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Enhanced Light Extraction from InGaN Quantum Wells using Refractive-index-matched TiO_2

Arthur J. Fischer[1], Frank Mont[2], Jong Kyu Kim[2], E. Fred Schubert[2], Daniel Koleske[1], and Mary Crawford[1]

[1]Sandia National Labs, Albuquerque, NM

[2]Rensselaer Polytechnic Institute, Troy, NY

Outline:

1.) Light extraction with dielectrics- device design
2.) Photoluminescence – angle dependent measurements
3.) Status of electrically-injected devices

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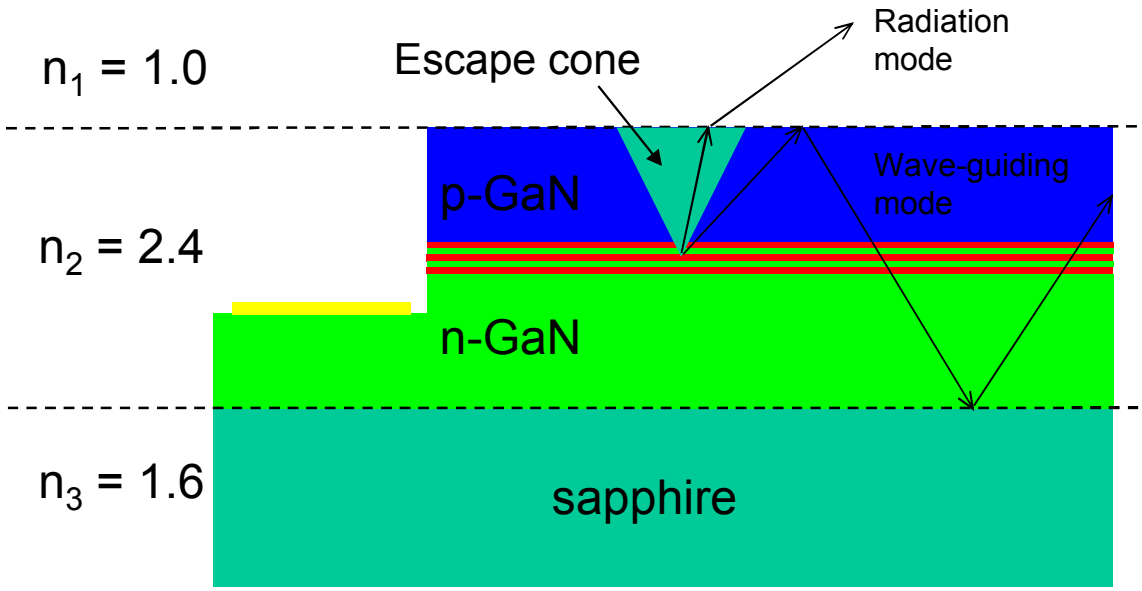
Light Extraction Problem in LEDs

- 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:

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

$$\eta_{EXT} = \frac{escape\ cone\ solid\ angle}{total\ solid\ angle} = \frac{2\pi\left[1-\cos\left(\sin^{-1}\left(\frac{n_1}{n_2}\right)\right)\right]}{4\pi} \sim \frac{n_1^2}{4n_2^2} = 4.3\% \quad \text{(per surface)}$$

