SAND2014-18741PE

SSLS EFRC
SOLID-STATE LIGHTING SCIENCE ENERGY FRONTIER RESEARCH CENTER

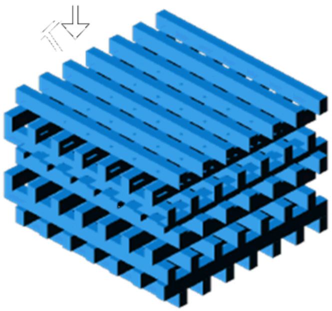
Sandia National Laboratories

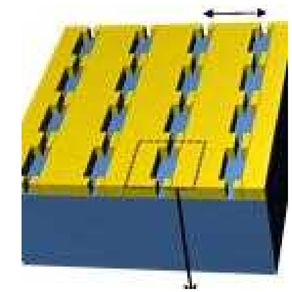
Nanophotonic Architectures for Nanoscale Light Control

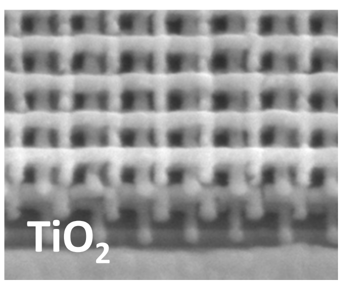
Ganesh Subramania

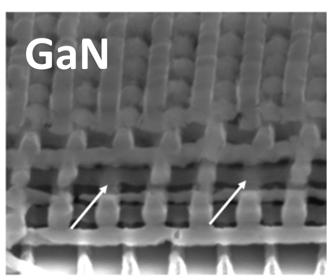
Advanced Material Science 01123
Sandia National Laboratories, Albuquerque, NM

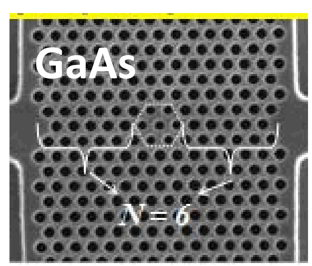
CHTM, October 17, 2014

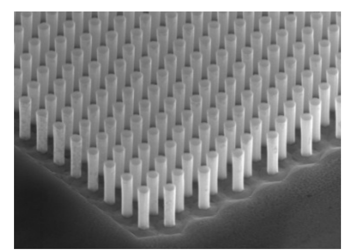


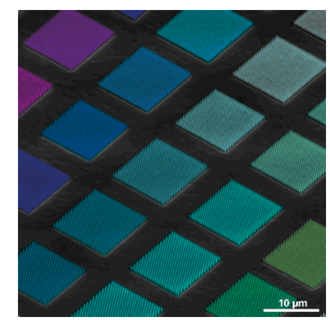












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U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

Collaborators

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- Jeremy Wright
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- Weng Chow
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- Joel Wendt
- Aaron Gin
- Paul Clem
- Jeff Brinker
- Qi Ming Li
- Bernadette Sanchez
- John Nogan
- Ed Gonzales
- Cathy M
- Doug Pete
- Carlos Sanchez
- Tony Coley
- Travis Young
- Bob Biefeld
- Jerry Simmons

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
- Summary

Nanophotonics Activity

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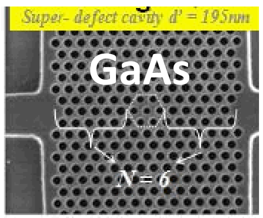
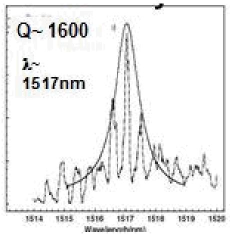
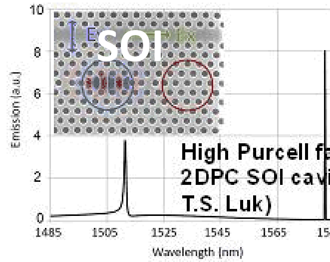
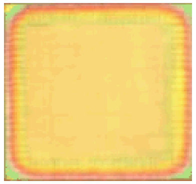
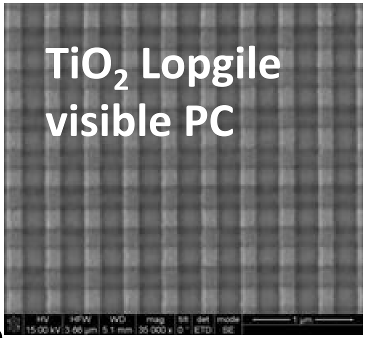
Integrated Photonics, Nanoscale lasing, Strong coupling, Full 3D emission control, Thermal control, Solid State lighting, Energy conversion

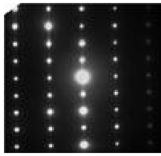


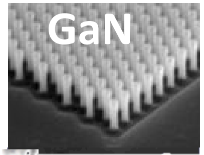




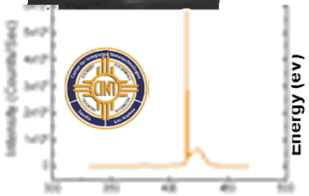


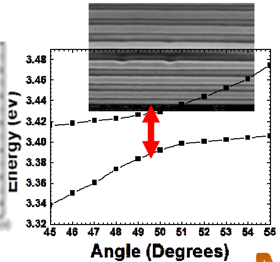






Strong coupling (w/A. Fischer



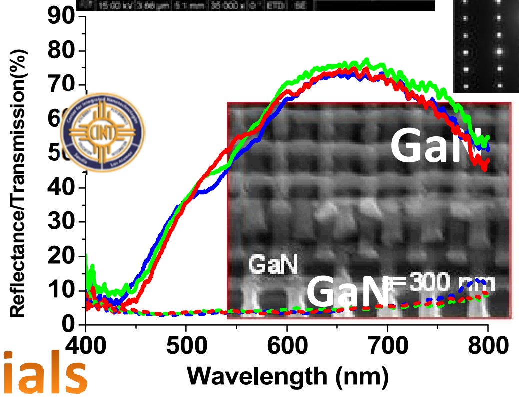


GaN 2DPC laser w/ G. Wang, I. Brener

1,2D PC

Photonic Nanostructures

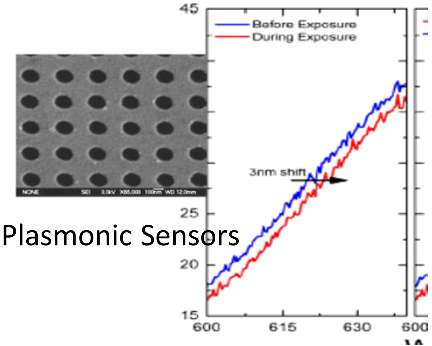
3D PC



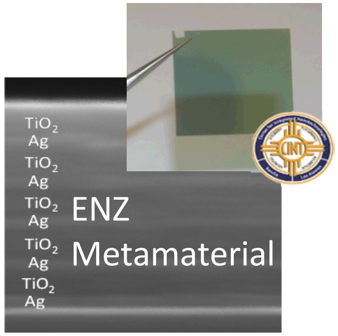
(w/ G.Wang, A. Fischer, D. Koleske)

Metal optics and Metamaterials

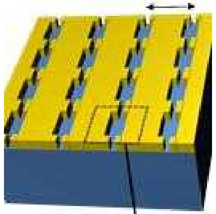
Ultrasubwavelength light control, Detection, Sensing , Nanocircuitry



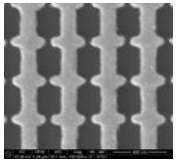
Plasmonic Sensors

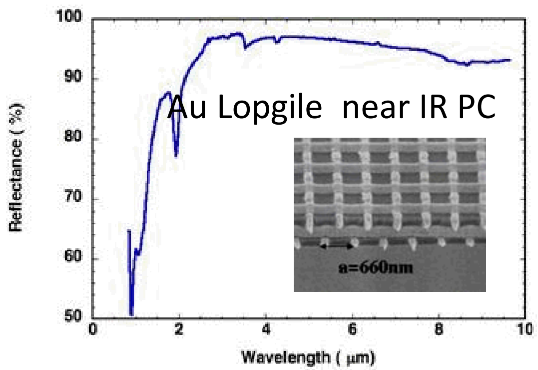


ENZ Metamaterial



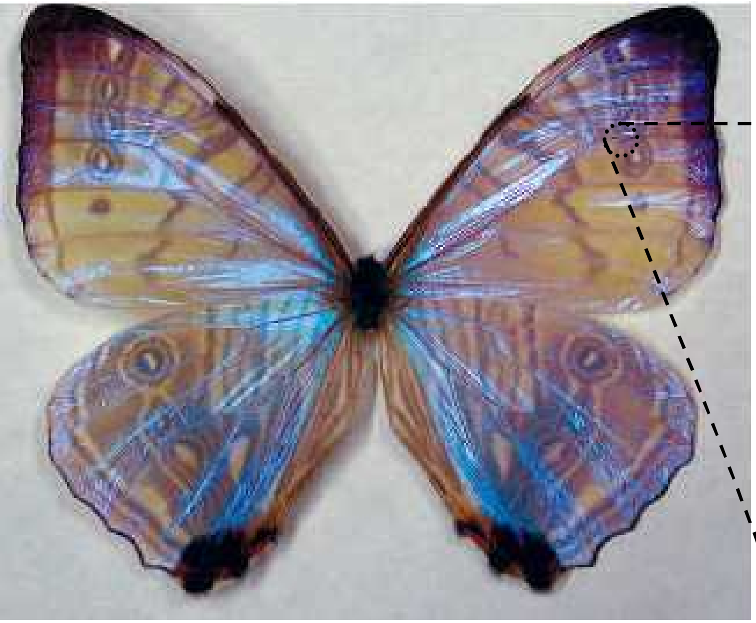
Double groove Metal Nanostructure





Au Lopgile near IR PC

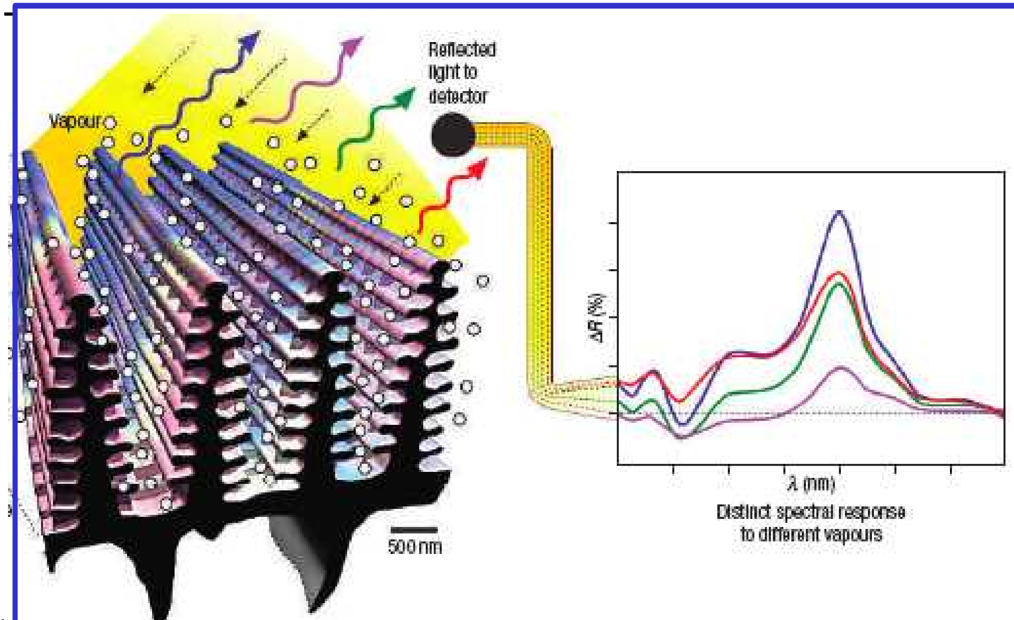
Light Control in Nature Via Nanostructuring



Morpho Butterfly

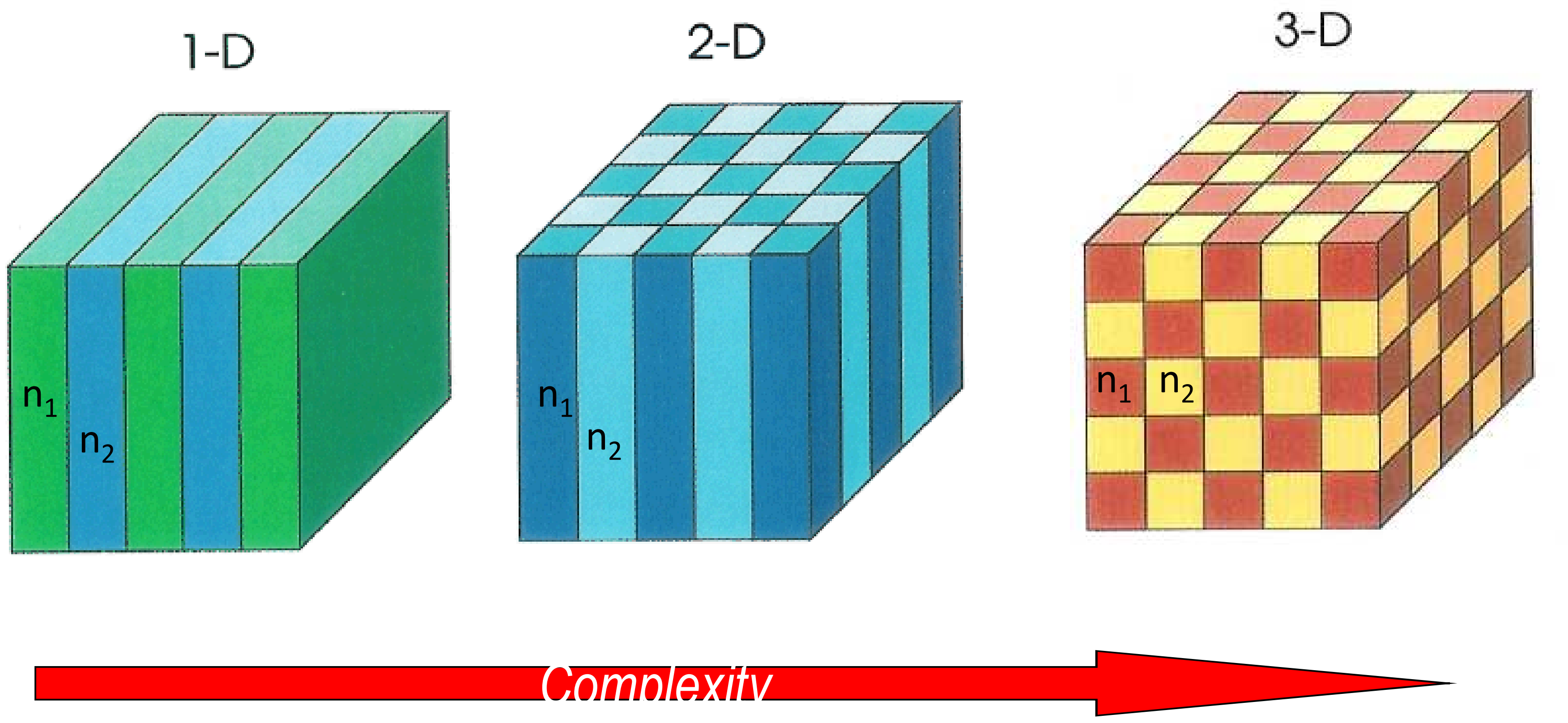
(M. Sulkowskyi)

- **Color response highly sensitive to different vapors**



* R.A. Potyrailo et. al. , Nature Photonics , **1**, 123(2007).

Photonic Crystals: Nanostructured Electromagnetic Environment



Reference: “Photonic crystals: Molding the flow of light”, J.D. Joannopoulos, R.D. Meade, J. Winn, Princeton Univ.Press, NJ(1995)

PC: A Great Platform for Light Manipulation

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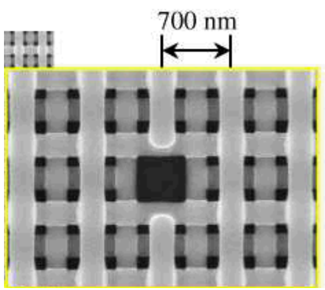
Control of light propagation

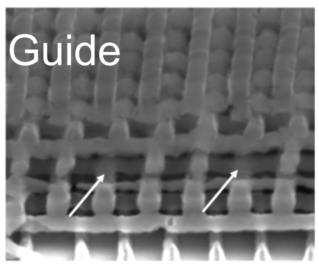
- Guiding, bending and splitting
- Negative refraction
- Self-collimation
- Localization
- Slow light
- Cloaking

Control of light emission

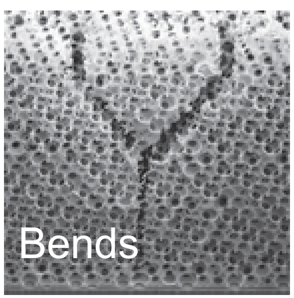
- Spontaneous emission enhancement
- Strong-coupling (Photon – Atom Bound states, Non-Morkovian emission process)
- Non-classical light sources



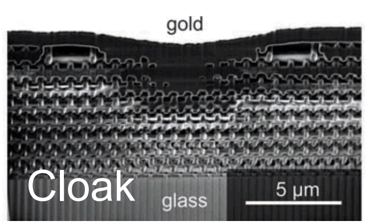
S. Kawashima et. al.., Opt. Exp. **18**, 386 (2010)



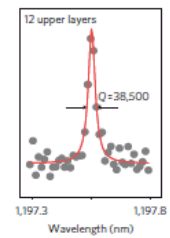
G. Subramania et. al, Nano Lett. **11**, 4591 (2011).

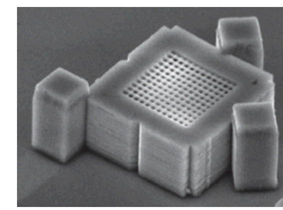


S.A. Rinne et. al., Nat. Phot. **2**, 52(2008)



T. Ergin et. al.,Science **328**, 337 (2010)

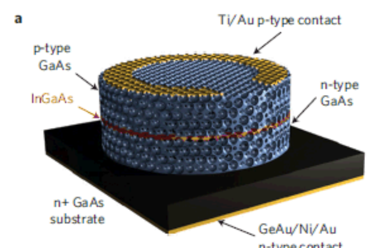




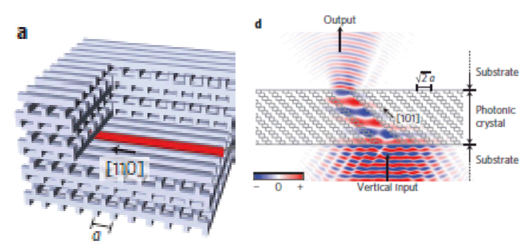
A. Tandaechanurat et. al., Nat Photon **5**, 91 (2011).

Emission enhancement

Electrical Injection



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



K. Ishizaki et.al. , Nat. Phot.,**7**, 133 (2013)).

Spontaneous Emission Control using PC

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Radiative rate of an emitting dipole in an EM field (Fermi's Golden Rule)

$$\Gamma_r(\omega) = \frac{\pi\omega\mu^2}{3\varepsilon_0\hbar}\rho(\omega)$$

Photonic Density of States (PDOS)

$$\rho_f(\omega) = \frac{\omega^2}{\pi^2 c^3}$$

← PDOS in free space

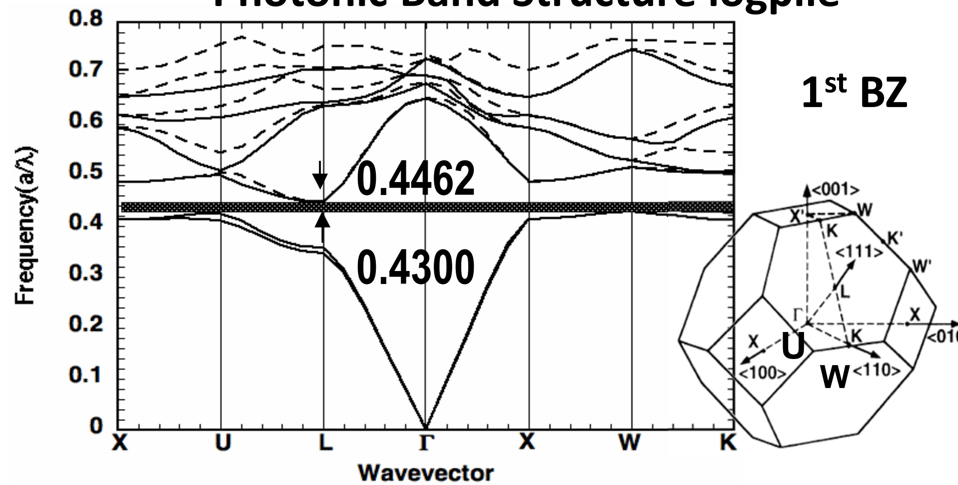
Radiative rate modification

$$\frac{\Gamma_{r\_PC}(\omega)}{\Gamma_{r\_free}(\omega)} = \frac{\rho_{PC}(\omega)}{\rho_f(\omega)}$$

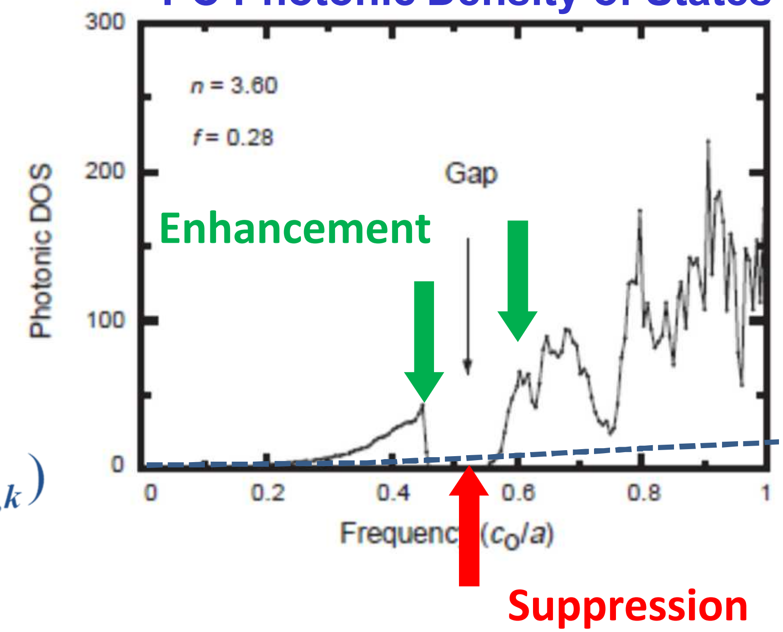
Local Photonic Density of States (LDOS)

$$\rho_L(\boldsymbol{r},\omega) = \sum_n \int_{1stBZ} d^3k \, |\overline{\mu}\cdot\boldsymbol{E}_{n,k}(\boldsymbol{r})|^2 \, \delta(\omega^2 - \omega_{n,k}^2)$$

Photonic Band Structure logpile



PC Photonic Density of States



K. Busch and S. John, Phys. Rev. E,**58**, 3896(1998)

Spontaneous Emission Control to Benefit SSL

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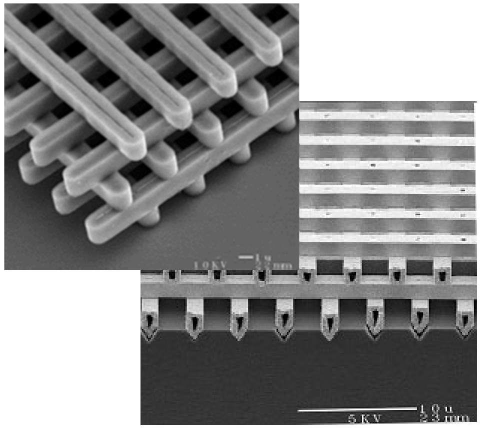
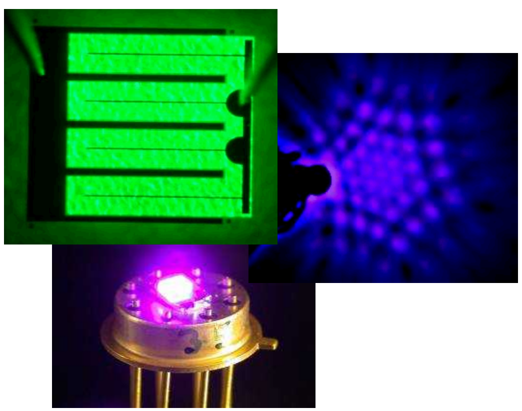
3D photonic crystals

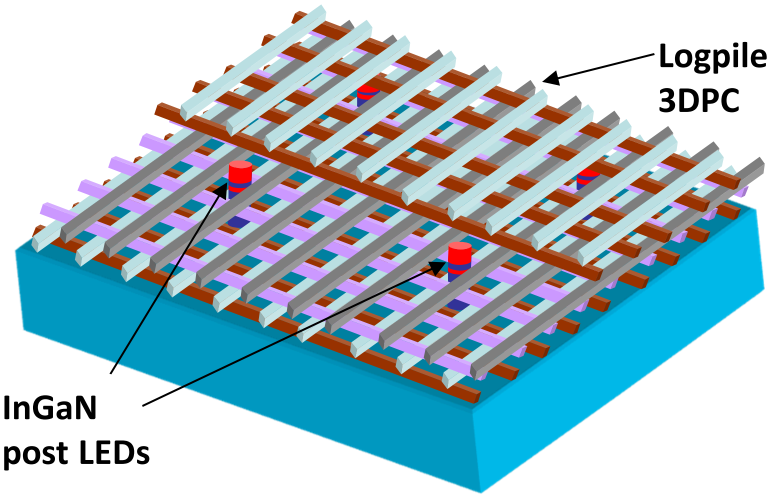


InGaN LEDs



- **Full 3D gap PCs can achieve ultimate emission control**
- **Sandia has strong capabilities in 3DPC and Nitrides**
- **Merge InGaN LED research with 3D photonic crystal research.**

InGaN LED array incorporated into a 3DPC



Improving InGaN LED efficiency enhancements will benefit SSL – e.g. Green emission.

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

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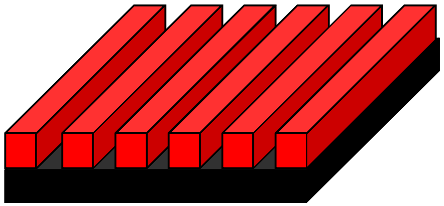
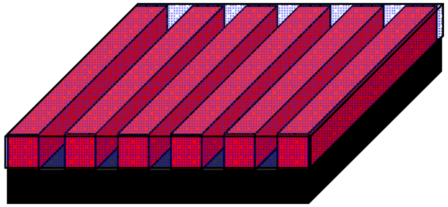
PC fabricated one layer at a time.

