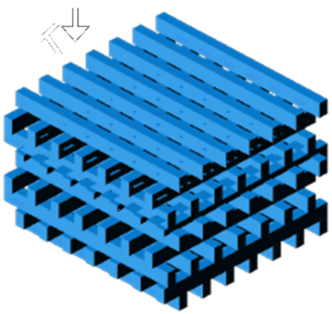
SSLS EFRC
SOLID-STATE LIGHTING SCIENCE
ENERGY FRONTIER RESEARCH CENTER

Sandia National Laboratories

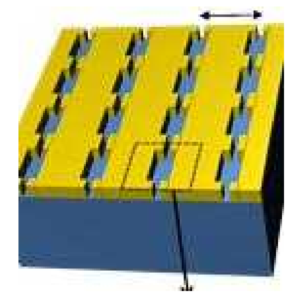
SAND2015-5234C

Nanophotonic structures for extreme light-confinement interaction

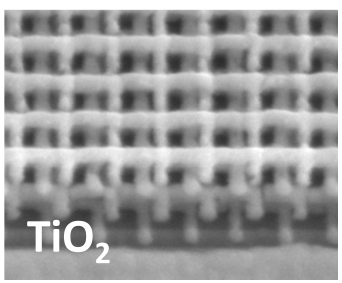


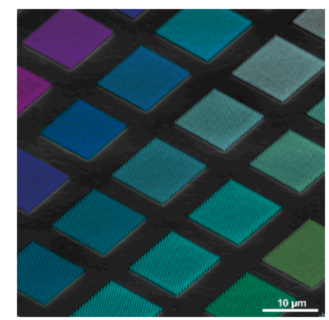
Ganesh Subramania

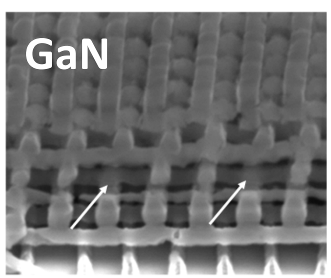
Advanced Material Science 01123
Sandia National Laboratories, Albuquerque, NM

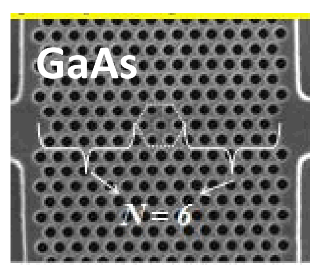


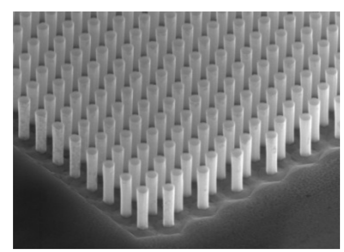
July 5-10, ICTON 2015, Budapest, Hungary











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U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

Collaborators

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- Jeff Brinker
- Bernadette Sanchez
- John Nogan
- Ed Gonzales
- Cathy M
- Doug Pete
- Carlos Sanchez
- Tony Coley
- Travis Young
- Bob Biefeld
- Jerry Simmons

Nanophotonics Activity

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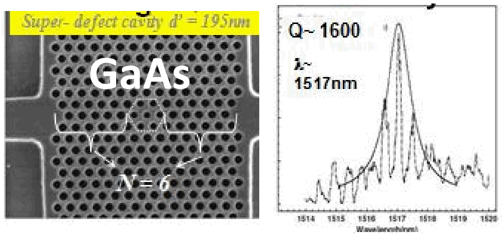
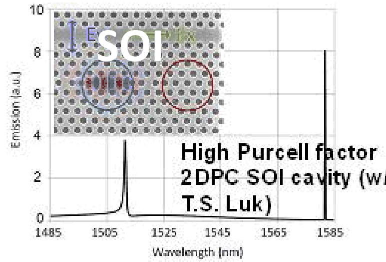
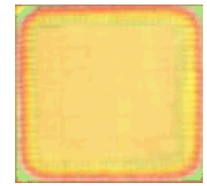
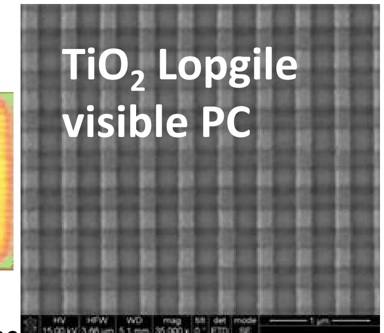
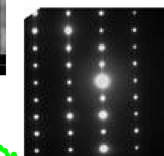
Integrated Photonics, Nanoscale lasing, Strong coupling, Full 3D emission control, Thermal control, Solid State lighting, Energy conversion

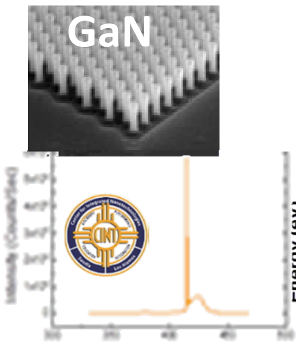




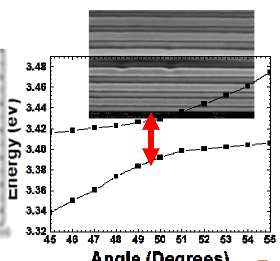


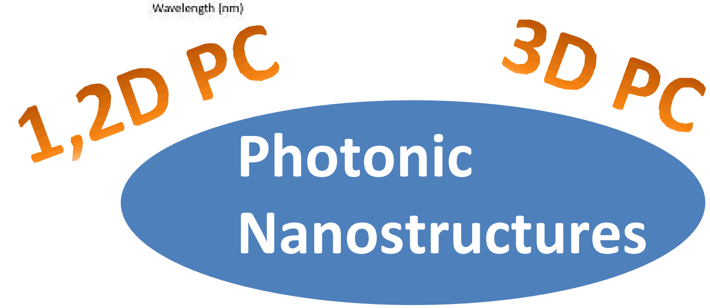


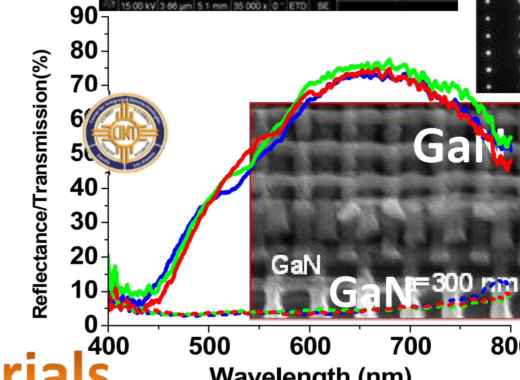




Strong coupling (w/A. Fischer





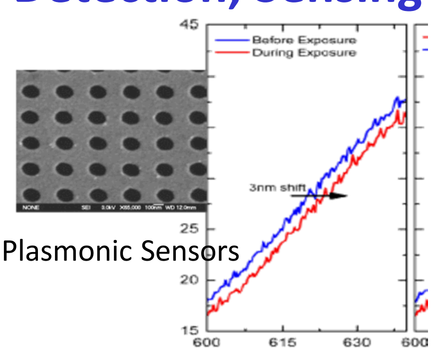


GaN 2DPC laser w/ G. Wang, I. Brener

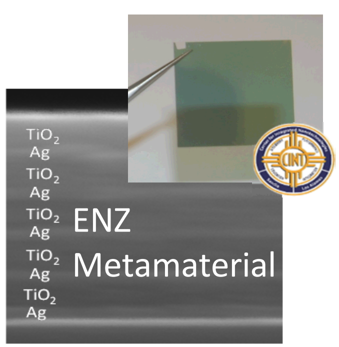
Metal optics and Metamaterials

(w/ G.Wang, A. Fischer, D. Koleske)

Ultrasubwavelength light control, Detection, Sensing , Nanocircuitry

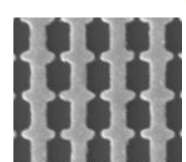


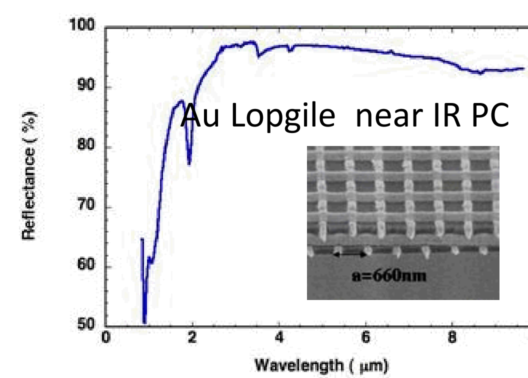
Plasmonic Sensors



ENZ Metamaterial

Double groove Metal Nanostructure





Au Lopgile near IR PC

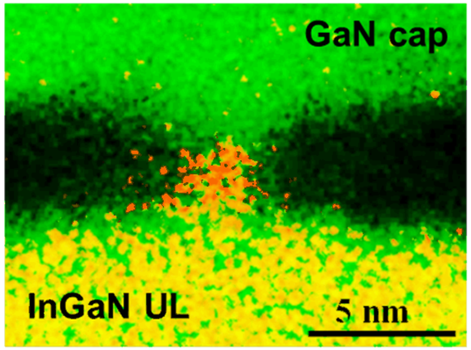
Outline

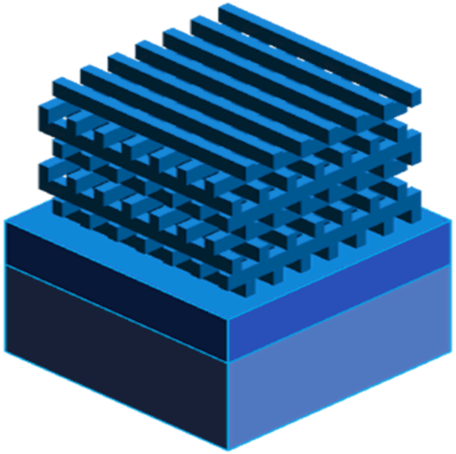
- Background and Motivation
- Dielectric Nanostructures
  - 3D logpile photonic crystals – TiO_2 and GaN
  - 2D photonic crystals – low threshold lasers, single photon sources
- Metal based Nanostructures
  - Epsilon-near-zero structures
  - Non-resonant broadband field confinement

Control of Light matter Interaction

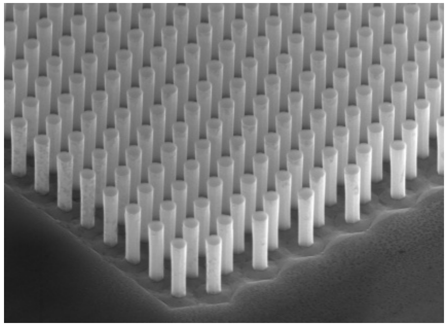
- Three dimensional electromagnetic control
- Photonic density of states modulation
- Nanoscale confinement

Single photon sources

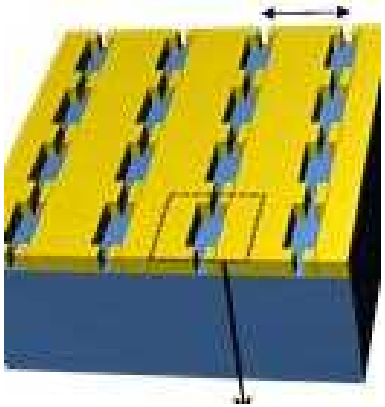




3D Photonic crystals



Low –threshold lasing



Broadband field confinement

3DPCs: Wavelength, Materials

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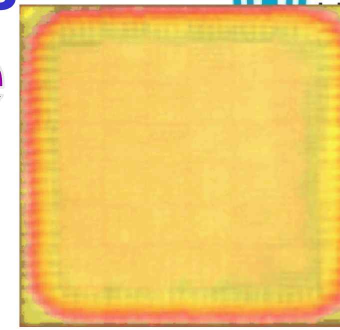
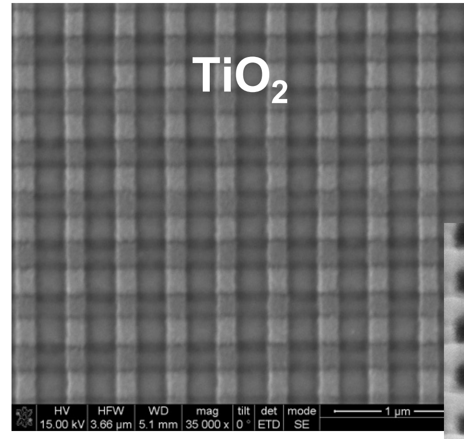
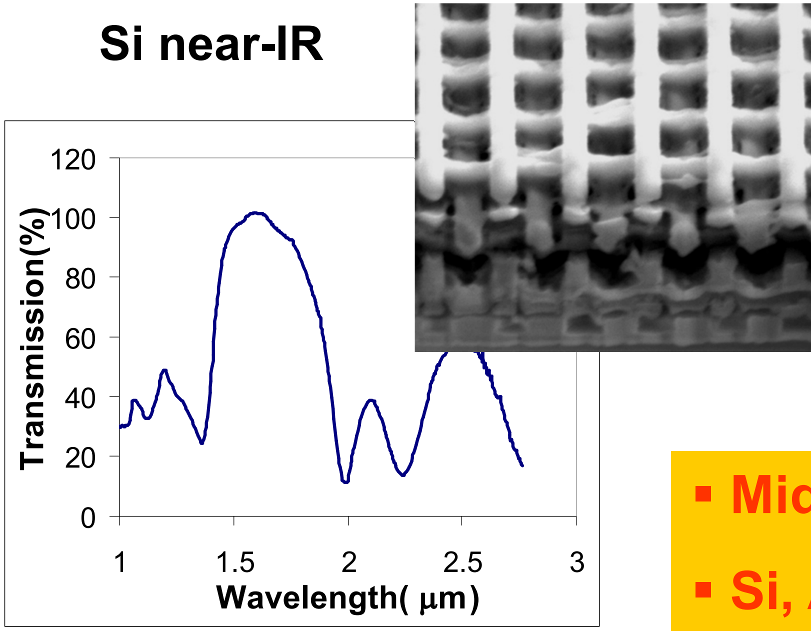
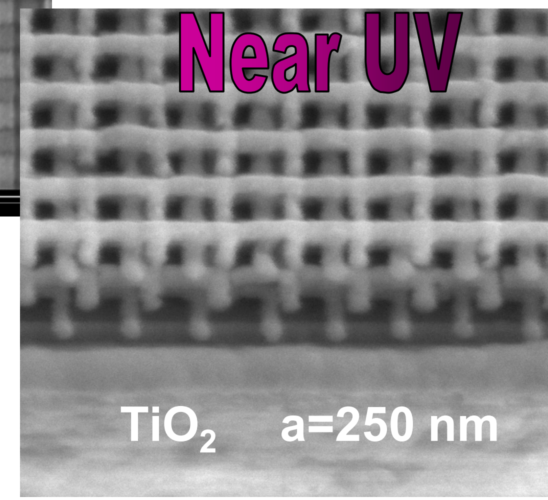
Visible



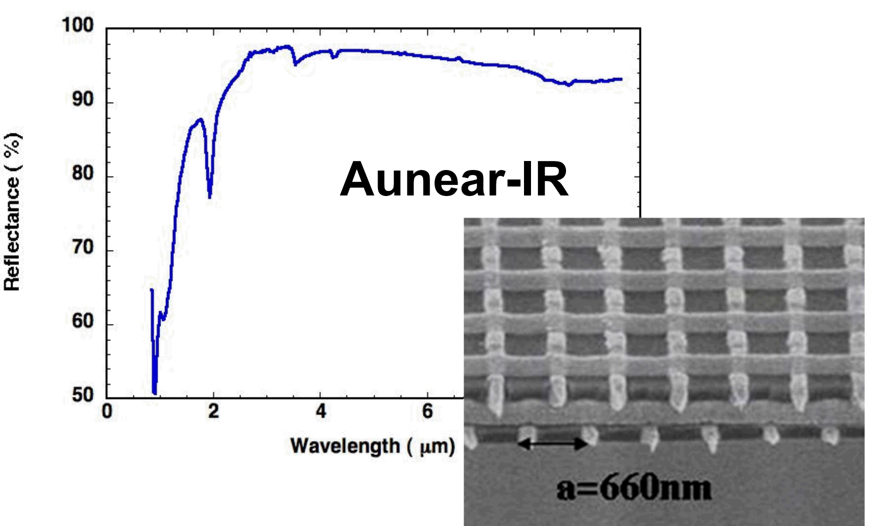


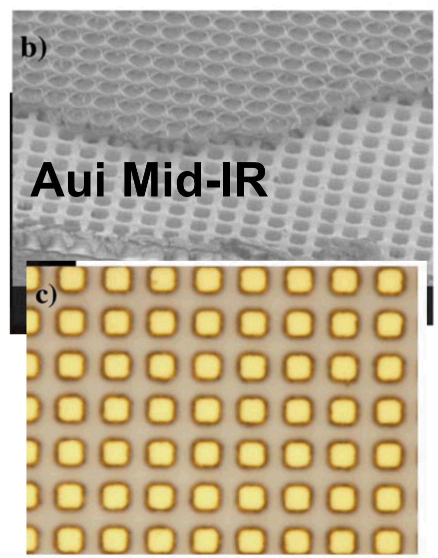
Si near-IR

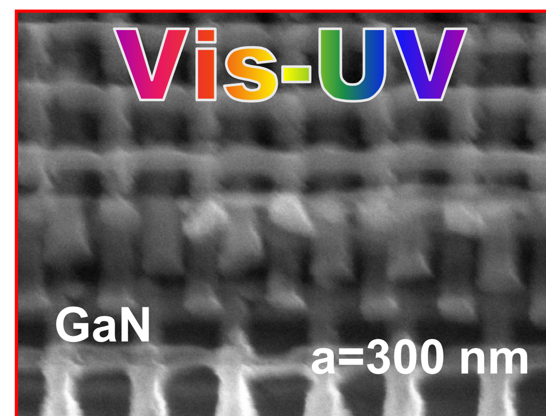




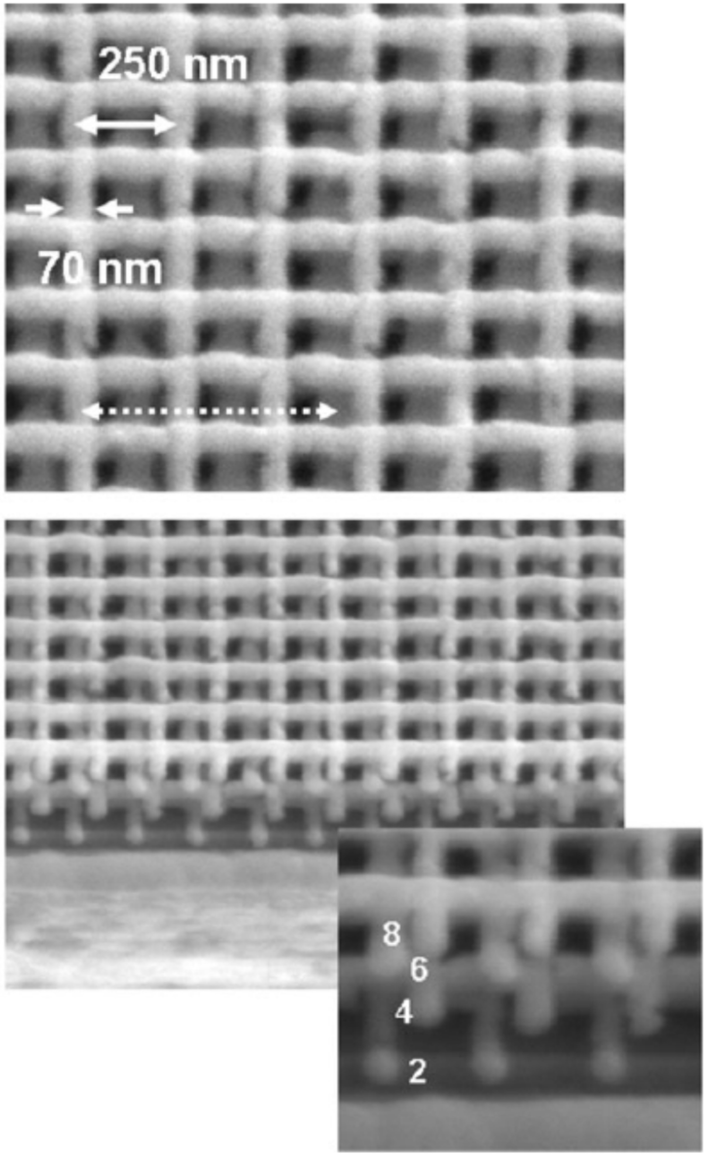
- Mid IR to Near UV
- Si, Au, TiO2 and GaN

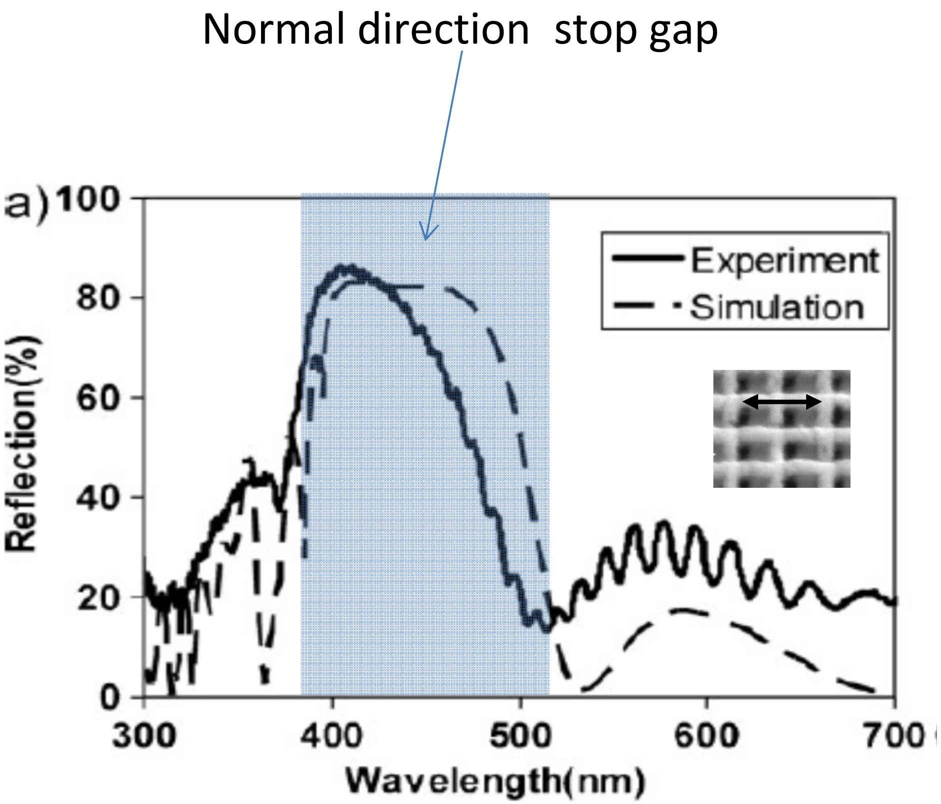






TiO_2 Logpile- Visible 3D PC

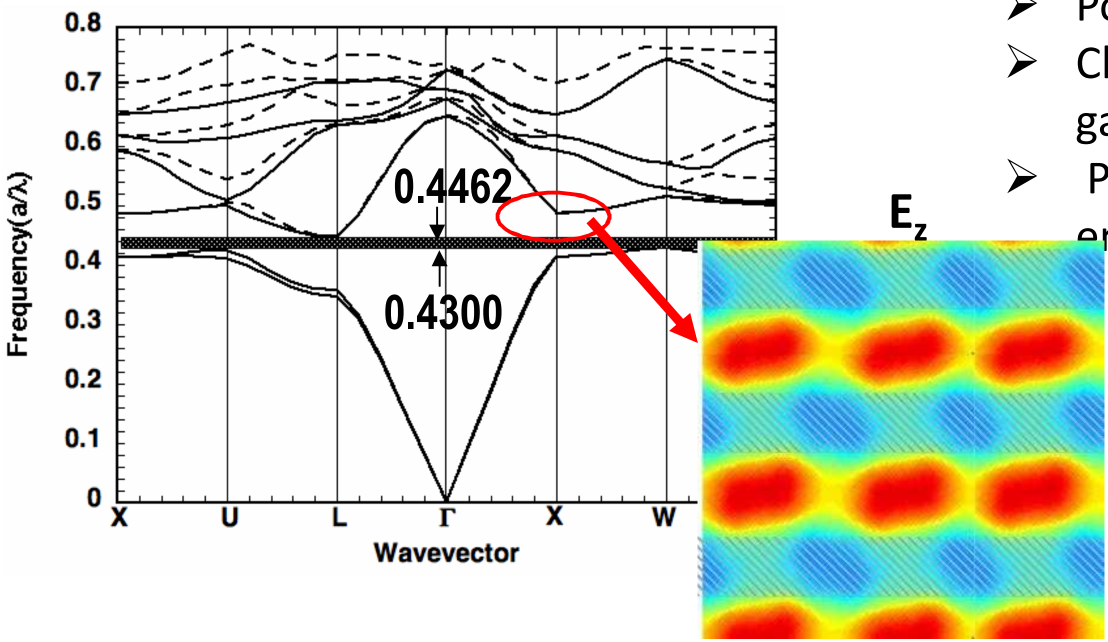


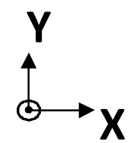


G. Subramania, Y.-J. Lee, A. J. Fischer, and D. D. Koleske, Advanced Materials **22**, 487-491 (2010)

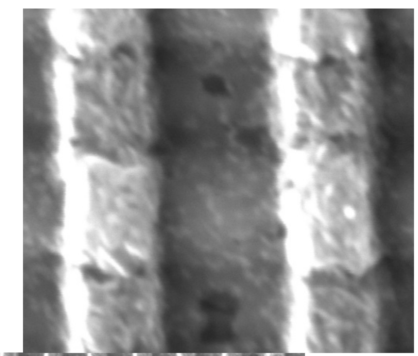
Air band Emission Modification in TiO_2 Logpile

- Post introduction of light source
- Choice of light source (QDs or dyes or gas)
- Potentially higher density of states enhancement



