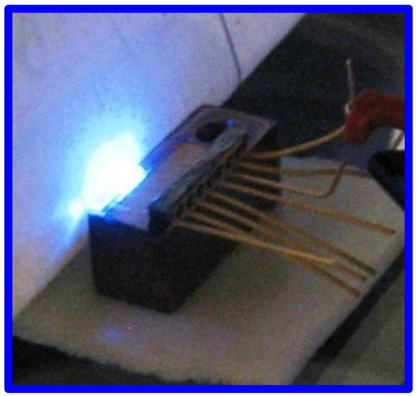
SAND2015-1188C

352-nm laser diodes enabled by low-dislocation-density AlGaN templates



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Veeco D-125 MOCVD system

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Sandia National Laboratories

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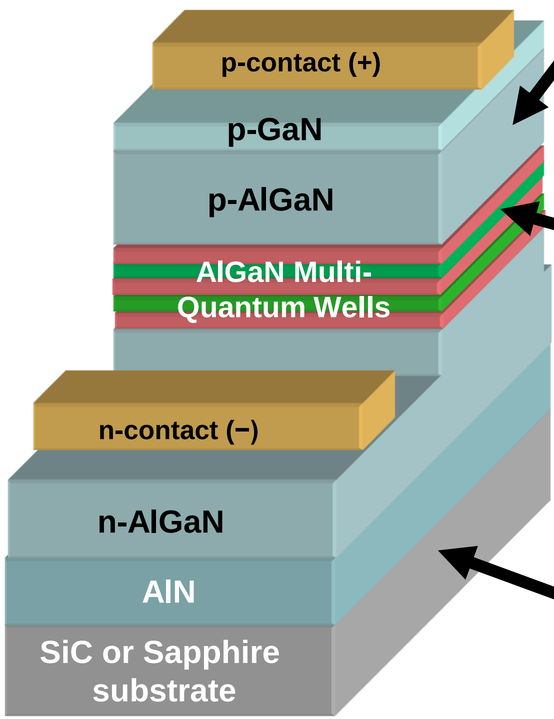
Outline

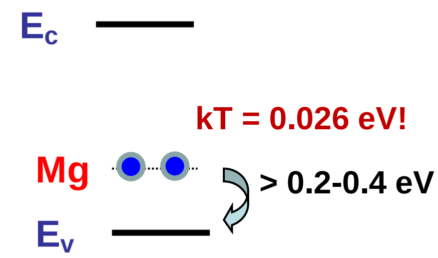
- Introduction:
  - Materials Challenges for UV LDs
  - Previous work on AlGaN LDs
- Dislocation reduction of $Al_{0.32}Ga_{0.68}N$ grown over etched trenches
  - Processing and growth
  - Improvements in PL and EL
- UV Lasing
  - Optical pumping
  - Electrical injection
- Summary

Materials challenges for high performance AlGaN deep UV LDs

AlGaN Deep UV LD (p-n junction device)

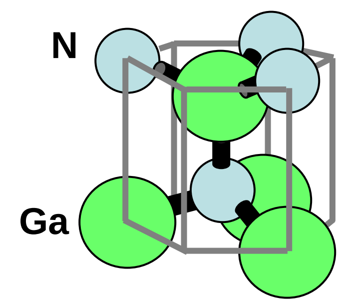


p-type AlGaN is very difficult
- → Large acceptor ionization energies
- → Compensating defects



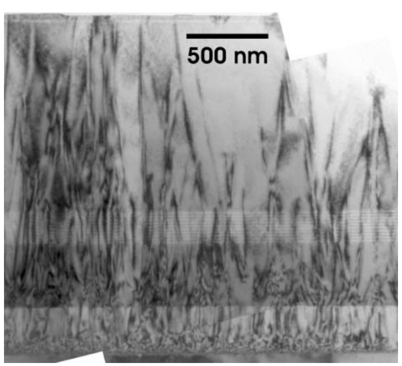
AlGaN Quantum Wells may have low optical efficiency
- → Non-radiative crystalline defects (e.g., impurities, vacancies)

GaN Unit Cell



Lack of AlGaN Substrates
- → high densities of extended defects (threading dislocations) > 10^9 cm^{-2}
- → Reduced device efficiency and operational lifetime

TEM image of AlGaN on sapphire



Sapphire substrate

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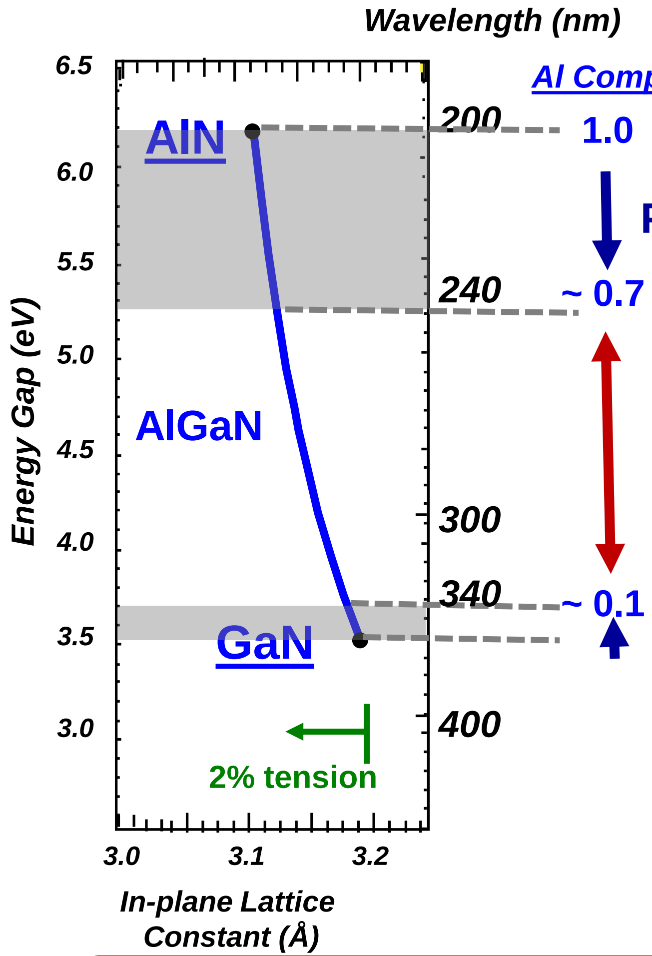
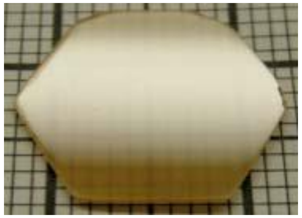
Options for Low Defect Substrates



Pseudomorphic limit
(relaxation by dislocation generation)

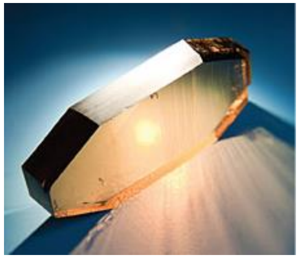


AlN
(Hexatech)

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

Excess tensile strain leads to cracking

(Ammono)
GaN

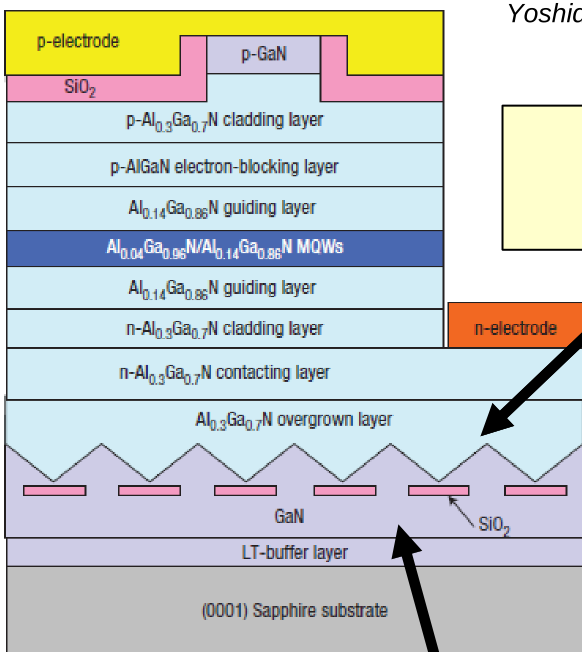


➡ How to fabricate a low dislocation template for mid-alloy AlGaN UV-emitters?