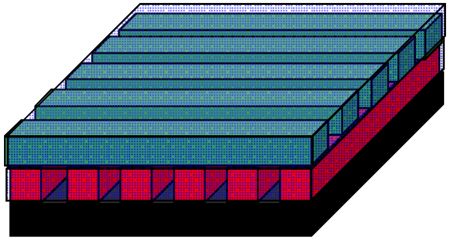
1.Fabricate first level



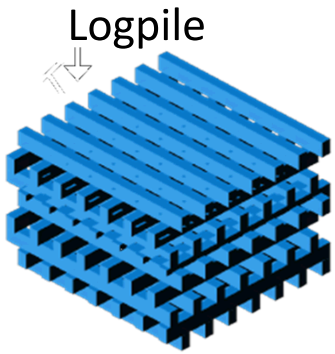
2. Fill and planarize



3. Make next level



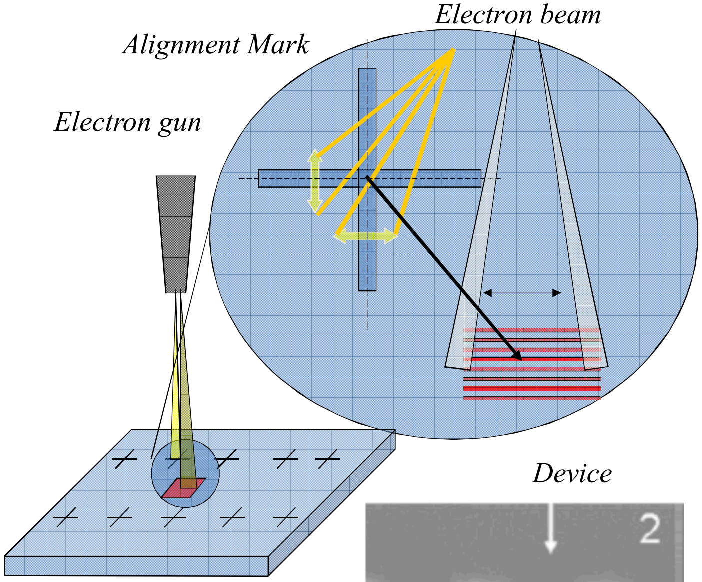
4. Repeat process to make additional levels

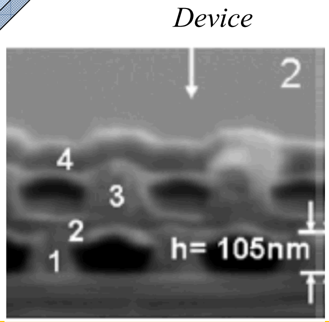


- Alignment
- Planarization

Alignment

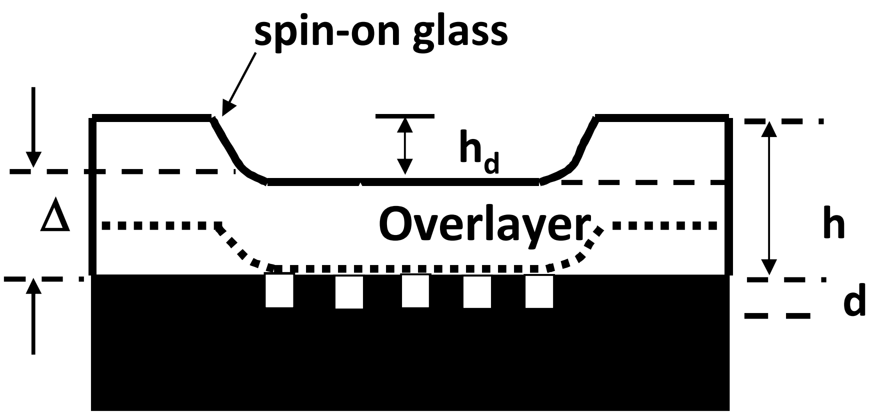
- Lattice constants < 400nm
- Alignment precision to within 10% of lattice constant needed
- High quality Au registration marks

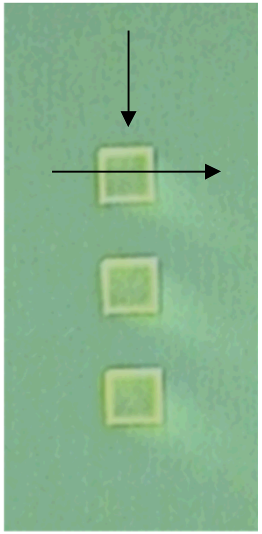


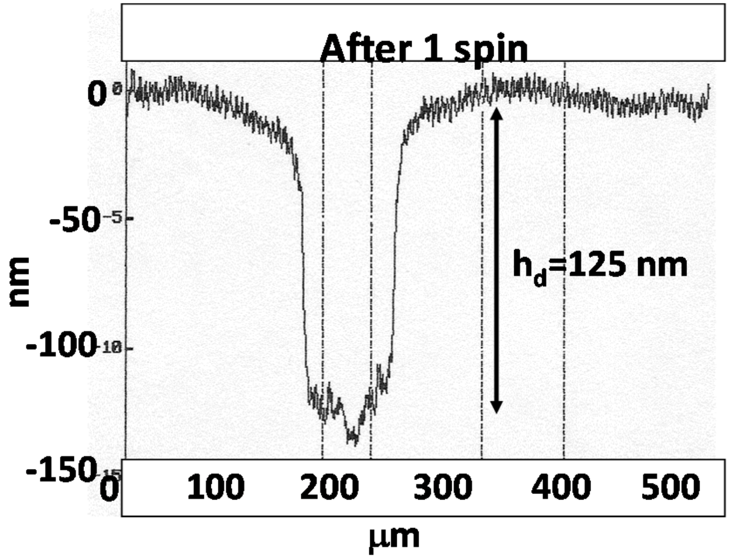


Excellent alignment was obtained with both JEOL- JBX5E and 9300FS

Planarization problem







Global degree of planarization:

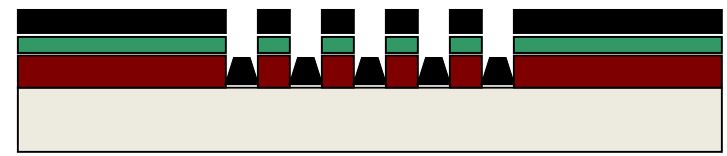
$DOP_G(\%) = (1 - h_d/d) \times 100$

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

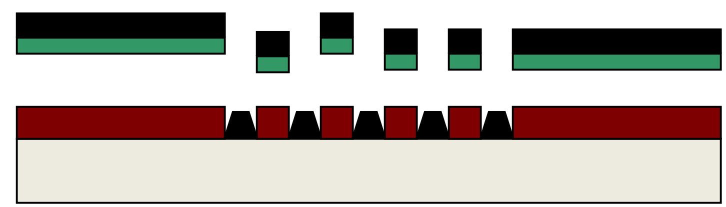
$DOP_G(\%) = 24.2\ \%$

Planarization approach:Pre-fill and etch back

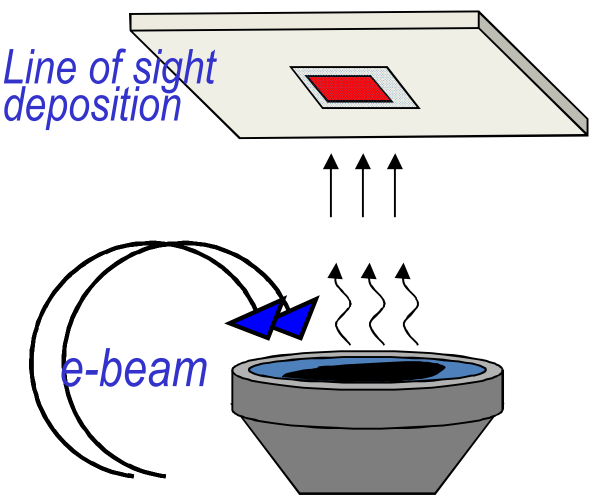
After Evaporation



Soak in solvent for lift-off



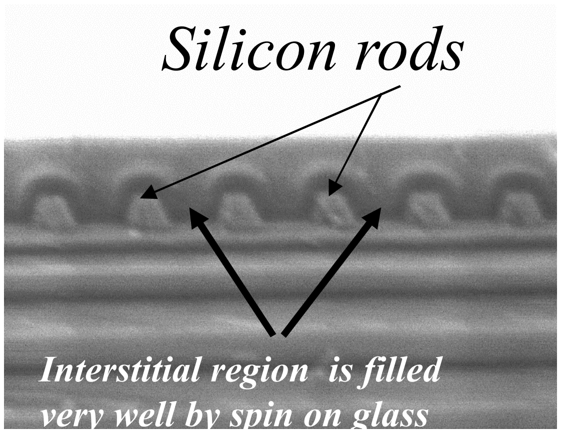
E-beam or thermal evaporation

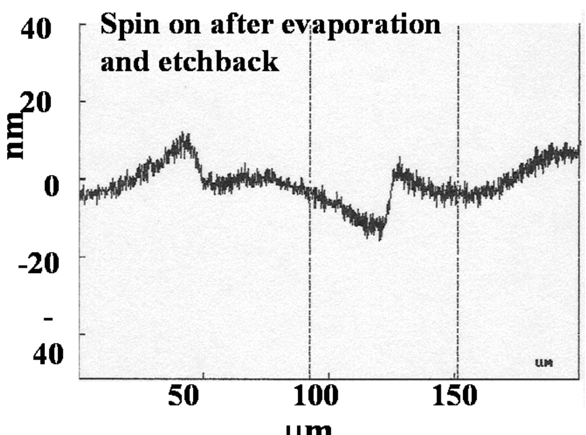


- Evaporated material should fill in the nanometer sized trenches
- Evaporated material should be compatible with spin on dielectric e.g., SiO_2
- Sufficient residual resist thickness ~1.5x trench depth
- Etch profile should be conducive to lift-off

Planarization

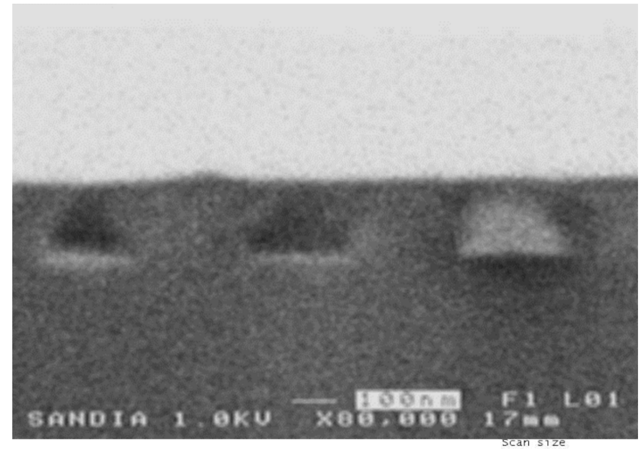
Device Level planarization

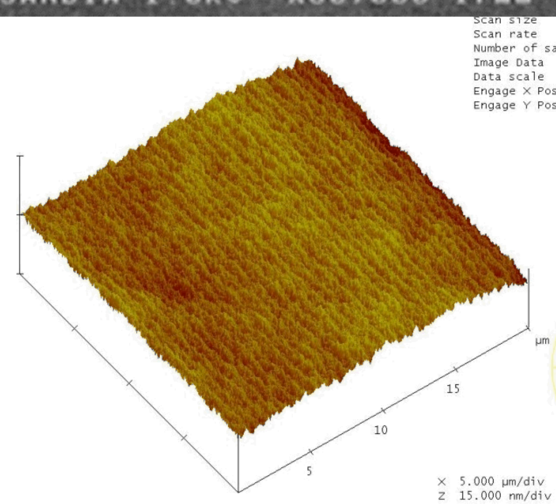




~ 10nm uniformity

Local planarization



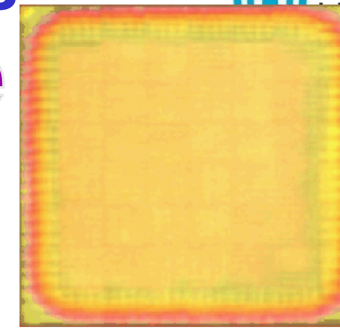


Atomic force microscope image: RMS waviness ~ 1 nm !

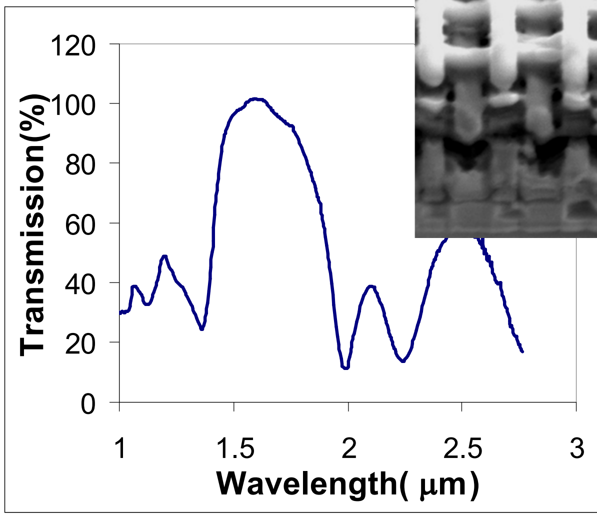
G.Subramania, Nanotechnology,**18**, 035303 (2007).

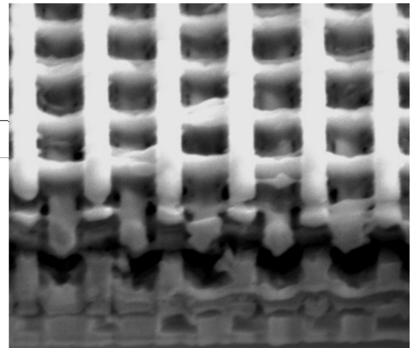
3DPCs: Wavelength, Materials

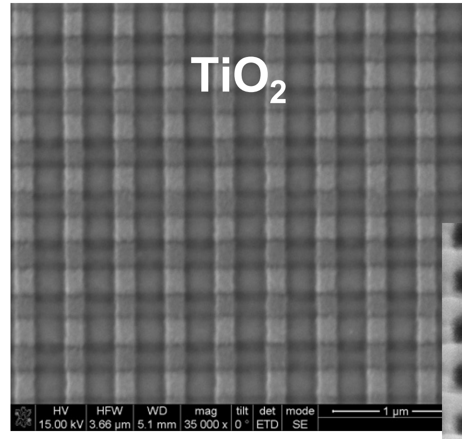
Visible

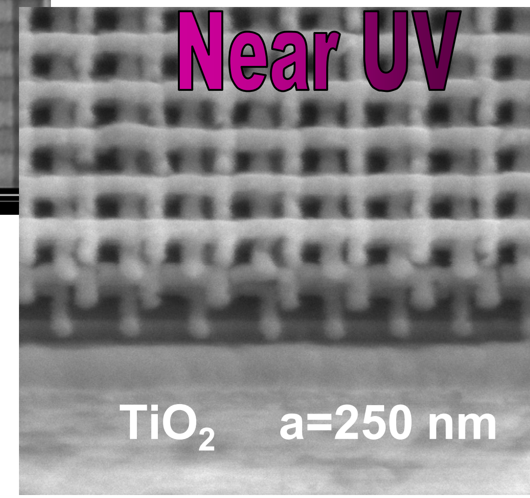


Si near-IR

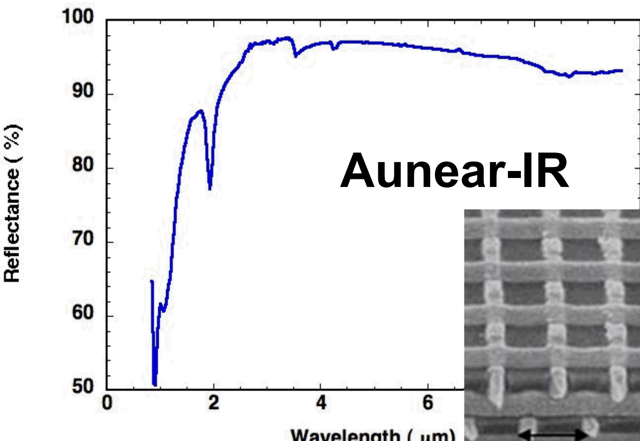


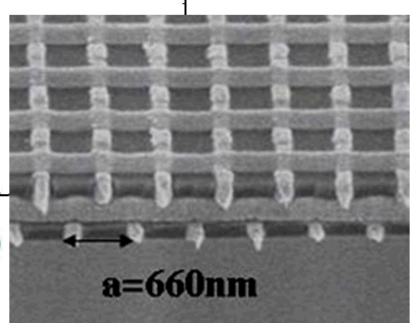


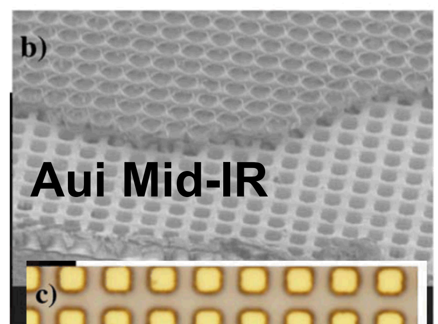


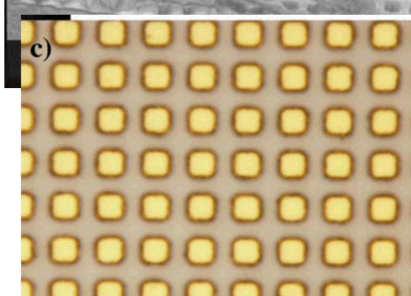


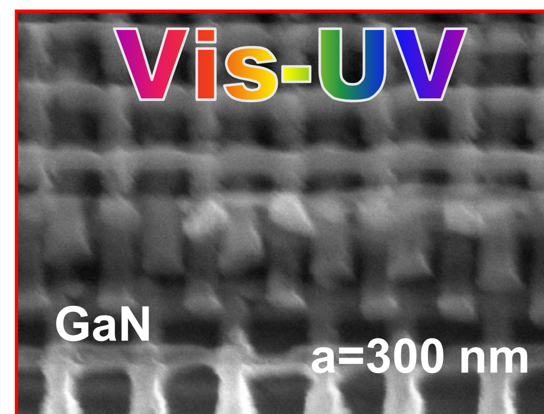
- Mid IR to Near UV
- Si, Au, TiO2 and GaN



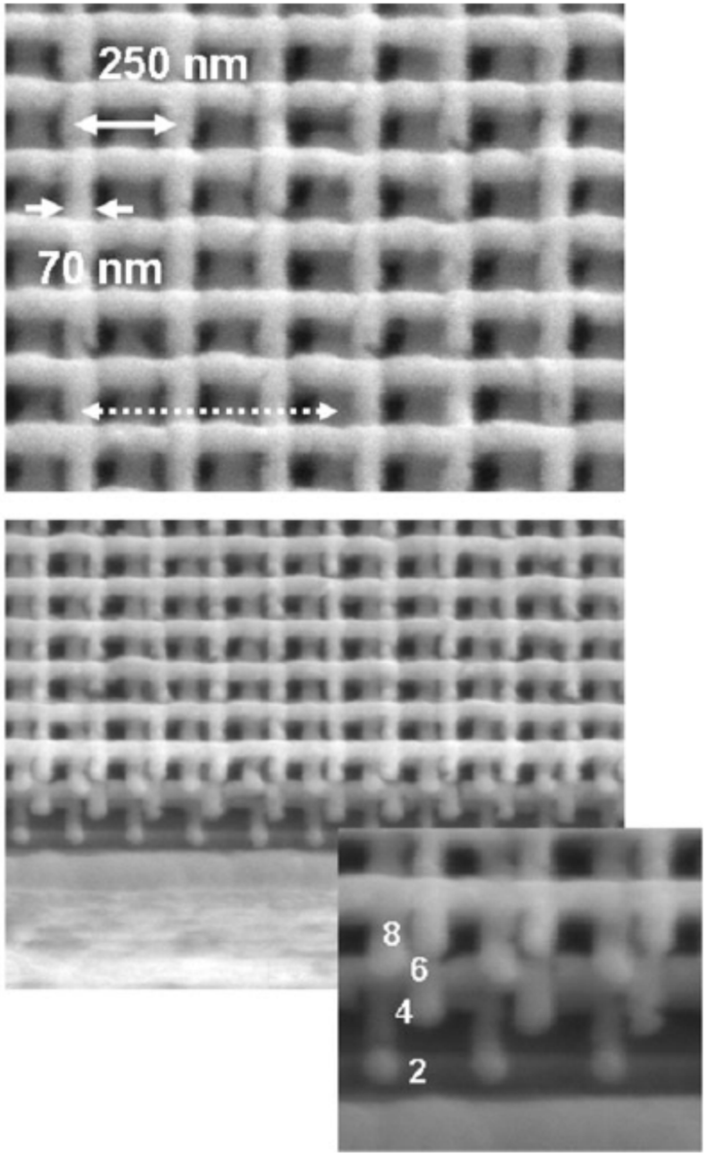




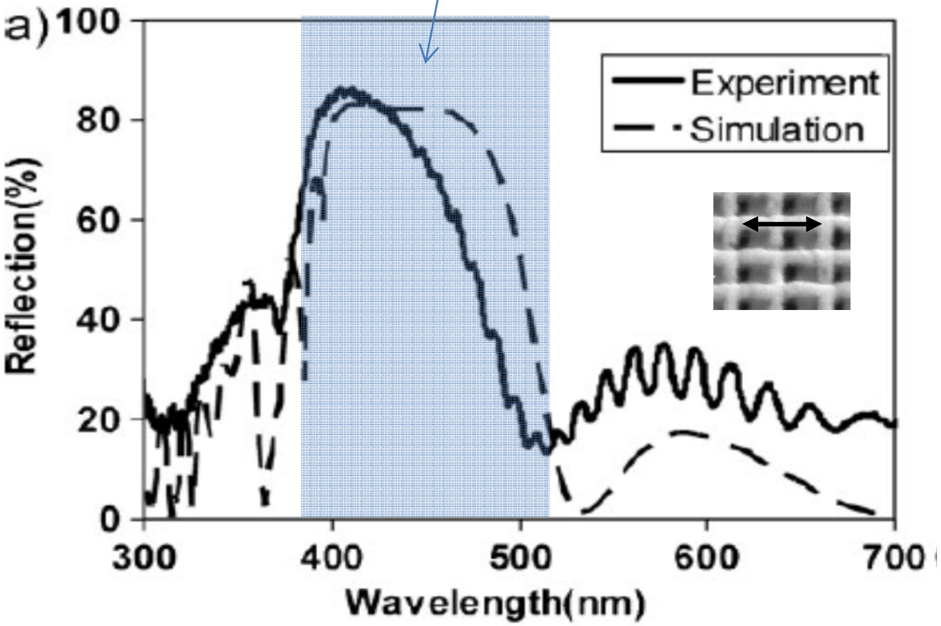




TiO_2 Logpile- Visible 3D PC



Normal direction stop gap

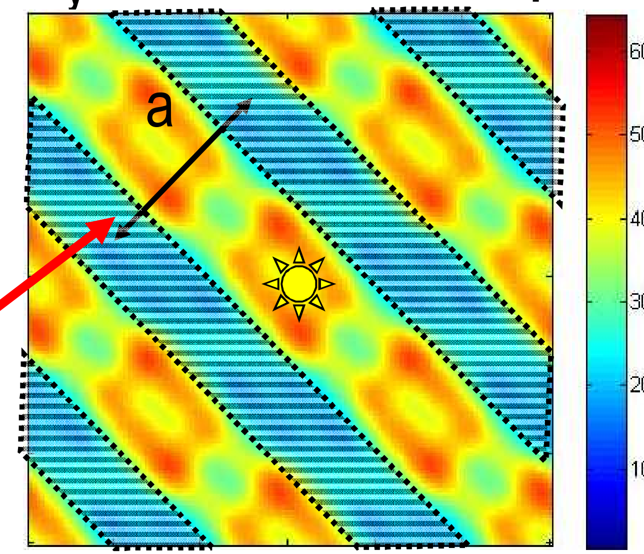


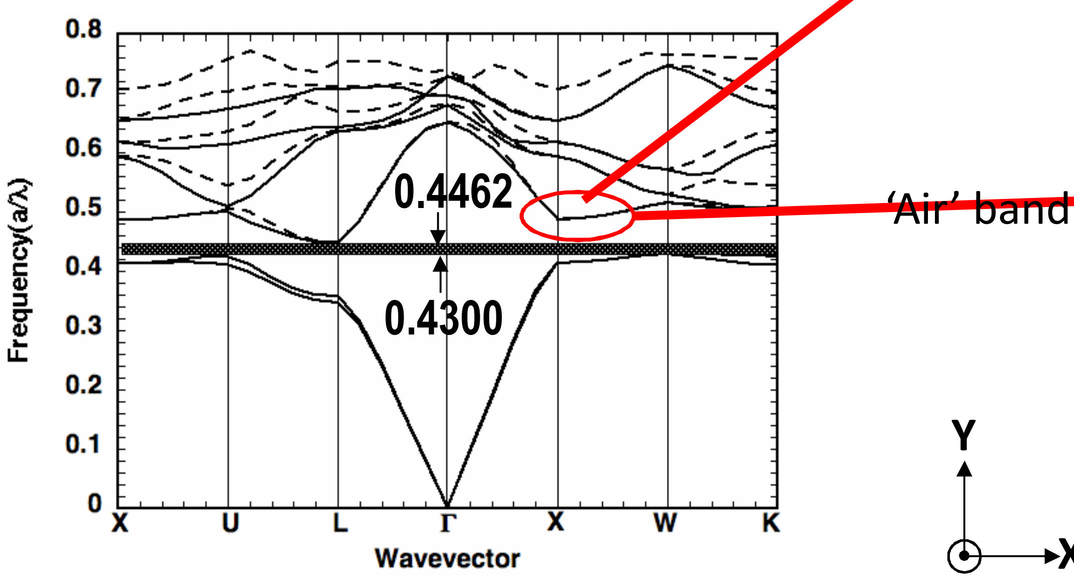
G. Subramania, Y.-J. Lee, A. J. Fischer, and D. D. Koleske, Advanced Materials **22**, 487-491 (2010)

Emission Modification in TiO_2 Logpile

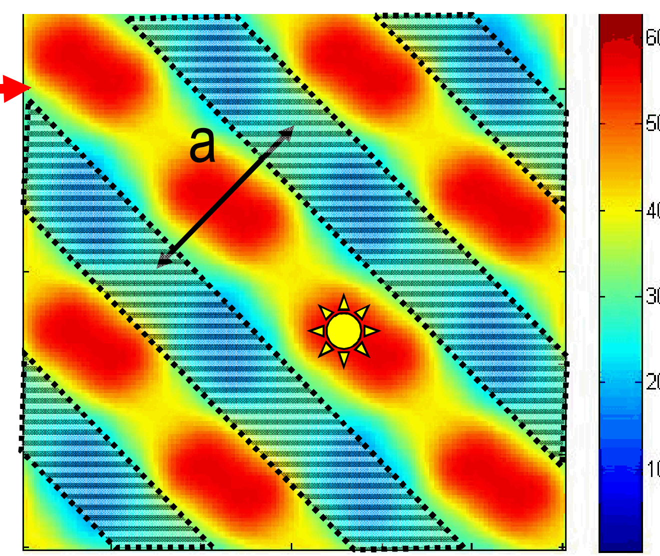
- Dielctric band vs. air band emission control
- Effect of 'air band' modes have not been probed
- Advantages
  - ➢ Post introduction of light source
  - ➢ Choice of light source (QDs or dyes or gas)
  - ➢ Potentially higher density of states enhancement

E_y field distribution at Xpt





E_z field distribution at Xpt



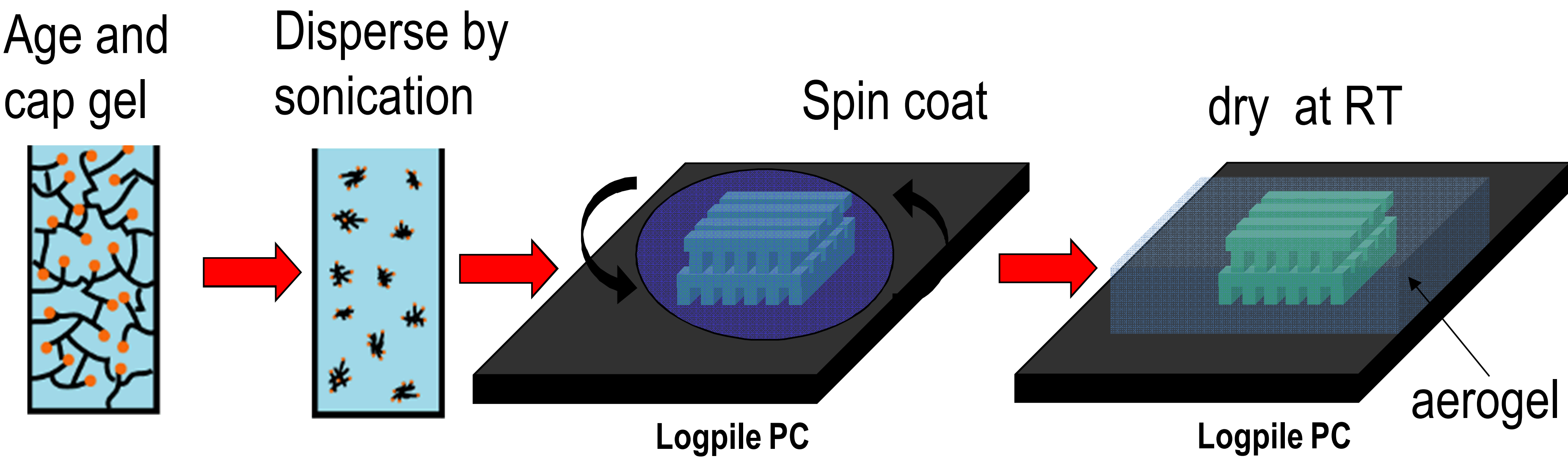
Field Distribution for the 'air band' using PWE method

