SAND2008-3727P

Improved InGaN LED Efficiency Using Photonic Crystal Patterning and Surface Plasmon Enhanced Emission

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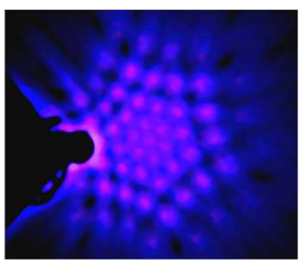
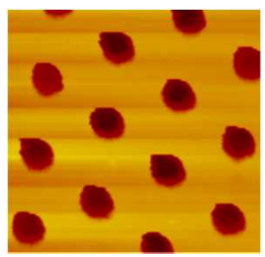
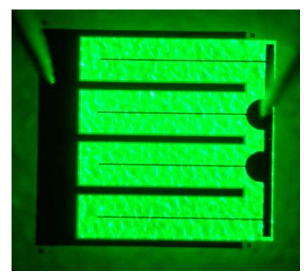
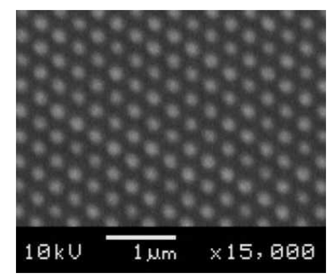




1 μm





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- collaboratored on photonic crystal LED research

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- collaboratored on large area patterning- interferometric lithography

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OUTLINE

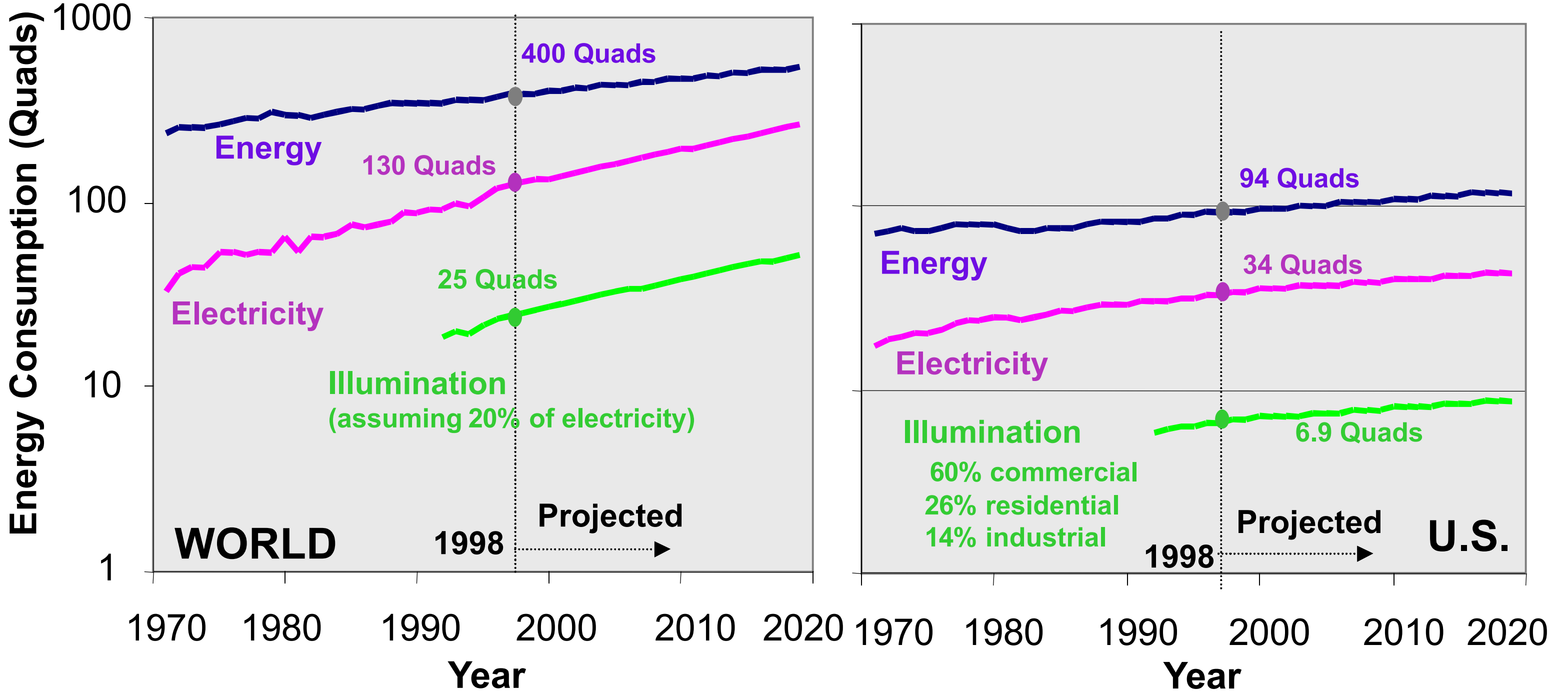
I. Introduction
   A. SSL energy savings potential
   B. InGaN LEDs and SSL
   C. Light extraction in semiconductors

II. Photonic crystals and LEDs
   A. Why use a photonic crystal in an InGaN LED?
   B. Photonic crystal fabrication in GaN
   C. Photonic crystal device results

III. Surface plasmon LEDs
   A. Surface plasmon LED device concept
   B. Photoluminescence data
   C. Electroluminescence data

IV. Summary

Lighting is responsible for a large fraction of energy consumption



- ~20% of electricity consumed is used for general illumination
- This 20% could be reduced to ~10% with 50% efficient SSL
- Reducecd carbon emissions, fewer power plants, money savings

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SSL-LED Targets

- Performance goals (achieve by 2020)
  - Efficacy of 200 lm/Watt
  - Lifetime > 100,000 hours
  - Flux of 1500 lm/lamp
  - Cost of < 2 $/klm
  - CRI of >80
- DOE Goal → reduce electricity for lighting by 50% by 2025

TECHNOLOGY	SSL-LED 2002	SSL-LED 2007	SSL-LED 2012	SSL-LED 2020	Incande-scent	Fluore-scent
Luminous Efficacy (lm/W)	25	75	150	200	16	85
Lifetime (hr)	20,000	>20,000	>100,000	>100,000	1,000	10,000
Flux (lm/lamp)	25	200	1,000	1,500	1,200	3,400
Input Power (W/lamp)	1	2.7	6.7	7.5	75	40
Lumens Cost ($/klm)	200	20	<5	<2	0.4	1.5
Lamp Cost ($/lamp)	5	<5	<5	<3	0.5	5
Color Rendering Index (CRI)	75	80	>80	>80	95	75

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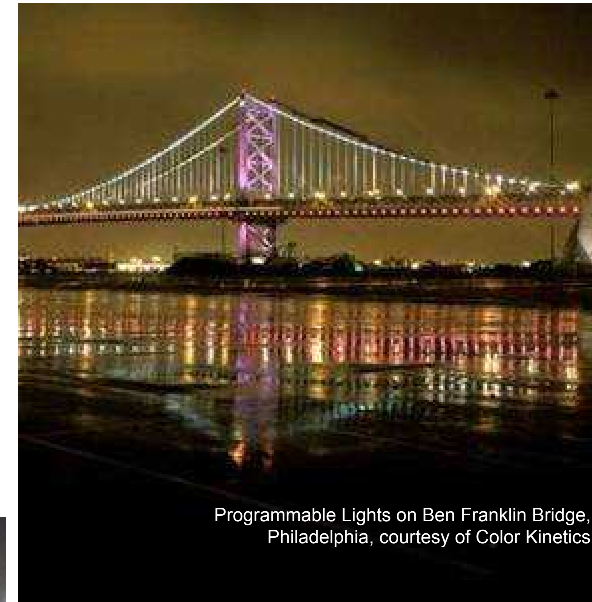
Niche Applications for Ultrabright LEDs

Red LEDs 10X more efficient than red-filtered incandescents



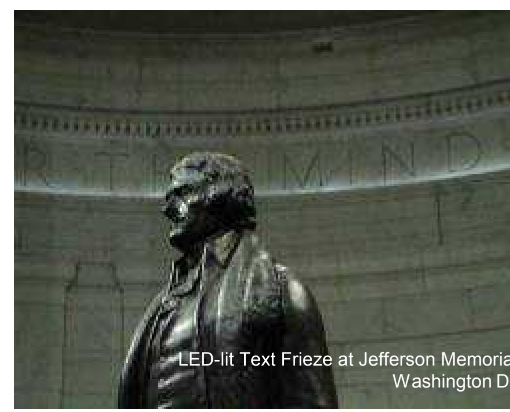
Programmable Lights on Ben Franklin Bridge, Philadelphia, courtesy of Color Kinetics

LED Backlit LCD Displa (SonyQualia)