Previous Work: Laser Diodes Employing Patterned Overgrowth

Laser Heterostructure

Yoshida (Nat. Photonics, 2008)

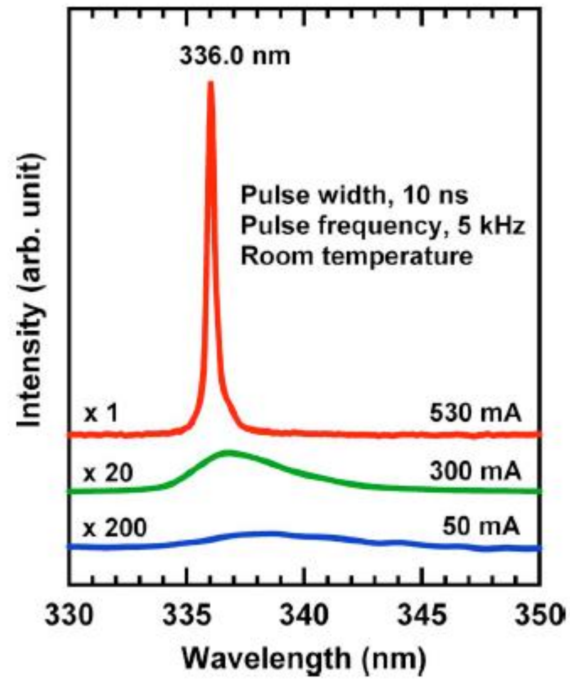


No c-plane surfaces

Pyramids by ELOG-GaN
(pattern: 3 x 3 µm, 6µm tall)

- **Dislocations uniformly reduced across wafer**

Pulsed Laser Performance



- ***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,**

Yoshida (APL, 2008)

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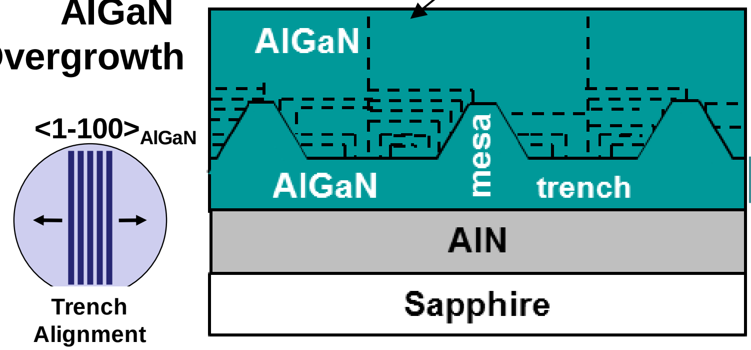
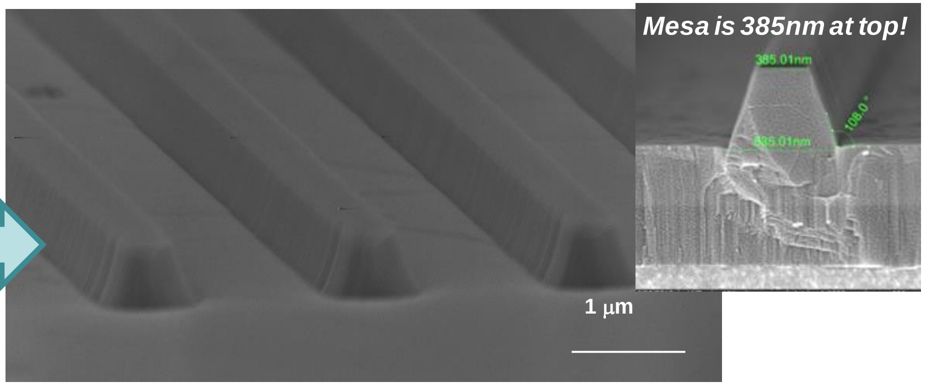
Dislocation reduction with AlGaN overgrowth of etched trenches

Patterned template formed by plasma etching

AlGaN with reduced dislocations

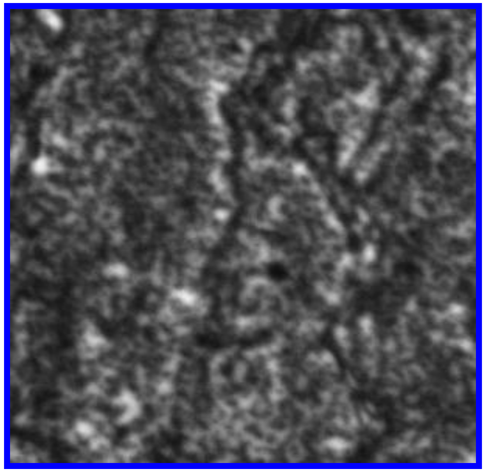
AlGaN Overgrowth



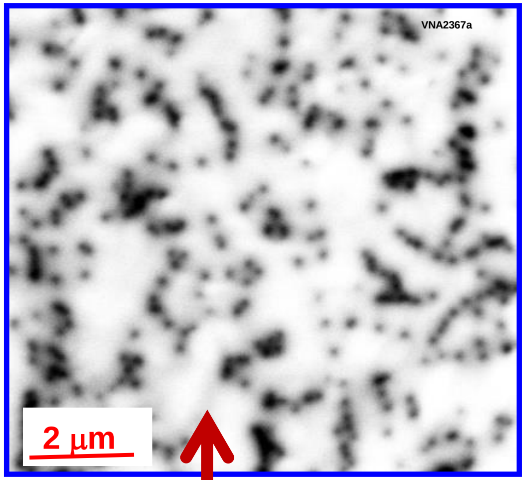


CL of 340 nm AlGaN QWs (Al=0.30)

Planar Growth



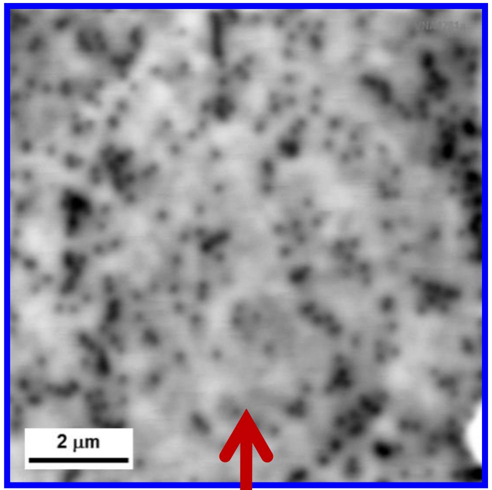
Patterned Overgrowth



10-30X TD reduction to 2-4 e8 cm^{-2}

CL of 280 nm AlGaN QWs(Al=0.70)