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))



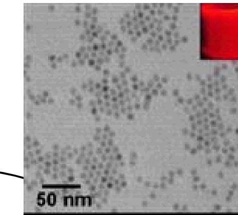
Introduce QDs through chemical attachment (3-mercaptopropyltrimethoxysilane chemistry)

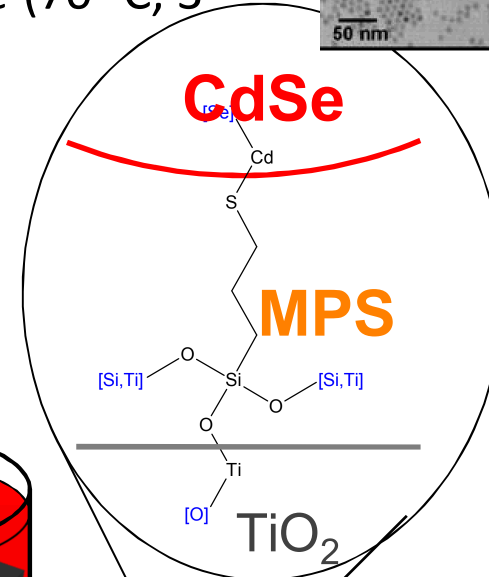
Developed by Alex Lee

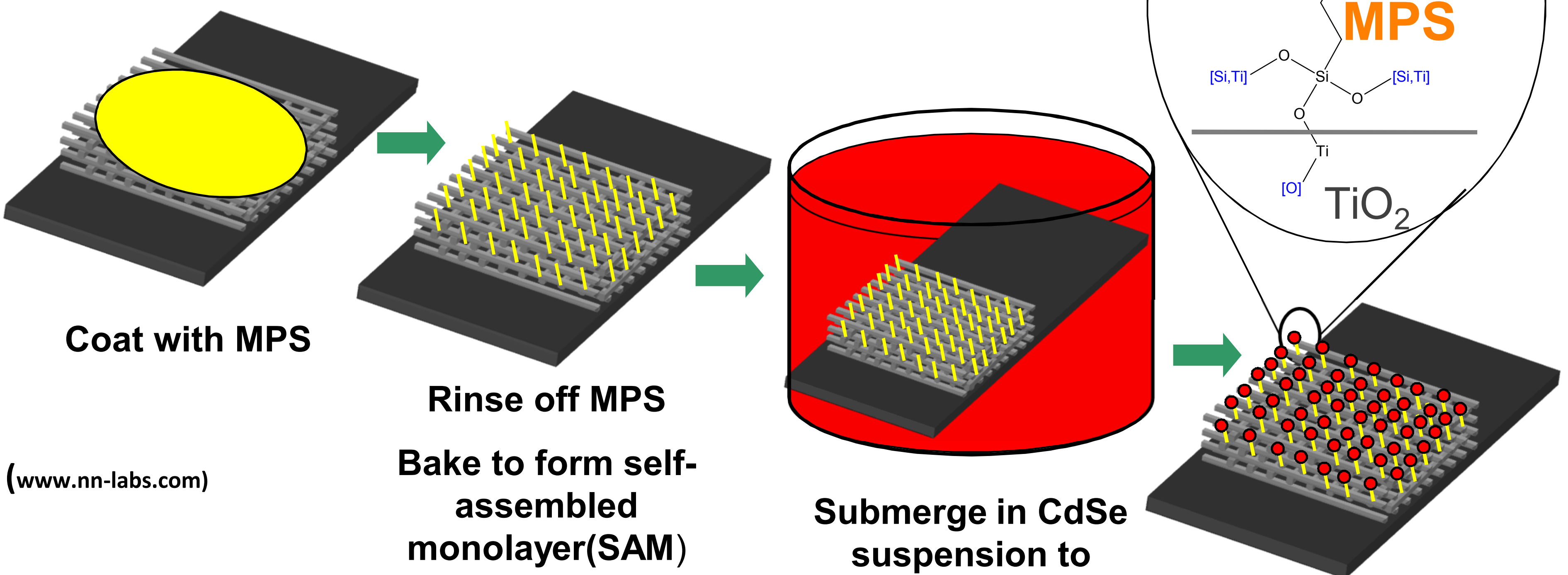
G. Subramania, Y. J. Lee, A. J. Fischer, T. S. Luk, C. J. Brinker, D. Dunphy, Appl. Phys. Lett. , **95**, 151101(2009)

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)



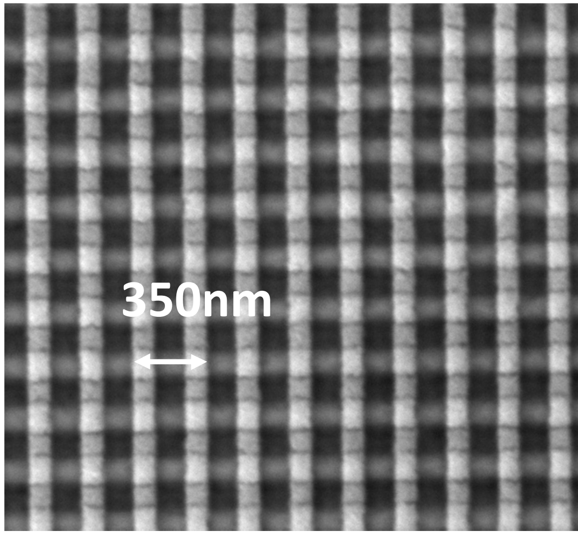




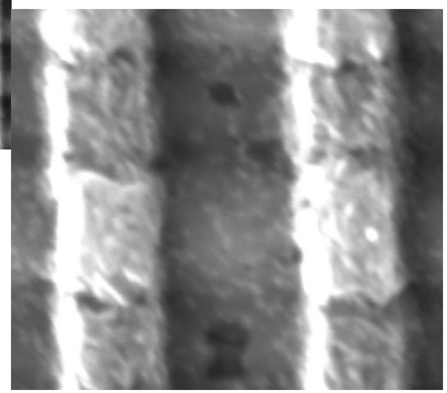
(www.nn-labs.com)

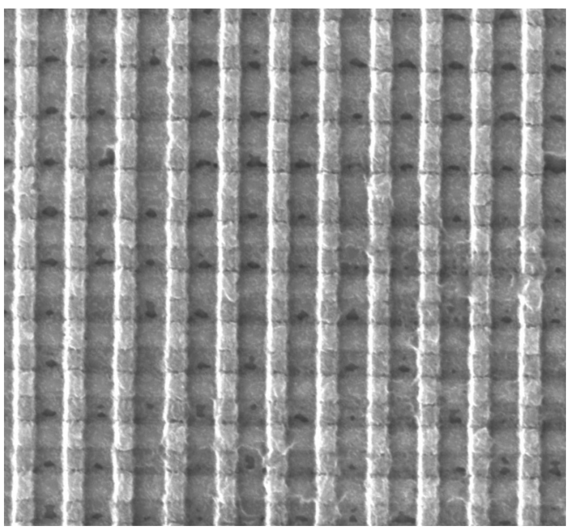
P. Guyot-Sionnest and C. Wang, J. Phys. Chem. B, **107**, 7355 (2003)
J. Pacifico, D. Gomez, and P. Mulvaney, Adv. Mater. **17**, 415 (2005)

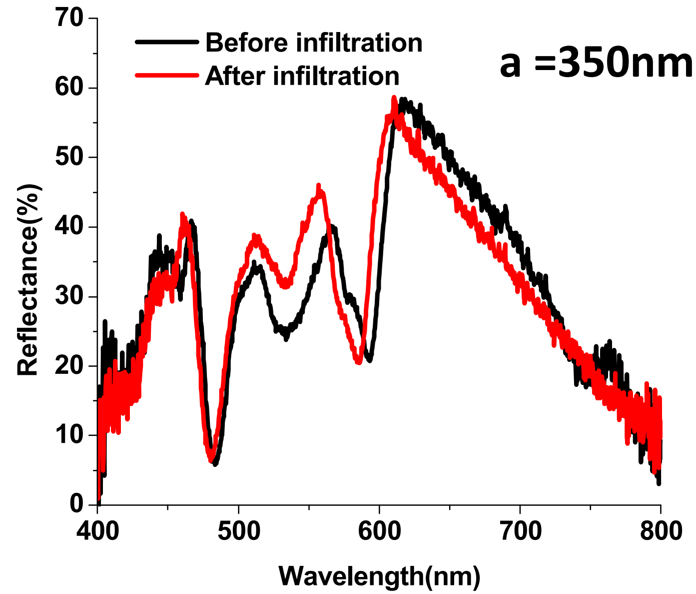
Effect of Aerogel and CdSe QD infiltration

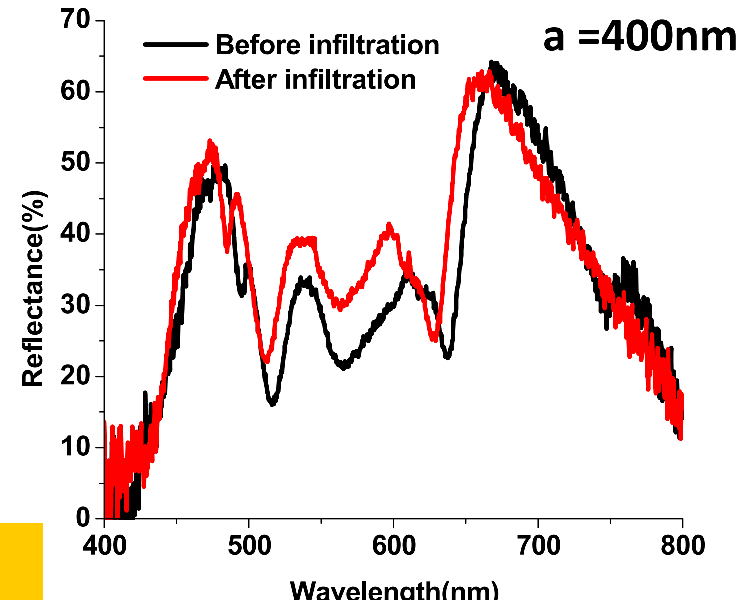


Aerogel Ref. index
~1.05-1.1





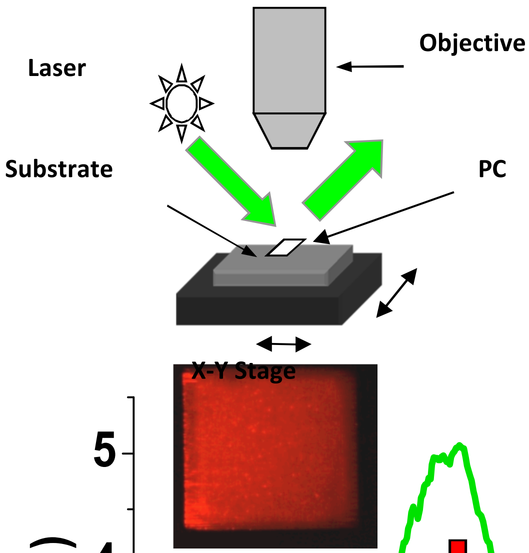




Aerogel and CdSe QD infiltration has negligible effect on the bandgap!

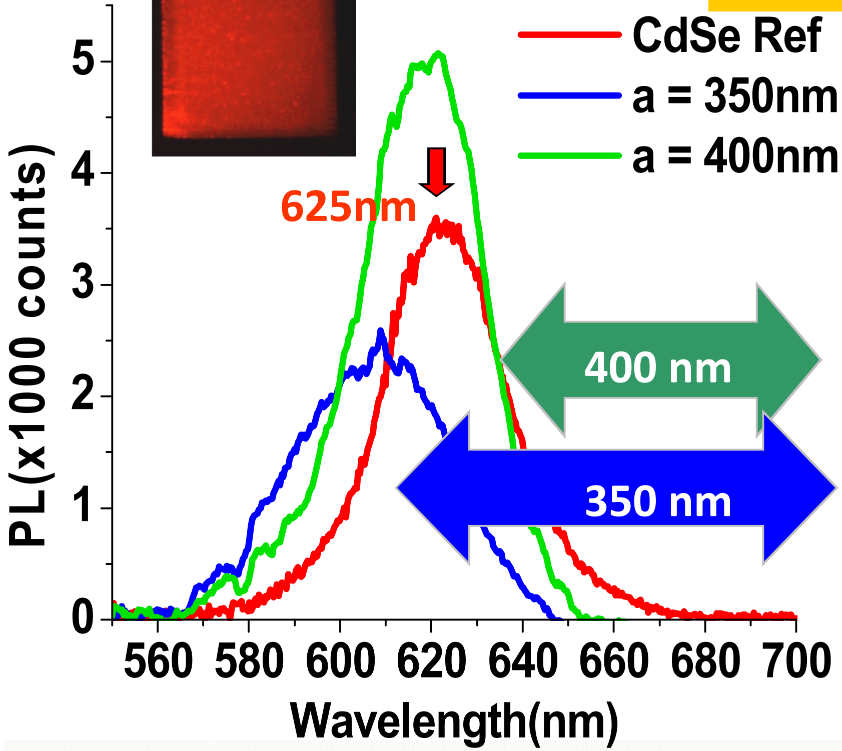
Spontaneous Emission Modification

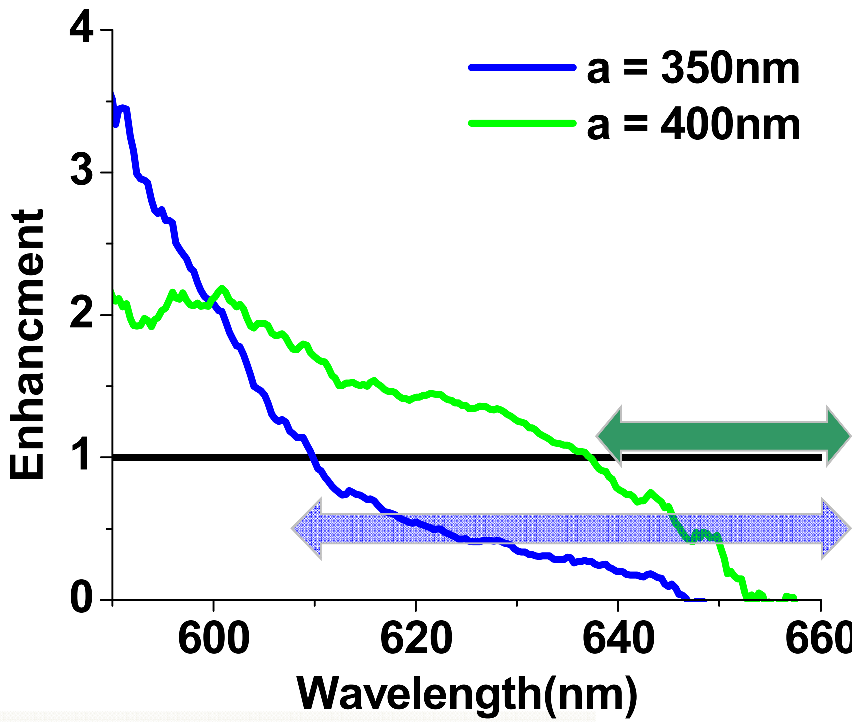
Sandia National Laboratories



- 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

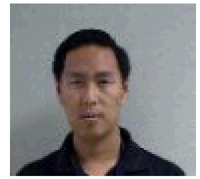


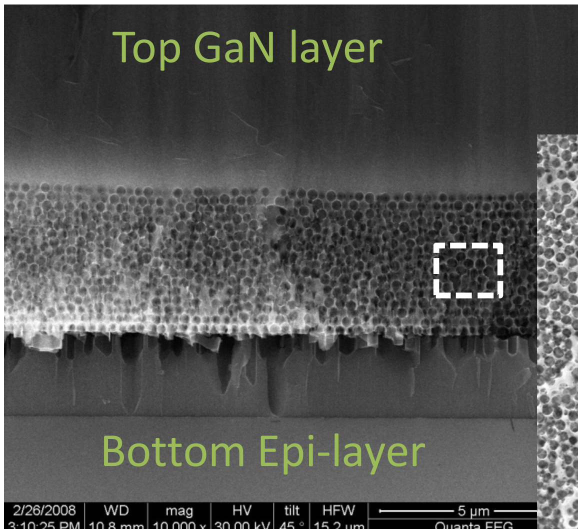


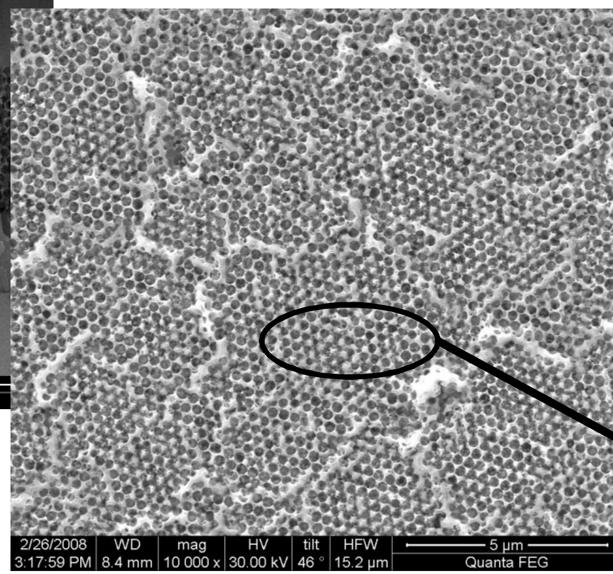
G. Subramania, Y. J. Lee, A. J. Fischer, T. S. Luk, C. J. Brinker, D. Dunphy, Appl. Phys. Lett. , **95**, 151101(2009)

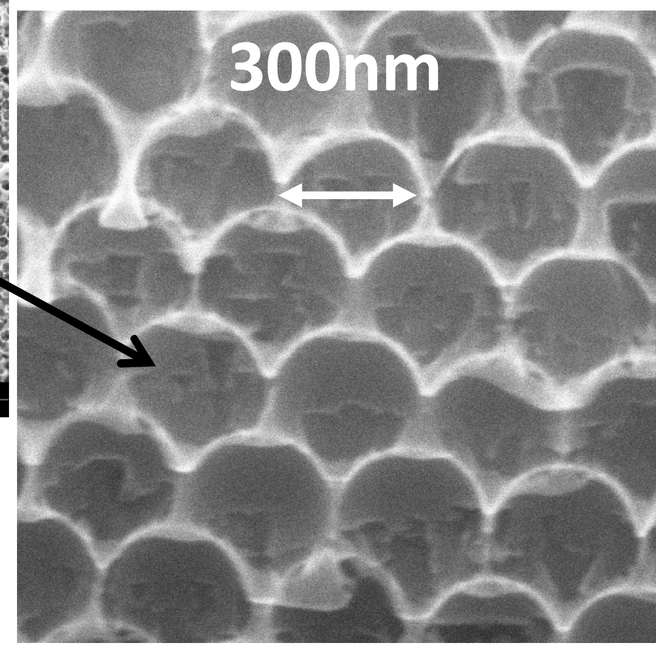
All GaN Logpile Photonic Crystal

Epitaxial GaN grown though nanostructured template reduces dislocation density



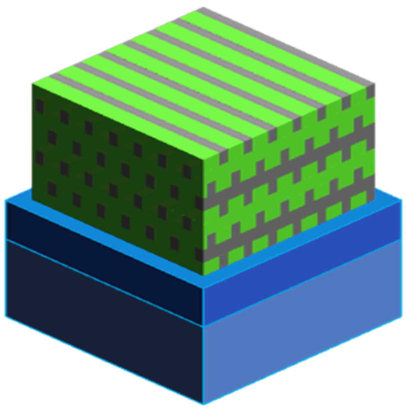




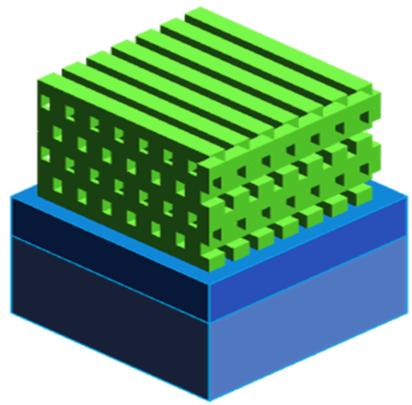


Qiming Li et. al., Appl. Phys. Lett. 94, 231105(2009).

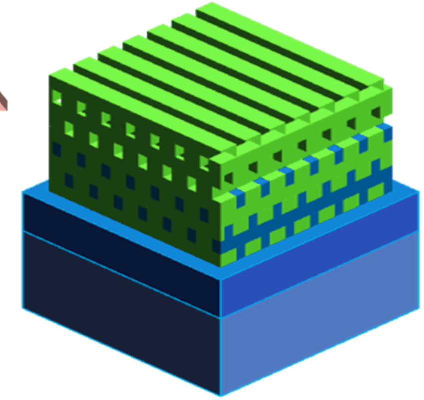
GaN growth through logpile template



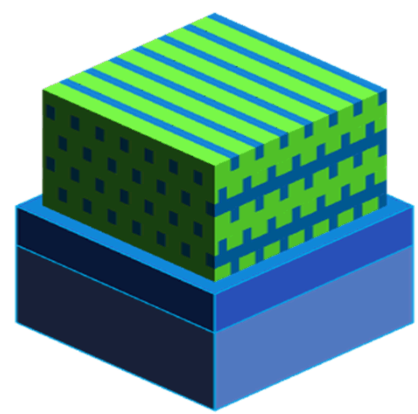
1. Si/SiO_2 logpile PC



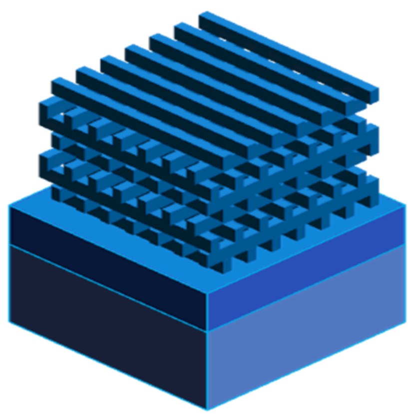
2. After Si is removed with KOH.



3. MOCVD GaN growth through SiO_2 template



4. After complete GaN infiltration into SiO_2 logpile template

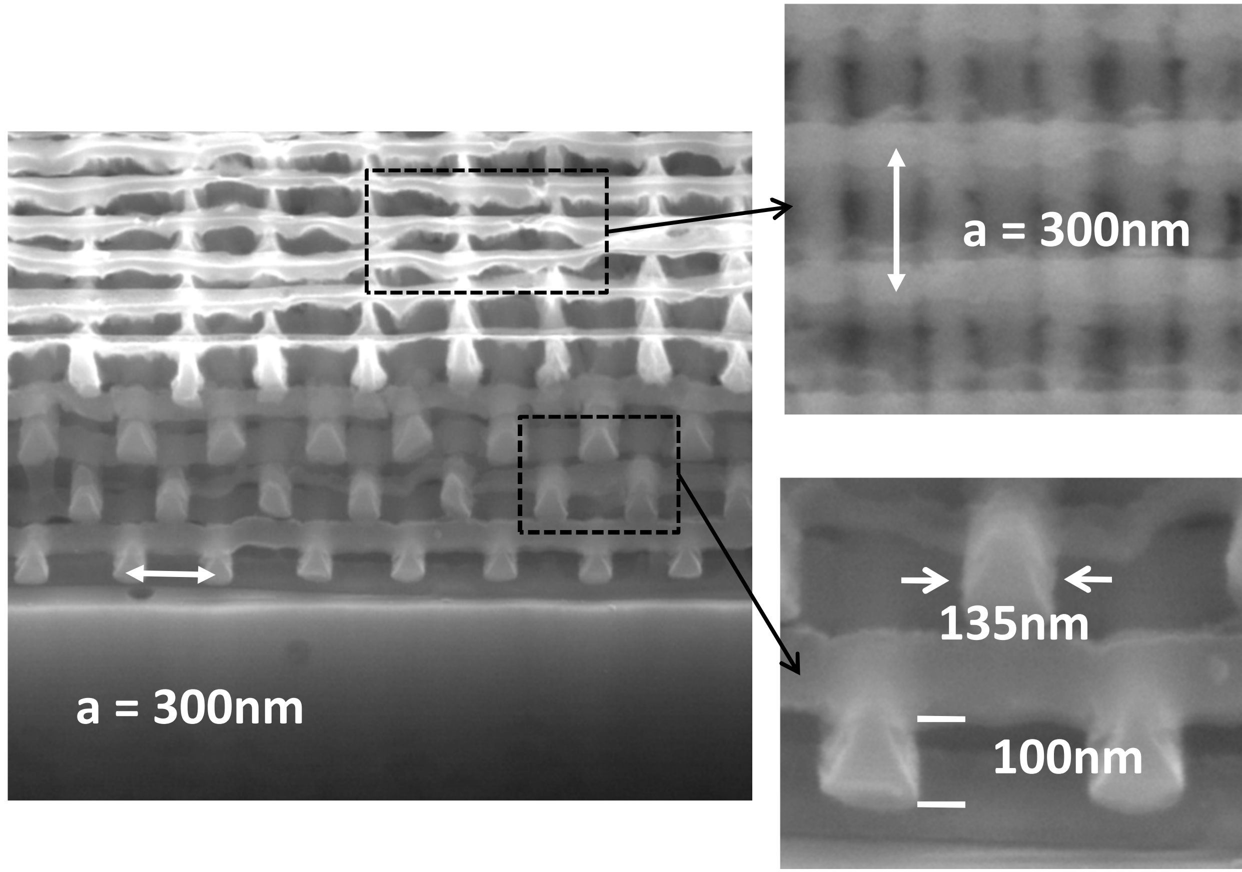


5. GaN logpile PC after SiO_2 logpile template removal

With optimized growth conditions …

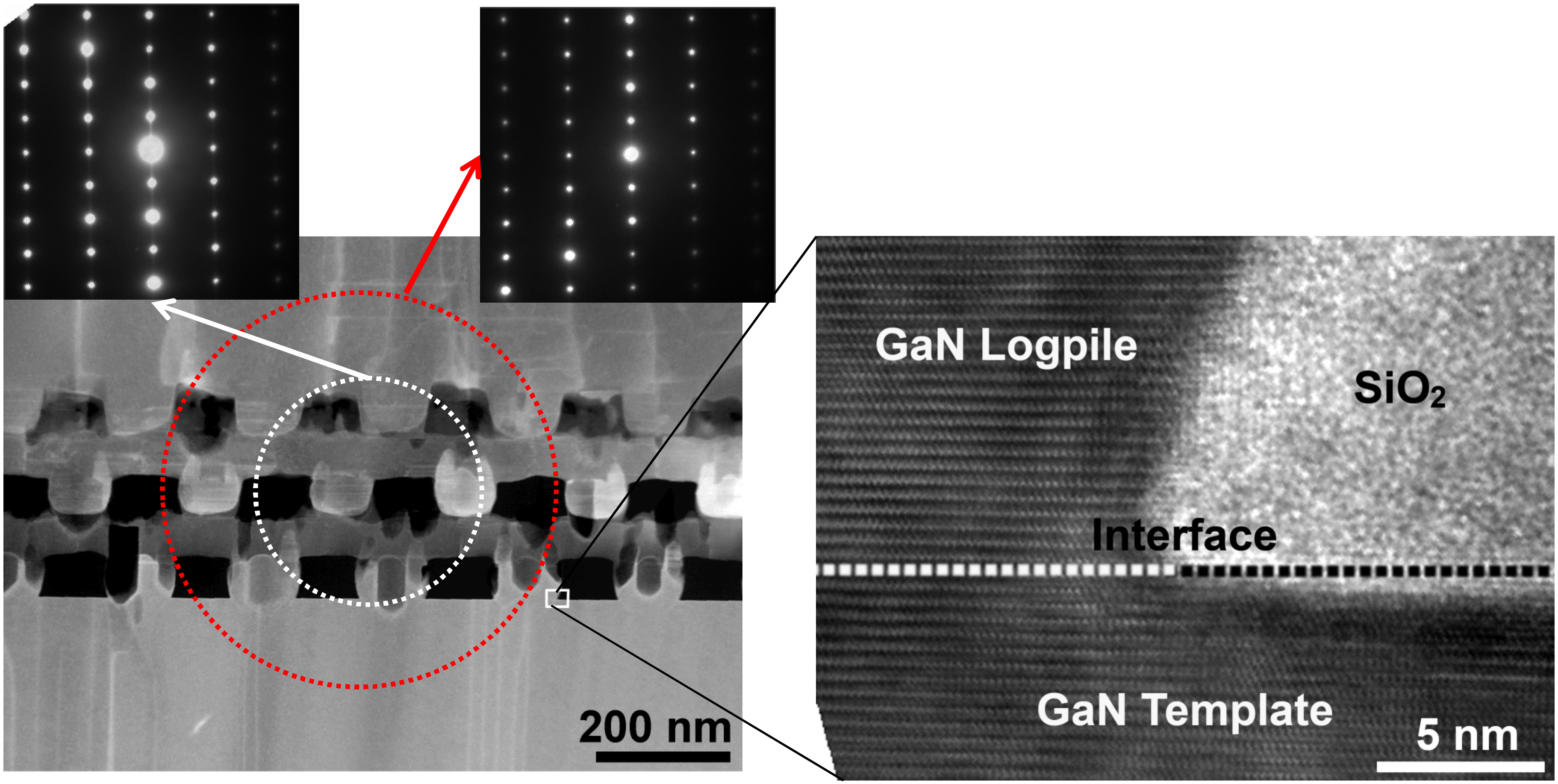
<u>Optimize Growth conditions</u>

- **Gas mixture:**
TMGa, NH_3 (~ 4 SLM), H_2, and N_2 (~ 100 sccm)
- **Temperature range:**
1000C-1075C
- **Pressure range:**
7 torr-30 torr



