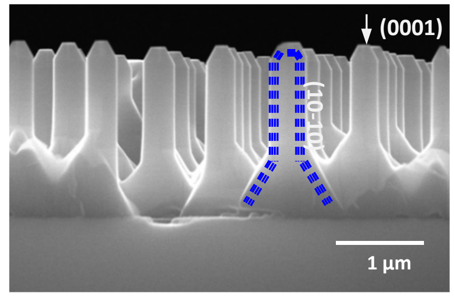
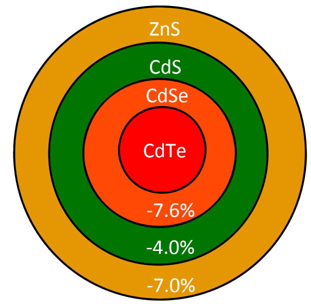
SSLS EFRC Research Challenges

Materials Architectures

1: Nanowires (George Wang)



2: Quantum Dots & Phosphors (Jim Martin)



Light Emission Phenomena

3: Competing Rad & Non-Rad Processes (Mary Crawford)

Power-conversion efficiency		Joule efficiency		Injection efficiency		Internal quantum efficiency (ε_{IQE})		Extraction efficiency

$$\varepsilon = \varepsilon_{Joule} \cdot \varepsilon_{inj} \cdot \frac{BN^2}{AN + BN^2 + CN^3 + \ldots} \cdot \varepsilon_{ext}$$

4: Defect-Carrier Interactions (Andy Armstrong)

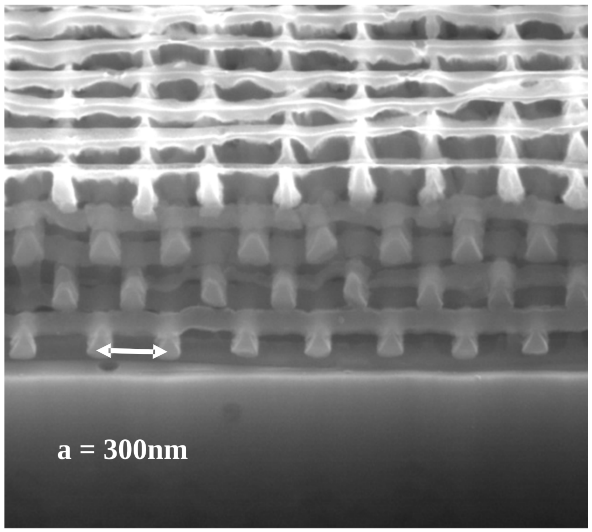
5: Enhanced Spontaneous Emission (Igal Brener)

6: Beyond Spontaneous Emission (Art Fischer)

Igal Brener
PI

Research Challenge 5: Enhanced Spontaneous Emission

Develop Photonic Approaches for Ultra-high Efficiency Solid State Lighting



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Steve Brueck *
University of New Mexico

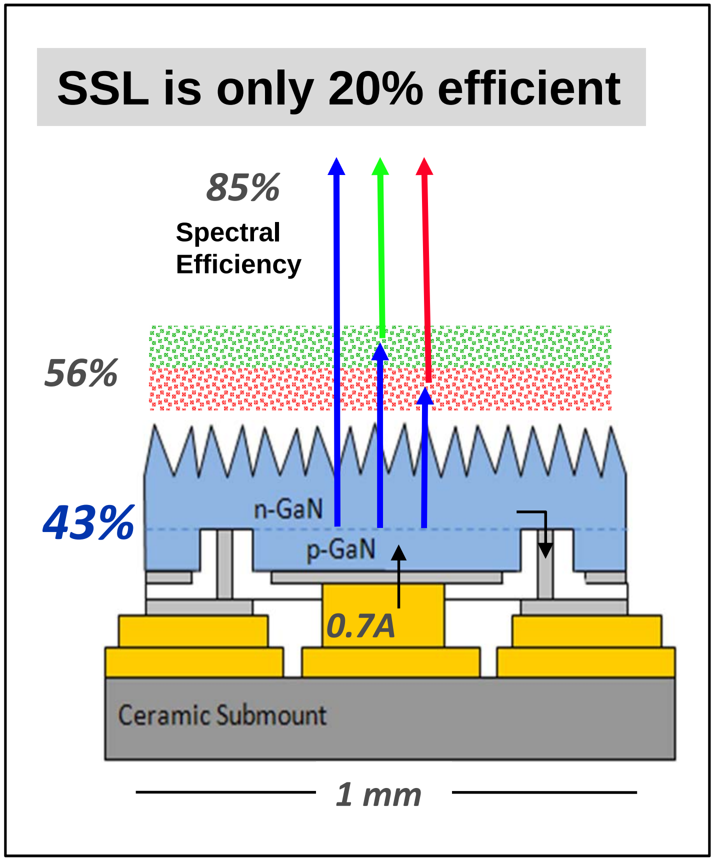
S. Ken Lyo
UC Irvine

***Participants in other Research Challenges**

Work at Sandia National Laboratories was supported by Sandia's Solid-State-Lighting Science Energy Frontier Research Center, funded by the U.S. Department of Energy, Office of Basic Energy Sciences. Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

Motivation

State of the art white light emitter



- Spontaneous emission can be enhanced through modification of the environment (photonic density of states)
- Absorption can be enhanced by cavity effects or field concentration

- Opportunities for efficiency improvements:
  - At the device level
  - At the phosphor/down-converter level

Radiative Rate and its Enhancement

- **Radiative rate Γ_r of an emitter is given by the Fermi Golden rule**

$$\Gamma_r \propto \frac{\omega\mu^2}{\varepsilon_0\hbar}\rho_L(\mathbf{r},\omega)$$

μ is the dipole moment; $\rho_L(\mathbf{r},\omega)$ is local photonic density of states (PDOS)

- **Thus, radiative rate of the emitter can be enhanced by modifying local Photonic Density of States**

- **Enhancement of Photonic Density of States in a electromagnetic cavity was proposed by Purcell in 1946 (Q-cavity quality factor, V_m -mode volume)**

$$F_p = \frac{3}{4\pi^2}\frac{Q}{V_m}\frac{\lambda^3}{n_{eff}^3}$$

Structures based on photonic crystals, plasmonics or metamaterials can be utilized to achieve this.