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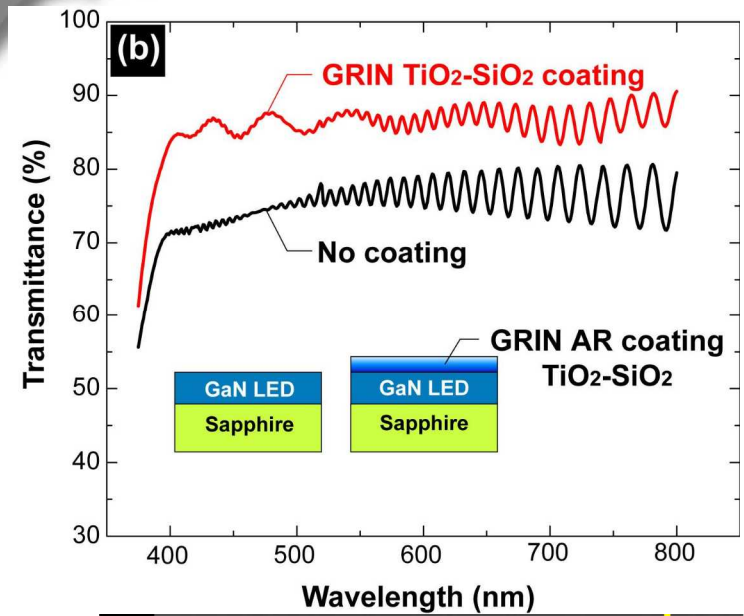
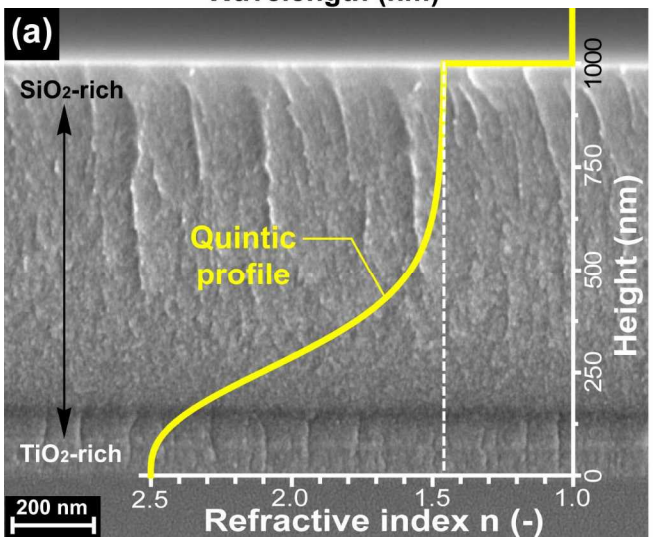
Graded TiO_2-SiO_2 dielectric films





- TiO_2 can be deposited as an index-matched film on GaN (n ~ 2.5)
- Grading of the index of the dielectric
  - Eliminate Fresnel reflection losses
  - An index as low as possible is desired
  - An index as low as n~1.1 has been demonstrated for SiO_2 nano-rods
  - For this work, dielectric was graded from TiO_2 (n ~ 2.5) to pure SiO_2 (n ~ 1.47).
- Dielectric films were deposited using co-sputtering with SiO_2 and TiO_2 targets
- Waveguiding modes still must be extracted- lateral patterning.

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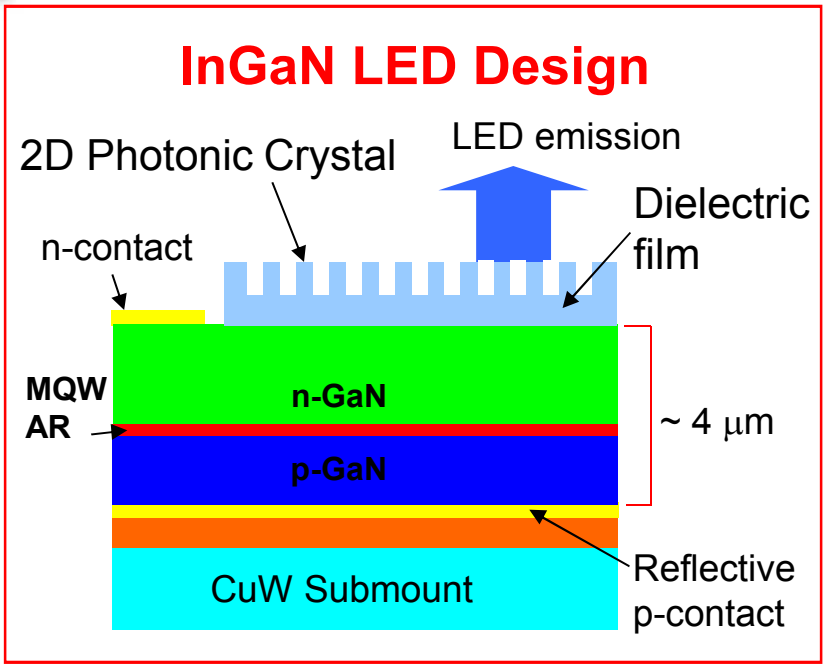
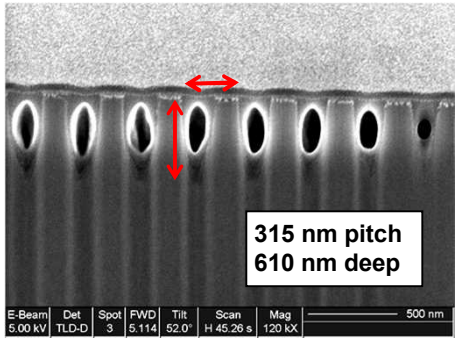
InGaN LED design for dielectric light extraction