Patterned Overgrowth



3-4 e8 cm^{-2}

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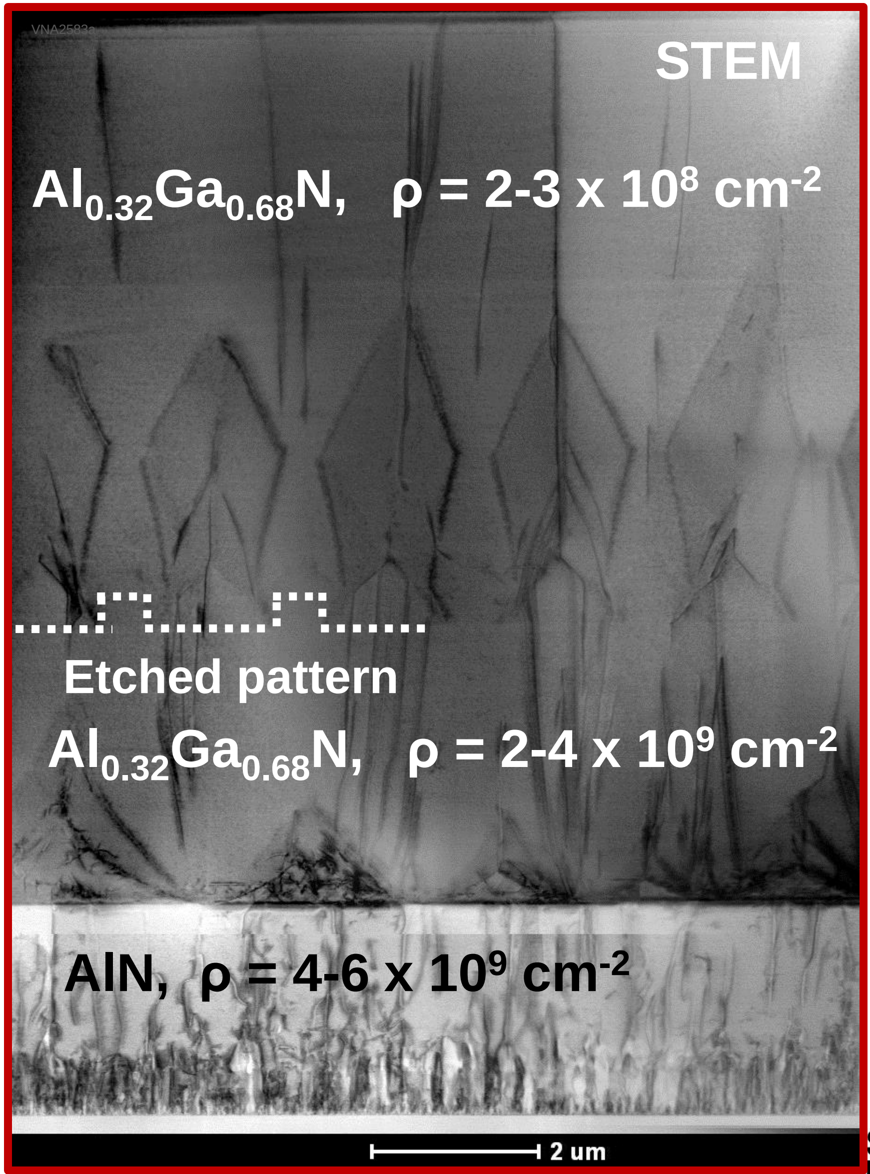
Two-beam BF-STEM of $Al_{0.32}Ga_{0.68}N$ Overgrowth of patterned $Al_{032}Ga_{0.68}N$

B. Clarke

Mask: 1 / 1 (μm)
Etch Depth: 0.66 μm
Overgrowth: 7 μm

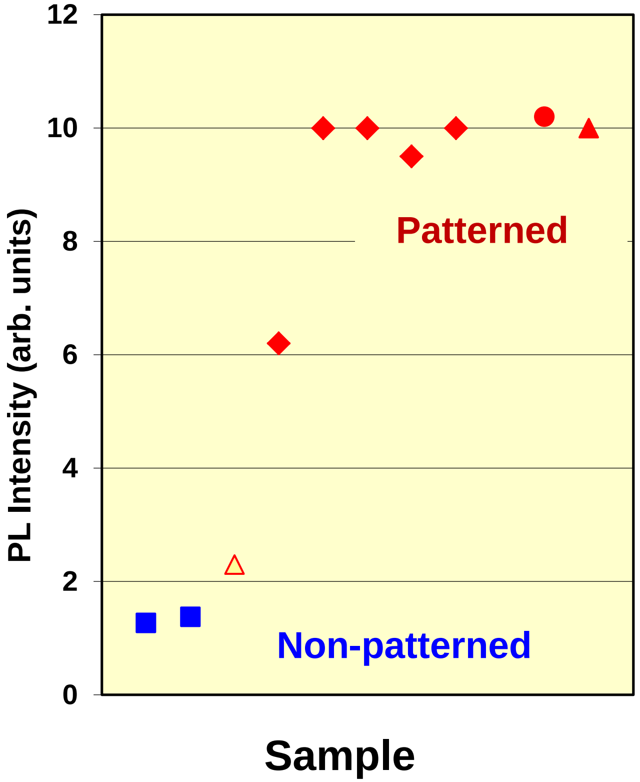
➡ ***Introducing surface roughness drives dislocation reduction***

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

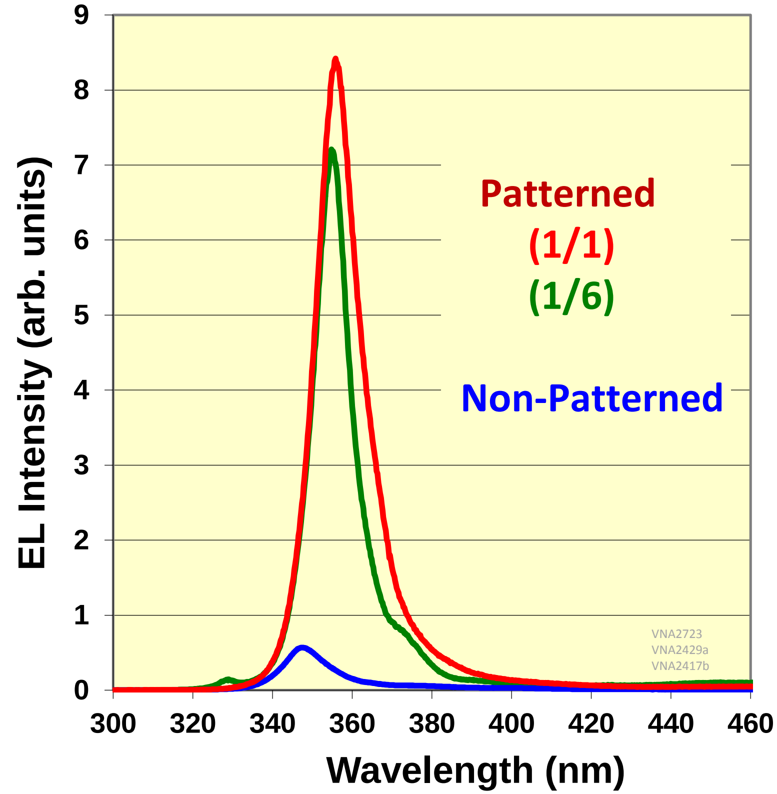


Photoluminescence and electroluminescence of GaN-AlGaN QWs on patterned and non-patterned templates

Photoluminescence (Quantum Wells)