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

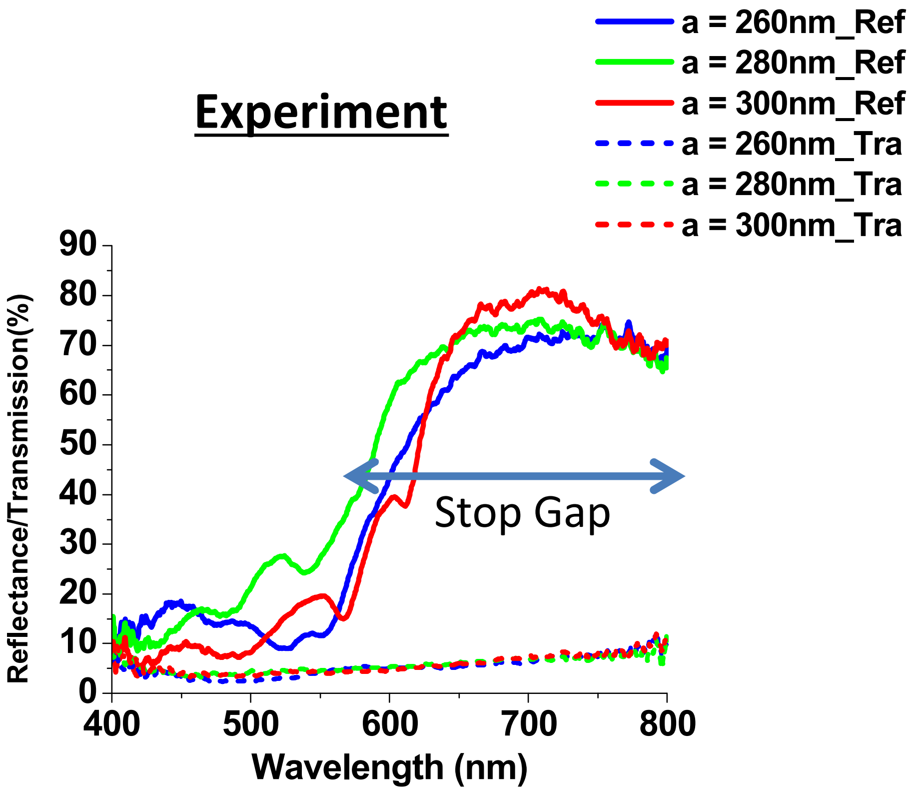
Bottom-up epitaxial growth of crystalline GaN



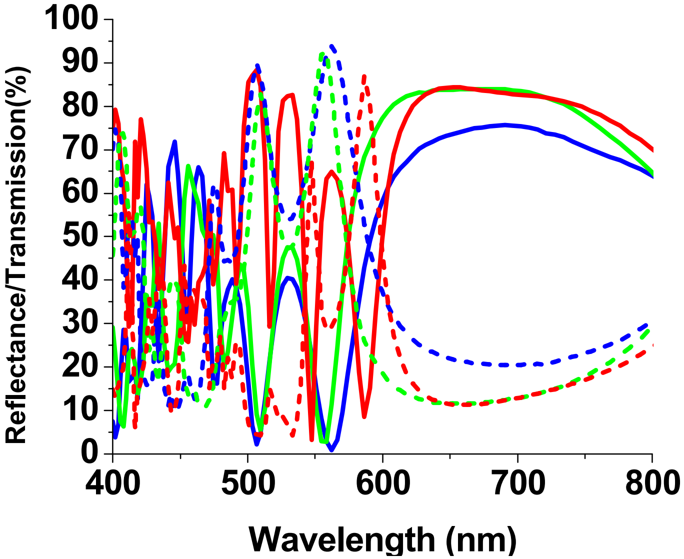
G. Subramania et. al. , Nano Lett. **11**, 4591 (2011).

Optical Response

Experiment



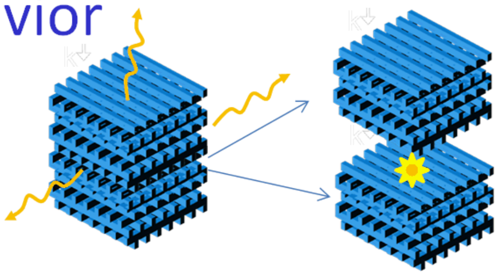
FDTD Simulation

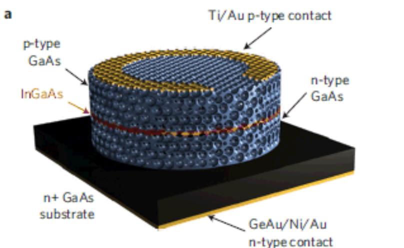


G. Subramania et. al. , Nano Lett. **11**, 4591 (2011).

Summary/Possibilities

- 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)





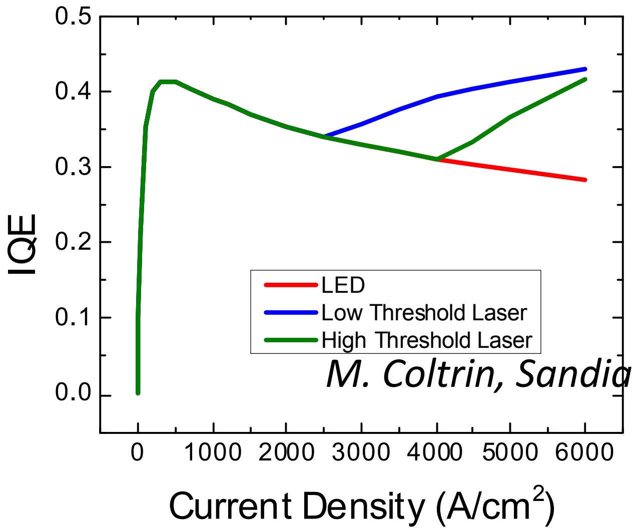
E. C. Nelson, et al., Nat Mater **10**, 676 (2011)

Three dimensional PC structure fabrication is resource and labor intensive.

Nanowire Photonic Crystal Lasers

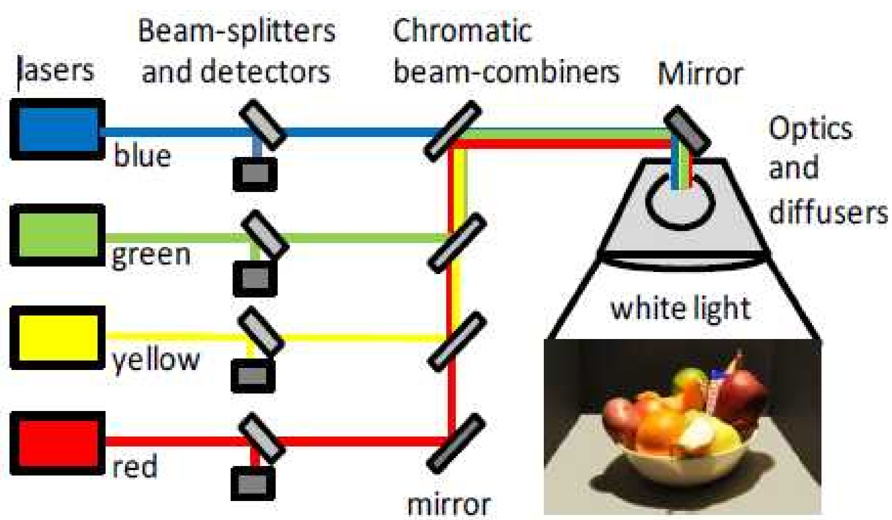
(Jeremy B. Wright, Sheng Liu, Alexander Benz, George T. Wang, Qiming Li, Daniel D. Koleske, Ping Lu, Huiwen Xu, Luke Lester, Ting S. Luk, Igal Brener)

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*

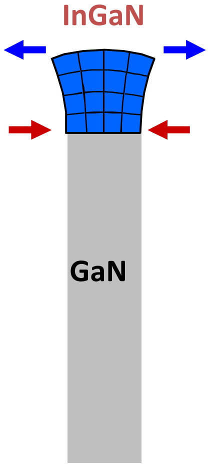


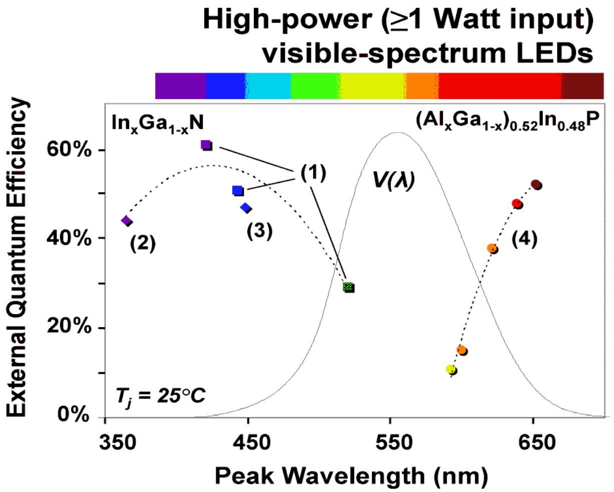
- ***4 color lasers suitably combined can achieve high color rendering***
- ***Lasers can potentially mitigate the efficiency droop problem !***

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

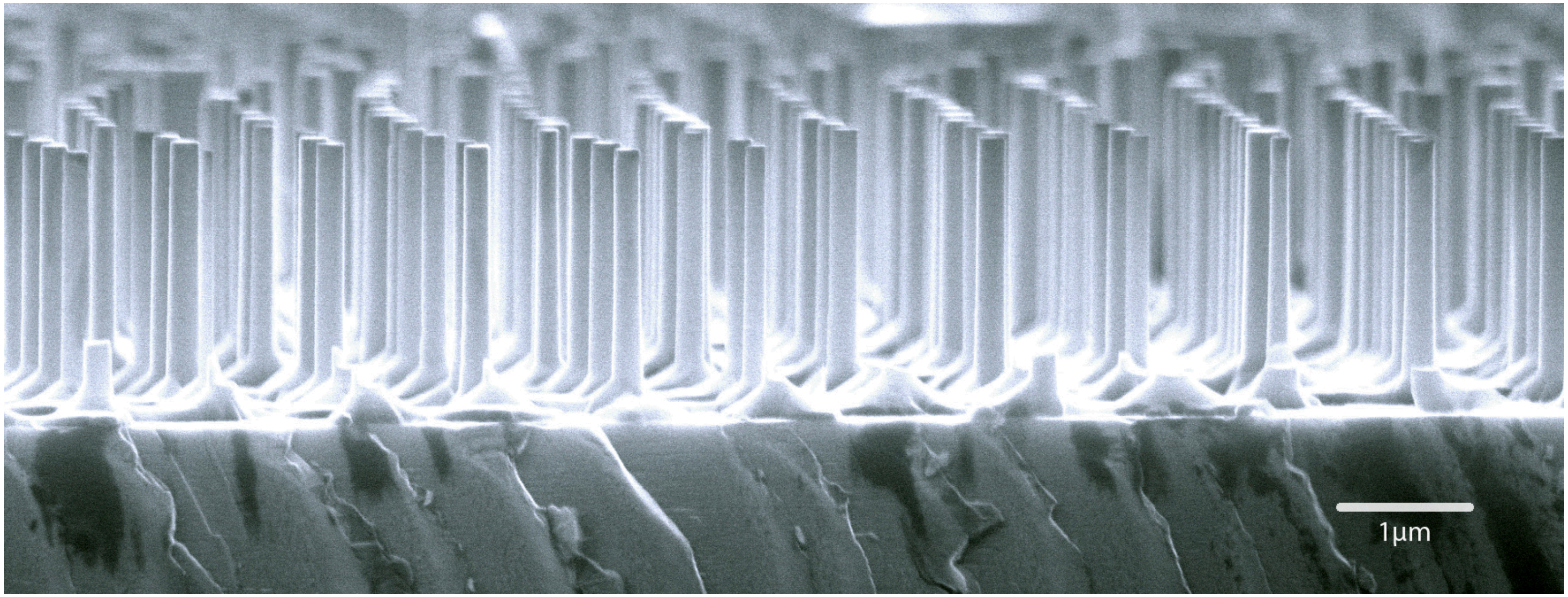
Why Nanowires for Lasing?

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



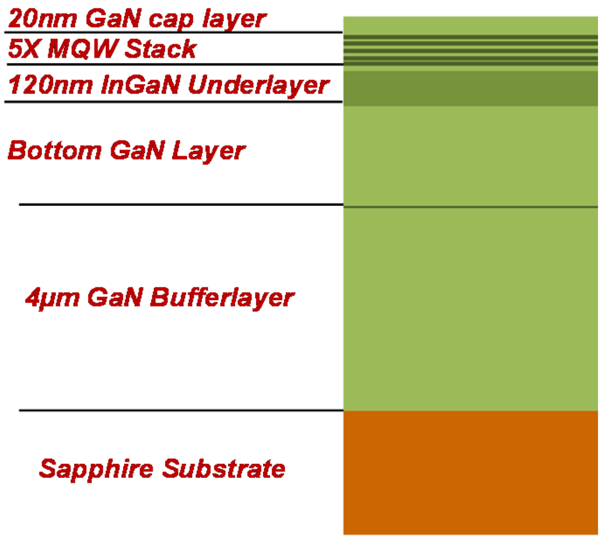


M. Krames, Philips Lumileds

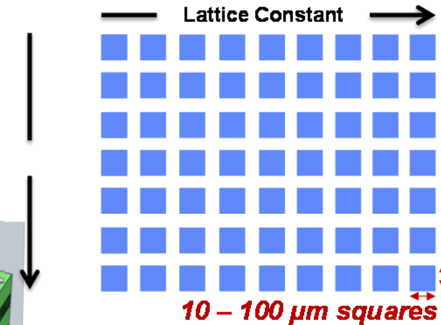


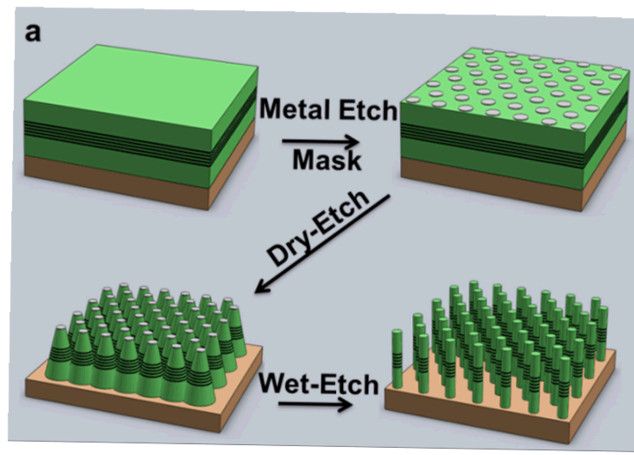
Fabrication of III-N nanowire laser array

Growth of III-N active material

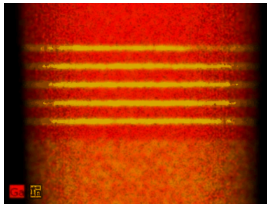


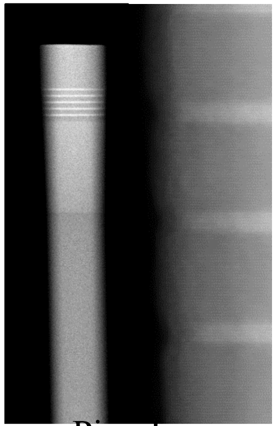
Patterning of 2DPC using e-beam lithography





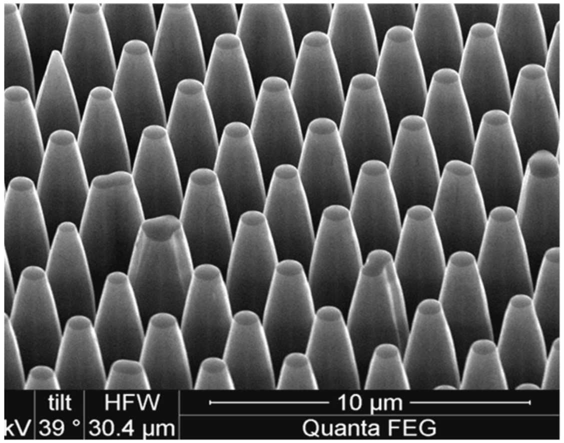
TEM images

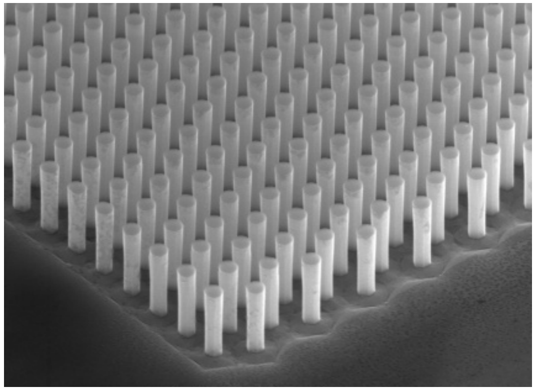




Ping Lu, Sandia

Inductively coupled plasma dry etch



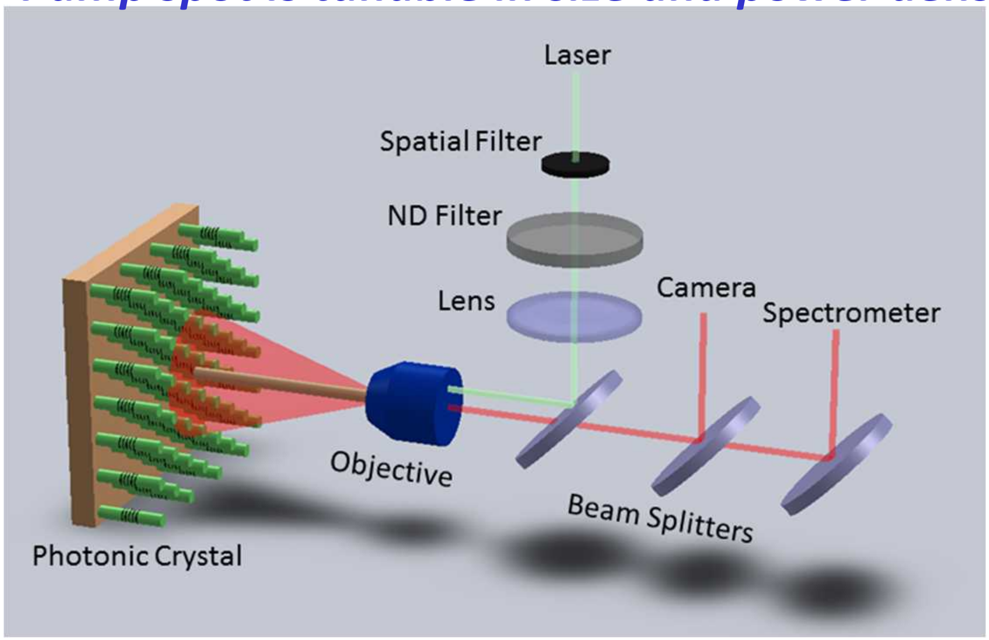


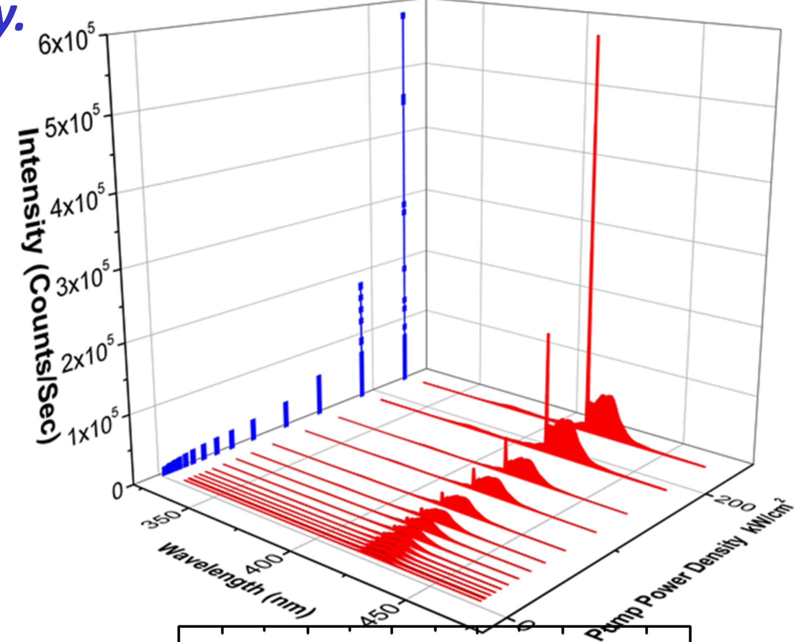
Wet etch using KOH process

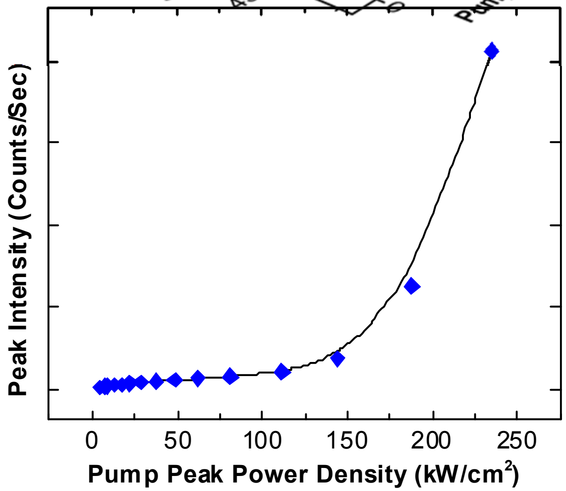
Optical response – low threshold lasing

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

Pump spot is tunable in size and power density.

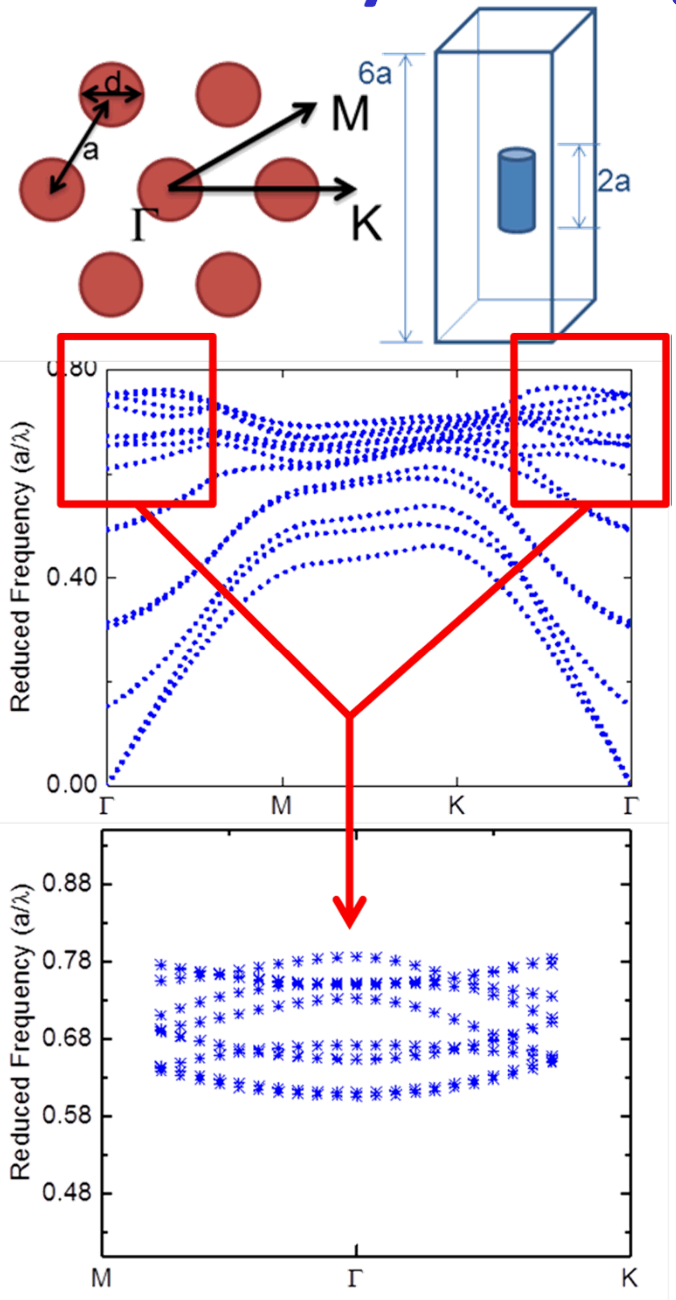






A low lasing threshold is achieved with < 500kW/cm2 for all PC lasers fabricated.