LED Flash Camera Phone (Motorola E815)

Ford Concept Car Headlights (LumiLeds)

Meeting Room Light KantonalbankLucerne (Osram)



LED-lit Text Frieze at Jefferson Memorial, Washington DC

- Payback time for LED traffic lights is ~ 1 year
- Biggest market is outdoor signage and buliding contour lighting

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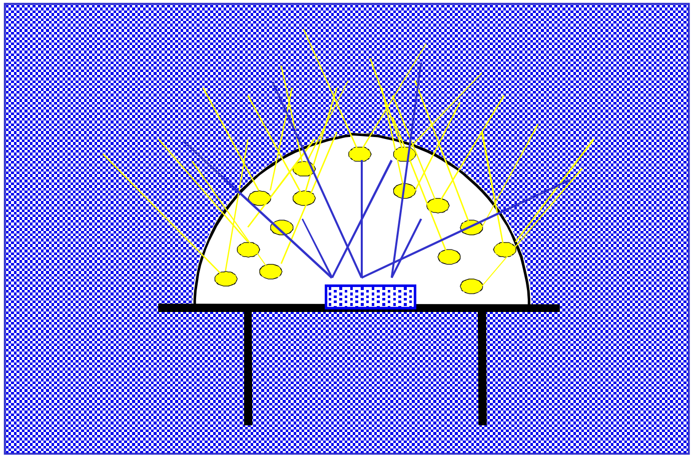
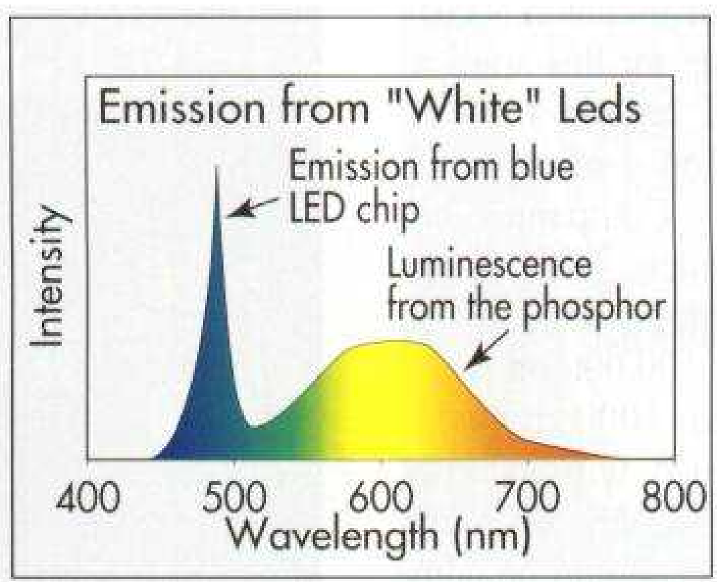
White light LEDs (1): InGaN LED(s) + Phosphor





- Blue or UV LED pumps a phospher
- Loss of energy converting blue photons to red
- Difficult to achieve 200 lm/W ?
- Most mature technology
  - Current products
    - **Large area (40 – 50 lm/W)**
      - **Incandescent – 15 lm/W**
      - **Fluorescent – 90 lm/W**
  - Research results*
    - Small area (131 lm/W)
    - Large area (70 lm/W)
- Difficult to control colors
  - Angular color changes
  - LED to phosphor ratio may change with aging

* Press release → www.cree.com

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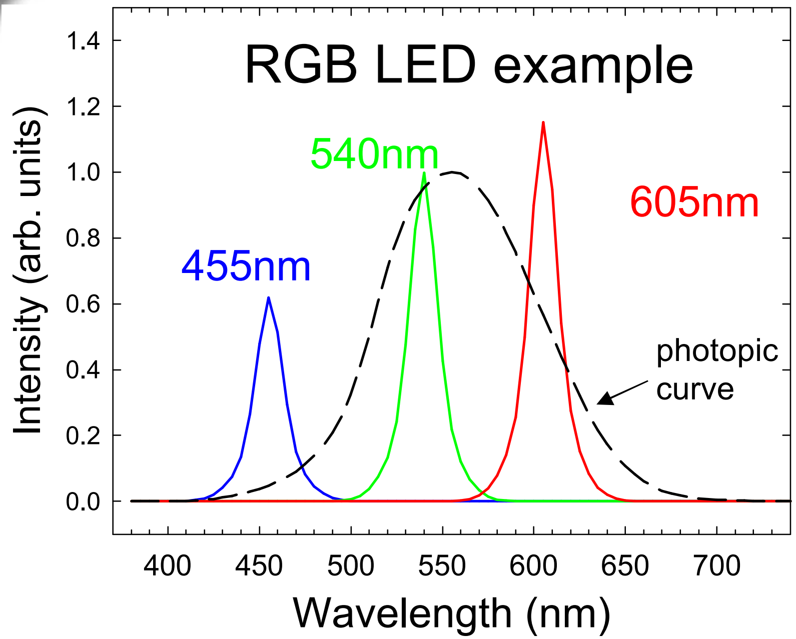
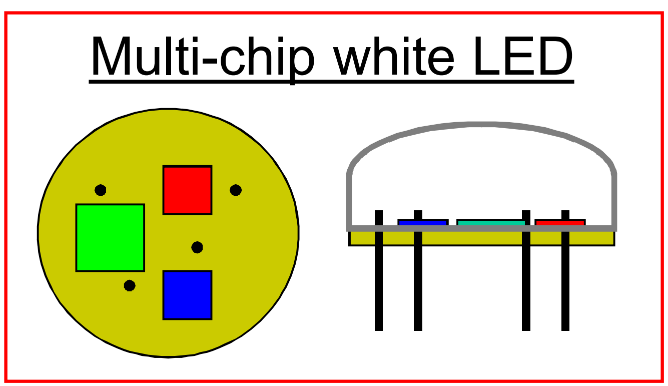
White light LEDs (2): Multi-chip approach





- **Red, green and blue LEDs plus color mixing optics**
- **Could use four or more LEDs to get CRI > 90**
- **RGB example* (shown in plot)**
  - **Assumes 50% WPE LEDs**
  - **CRI 80**
  - **197 lm/W**
- **Potential for highest efficacies**
- **No phosphor losses**
- **Aging of different material systems ?**
- **Control electronics ?**

*Calculated using Y. Ohno's white LED simulator

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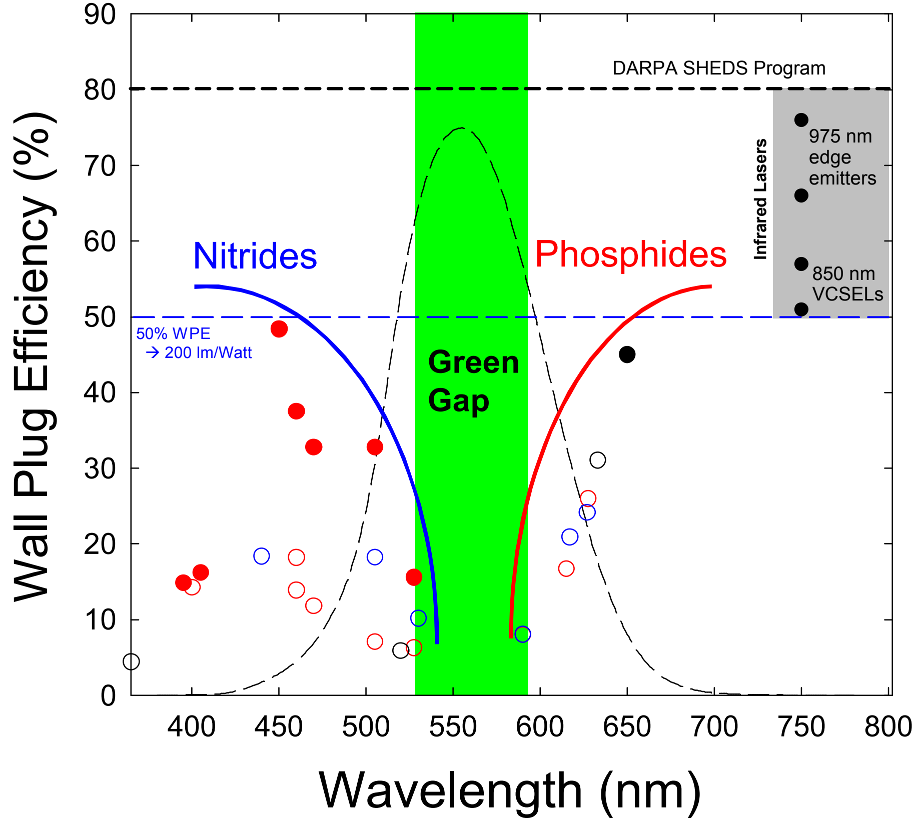
Semiconductor-based light emitters have the potential to exceed 50% efficiency across the visible