Electroluminescence (LD structure)



With AlGaN overgrowth of patterned templates:

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

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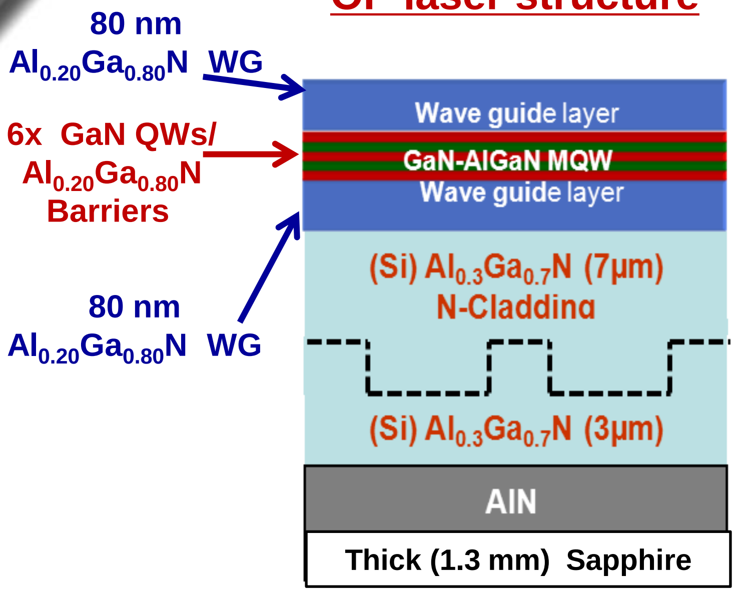
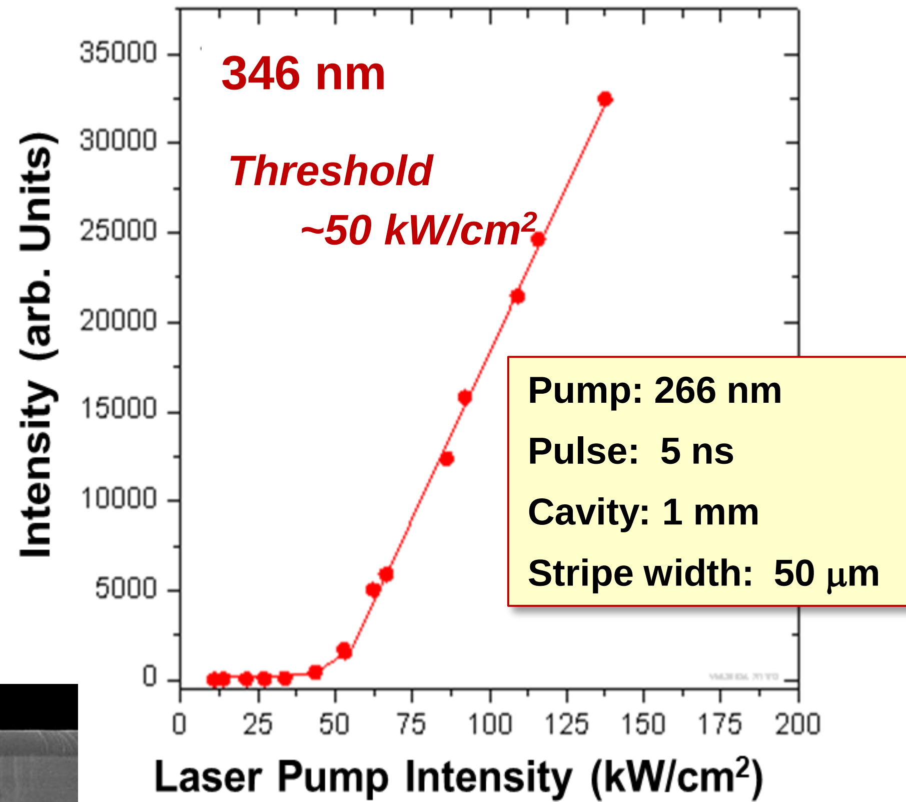
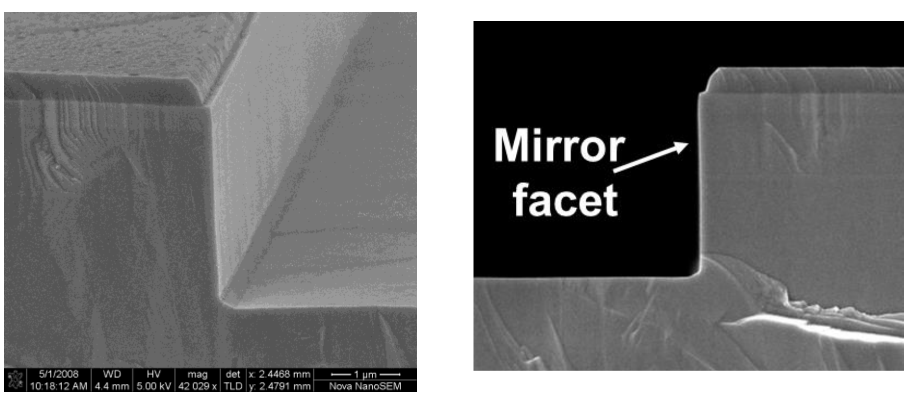
Optically pumped lasing at 346nm