Photonic crystal etched in GaN:

- 315 nm lattice constant
- 180 nm in diameter
- 610 nm deep
- 3.39 : 1 aspect ratio

- Non-conducting films for light extraction
  - p-GaN conductivity is low
  - Use n-up structure with current spreading in n-GaN
- Etch photonic crystal in dielectric film to extract waveguiding modes.
  - Potentially easier etching of SiO_2 or TiO_2 compared to GaN
  - Eliminates issues of leakage
- Previously demonstrated photonic crystal patterns etched into GaN
- Photonic crystal diffracts waveguide modes into the escape cone.

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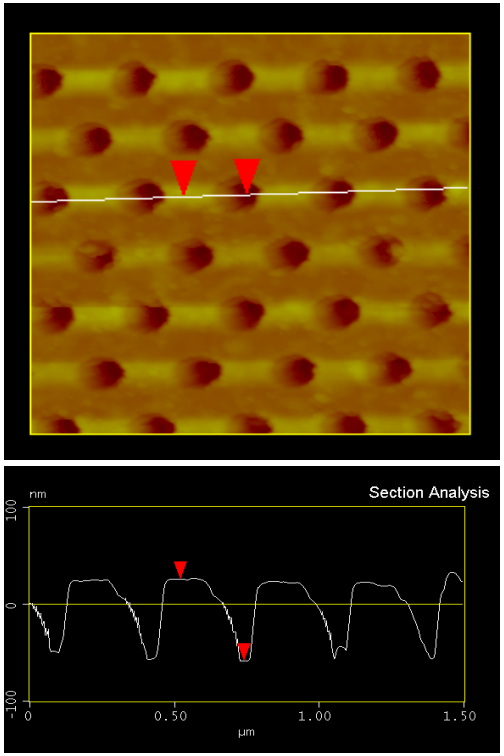
Patterning of dielectric layers for light extraction

Photonic Lattice etched in TiO_2



Depth ~100nm
Pitch ~ 315nm
Diameter ~ 220nm

- Triangular lattice of holes
  - 315 nm pitch, 220 nm diameter
- Electron beam lithography used to pattern films
  - Very slow patterning method
  - Flexibility, easy to vary pitch, etc.
- Wafer scale patterning
  - Large area LEDs
  - Large area patterning techniques
    - Interferometric lithography (UNM)
    - Nano-imprint lithography
    - Deep UV lithography
- Etched using Fl-based dry etching.
- AFM Data
  - High aspect ratio probe used
  - Tip still doesn't map out the shape of the hole