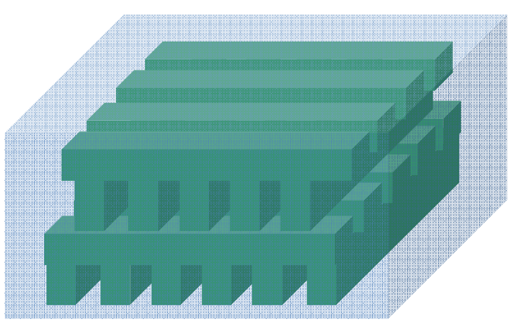


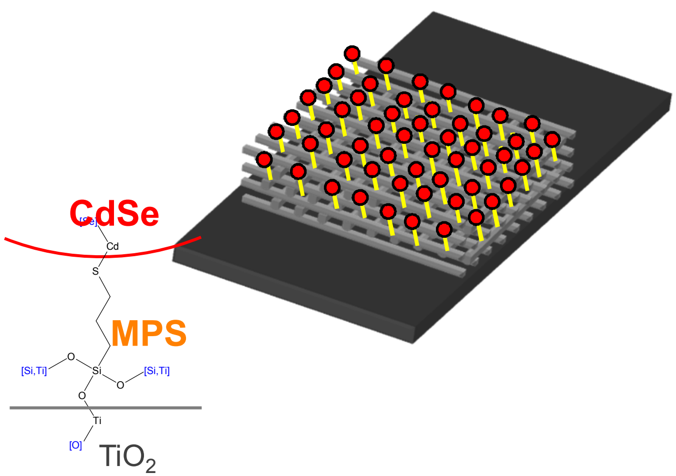
Aerogel Ref. index ~1.05-1.1

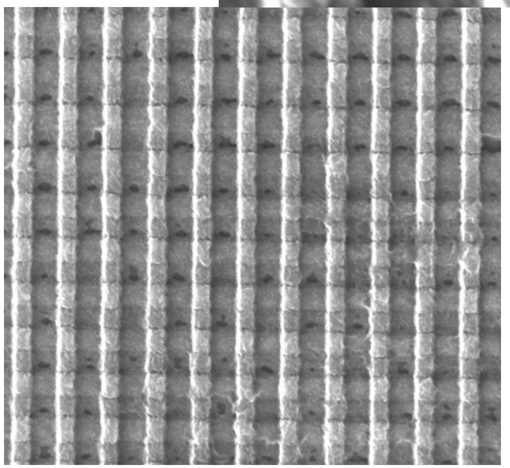


Surface attachment of QDs

Spin coatable aerogel

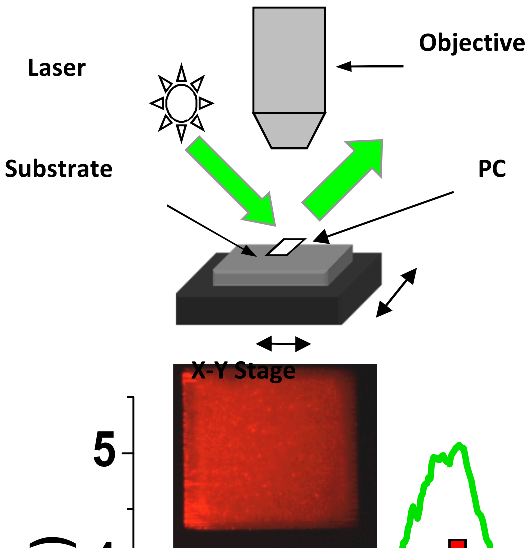




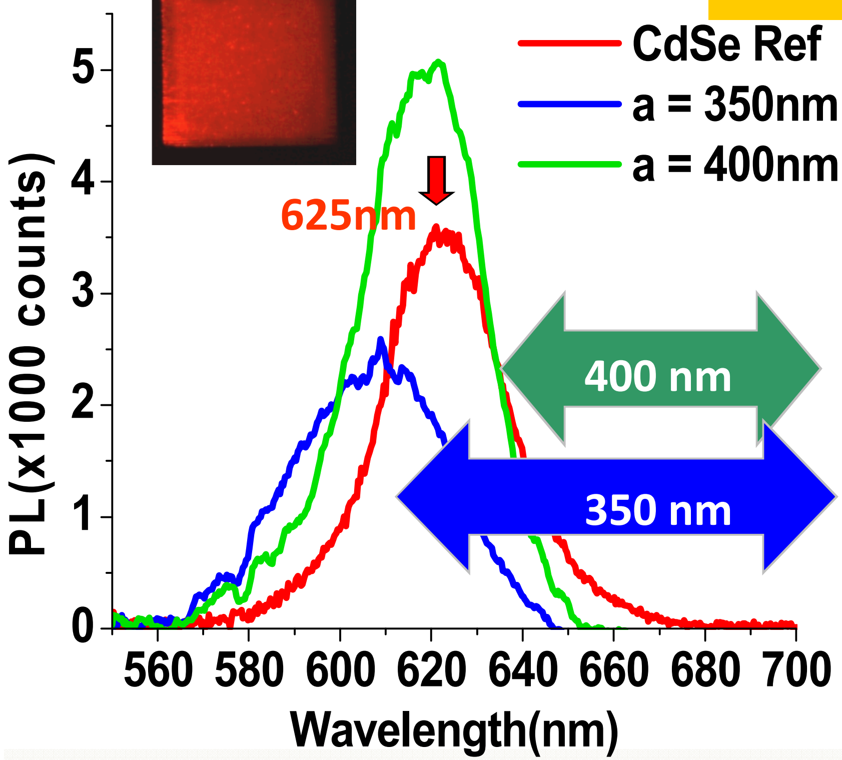


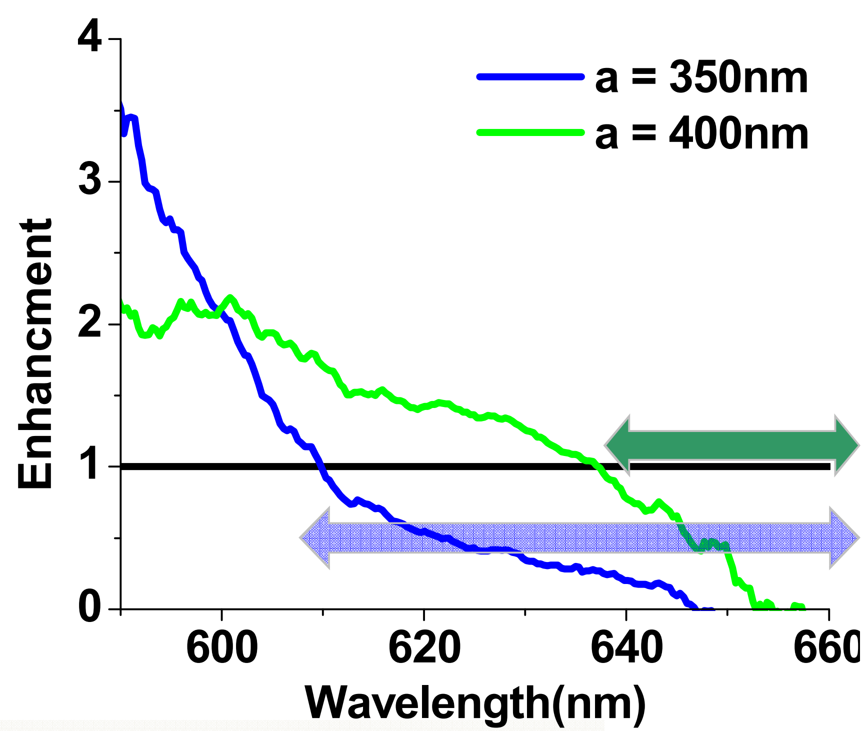
Spontaneous Emission Modification

- Microphotoluminsecence with 532nm (5mW CW pump)
- Equivalent volume of unpattened CdSe infiltrated aerogel as reference



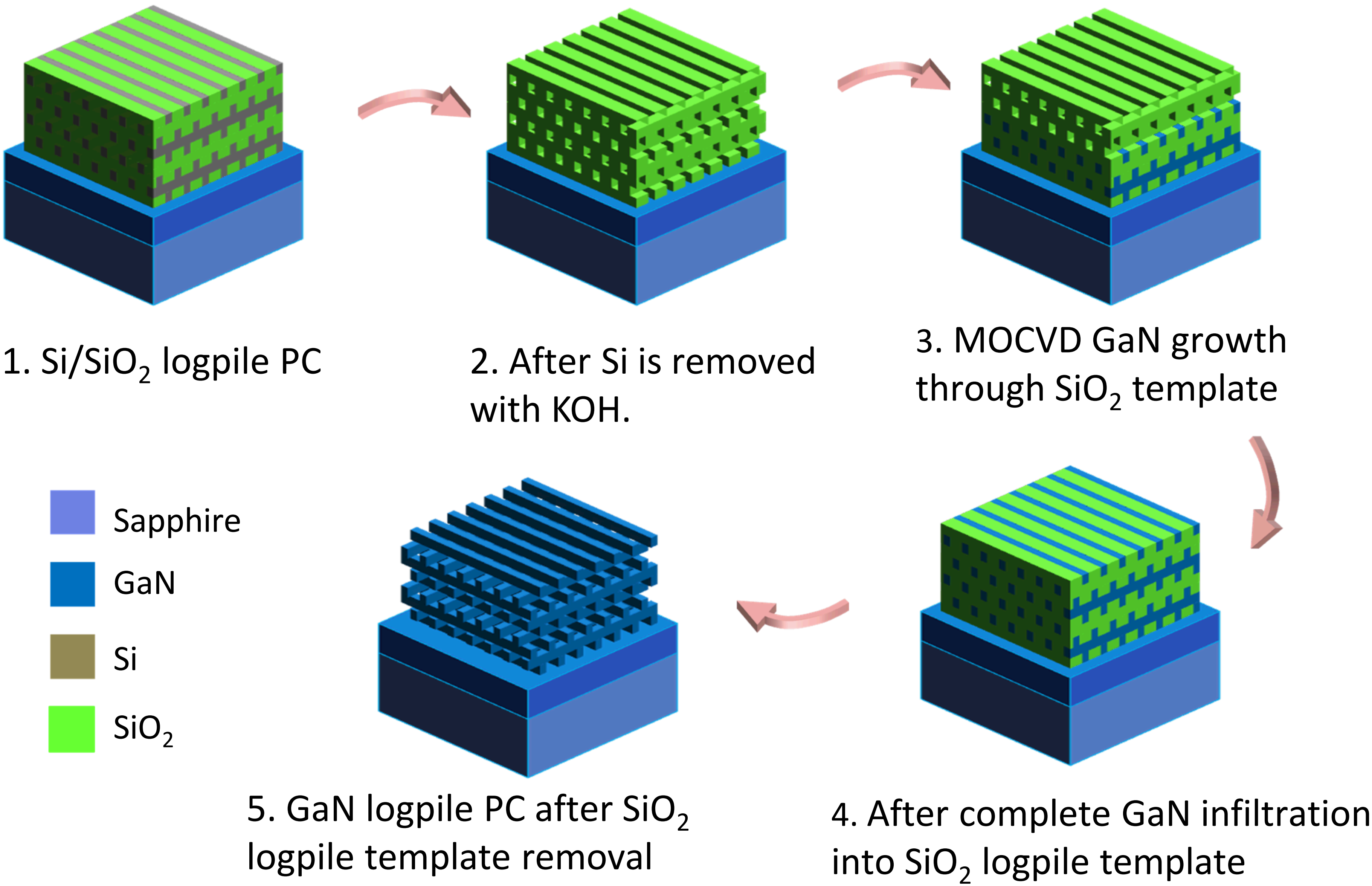
Light emission suppression inside the bandgap and enhancement at the band edge



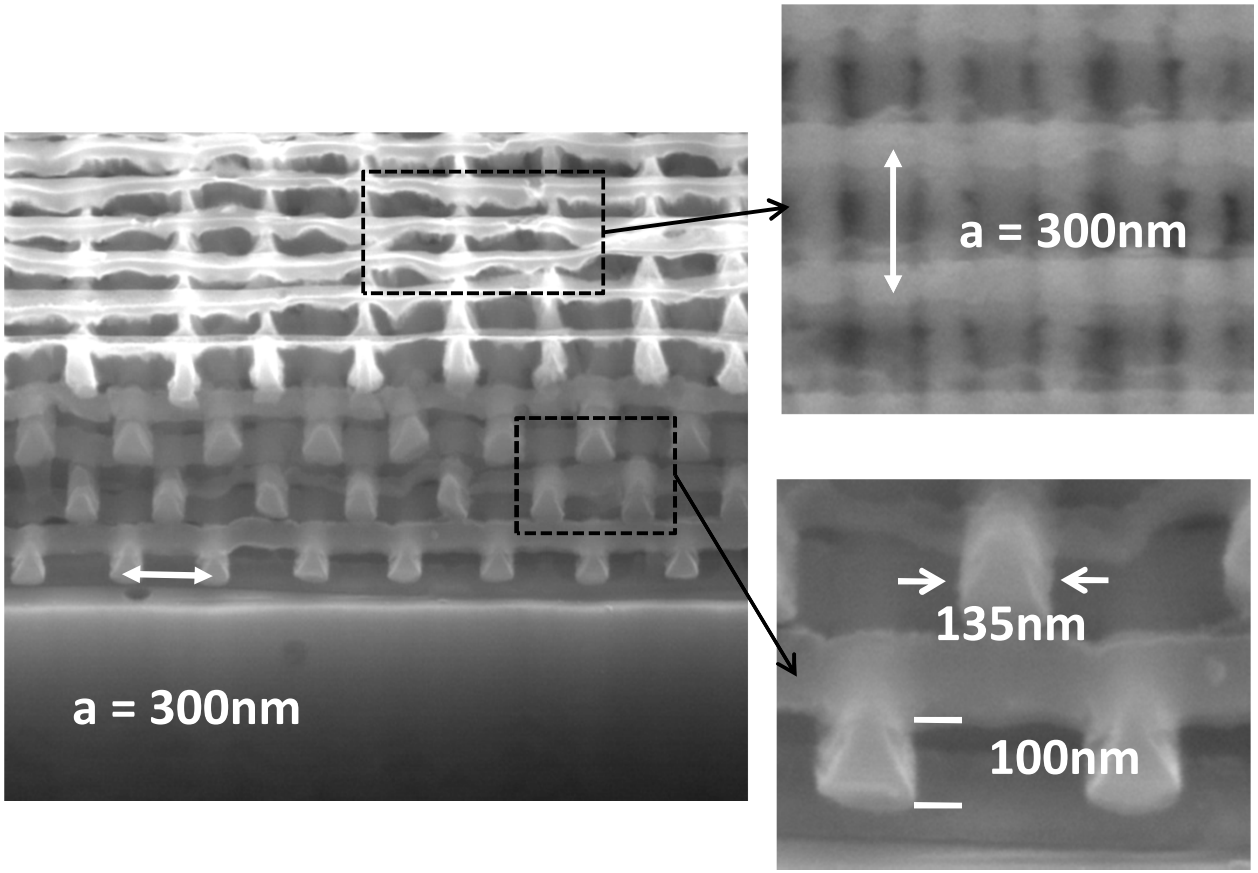


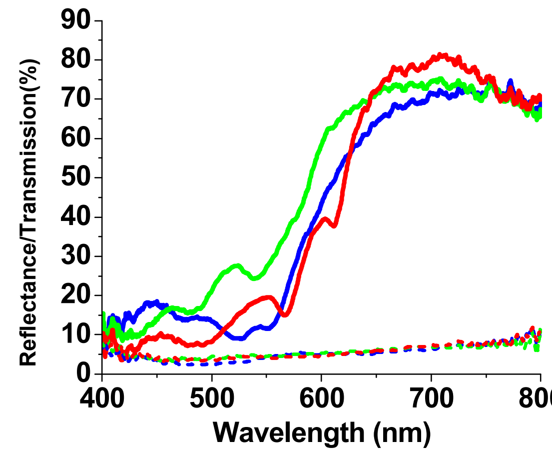
G. Subramania, Y. J. Lee, A. J. Fischer, T. S. Luk, C. J. Brinker, D. Dunphy, Appl. Phys. Lett. , **95**, 151101(2009)

GaN growth through logpile template



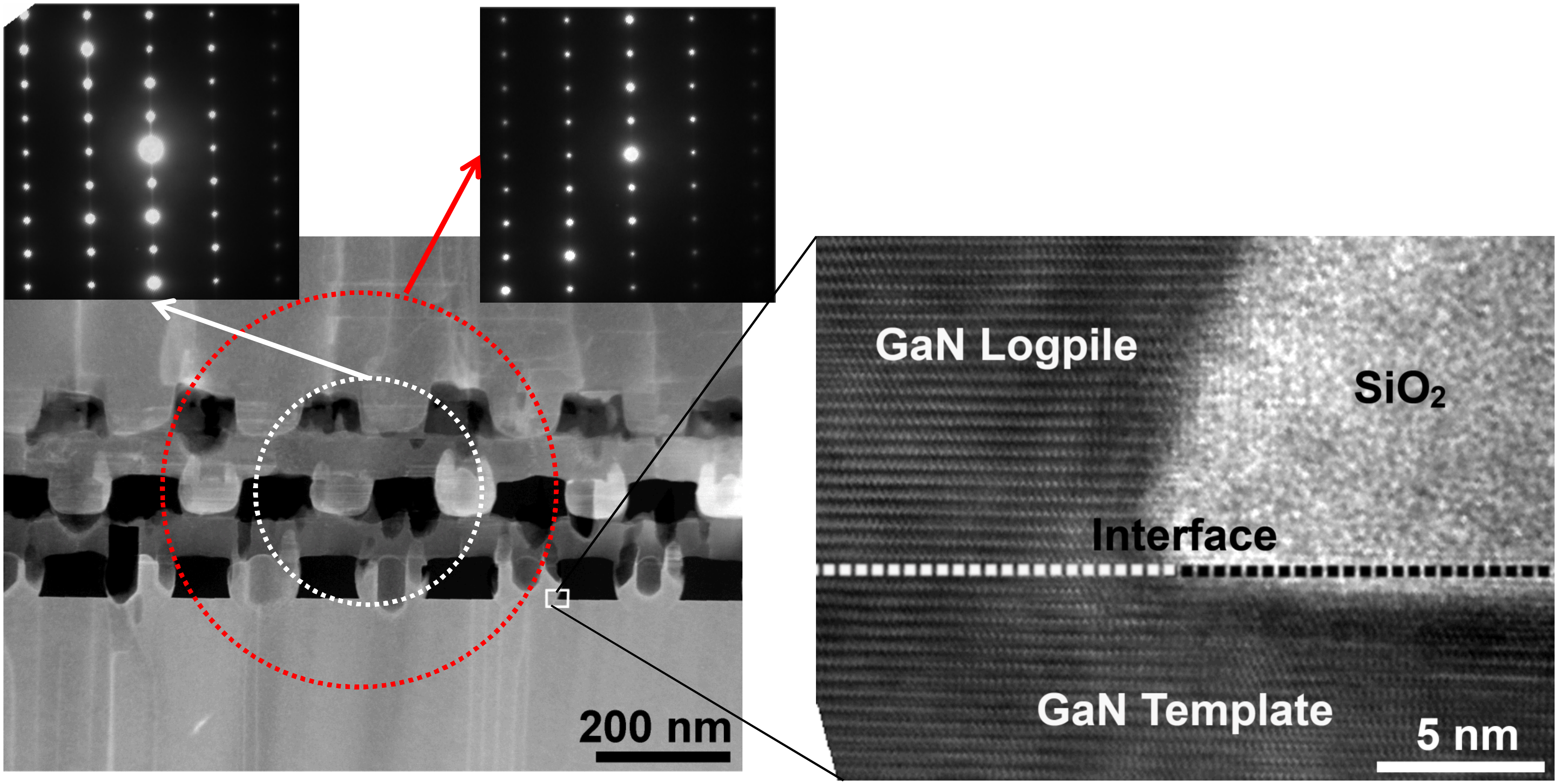
Epitaxial GaN logpile Photonic Crystal





G. Subramania, Q. Li, Y.-J. Lee, J. J. Figiel, G. T. Wang, and A. J. Fischer, Nano Lett. **11**, 4591 (2011).

Bottom-up epitaxial growth of crystalline GaN



G. Subramania et. al. , Nano Lett. **11**, 4591 (2011).

Fabrication of III-N nanowire laser array

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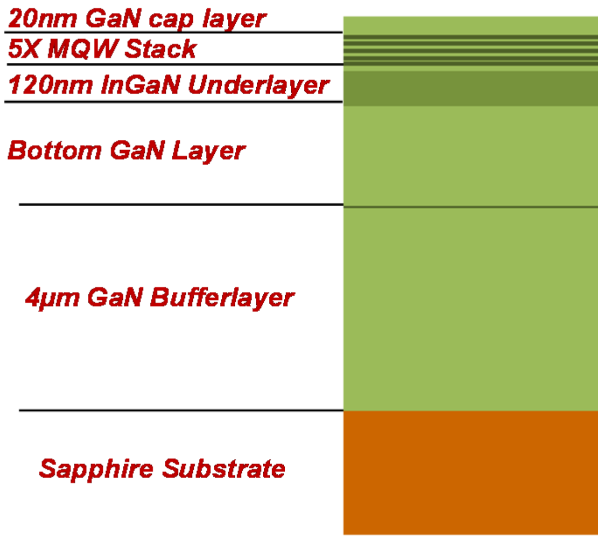
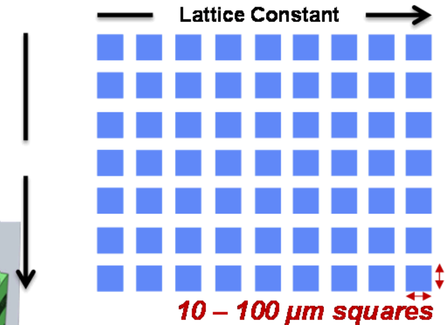
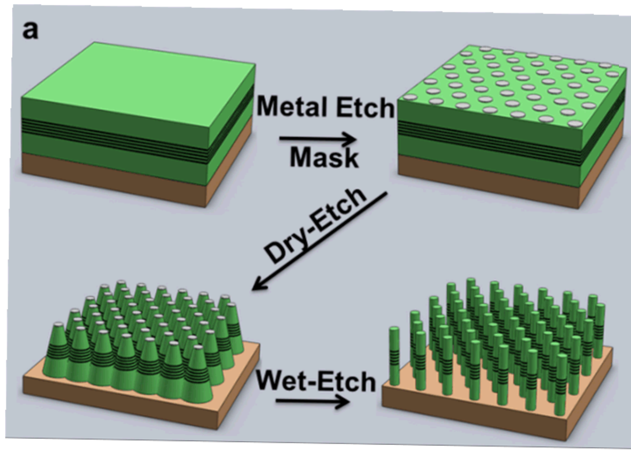
Growth of III-N active material

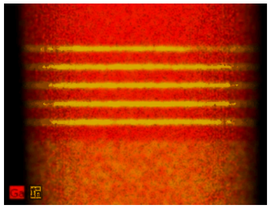


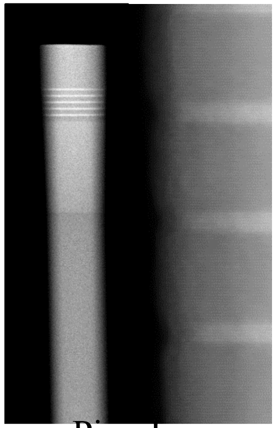
Patterning of 2DPC using e-beam lithography