- **~ 50% WPE demonstrated for blue and red**
  - **Phosphide-based LEDs***
    - **(45% WPE, 650nm)**
  - **Small area InGaN LEDs†**
    - **(50% WPE, ~460nm)**
- **Lasers in the IR have already demonstrated > 70% WPE**
  - **JDSU (76% WPE, 950nm)**
  - **Alphalight (73% WPE, 975nm)**
- **IQE needs improvement (green and yellow)**
- **Need improvements to light extraction**

* M. R. Krames et al. Appl. Phys. Lett, **75**, 2365 (1999)
† press release → www.cree.com

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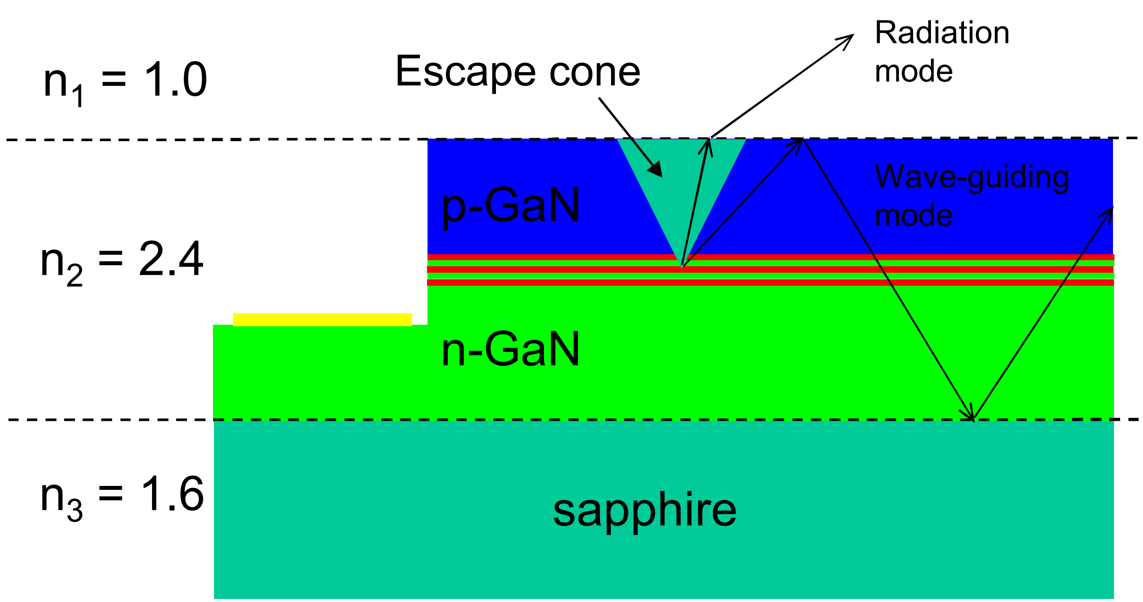
Light Extraction Problem in LEDs

- Photons are trapped inside the high index layer (TIR)
- With high IQE, photon recycling can help extraction
- For lower IQE materials
  - non-radiative recombination is significant
  - more internal reflections → more chance of absorption
  - better to get the photons out with a minimum of reflections
- Without advanced light extraction techniques, LED efficiency is usually quite low



The escape cone is defined by the critical angle:

$$\theta_{CRIT} = \sin^{-1}\left(\frac{n_1}{n_2}\right) = 24.6\,\text{deg}$$

$$\eta_{EXT} = \frac{\textit{escape cone solid angle}}{\textit{total solid angle}}$$

$$= \frac{2\pi\left[1-\cos\left(\sin^{-1}\left(\frac{n_1}{n_2}\right)\right)\right]}{4\pi}$$

$$\sim \frac{n_1^2}{4n_2^2} = 4.3\% \quad \text{(per surface)}$$

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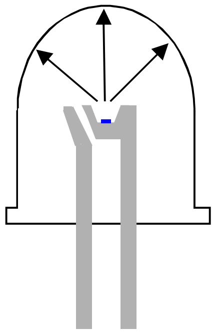
Methods of light extraction

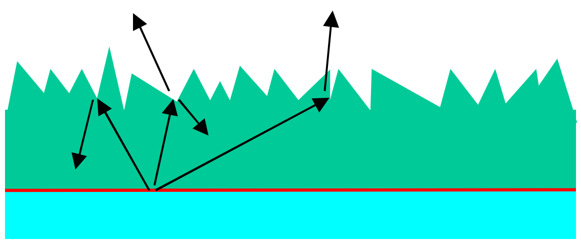
Epoxy encapsulation

- Reduce index step from Semiconductor to air
- Create a favorable geometry
- High index encapsulants are desired
- Issues of transparency and thermal degradation



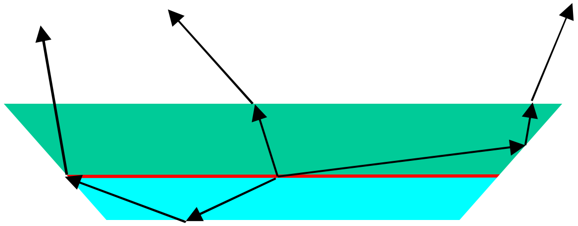
Surface Texturing

- Random scattering at surface
- Some fraction of light scatters out
- light scattered back inside can be absorbed



Chip Shaping

- Modify chip to improve light extraction
- Angle chip sides to redirect waveguided light
- Long path length → possibility for absorption



Photonic Crystals...

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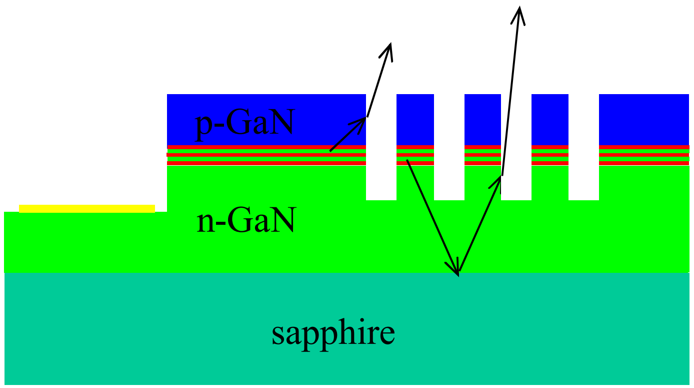
Photonic Crystals for Light Extraction

- Etch a photonic crystal into the surface of an LED
- Photonic crystal can improve extraction two ways
  1.) Inhibit emission into waveguiding modes
     - Requires very small lattice constant (~ 100nm)
     - 2D photonic bandgap in the plane
  2.) Bragg scatter wavguided light out of semiconductor
     - Relaxed lattice constants (200 – 500 nm)
- Immediate diffraction of light (not random scattering)
- Eliminate encapsulant
- Increase source brightness

Light extraction with a photonic crystal



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Characteristic hole sizes for PX-LEDs

- First order gratings will be difficult to fabricate in GaN
- Diameter = 0.6 X lattice constant (d = 0.6 · a)
- Hole sizes are smaller for shorter wavelengths (or larger indices)

1.) InGaAs LED - 980 nm emitter		period (a)	diameter (d)
Requirements for λ →	$(\lambda_0/2n)$ 1st order	144 nm	86 nm
fixed at 980 nm	(λ_0/n) 2nd order	288 nm	173 nm
(n = 3.4)	$(2\lambda_0/n)$ 4th order	576 nm	346 nm

2.) InGaN LED - 460 nm emitter		period (a)	diameter (d)
Requirements for λ →	$(\lambda/2n)$ 1st order	96 nm	58 nm
fixed at 460 nm	(λ/n) 2nd order	192 nm	115 nm
(n = 2.4)	$(2\lambda/n)$ 4th order	383 nm	230 nm