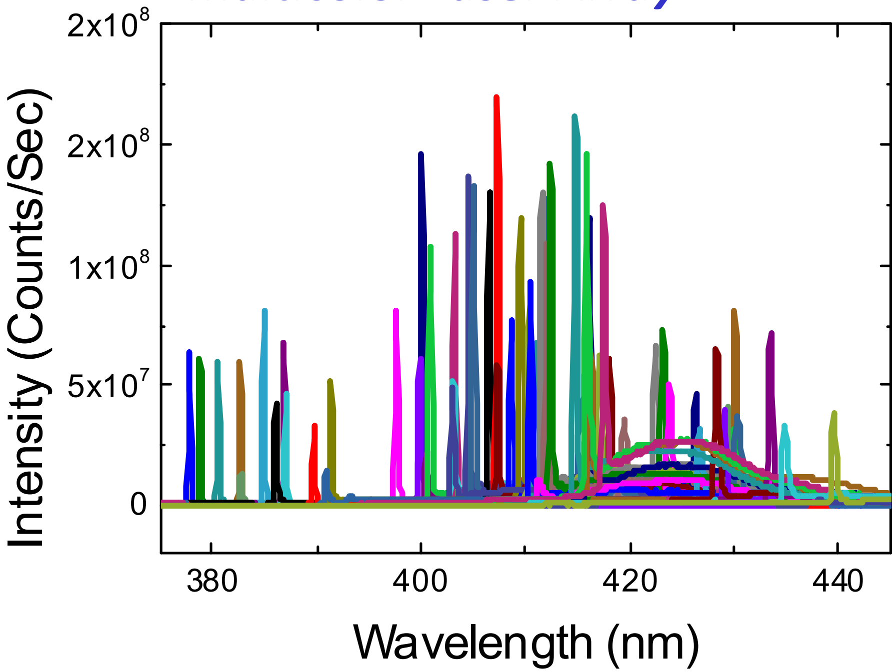
Vertically emitting photonic crystal lasers - Theory



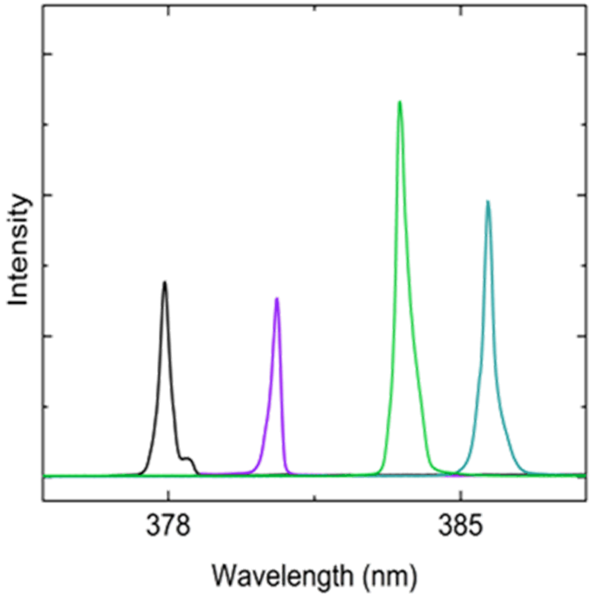
- ***Low lasing threshold***
  - ***Increase interaction of light with the gain region***
  - ***Enabled by 'Low group velocity modes' in photonic crystal****
- ***Vertical Emission***
  - ***At higher bands there are low group velocity modes near the Gamma point***
  - ***Near the Gamma point the in-plane 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).

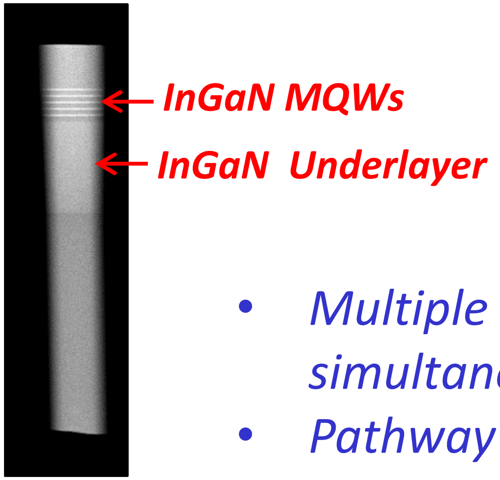
Multicolor Laser Array



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



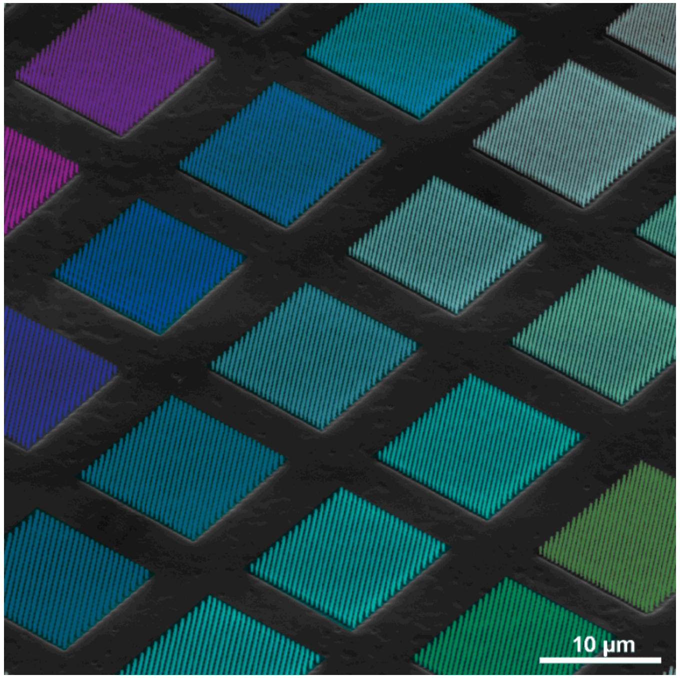
Gain from multiple gain sections



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

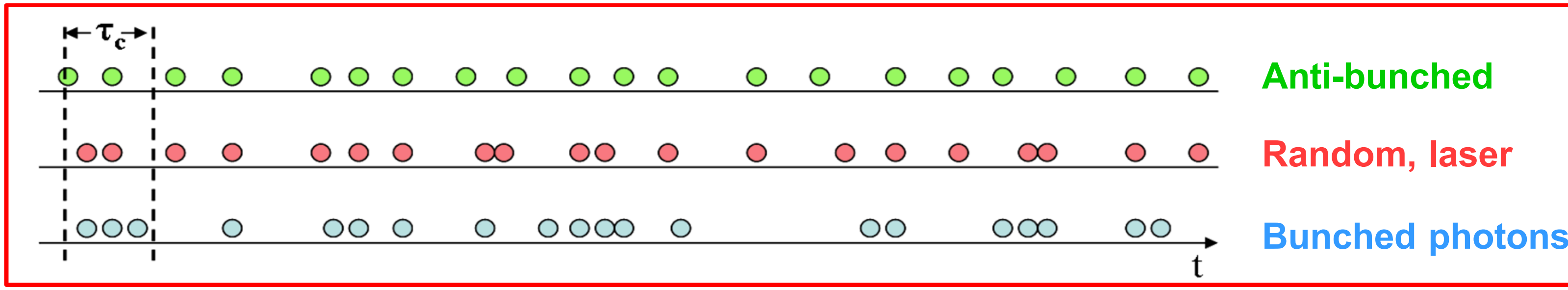
Possibilities

- ***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

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: $g(2)(t = 0) < 1$

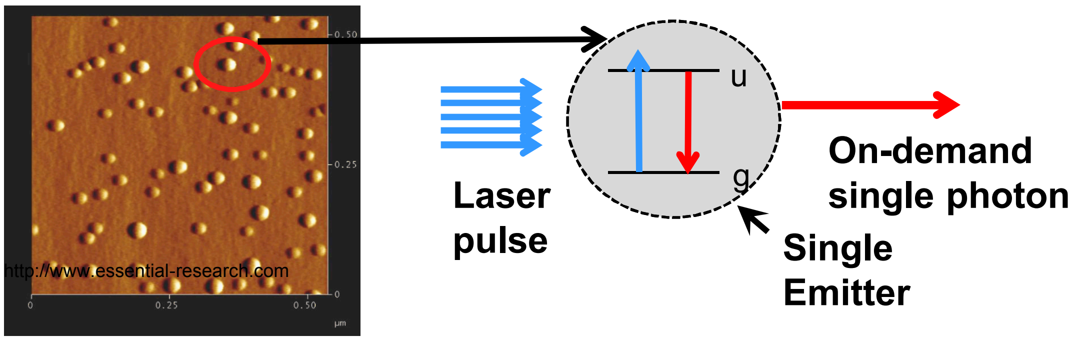
- Anti-bunched photons (Quantum optics theoretical treatment)

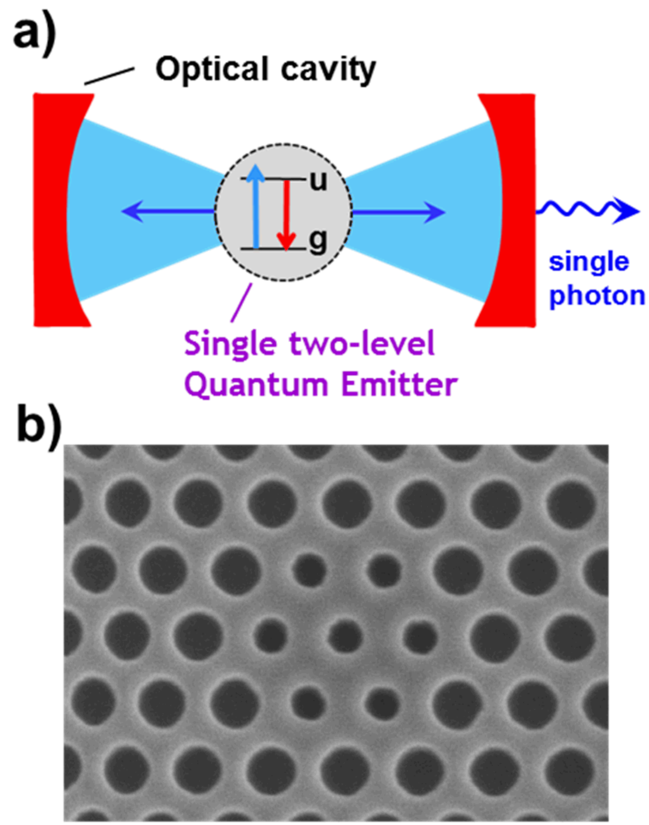
Applications:

- **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**

Single Photon Source based on Quantum Dots

AFM image of InAs QDs





Sandia 2D photonic Crystal Cavity

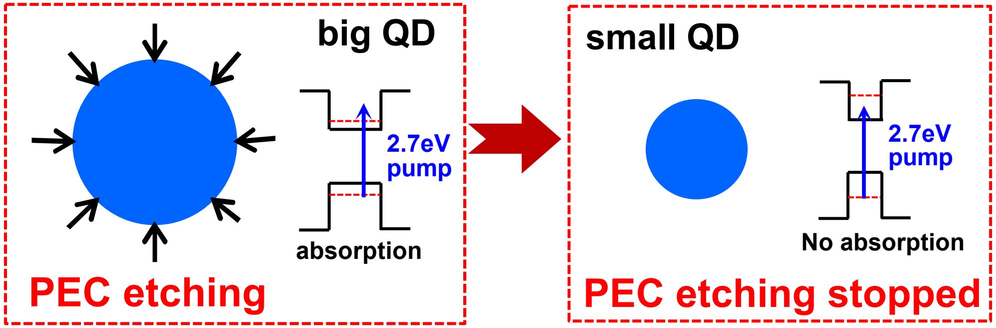
QD Single Photon Source:

- Isolate emission from a singe quantum dot
- 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
- **Path to electrical-injection/chip-scale integration**

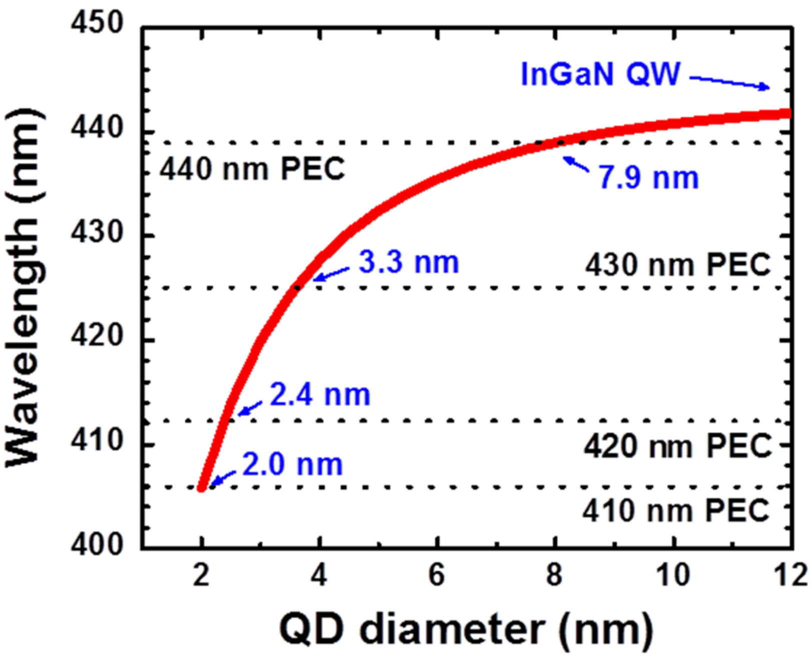
Fabrication of InGaN QDs via PEC etching

Quantum Size Control: Use size quantization to control QD size

Self-limiting PEC etch process:



- **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**
- **QD size depends on PEC wavelength**
- **Monodisperse QD distributions ??**



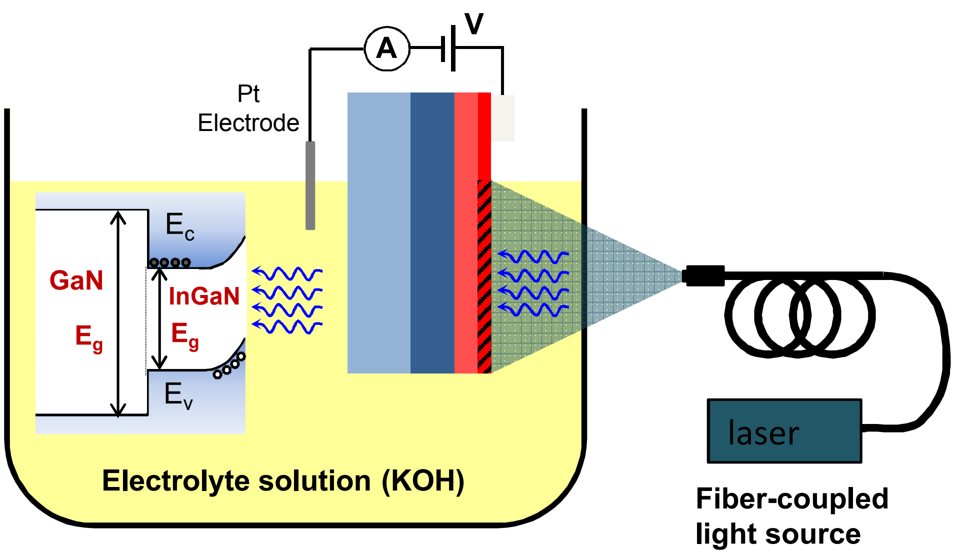
G. Pellegrini, et al., Journal of Applied Physics 97, 073706 (2005).

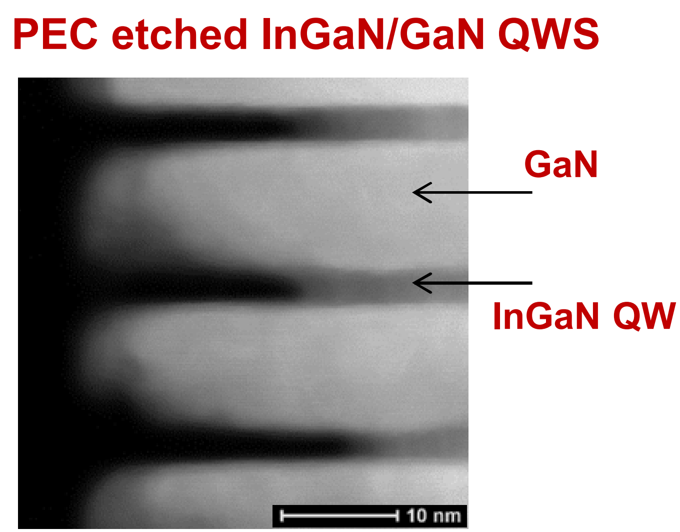
Xiao, X. *et al.* Quantum-Size-Controlled Photoelectrochemical Fabrication of Epitaxial InGaN Quantum Dots. *Nano Lett.* **14**, 5616-5620, doi:10.1021/nl502151k (2014).

Introduction to InGaN PEC Etching

Photoelectrochemical (PEC) Etching:

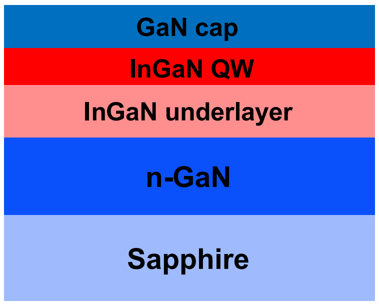
- Very few wet etches work for III-nitrides
- Band gap selective (Etch InGaN over GaN)
- Dopant selective, light intensity dependent, etch current can be monitored
- Laser or lamp excitation (Xe arc lamp, tunable ps Ti:S)
- KOH (~0.1M) typically used as electrolyte



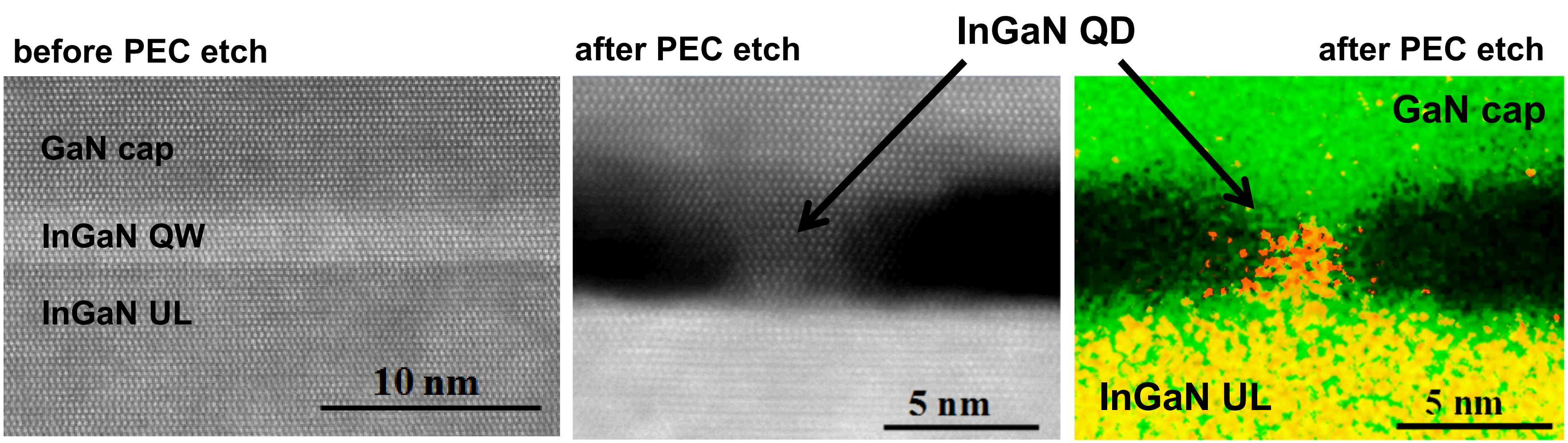


Transmission Electron Microscope Images

Capped InGaN QW



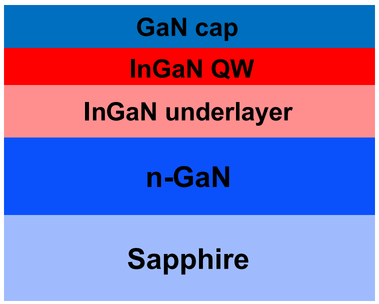
- High-angle annular dark-field (HAADF) TEM images
- Sample etched at 420 nm
- EDX mapping shows that dots are InGaN
- InGaN QDs are epitaxial to the underlying GaN
- 2% InGaN underlayer + GaN cap → PL is much brighter
- GaN cap provides partial passivation



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

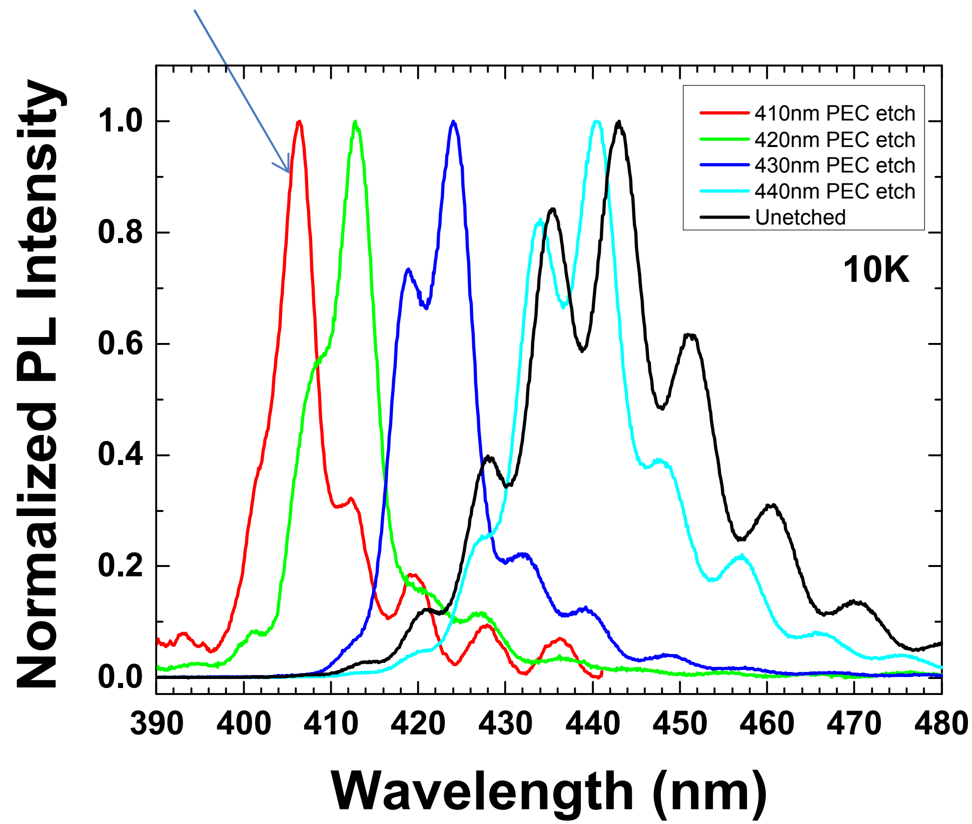
Photoluminescence from fabricated InGaN QDs

Capped InGaN QW

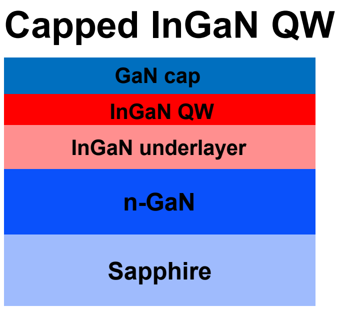


Photoluminescence (PL) data:
- 375 nm pump (ps pulsed)
- 10K PL data
- PL wavelength determined by PEC etch wavelength
- PL linewidth: 24 nm → 6 nm
- Quantum size-controlled PEC etching works!

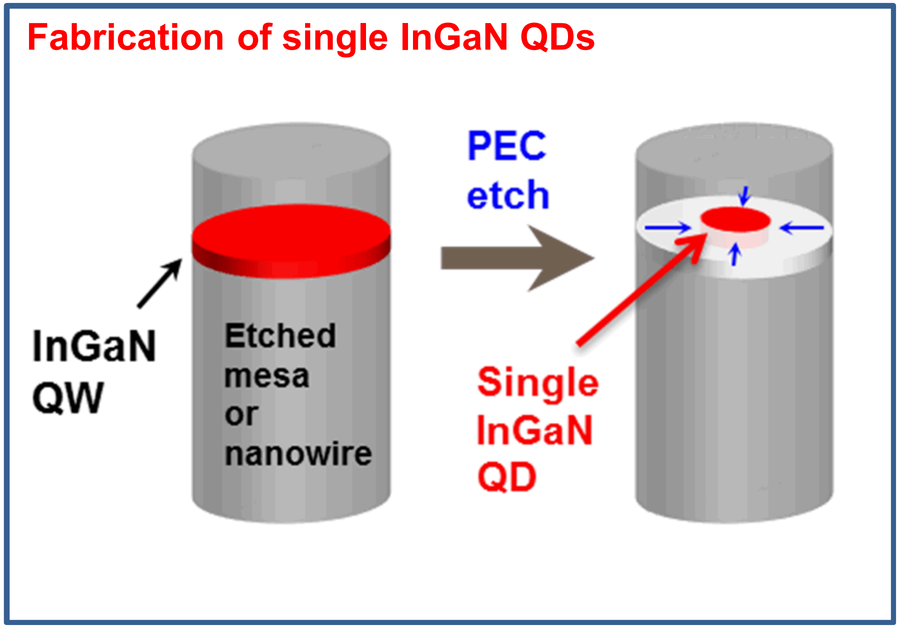
As narrow as **6 nm** FWHM is consistent with a narrowing of the QD size distribution

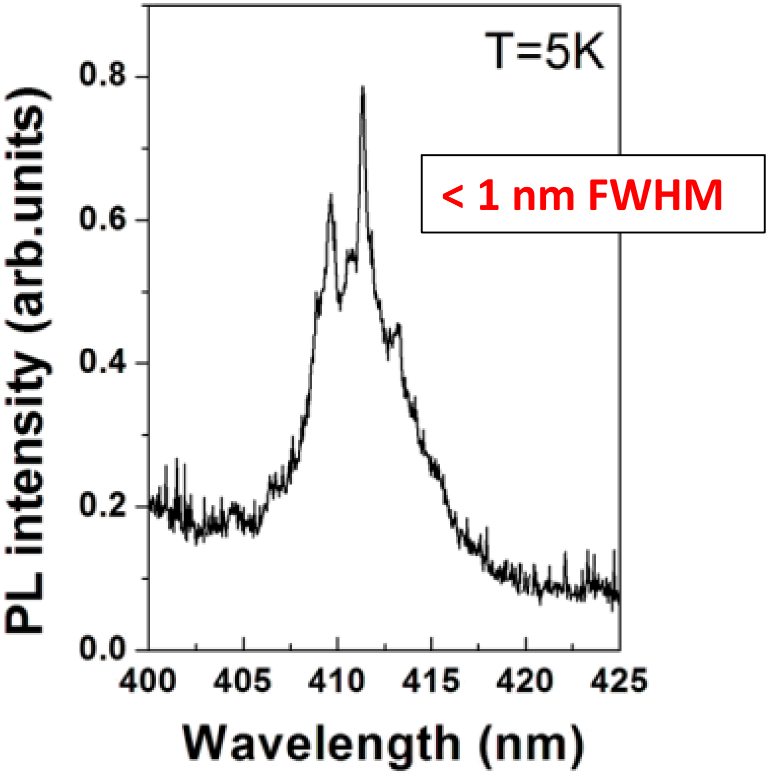


Emission from single InGaN QDs



- 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





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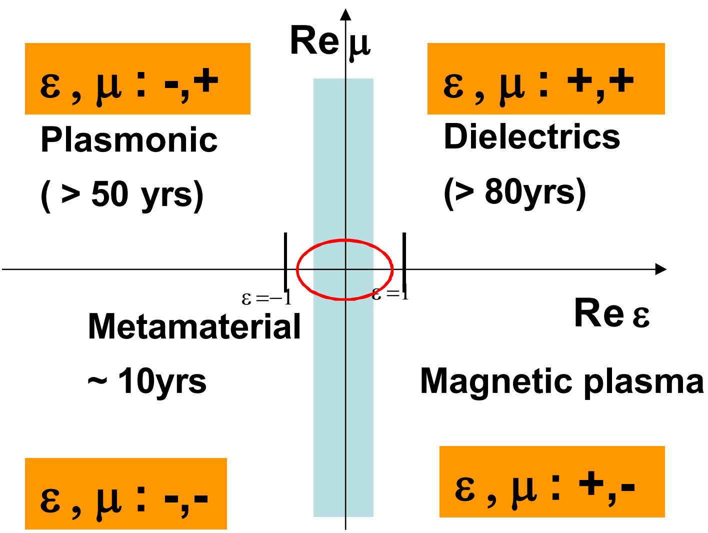
Metal Nanostructure Optics

Epsilon Near Zero Material and What Can it Impact?