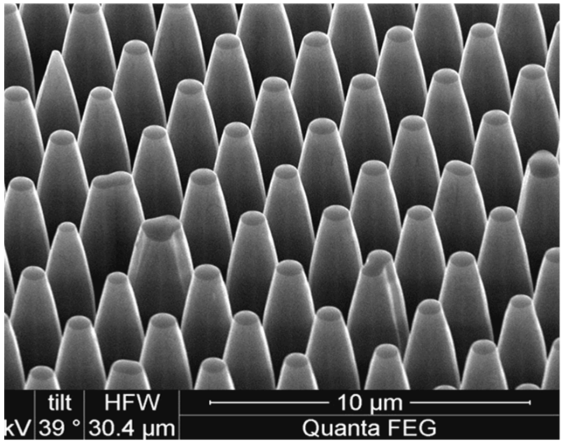
TEM images

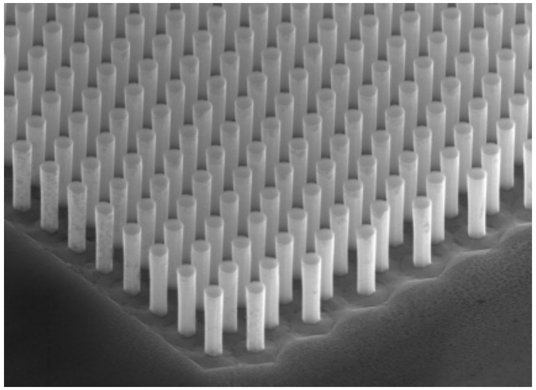




Ping Lu,
Sandia

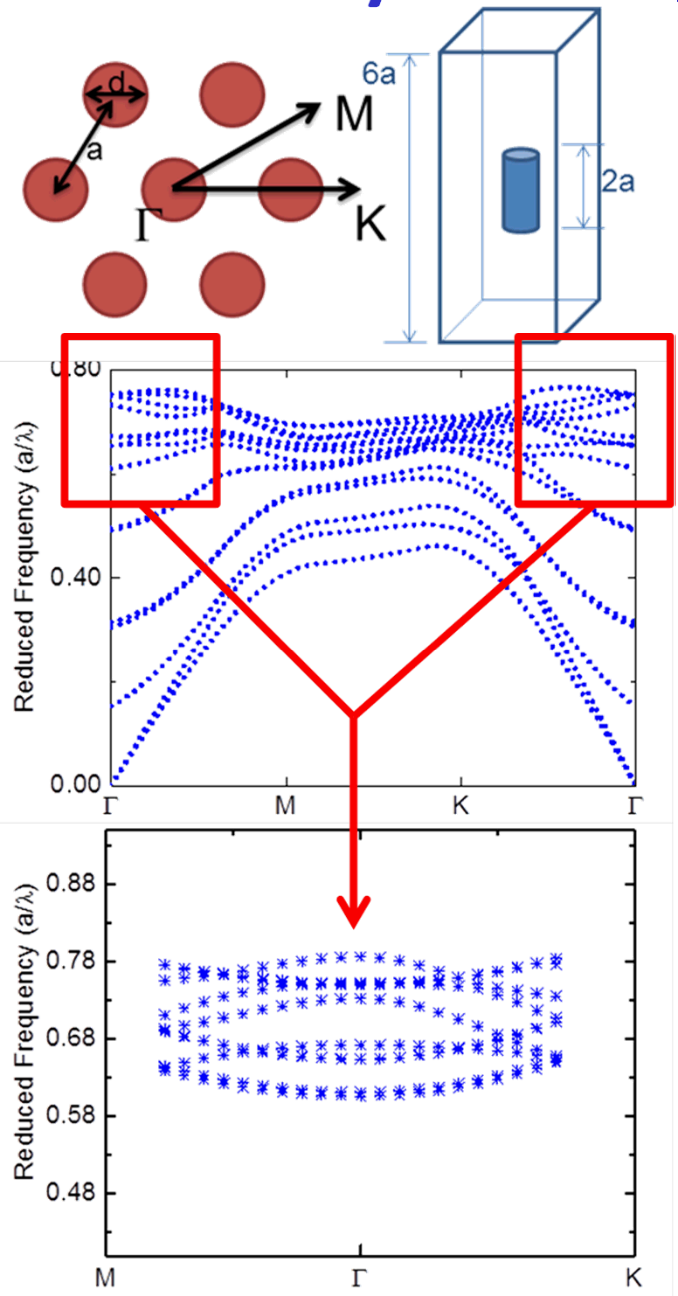
Inductively coupled plasma dry etch





Wet etch using KOH process

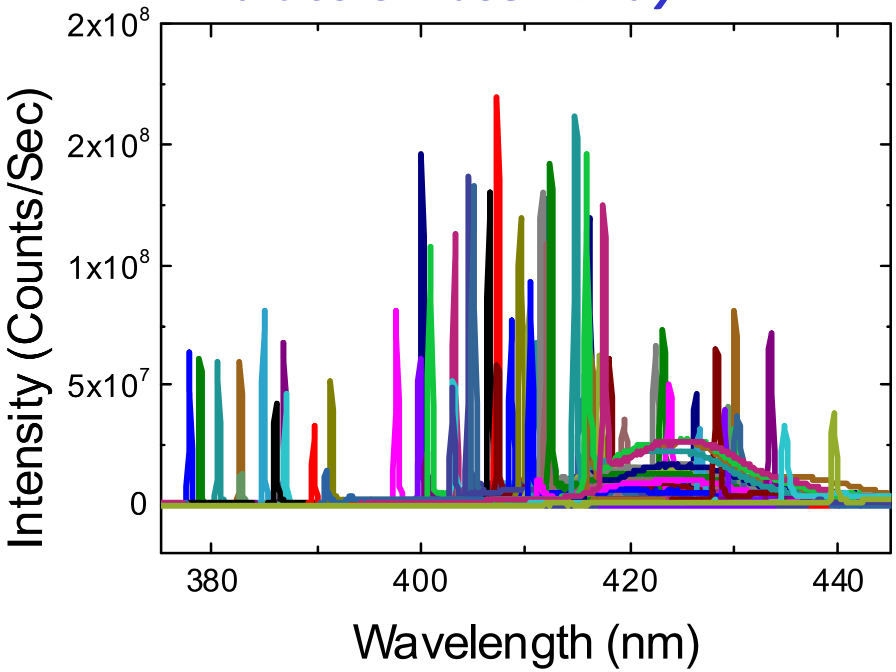
Vertically emitting photonic crystal lasers - Theory



- ***Low lasing threshold***
  - ***Increase interaction of light with the gain region***
  - ***Enabled by 'Low group velocity modes' in photonic crystal****
- ***Vertical Emission***
  - ***At higher bands there are low group velocity modes near the Gamma point***
  - ***Near the Gamma point the in-plane wave vectors are small resulting in near-normal emission***
- ***Wavelength Tunability***
  - ***Achieved through lattice constant and nanowire diameter variation***

*Sakoda, K. *Optical Properties of Photonic Crystals*. (Springer-Verlag, 2001).

Multicolor Laser Array



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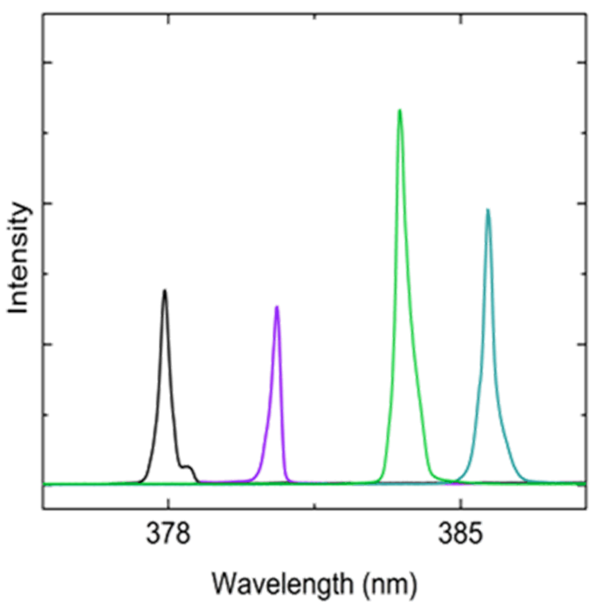
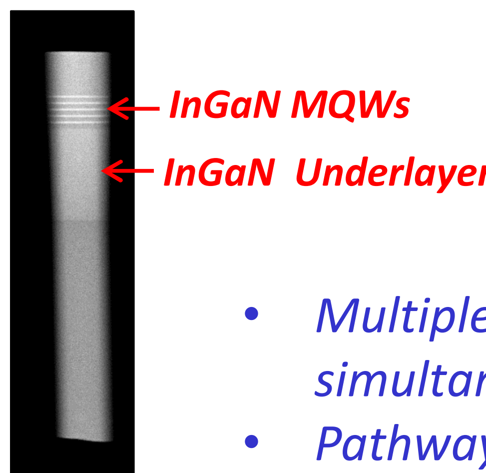
- *Wavelength tunability (lattice constant and nanowire diameter).*
- *Multiple color laser emission on a single epitaxial wafer covering a spectral range from 380-440nm.*



Gain from multiple gain sections

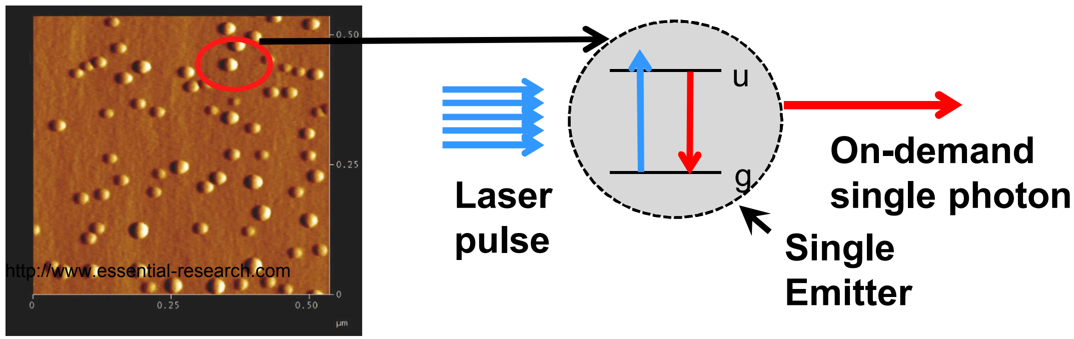


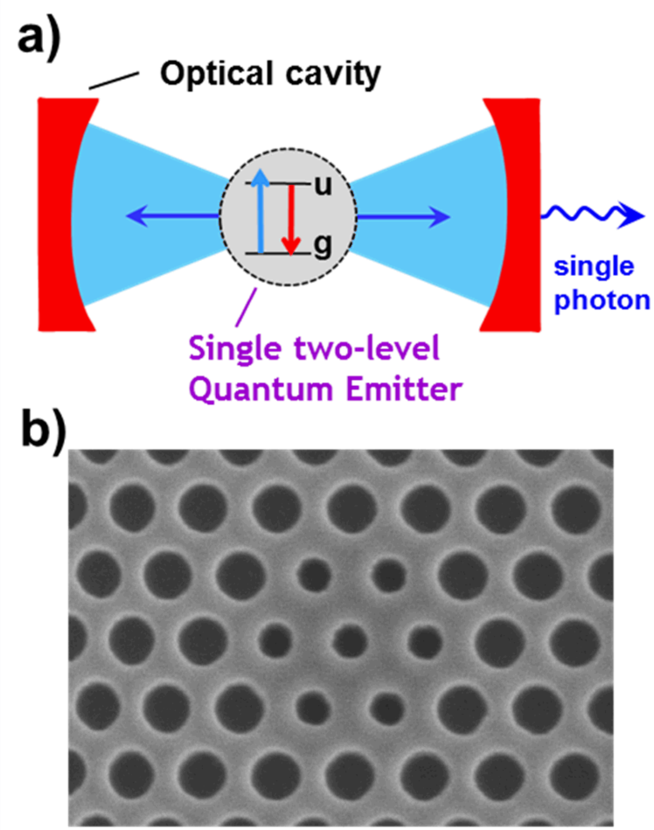
- *Multiple gain regions can simultaneously lase*
- *Pathway for enhancing the available lasing spectral range*

Single Photon Source based on Quantum Dots

with A.J.Fischer; D.Koleske; W.Chow

AFM image of InAs QDs



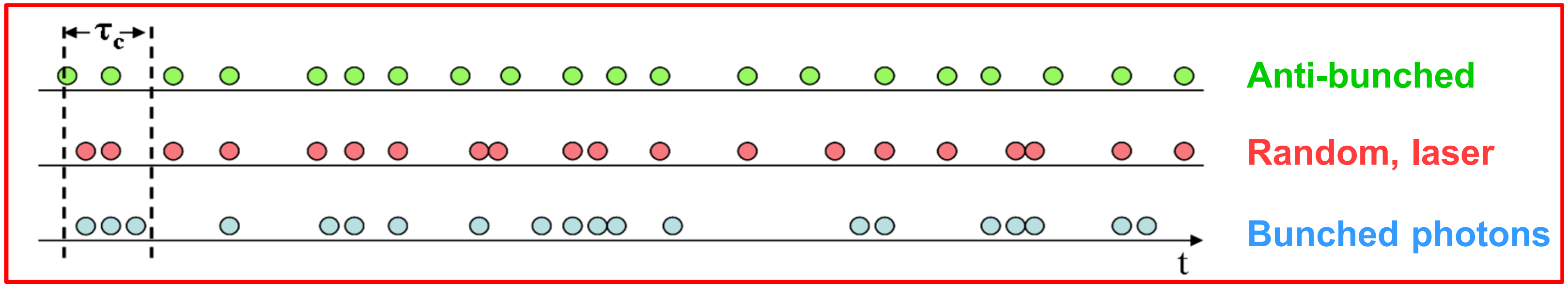


Sandia 2D photonic Crystal Cavity

Nitride based QD Single Photon Source:

- Large exciton BE so R.T operation
- Path to electrical-injection/chip-scale integration
- Only one photon can be emitted
  - Absorption of one photon saturates transition
  - Can be excited using many photons
  - **Deterministic Source: on demand**
- Triggered emission within radiative lifetime
  - Short emitter lifetime (~ 1 ns) → Fast rep. rate
- Isolate emission from a single quantum dot

Single Photon Source: Photon Statistics



source: J.S. Lundeen

Classical light sources: **$g(2)(t = 0) \geq 1$**

- Bunched or random photons (Laser, LED, thermal source)

Quantum light source: **$g(2)(t = 0) < 1$**

- Anti-bunched photons (Quantum optics theoretical treatment)

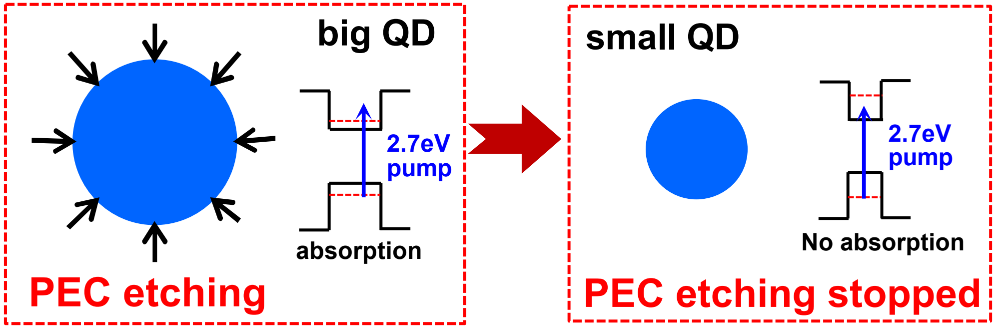
Applications:

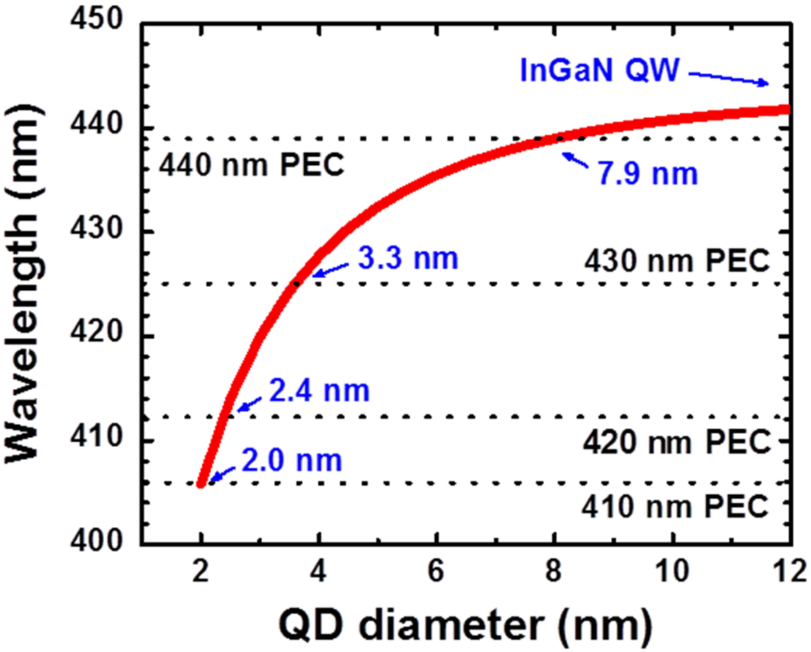
- **Quantum key distribution**
  - **Attenuated laser can be used**
  - **SPS is the gold standard for QKD**
  - **Future QKD involving quantum repeaters**
- **Quantum metrology**
- **Quantum computing with photons**
- **True random number generation**

Fabrication of InGaN QDs via PEC etching

Quantum Size Control: Use size quantization to control QD size

Self-limiting PEC etch process:





G. Pellegrini, et al., Journal of Applied Physics 97, 073706 (2005).

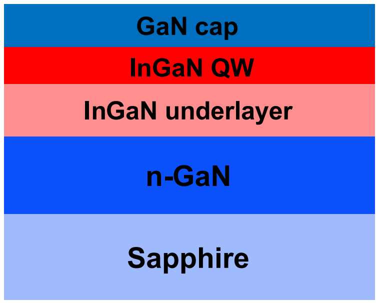
- **For QDs, band gap depends on size**
- **As etch proceeds,**
  - **QD size gets smaller, band gap goes up**
  - **Etch terminated for $E_g > E_{photon}$ pump**
- **Self-terminating etch process**
- **Band gap selective**
- **QD size depends on PEC wavelength**
- **Monodisperse QD distributions ??**

Xiao, X. *et al.* Quantum-Size-Controlled Photoelectrochemical Fabrication of Epitaxial InGaN Quantum Dots. *Nano Lett.* **14**, 5616-5620, doi:10.1021/nl502151k (2014).

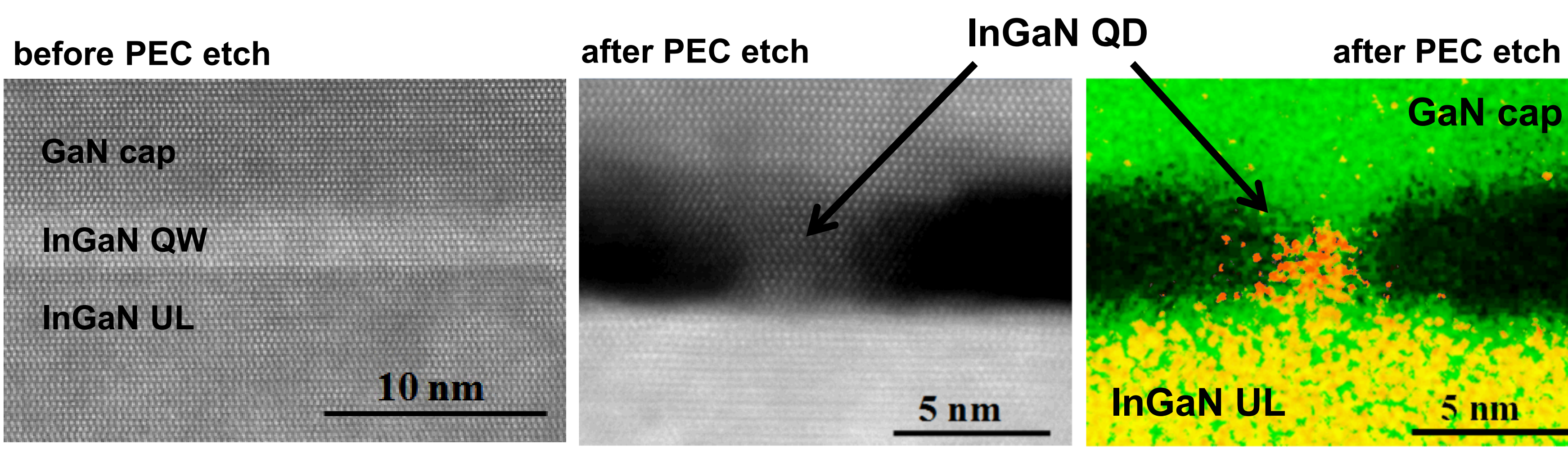
Transmission Electron Microscope Images

Xiaoyin Xiao

Capped InGaN QW



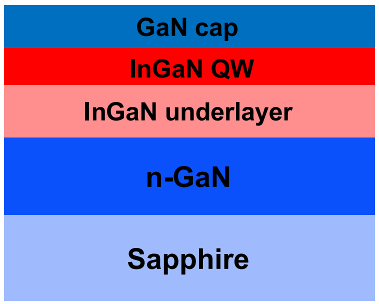
- High-angle annular dark-field (HAADF) TEM images
- Sample etched at 420 nm
- EDX mapping shows that dots are InGaN
- InGaN QDs are epitaxial to the underlying GaN
- 2% InGaN underlayer + GaN cap → PL is much brighter
- GaN cap provides partial passivation



Xiao, X. *et al.* Quantum-Size-Controlled Photoelectrochemical Fabrication of Epitaxial InGaN Quantum Dots. *Nano Lett.* **14**, 5616-5620, doi:10.1021/nl502151k (2014).

Photoluminescence from fabricated InGaN QDs

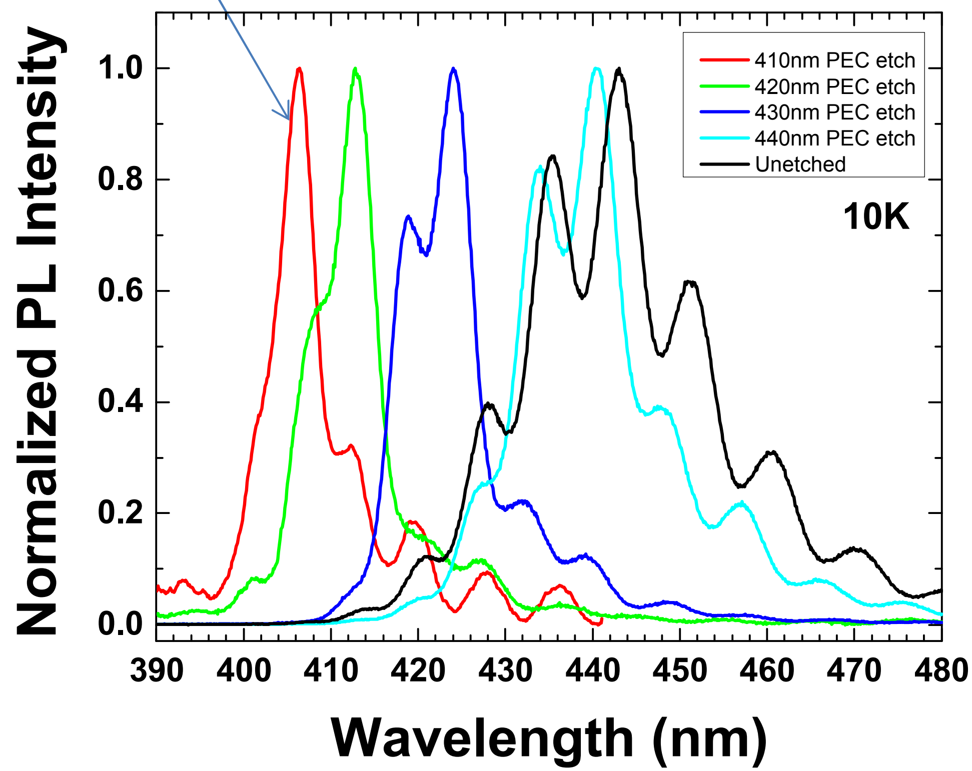
Capped InGaN QW



Photoluminescence (PL) data:

- **375 nm pump (ps pulsed)**
- **10K PL data**
- **PL wavelength determined by PEC etch wavelength**
- **PL linewidth: 24 nm → 6 nm**
- **Quantum size-controlled PEC etching works!**

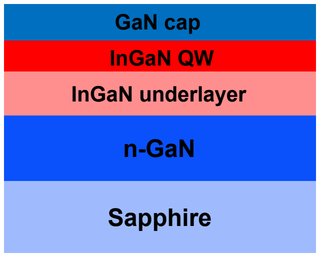
As narrow as **6 nm** FWHM is consistent with a narrowing of the QD size distribution



Xiao, X. *et al.* Quantum-Size-Controlled Photoelectrochemical Fabrication of Epitaxial InGaN Quantum Dots. *Nano Lett.* **14**, 5616-5620, doi:10.1021/nl502151k (2014).

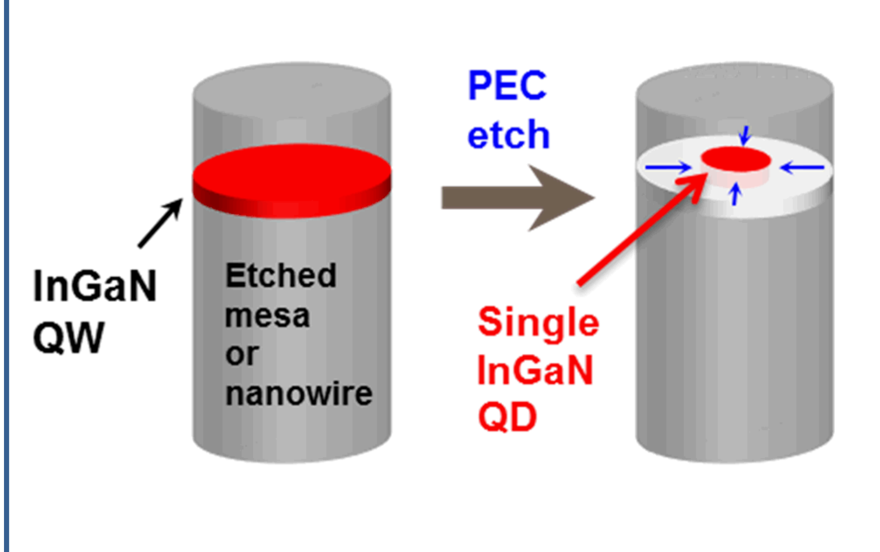
Emission from single InGaN QDs

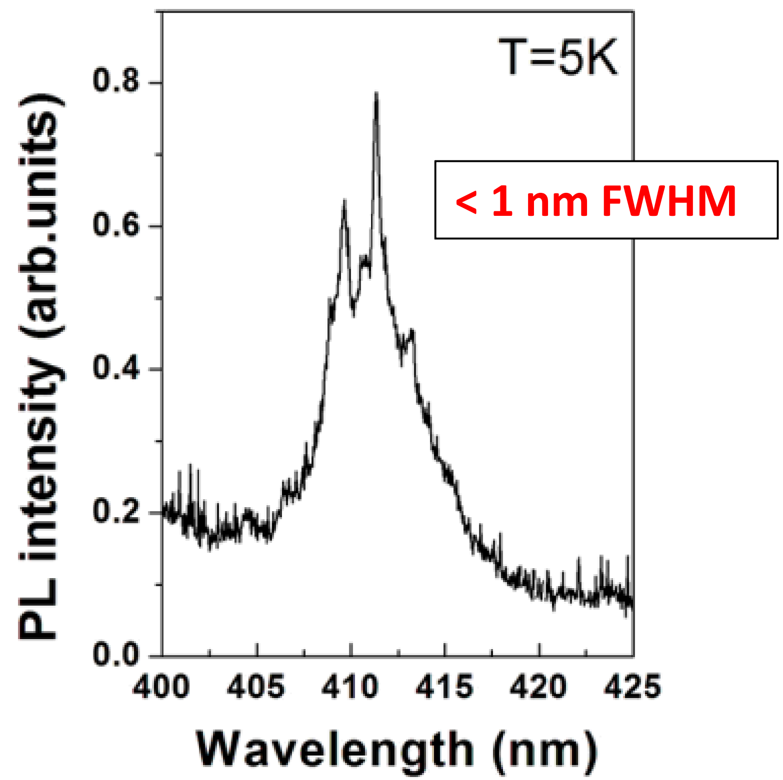
Capped InGaN QW



- Posts (150 – 200 nm) patterned with e-beam lithography
- Narrow PL emission (<1 nm FWHM) observed
- Fabricate InGaN QDs at deterministic locations
- InGaN QD single photon source

Fabrication of single InGaN QDs





Next steps:

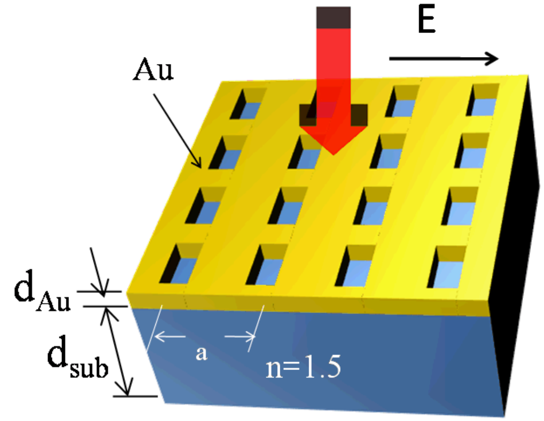
- Perform g2 measurement
- Create cavity for photon confinement for SPS

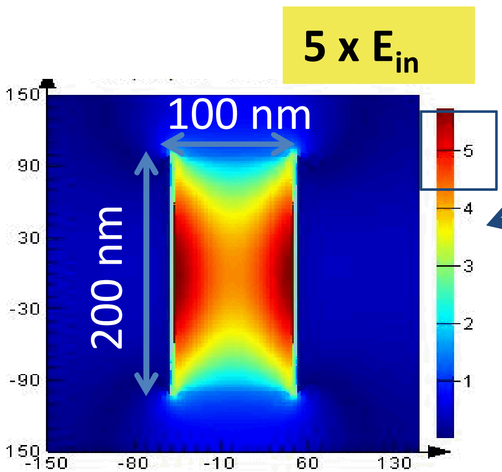
Light Confinement in Nanoscale Area

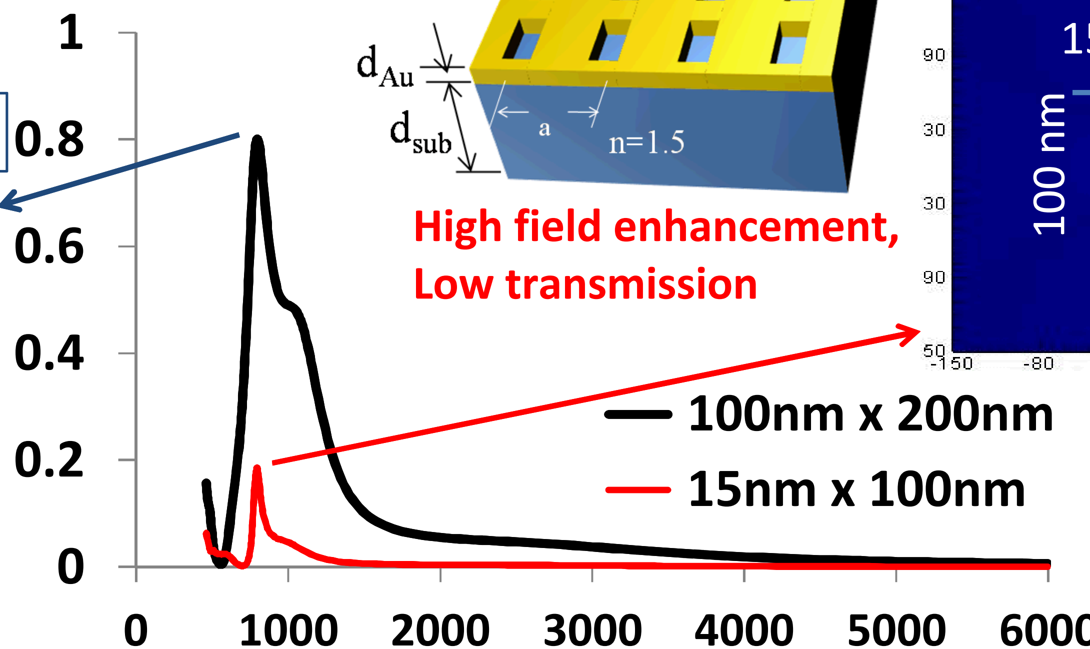
Sandia National Laboratories

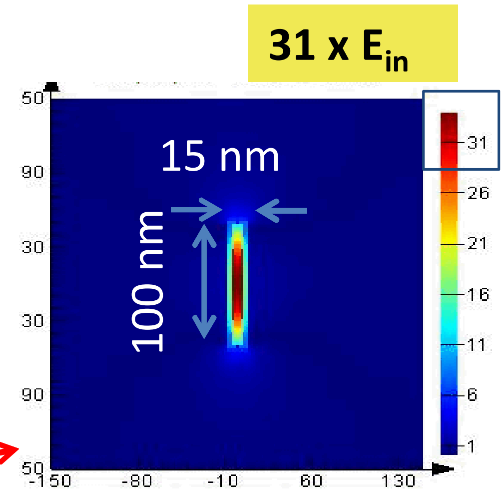
Current approach : Surface plasmon based using EOT phenomenon

Resonant









High field enhancement, Low transmission

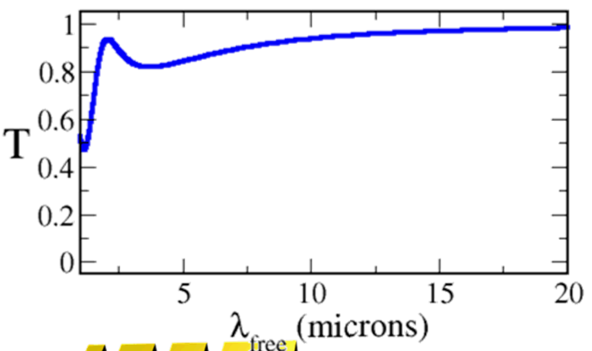
Large transmission, Low field enhancement

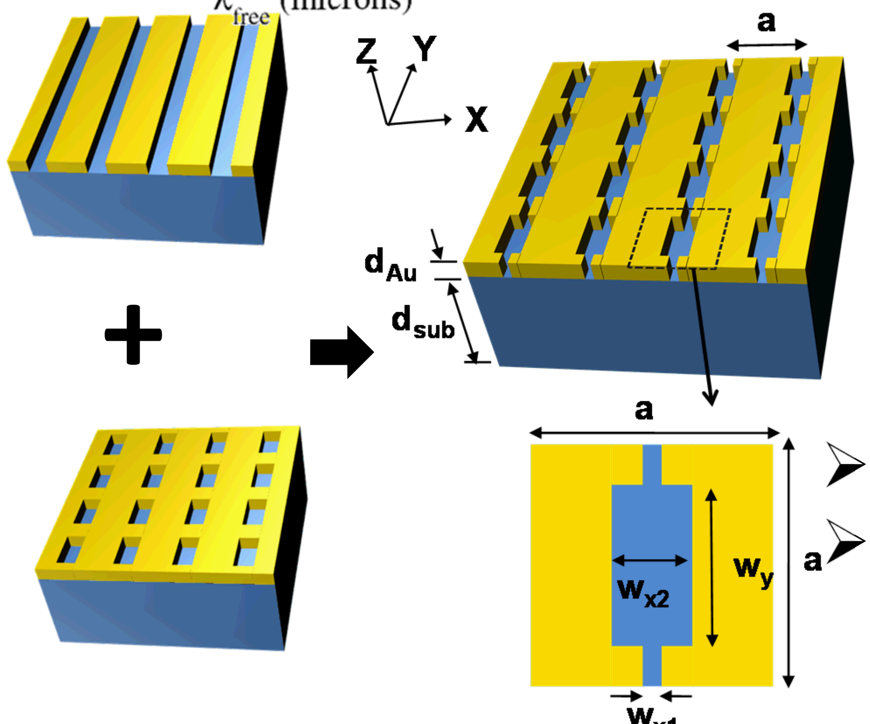
Can we achieve light confinement/field enhancement with broadband operation?

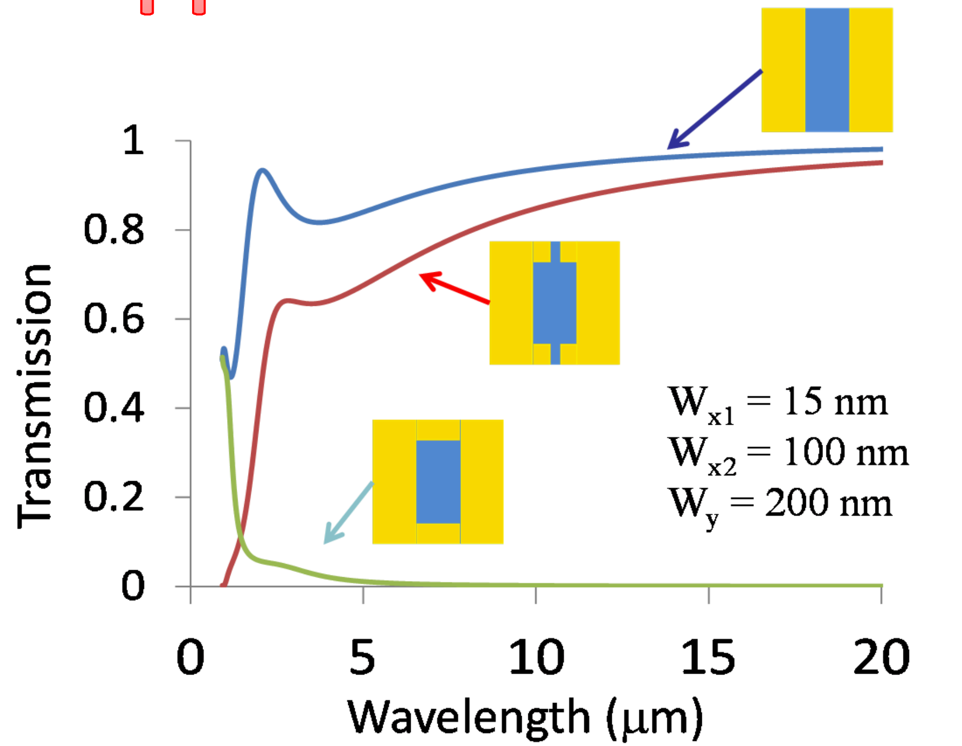
The Double-groove Structure

(In collaboration with S. Foteinopoulou- Univ. of Exeter, UK (*Now at UNM*)and I. Brener)

A: Non-resonant Approach







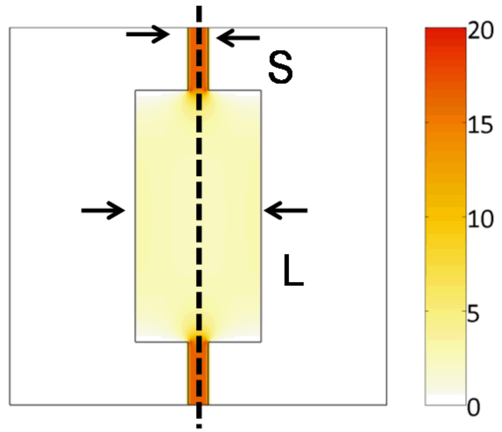
- Broadband transmission
- Large electric field enhancement and confinement

G. Subramania, S.Foteinopoulou and I. Brener, Phys. Rev. Let., 107, 163902(2011).

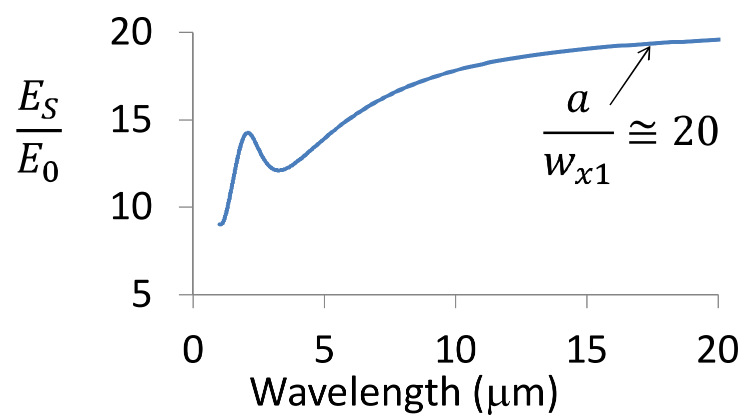
Key Results

Sandia National Laboratories

Electric field (E_x)

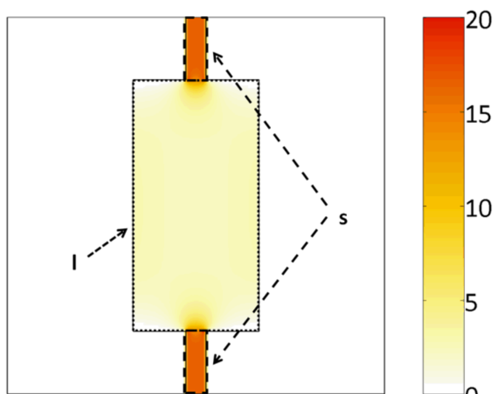


Electric field enhancement in the small gap

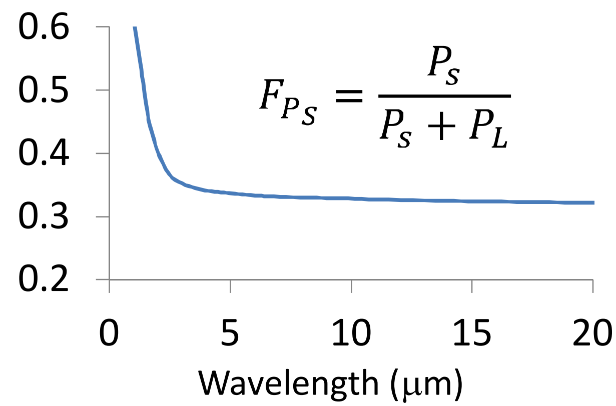


We can achieve large electric field enhancements in an ultra-subwavelength area (~ **$(\lambda/250)^2$**) across broadband that can be controlled via structural geometry

Power Density (S_z)

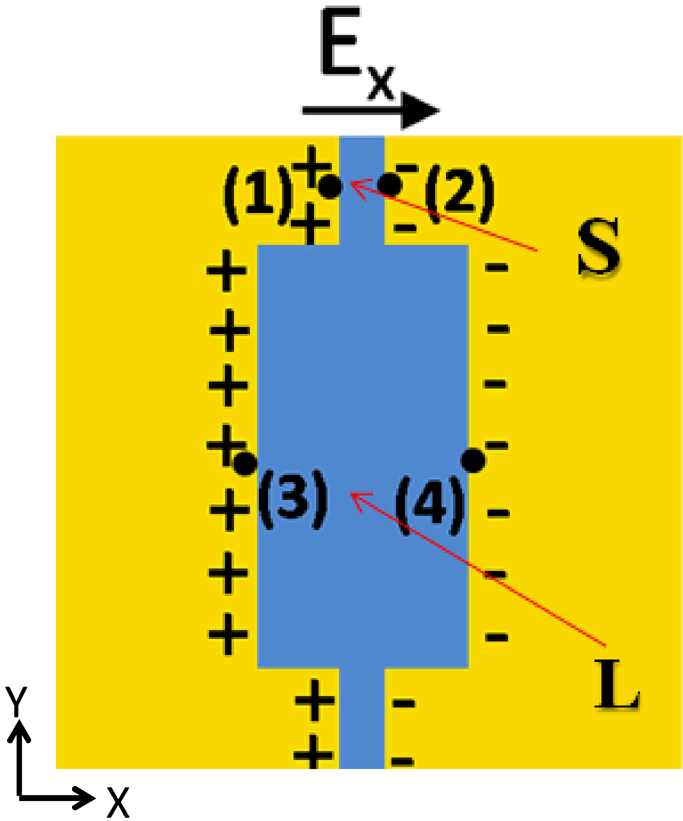


Power Fraction through the small gap



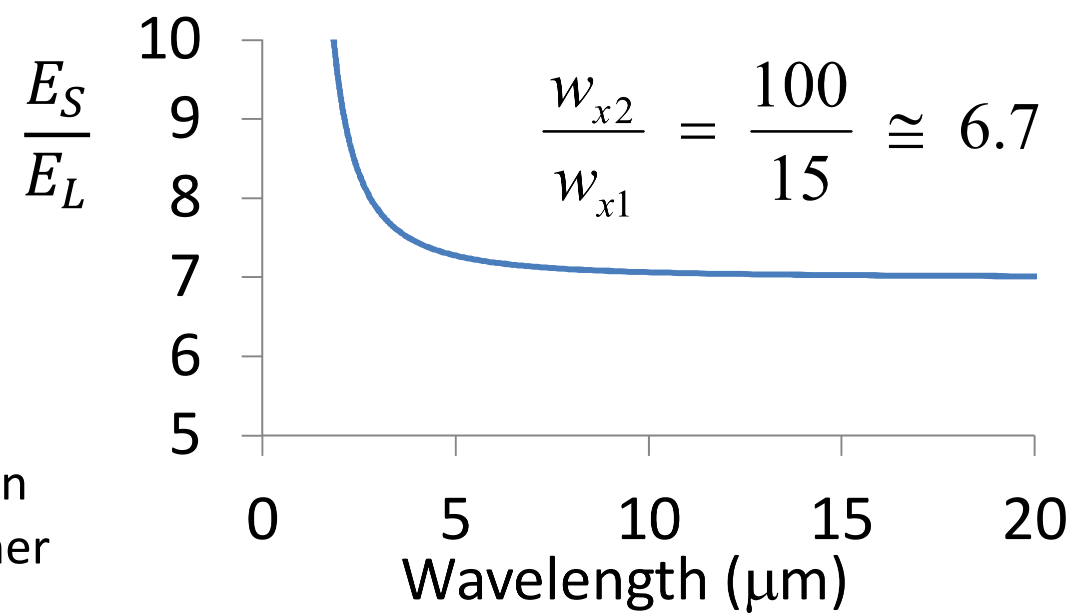
Surprisingly, nearly 30% of the transmitted power that is channeled through an area ~ **$(\lambda/250)^2$** that is **1/60th** of the unit cell area.

Mechanism: Quasi-static response



- Voltage across the small and large gaps are nearly equal

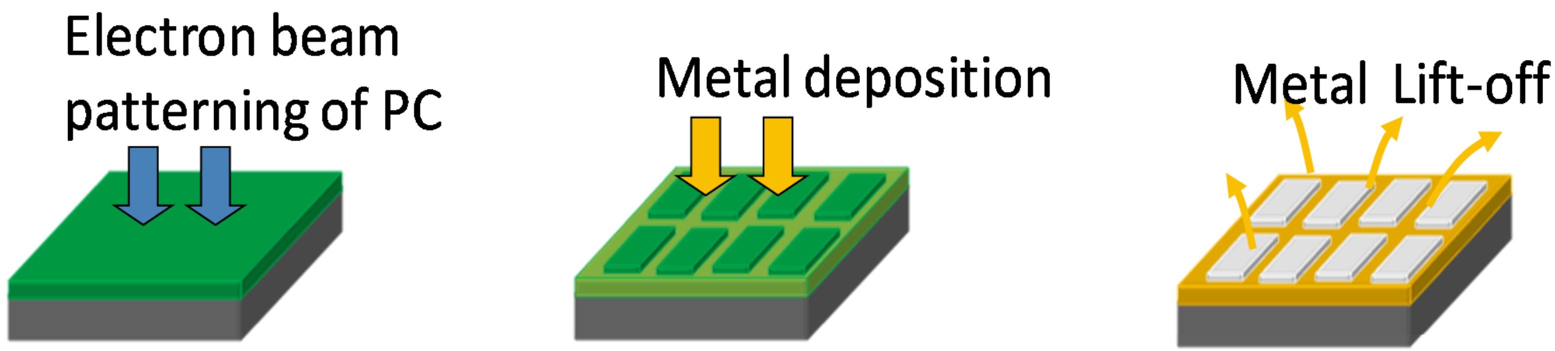
$$V_S \cong V_L \Rightarrow \frac{E_S}{E_L} = \frac{w_{x2}}{w_{x1}}$$

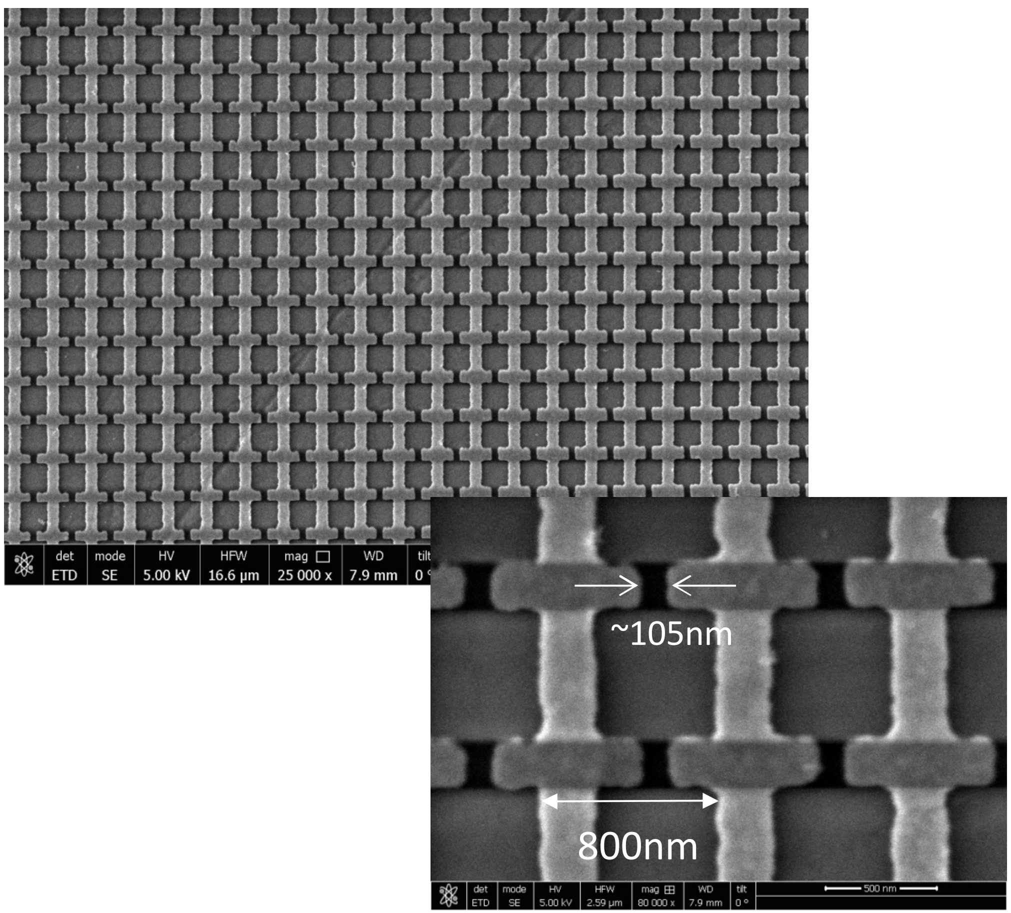


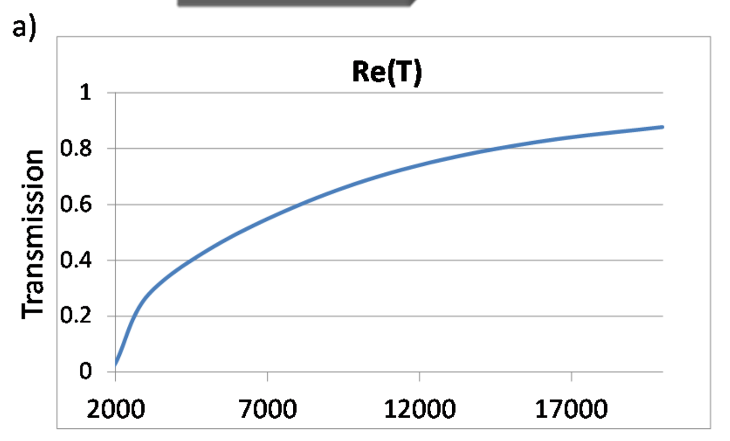
- Near-instantaneous response of charges even at mid-IR
- No effective current flow between small and large gap region on either side

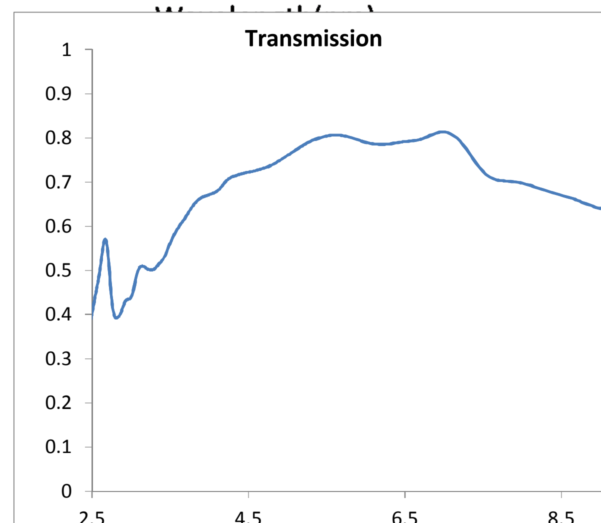
G. Subramania, S.Foteinopoulou and I. Brener, Phys. Rev. Let., 107, 163902(2011).