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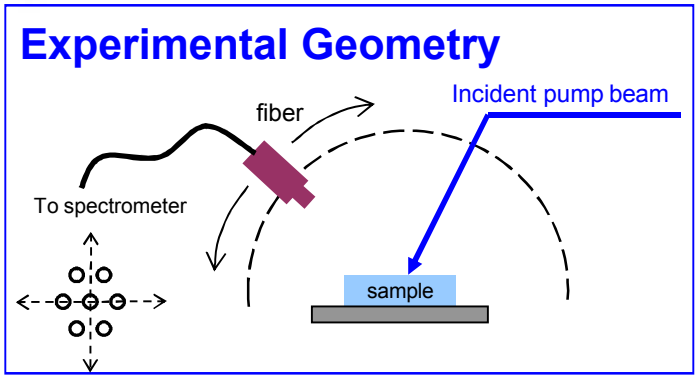
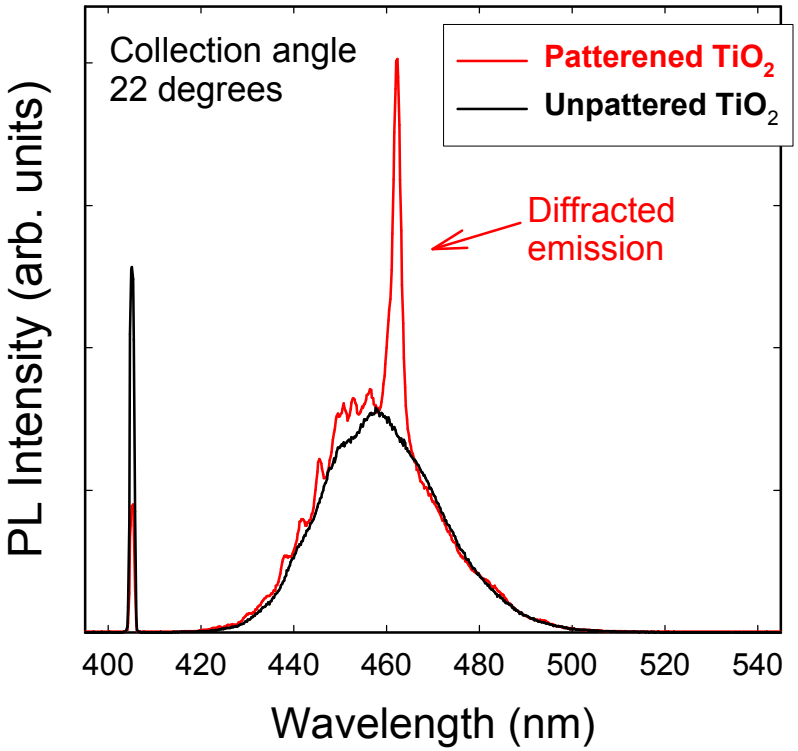
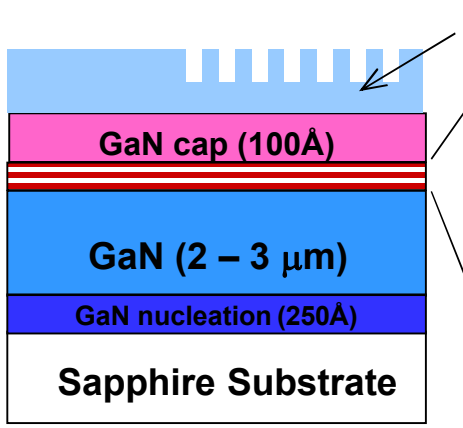
Photoluminescence from QW test structures





- Angle-resolved PL performed using a fiber on a rotation stage
- 407nm pump was used to pump InGaN QWs (rather than TiO_2 or GaN)
- Photonic crystal causes diffraction spikes in the PL spectra
- InGaN MQW test structures
  - Pure TiO_2 index matched to GaN
  - Graded SiO_2-TiO_2 co-sputtered film

