Nonpolar and Semipolar III-Nitride Optoelectronic Materials and Devices

Prof. Daniel Feezell

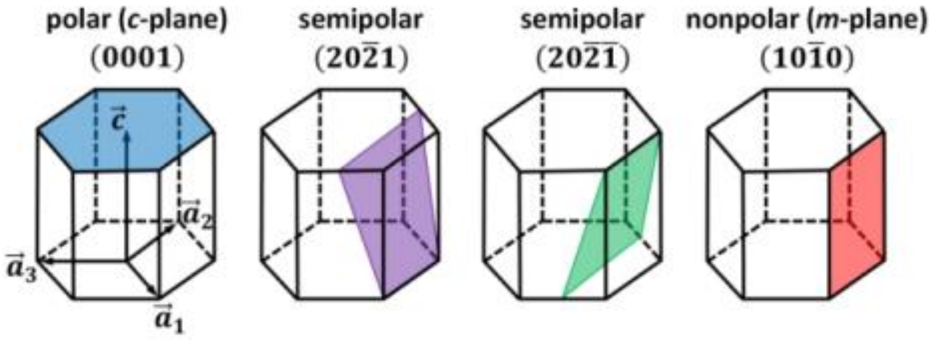
Center for High Technology Materials

Department of Electrical and Computer Engineering

University of New Mexico, Albuquerque, NM – 87131

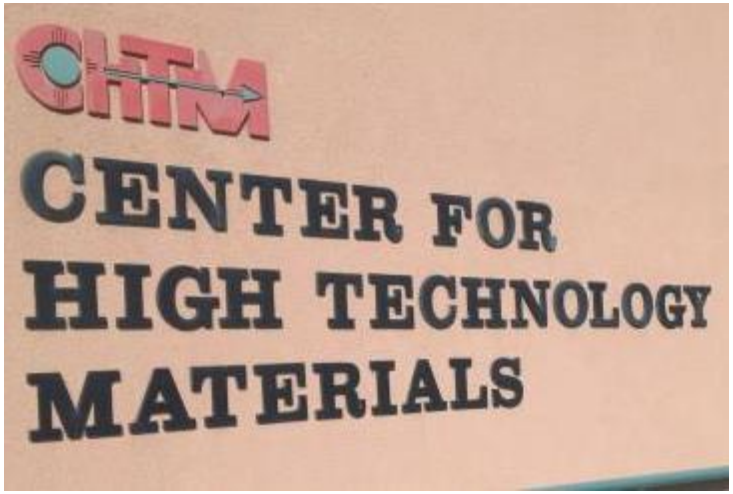
dfeezell@unm.edu

505-272-7823



III-Nitride Materials and Devices Group

Group: 3 postdocs, 8 graduate students, 1 undergraduate student, 1 MOCVD research engineer

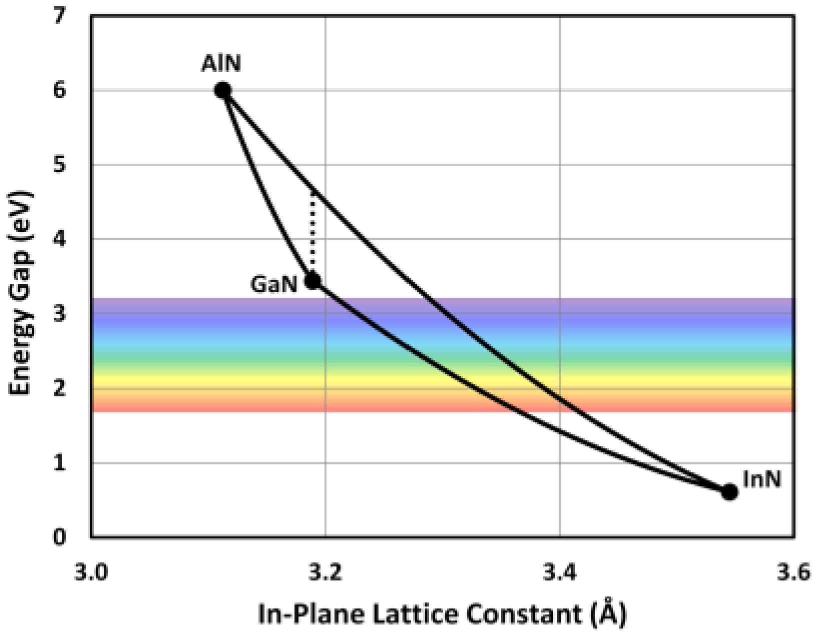


Outline

- Introduction to III-nitride materials
- Characteristics and advantages of nonpolar/semipolar III-nitrides
- Semipolar $(20\bar{2}\bar{1})$ and nonpolar $(10\bar{1}0)$ InGaN/GaN LEDs
- Nonpolar/semipolar LEDs based on bottom-up selective-area epitaxy
- Polarization-pinned nonpolar vertical-cavity surface-emitting lasers
- Summary

Introduction to III-Nitrides

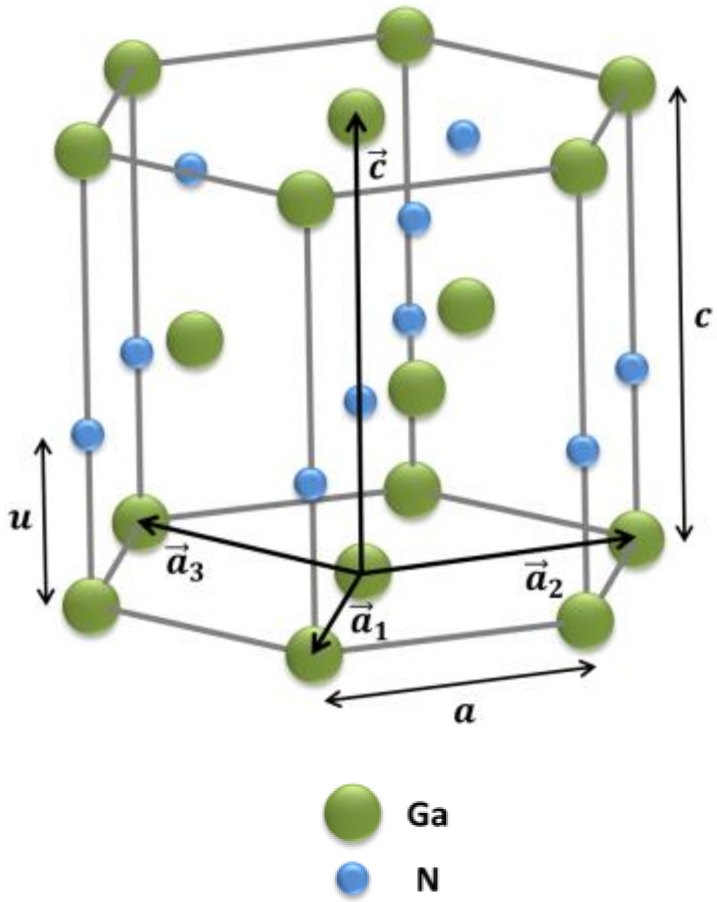
III-Nitride Materials



- Solid-state lighting
- Visible and UV lasers
- Power electronics
- Multijunction solar cells
- Radiation hard devices

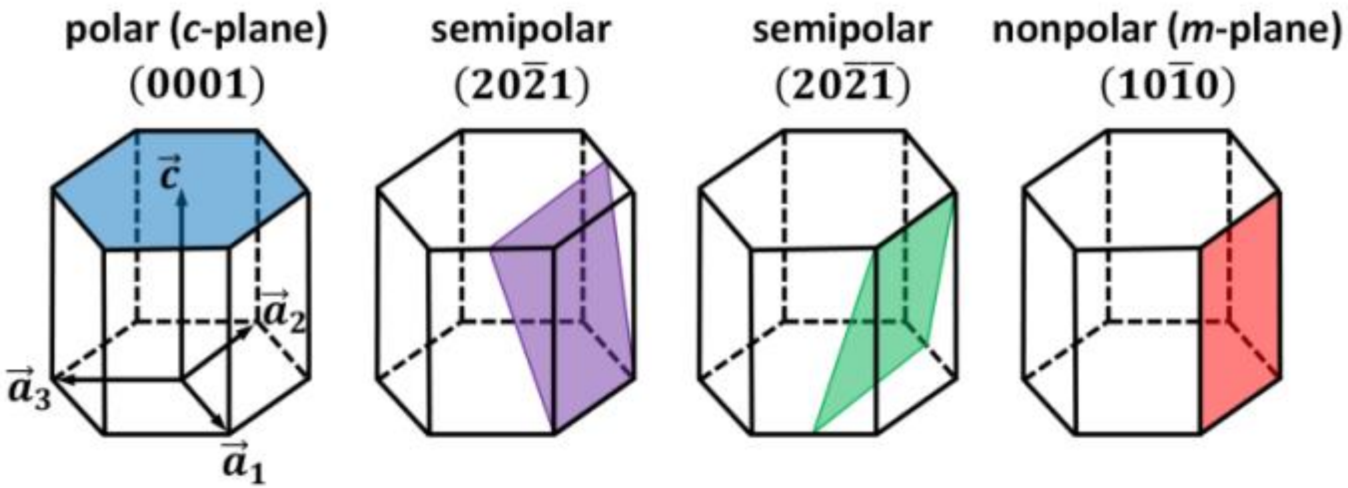
- Direct band gaps ranging from 0.7 eV (InN) to 3.4 eV (GaN) to 6.0 eV (AlN)
- Enable high-performance UV, violet, blue, and green emitters
- Robust against high dislocation densities (10^8 cm^{-2}), thermally stable, radiation tolerant
- In general, alloys not lattice matched to GaN

GaN Crystal Structure (Wurtzite)



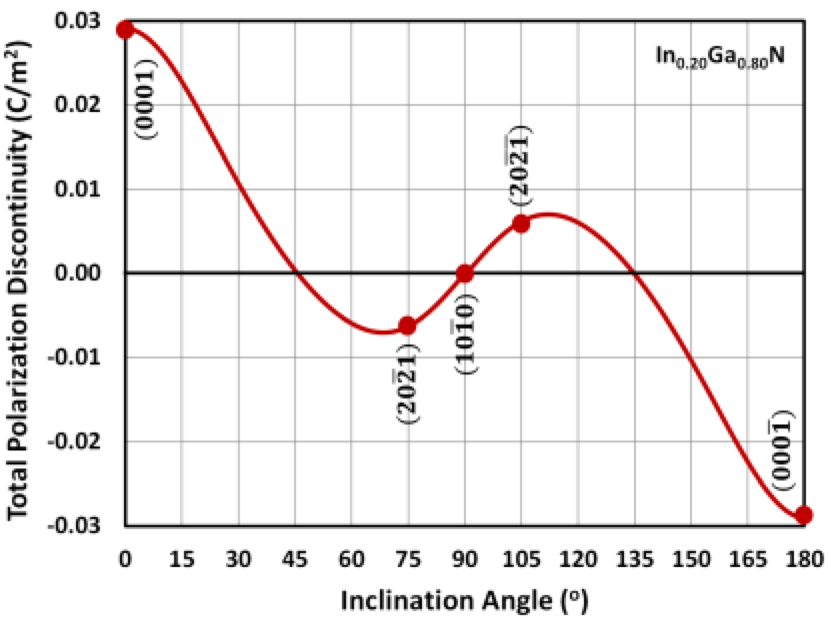
- Two interlaced hexagonal close packed (HCP) lattices
- Horizontal planes of Ga atoms and N atoms
- Each unit cell contains 2 Ga atoms and 2 N atoms
- Bonding in GaN is 60% covalent with 40% ionic character

Select GaN Crystal Planes



Polarization in III-Nitrides

Polarizations induce large internal electric fields (~MV/cm) which distort the band diagrams

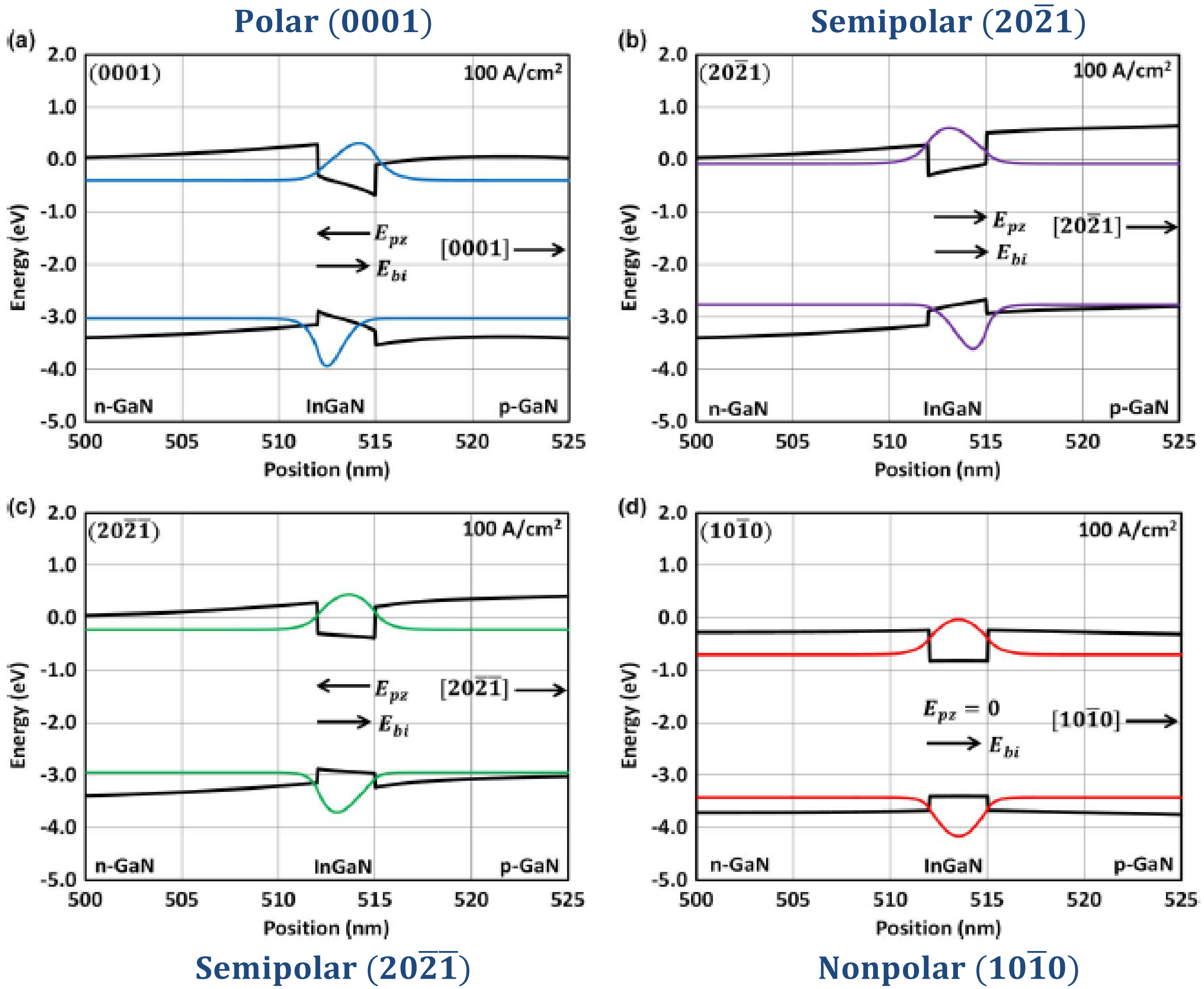


- *Piezoelectric polarization (P_{PZ})* – due to strain (e.g. – InGaN/GaN or AlGaN/GaN)
- *Spontaneous polarization (P_{SP})* – present in unstrained lattices and is due to charge asymmetry
- P_{PE} becomes larger for higher indium contents (i.e. – green and yellow emitters)

We can use nonpolar and semipolar orientations to eliminate the effects of polarization

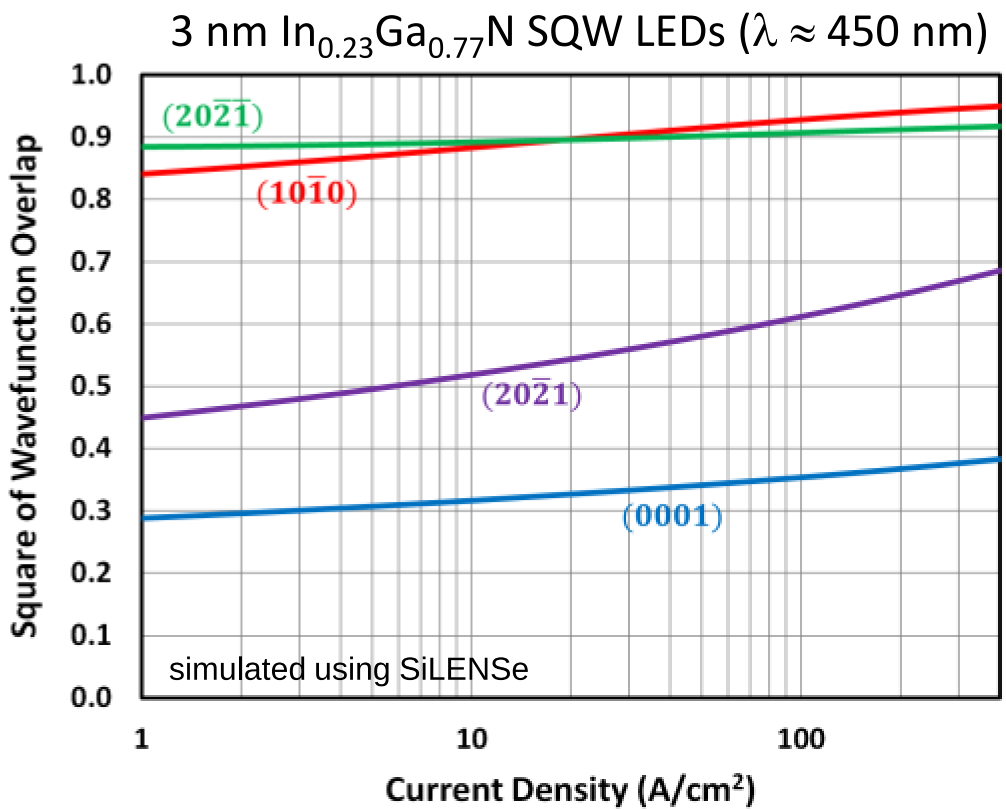
Characteristics and Advantages of Nonpolar/Semipolar III-Nitrides

