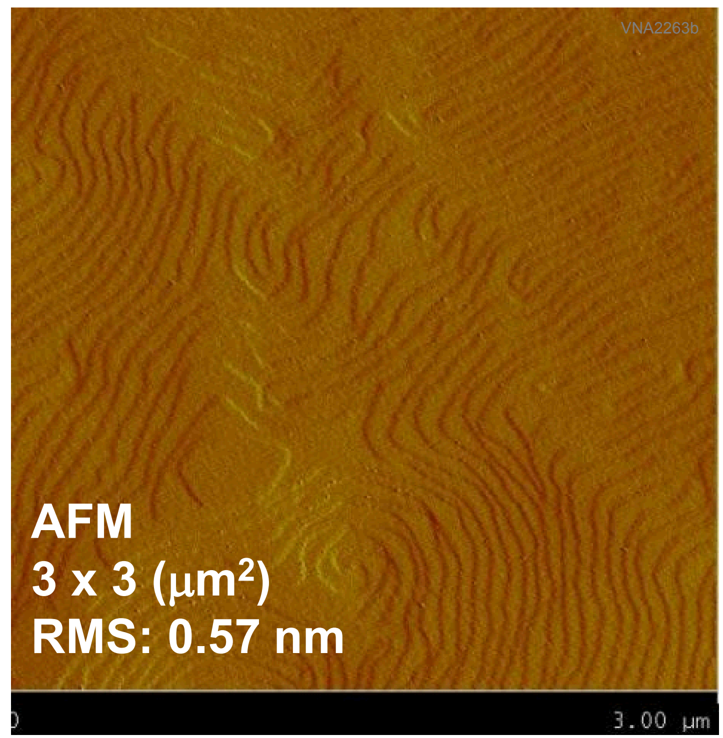


Overgrowth: 9 μm

Group-III: 32 μmoles/min.

V/III Ratio: 1820





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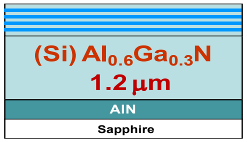
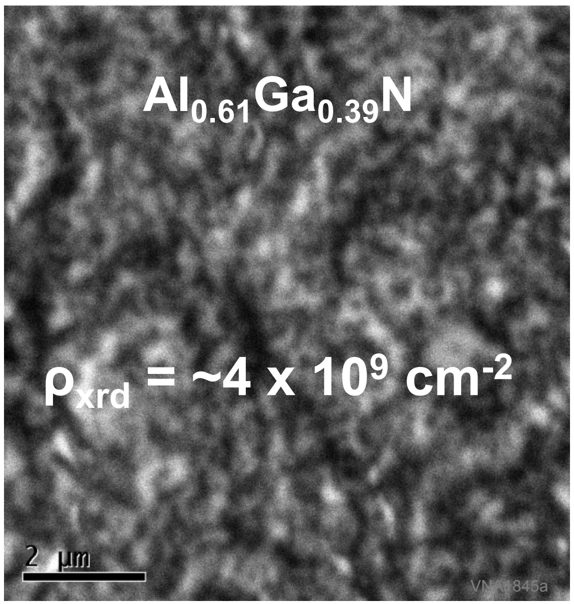
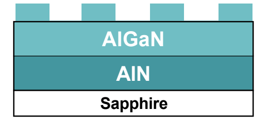
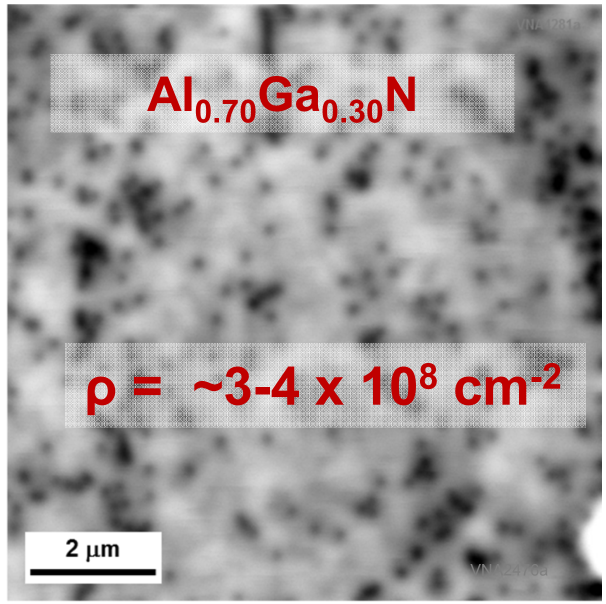
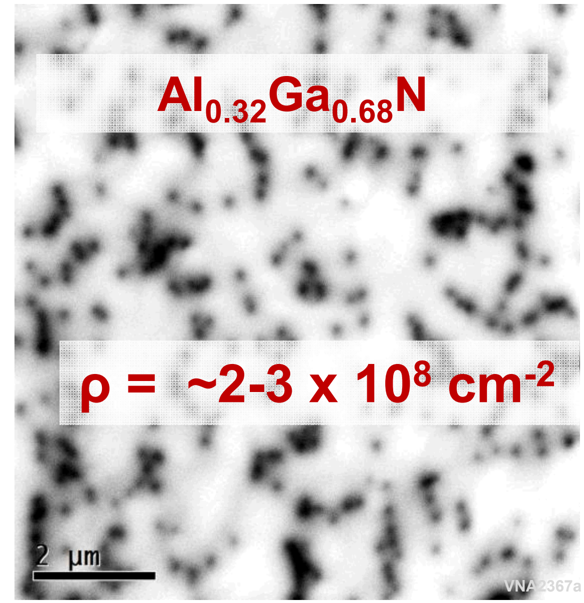
Cathodoluminescence of $Al_xGa_{1-x}N$ overgrowth of patterned $Al_xGa_{1-x}N$ (1/1)











➡ **Overgrowth of etched AlGaN templates is effective in reducing dislocation density (~10-30x) in $Al_xGa_{1-x}N$ epilayers**

Summary

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

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

  - Transparent template ➡ *bottom emitting LEDs*
  - Spatially uniform reduction ➡ *no device alignment to template*
  - Doped with Si ➡ *simplifies vertical structure*

- Optically pumped lasing at low thresholds (Jth ~ 50 kW/cm-2)

- Diode lasing at 352-355nm from doped and undoped waveguide structures.

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