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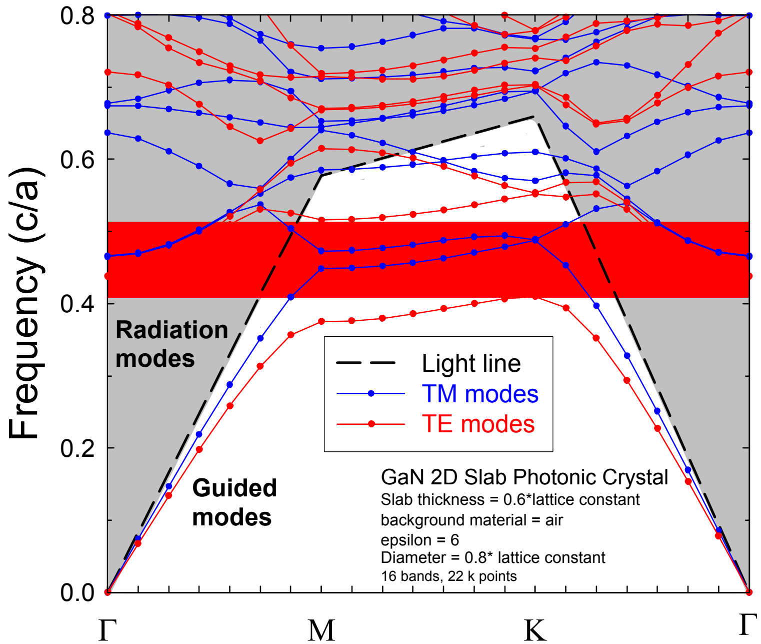
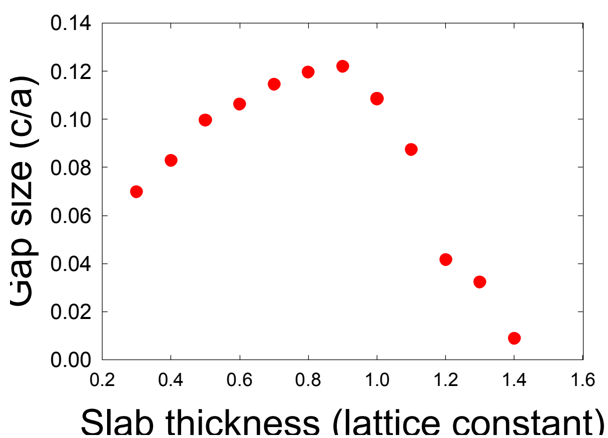
GaN thin slab band structure calculations





- Band structure calculated using MIT photonic bands software (also Optiwave)
- Gap only for TE modes for most structures
- GaN slab suspended in air with holes etched all the way through
- Triangular lattice of holes
- TE-like gap from 0.41 to 0.51 c/a
- For a 450 nm LED
  - gap is centered at 450 nm for a=207 nm, d=165.6 nm
  - TE-like gap 406 nm → 504 nm
- Calculation assumptions:
  - Hole diameter = 0.8* lattice constant
  - Epsilon = 6 for GaN
  - Background material is air
- Gap for thin slabs only
  - Slab must be less than 400 nm
  - This is the thinnest GaN slab we have made

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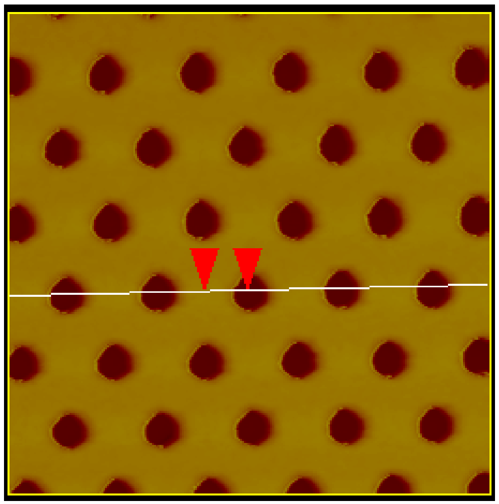
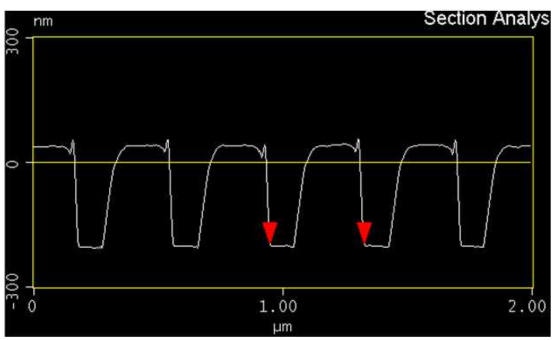
E-beam lithography for GaN Photonic Lattices

Photonic Lattice in GaN





- Electron beam patterning is slow
  - ~ 1 hr for ea. 1 x 1 mm^2.
  - Demonstrate PX-LEDs
- Wafer scale patterning
  - Large area LEDs
  - Production
  - Accelerate research
  - Large area patterning techniques
    - Interferometric lithography (UNM)
    - Nano-imprint lithography
    - Deep UV lithography

d ~160nm
a ~ 380nm
r/a ~ 0.21

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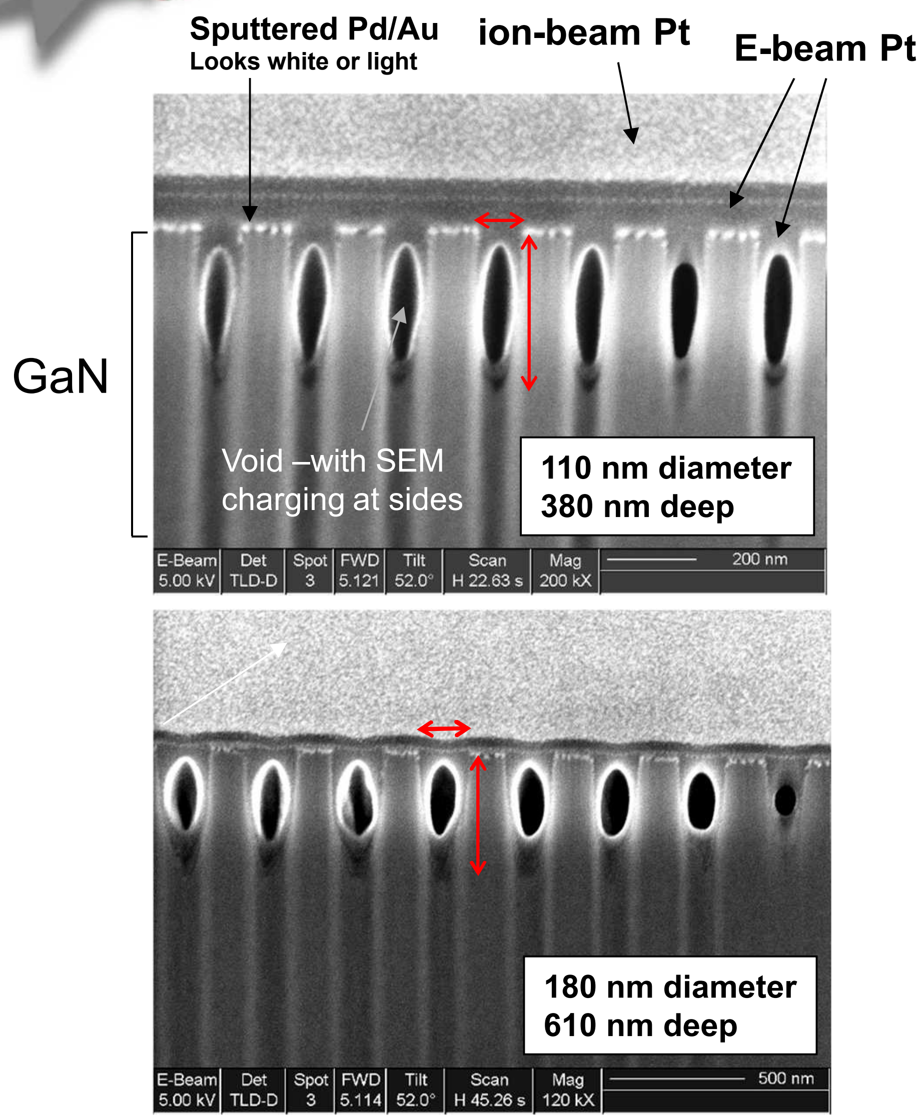
Photonic Crystal Fabrication in GaN



- These images represent the best etching we have done to date.
- Top Image
  - 205 nm lattice constant
  - 110 nm in diameter
  - 380 nm deep
  - 3.45 : 1 aspect ratio
- Bottom Image
  - 315 nm lattice constant
  - 180 nm in diameter
  - 610 nm deep
  - 3.39 : 1 aspect ratio
- FIB-SEM used for characterization
  - Images taken with a tilt of 52˚
  - Note that scale bars are different in the two images
- Very straight sidewalls- particularly for the 110 nm diameter holes
- Etch mask has been removed