Epsilon(ε): Dielectric constant



Epsilon Near Zero (ENZ) material is a metamaterial with unique and interesting properties.

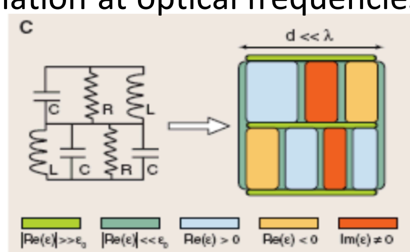
- $\underline{D} = \varepsilon\, \underline{E} \sim 0$ for $\varepsilon \sim 0$
- $V_p \rightarrow \infty$; No phase variation
- DC behavior at optical frequencies

Properties

- Sub-wavelength squeezing of light (λ/20)
- Lower loss, broadband at optical wavelengths (non-resonant, effective medium)

Optical Nanocircuits

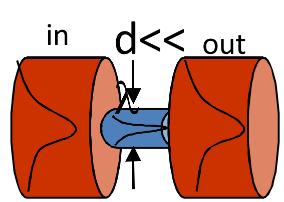
Vacuum light guiding, electrical isolation at optical frequencies



[Engheta, N., *Science* 317 1698(2007)]

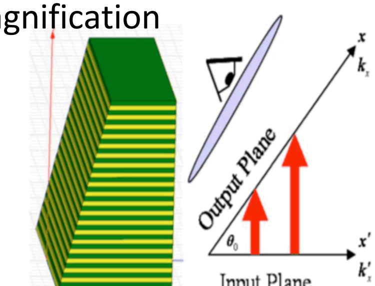
Supercoupling

Light squeezing through sub-wavelength channels



Subdiffraction Imaging

Far field subwavelength magnification



A. Salandrino and N. Engheta, Phys. Rev. B. 74, 075103(2006)

Effective Medium Approach to ENZ

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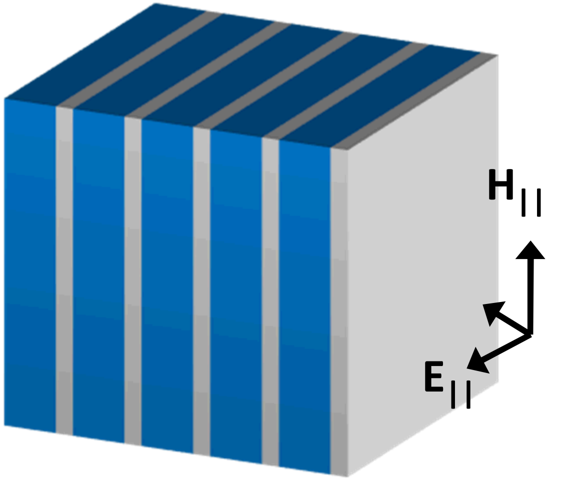
$$\varepsilon_{effective} = f\varepsilon_{+} + (1-f)\varepsilon_{-}$$

dielectric (ε_{+}), metal (ε_{-})



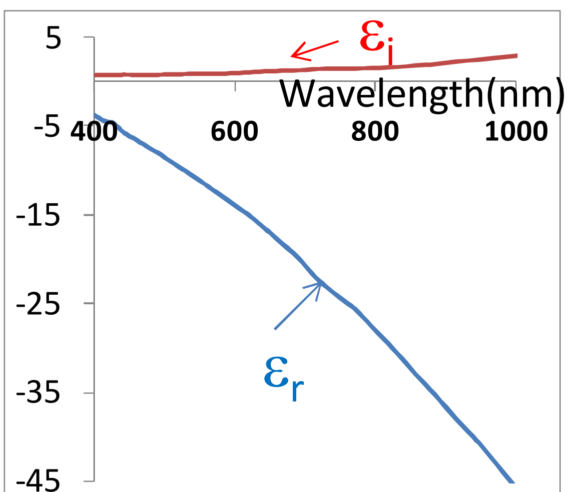
Goals

- Minimize losses due to metal
- Effective medium behavior-finer subdivision
- Reduce non-local effects – Smoother field distribution
- Easy fabricate , easy characterization

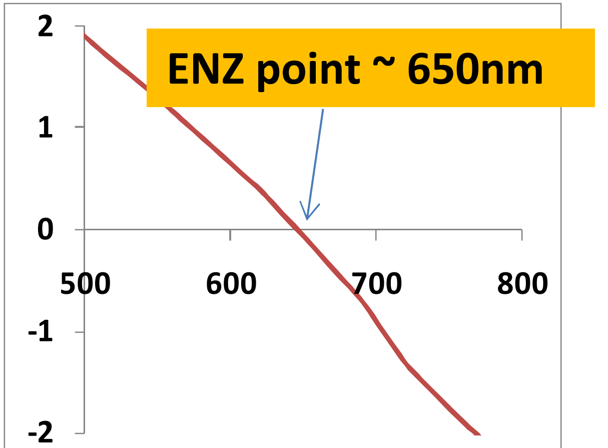
Materials Choice ε_{-} : Ag and **ε_{+} : TiO_2**

Ag (23%) + TiO_2 (77%)

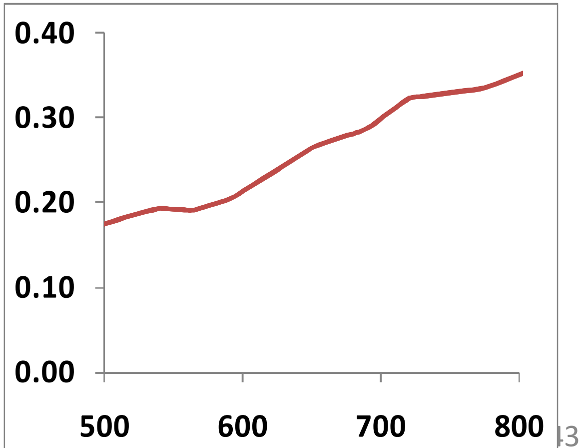
Silver(Ag)dispersion (Palik)



Composite-ε_{real}



Composite-ε_{imag}



Effective Medium Multilayer Comparison

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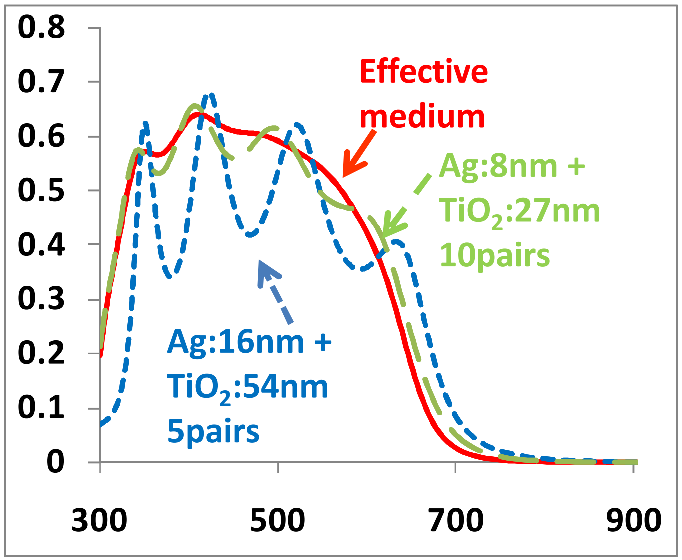
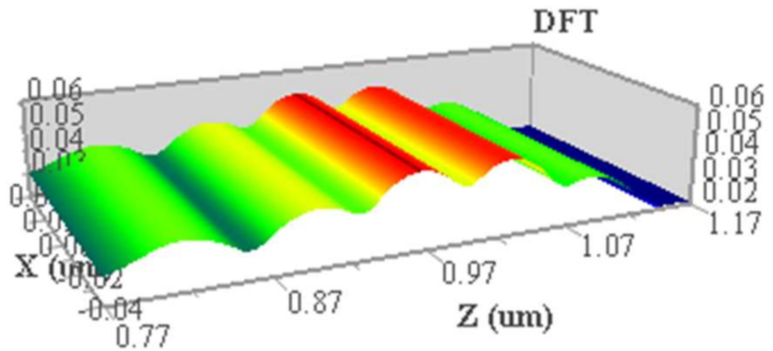
Finite Difference Time Domain Simulation

Ag/TiO_2 Composite
Ag = 16nm (23%); TiO_2 = 54nm (77%)

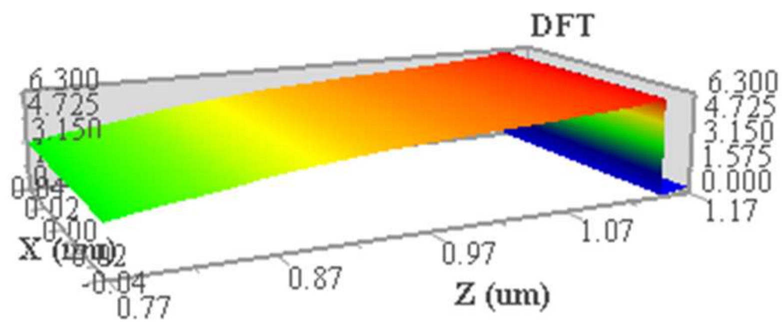


E field amplitude at ~ 653nm , ENZ point



E field phase at ~ 653nm , ENZ point

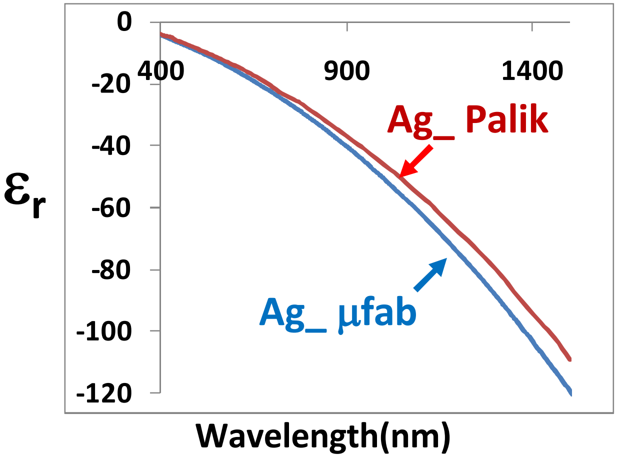
Small Phase Change

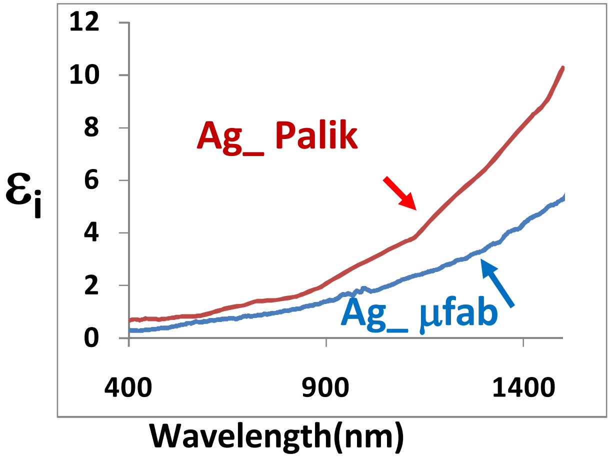


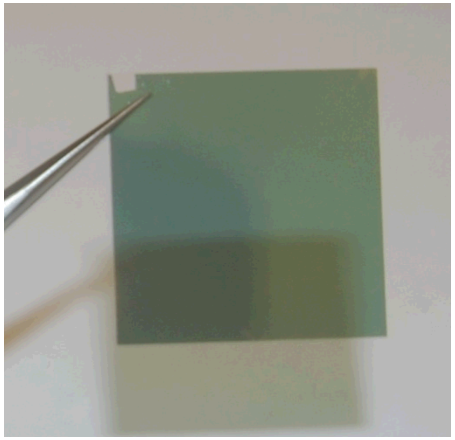
Ag thickness was chosen to be 16nm to obtain a continuous film using e-beam evaporation while remaining as thin as possible.

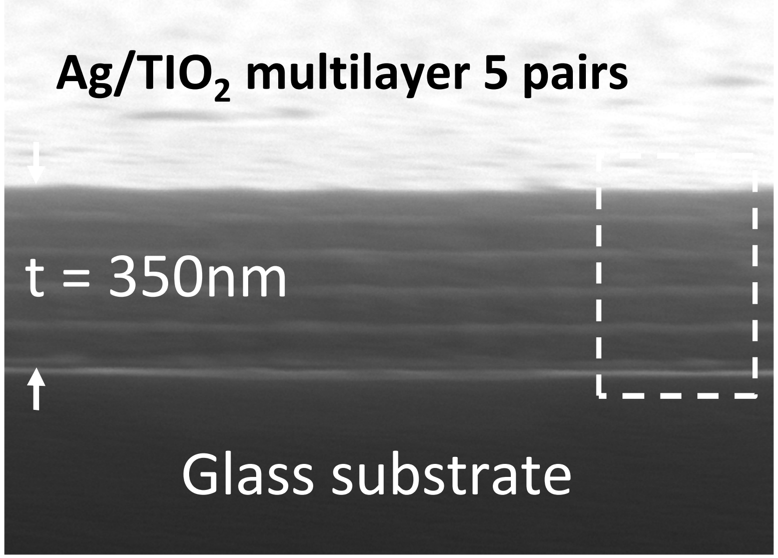
ENZ Sample Fabrication

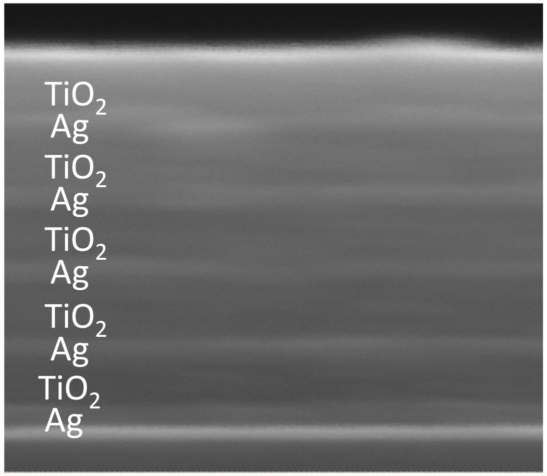
Electron beam evaporation of alternating layers of Ag and TiO_2









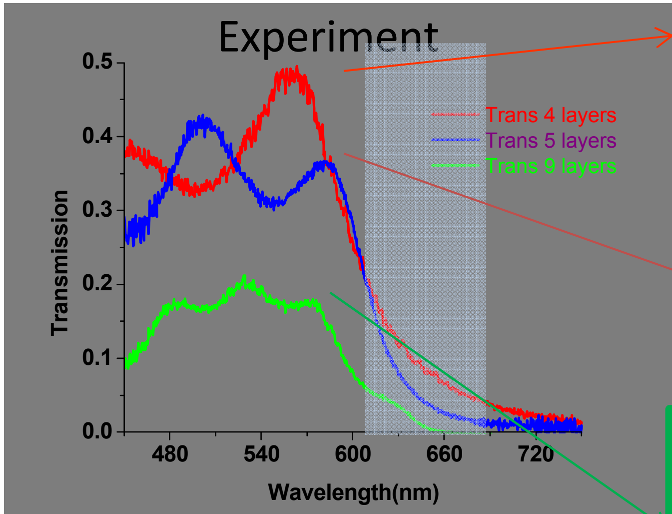


TiO2 = 54nm

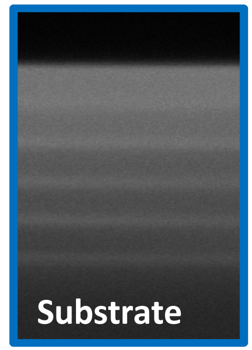
Ag = 16nm

G. Subramania, A. J. Fischer, T. S. Luk – Submitted to Appl. Phys. Lett.

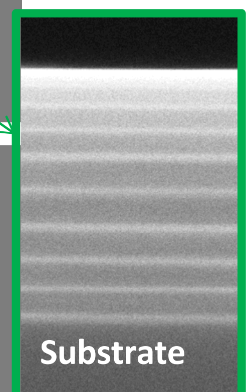
Optical Characterization and FDTD Simulations



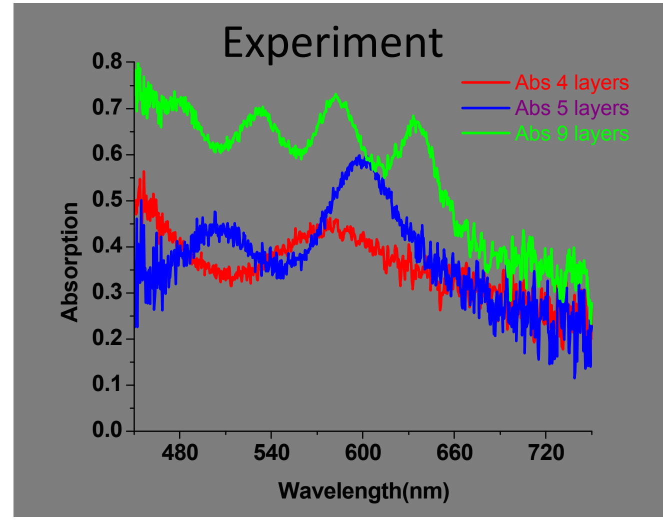
4pairs

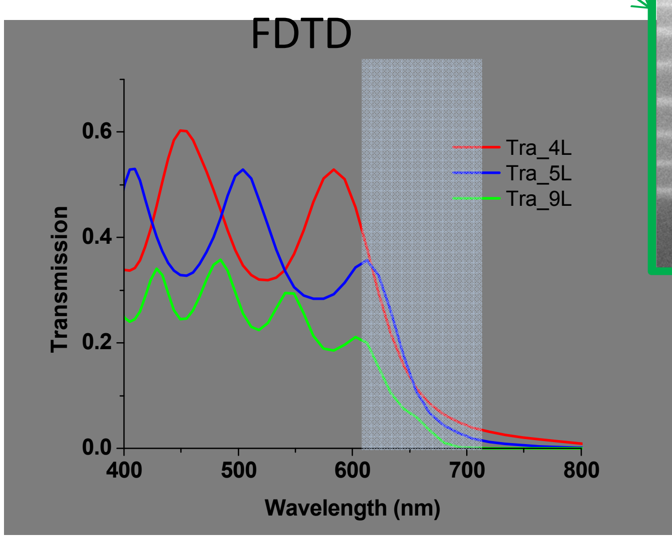


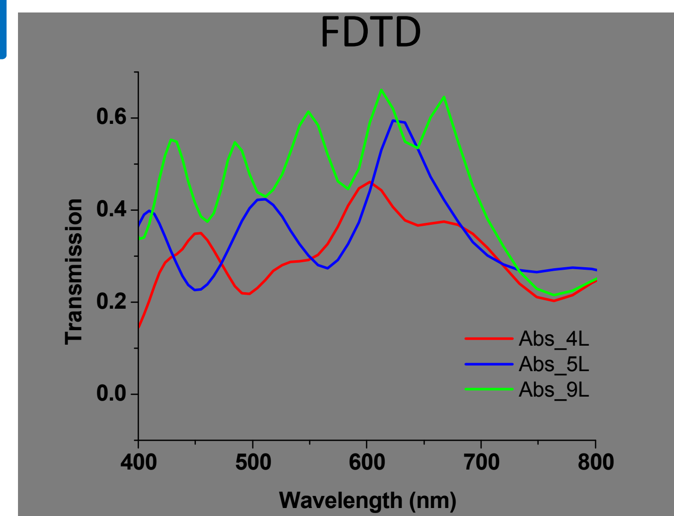
5pairs



9 pairs







- Transmission reduces with increased number of pairs – Metal absorption
- Experimental absorption about 10% more than FDTD

Approach to Reducing Metal Absorption effects

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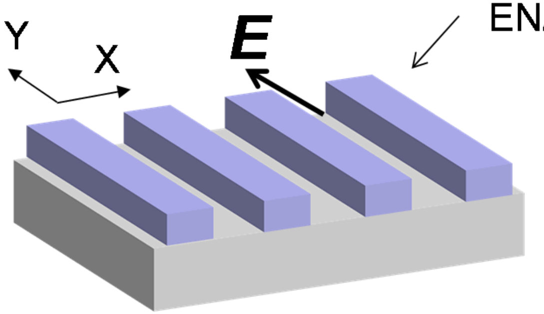
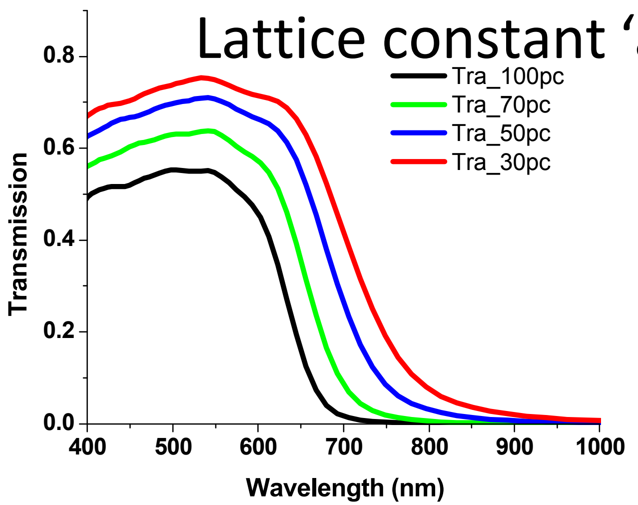


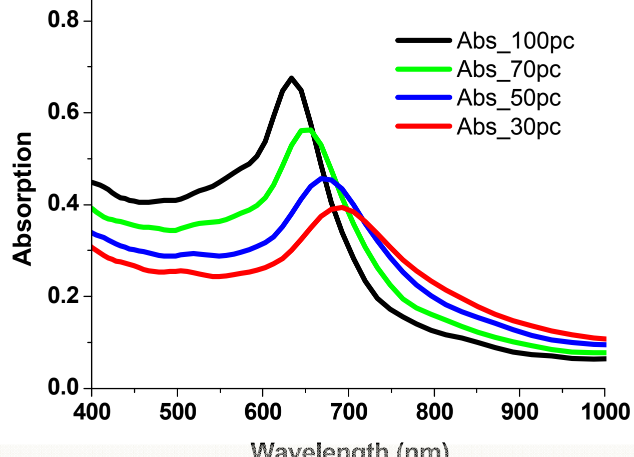
dielectric

$$\varepsilon_{effective} = f\varepsilon_{+} + (1 - f)\varepsilon_{ENZ}$$

- Light polarized along the grating
- Ideally, grating period as small as possible for effective medium
- Increased transmission
- ENZ wavelength redshifts with grating duty cycle

Lattice constant 'a'= 100nm





Grat	λ_{ENZ}	Trans
100	660	~0.1
70	690	~0.12
50	725	~0.17
30	800	~0.09

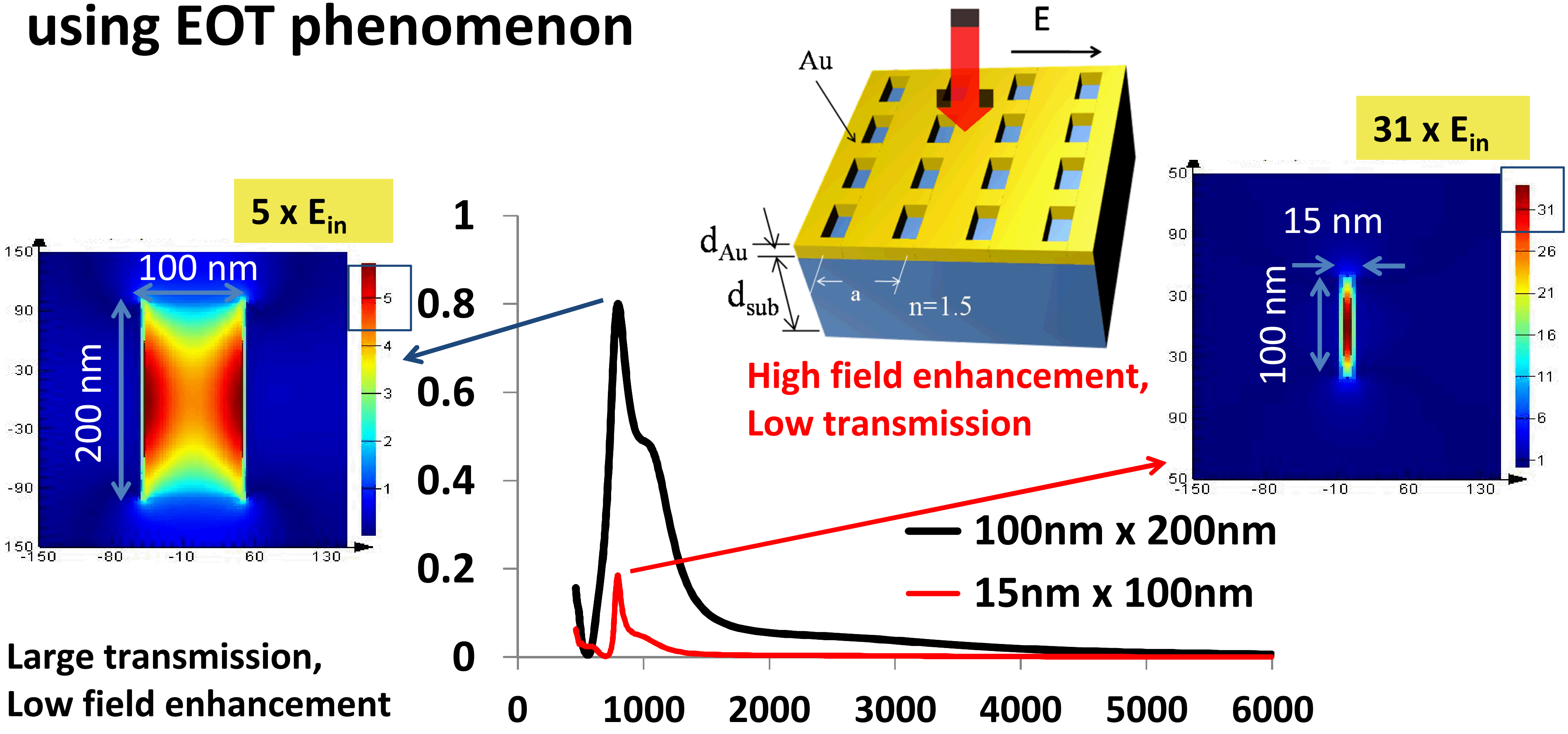
G. Subramania, A. J. Fischer, T. S. Luk – Submitted to Appl. Phys. Lett.