OP laser structure





Etched Facets



→ Cl_2-based plasma etch and crystallographic wet etch*

→ *Low lasing threshold ~50 - 150 kW/cm²*

* Miller et al. J Electron Mat 2009

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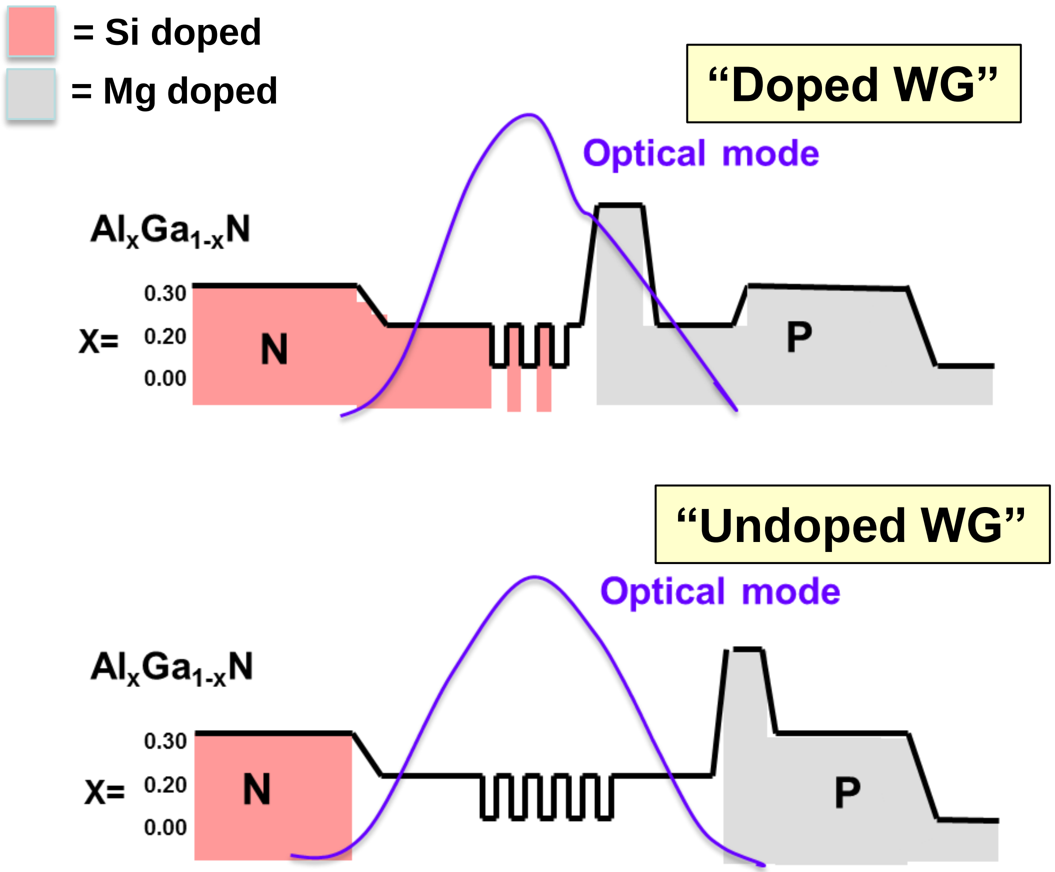
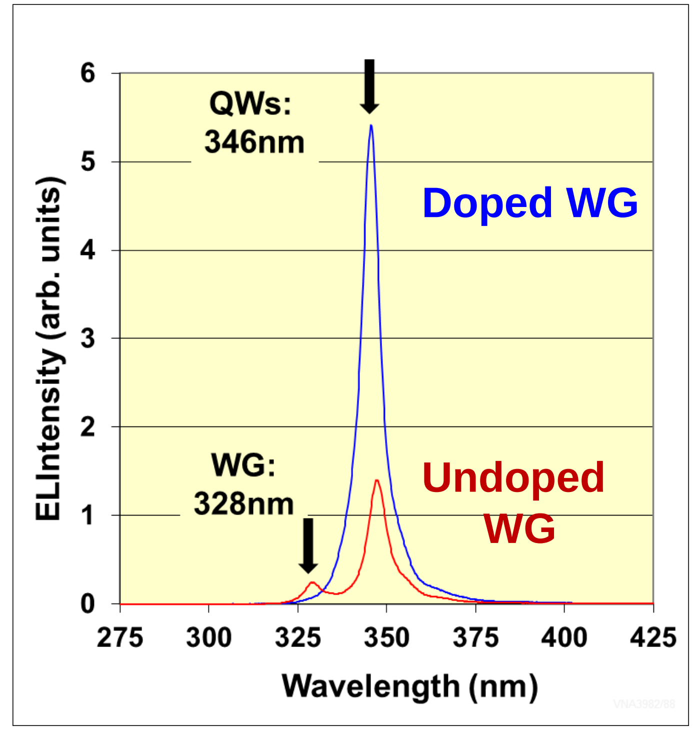
Laser Heterostructure Designs

Two designs to examine trade-off between carrier injection efficiency and optical loss



Electroluminescence (~13 A/cm^2)



- Eliminate doping in waveguide for reduced optical loss
- Thin barriers, increase quantum well number for increased gain

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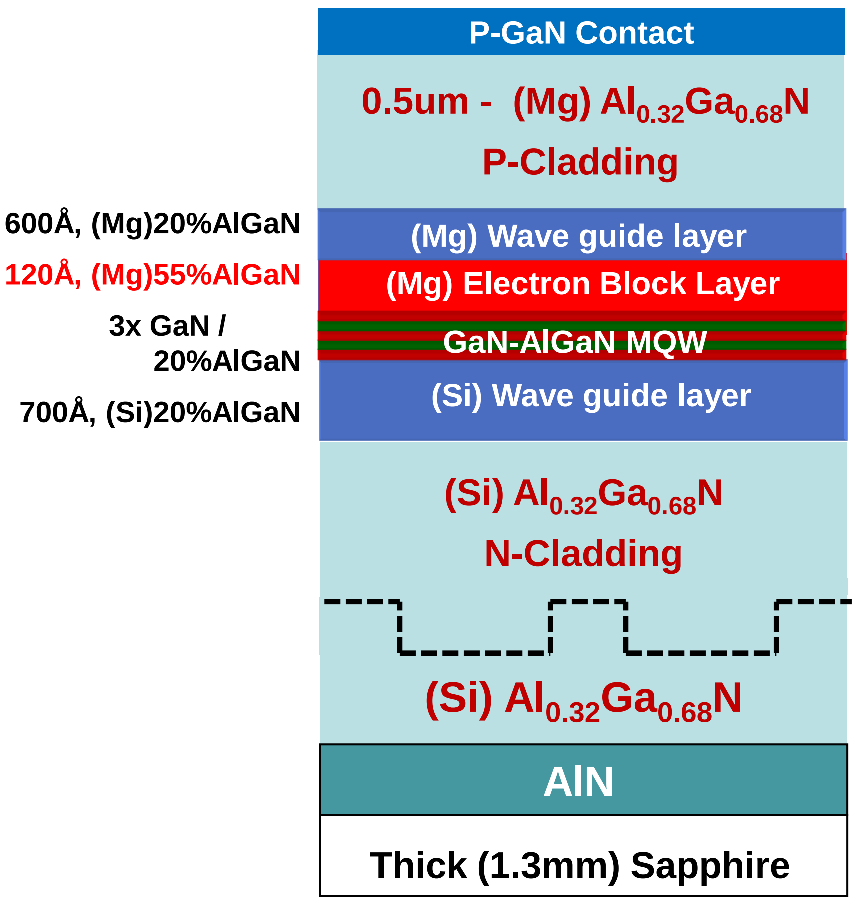
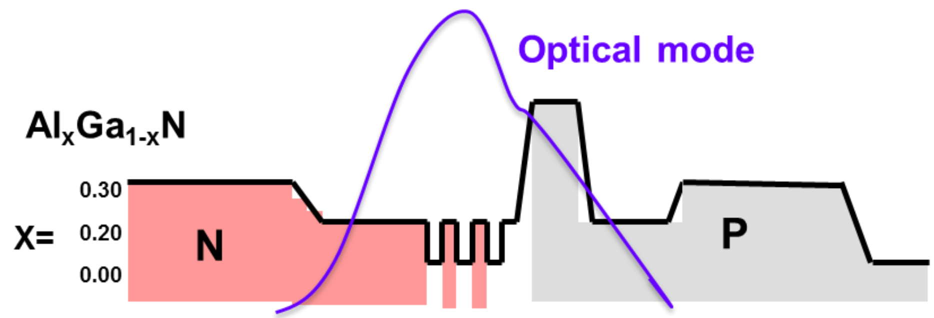
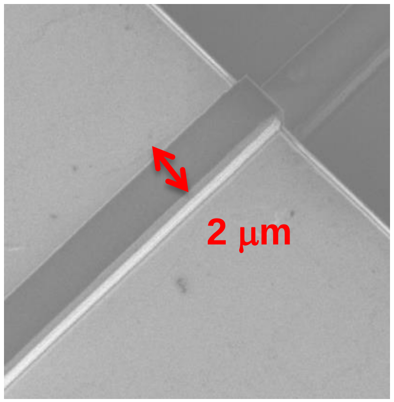
Doped waveguide laser design