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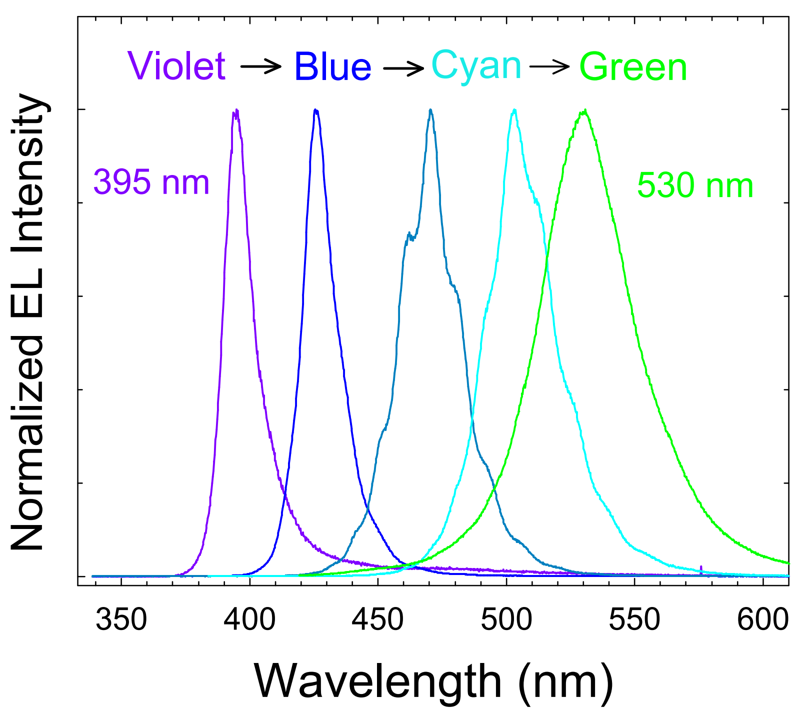
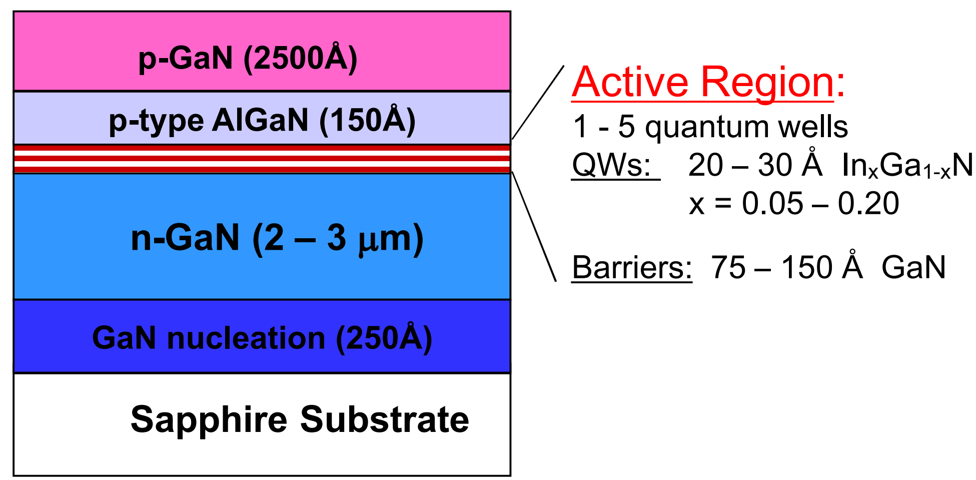
Sandia InGaN LED Development

- Sandia LEDs grown using one of two Emcore D-125 reactors
- LEDs from near UV (380 nm) to green (530 nm)
- Also developed deep UV LEDs (237 nm – 300 nm)
  - Based on AlGaN with high Al content
- Working to improve green LED efficiency





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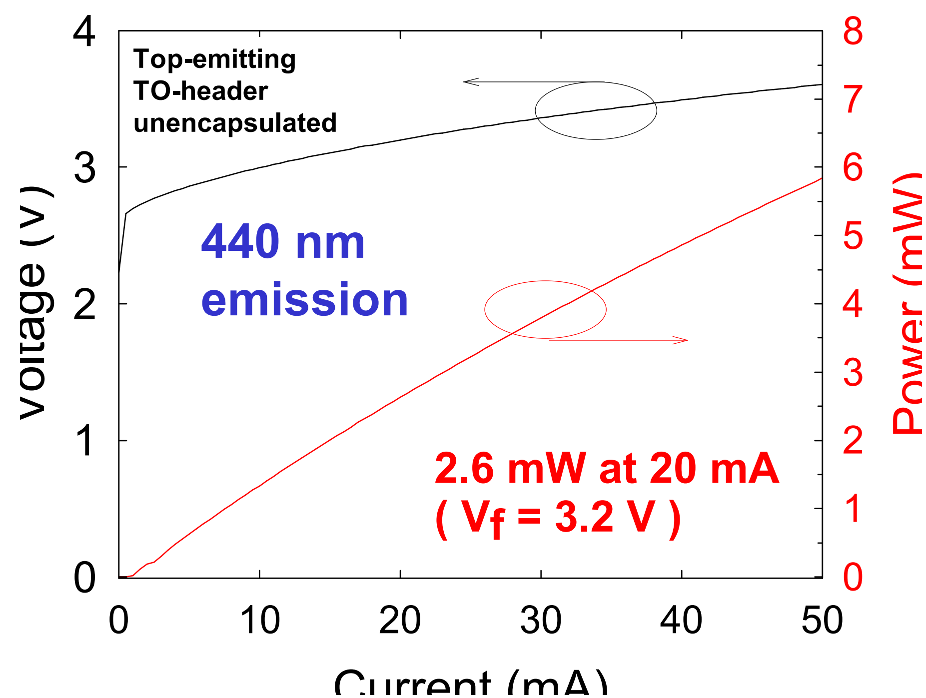
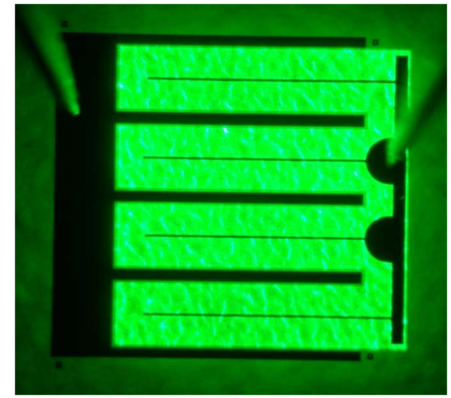
Sandia InGaN LED Development

- Sandia uses research grade packaging
  - TO-headers with no encapsulation
- Top-emitting LEDs with a transparent contact are used as a metric for LED development.
- Encapsulation can show 2X increase in power
- Developed a simple flip-chip process (2X power)





Sandia top-emitting green LED with transparent contact

Sandia flip-chipped InGaN LED on TO-header

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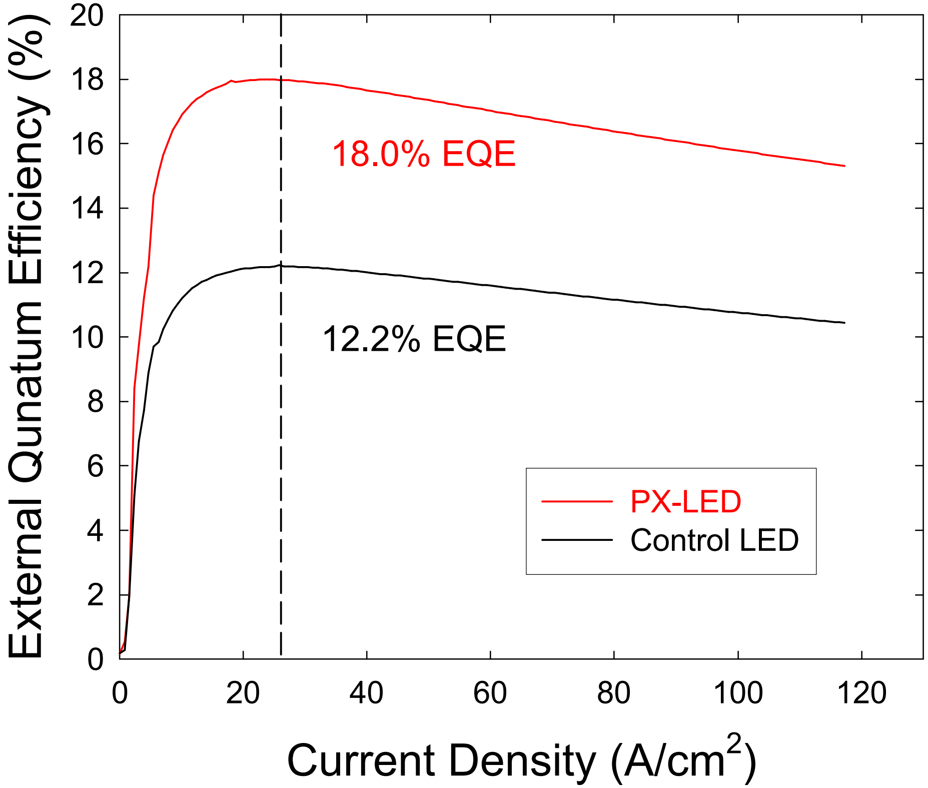
Efficiency of small area InGaN PX-LEDs