Energy Transport through Ultra Sub-wavelength Channels

Sandia National Laboratories

Current approach : Surface plasmon based using EOT phenomenon

Resonant

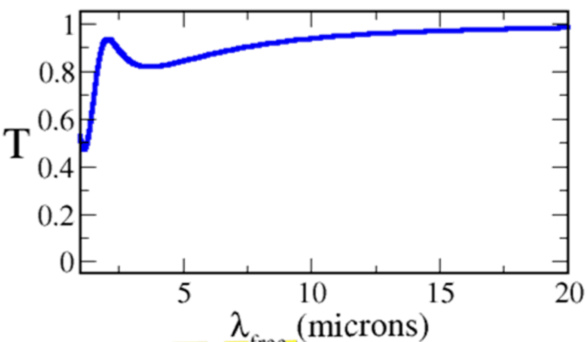


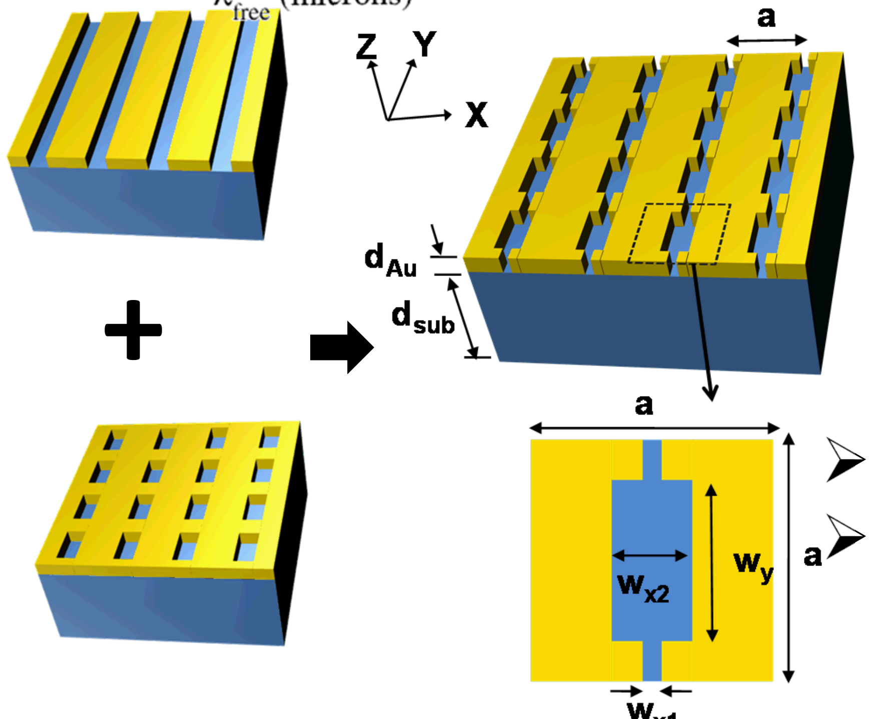
Can we achieve light confinement/field enhancement with broadband operation?

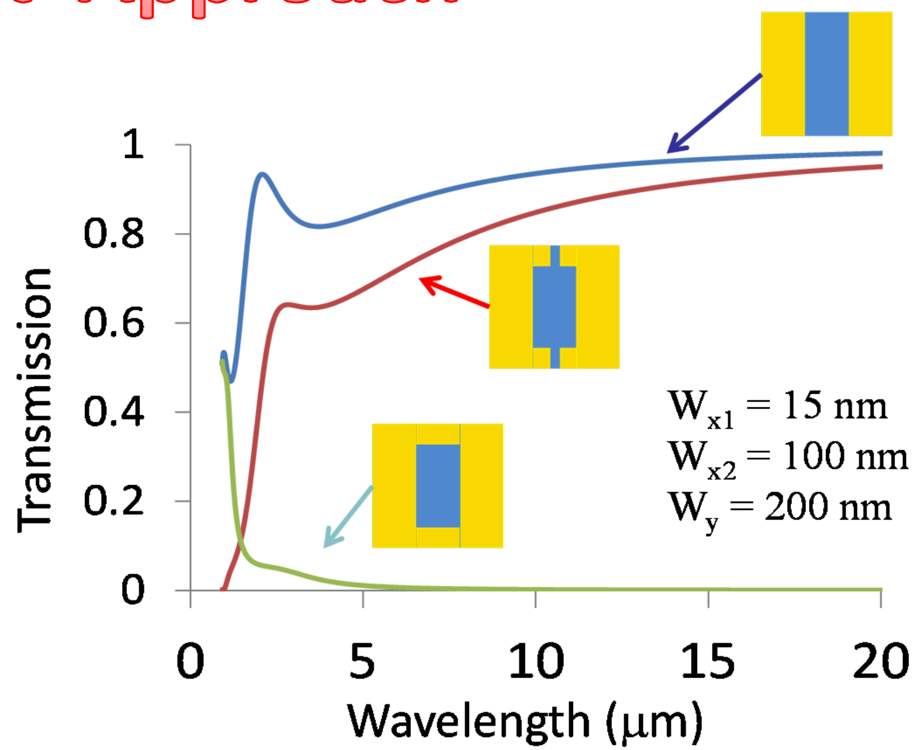
The Double-groove Structure

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

A: Non-resonant Approach



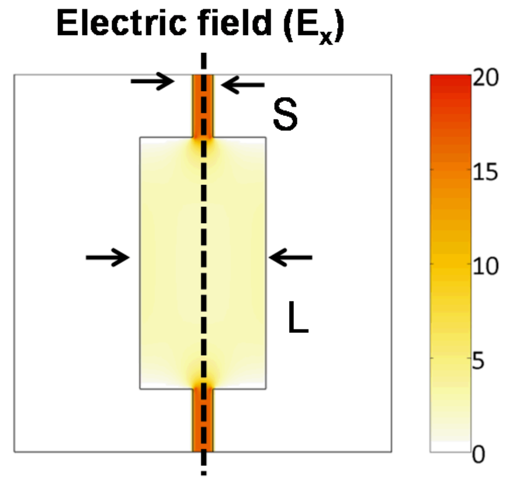


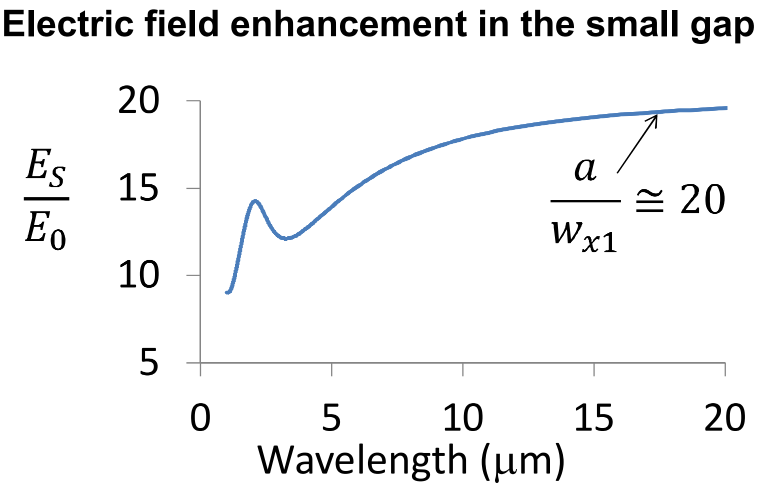


- Broadband transmission
- Large electric field enhancement and confinement

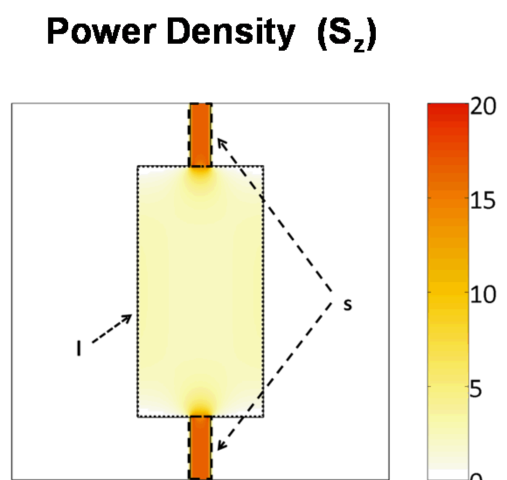
G. Subramania, S.Foteinopoulou and I. Brener, Phys. Rev. Let., 107, 163902(2011).

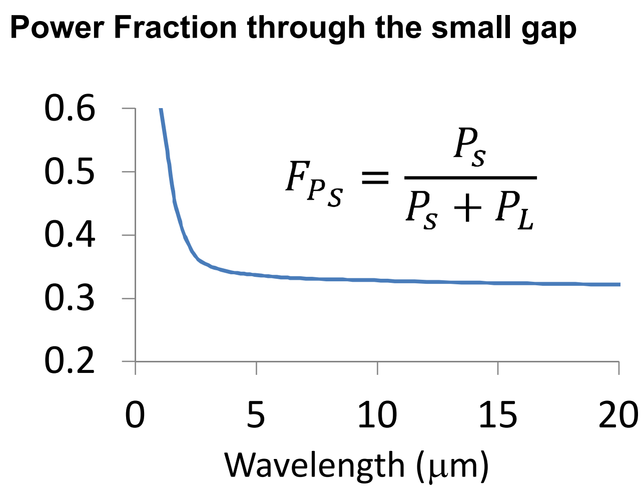
Key Results





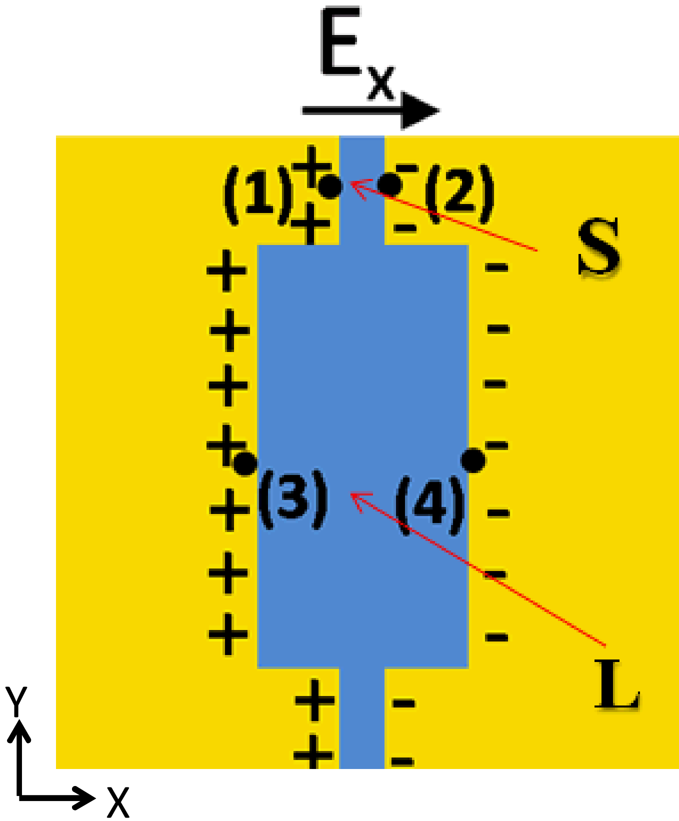
We can achieve large electric field enhancements in an ultra-subwavelength area (~ **$(\lambda/250)^2$**) across broadband that can be controlled via structural geometry





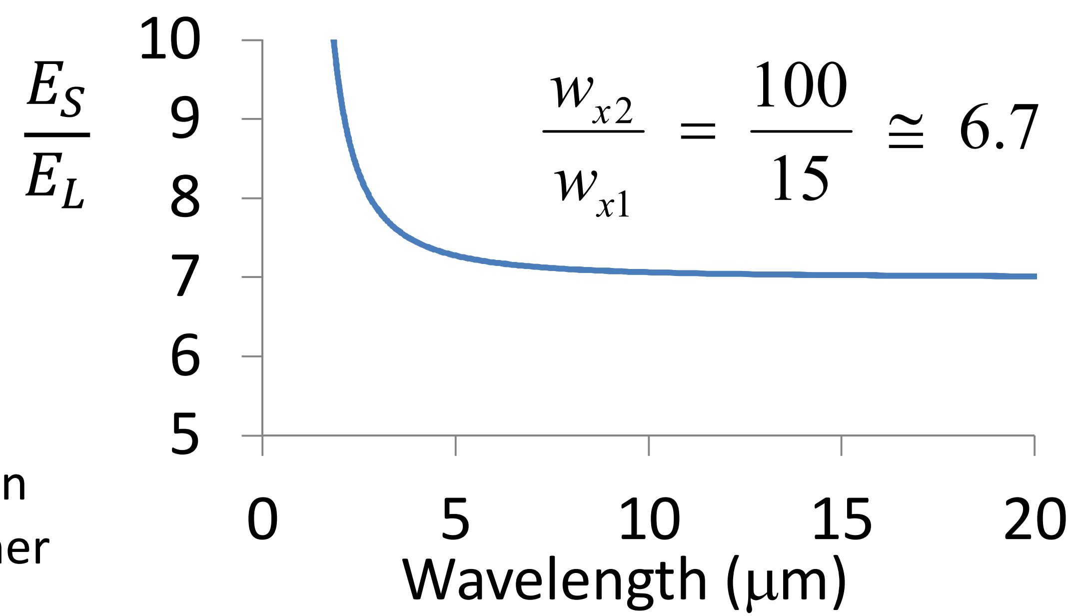
Surprisingly, nearly 30% of the transmitted power that is channeled through an area ~ **$(\lambda/250)^2$** that is **1/60th** of the unit cell area.

Mechanism: Quasi-static response



- Voltage across the small and large gaps are nearly equal

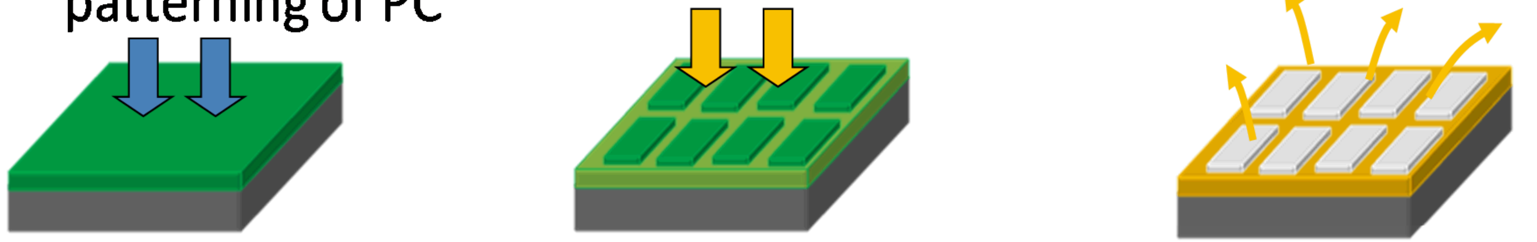
$$V_S \cong V_L \Rightarrow \frac{E_S}{E_L} = \frac{w_{x2}}{w_{x1}}$$

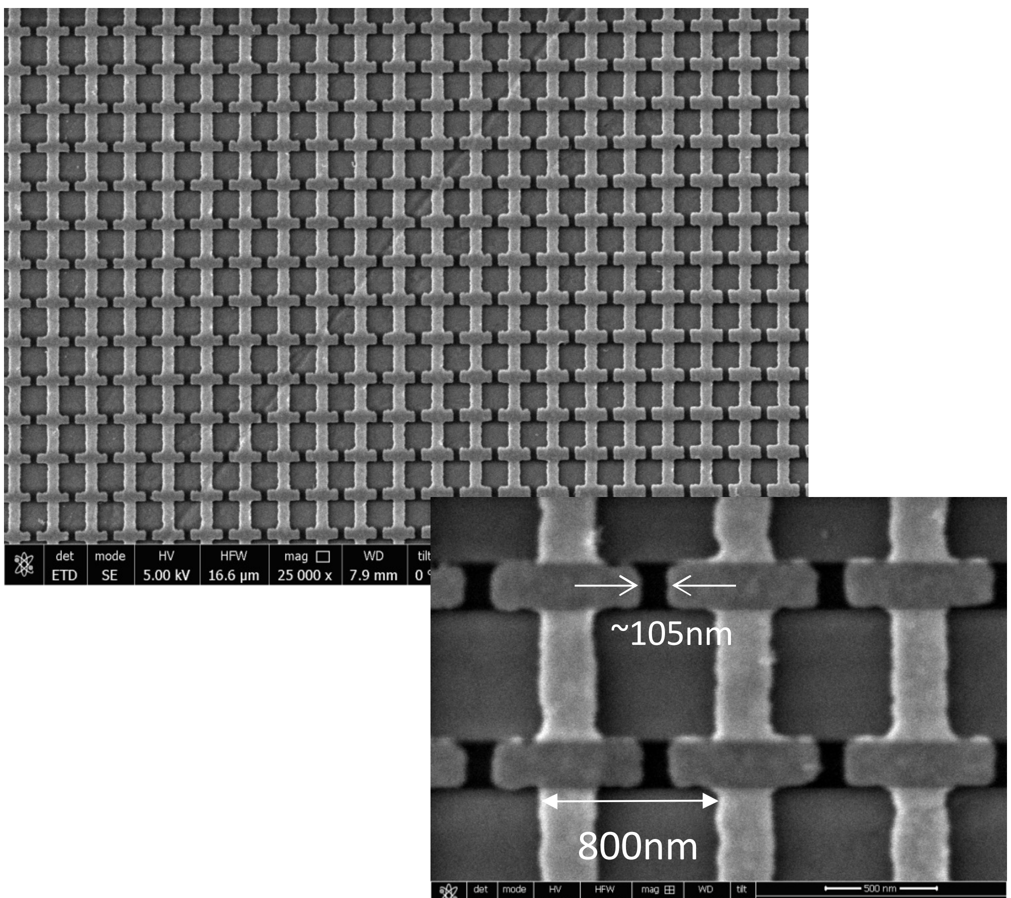


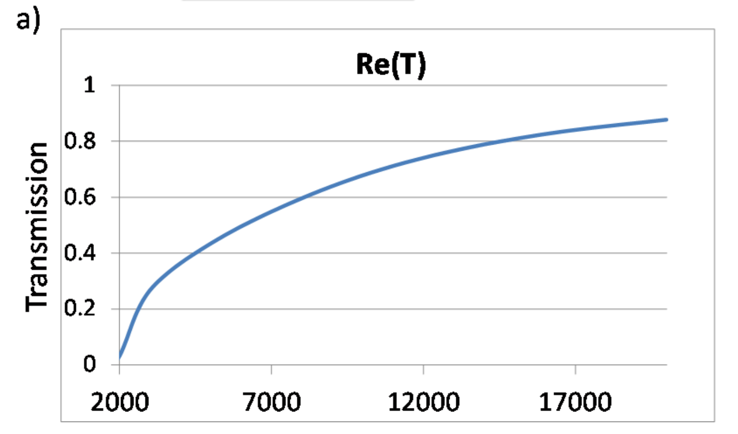
- Near-instantaneous response of charges even at mid-IR
- No effective current flow between small and large gap region on either side

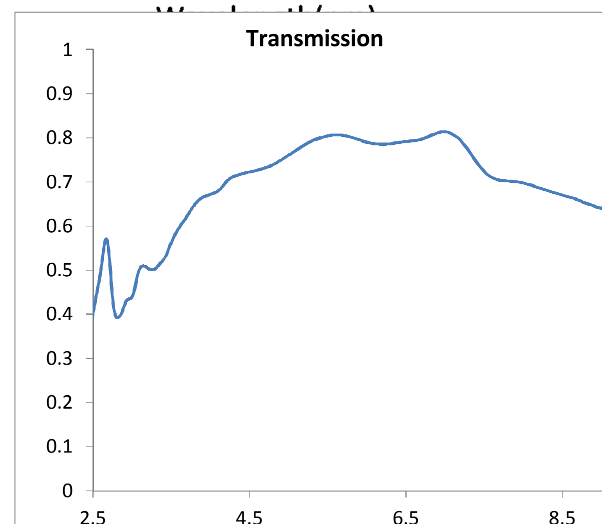
G. Subramania, S.Foteinopoulou and I. Brener, Phys. Rev. Let., 107, 163902(2011).

Fabrication- Some recent results









Impact and Future Challenges

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Summary of DG Structure properties

- Large field enhancement (> 20X)
- Subwavelength confinement ~ $\lambda^2/500^2$
- Broadband transmission (λ ~ 20 μm range)

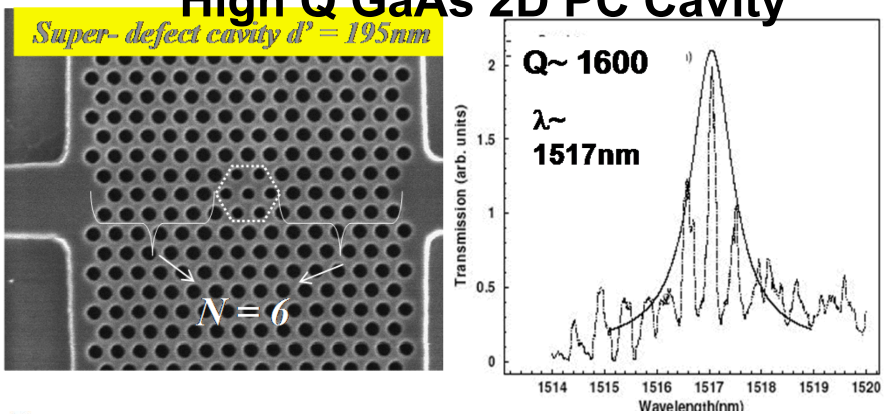
Impact

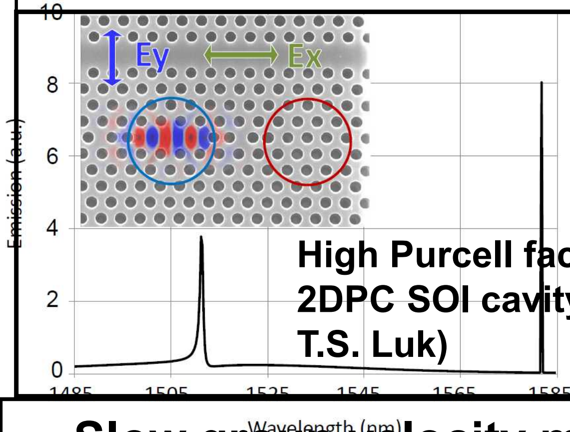
- PDOS enhancement – MidIR sources, Energy conversion, midIR based sensing and detection,
- Non-linear enhancement – Switching, SHG, Parameteric conv., Raman

Thank you for your attention!

L-M Interaction in 2DPC

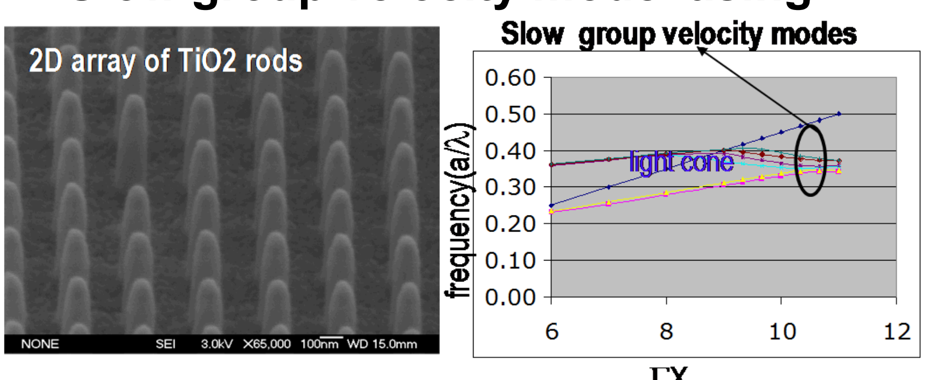
High Q GaAs 2D PC Cavity



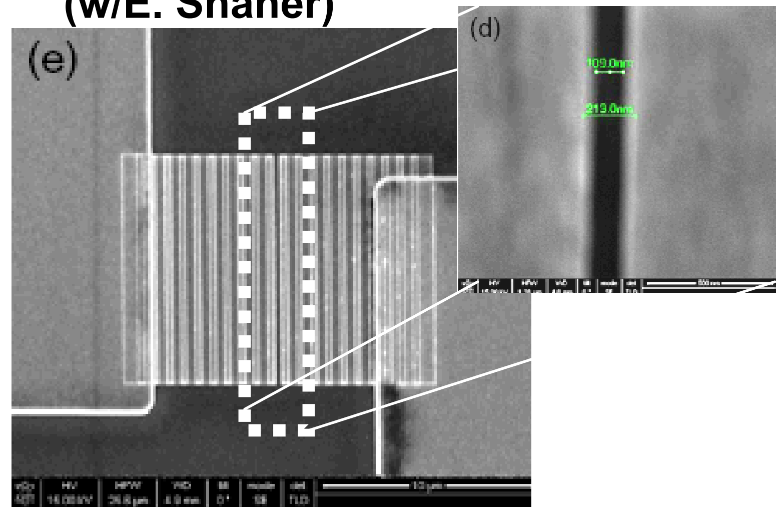


High Purcell factor 2DPC SOI cavity (w/ T.S. Luk)

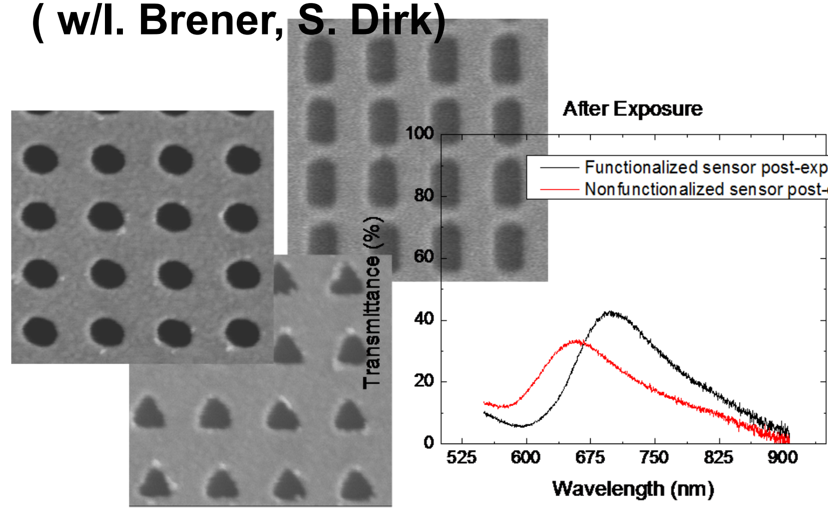
Slow group velocity mode lasing



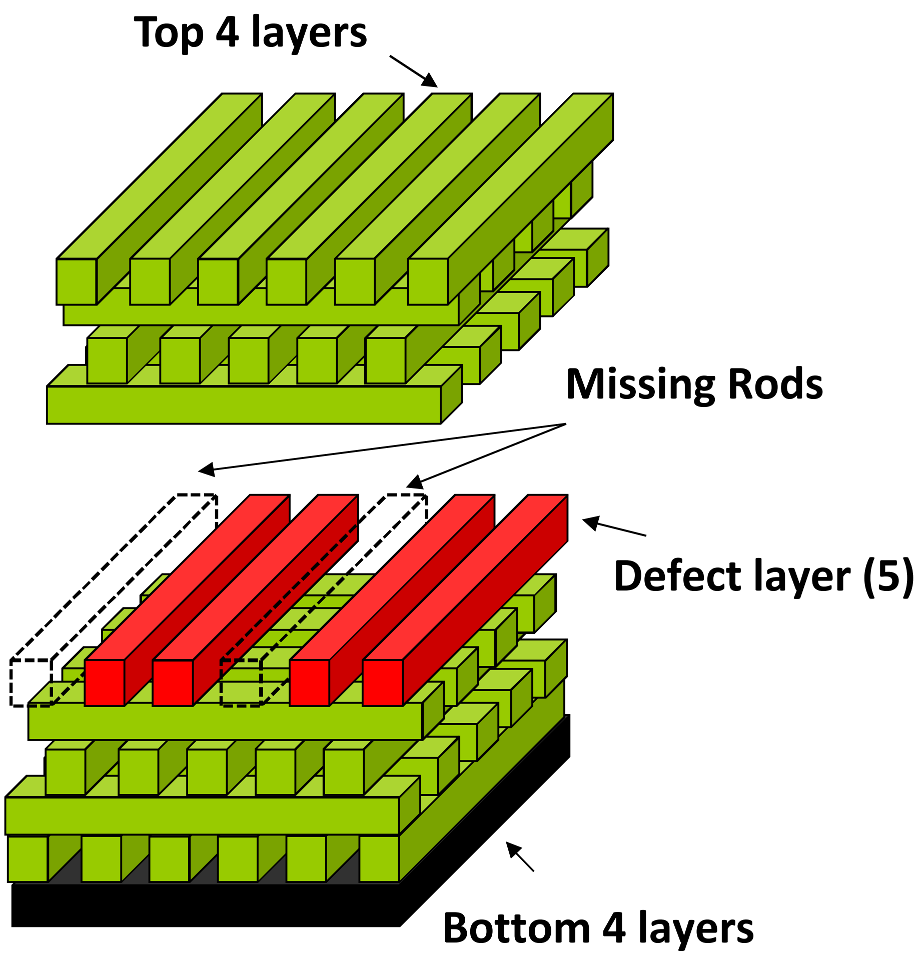
Surface plasmon Auston Switch (w/E. Shaner)