Energy Band Diagrams for SQW Blue LEDs



D. Feezell, *J. Disp. Technol.* **9**, *190-198 (2013)*

Wavefunction Overlaps for SQW Blue LEDs

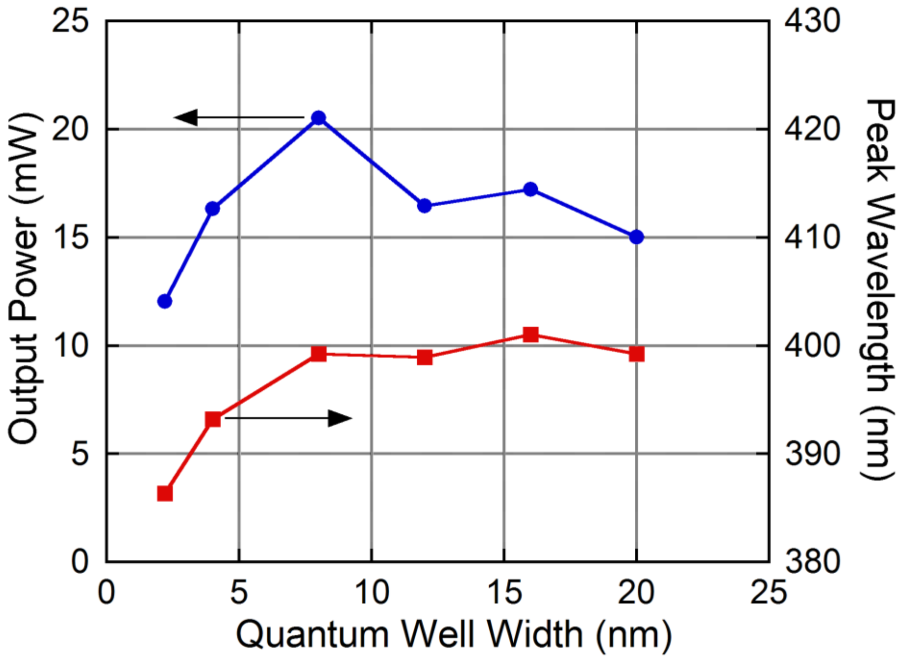


Wavefunction overlap is strongly affected by direction and magnitude of internal electric fields

D. Feezell, *J. Disp. Technol.* **9**, *190-198 (2013)*

Novel Device Designs

Violet LEDs: 6x MQW QW-width series



c-plane:

- QWs ≤ 3 nm thick
- Polarization-related fields
- Decline in output power for thick QWs

m-plane:

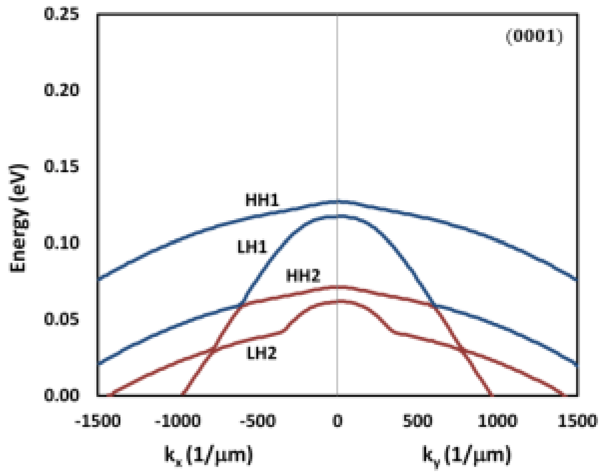
- High output power for QW widths up to 20 nm
- P_{max} for QW widths of 8-12 nm

Reduction of internal electric fields enables novel devices designs

K. C. Kim et al., Appl. Phys. Lett. **91**, 181120 (2007).

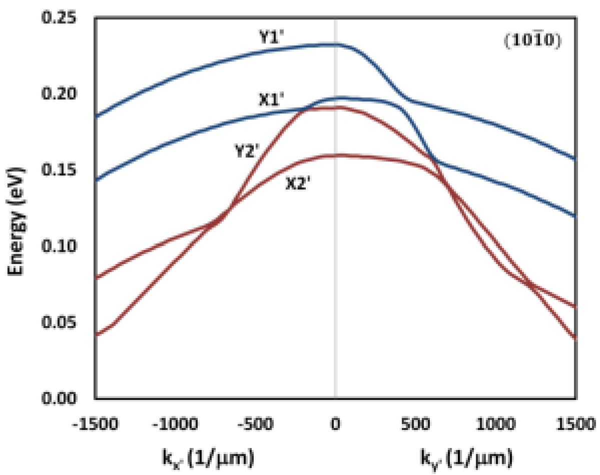
Polarized Emission

c-plane (polar)



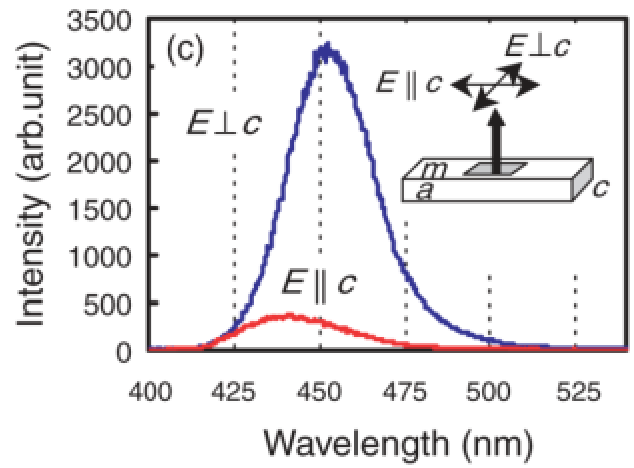
$$|HH\rangle, |LH\rangle = |X \pm iY\rangle$$
$$\rightarrow unpolarized\ emission$$

m-plane (nonpolar)



$$|Y'\rangle \rightarrow E \perp c$$

$$|X'\rangle \rightarrow E \parallel c$$

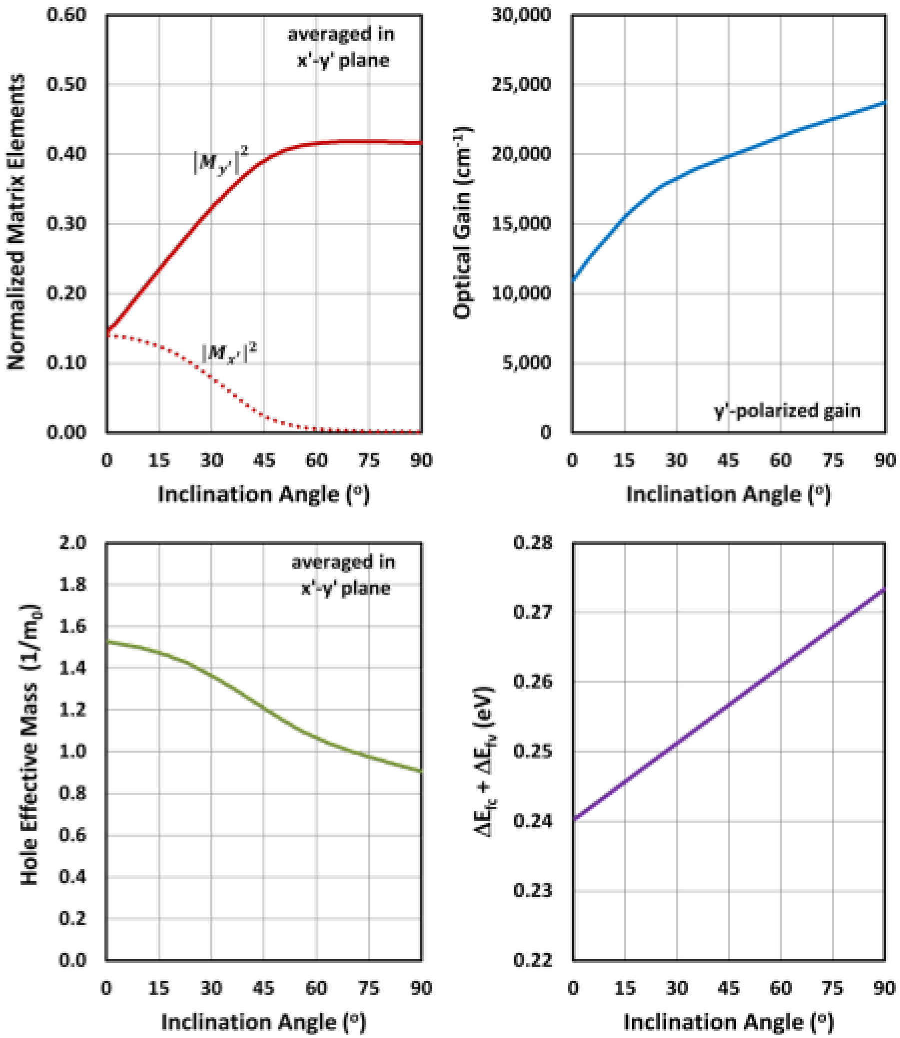


Nonpolar VCSELs are polarization pinned with E ⊥ c

Band structures after Scheibenzuber, Phys. Rev. B **80**, 115320 (2009).

H. Tsujimura et al., Jpn. J. Appl. Phys. **42**, L1010 (2007).

Summary of Benefits for Nonpolar/Semipolar



- QCSE reduced
- Optical matrix elements increased
- Emission anisotropic
- Optical gain increased
- Hole effective mass reduced
- Transparency carrier density reduced
- *Growth and design flexibility improved*

D. Feezell and S. Nakamura, "Nonpolar and Semipolar Group III-Nitride Lasers," in *Semiconductor Lasers: Fundamentals and Applications*, Edited by A. Baranov and E Tournie, Woodhead Publishing, ISBN13: 9780857091215 (2013).

Semipolar $(20\bar{2}\bar{1})$ and Nonpolar $(10\bar{1}0)$ InGaN/GaN LEDs

Applications for III-Nitride LEDs

Solid-state lighting

Architectural lighting

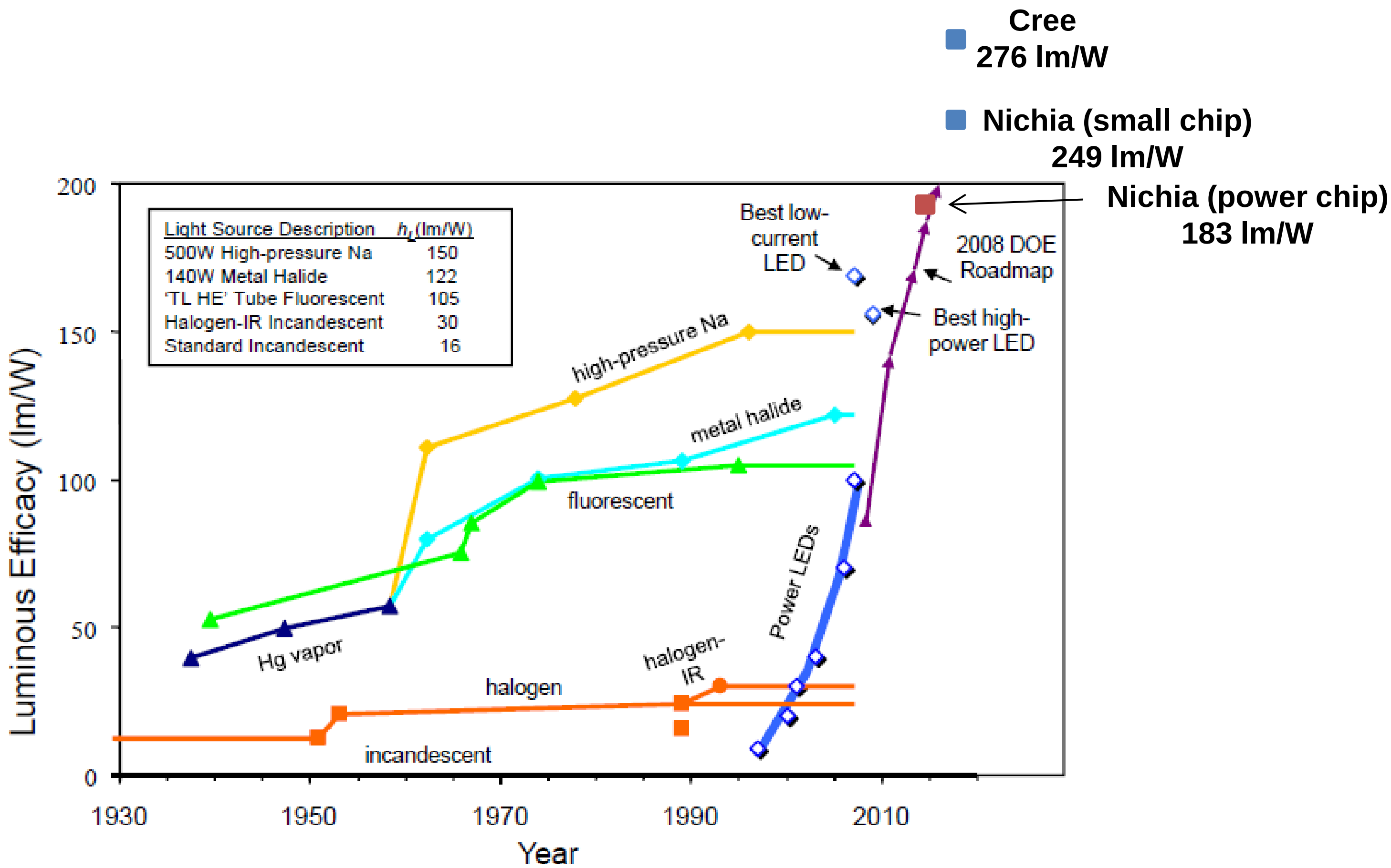
Automotive lighting

Backlighting

Horticulture

Street lighting

White LEDs vs. Conventional Lighting

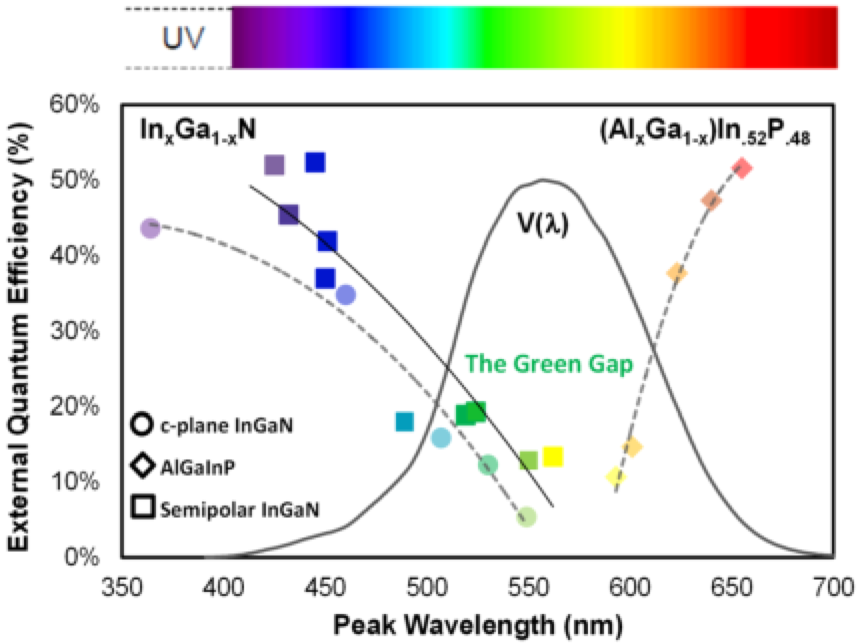


- Available >130 lm/W phosphor-converted commercial LED products
- Emerging >200 lm/W LED prototypes
- ~250 lm/W possible for phosphor converted LEDs

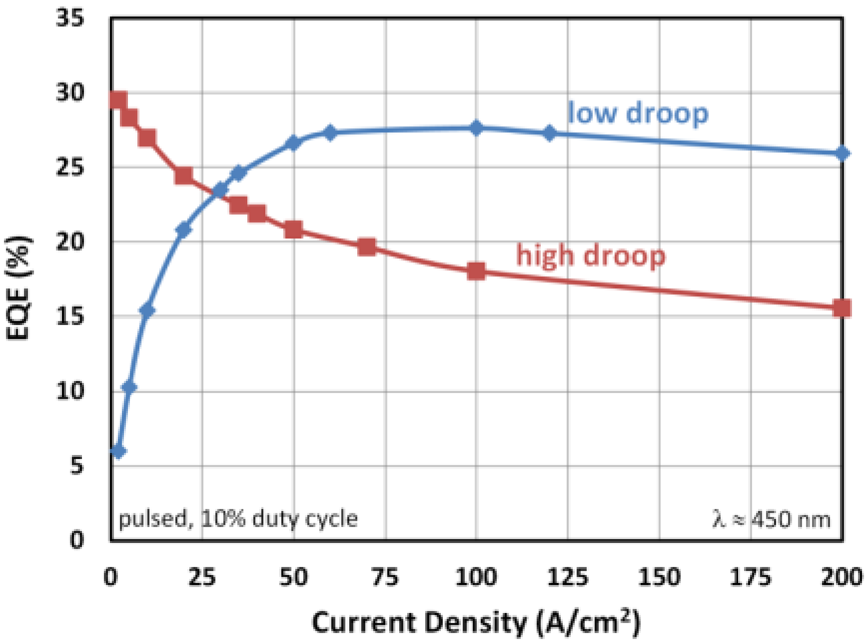
M. Krames, CLEO (2009)

Issues Plaguing GaN-Based LEDs

Green Gap



Efficiency Droop

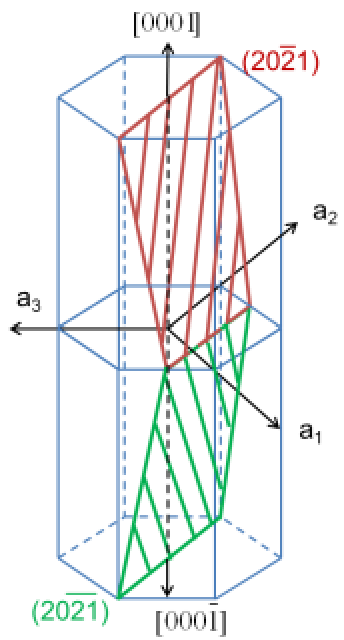


- Threading dislocations
- Indium inhomogeneity
- Polarization-related electric fields
- Strain
- *Auger recombination*
- Carrier leakage

Semipolar $(20\bar{2}\bar{1})$ Light-Emitting Diodes

<u>Semipolar $(20\bar{2}\bar{1})$ is a promising new orientation:</u>

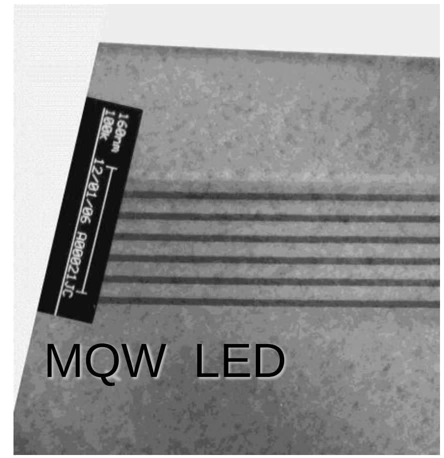
- Low polarization-related electric fields
- Fields in same direction as *c*-plane, ¼ the magnitude
- Large wavefunction overlap for LED current densities
- Very small blue shift
- Very narrow FWHM
- Highly polarized emission
- High indium uptake for high growth temperature

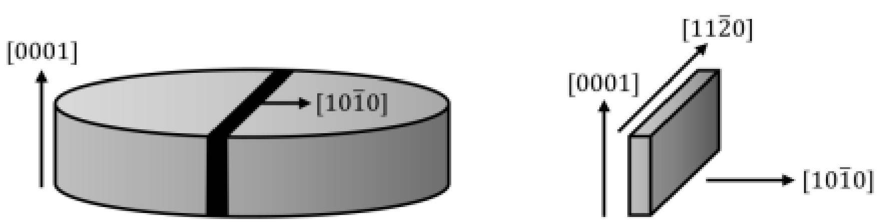


Growth on Free-Standing GaN Substrates

Nonpolar/semipolar GaN substrates cut from HVPE-grown c-plane GaN boules

- Mitsubishi Chemical Corporation
- Dislocation density < 5×10^6 cm^{-2}
- MOCVD growth conditions are similar to those for *c*-plane on sapphire