Fabrication- Some recent results

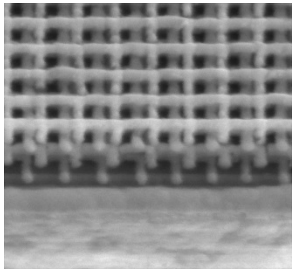




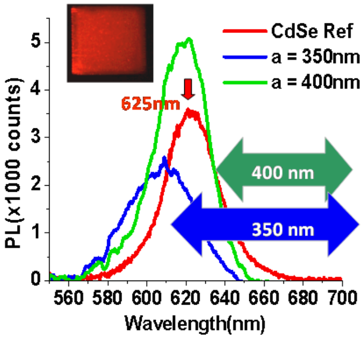




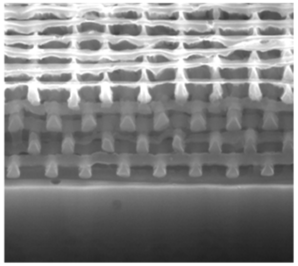
Summary

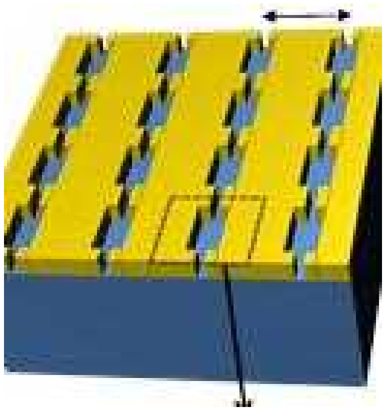


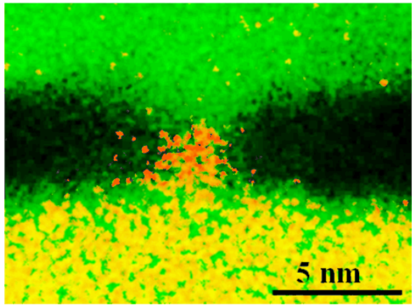
- Spontaneous emission control in logpile TiO_2 PC
- Epitaxially grown GaN logpile PC

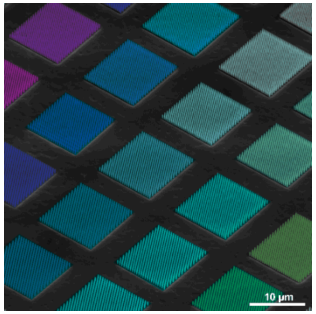


- Low-threshold multicolor nanowire lasers
- PEC etched size controlled III-nitride quantum dots
- Non-resonant nanoscale light confinement structures





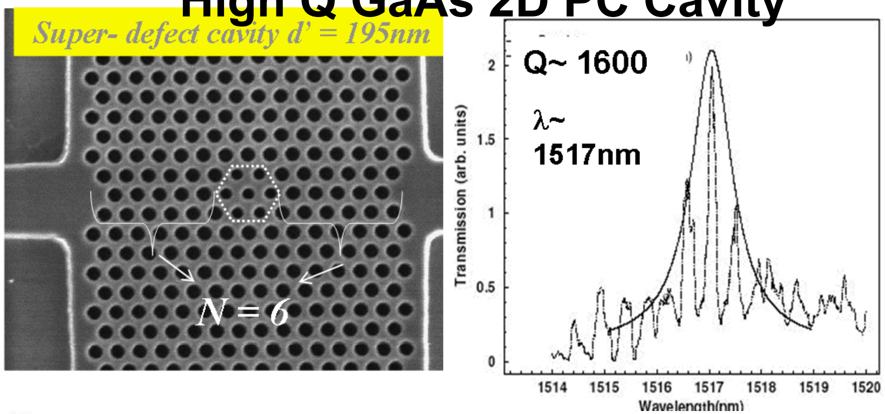




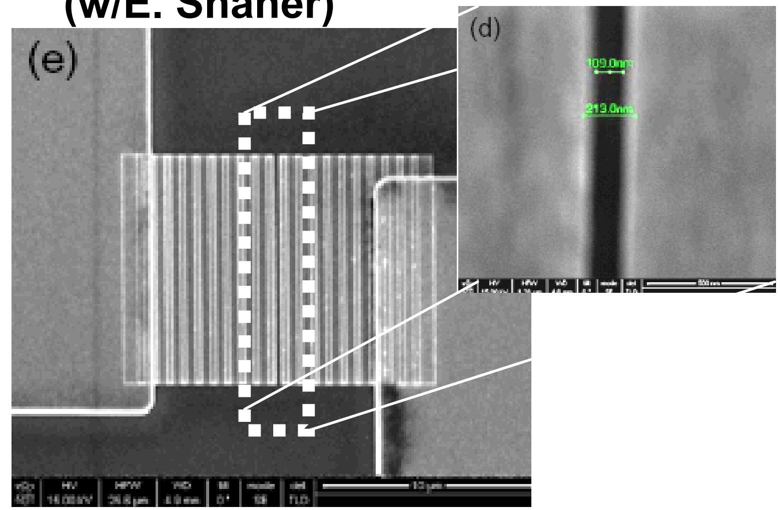
Thank you for your attention!

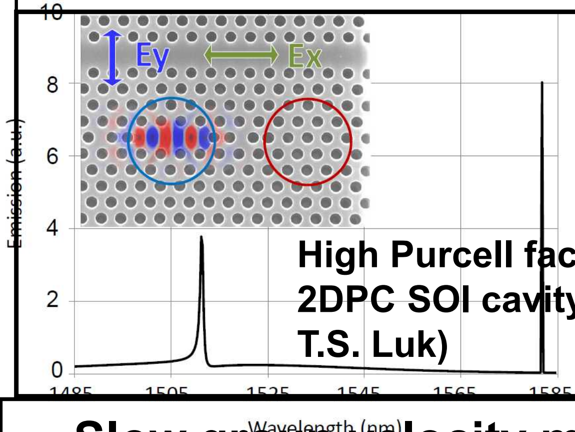
L-M Interaction in 2DPC

High Q GaAs 2D PC Cavity



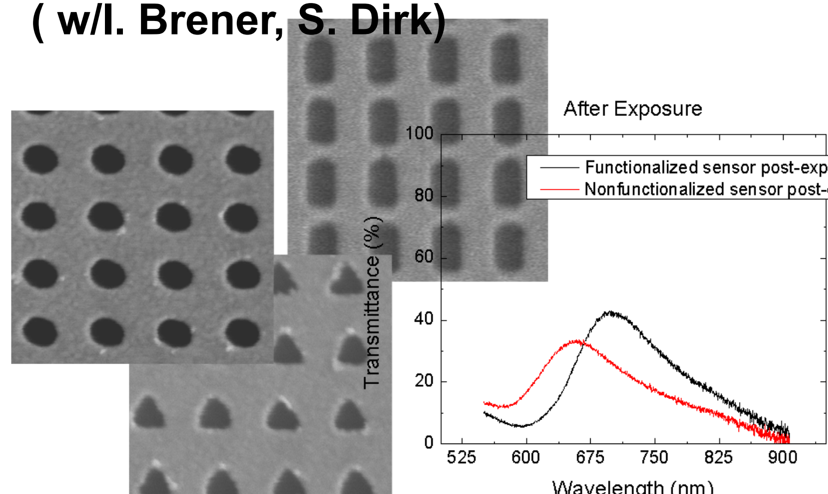
Surface plasmon Auston Switch (w/E. Shaner)



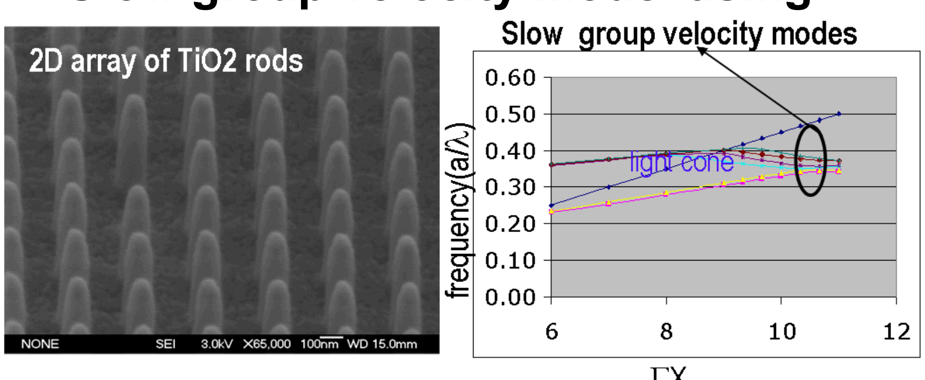


High Purcell factor 2DPC SOI cavity (w/ T.S. Luk)

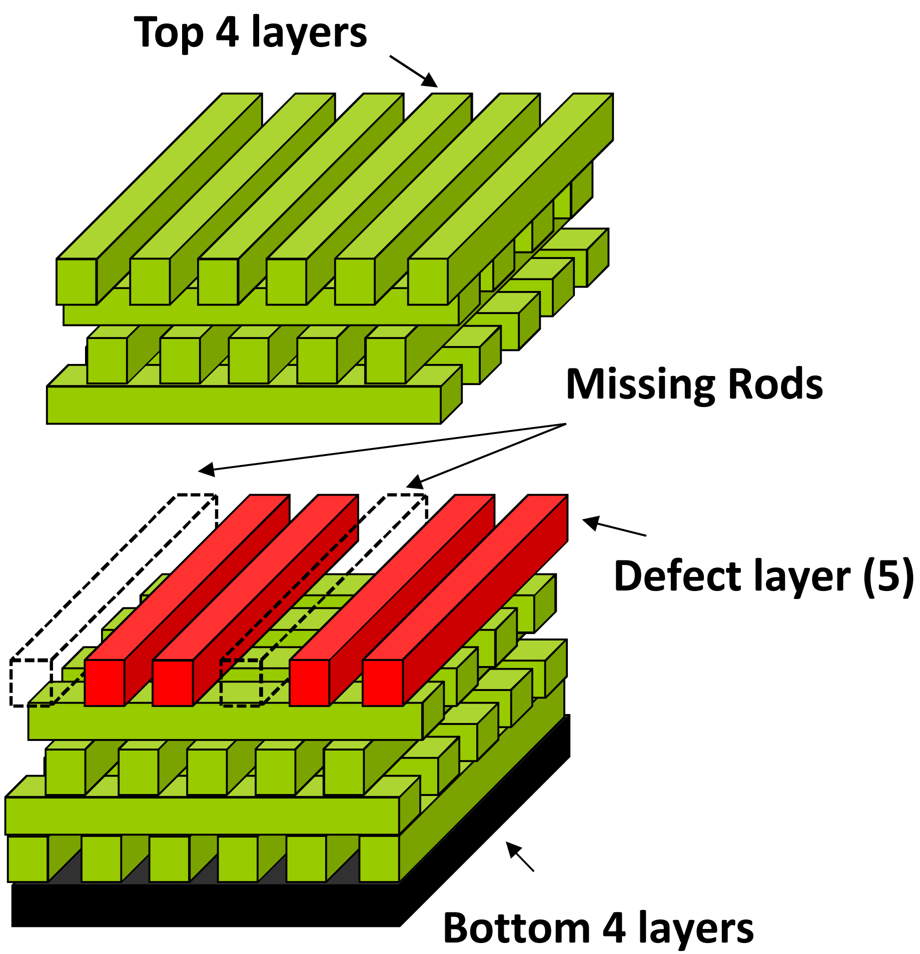
Nanhole EOT based sensors (w/I. Brener, S. Dirk)

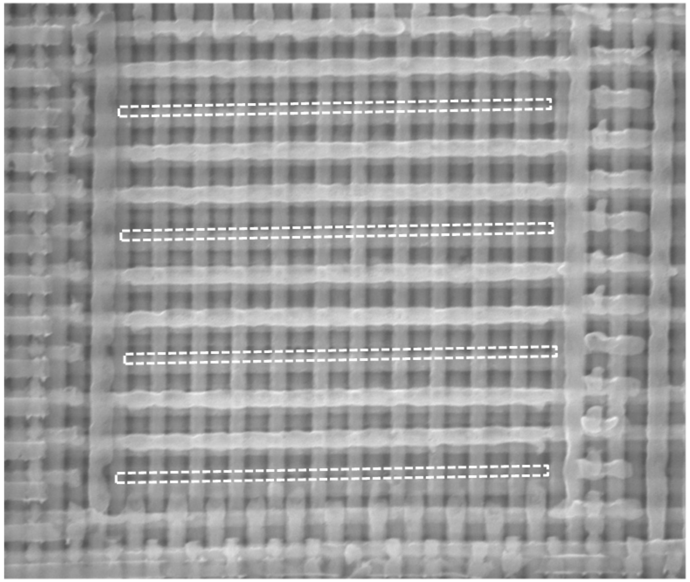


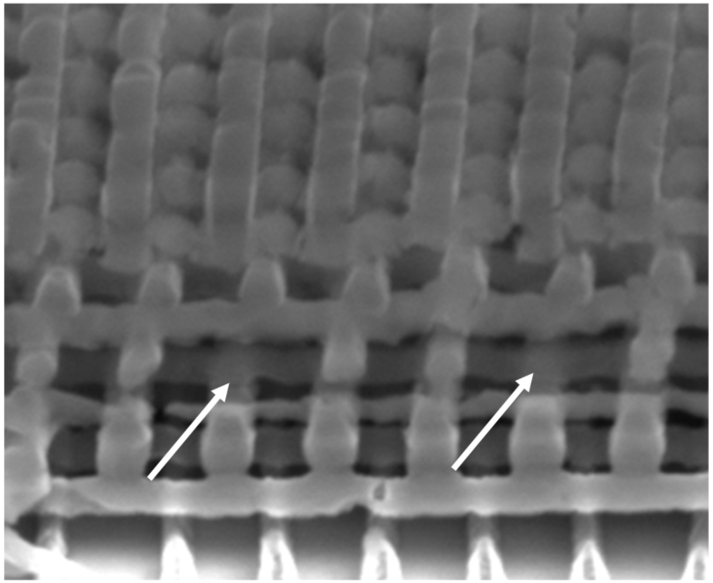
Slow group velocity mode lasing



Logpile PC Cavity



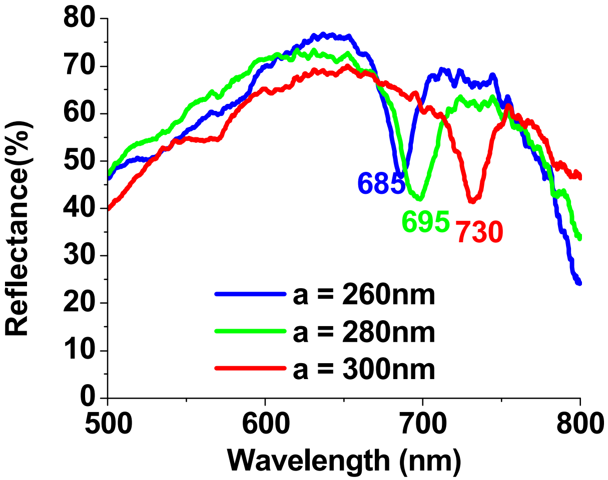




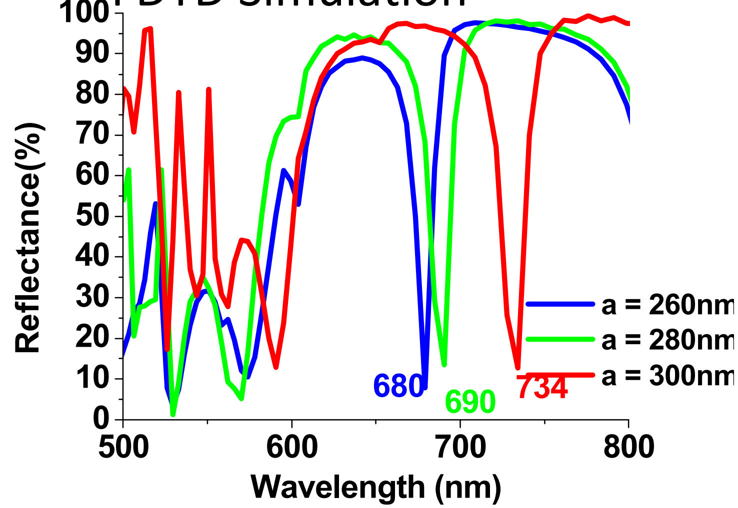
Logpile PC Cavity Optical Response

Reflection

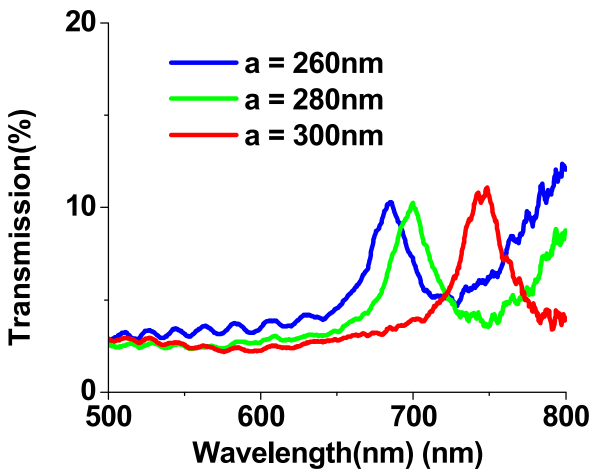
Experiment

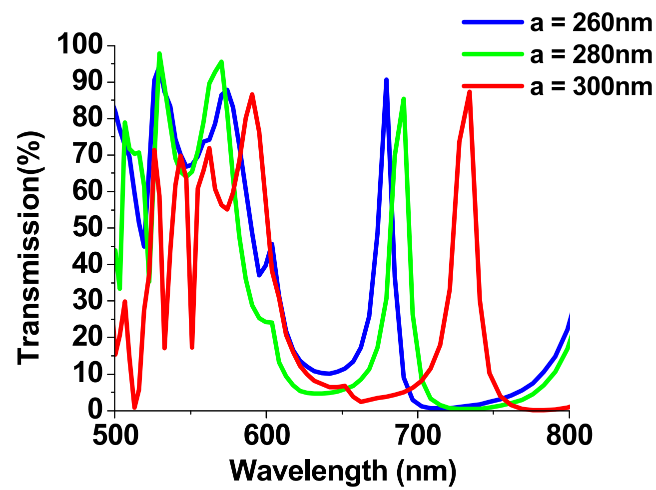


FDTD Simulation



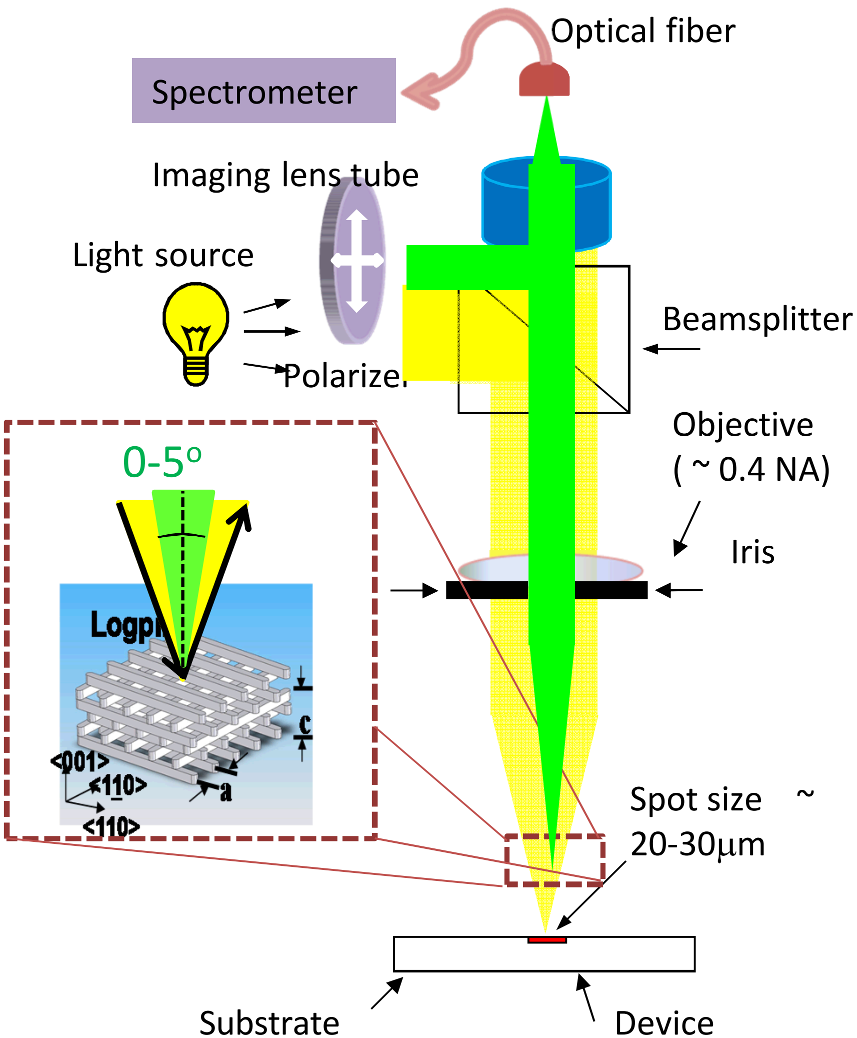
Transmission

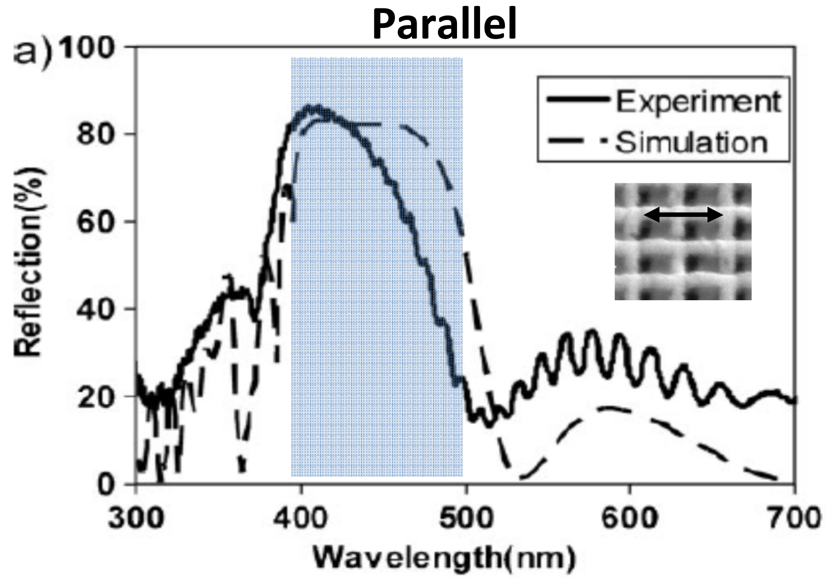


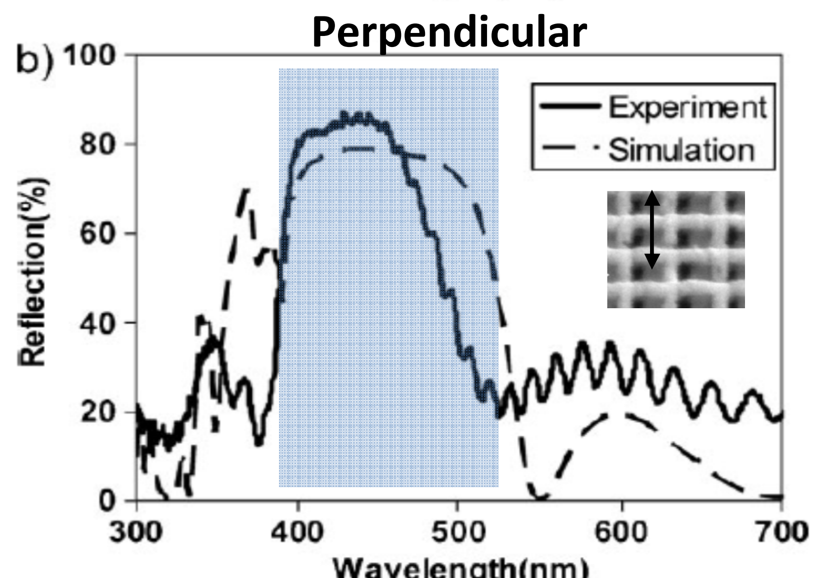


G. Subramania et. al. , Nano Lett. **11**, 4591 (2011).

Visible- Near UV 9 Layer TiO_2 Logpile



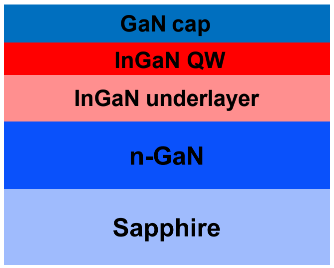




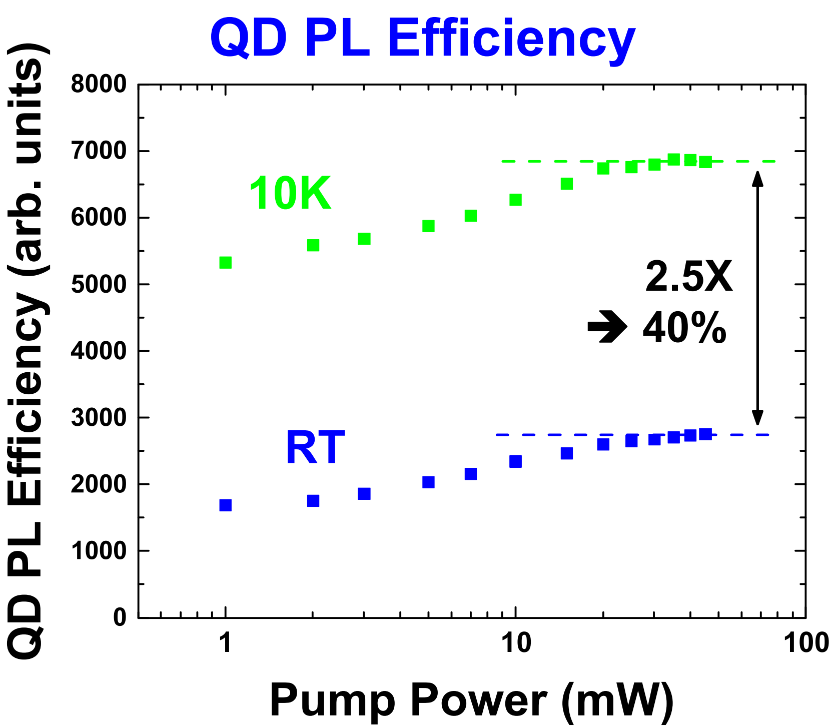
G. Subramania, Y.-J. Lee, A. J. Fischer, and D. D. Koleske, Advanced Materials **22**, 487-491 (2010)