- Small area LEDs fabricated using e-beam lithography for patterning
- LEDs were mounted on TO-Headers and left unencapsulated
- Total light emission was measured using a calibrated integrating sphere.
- low current densities (25 A/cm^2)
  - PX-LED →18.0% EQE
  - Control LED →12.2% EQE
  - 1.48 X increase in power
- Higher current densities (100 A/cm^2)
  - PX-LED →15.8% EQE
  - Control LED →10.8% EQE
  - 1.46 X increase in power
- LEDs for SSL will be run at high current densities

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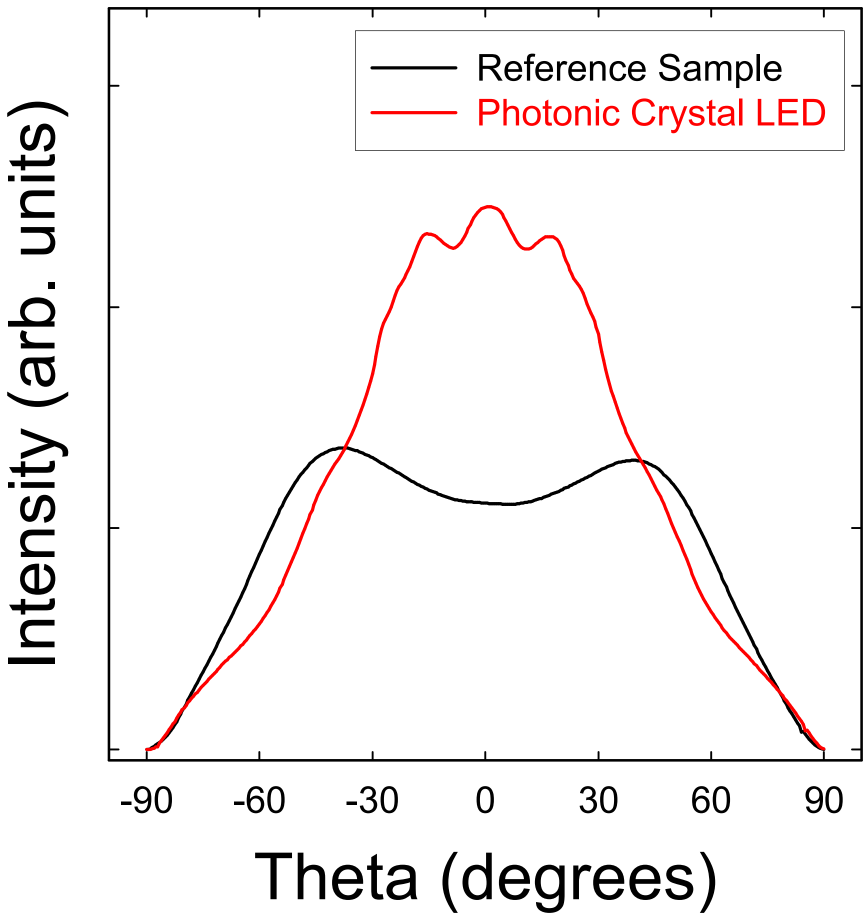
PX-LED Fabrication : Enhanced brightness from PX-LEDs



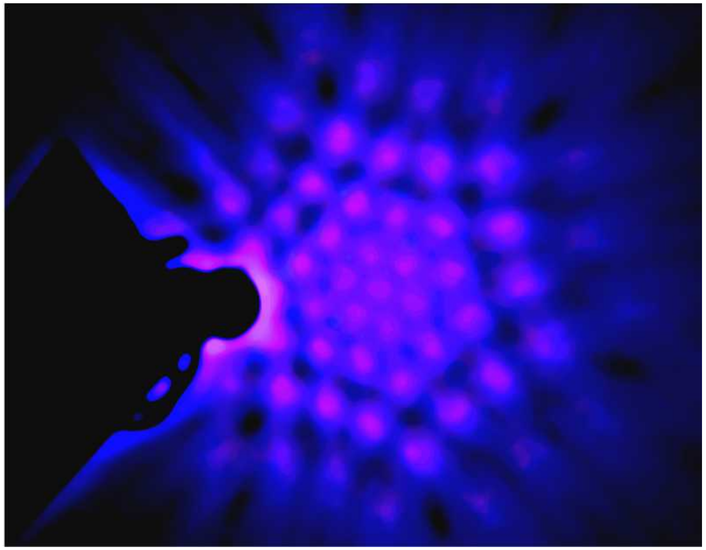
- Angular measurements were performed on a large number of samples
- Angular data could be used to rapidly measure output power without dicing and packaging
- LEDs mounted on TO-headers were compared to devices on wafer
- Photonic crystal LEDs can be used to direct more light in the forward direction and increase source brightness.
- Far field patterns are strongly modified for PX-LEDs
- Photonic crystal is diffracting waveguiding modes into the escape cone

PX-LED Far Field Patterns

- Small area photonic crystal LEDs
- LEDs were mounted on TO-headers
- Emission pattern was projected onto a piece of white paper
- Far field patterns are strongly modified for PX-LEDs
- Photonic crystal is diffracting waveguiding modes into the escape cone

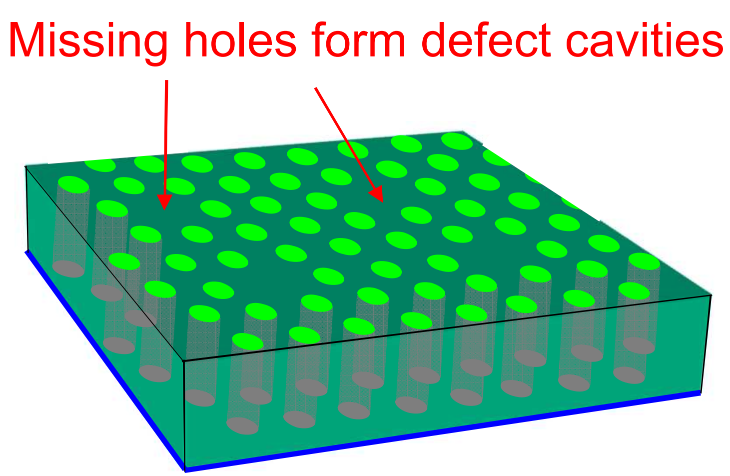
Control LED – No Photonic Crystal

LED with Photonic Crystal



PX-LED with defect cavities

Planar microcavity plus in-plane defect cavities



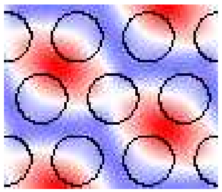
PX-LED semiconductor slab with a an array of defect cavities

- Design a photonic lattice with an array of missing holes
- Combined with a planar microcavity will form a 3D cavity
- FDTD calculations indicate that very high extraction should be possible
- First order grating probably required
    - 150 nm pitch
    - In-plane photonic bandgap
- Resonant injection into defect cavities
    - Bypasses issues of current leakage
- Very promising advanced design

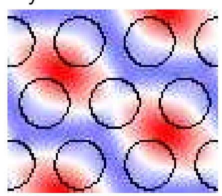
Defect cavity electric field calculations

Simple triangular lattice:

E_x of TE band 1

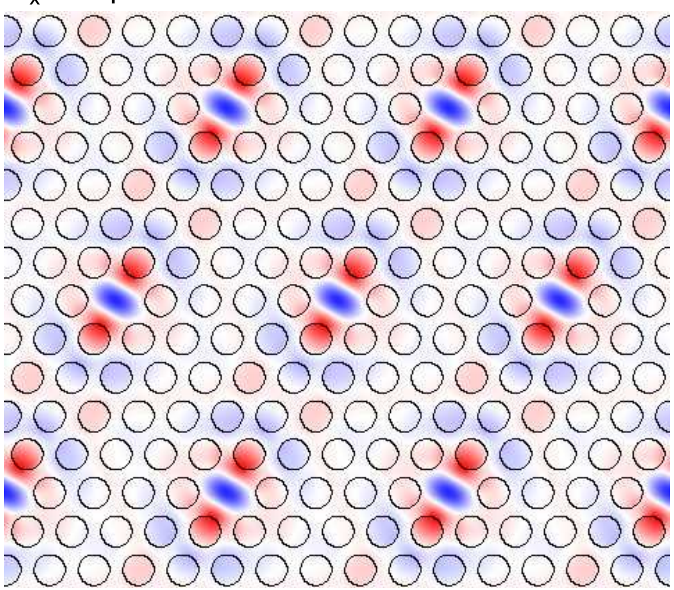


E_y of TE band 1



Arrays of Defect Cavities:

E_x component of TE band number 26



- Calculate the spatial Electric field distribution for defect cavities in GaN
- Calculated using MIT photonic bands software (also using Optiwave)
- Triangular lattice of holes with a missing hole every 5 lattice constants
- For a simple triangular lattice the field extends across many lattice constants
- Defect cavities do a good job of confining the radiation for modes in the gap
- Lateral propagation is minimal