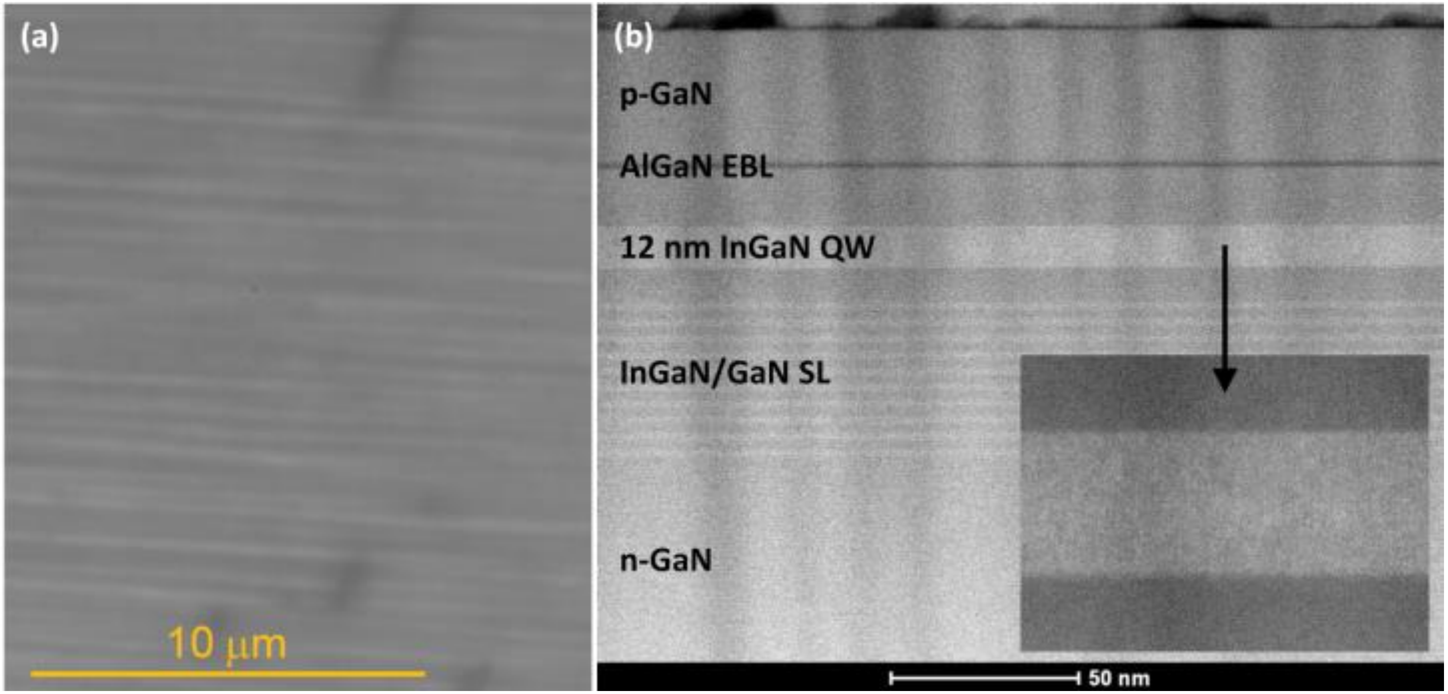




free-standing GaN m-plane substrate

K. Fujito *et al.*, MRS Bulletin **34** 313 (2009)

High Quality Blue InGaN ($20\bar{2}\bar{1}$) QWs



Higher growth temperature results in high-quality InGaN active regions

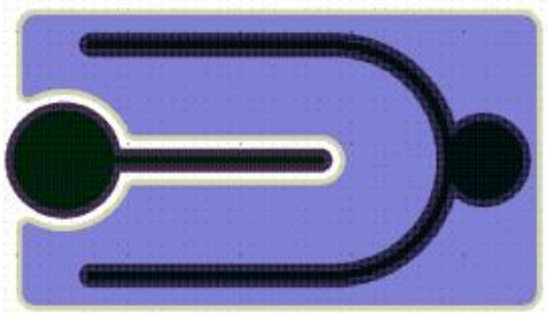
*TEM image courtesy of Feng Wu

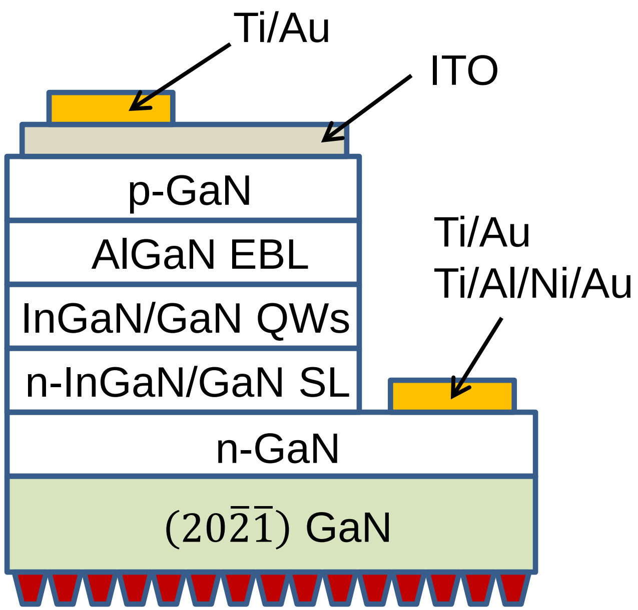
C. Pan *et al.*, Appl. Phys. Express **5** 062103 (2012)

LED Structure and Process

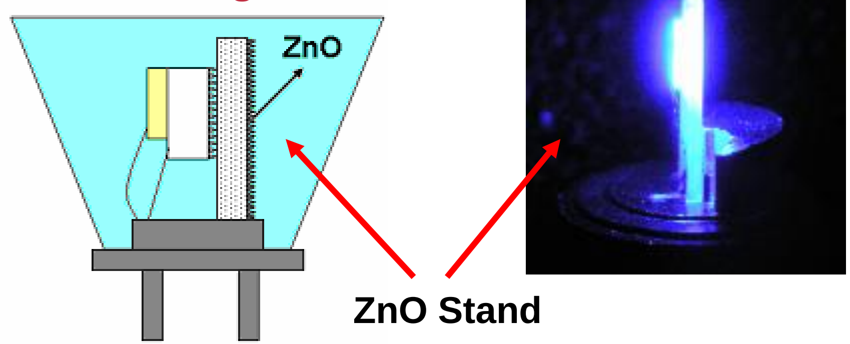
- Top-emitting ITO-based chip
- 0.1 mm^2 active area
- Patterned backside roughening
- ZnO-based transparent LED package

ITO-based p-contact





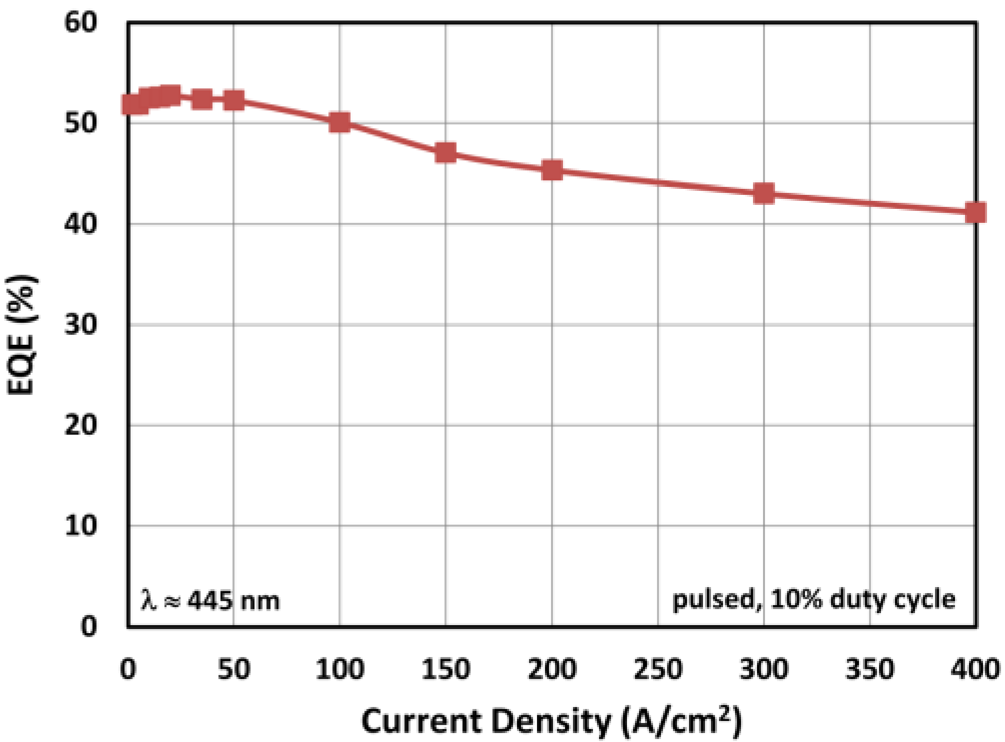
Transparent Package



Simulated Light Extraction Efficiency ~75%

Y. Zhao et. al., Appl. Phys. Express ***3*** *10210 (2010)*
C. Pan et. al., Jpn. J. Appl. Phys. ***49*** *080210 (2010)*

Blue ($20\bar{2}\bar{1}$) LEDs: EQE vs. Current Density



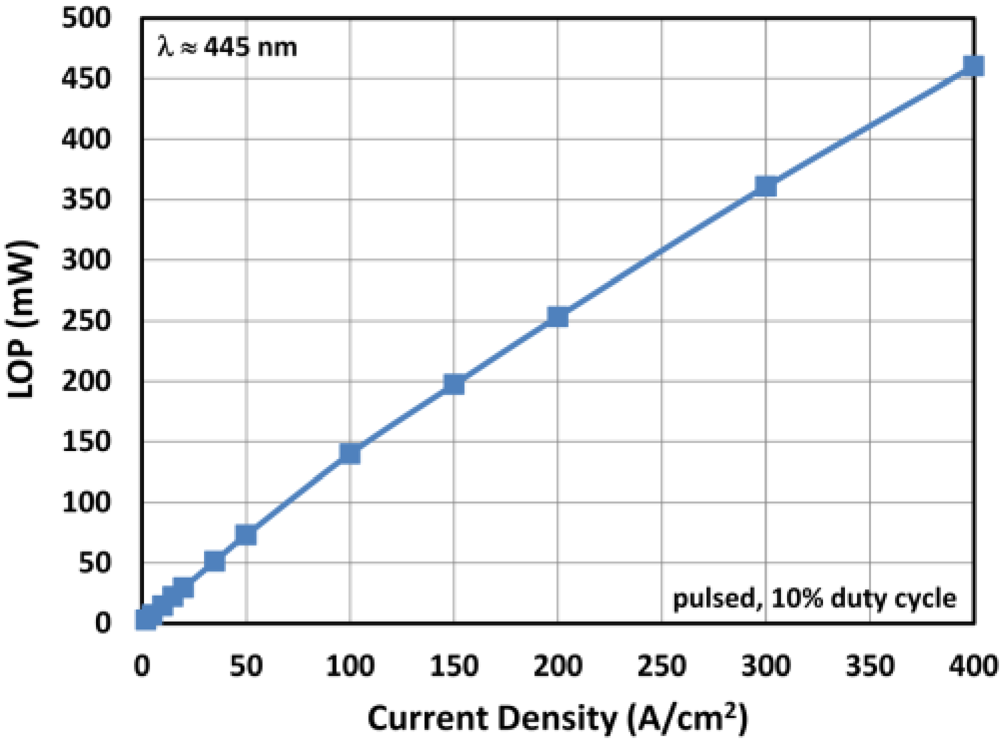
- 0.1 mm^2 active area
- Thick (12 nm) SQW active region
- ITO-based chip

$$Droop\ (\%) = \frac{(EQE_{Peak} - EQE)}{EQE_{Peak}}$$

	35 (A/cm²)	100 (A/cm²)	200 (A/cm²)	300 (A/cm²)	400 (A/cm²)
EQE (%)	52.4	50.1	45.3	43.0	41.2
Droop (%)	0.7	5.1	14.1	18.4	21.9

C. Pan *et al.*, Appl. Phys. Express **5** 062103 (2012)

Blue (20$\bar{2}\bar{1}$) LEDs: LOP vs. Current Density



- 0.1 mm^2 active area
- Thick (12 nm) SQW active region
- >450 mW peak output power
- ~5 chips needed for 60 W incandescent replacement

	35 (A/cm^2)	100 (A/cm^2)	200 (A/cm^2)	300 (A/cm^2)	400 (A/cm^2)
LOP (mW)	51.2	140.0	253.4	360.9	460.3

C. Pan *et al.*, Appl. Phys. Express **5** 062103 (2012)

Blue $(20\bar{2}\bar{1})$ LEDs: IQE and Carrier Lifetimes

Epitaxial Structures

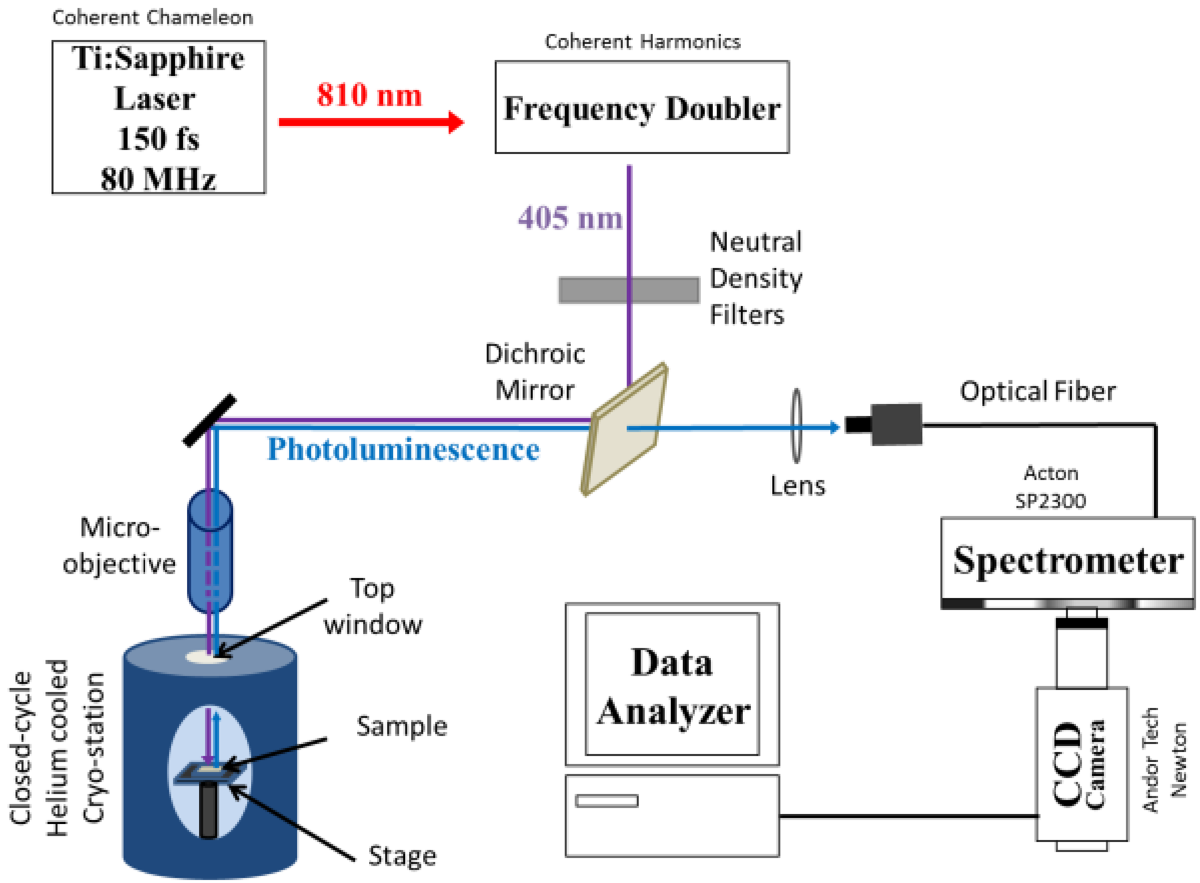
<table>
<tr><th rowspan="2">Wafer</th><th>1 QW</th><th>2 QW</th><th>3 QW</th></tr>
<tr><td>141127EL</td><td>141127FL</td><td>141127DL</td></tr>
<tr><td>p/p++ GaN</td><td colspan="3">110 nm (Mg = 2e19 cm^{-3}/1.6e20 cm^{-3})</td></tr>
<tr><td>AlGaN EBL</td><td colspan="3">10 nm (Mg = 1e19 cm^{-3})</td></tr>
<tr><td>GaN Barrier</td><td colspan="3">12 nm (uid)</td></tr>
<tr><td rowspan="5">Active region</td><td rowspan="5">12 nm InGaN QW</td><td>6 nm InGaN QW</td><td>4 nm InGaN QW</td></tr>
<tr><td rowspan="3">4 nm GaN barrier</td><td>4 nm GaN barrier</td></tr>
<tr><td>4 nm InGaN QW</td></tr>
<tr><td>4 nm GaN barrier</td></tr>
<tr><td>6 nm InGaN QW</td><td>4 nm InGaN QW</td></tr>
<tr><td>GaN Barrier</td><td colspan="3">12 nm (uid)</td></tr>
<tr><td>n GaN</td><td colspan="3">2 µm (Si = 3e18 cm^{-3})</td></tr>
</table>

- Studied IQE and carrier lifetimes in three $(20\bar{2}\bar{1})$ structures
- 12 nm total active region thickness (1x12 nm, 2x6 nm, 3x4 nm)
- 450 nm peak wavelength

S. Okur, et al., submitted to Optics Express

Micro-Photoluminescence (μ-PL) System

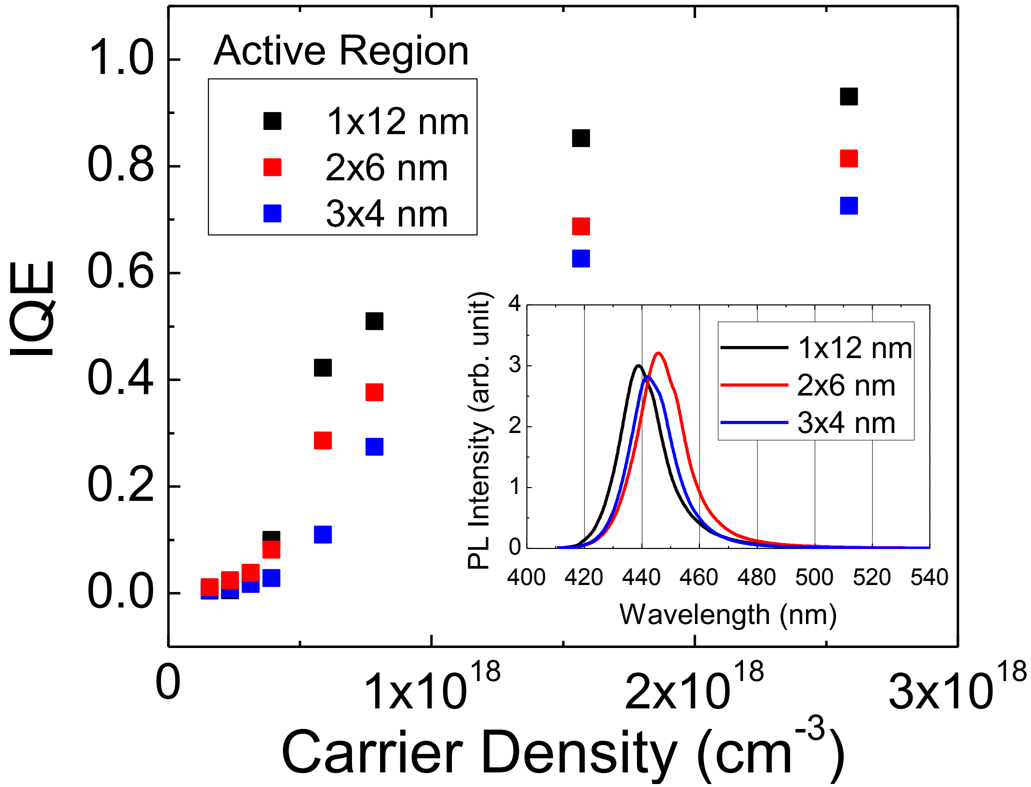
Temperature-dependent and time-resolved photoluminescence