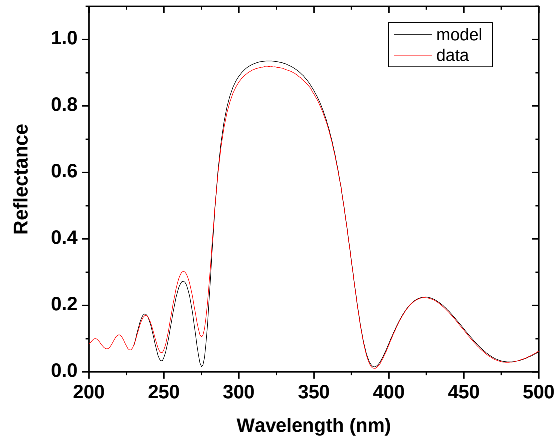
Laser Heterostructure





Fabrication





- Ridge Waveguide
  → 2-7 μm width
- Cavity lengths
  → 0.7-1.3 mm

HfO_2 /SiO_2 Facet Coating

➡ Demonstrated
R > 0.90 @ 320nm

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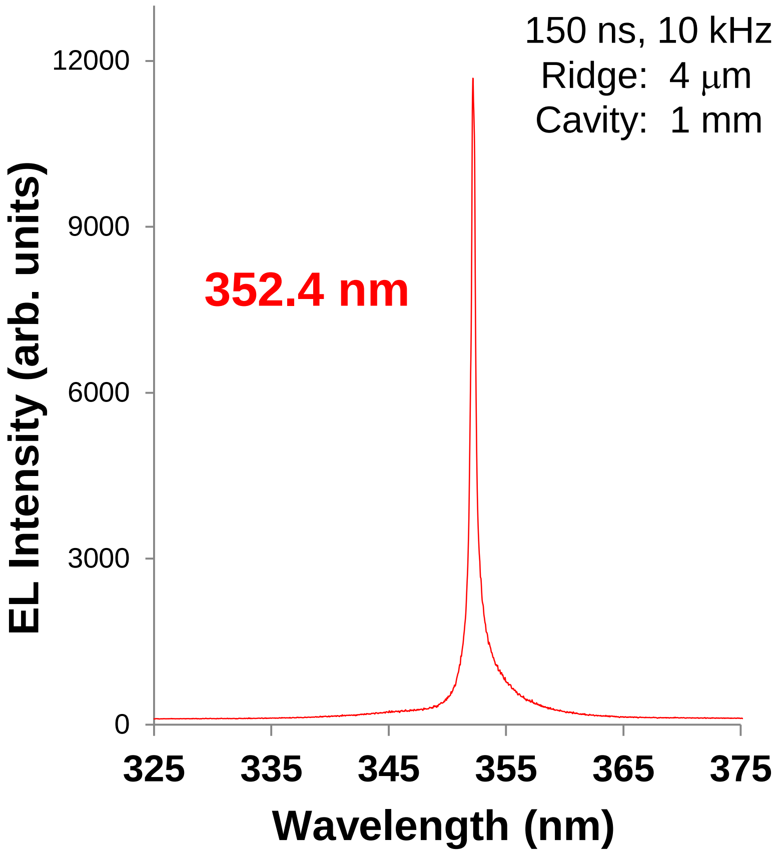
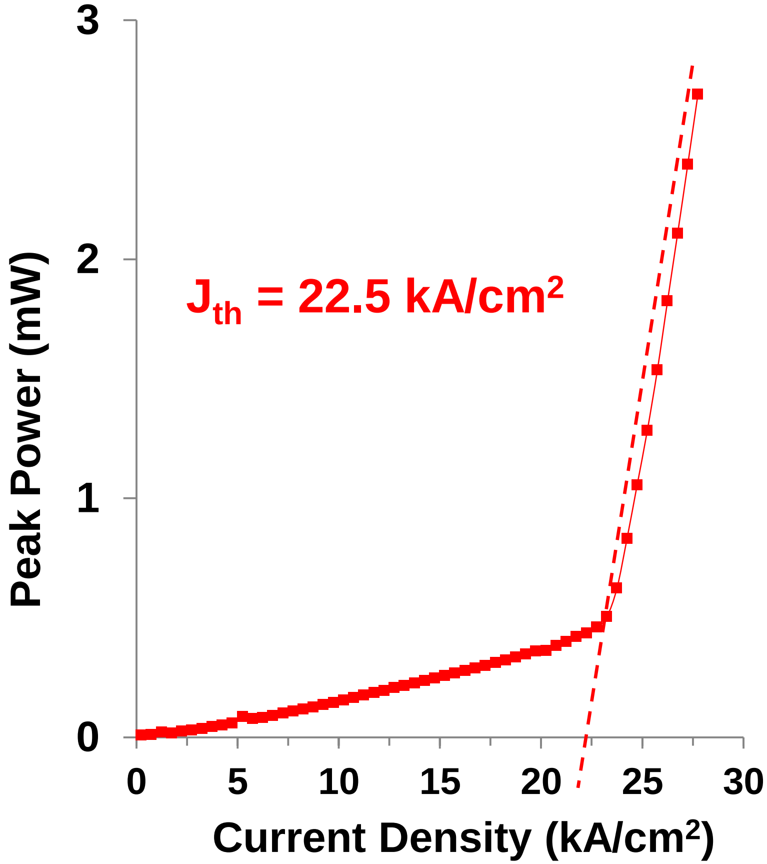
Doped waveguide design:
Spectra and LI-data (pulsed)