InGaN MQW test samples



Active Region:
5 quantum wells
QWs: 20 – 30 Å $In_xGa_{1-x}N$
x = 0.05 – 0.20

Barriers: 75 – 150 Å GaN

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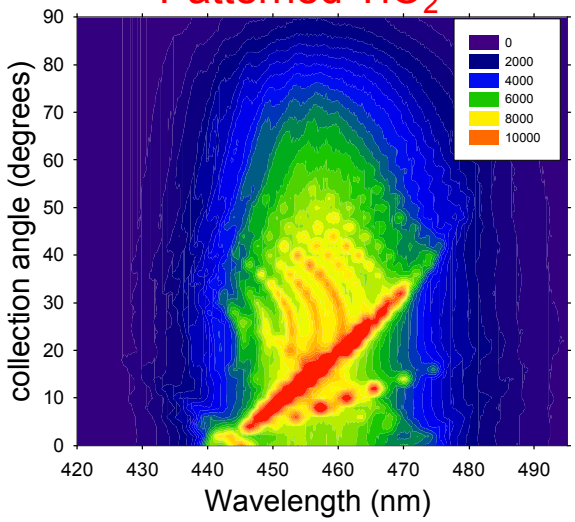
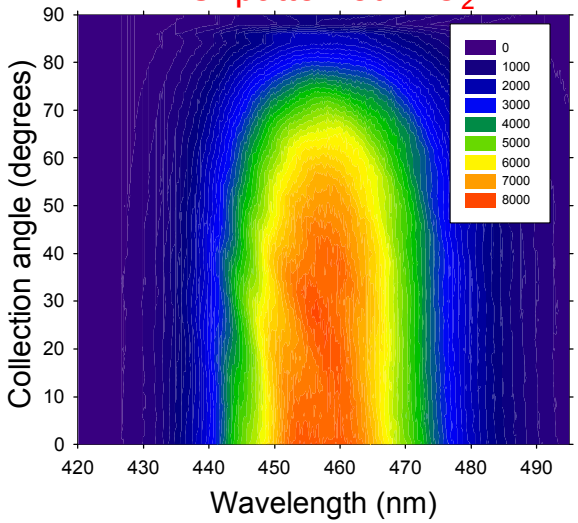
Photoluminescence: Pure TiO_2 on InGaN QW

Patterned TiO_2

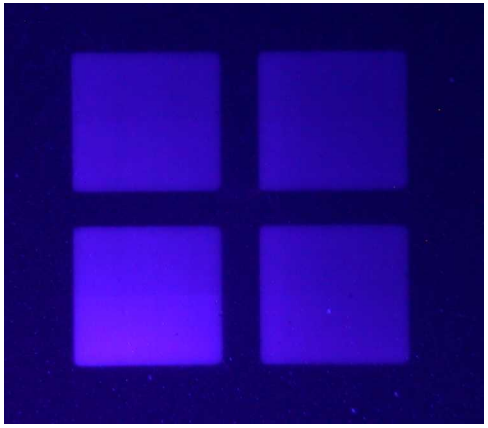


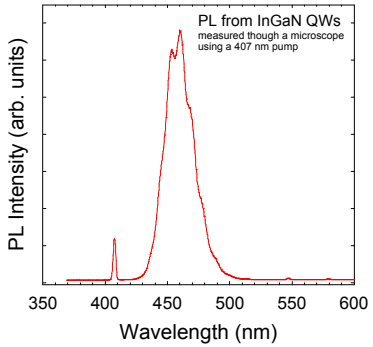
- Pure TiO_2 film on an InGaN QW sample.
- Data taken at 2 degree intervals
- Position of diffraction peaks in wavelength is consistent with diffraction from a grating with a pitch of 315 nm
- Data show effective extraction of waveguided modes
- Alternate patterns may yield better extraction