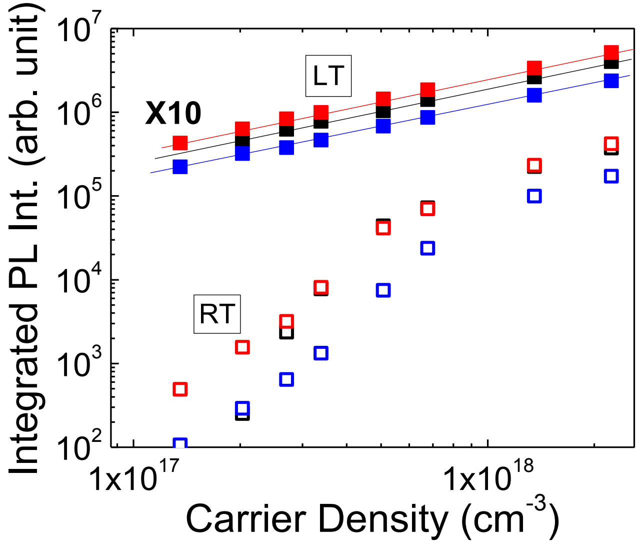
~50 μm spot diameter

Collaboration with Center for Integrated Nanotechnologies

Internal Quantum Efficiency (IQE)



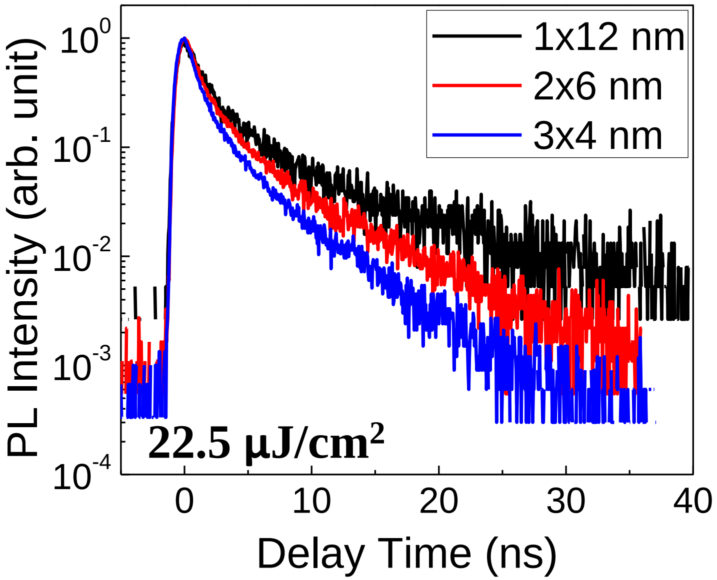
$$IQE = \frac{\int I_{295K}(\lambda)d\lambda}{\int I_{10K}(\lambda)d\lambda}$$

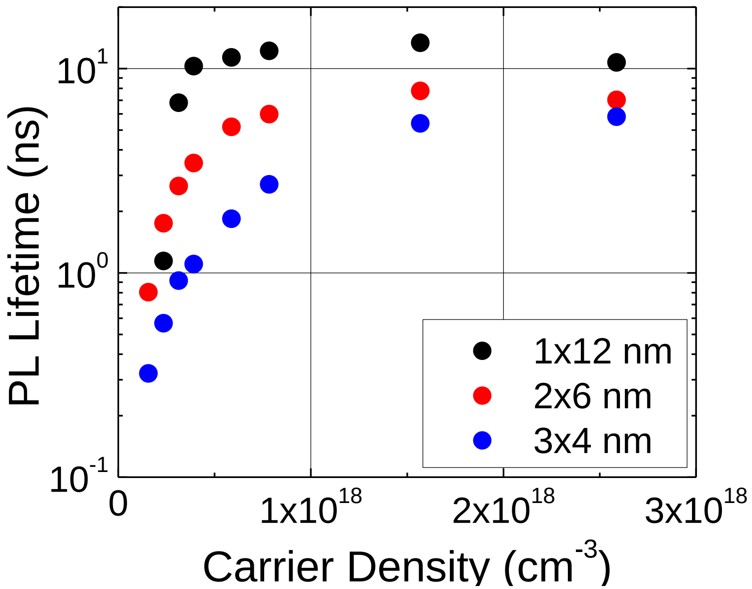


- Non-radiative lifetime assumed to be infinite at 10 K
- IQE maximum in the 1 x 12 nm structure
- Excitation power level accesses SRH and radiative regimes

S. Okur, et al., submitted to Optics Express

Time-Resolved Photoluminescence



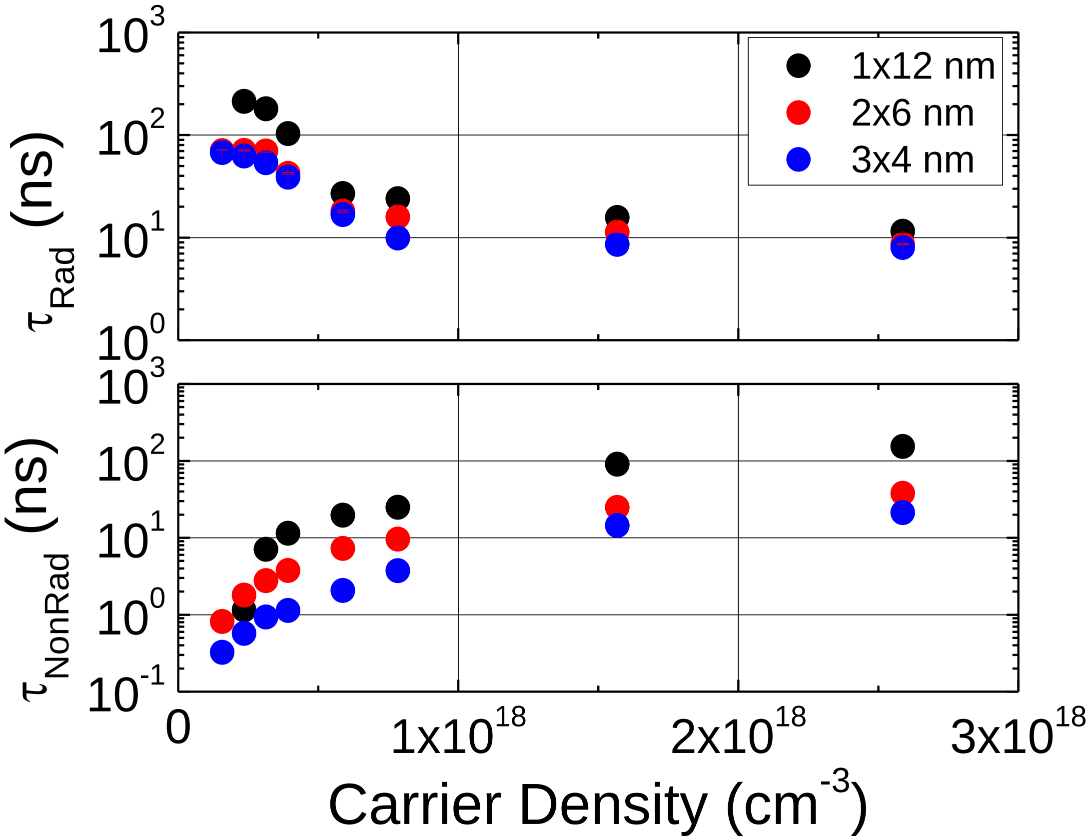


- TRPL decay fit with bi-exponential function ($A_1 e^{-t/\tau_1} + A_2 e^{-t/\tau_2}$) to extract PL lifetime
- Slower decay associated with carrier lifetime
- PL lifetime longest for 1 x 12 nm structure

S. Okur, et al., submitted to Optics Express

Radiative and Non-Radiative Carrier Lifetimes

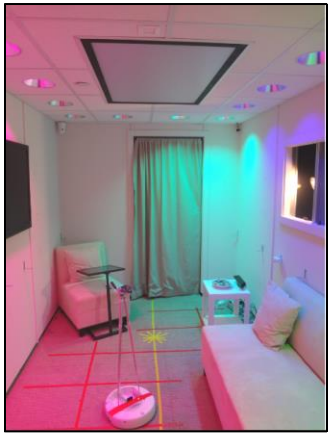
$$\tau_R = \tau_{PL}/IQE\,, \qquad 1/\tau_{PL} = 1/\tau_R + 1/\tau_{NR}$$



- Similar radiative lifetime for all structures
- Longer non-radiative lifetime for thicker QWs
- Correlated with higher IQE for thicker QWs
- Related to influence of QW interface defects

S. Okur, et al., submitted to Optics Express

The Second Wave: Smart Lighting



Translational Research

Testbeds

Goal: Maximize light quality and minimize energy use

Goal: Communications with Illumination (Dual Use)

CONTROLS

SOURCES

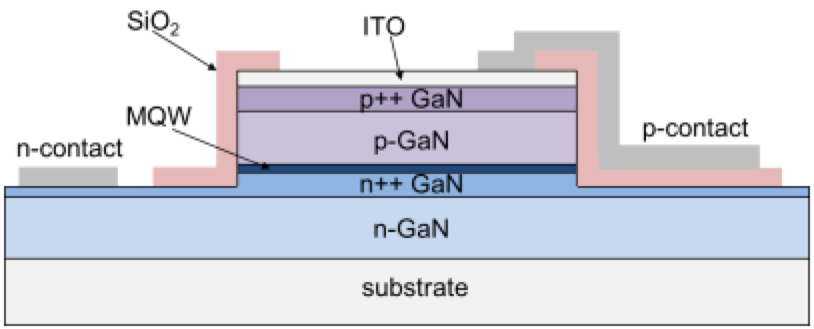
SENSORS

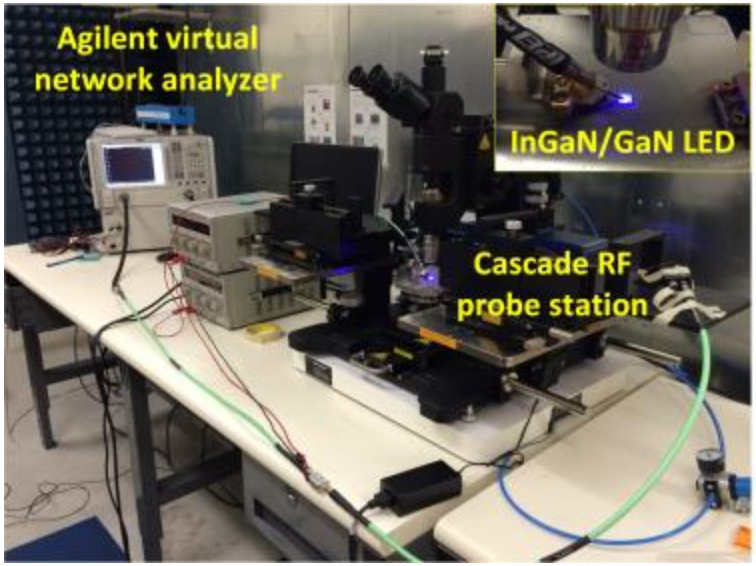
Goal: Luminaires with dynamic
- Brightness control
- Spectral control
- Beam shaping capability
- Integrated data communications

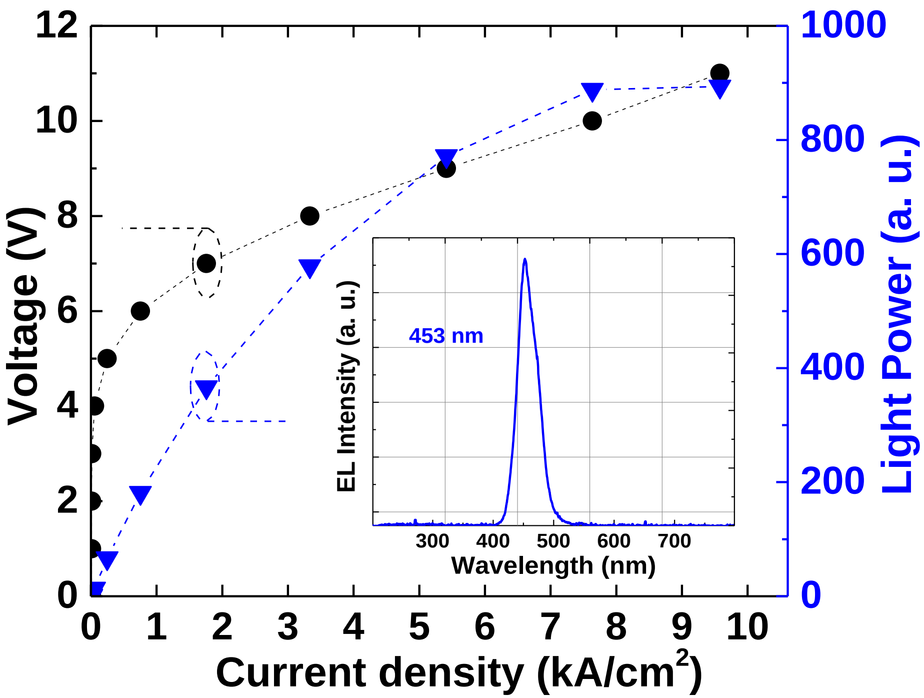
Goal: Plenoptic light field sensing
- Color quality
- Intensity
- Direction (Light Flow)
- Data

Slide courtesy of Prof. R. Karlicek, RPI

High-Speed Nonpolar $(10\bar{1}0)$ LEDs



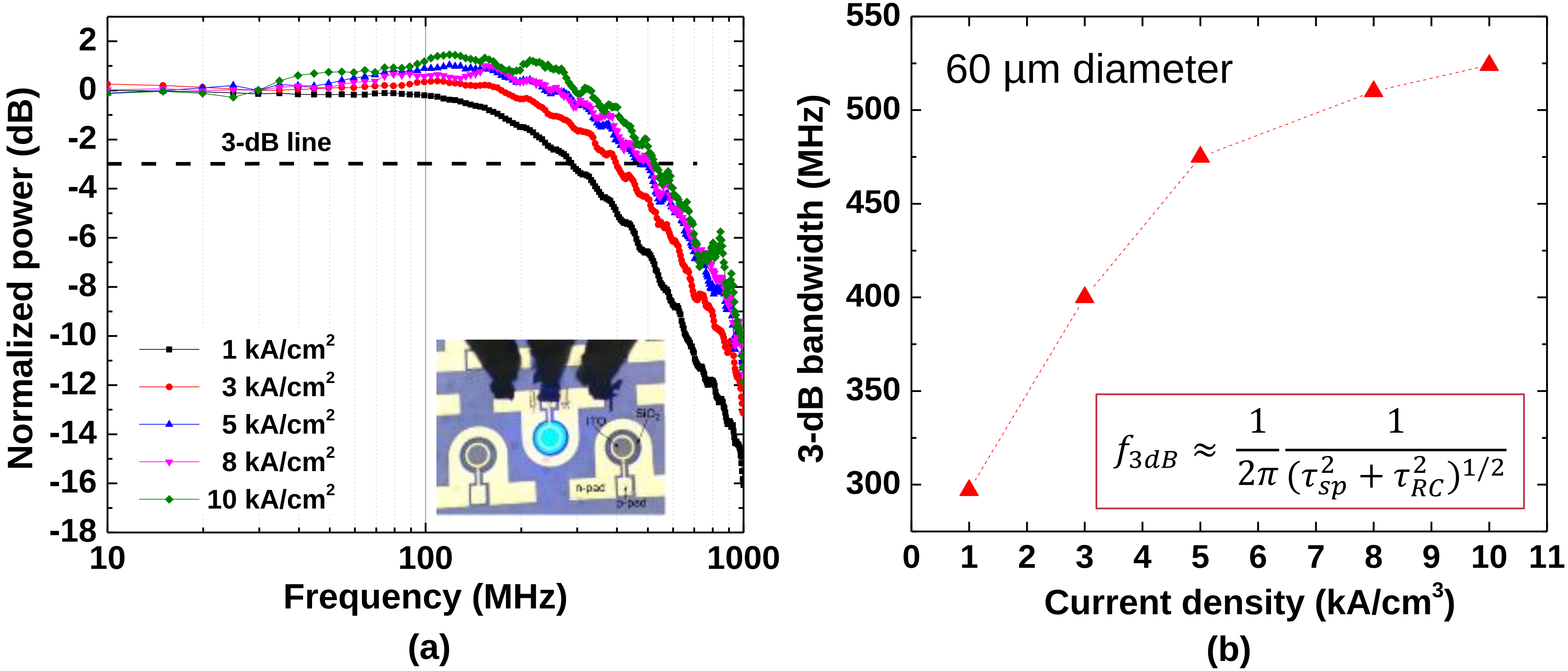




- Short carrier lifetime on nonpolar
- Micro-LEDs for large RC bandwidth
- 3 x 6 nm QWs, 15 nm barriers
- RF bandwidth characterized

A. Rashidi, et al., submitted to Photon. Technol. Lett.

RF Bandwidth Characterization

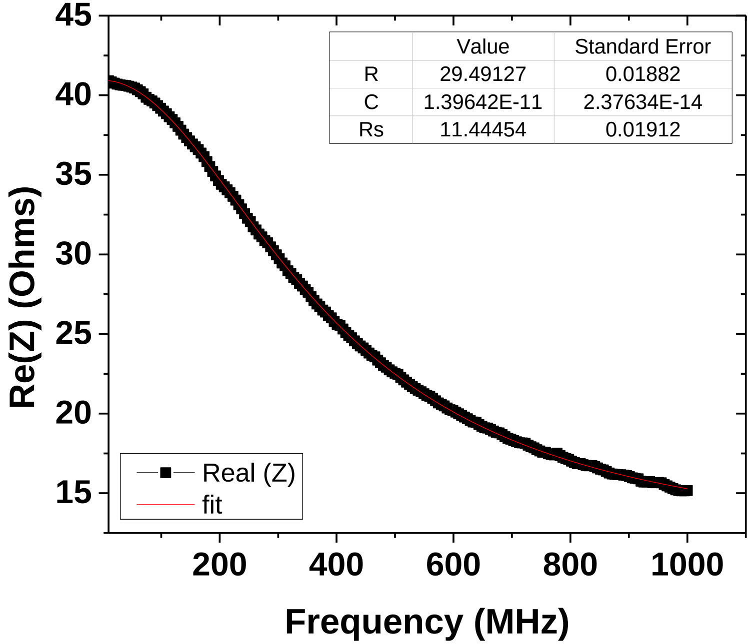


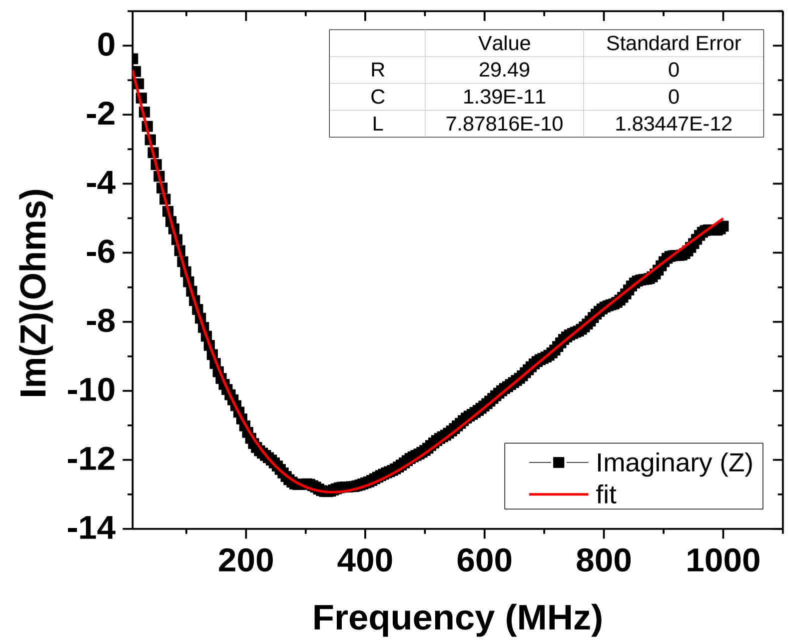
- Maximum 3 dB bandwidth is 524 MHz at 10 kA/cm^2
- Bandwidth increases with current density but saturates due to heating and carrier escape
- Among the highest bandwidths reported for GaN-based LEDs

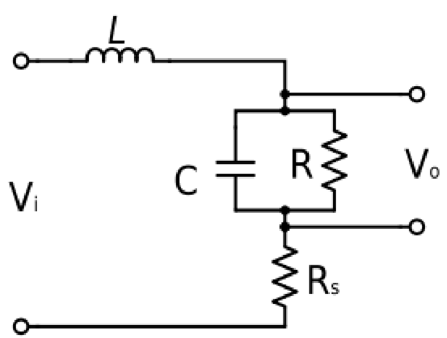
A. Rashidi, et al., submitted to Photon. Technol. Lett.