<u>Calculation parameters</u>
Triangular lattice of air holes etched in GaN
Epsilon of GaN = 6.0
Defect cavity every 5 lattice constants
Diameter/lattice constant = 0.7
Two dimensional calculation

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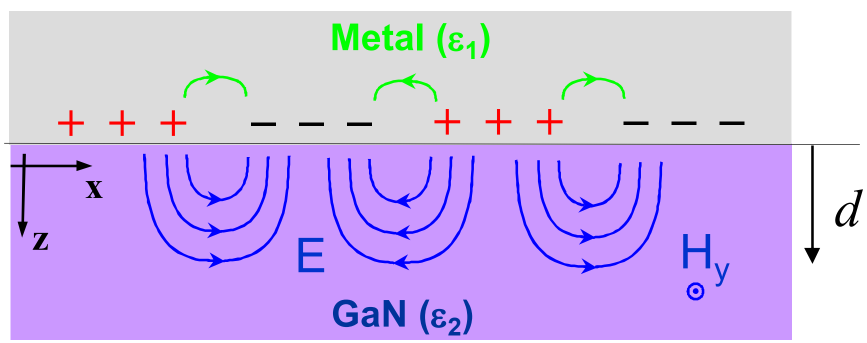
Introduction to Surface Plasmons

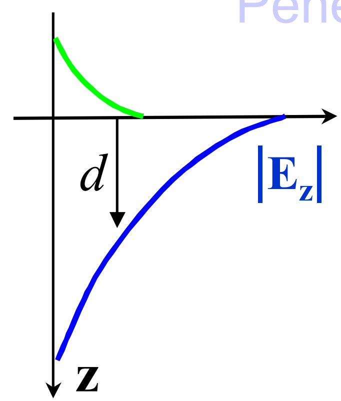
Bulk Plasmon → Collective oscillation of electronic charge in a material

Surface Plasmon →

- Combined EM wave and surface charge oscillation
- Excitation confined to the interface
- Exponential decay of electric field from the interface
- Transverse magnetic in character
- Mixed longitudinal and transverse E-field
- ε'_1 and ε'_2 must have opposite signs



$$E = E_0^{\pm} \exp\left[ik_x x \pm k_z z - i\omega t\right]$$

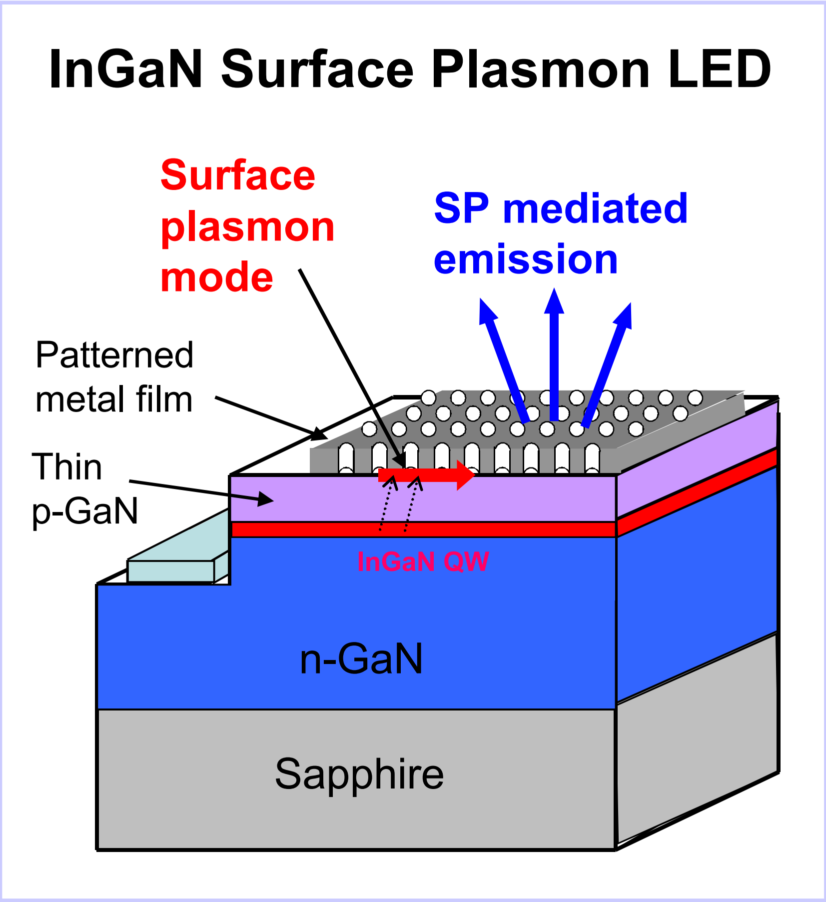


Penetration depth

$$d = \frac{\lambda}{2\pi}\left[\frac{\varepsilon_{dielectric} - \varepsilon_{metal}}{\left(\varepsilon_{dielectric}\right)^2}\right]^{\frac{1}{2}}$$

for a GaN/Ag interface
d = 400 Å

Surface Plasmon Light Emitting Diodes



Device Design:

<u>Step one</u> – coupling of QW to SP mode:

- Single QW close to air interface
- Thin p-GaN (100 – 500Å)
- Match SP energy to QW emission

<u>Step two</u> – extraction of SP mode:

- Patterned metal film for extraction
- Metal also provides current injection

Advantages of Design:

- Improved IQE (green LEDs)
  - rapid coupling from QW to SP
- Same design improves IQE and extraction
- Enhanced IQE using existing materials

Primary Challenges:

- QW placement near surface
- Design of patterned metal film

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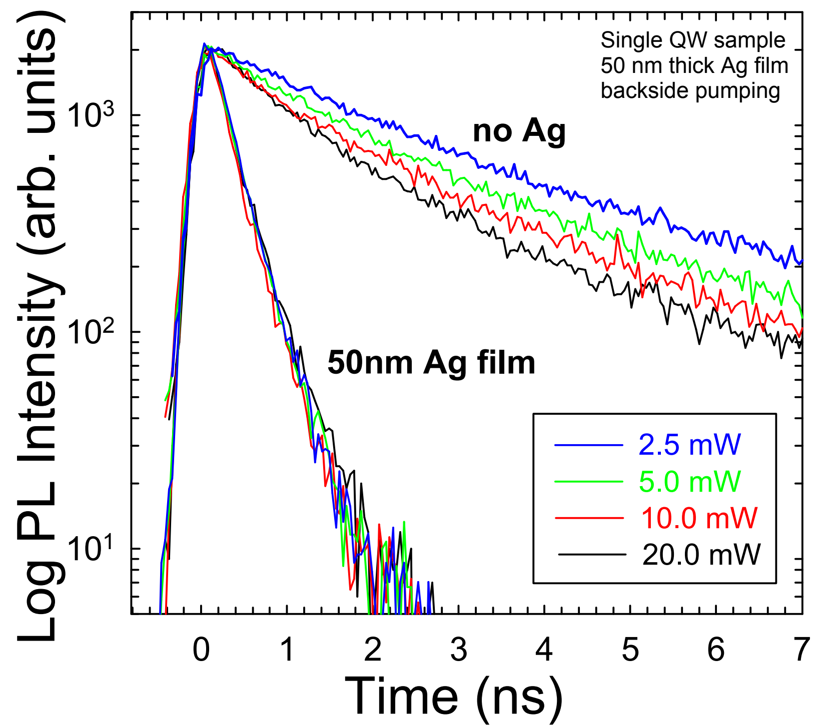
Time-resolved Photoluminescence

TRPL Measurements:

- Single quantum well samples- 10nm GaN cap
- Various metal films were deposited (Ag, Pt, Ni, Au)
- For data here, $_{Ag}\tau$=0.28ns and $_{noAg}\tau$ =2.75ns
- Shows rapid coupling from QW to SP modes
- Measurements were performed using backside pumping and collecting through the sapphire substrate
- Significant changes in PL decay time are possible
- PL lifetime can be longer or shorter depending on surface plasmon extraction.