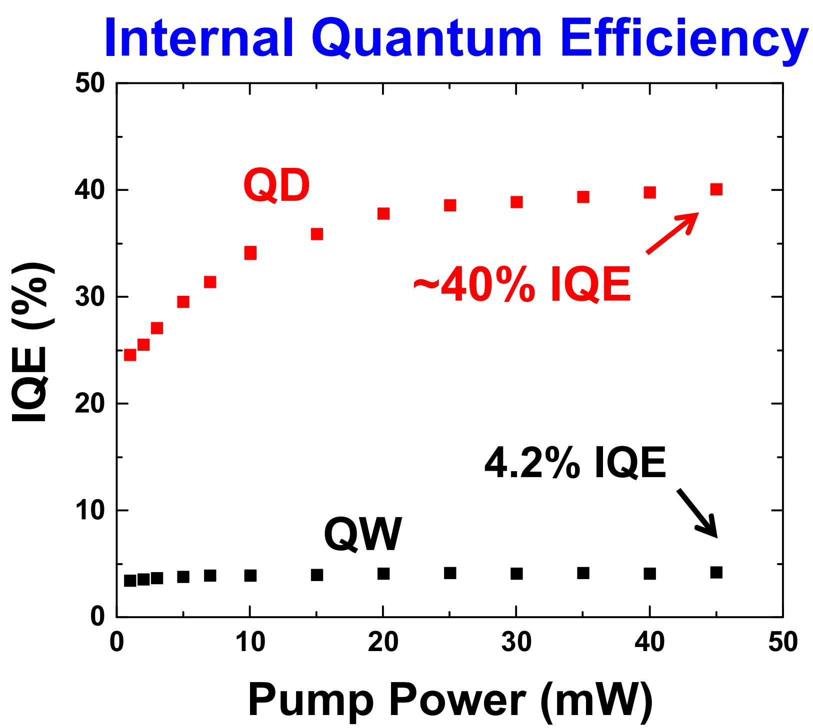
InGaN QD internal quantum efficiency

Capped InGaN QW



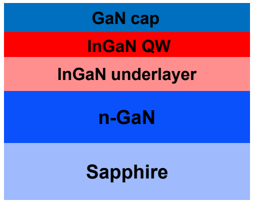
- Compare 10K and RT PL efficiency
- Assumes 10K PL is 100% efficient
- PL Intensity drops by >100X after QD etching
- IQE goes up by almost 10X after QD etching
- QDs are expected to have better IQE

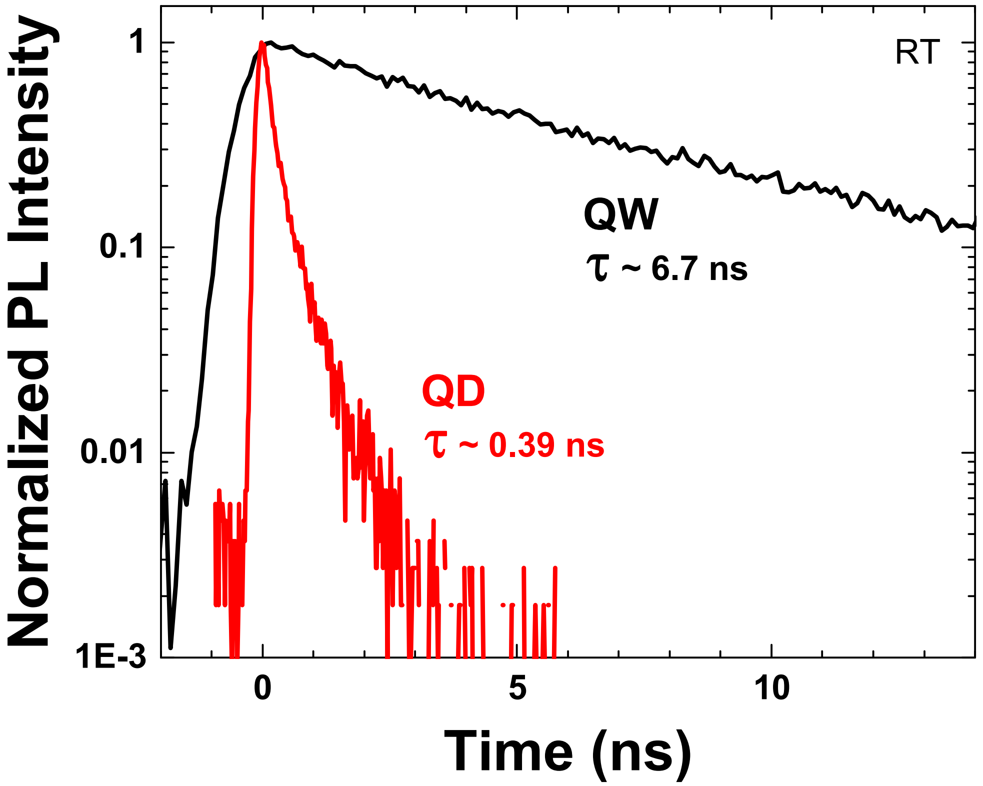




Time-resolved PL data from InGaN QDs

Capped InGaN QW

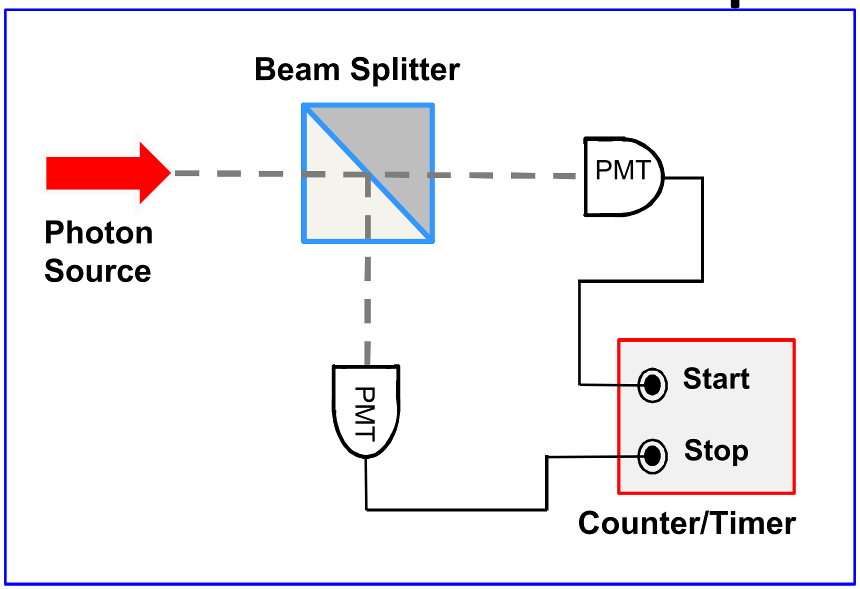




TRPL data:

- 405 nm pump (~ 2 ps, pulsed)
- Resonant pumping into InGaN
- Room temperature TRPL data
- Hamamatsu streak camera data
- 17X change in PL lifetime
- Lifetime is expected to be much shorter for QDs
- Shows that we have fundamentally changed the InGaN material
- QW → QDs

Single Photon Measurement: HBT experiment

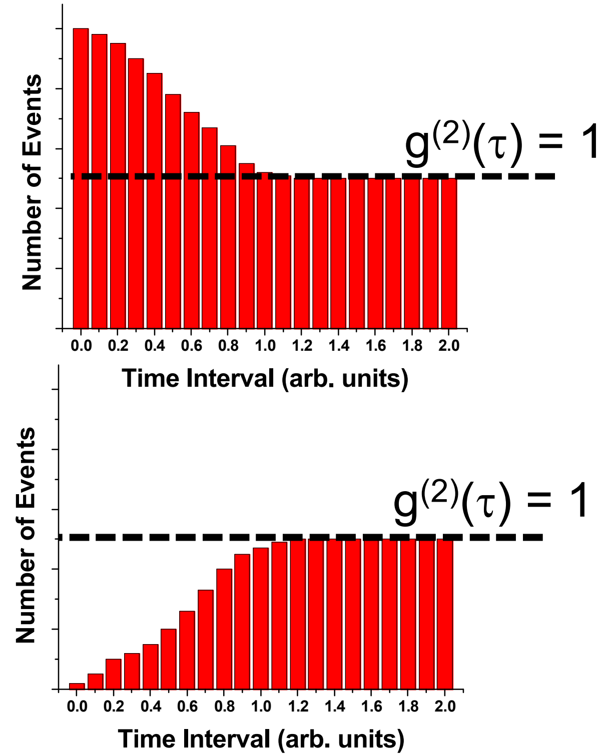


Thermal Source

$g^{(2)}(0) > 1$

Quantum Source

$g^{(2)}(0) < 1$

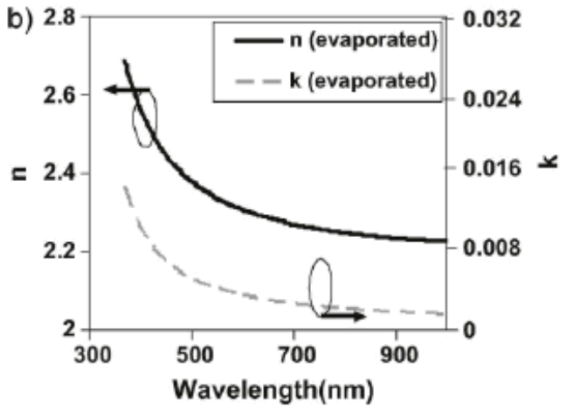


- Non-polarizing beamsplitter to split intensity between detectors
- Single photon counting required
  - Use PMTs or avalanche photodiodes
  - Single photon counting modules
- Measure correlation between detected photons
- Detectors: low QE, speed, and dark counts

Visible Frequency Logpile Photonic Crystal

Sandia National Laboratories

Choice : TiO_2



Requirements:

- **High enough index with low loss in the visible :**
  - n ~ 2.3-2.4 in the visible /w k< 0.015
- **Easy to deposit :**
  - Sputtering, evaporation, solgel, Atomic Layer Deposition

Band Structure Calculation

Solve Electromagnetic wave equation for Plane wave

$$\begin{cases} E(r,\ t) \propto e^{-i\omega t} \\ H(r,\ t) \propto e^{-i\omega t} \end{cases}$$

$$\nabla \times \left(\frac{1}{\varepsilon(r)} \nabla \times H(r) \right) = \left(\frac{\omega}{c} \right)^2 H(r)$$

In a periodic potential

$$\varepsilon(r + R) = \varepsilon(r)$$

$$R = a_1\hat{x} + a_2\hat{y} + a_3\hat{z}$$

Apply Bloch's Theorem

$$E, H(r + R) = E, H(r)$$

Plane Wave Expansion Method

Sandia National Laboratories

Reciprocal (K) space

Reciprocal Lattice vector

$$\varepsilon(r) = \sum_G \overline{\varepsilon}(G) e^{iG.r} \qquad E, H(r) = \sum_G \overline{E}, \overline{H}(G) e^{-i(-k+G).r} \qquad G \cdot R = 2\pi n$$

Bloch Waves $\overline{H}(G) = H_x(G)\hat{x} + H_y(G)\hat{y} + H_z(G)\hat{z}$

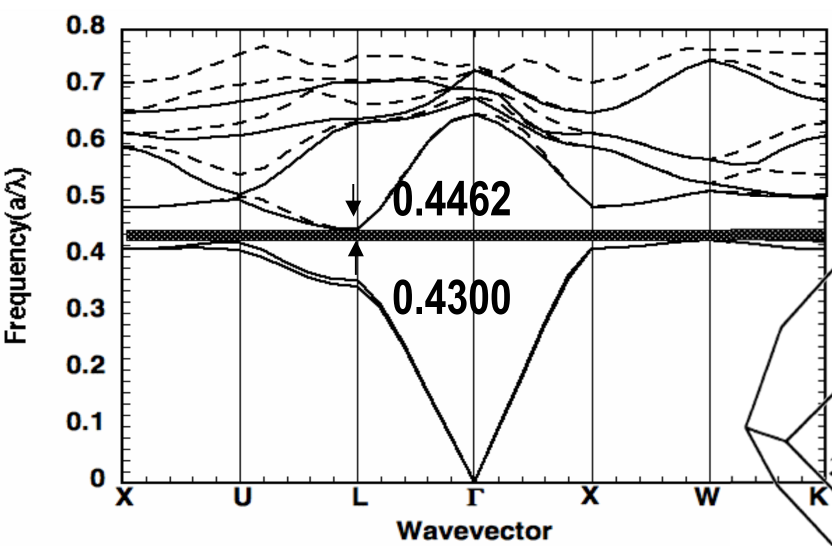
Eigen value equation

$$\nabla \times \left(\frac{1}{\varepsilon(r)} \nabla \times H(r) \right) = \left(\frac{\omega}{c} \right)^2 H(r) \quad \Rightarrow \quad A\overline{H_n}(k) = -\frac{a^2 \omega_n^2}{c^2} \overline{H_n}(k)$$

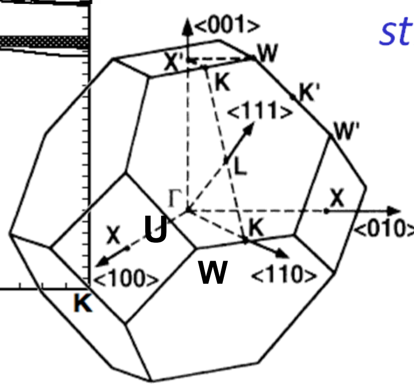
Band index

Wave vector within the first BZ

Photonic Band Structure for TiO_2 logpile



1st BZ



Eigen value equation becomes a matrix equation for which you can write a code and solve for band structure within the first Brillouin zone.

- **n ~ 2.3**
- **4% bandgap**
- **~ 20nm @ 500nm**

Summary / Future Possibilities

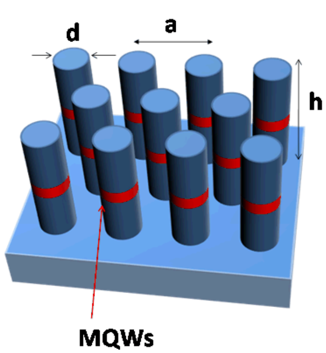
GaN

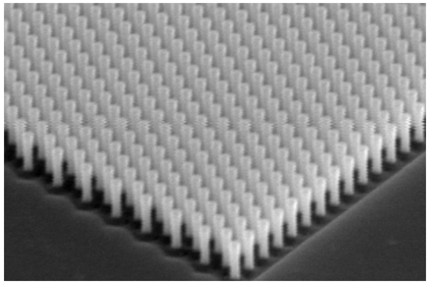
- Nanotemplated 3DPC growth possible (also demonstrated by UIUC group in GaAs)
- The GaN grows epitaxially maintaining crystallinity

- Solid state lighting app.
- Introducing InGaN QW emitters within the 3DPC during growth
- Newer QW geometries ? (axial vs. radial)
- Electrical injection

Fabrication is time consuming and challenging at this point !

Investigating 2DPC GaN nanopillar array based light emission

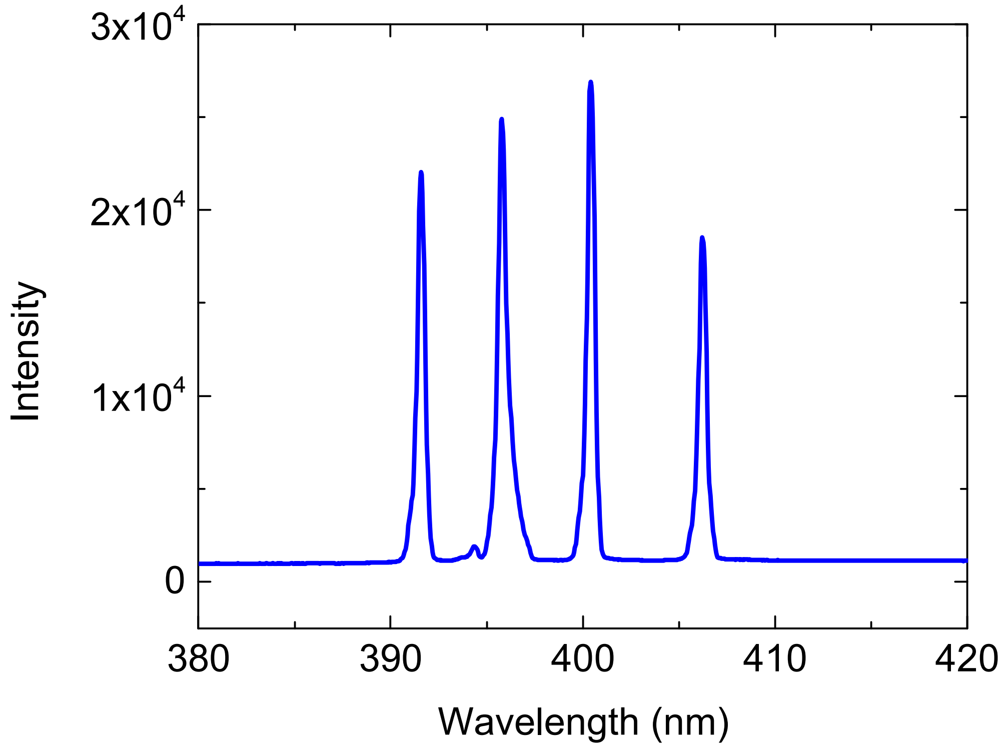


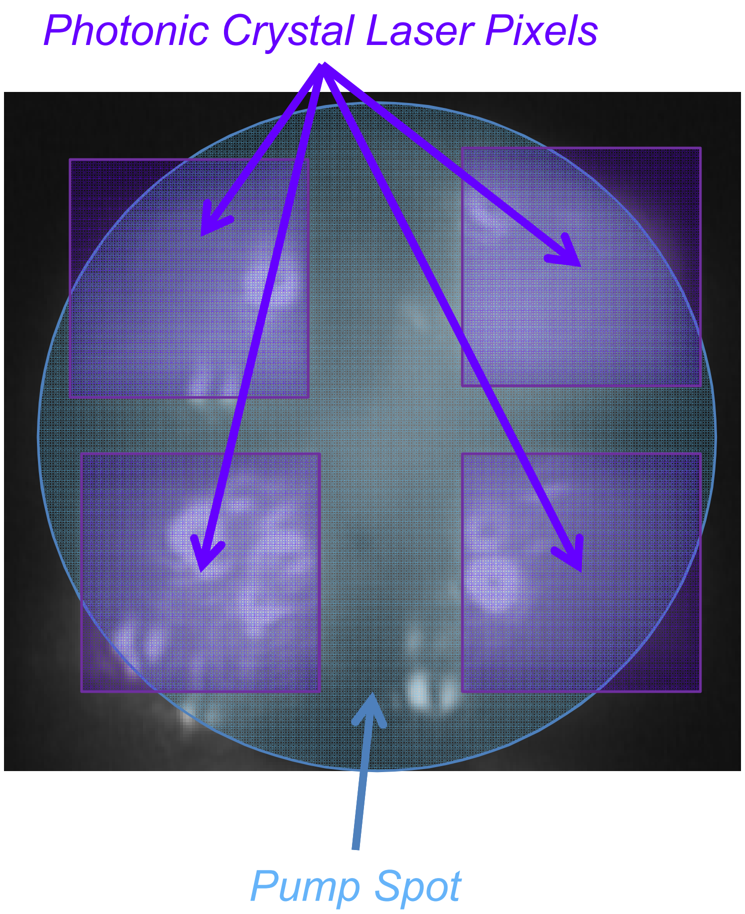


w/ G. Wang , I. Brener, T.S. Luk

Multiple Laser Pixels Coexcited

Emission from 4 adjacent laser pixels.



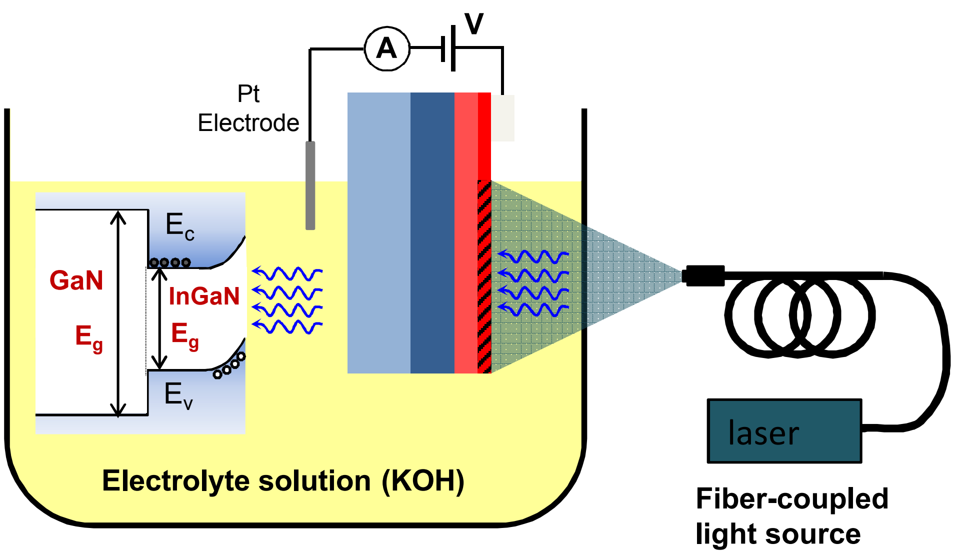


Wright, J. B. *et al.* Multi-Colour Nanowire Photonic Crystal Laser Pixels. *Sci. Rep.* **3**, 2982, doi:10.1038/srep02982

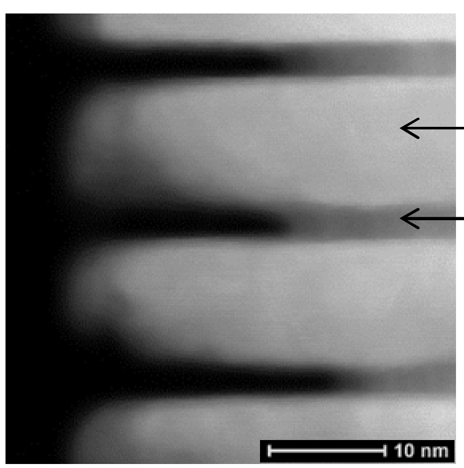
Introduction to InGaN PEC Etching

Photoelectrochemical (PEC) Etching:

- Very few wet etches work for III-nitrides
- Band gap selective (Etch InGaN over GaN)
- Dopant selective, light intensity dependent, etch current can be monitored
- Laser or lamp excitation (Xe arc lamp, tunable ps Ti:S)
- KOH (~0.1M) typically used as electrolyte



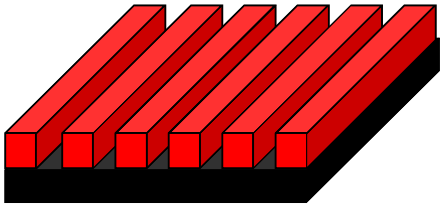
PEC etched InGaN/GaN QWS



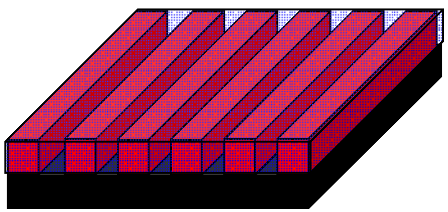
Multilevel E-beam Fabrication-Tour-de-force approach

PC fabricated one layer at a time.

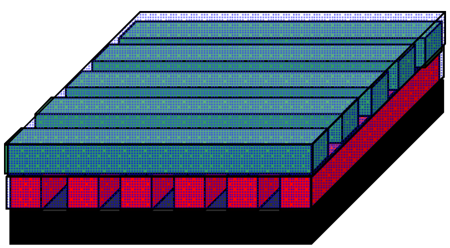
1.Fabricate first level



2. Fill and planarize

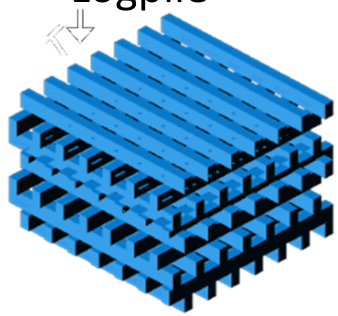


3. Make next level



4. Repeat process to make additional levels

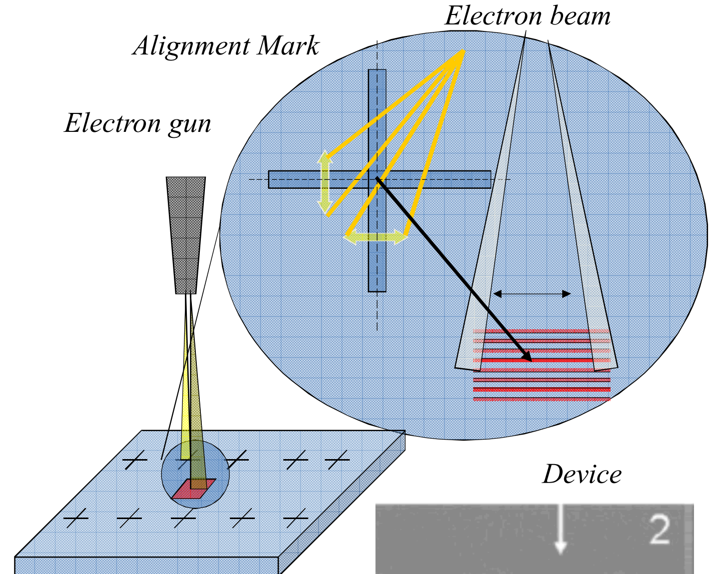
Logpile

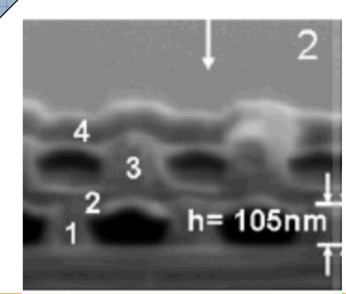


- ➢ Alignment
- ➢ Planarization

Alignment

- Lattice constants < 400nm
- Alignment precision to within 10% of lattice constant needed
- High quality Au registration marks