Equivalent Circuit Model

Fitting real and imaginary parts of the transfer function yields R and C



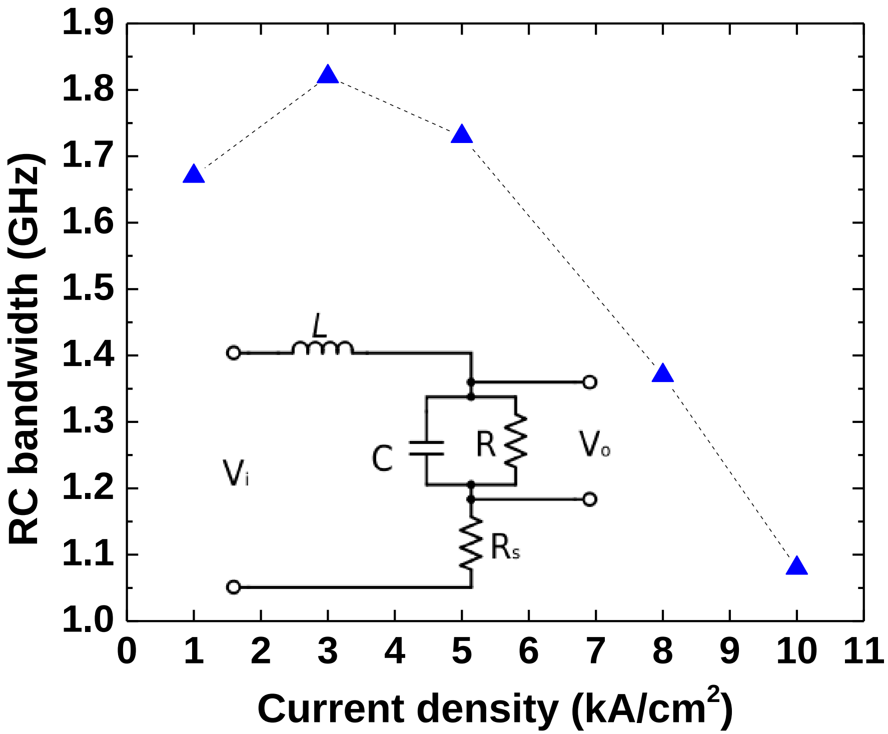




$$H(\omega) = \frac{R - j\,\omega R^2 C}{R - j\,\omega R^2 C + (1+\omega^2 R^2 C^2)(R_s + j\omega L)}$$

A. Rashidi, et al., submitted to Photon. Technol. Lett.

RC Bandwidth



Frequency response of equivalent circuit plotted and RC limited 3 dB bandwidth determined

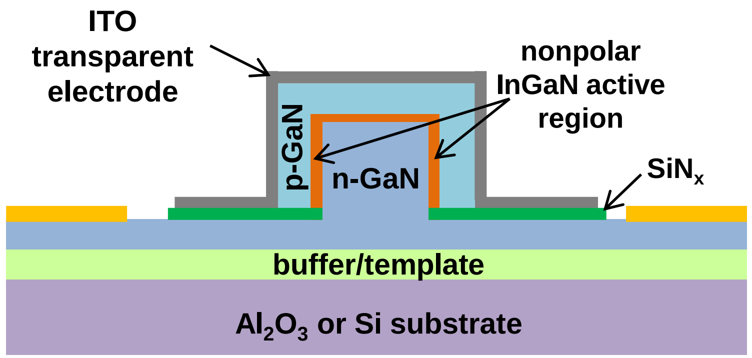
$$f_{RC} = \frac{1}{2\pi}\frac{1}{\tau_{RC}}$$

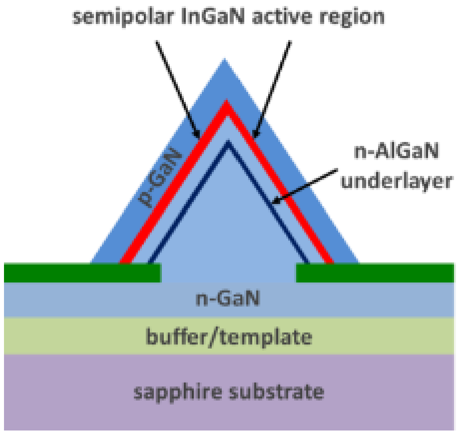
- LEDs are currently carrier lifetime limited since $f_{RC} > f_{3dB}$
- Reduce active region volume to increase carrier density ($R_{sp} \propto N^2$)
- Reduce barrier widths to increase tunneling

A. Rashidi, et al., submitted to Photon. Technol. Lett.

Bottom-Up Selective-Area Growth

Core-Shell Nanostructure LEDs

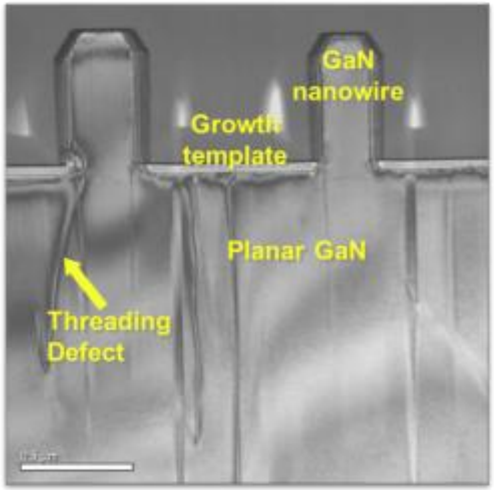


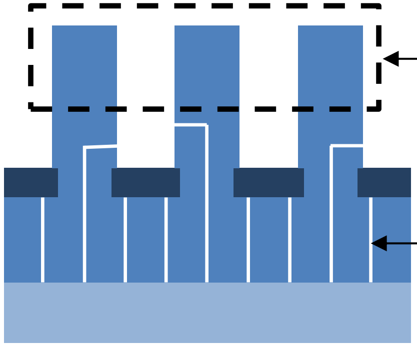


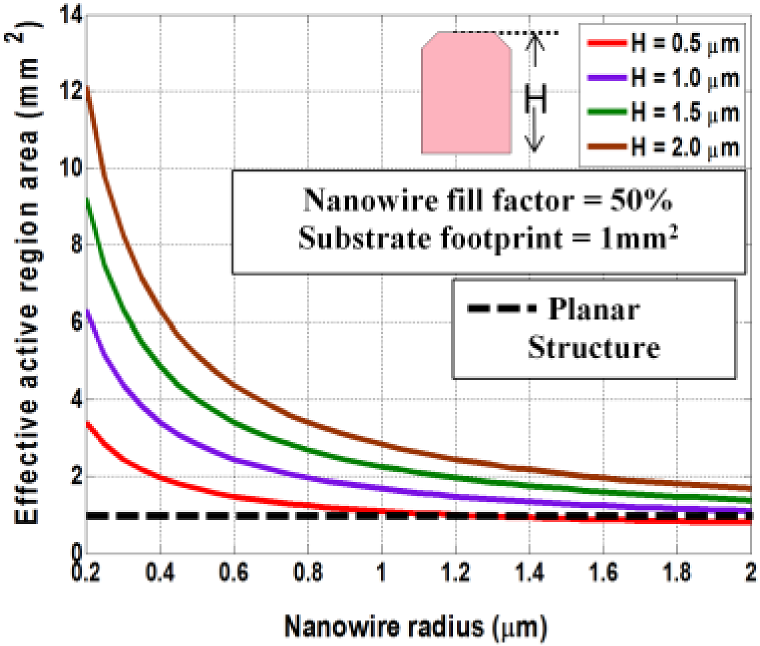
Potential Advantages of Nanowall LEDs:

- **Polarization-free**, nonpolar (*m*-plane) active regions will help reduce droop
- **Large effective active region area** will reduce carrier density for a given current density and mitigate droop
- **Elimination of threading dislocations** (TDs) will reduce non-radiative recombination and improve lifetime
- **Strain relaxed** structures may allow for higher indium contents without defect generation (potential green gap solution)
- **Cost effective** nonpolar/semipolar structures in patterned dielectric apertures on sapphire or silicon

Core-Shell Advantages





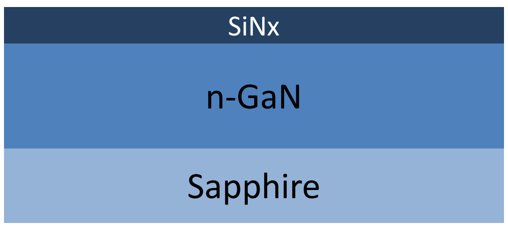


- Threading dislocations bend 90° near free surface → Large areas of defect-free nanostructures

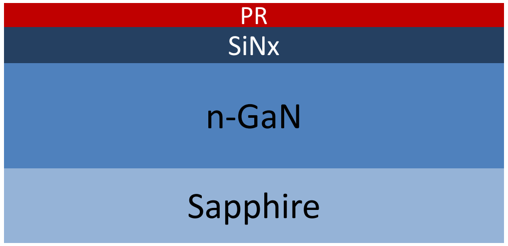
- Larger effective active region area for the same planar footprint → Lower carrier density for a given current

A. Rishinaramangalam et al., EMC (2010)

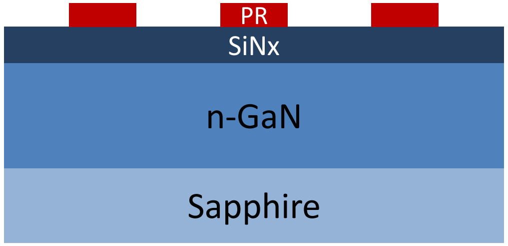
Nanostructure Template Processing



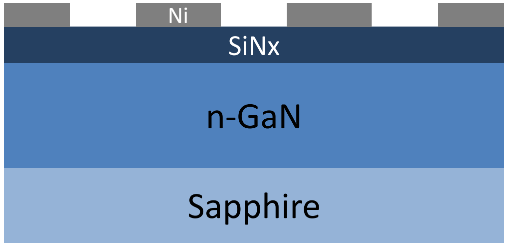
1) Starting wafer



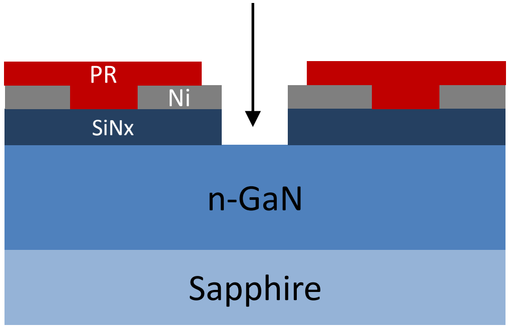
2) Spin ARC and PR



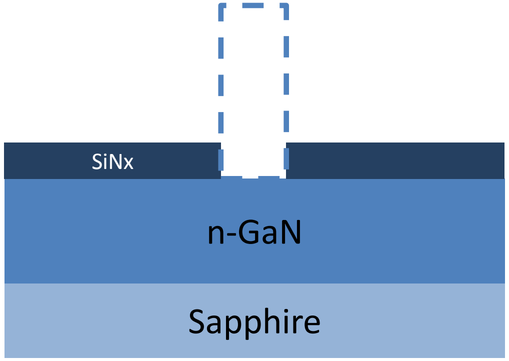
3) Interferometric lithography



4) Ni deposition and lift-off

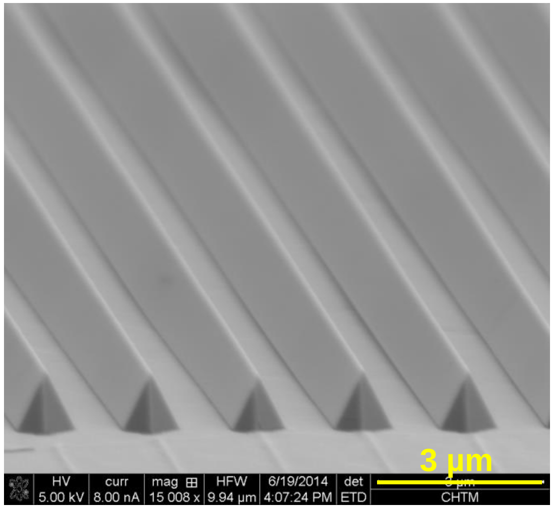


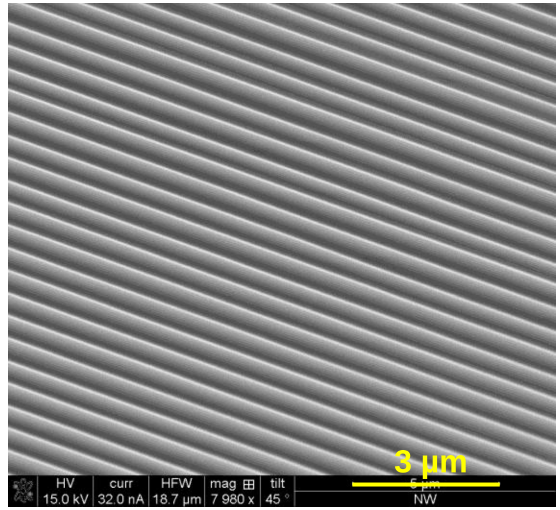
5) Secondary photolithography and RIE of SiN_x

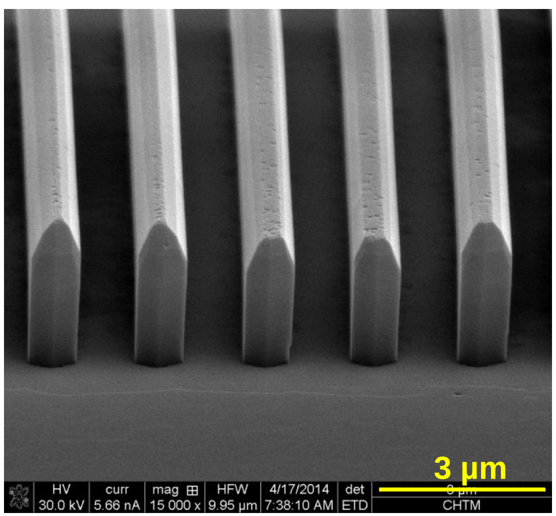


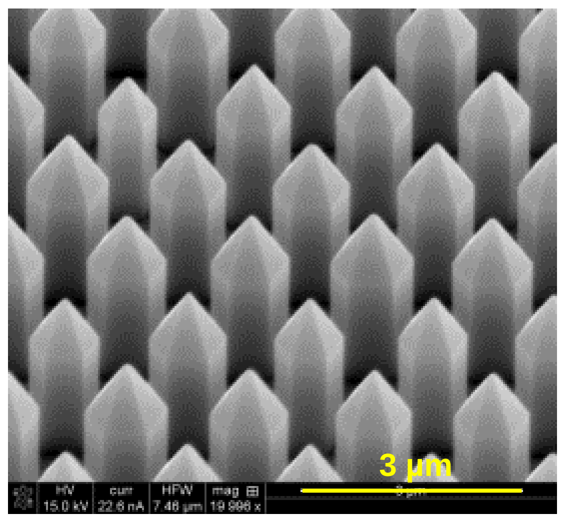
6) Liftoff and piranha clean

Core-Shell Nanostructures - Applications





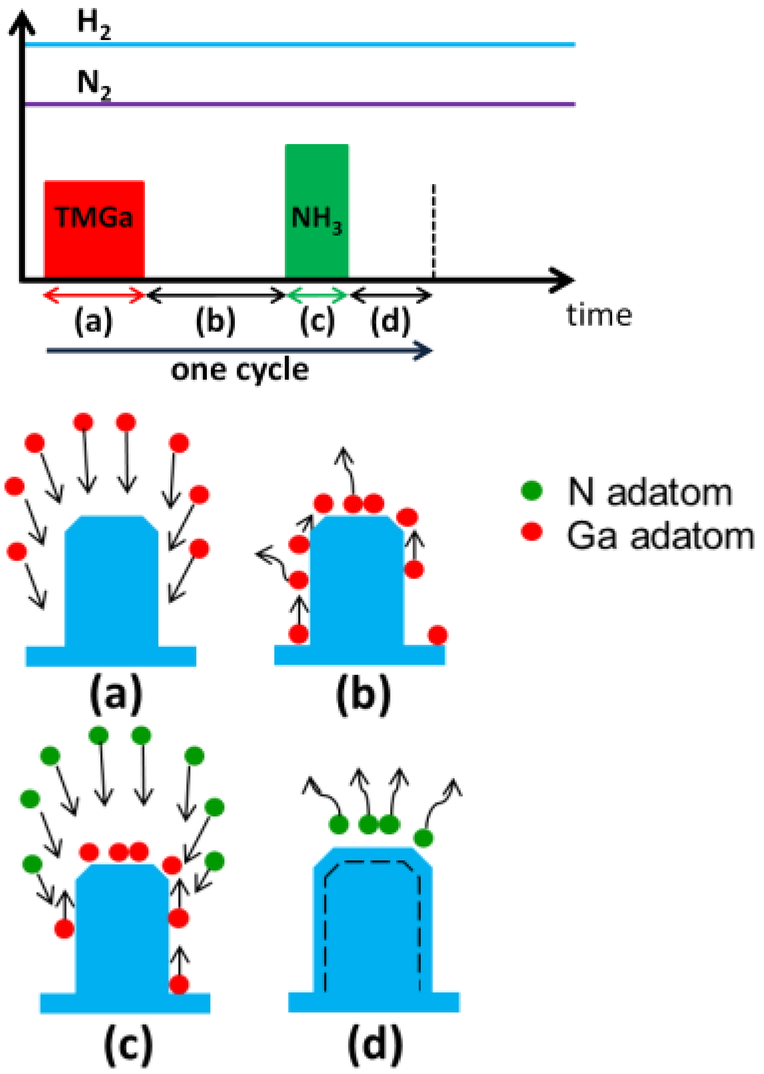




- Nanoscale light-emitting diodes
- Nanoscale lasers
- Nanoscale transistors
- Solar cells
- Intersubband detectors
- Hydrogen generation