PL decay measurements



Increase spontaneous rate → energy is effectively coupled to SP modes

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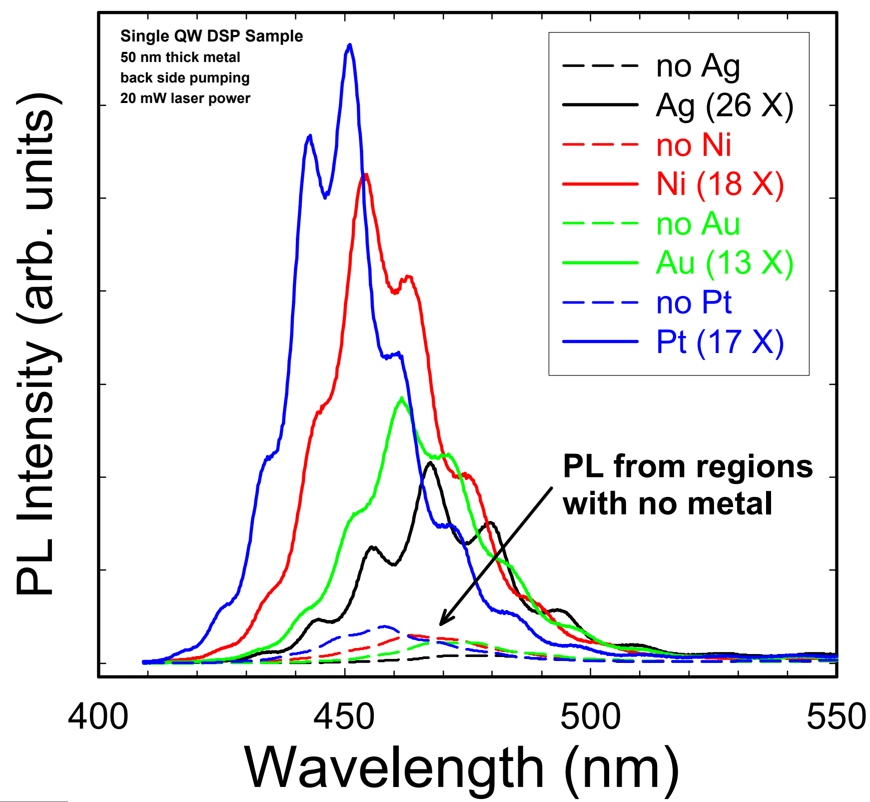
Time-Integrated Photoluminescence

TIPL Measurements:

- Single quantum well samples- 10nm GaN cap
- Various metal films were deposited (Ag, Pt, Ni, Au)
- Peak PL enhancements up to 26 times were observed
- Measurements were performed using backside pumping and collecting through the sapphire substrate
- Surface plasmon enhancements were greater at higher pump densities
- Scattering due to surface roughness improves coupling of light out of sample

PL using different metals



Increase in total PL intensity → light is effectively extracted from SP modes

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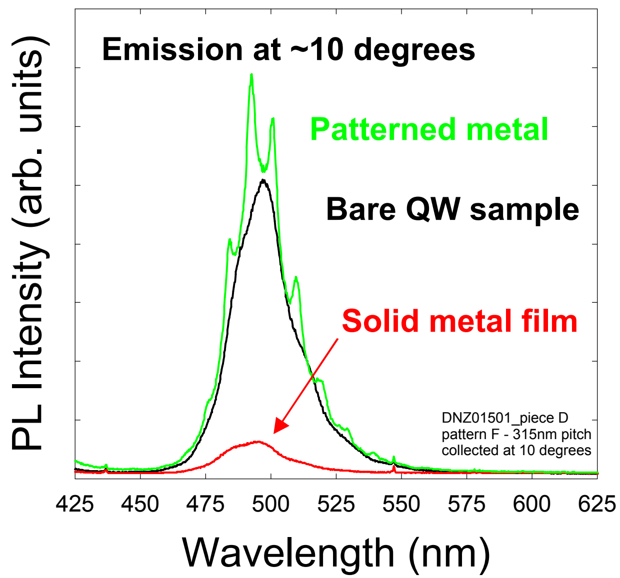
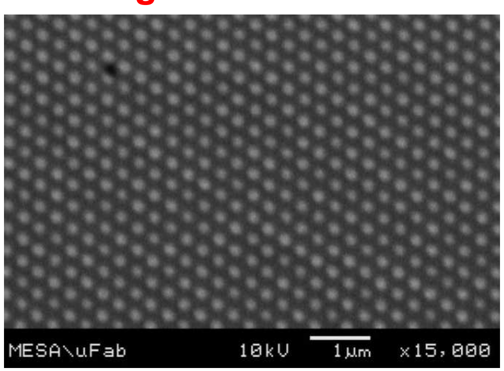
Photoluminescence from patterned samples

PL from pattern Ag InGaN QW sample



Patterned Ag disks on InGaN QW sample



- **This sample shows decreased emission due to surface plasmon effects.**
- **QWs couple to SP modes but light cannot escape.**
- **Data shown is angularly resolved PL data collected using a fiber position over sample.**
- **Regions with patterning show an increase in PL intensity.**
- **Increase is for certain directions and angles consistent with Bragg scattering.**
- **Surface texturing may work just as well as photonic lattice patterning.**

Patterning or texturing will be required for samples with smooth interfaces

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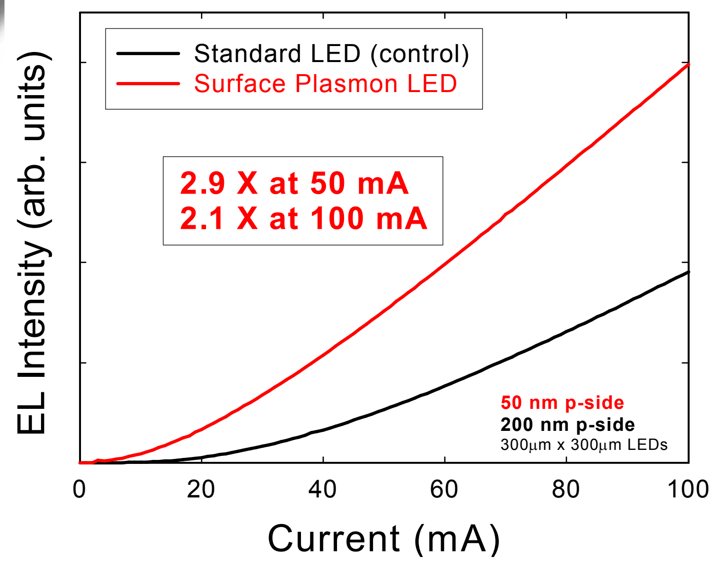
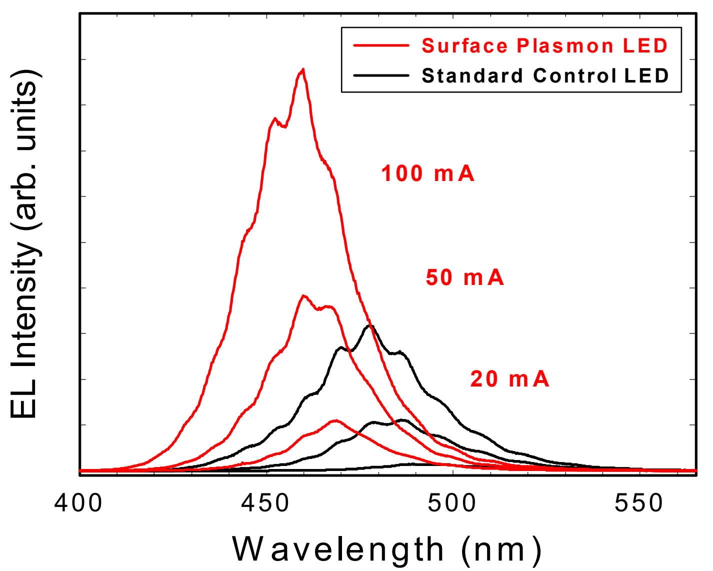
Electrically Injected Surface Plasmon LEDs





Surface Plasmon LED data:

- LEDs were grown with different p-side thicknesses (20 nm → 200 nm)
- Regrow different top LED structures on identical GaN templates
- LEDs with a very thin p-side are expected to show surface plasmon enhancement
- SP-LEDs show a large blue shift in their emission spectra
- **LED output power is enhanced by 2 to 3 times**

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Summary and Future Work

Summary

Photonic crystal LEDs:

- Fabricated 2D photonic crystals in GaN material
  - 110 nm diameter, 380 nm deep, > 3:1 aspect ratio
- Incorporated Photonic Crystals in Electrically injected LEDs
- Demonstrated a 1.5X increase in total LED power
- Far field patterns are strongly modified due to photonic crystal

Surface plasmon LEDs:

- Showed increase in total PL intensity using surface plasmon effects
- Demonstrated changes to the radiative lifetime using TRPL
- Demonstrated a 2 – 3 times increase in LED power using SP-LEDs

Future Work

PX-LEDs

- 2D photonic crystals with smaller, deeper holes
- Defect cavity photonic crystal LEDs
- Utilize Purcell effect, inhibited lateral modes

SP-LEDs

- Explore alternate metalization schemes for SP-LEDs
- Move to longer wavelengths (green InGaN emitters)
- Fabricate devices with patterned (or textured) metal

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