Outline

I. Highlights of Work

A. Photonic Crystal Control of Photonic Density of States and Spontaneous Emission (2D & 3D) *

B. Control of Field Enhancement and Spontaneous Emission Using Plasmonic Approaches

*Poster Presentation: W. Luk

II. Future Work

A. 2D Photonic Crystals using Nanowire Arrays*

B. Plasmonic approaches for efficient electrically injected red LEDs

C. Nanoantennas and Nanowires

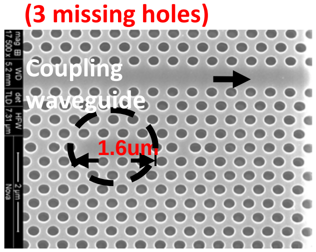
*Poster Presentation: J. Wright

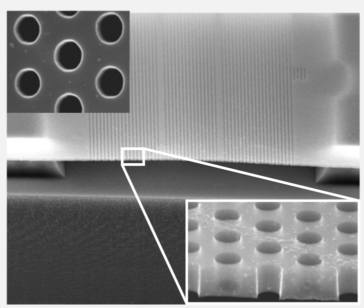
Highlight: 2D Photonic Crystal for Spontaneous Emission Enhancement

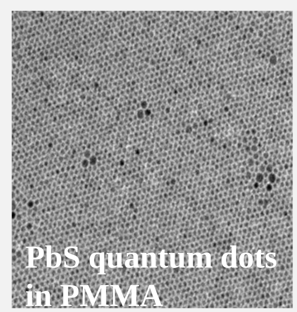
Motivation: Understand spontaneous emission enhancement for QD emitters in the weak coupling regime and with many body effects

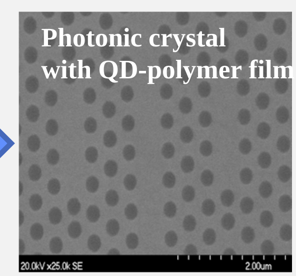
- **More realistic scenario: emitter linewidths broader than cavity linewidth (How high cavity Q is needed for maximum Sp. Emission enhancement?)**
- **This is relevant to enhancement of emission in QD down converters.**
- **We choose 2D Photonic Crystals (Silicon) and Near IR QDs as a good model system: ease of fabrication**

L3 defect cavity
(3 missing holes)





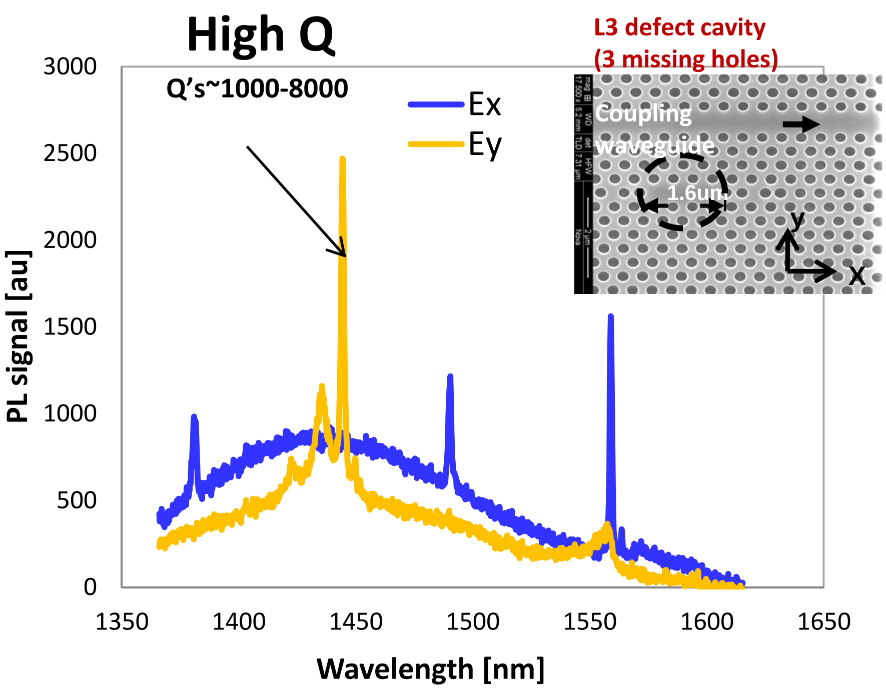


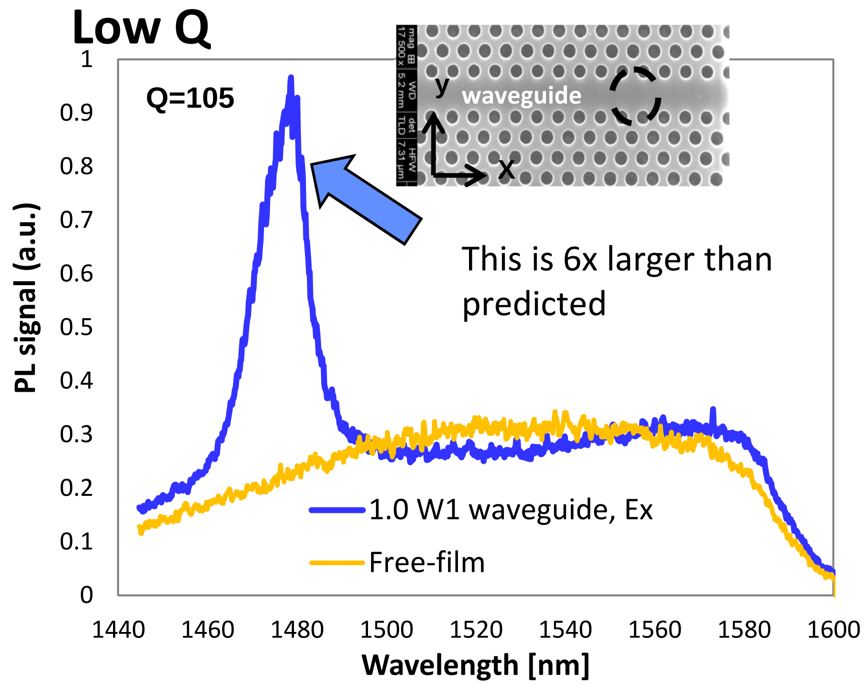


PI: Luk

(This is a 3D cavity)