Unpatterned TiO_2



Microscope image of PL from patterned TiO_2





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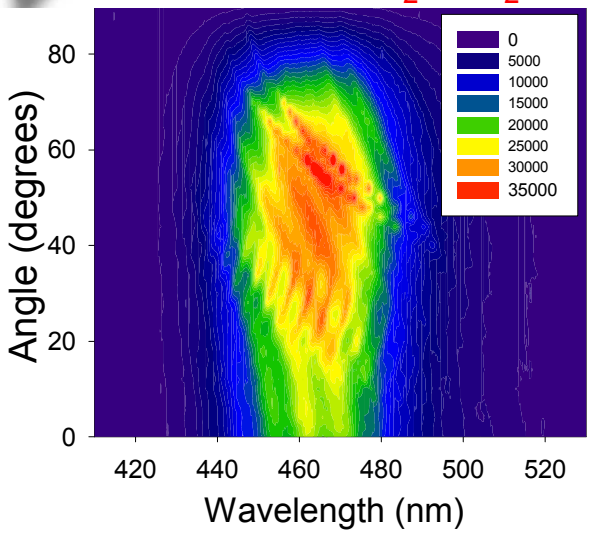
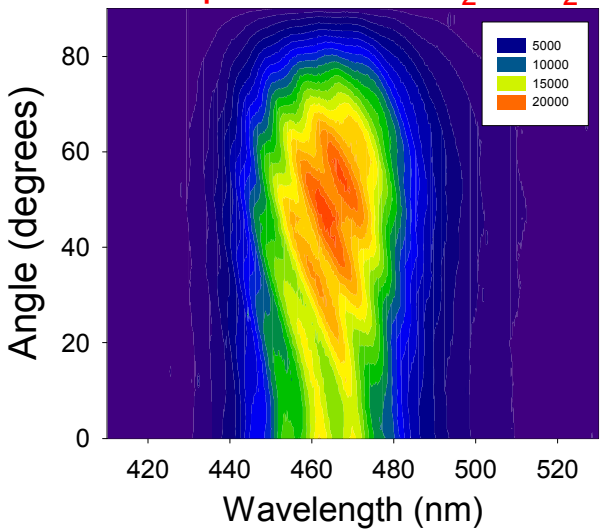
PL: Graded TiO_2-SiO_2 on InGaN QW

Patterned TiO_2-SiO_2

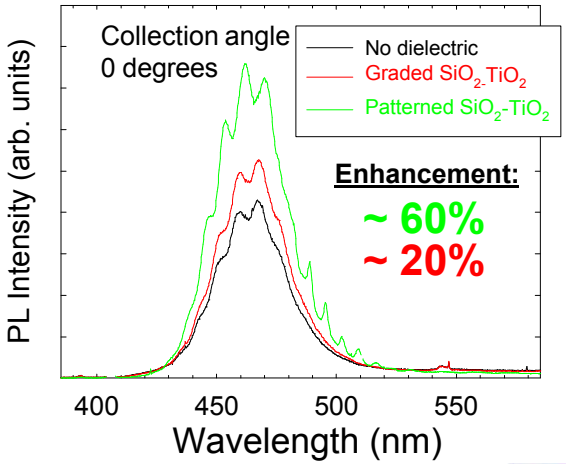


Unpatterned TiO_2-SiO_2

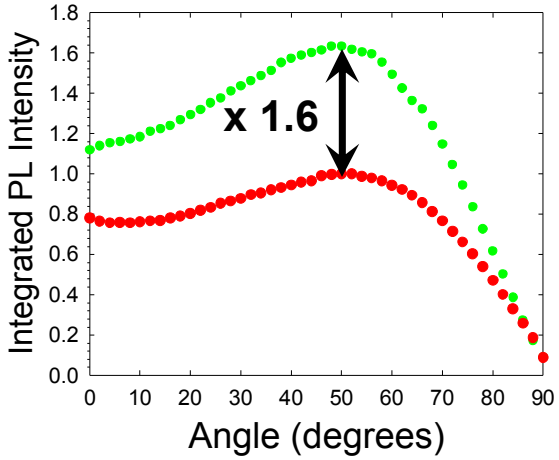


- Graded TiO_2-SiO_2 film on an InGaN QW sample.
- Integrated PL Intensity as much as 1.6X brighter for patterned dielectric films
- Complicated luminescence far-field patterns.
  - Triangular far-field pattern expected
- Interpretation of PL data is difficult
  - Photonic crystal may change pump density
  - Electrically-injected device is needed