Excellent alignment was obtained with both JEOL- JBX5E and 9300FS

Planarization problem

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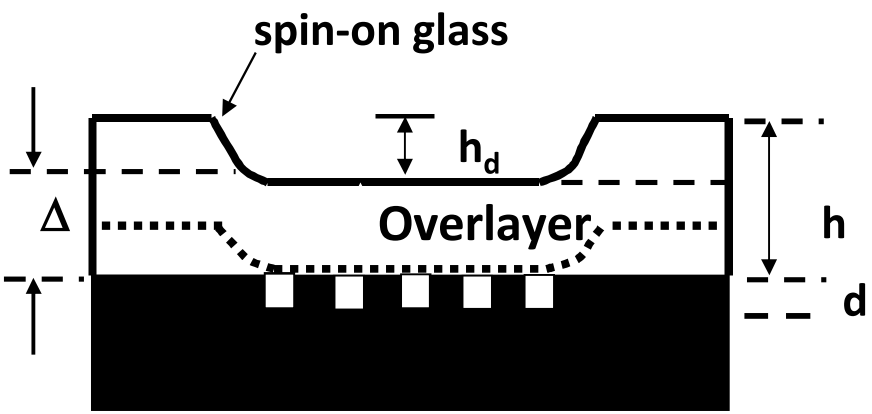
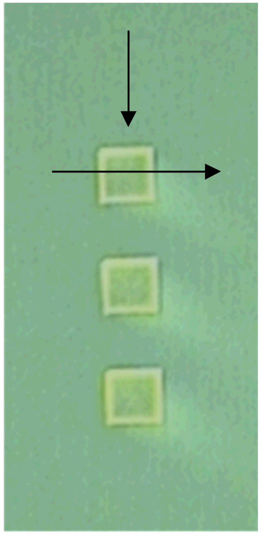
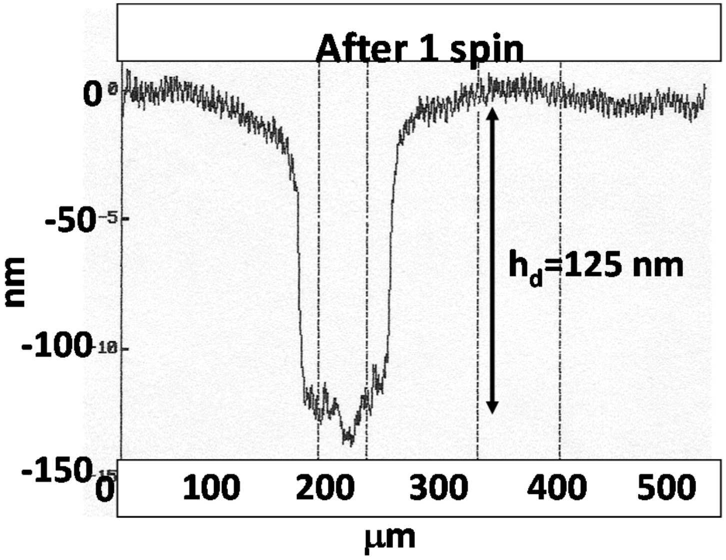






Global degree of planarization:

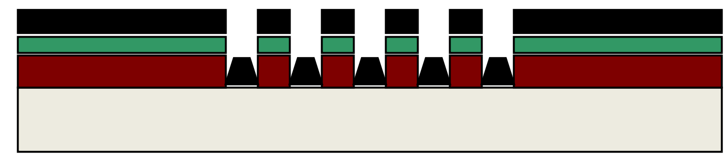
$DOP_G(\%) = (1 - h_d/d) \times 100$

with $h_d \sim 125nm$ and $d = 165nm$

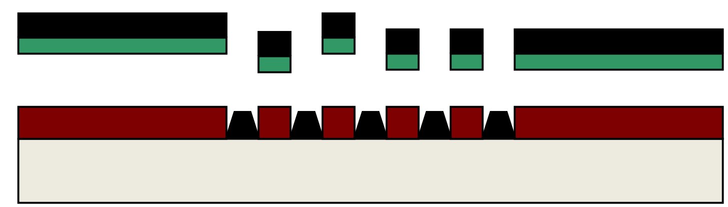
$DOP_G(\%) = 24.2\ \%$

Planarization approach:Pre-fill and etch back

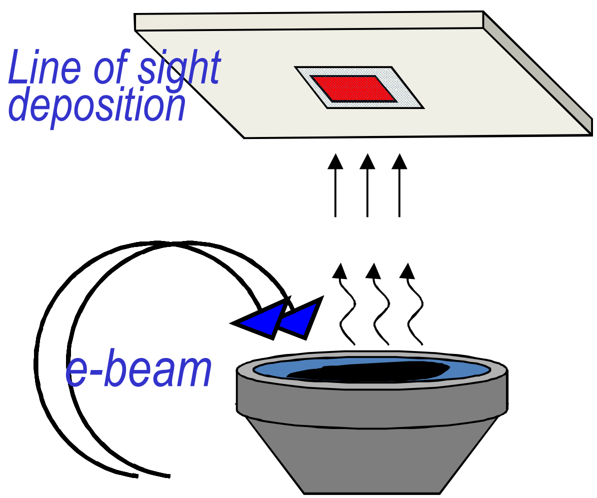
After Evaporation



Soak in solvent for lift-off



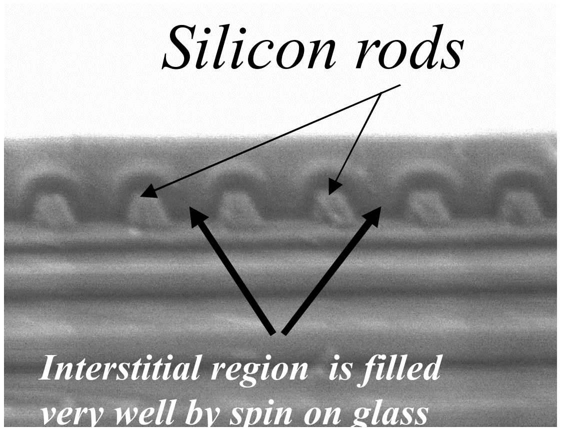
E-beam or thermal evaporation

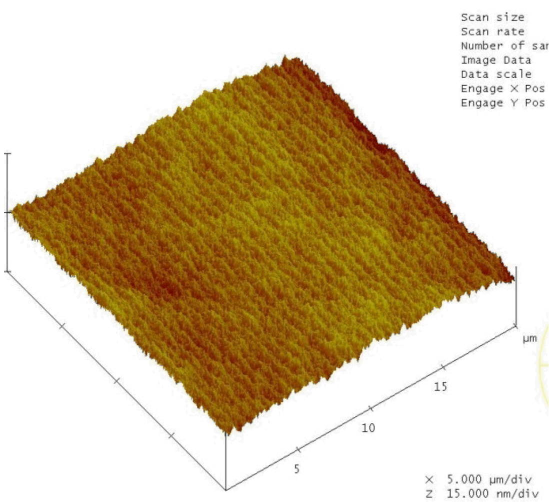


- Evaporated material should fill in the nanometer sized trenches
- Evaporated material should be compatible with spin on dielectric e.g., SiO_2
- Sufficient residual resist thickness ~1.5x trench depth
- Etch profile should be conducive to lift-off

Planarization

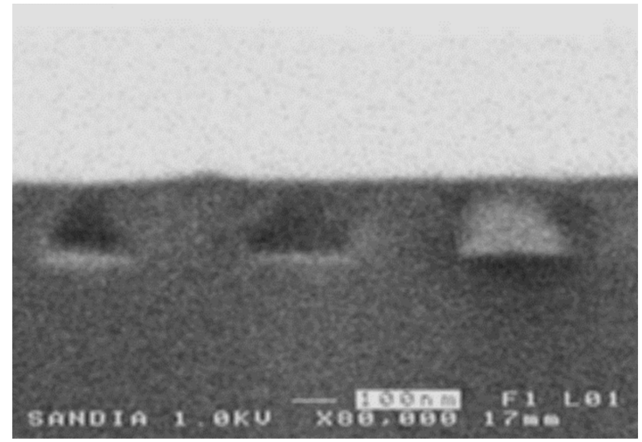
Device Level planarization

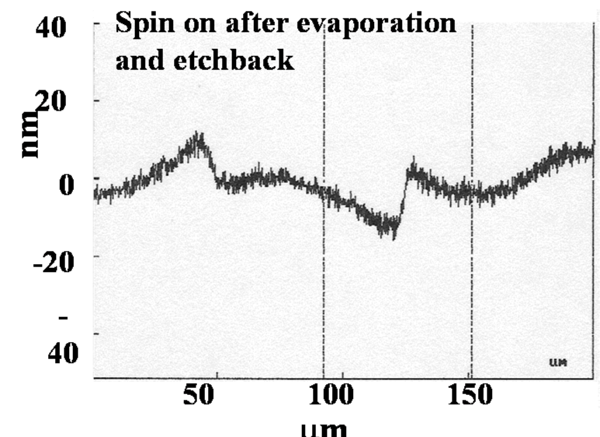




Atomic force microscope image: RMS waviness ~ 1 nm !

Local planarization





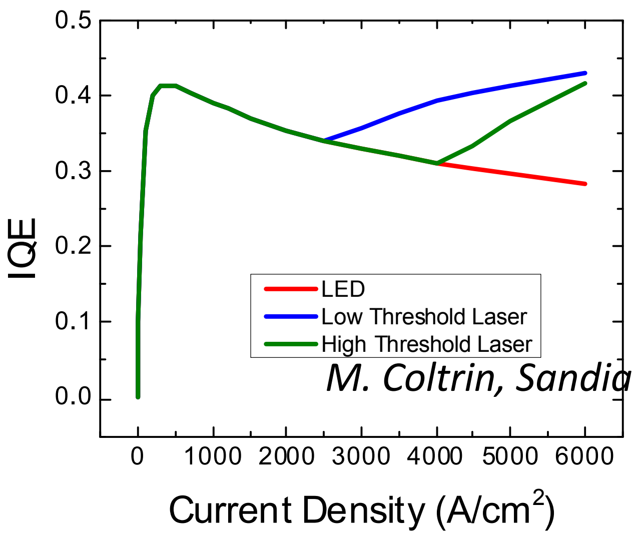
~ 10nm uniformity

*G.Subramania, Nanotechnology,**18**, 035303 (2007).*

Nanowire Photonic Crystal Lasers

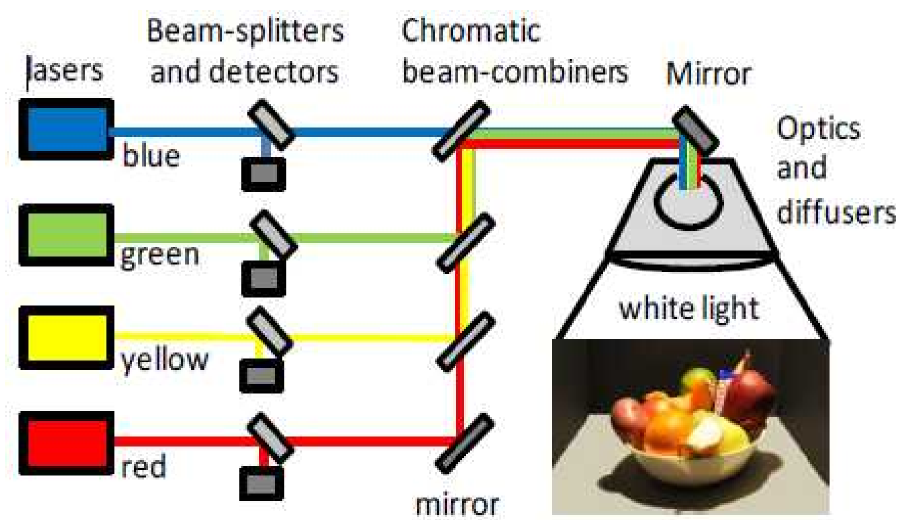
(Jeremy B. Wright, Sheng Liu, Alexander Benz, George T. Wang, Qiming Li, Daniel D. Koleske, Ping Lu, Huiwen Xu, Luke Lester, Ting S. Luk, Igal Brener)

Why Lasers in Solid State Lighting?



The LED "efficiency droop" problem:

- *InGaN LEDs exhibit a decrease in efficiency at high drive currents*
- *limits the operating current density*
- *increases the cost per lumen*

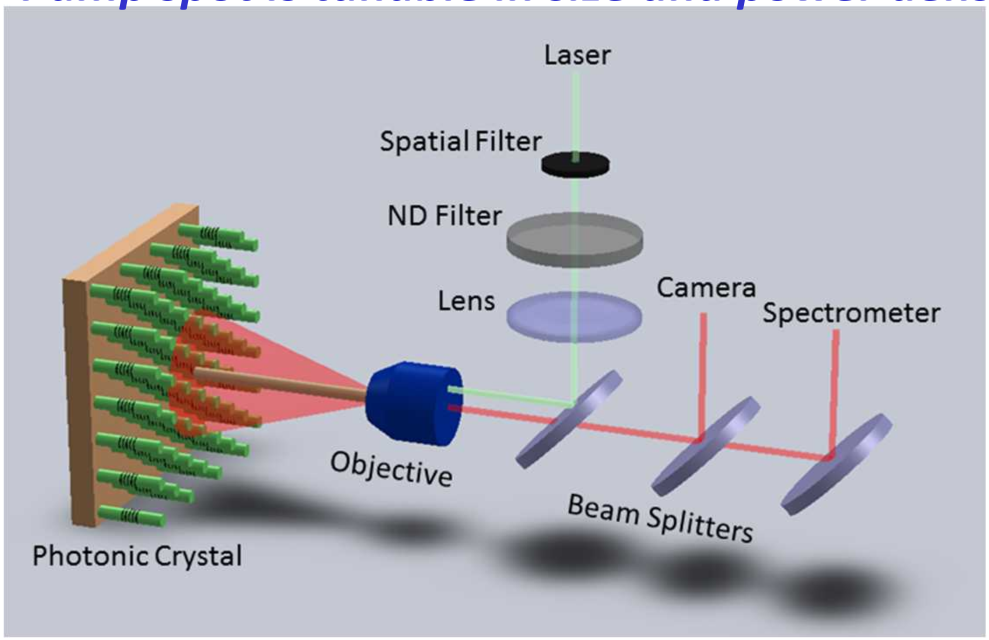


- ➢ ***4 color lasers suitably combined can achieve high color rendering***
- ➢ ***Lasers can potentially mitigate the efficiency droop problem !***

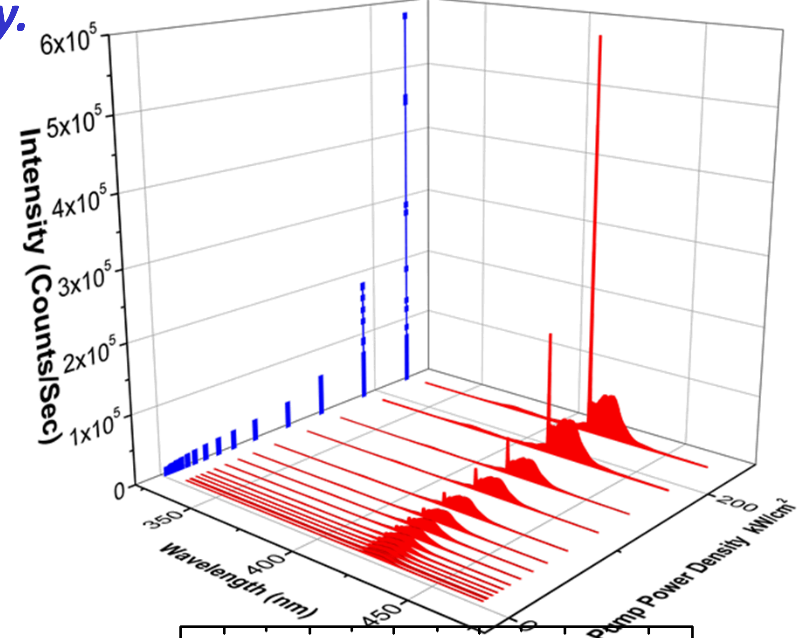
A. Neumann et al., "Four-color laser white illuminant demonstrating high color-rendering quality," Opt. Express, vol. 19, pp. A982-A990, 2011.

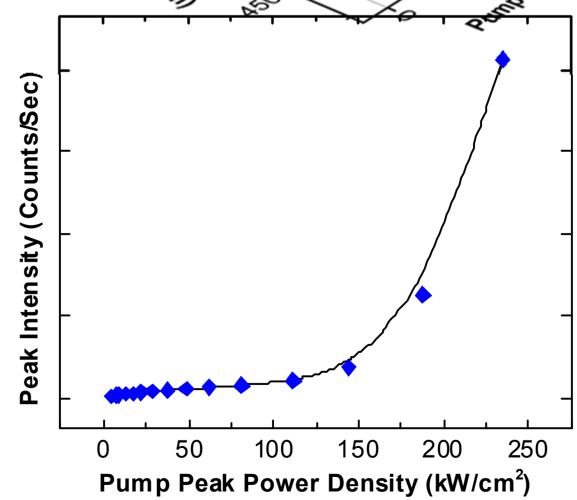
Optical response – low threshold lasing

Pump spot is tunable in size and power density.



Array Element Dimensions: d=145 nm and a=320 nm.

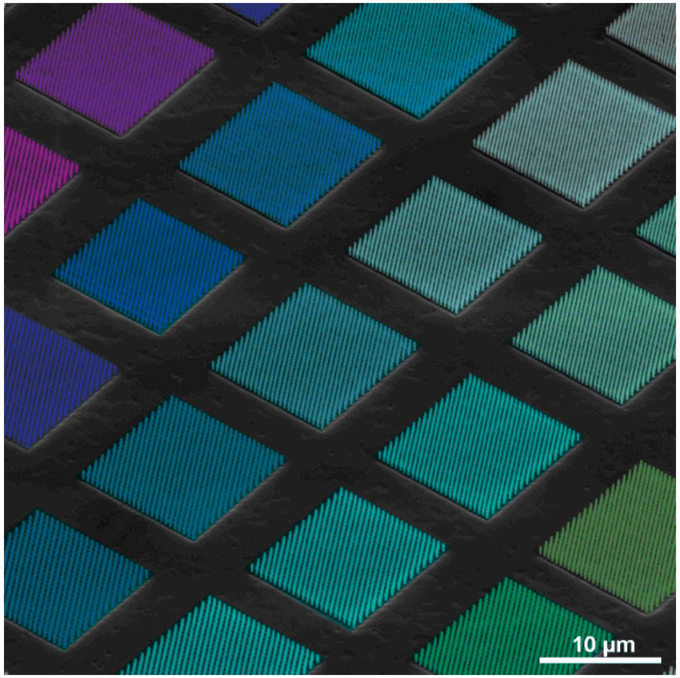




A low lasing threshold is achieved with < 500kW/cm2 for all PC lasers fabricated.

Possibilities

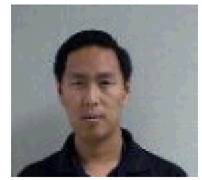
- *Laser arrays that span a broad spectral range*
- *Near-vertical single-mode emitters*
- *Low thresholds with optical pumping with wavelength tunability*
- *Possible to fabricate high density of emitters with a larger wavelength span*
- *Potential extension of lasing spectral range all the way to the green.*
- *Significant technological implications for solid state lighting , projectors and displays.*

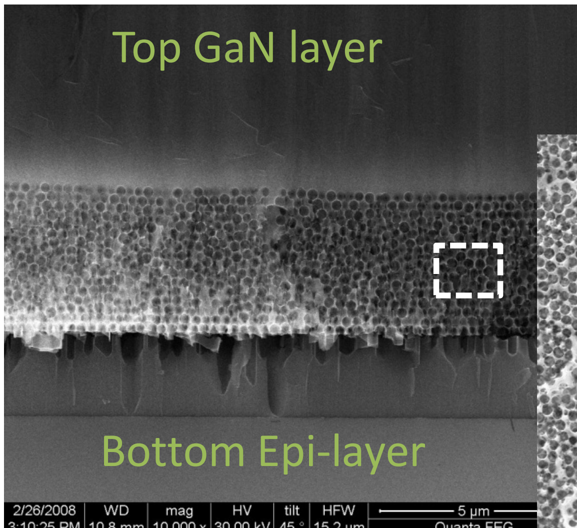


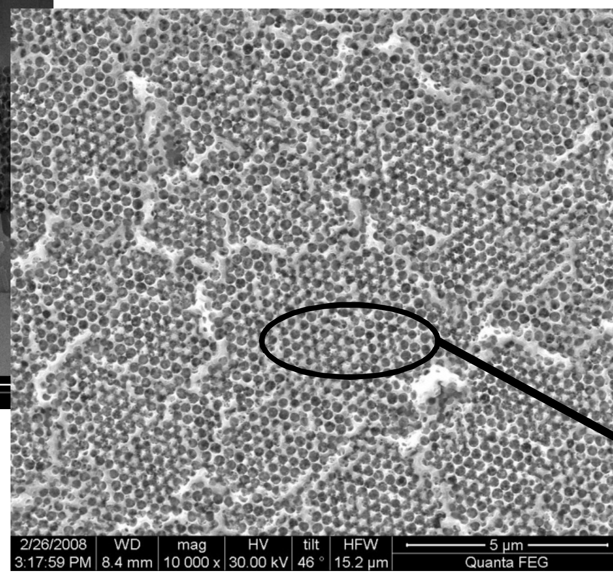
Wright, J. B. *et al.* Multi-Colour Nanowire Photonic Crystal Laser Pixels. *Sci. Rep.* **3**, 2982, doi:10.1038/srep02982

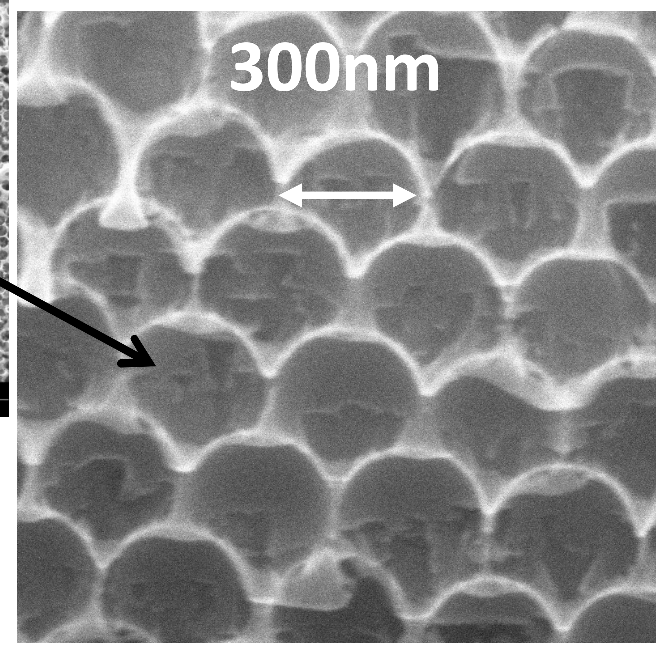
All GaN Logpile Photonic Crystal

Epitaxial GaN grown though nanostructured template reduces dislocation density







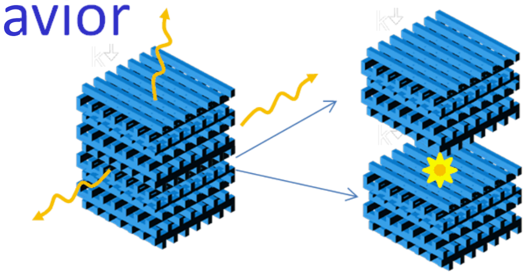


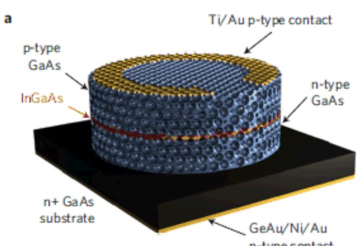
Qiming Li et. al., Appl. Phys. Lett. 94, 231105(2009).

Summary/Possibilities

Sandia National Laboratories

- Measure full 3D gap effect using emission behavior
- Emission life-time measurements - PDOS
  - QDs in the bulk of the 3DPC
- Strong-coupling at band edge
- Electrically injected 3DPC (GaN)

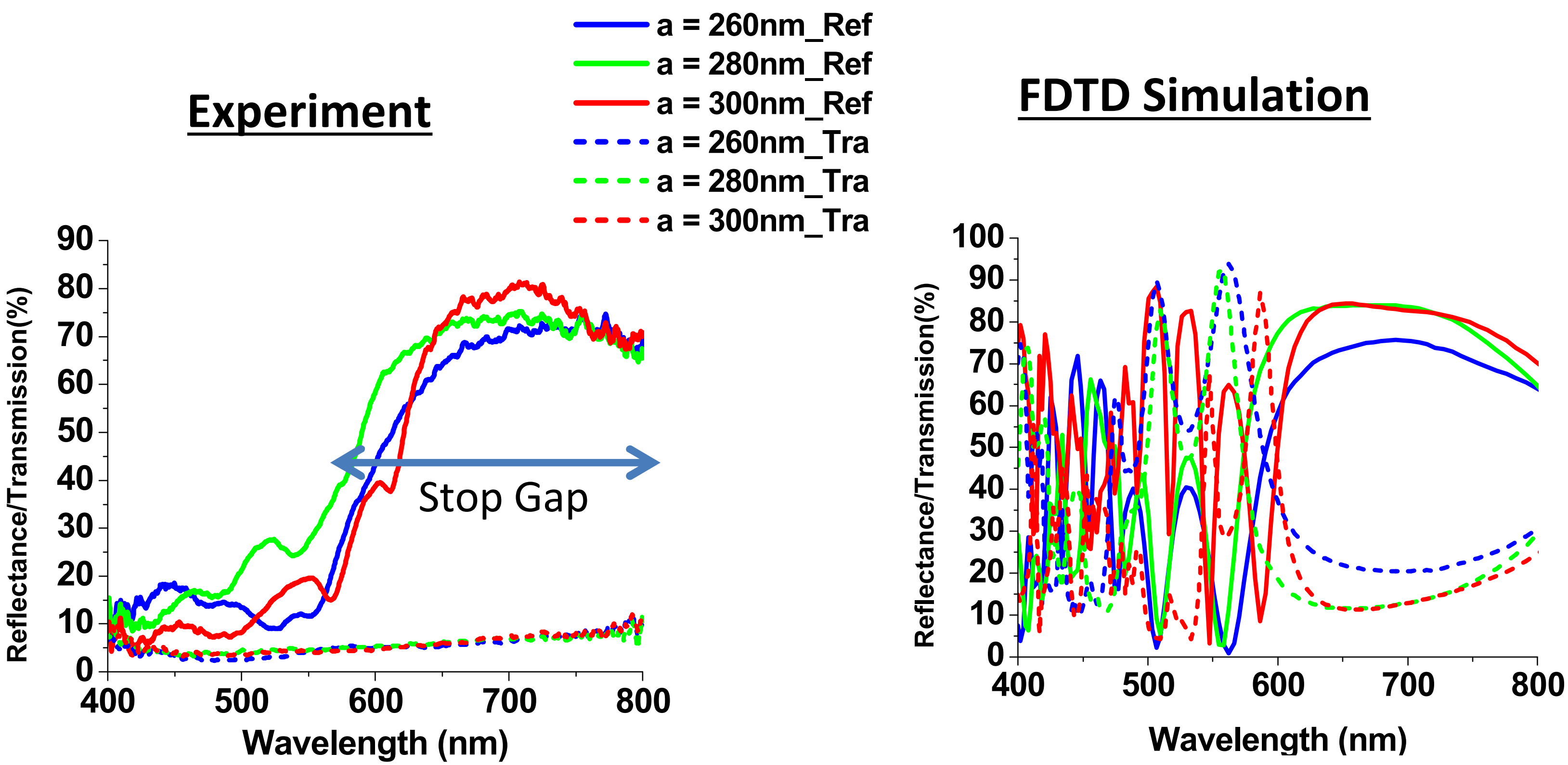




E. C. Nelson, et al., Nat Mater **10**, 676 (2011)

Three dimensional PC structure fabrication is resource and labor intensive.