Anomalous Enhancement Observed from Close-Packed Quantum Dots





Results:

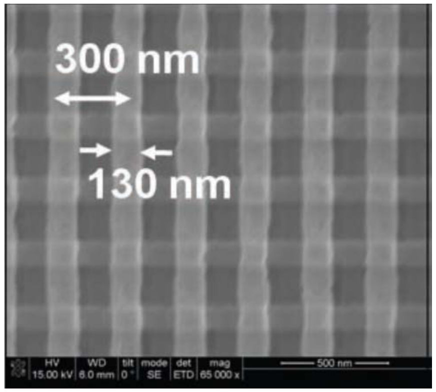
1. **Both low and high Q cavities display an enhancement <u>5-6x larger</u> than what it should be (dielectric, Purcell, angular redistribution, etc).**
2. **Speculation: spectral diffusion and/or Forster process could play a role not accounted for in Fermi's golden rule.**
3. **Conclusion: high density of emitters relaxes requirement for high Q cavity**

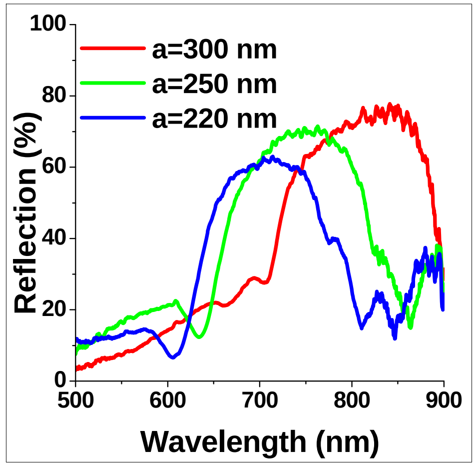
PI: Luk

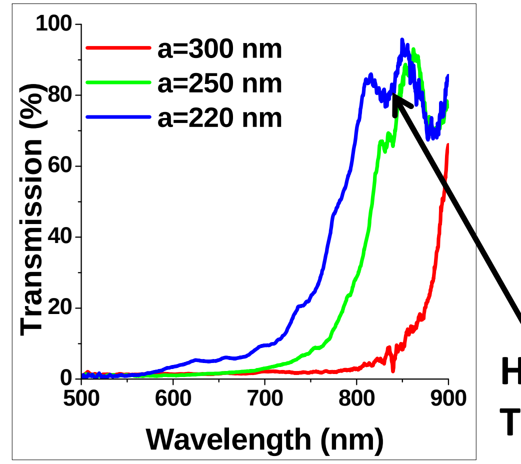
JOSA B **28**, 1365, (2011).

Highlight:
Silicon Logpile 3D Photonic Crystals for the Visible

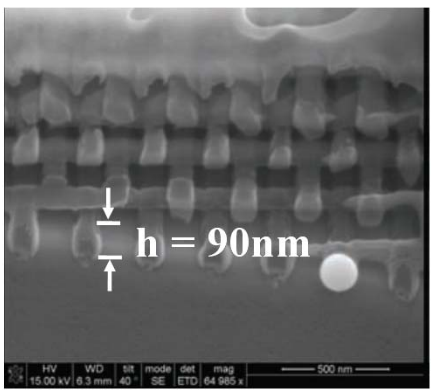
Top View







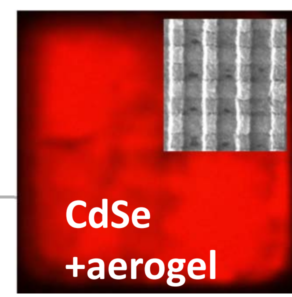
High Transmission!



Cross-section View

Advanced Materials **22**, 4180 (2010)

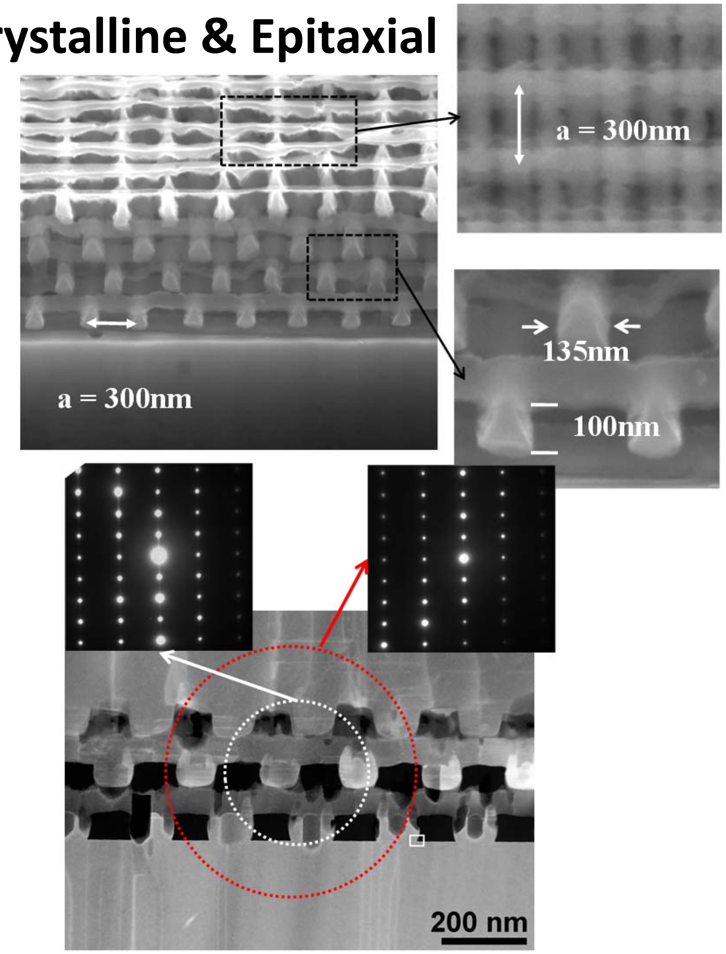
- Silicon's large refractive index (n~3.4) provides strong photonic confinement (large bandgap, enhanced PDOS)
- Its near infrared absorption (~ 1100nm) edge has been a discouragement for use in visible 3DPC.
- This work demonstrates that 3D PhCs composed of Si can operate for wavelengths shorter than its absorption edge and with minimal loss