Ridge waveguide process with etched, coated facets





➡ **Lasing from devices with 2-4um ridges, 0.7 - 1.3 mm cavities**

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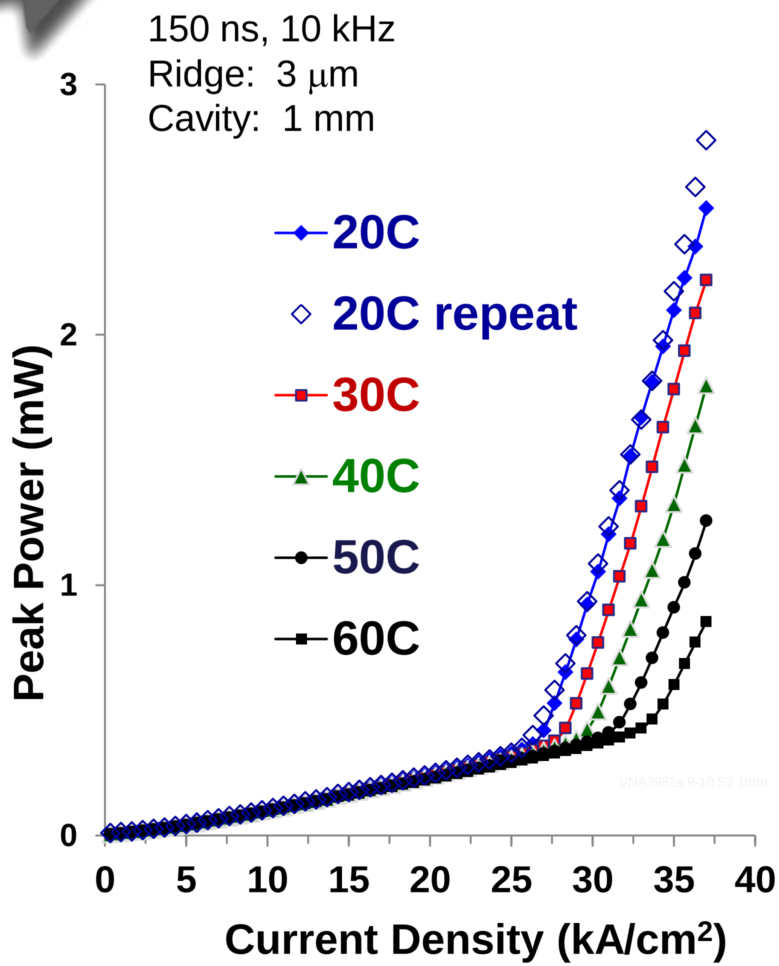
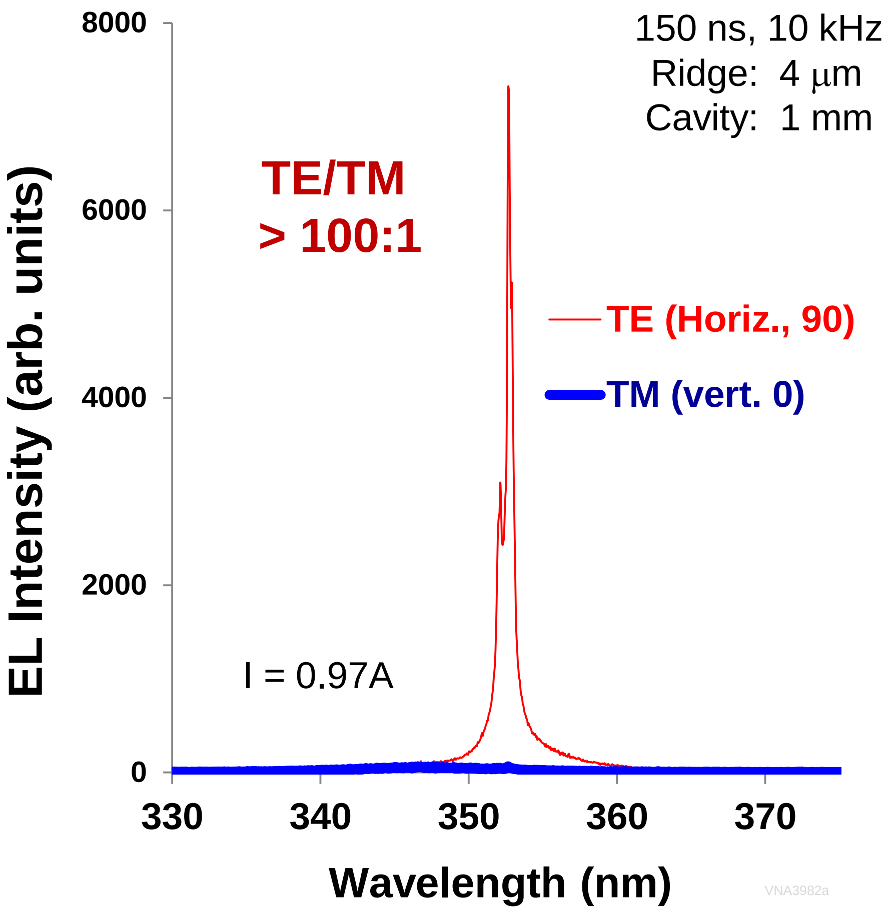
Doped waveguide design: Temperature dependent LI and polarization





- ➡ Devices are robust to 60°C and 37 kA/cm²
- ➡ TE / TM polarization > 100:1

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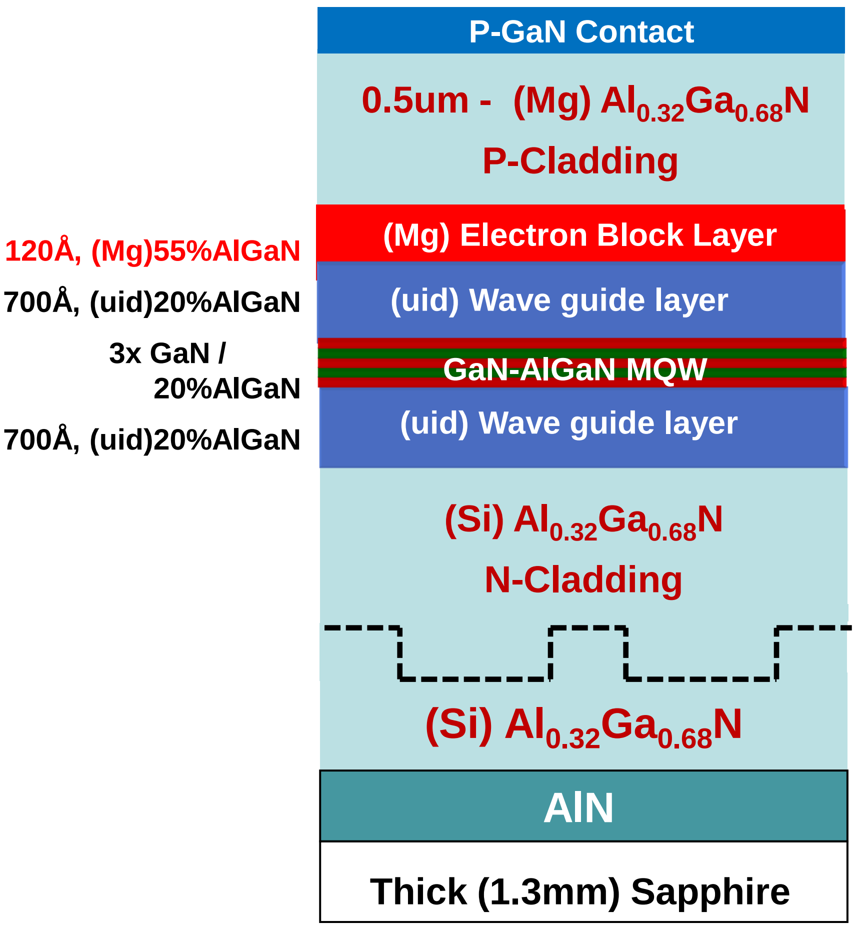
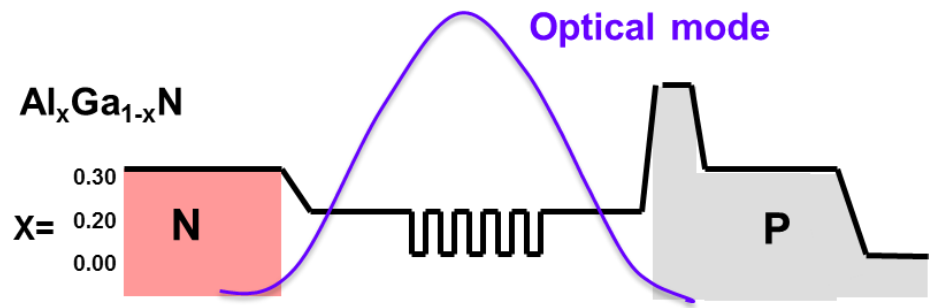
Undoped waveguide laser design