Optical Response

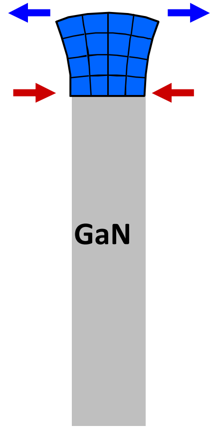


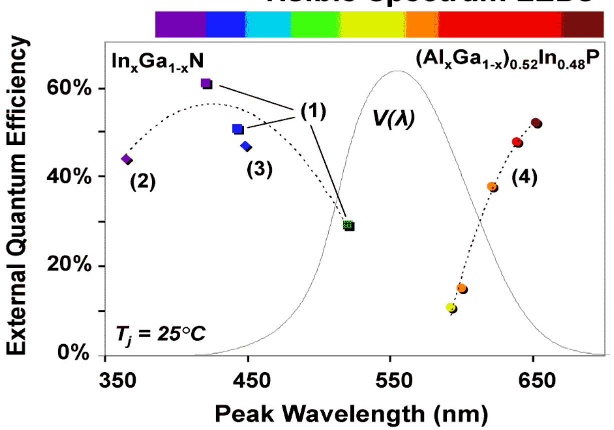
G. Subramania et. al. , Nano Lett. **11**, 4591 (2011).

Nitride Nanowire Arrays

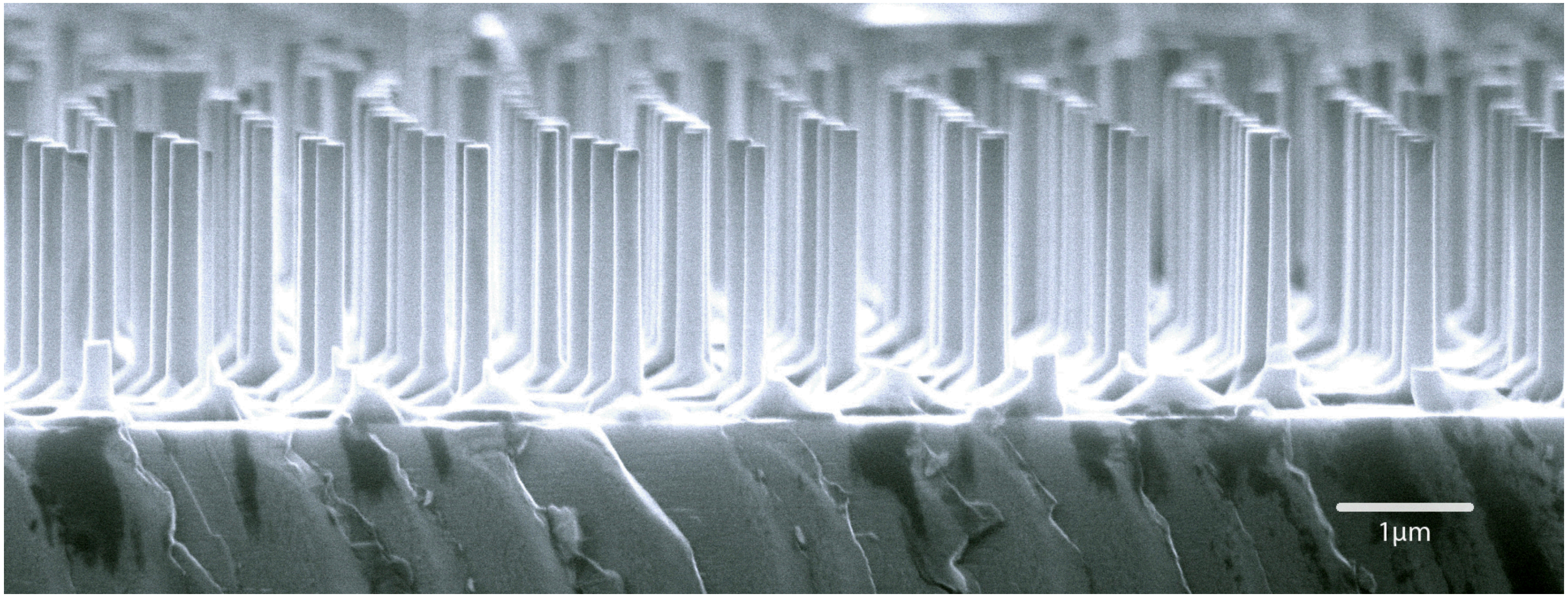
G.Wang

- Reduced strain
  - Greater range of alloy compositions
- Easily integrated into two-dimensional arrays





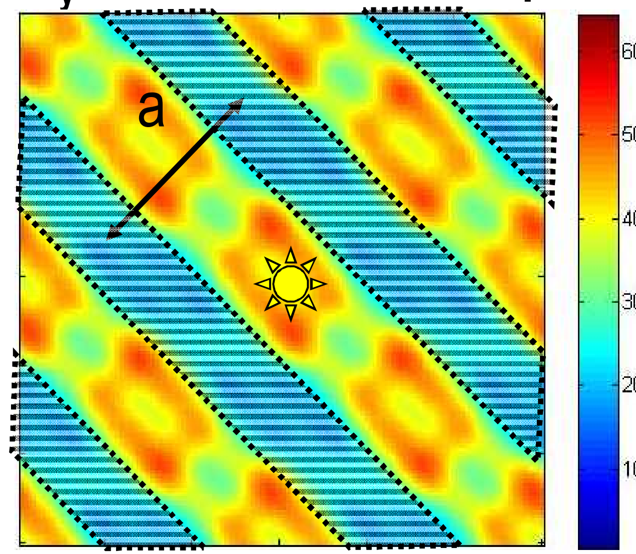
M. Krames, Philips Lumileds



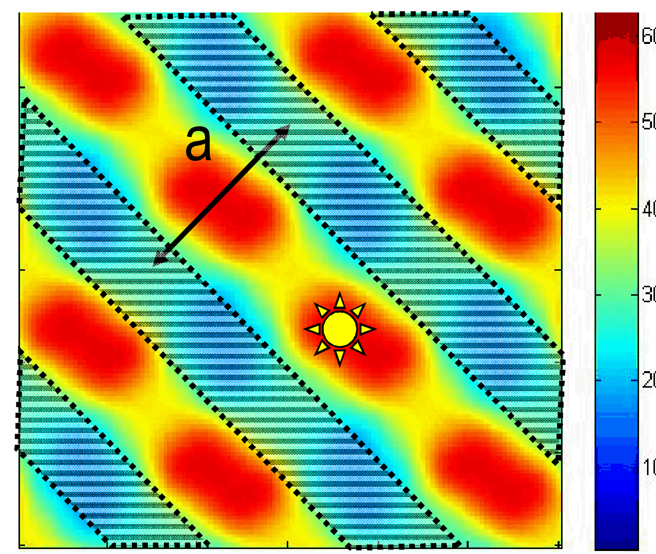
Emission Modification in TiO_2 Logpile

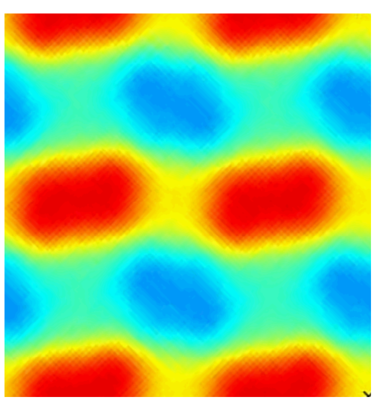
- Dielctric band vs. air band emission control
- Effect of ‘air band’ modes have not been probed
- Advantages
  - Post introduction of light source
  - Choice of light source (QDs or dyes or gas)
  - Potentially higher density of states enhancement

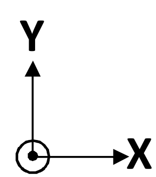
E_y field distribution at Xpt

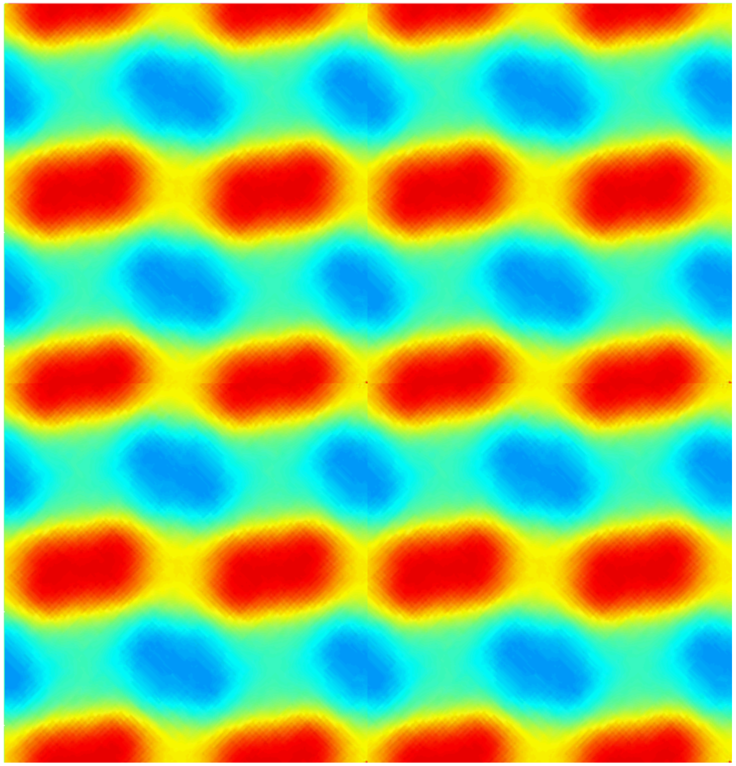


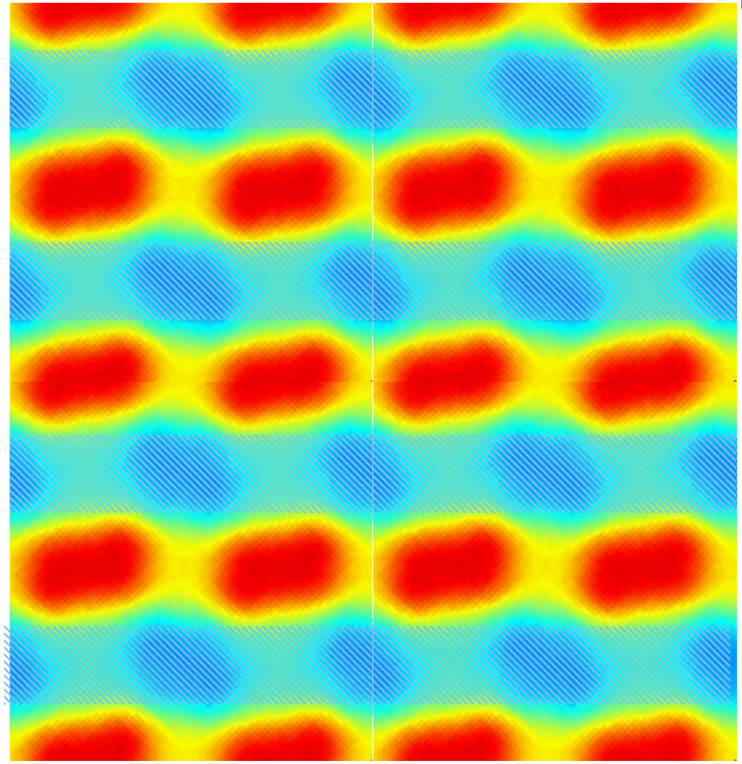
E_z field distribution at Xpt

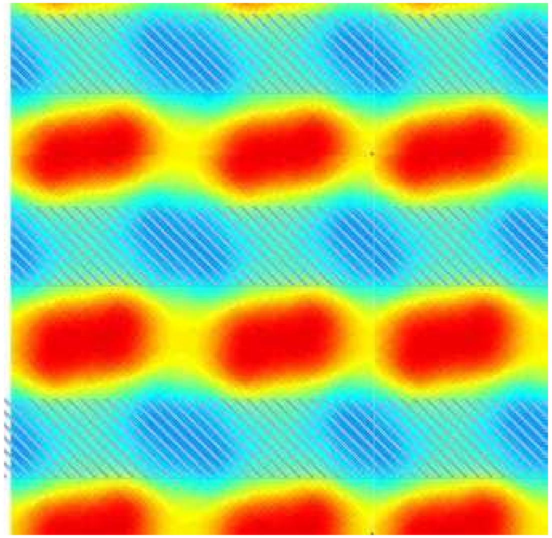










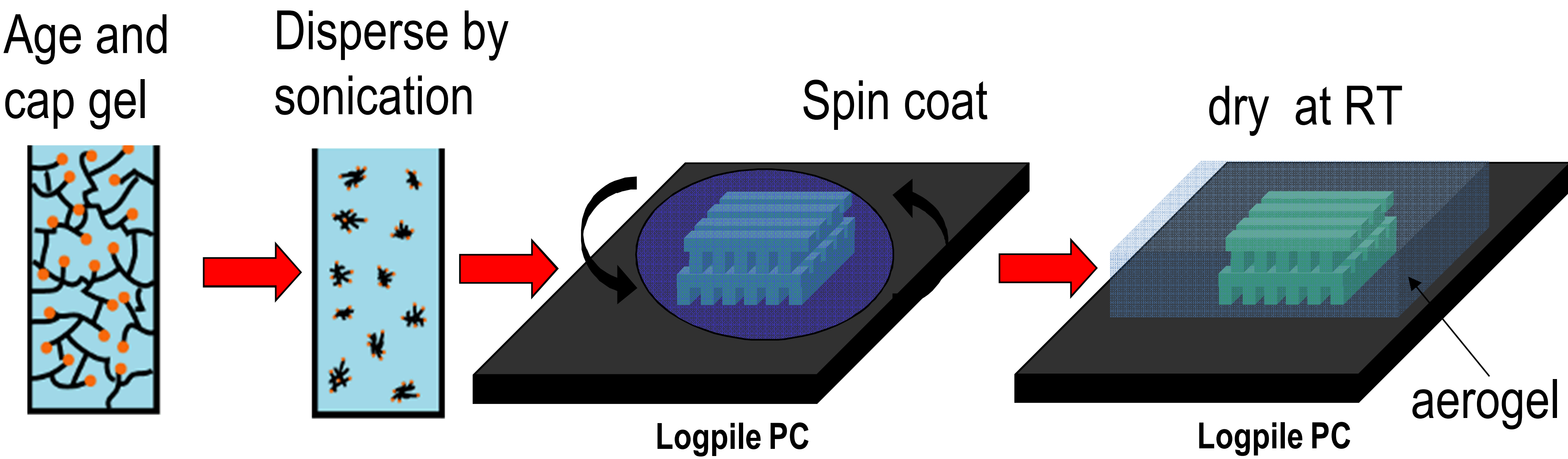


Requirements for Accessing the 'Air' Void Region of the PC

- **Key Challenge: Locating the QDs in the void region without affecting the photonic bandgap**
- Physical access to the 'air' region with ability to attach QDs
- Low refractive index: minimal disturbance to photonic bandgap

Room temperature Spin Coatable Aerogel

Brinker group (S. S. Prakash et al., Nature **374**, 439 (1995))



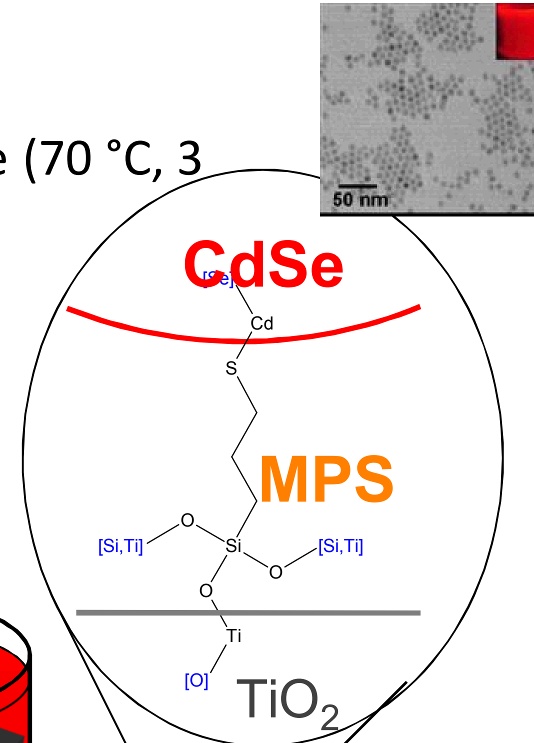
Introduce QDs through chemical attachment (3-mercaptopropyltrimethoxysilane chemistry)

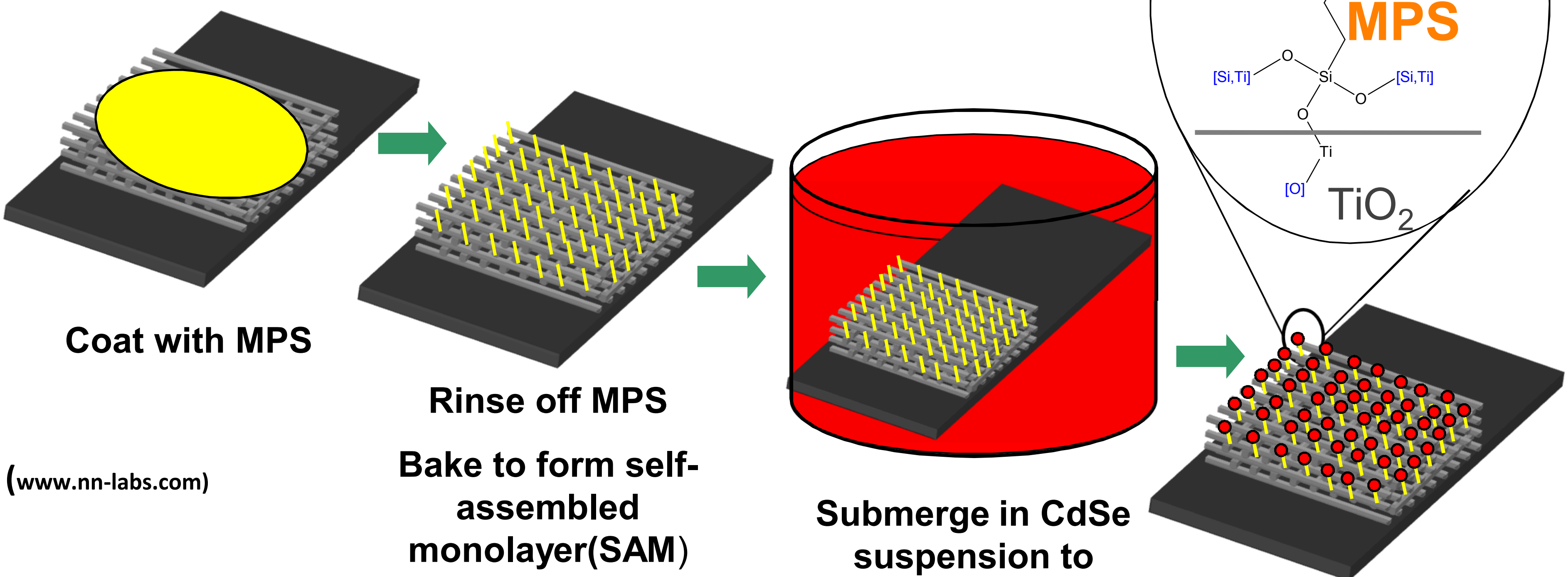
Developed by Alex Lee

G. Subramania, Y. J. Lee, A. J. Fischer, T. S. Luk, C. J. Brinker, D. Dunphy, Appl. Phys. Lett. , **95**, 151101(2009)

Controlled Coating of Cdse Self-assembled Monolayer On TiO_2 Rods

1. Coat TiO_2 wp with neat 3-mercaptopropyltrimethoxysilane (70 °C, 3 min)
2. Rinse with chloroform
3. Bake wp on hot plate to form linkage (120 °C, 30 min)
4. Place TiO_2 wp in TOPO-capped CdSe in toluene (RT, 1 hr)



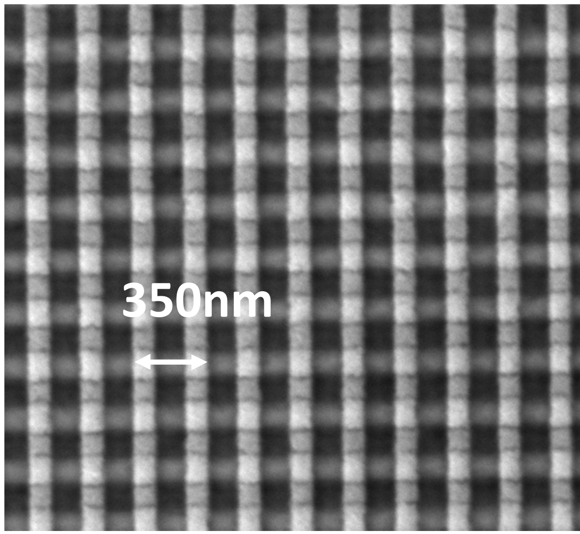


(www.nn-labs.com)

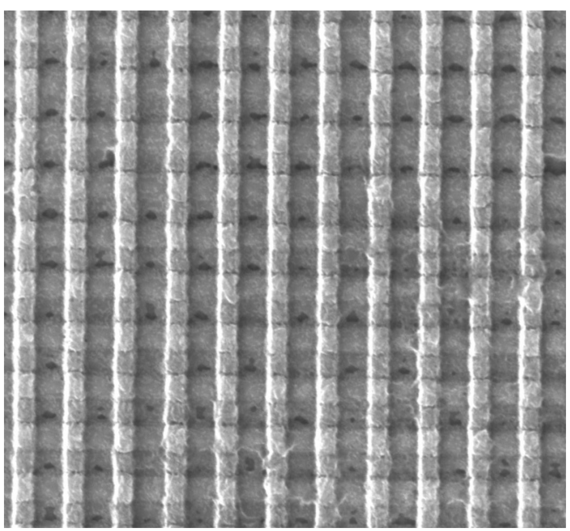
P. Guyot-Sionnest and C. Wang, J. Phys. Chem. B, **107**, 7355 (2003)
J. Pacifico, D. Gomez, and P. Mulvaney, Adv. Mater. **17**, 415 (2005)

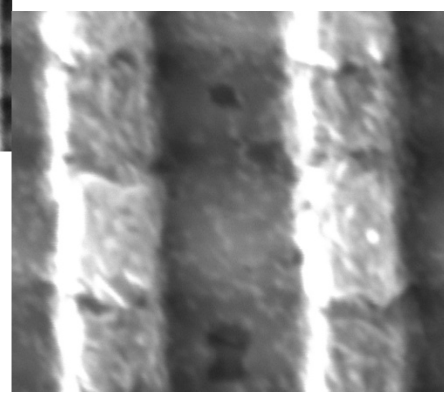
Effect of Aerogel and CdSe QD infiltration

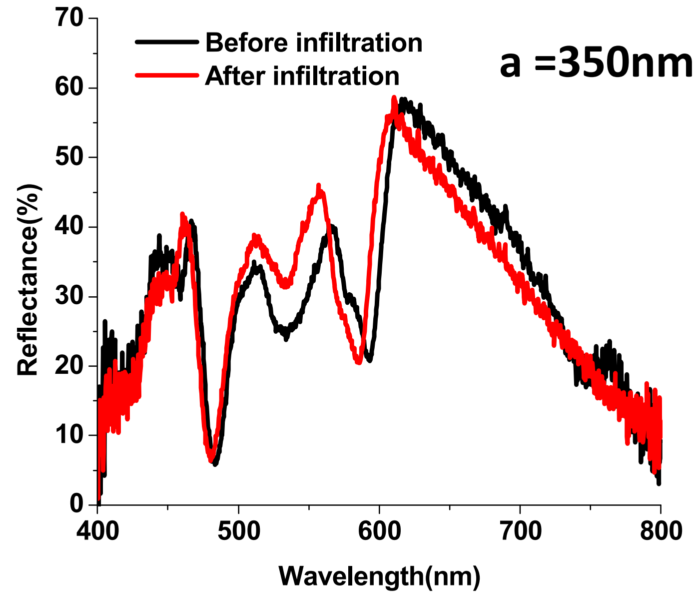
Sandia National Laboratories

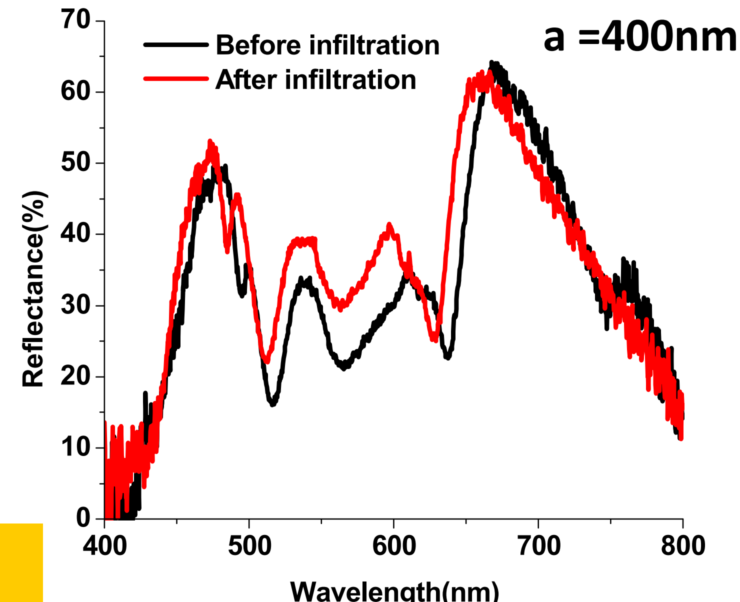


Aerogel Ref. index ~1.05-1.1









Aerogel and CdSe QD infiltration has negligible effect on the bandgap!