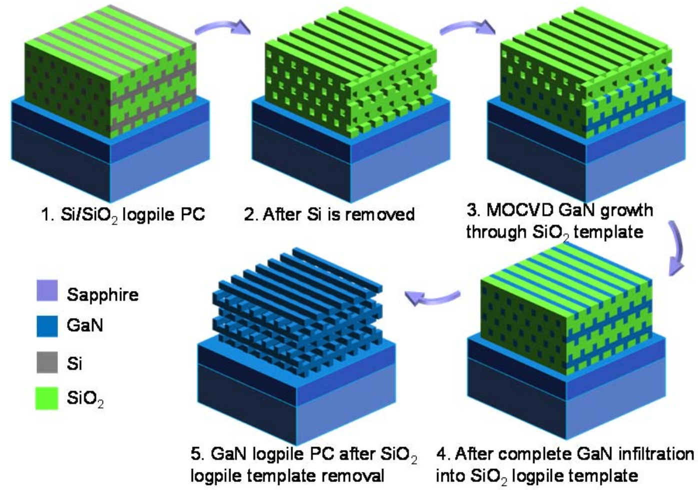


PI: Subramania

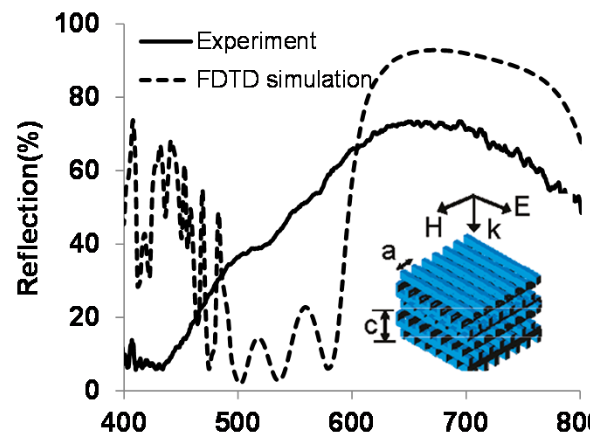
Highlight:
GaN Logpile 3D Photonic Crystals for the Visible

Crystalline & Epitaxial





Normal Incidence Optical Response



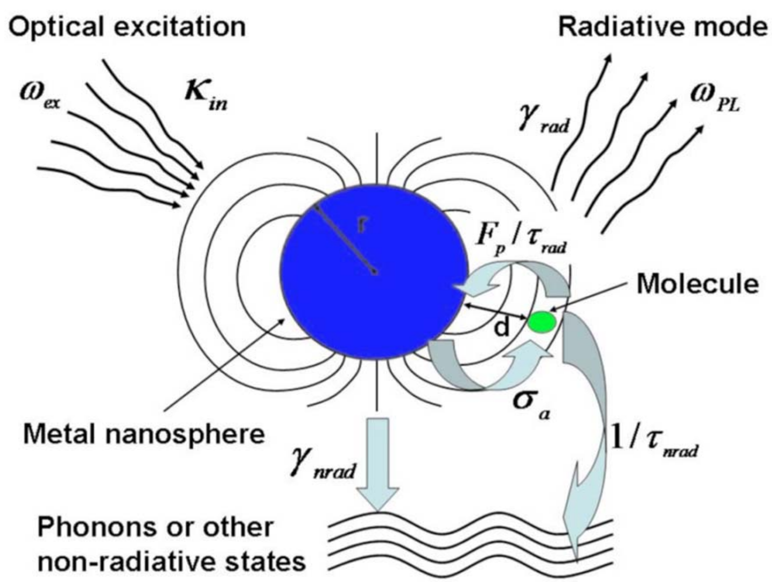
Nano Letters **11**, 4591 (2011).

This could be used to control light emission of nitride LEDs

PI: Subramania

Plasmonic Approaches for Enhanced Emission

Emitters coupled to Plasmons have been studied and used for decades as a viable way to enhance radiative rate. For ex: dye molecules on top of metallic surfaces, etc.



(Lakowicz)

Control of Emission:

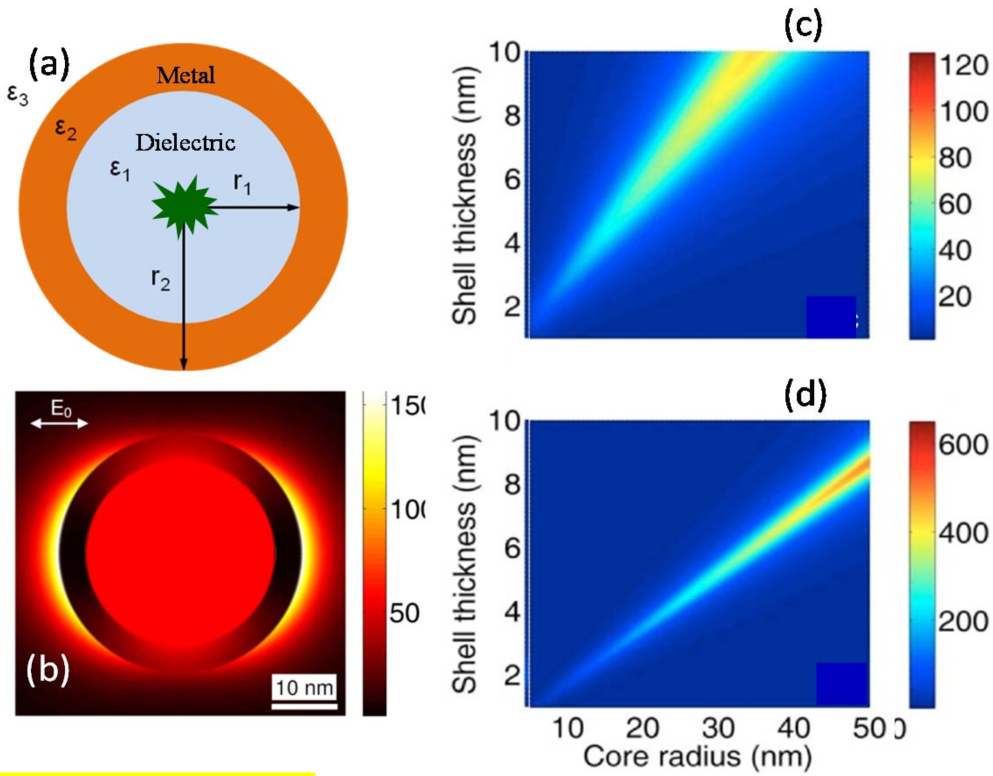
Purcell effect, PDOS

Control of Absorption:

Optical Field Enhancement

Highlight: Enhancement of Emitters using Plasmonic Core-Shell Nanoparticles

<u>**An emitter encapsulated in a dielectric/metallic core/shell nanoparticle**</u>



JOSA B **27**, 1561 (2010)

Advantages of this structure

- **Insensitive to emitter placement**
- **Circumvent the need for spacer layer**
- **Emitter protected from environment**

Results:

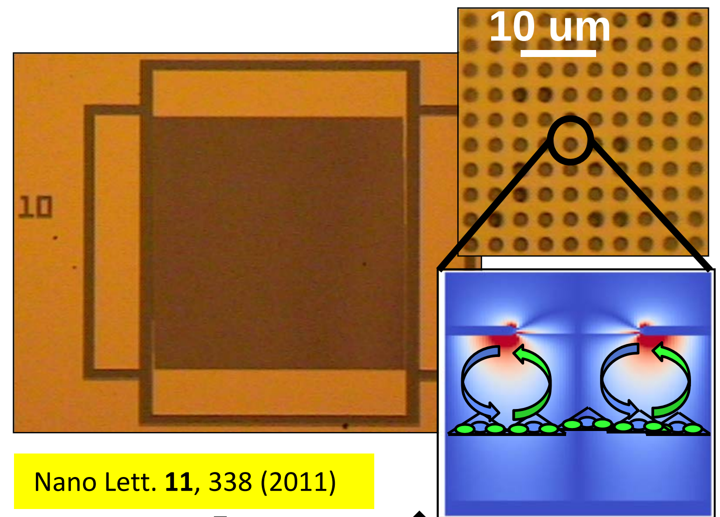
- **Optimal shell thickness ~ 1/3 of the inner radius**
- **QY can reach 0.5-0.6**

A possible application could be enhancement of absorption cross section for Phosphor Rare Earth ions (i.e. Eu)

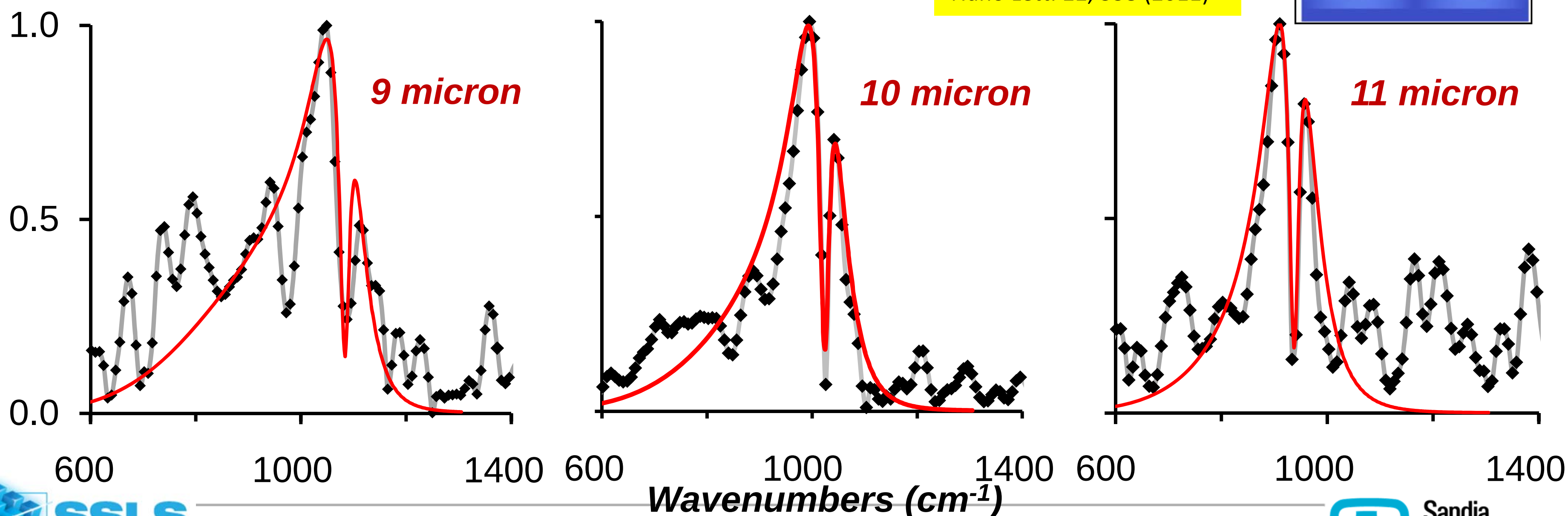
PIs: Brener&Luk

Highlight: Strong Coupling between QDs and Plasmons

- Investigated coupling between plasmonic geometries and electrically pumped epitaxial quantum dots.
- Observed strong coupling effects in splitting of electoluminescence from devices which was described by plasmon field driving Rabi oscillations in quantum dots.
- Strong coupling effects were observable despite large inhomogeneous broadening of material system.



Nano Lett. **11**, 338 (2011)



Summary: Selected Research Highlights

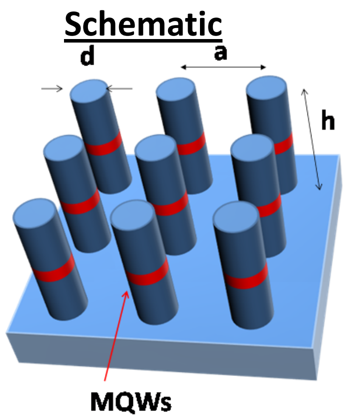
- Surprising emission enhancement when high density of broad-luminescence QDs are coupled to 2D Photonic Crystals: relaxation of high Q cavity requirement
- First demonstration of 3D logpile Si & GaN Photonic Crystals working in the visible
- Core shell plasmonic nanoparticles provide a new platform for bright emitters
- Demonstrated strong coupling between *electrically injected* QDs and plasmonic resonances