Pulsed Mode MOCVD Technique

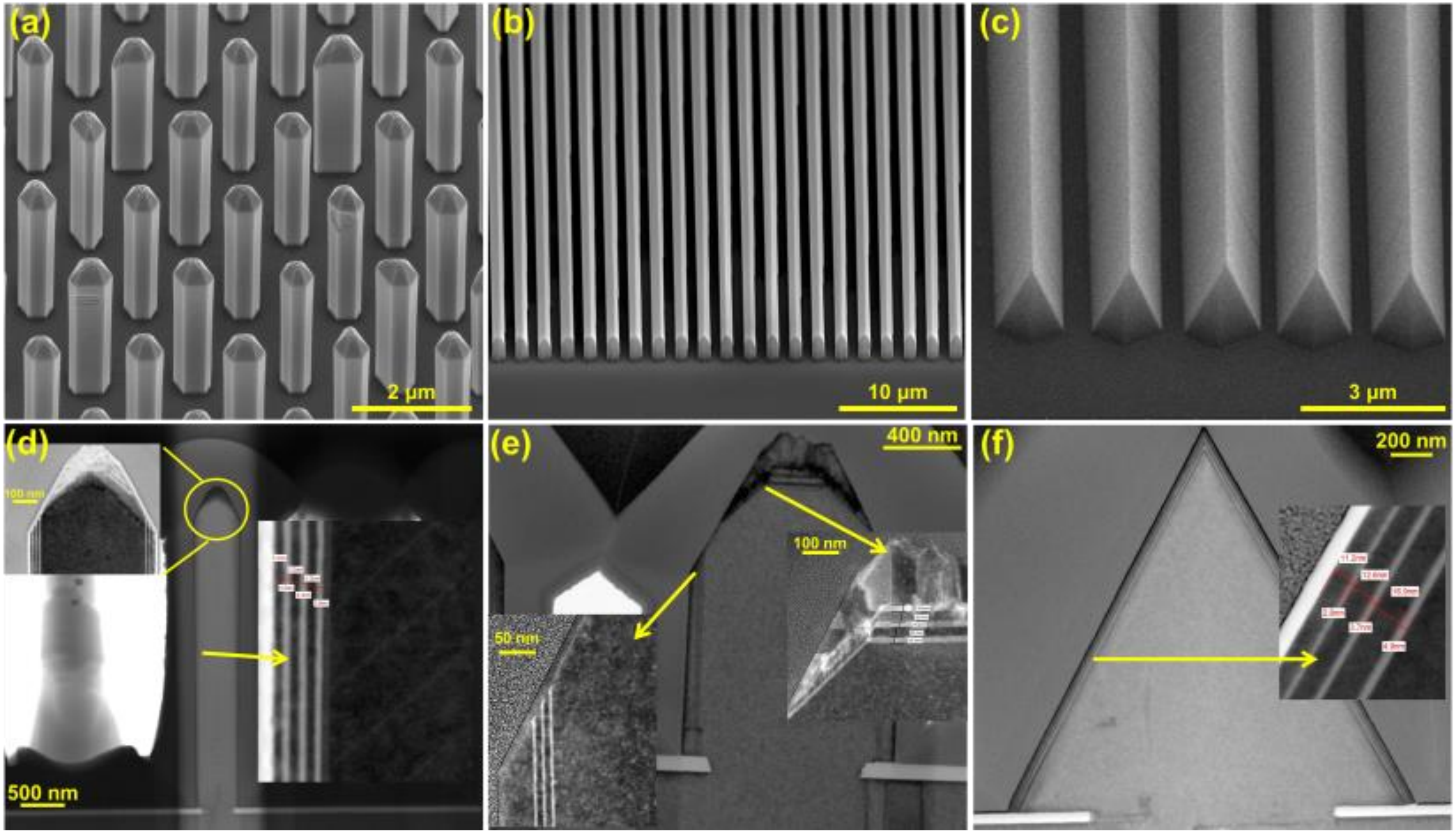
- Pulsed mode technique → locally low V/III ratio
- Temperature from 900°C to 950°C
- Pressure 100 Torr
- TMGa flow 26.7 µmol/min
- V/III ratio of 100
- H_2 flow of 3000 sccm
- N_2 flow of 1000 sccm



Y. T. Lin et.al. Nanotechnology. **23** (46) (2012)

A. Rishinaramangalam et al., *J. Electron. Mat.* 44, 1255 (2015)

GaN Cores with 3X InGaN Quantum Wells

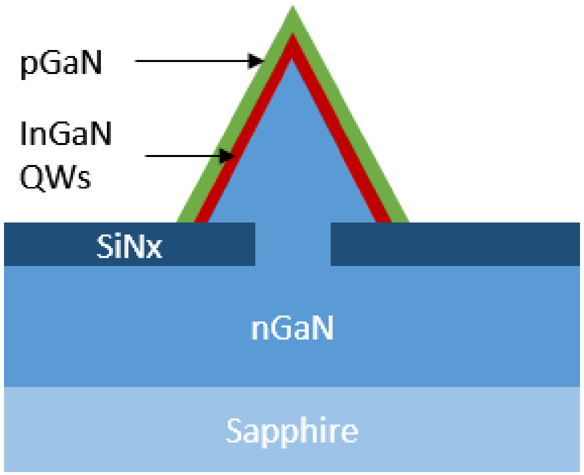


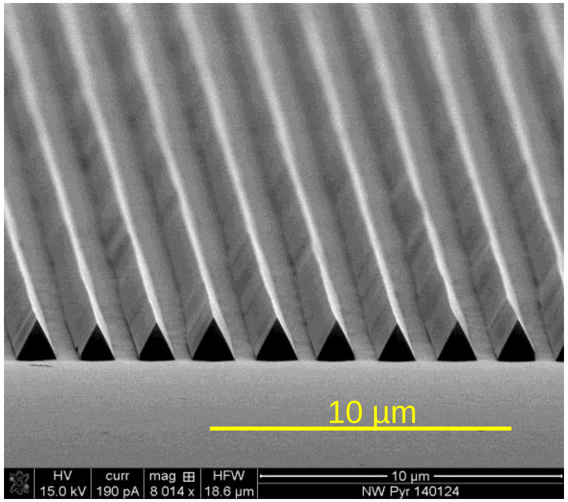
InGaN quantum wells on nanowires, nanowalls, and triangular stripes

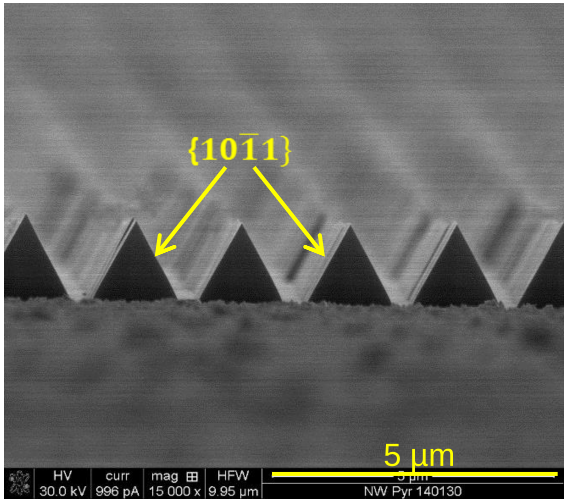
A. Rishinaramangalam et al., *J. Electron. Mat.* 44, 1255 (2015)

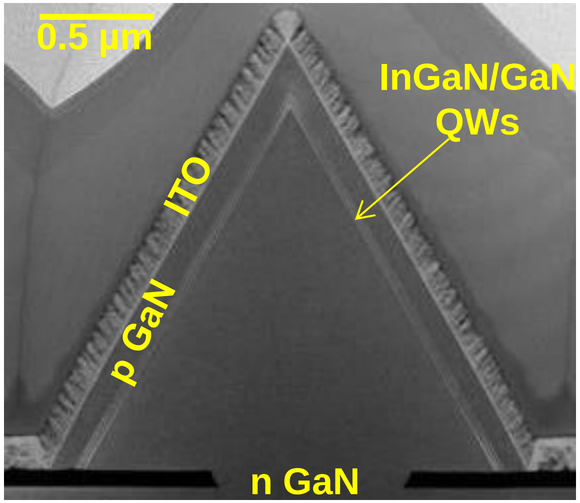
Triangular Nanostripes

- Higher indium uptake on $\{10\bar{1}1\}$ family of planes
- Low polarization-related electric fields compared to c-plane
- High light extraction efficiency
- Continuous flow MOCVD
- ***Key challenge is current leakage in the diode***

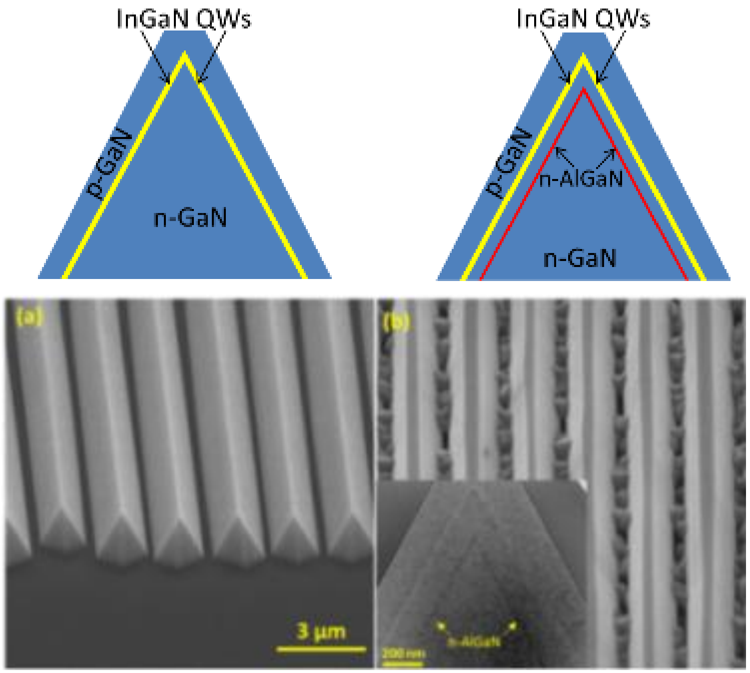


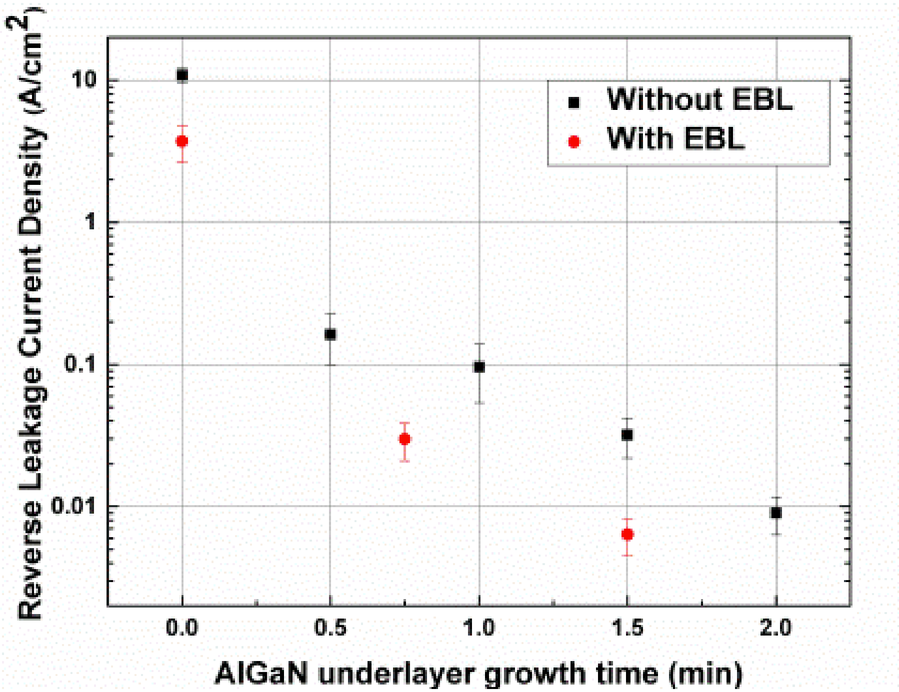






Leakage Current Reduction with AlGaN

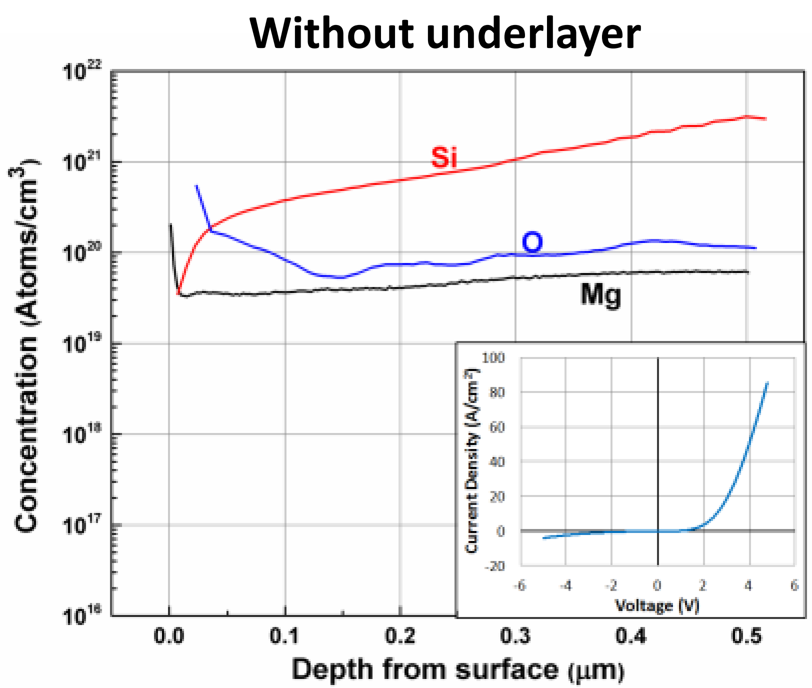


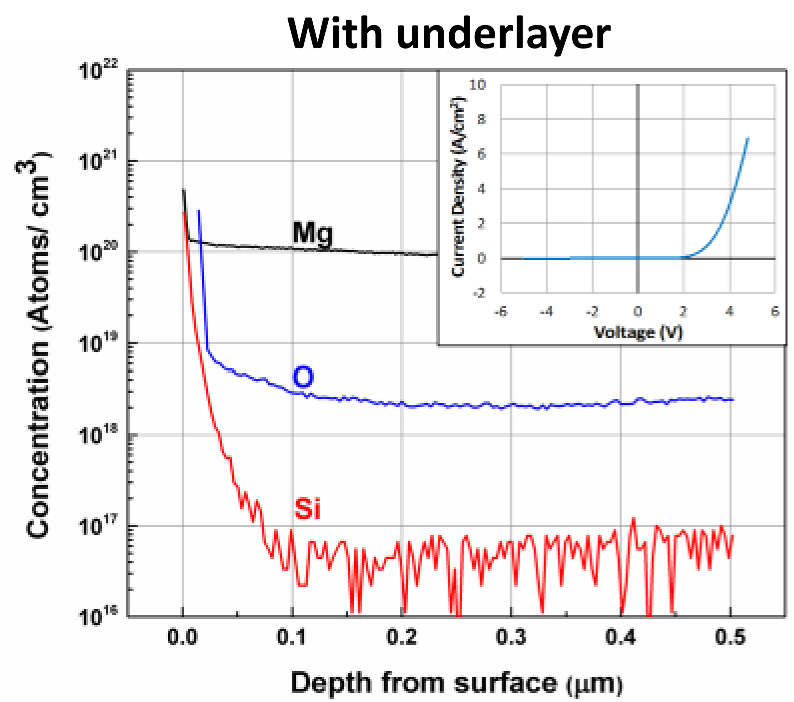


- ***Addition of n-AlGaN underlayer significantly reduces leakage current***
- Addition of p-AlGaN electron blocking layer (EBL) has smaller effect
- Poly-AlGaN grows on dielectric mask, covering the mask and filling voids
- Effect on impurity concentration shown with SIMS