Undoped WG

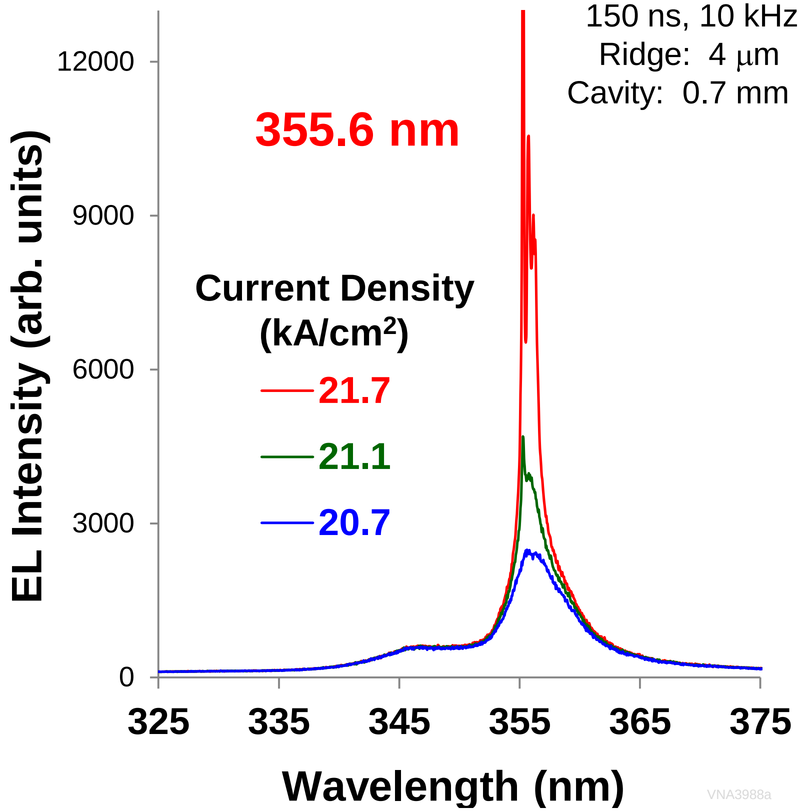


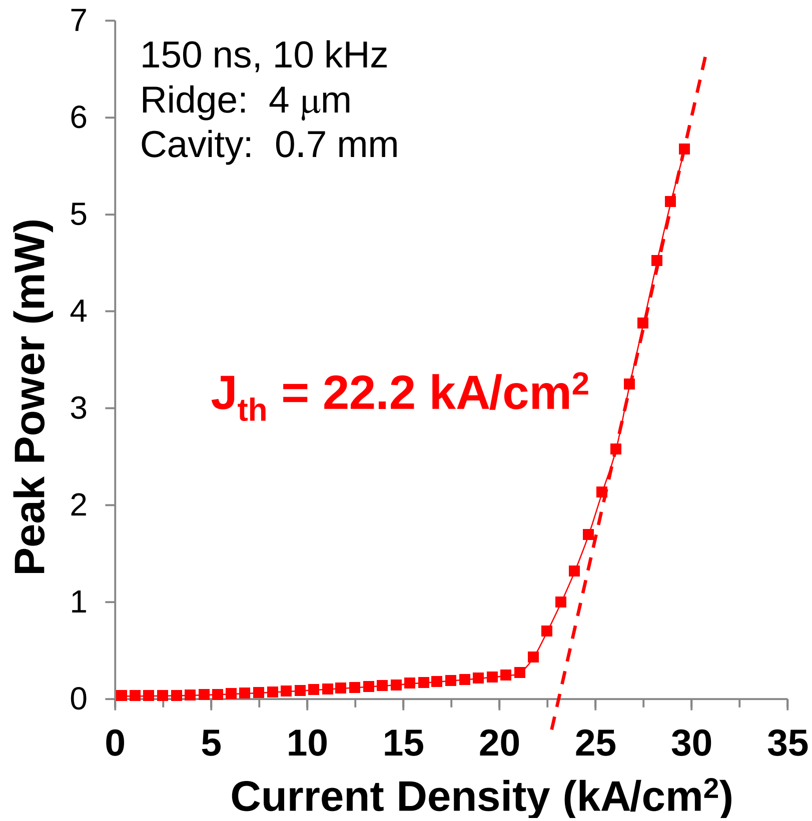


- Lower optical losses
- Reduced carrier injection efficiency

Undoped waveguide design: Spectra and LI (pulsed)

Ridge waveguide process with etched, coated facets





- Threshold current densities are similar for both doped and undoped waveguide laser structures
- Anticipate common loss mechanism (e.g., p-cladding thickness)

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Summary

- Reduced dislocation density of $Al_{0.3}Ga_{0.7}N$ epilayers by growing over trenches etched in $Al_{0.3}Ga_{0.7}N$.

$$\rho = 2\text{-}3 \times 10^{8}\ cm^{-2}$$

  - 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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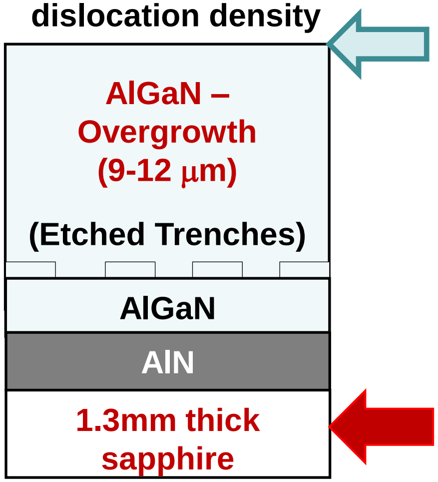
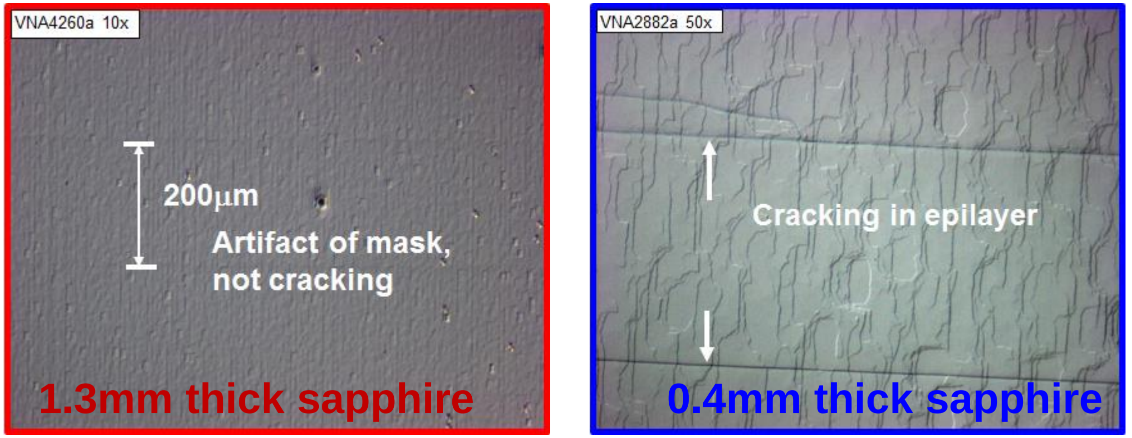
Back up Slides

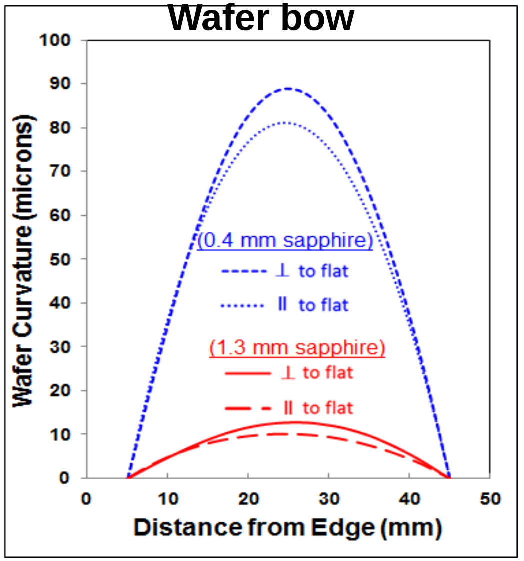
Reduction of wafer bow and cracking using 3x thicker sapphire substrates

AlGaN template for low dislocation density



Optical Image of AlGaN surface





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

➡ 3x thicker sapphire substrate reduced wafer bow and epilayer cracking, greatly increasing wafer area for devices

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