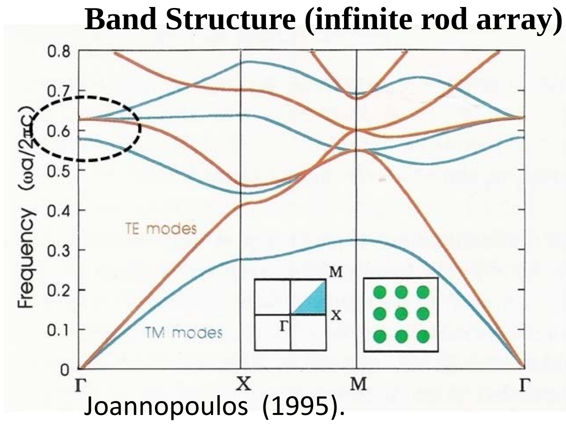
Publications and Presentations

- **Publications (published, accepted or submitted): 9**
- **Selected:**
  - "Gallium Nitride Based Logpile Photonic Crystals", ***Nano Lett.*** 11, 4591(2011).
  - "Observation of Rabi Splitting from Surface Plasmon Coupled Conduction State Transitions in Electrically Excited InAs Quantum Dots", ***Nano Lett.*** 11, 338 (2011).
  - "Nanocomposite Plasmonic Fluorescence Emitters With Core/Shell Configurations, ***J. Opt. Soc. Am.*** **B**, 27, 1561 (2010).
  - "Energy transfer from an electron-hole plasma layer to a quantum well in semiconductor structures", ***Phys. Rev. B*** 81, 115303 (2010).
  - "Strong Coupling between Nanoscale Metamaterials and Phonons", ***Nano Lett.*** 11, 2104 (2011
  - "Anomalous enhanced emission from PbS quantum dots on a photonic-crystal microcavity", ***J. Opt. Soc. Am.*** **B** 28, 1365 (2011).
- **Invited Presentations: 23**

Future Work:
Nanowire Arrays 2D Photonic Crystals

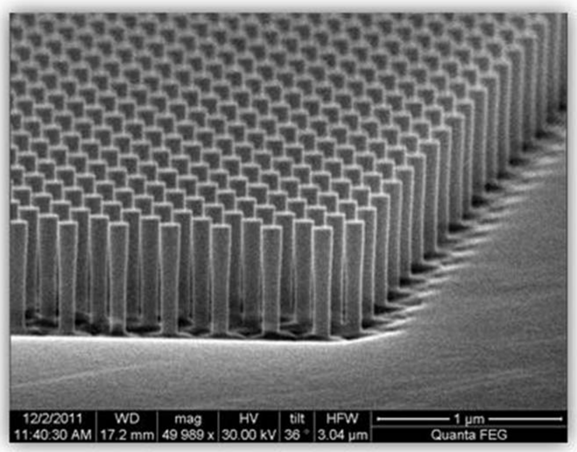
Top down NWs are excellent emitters. Use 2D Photonic Crystals to suppress in-plane emission and thus enhance vertical emission

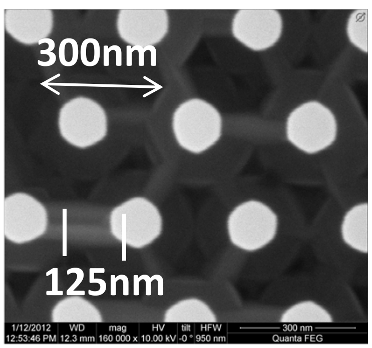


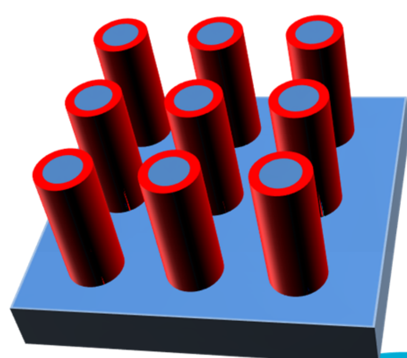


- Time resolved PL to determine radiative rate enhancement by PhC.
- Optimize PhC design with simulations
- Fabrication of large area devices (1" x 1") using interference lithography
- Explore electrical contacting scheme
- Explore radial MQW architecture to increase emitter volume.