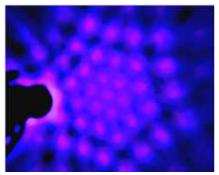
PL at a 0 degree collection angle



PL integrated vs. angle



Photonic crystal LED Far-field pattern



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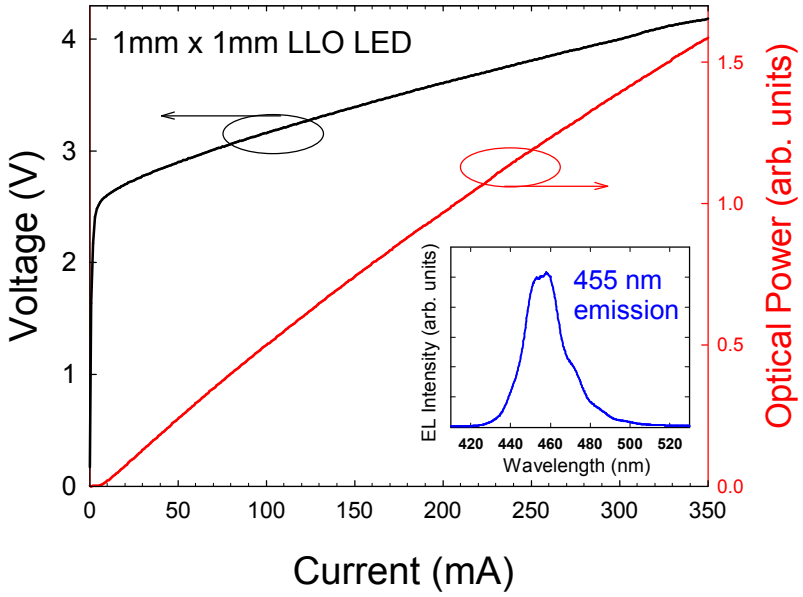
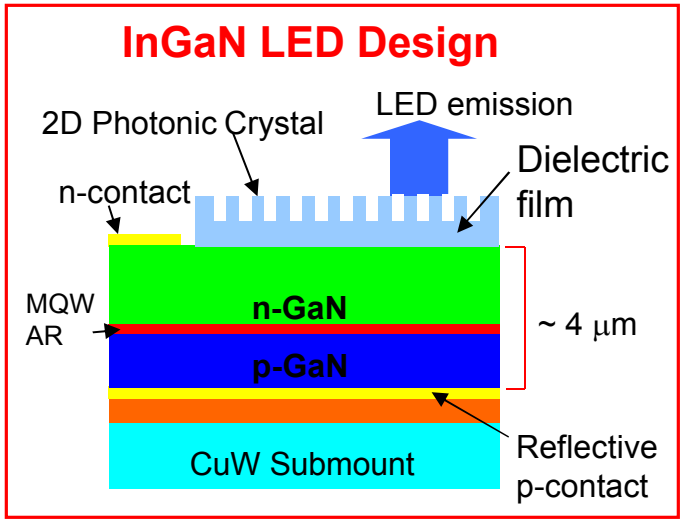
Development of n-up InGaN LEDs





- Developing n-up InGaN LED process for use with dielectric films.
- Laser-lift off for sapphire substrate removal
  - 4th Harmonic of a 10 Hz Nd:YAG
- Demonstrated operation of large area 1mm x 1mm LEDs
  - LED wavelength 455 nm
  - Some leakage at low currents
- Further work required to improve uniformity and yield

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Summary and Future Work

Summary

- Investigated dielectric films for light extraction in InGaN LEDs
- Prepared patterned dielectric films on InGaN QW samples
  - Pure TiO_2 dielectric layer
  - Graded index TiO_2-SiO_2 dielectric layer
- Measured angle-resolved photoluminescence
  - Demonstrated enhanced emission due dielectric films
  - Measured an integrated PL intensity 1.6X greater for patterned dielectric films
- Demonstrated operation of n-up InGaN LEDs for use with dielectric films

Future Work

- Incorporate graded index films with n~ 1.1 using SiO_2 nanorods
- Use FDTD modeling to model patterned, graded dielectric films
- Incorporate dielectric films into n-up LED structures
  - Improve processing uniformity and yield for LLO LED
  - Evaluate performance enhancements using electrically-injected devices

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