A. Rishinaramangalam, et al., submitted to Appl. Phys. Mat.

SIMS Profiles Without and With Underlayer

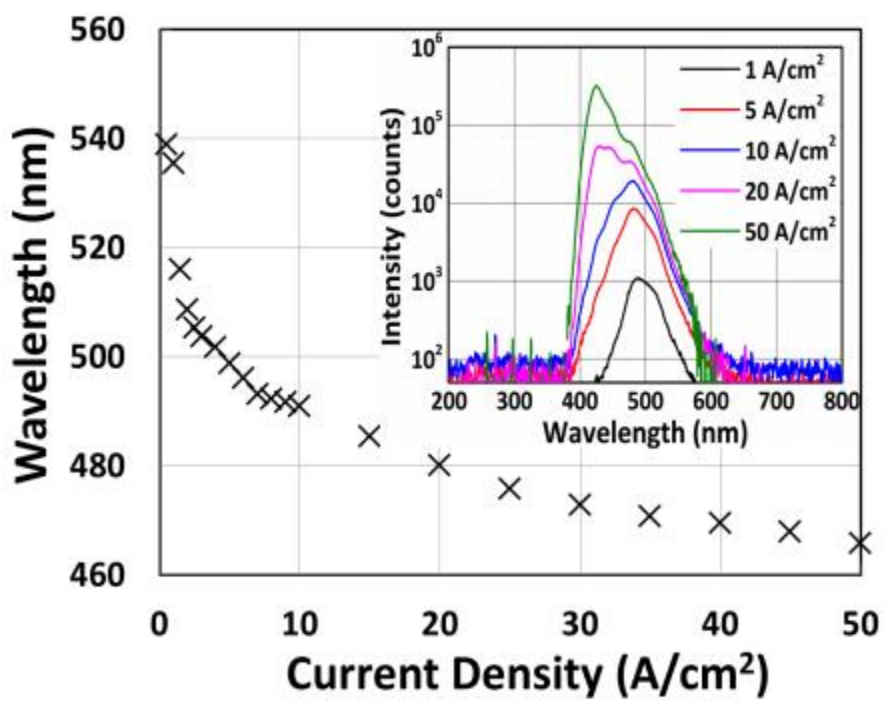




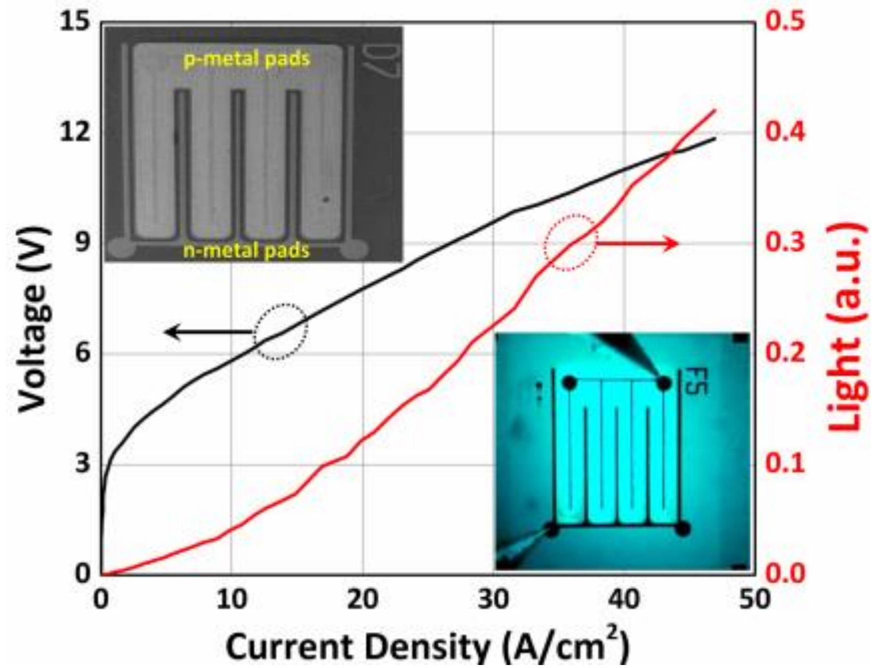
- Silicon and oxygen impurities significantly reduced in sample with AlGaN underlayer
- Mg incorporation increased in sample with AlGaN underlayer
- Leakage current eliminated by addition of AlGaN underlayer

A. Rishinaramangalam, et al., submitted to Appl. Phys. Mat.

Electrically Injected Triangular Nanostripe LEDs



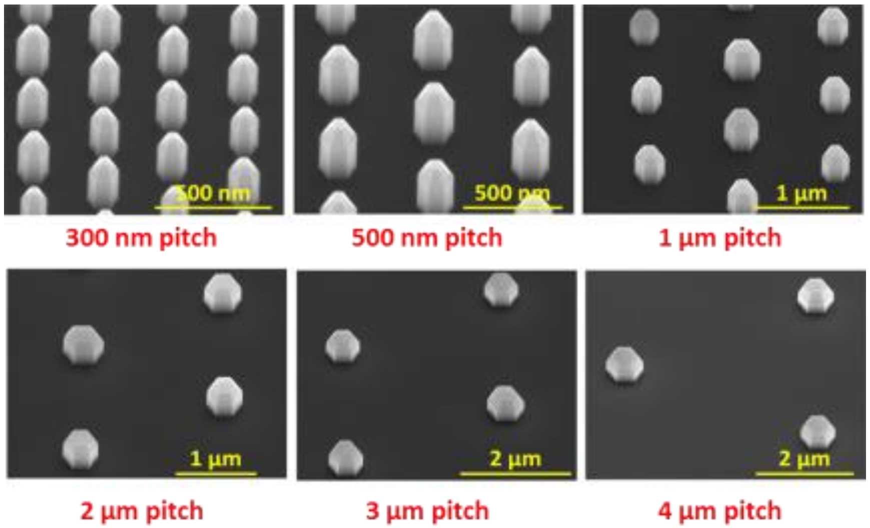
*Unpackaged, on-wafer measurement

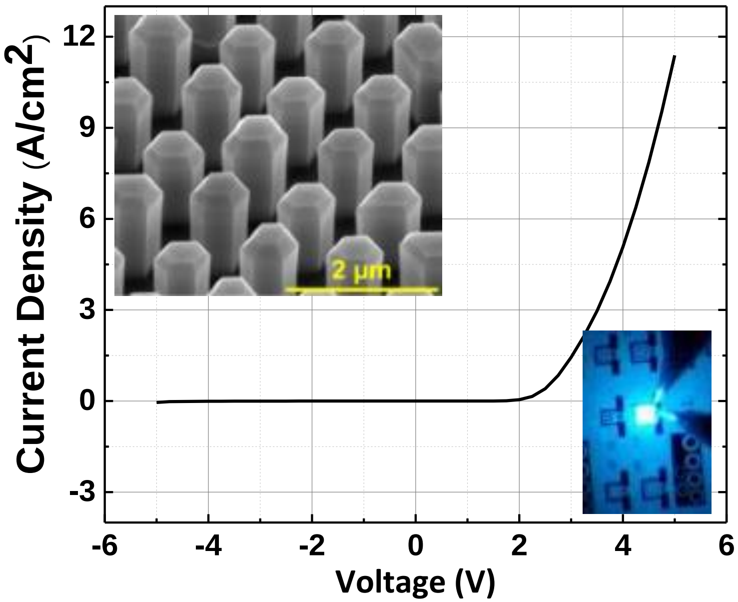


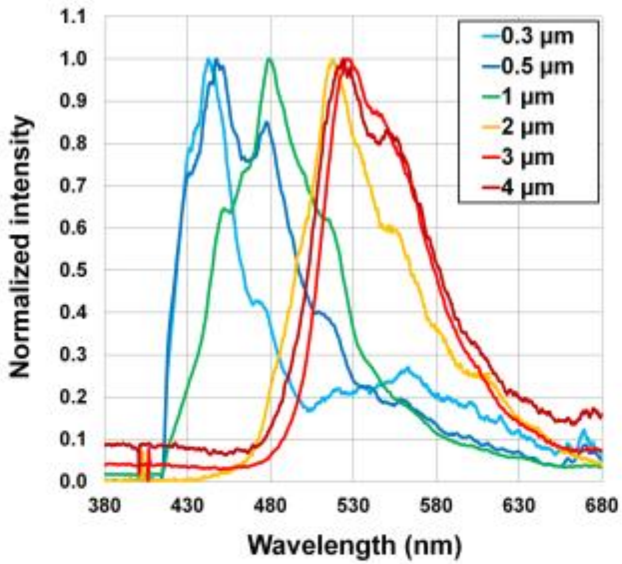
- Spectra exhibit multiple evolving peaks
- Initial blue shift evolves to stable wavelength at higher current
- Broad spectrum related to QW non-uniformities and poor current spreading

A. Rishinaramangalam, et al., Appl. Phys. Express **9**, 032101 (2016)

Electrically Injected Nanowire LEDs



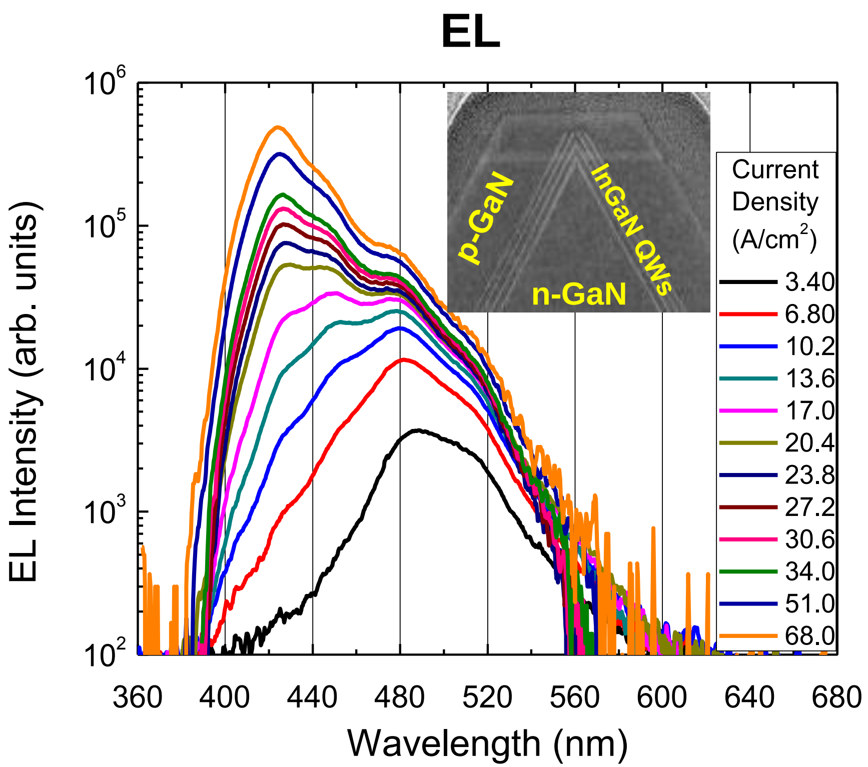


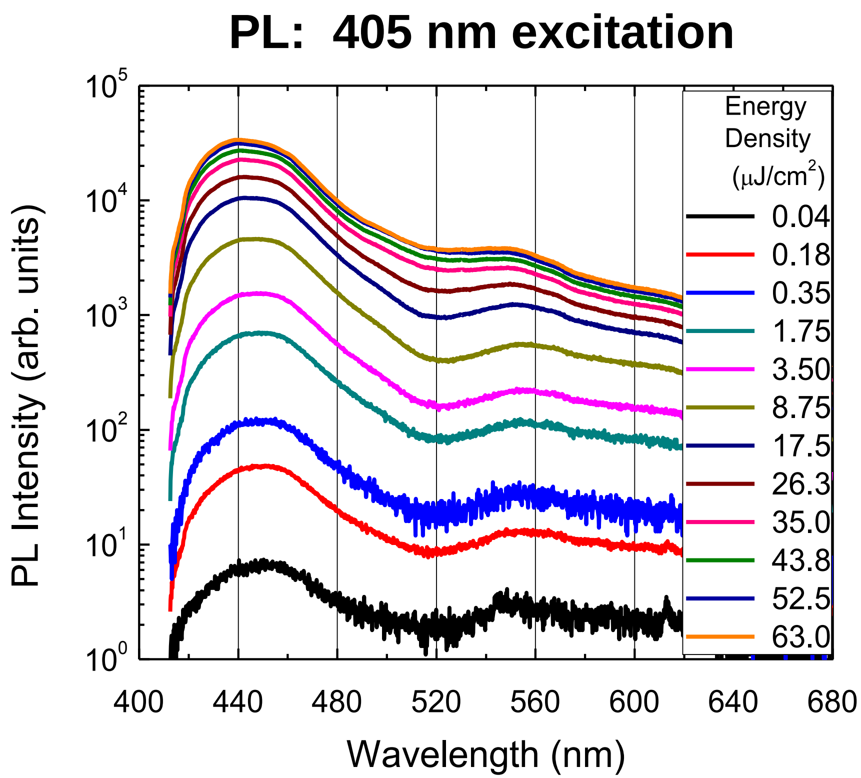


- Single growth of arrays with different pitches
- Red shift as pitch increases
- *Potential for monolithic multi-color LEDs*

M. Nami, et al., submitted to Nanotechnology (2016)

Room-Temperature PL and EL



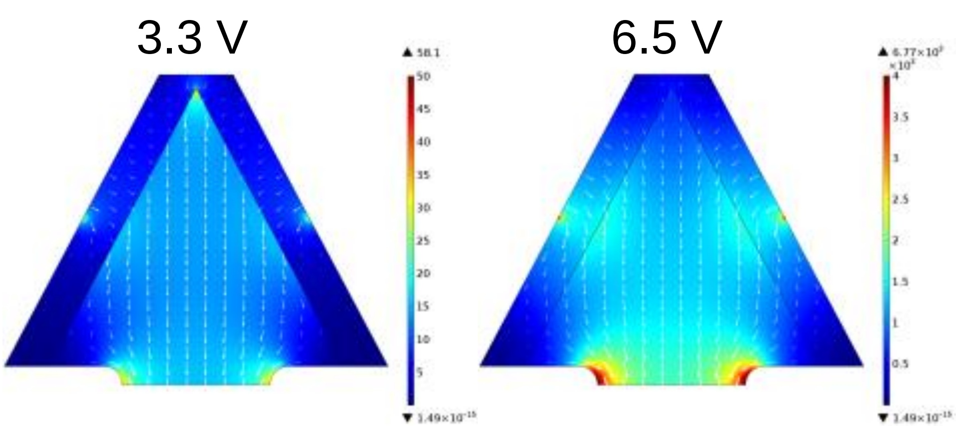


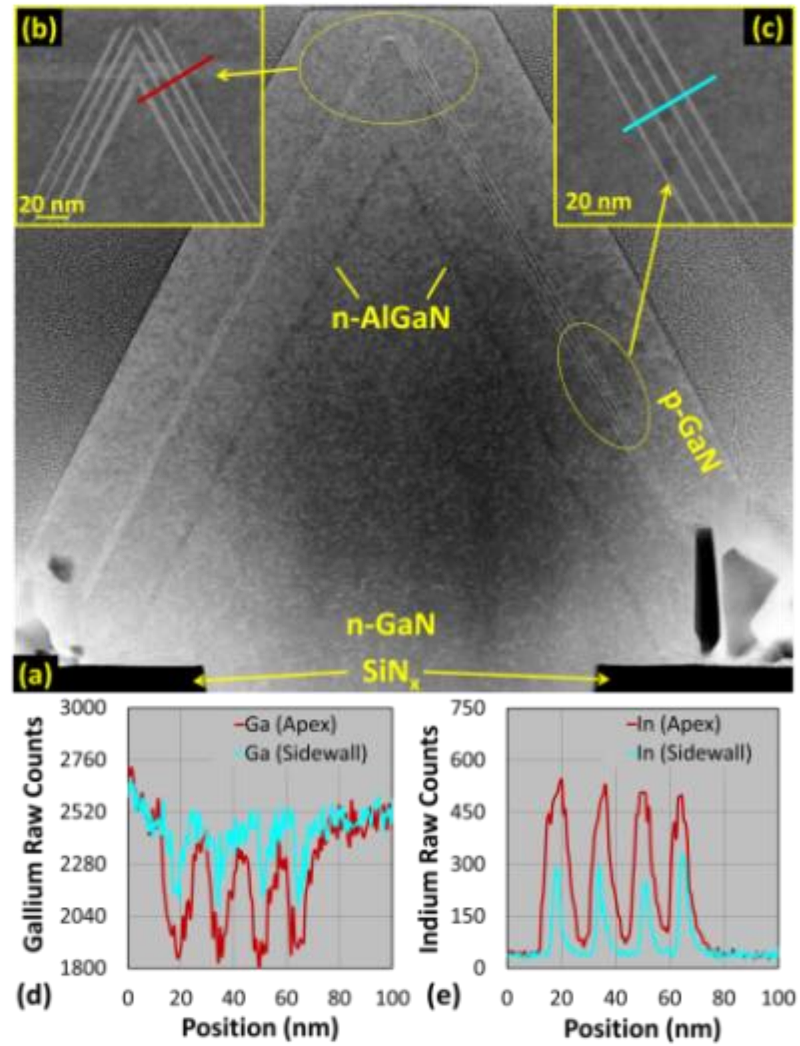
- EL spectra show broad emission and evolving dominant wavelength
- PL spectra show broad emission but no change in shape

S. Okur et al., submitted to Appl. Phys. Letters

TEM and EDS Show QW Non-Uniformities

- Indium composition higher near the apex
- QWs thicker near the apex
- Poor current spreading leads to non-uniform injection, causing change in wavelength with current
- *Longer wavelengths from the apex, shorter wavelengths from the sidewalls*

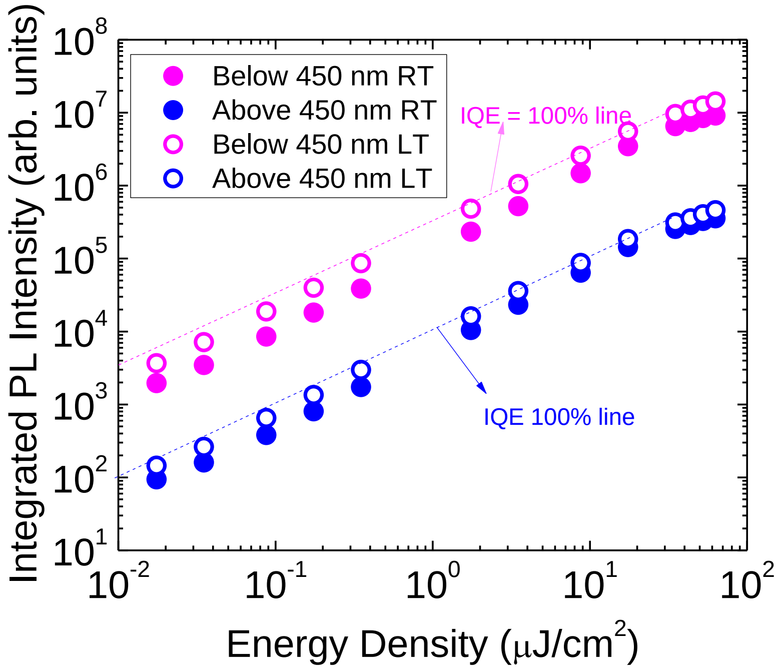


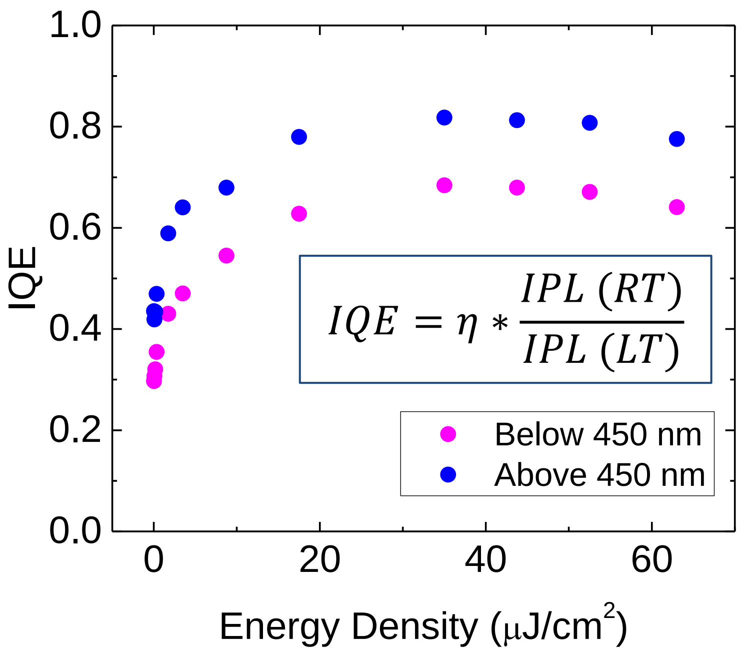


A. Rishinaramangalam, et al., Appl. Phys. Express **9**, 032101 (2016)

S. Okur et al., submitted to Appl. Phys. Letters

Spectrally Resolved Internal Quantum Efficiency





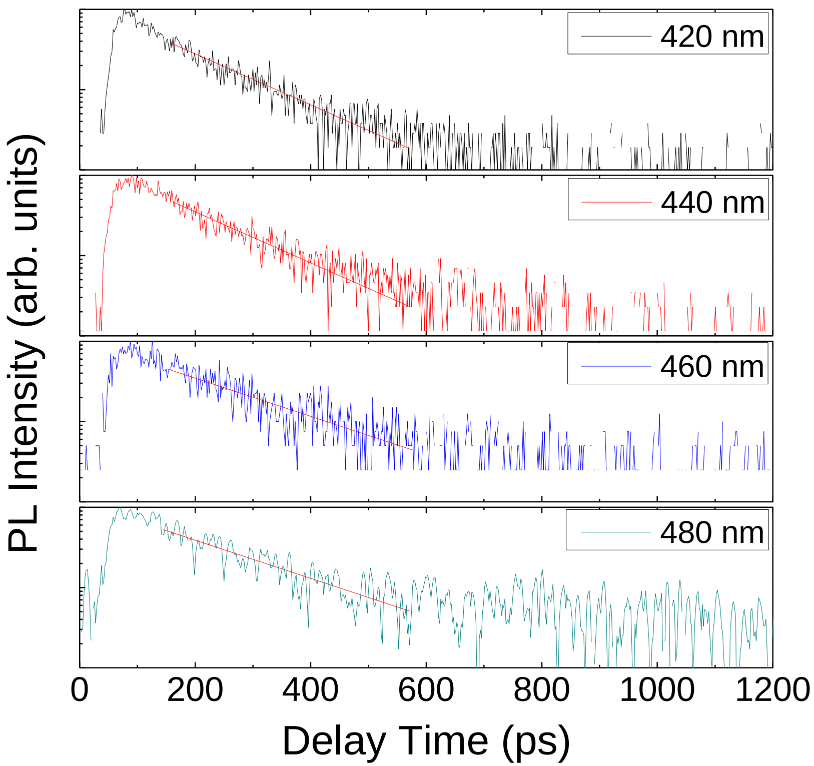
- TEM, EDS, and current spreading simulations indicate longer wavelength emission from the apex and shorter wavelength emission from the sidewalls
- Spectrally resolved integrated PL gives an indication of the IQE in different regions of the stripe (e.g., apex vs. sidewalls)
- ***IQE is higher in the longer wavelength portion of the spectrum!***