Recent Results



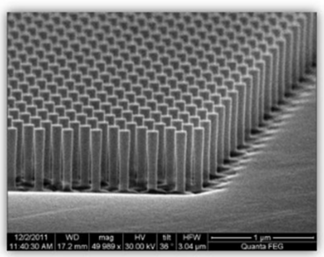


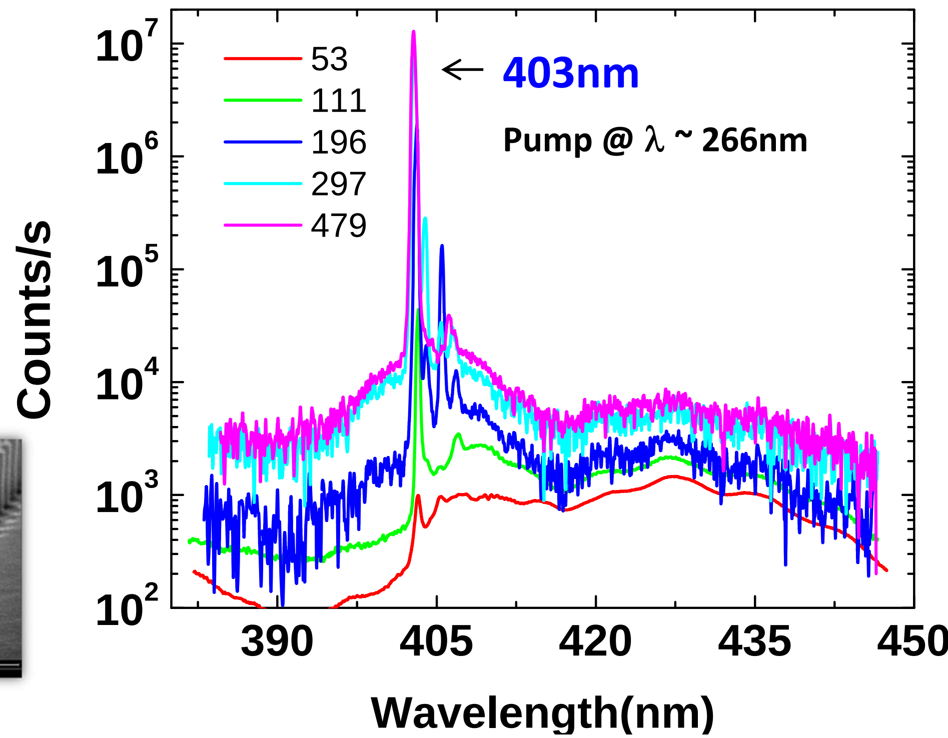


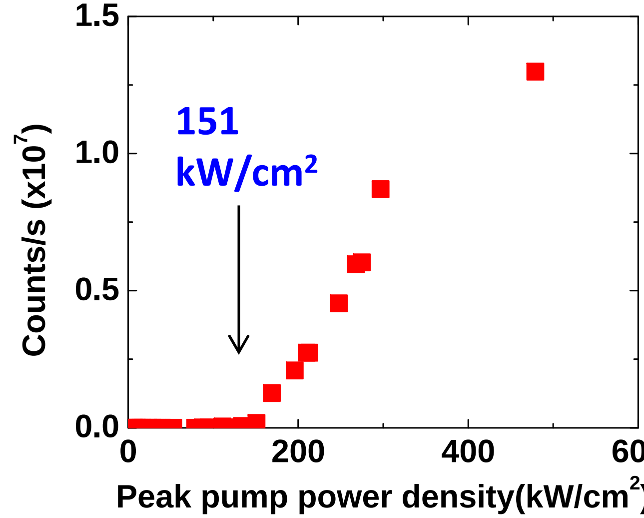
Future Work: 2D Photonic Crystal NW Lasers

- This is another approach for low threshold NW lasers
- Will attempt electrical injection
- Will map the photonic bandgap dispersion through angular PL dependence

Preliminary PL & lasing







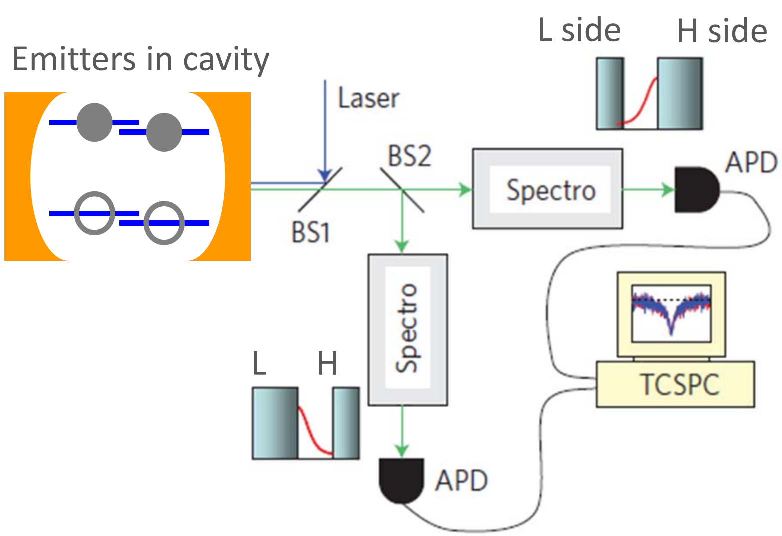
*Poster Presentation: J. Wright

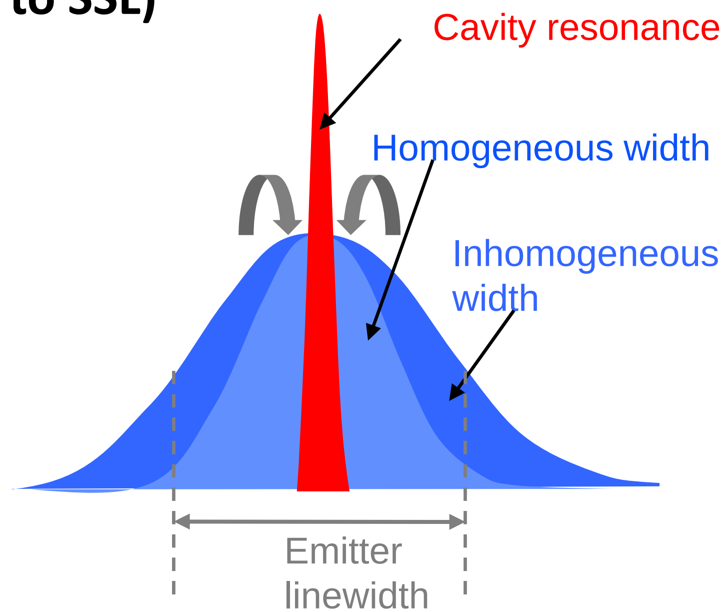
First axial-heterostructure III-nitride NW laser

Future work: 2D Photonic Crystals + QDs

Confirmation of enhanced radiative rate through lifetime measurements in the regime: $Q_{emitter}<Q_{cavity}$ ($Q_{emitter}$ related to PL linewidth)

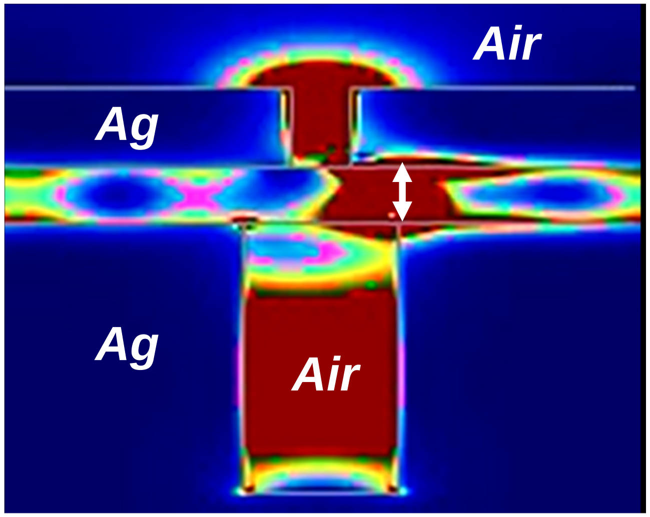
- **High density emitters: lifetime**
- **Low density emitters (single QD): correlation measurements**
- **Repeat all this for red emitters (relevant to SSL)**



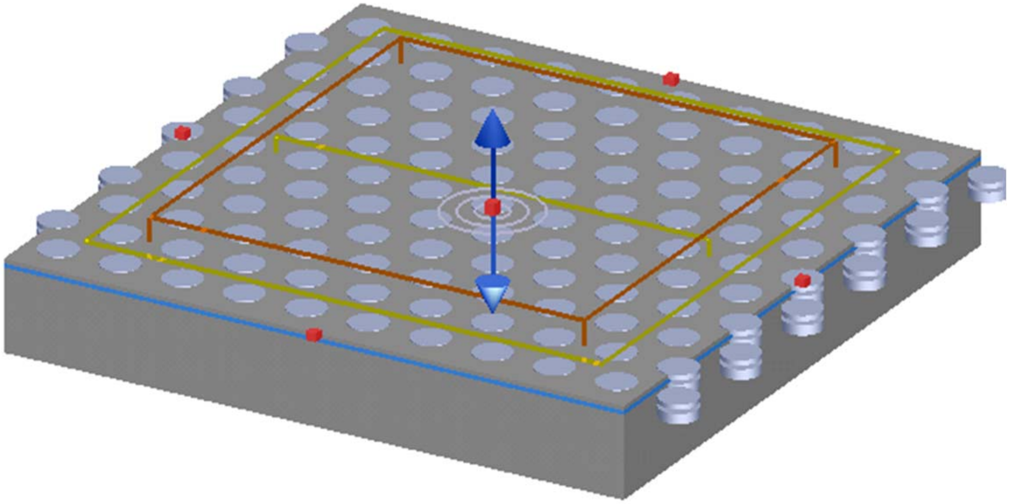


Future Work: Plasmonics for Red

- **Use plasmonics to enhance spontaneous emission rates, but implement in a high efficiency design with reduced heating.**
- **Basic LED concept is InGaP active region with <u>metal-insulator-metal plasmonic</u> geometry. Plasmon out-coupling structures are implemented in top and bottom metal layers.**
- **Any reasonable device will need to be hybrid: integrate LED texturing concepts, as well as plasmonics, in order to achieve good output coupling and avoid waveguiding effects.**



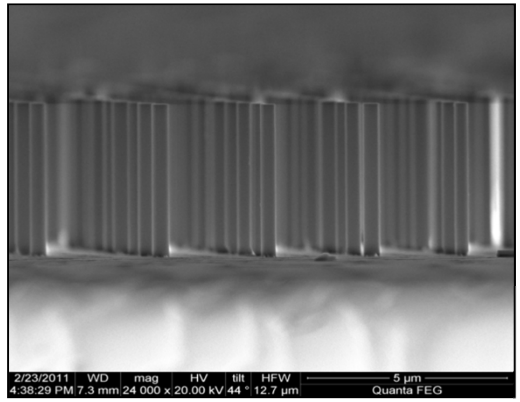
2D –instructive, but misleading



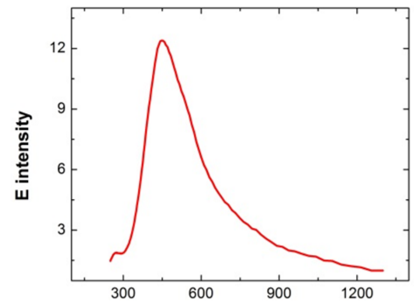
3D large area – much more realistic

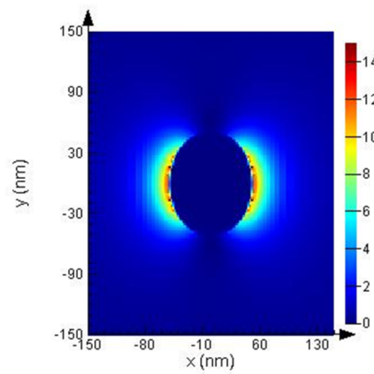
Future Work: NWs and Plasmonic Nanoantennas

- The nanoantenna can be designed to resonate at absorption or emission wavelength
- Currently exploring a liftoff process and short-wavelength plasmonic metals (Ag & Al)

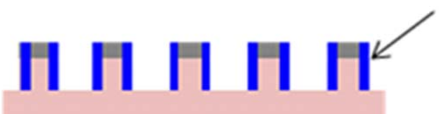


Aluminum nanoantennas (disks) scatt. spectrum

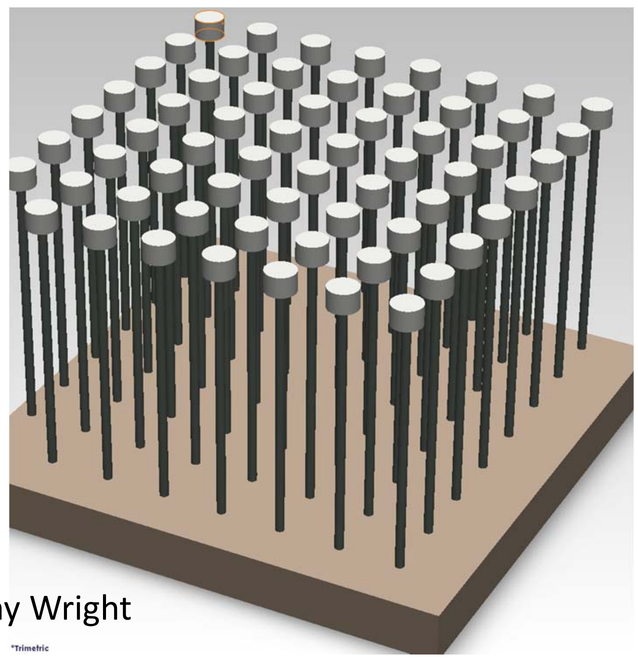




Or NW encased in a metal shell



Qiming Li



Jeremy Wright

Summary: Selected Future Directions

- Exploit 2D Photonic Crystals made from NW arrays as a new platform for high efficiency emission and lasing: synergistic with Challenges 1 & 6
- Elucidate the mechanism for emission enhancement for QDs coupled to 2D-Photonic Crystals when $Q_{emitter} < Q_{cavity}$
- Design and fabricate electrically pumped LEDs that use plasmonics for out-coupling and plasmonic Purcell enhancement
- Combine plasmonic nanoantennas and top down nanowires for lower threshold nanowire lasers