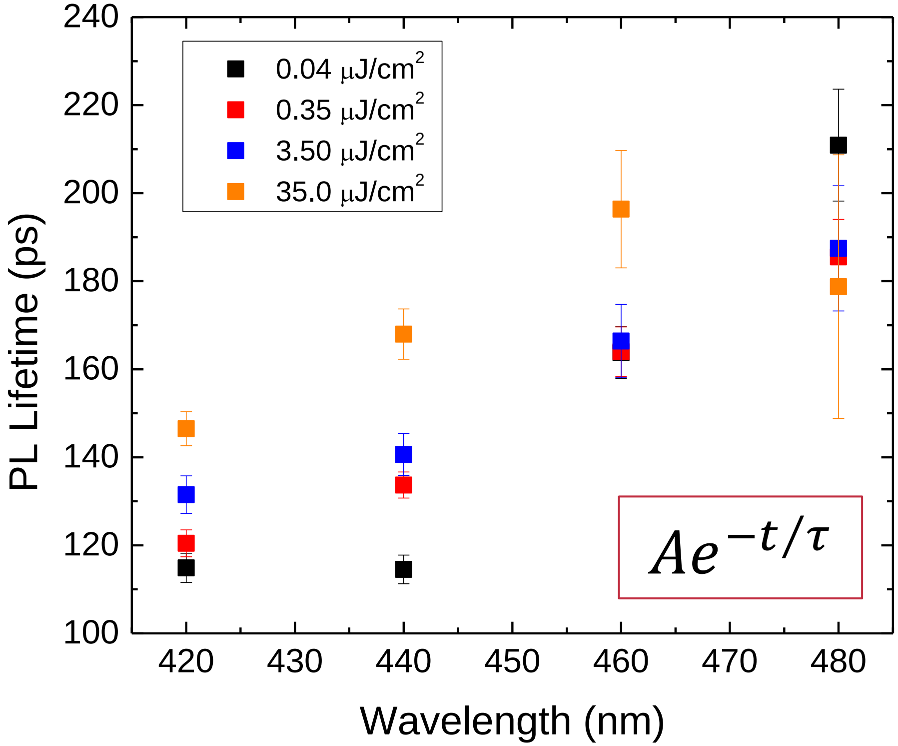
Y. Iwata et. al, J. Appl. Phys. **117**, 075701 (2015).

S. Okur et al., submitted to Appl. Phys. Letters

PL Lifetimes

35 μJ/cm²



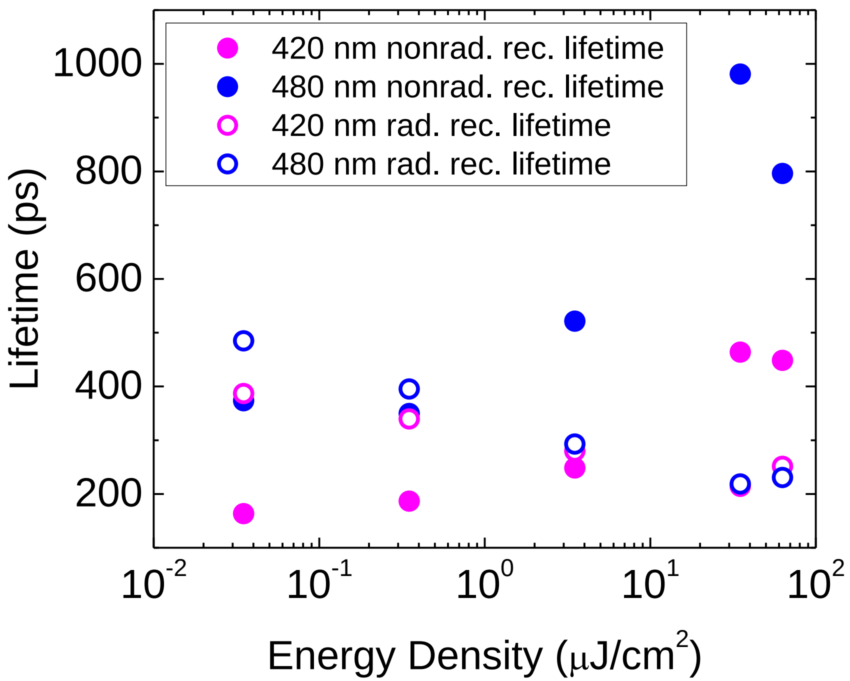


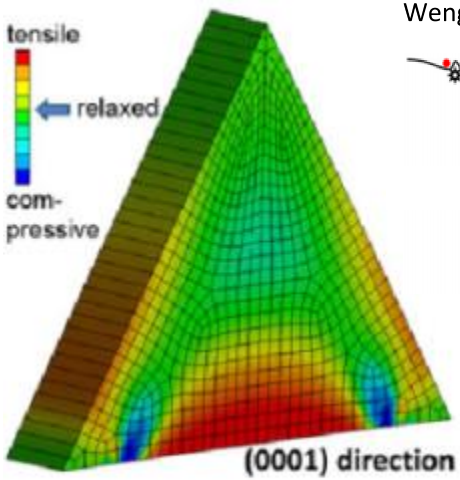
$$Ae^{-t/\tau}$$

- PL transients measured within a 5 nm linewidth around central wavelengths of 420, 440, 460, 480 nm at different excitation levels
- PL lifetime (τ) generally increases as wavelength increases and as injection level increases

S. Okur et al., submitted to Appl. Phys. Letters

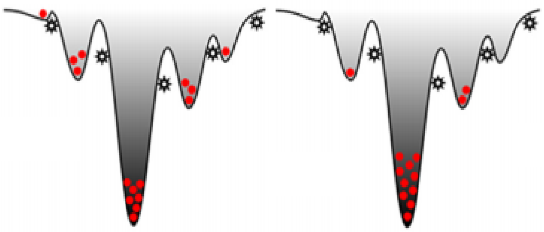
Radiative and Non-Radiative Carrier Lifetimes





I. Tischer et. al, J. Mater. Res. **2**, 7 (2015).

Weng et al., Nanoscale Research Letters (2015)



- Radiative recombination lifetimes for the two central wavelengths are very similar in magnitude
- Non-radiative recombination lifetimes around 480 nm are at least two times larger than those around 420 nm → lower density of defects near the apex, reduced strain near the apex, inhomogeneous indium composition near the apex

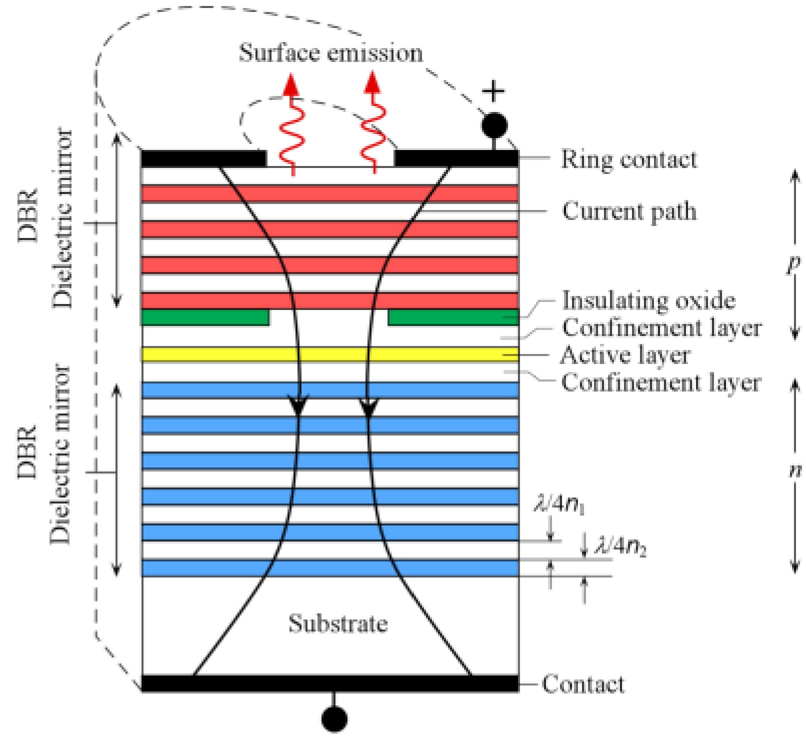
S. Okur et al., submitted to Appl. Phys. Letters

Nonpolar $(10\bar{1}0)$ GaN-Based VCSELs

VCSEL Geometry and Characteristics

S.O. Kasap, Optoelectronics and Photonics (2013)

Invented by Kenichi Iga at the Tokyo Institute of Technology (1977)



- Low power consumption
- Small device footprint
- Circular output beam
- Single-longitudinal-mode operation
- Densely-packed, two-dimensional arrays
- Wafer-level characterization

One challenge is achieving stable and predictable polarization of the output

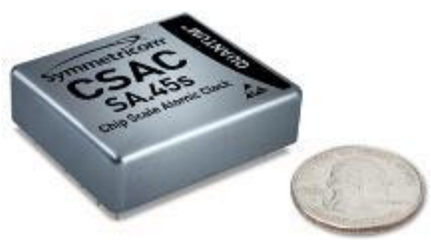
Applications for GaN-Based VCSELs

Projectors

Optical data storage

High-resolution printing

Head-up displays



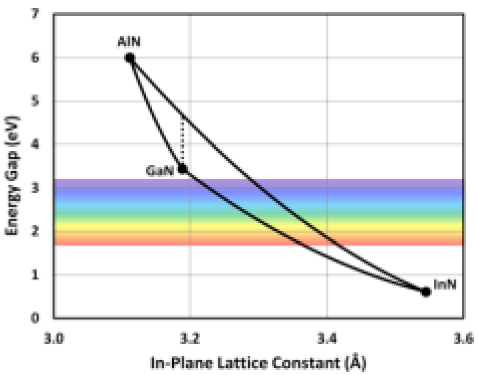
Chip-scale atomic clocks

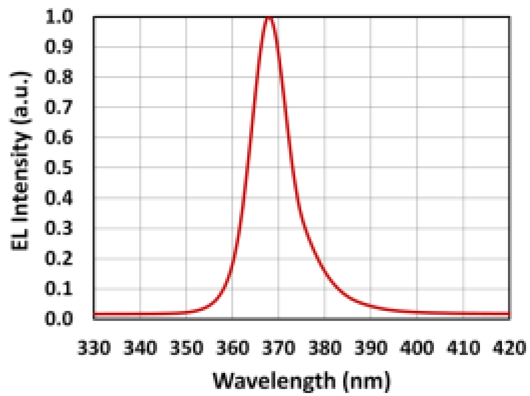
Bio-sensing

Nonpolar GaN-Based VCSELs

Nonpolar GaN enables polarization-pinned VCSELs

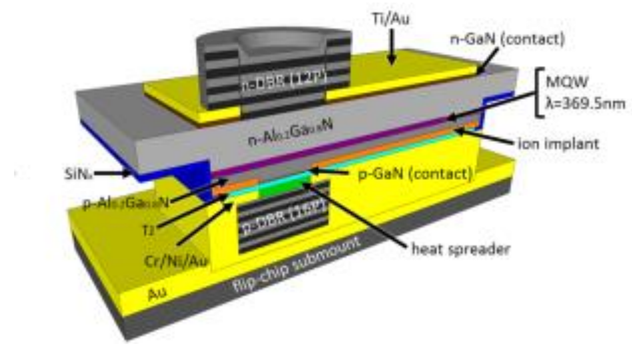
III-Nitrides





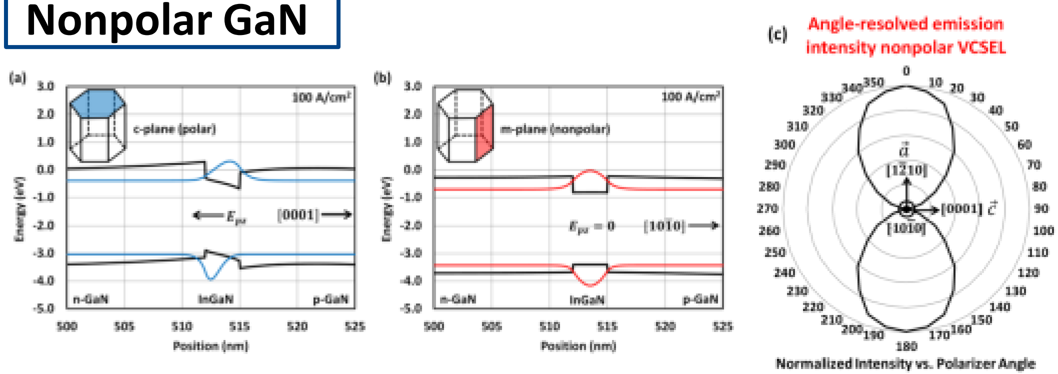
Access to UV wavelengths

VCSELs



Small footprint, low power consumption, single-mode operation

Nonpolar GaN



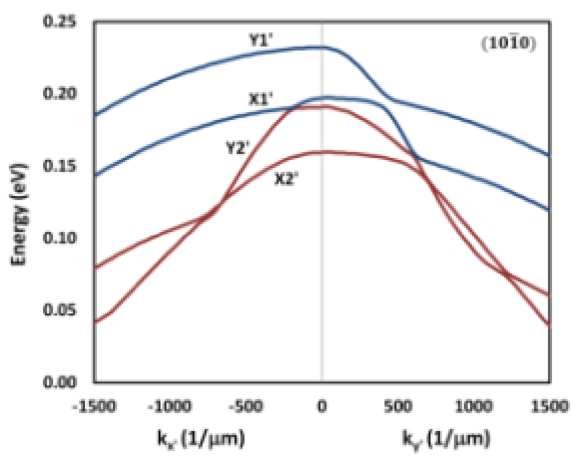
Large optical gain and emission with polarization stability

Flip-Chip Process

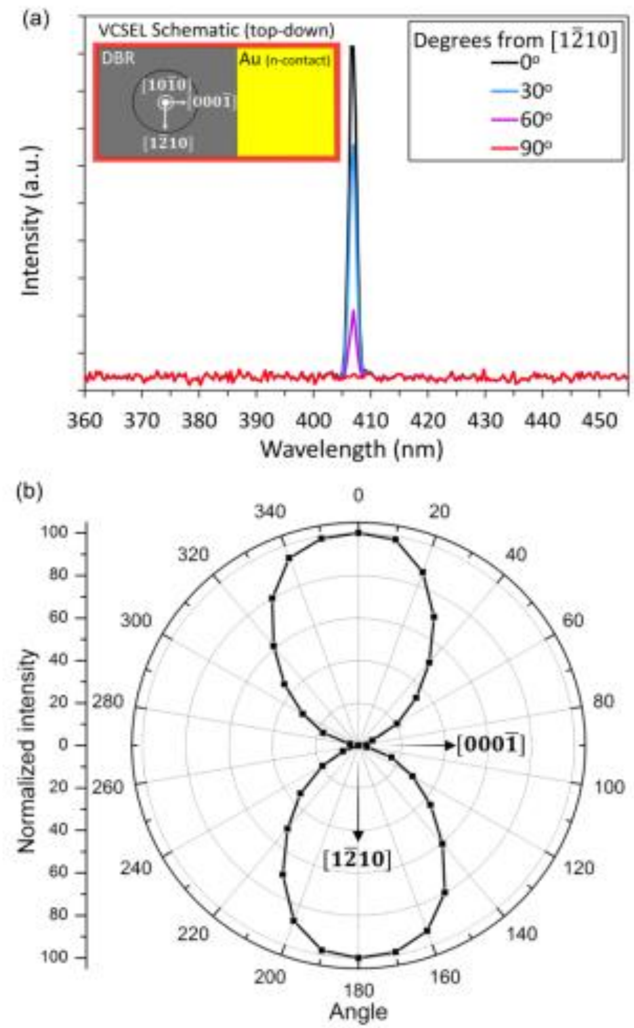
Overcomes key materials challenges

Polarization-Pinned Emission

- Polarization of the light output pinned with $E \perp c$
- Confirmed on multiple devices and multiple wavelengths under a range of injection levels
- Polarization ratio of ~100% measured
- Advantageous for polarization-sensitive optical systems: spectroscopy, atomic clocks, data storage, backlighting



C. Holder, *et al.*, Appl. Phys. Lett. **105**, 031111 (2014)



Angle-resolved emission intensity nonpolar VCSEL

Summary

- Nonpolar/semipolar III-nitrides eliminate effects from polarization-related electric fields
  - High optical efficiency and gain
  - Fast carrier lifetime
  - Polarized emission
  - Lower QCSE - design flexibility
- Demonstrated high-efficiency LEDs with low droop, high IQE, and large modulation bandwidth on free-standing GaN substrates
- Nanostructures exhibit unique properties that may be beneficial for solving some long-standing III-nitride materials issues
- Demonstrated electrically injected nanostructure LEDs and analyzed the QW properties in core-shell structures
- Higher efficiency green emitters may be enabled by growth on strain-relaxed 3D structures
- Nonpolar GaN enables polarization pinned UV and visible VCSELs

Funding Sources

NSF

DARPA

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Thank You!