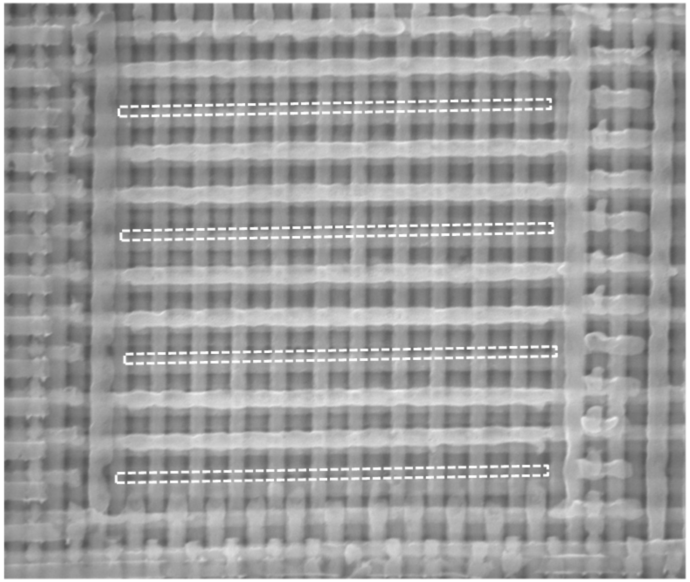


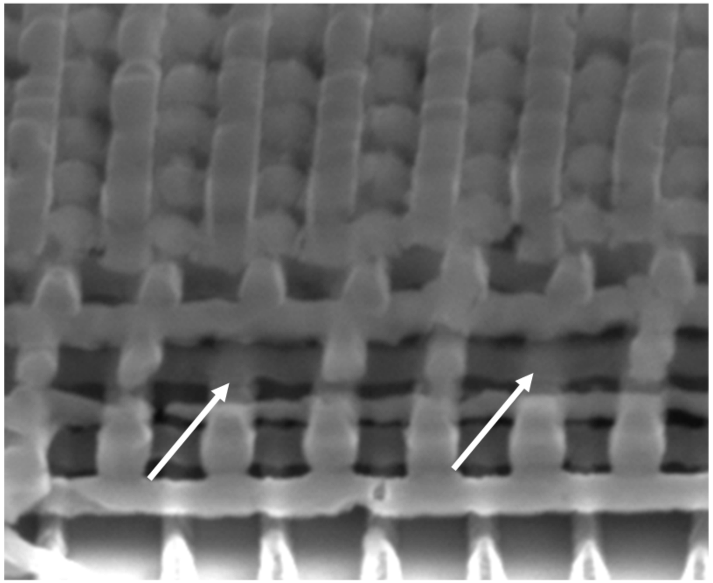
Nanhole EOT based sensors (w/I. Brener, S. Dirk)



Logpile PC Cavity







Logpile PC Cavity Optical Response

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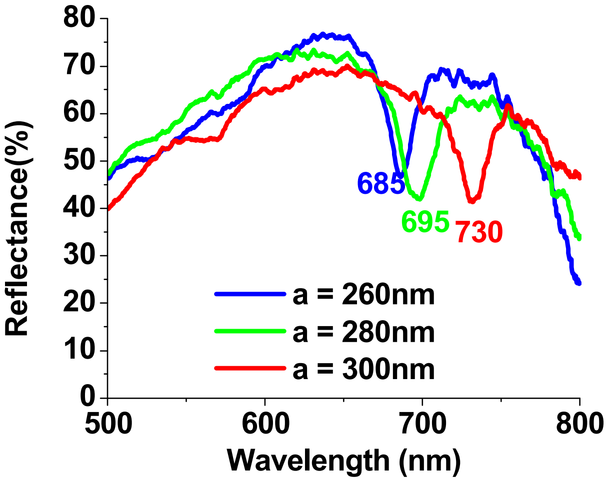
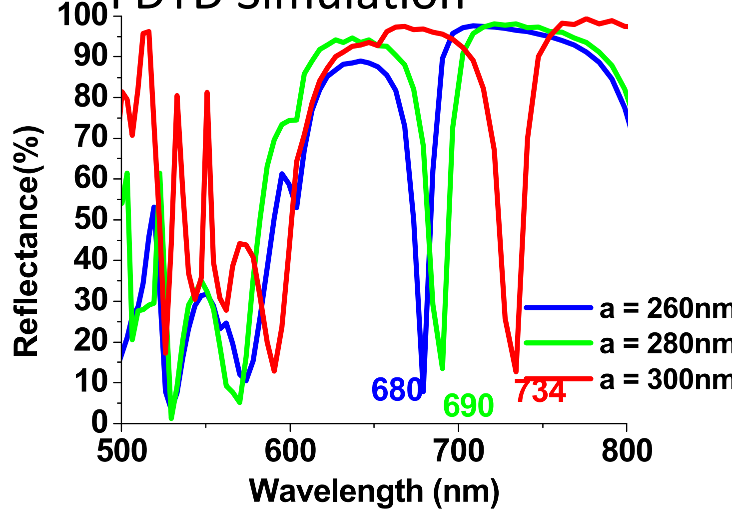
Reflection

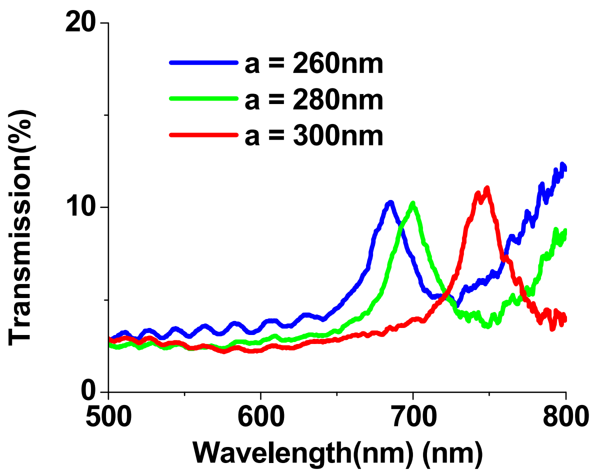
Experiment

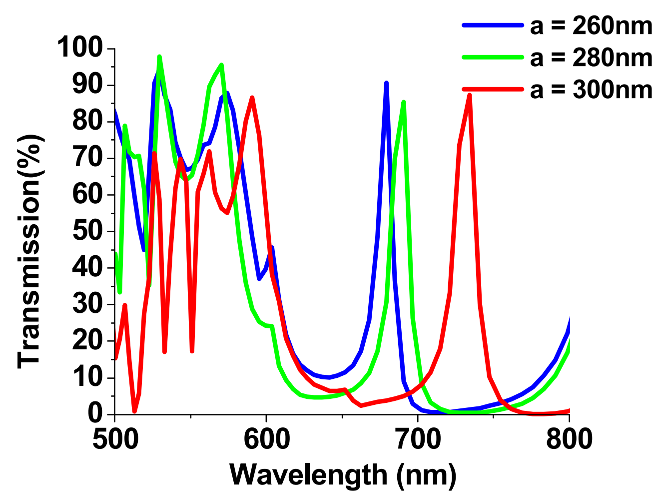


FDTD Simulation



Transmission

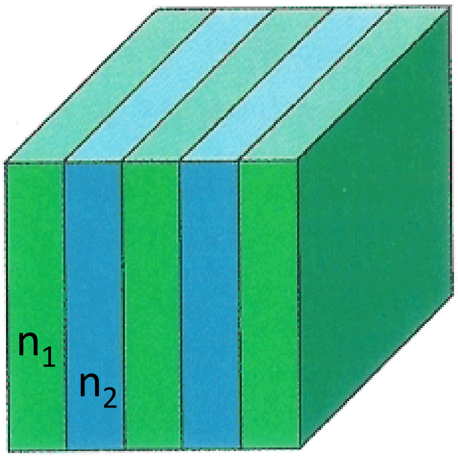




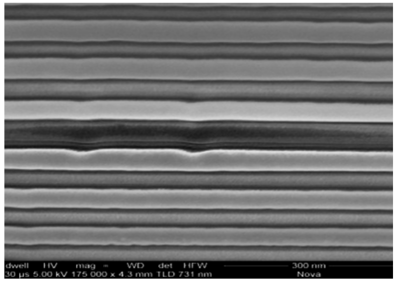
G. Subramania et. al. , Nano Lett. **11**, 4591 (2011).

Periodic Sub-wavelength Structures for EM Control: Photonic Crystals (PC)

1-D

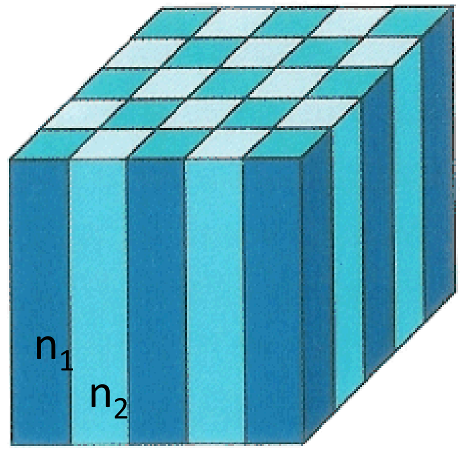


Periodic in 1 dimension

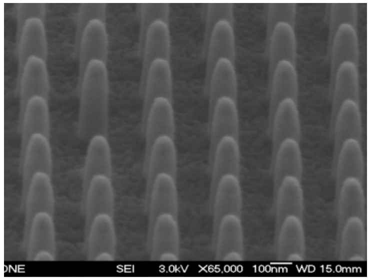


HfO_2/SiO_2 DBR cavity

2-D

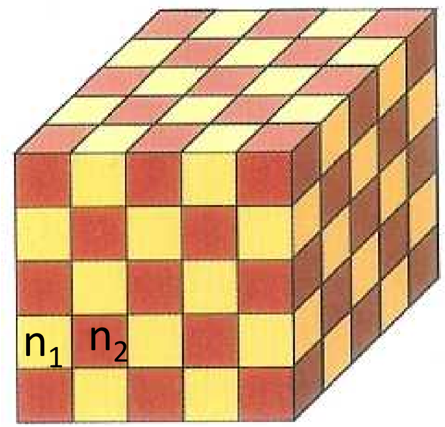


Periodic in 2 dimensions

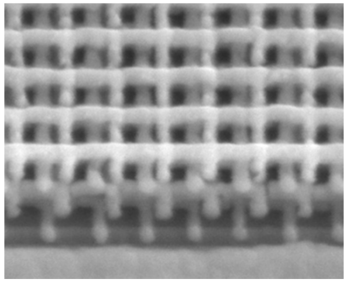


Array of TiO_2 rods

3-D



Periodic in 3 dimensions



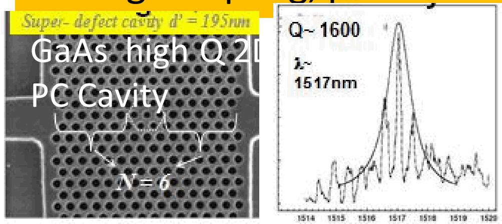
TiO_2 logpile PC

Reference: "Photonic crystals: Molding the flow of light", J.D. Joannopoulos, R.D. Meade, J. Winn, Princeton Univ.Press, NJ(1995)

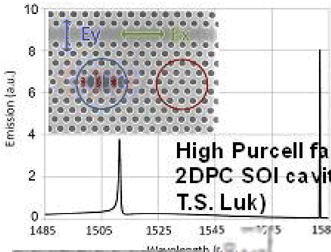
Nanophotonics Activity

Sandia National Laboratories

Integrated Photonics, Purcell enhancement, Nanoscale Lasing, strong Coupling, polariton lasing

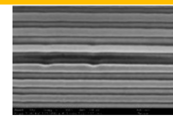


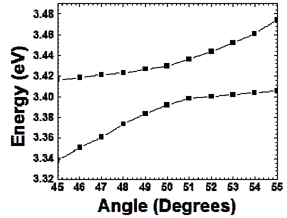
G. Subramania, et.al. APL 83 4491 (2003)

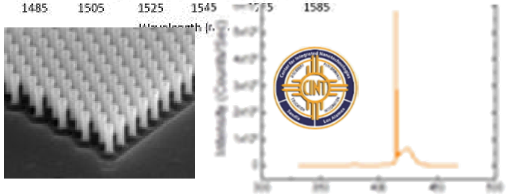


High Purcell factor 2DPC SOI cavity (w/ T.S. Luk)

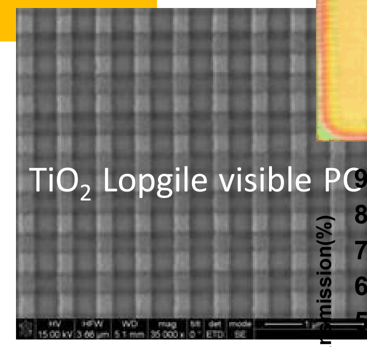
T.S. Luk et.al., JOSA-B **28** ,1365 (2011)

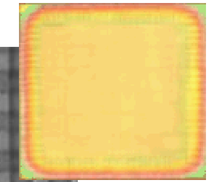




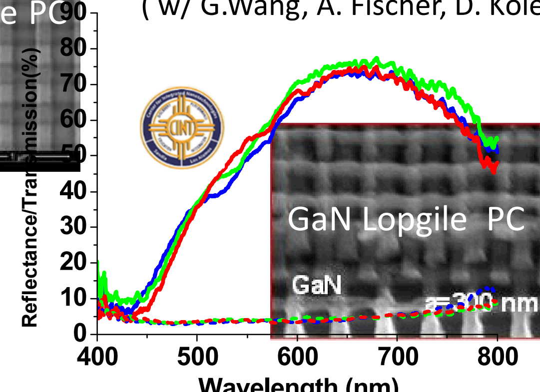


GaN 2DPC laser w/ G. Wang, I. Brener





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



1,2D PC

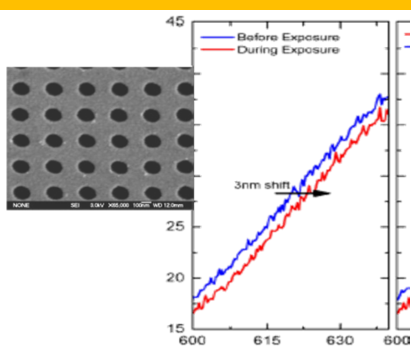
3D PC

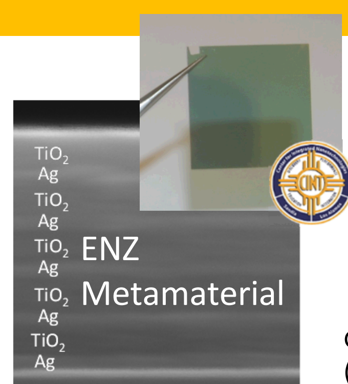
Photonic Nanostructures

Full 3D Light matter interaction control, SSL and thermal control

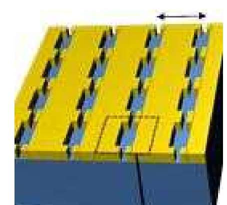
Metal optics and Metamaterials

Ultrasubwavelength light control, detection, sensing , nanocircuitry

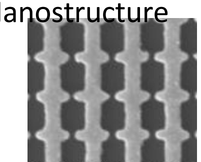




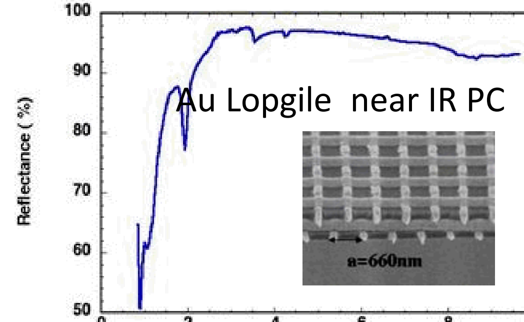
ENZ Metamaterial

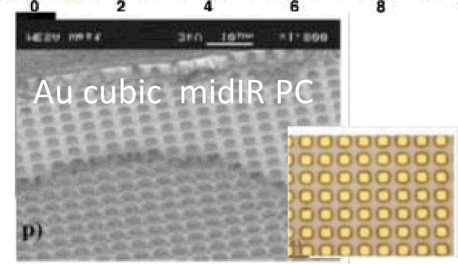


Double groove Metal Nanostructure



G. Subramania et.al., PRL. **107** (16), 163902 (2011).



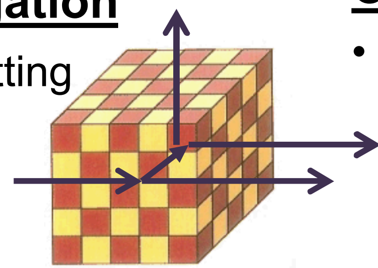


3D PC: A Great Platform for Light Manipulation

Sandia National Laboratories

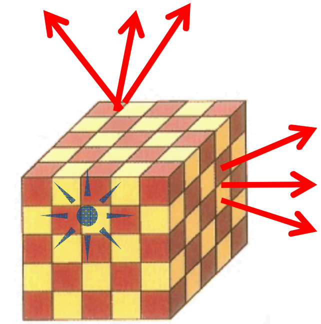
Control of light propagation

- Guiding, bending and splitting
- Negative refraction
- Self-collimation
- Localization
- Slow light
- Cloaking

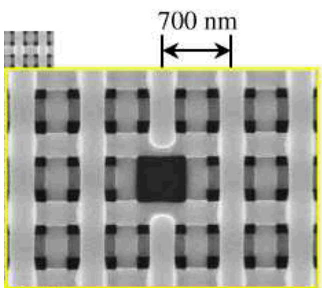


Control of light emission

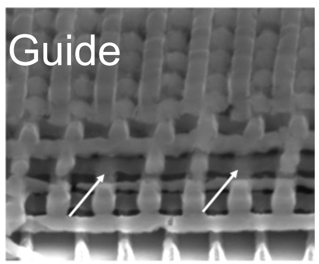
- Full 3D confinement effect
    - Photon – Atom Bound states, Non- Morkovian emission process



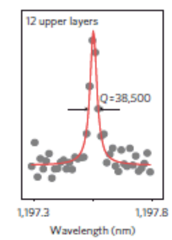
- Photonic Density of States effect
    - Spontaneous emission enhancement

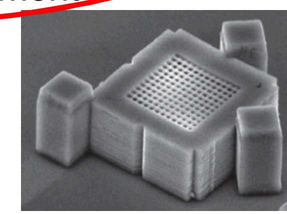


S. Kawashima et. al.., Opt. Exp. **18**, 386 (2010)

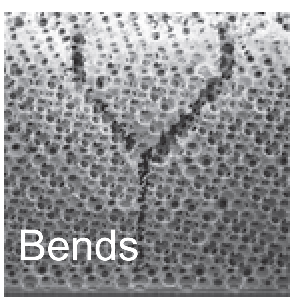


G. Subramania et. al, Nano Lett. **11**, 4591 (2011).

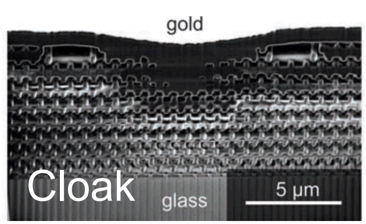




A. Tandaechanurat et. al., Nat Photon **5**, 91 (2011).

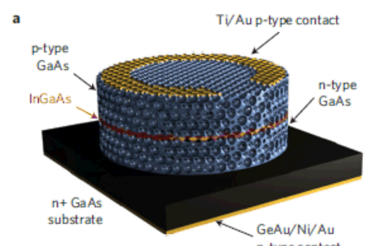


S.A. Rinne et. al., Nat. Phot. **2**, 52(2008)



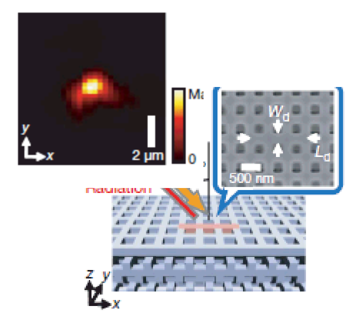
T. Ergin et. al.,Science **328**, 337 (2010)

Electrical Injection



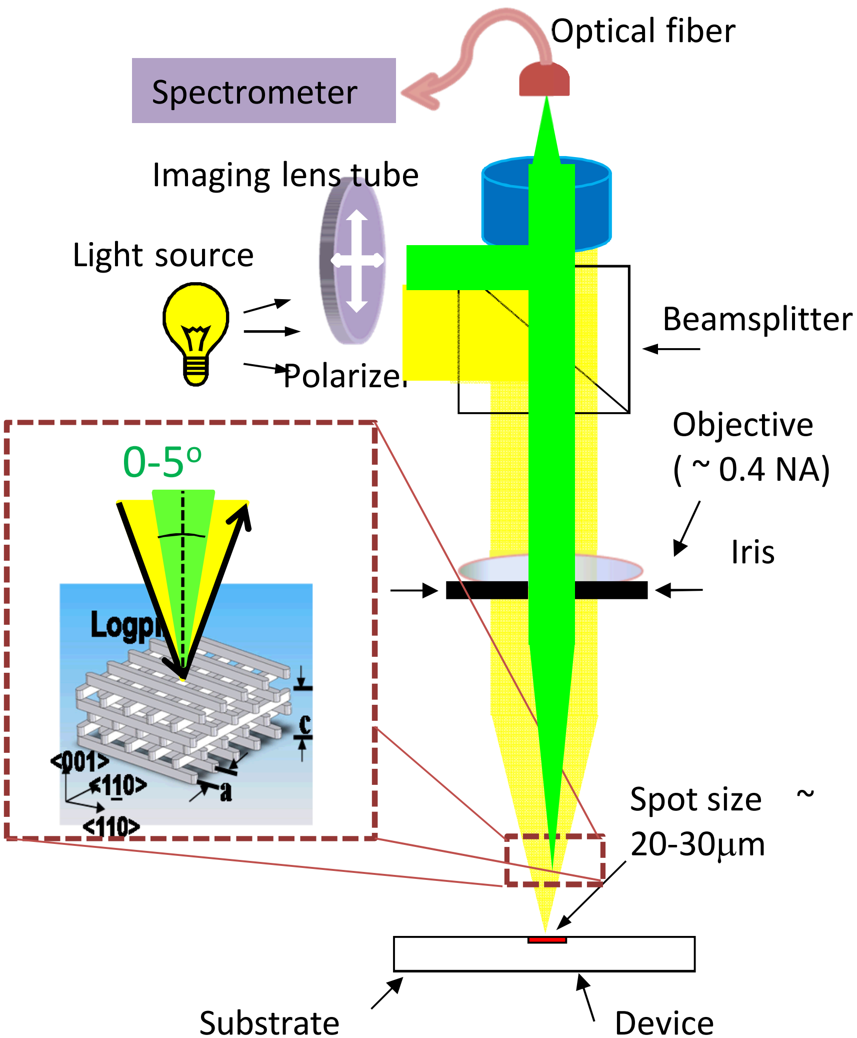
E. C. Nelson, et al., Nat Mater **10**, 676 (2011)

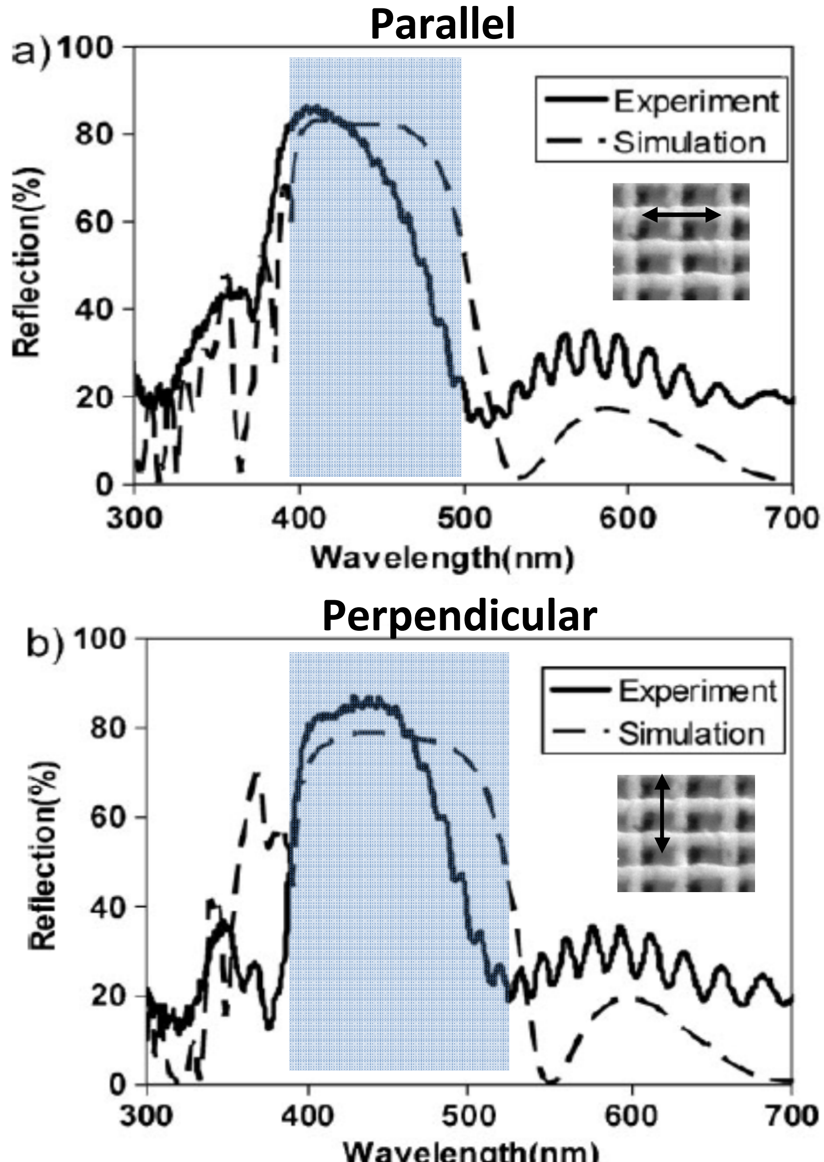
Emission enhancement



K. Ishizaki and S. Noda, Nature **460**, 367 (2009)).

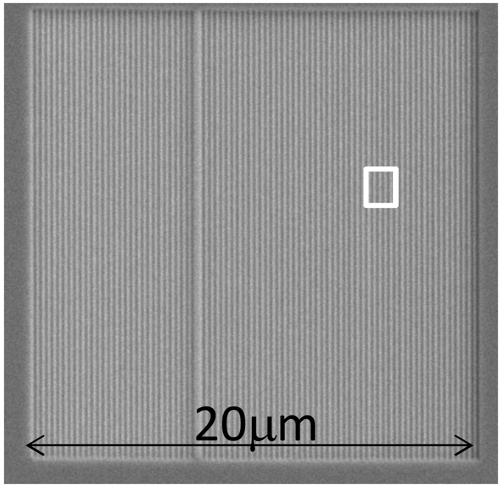
Visible- Near UV 9 Layer TiO_2 Logpile

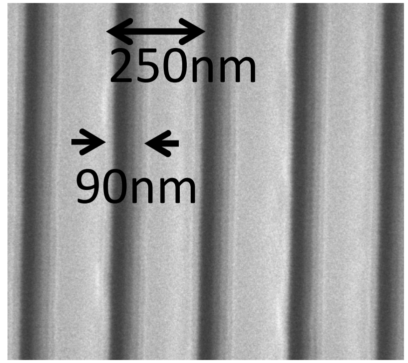




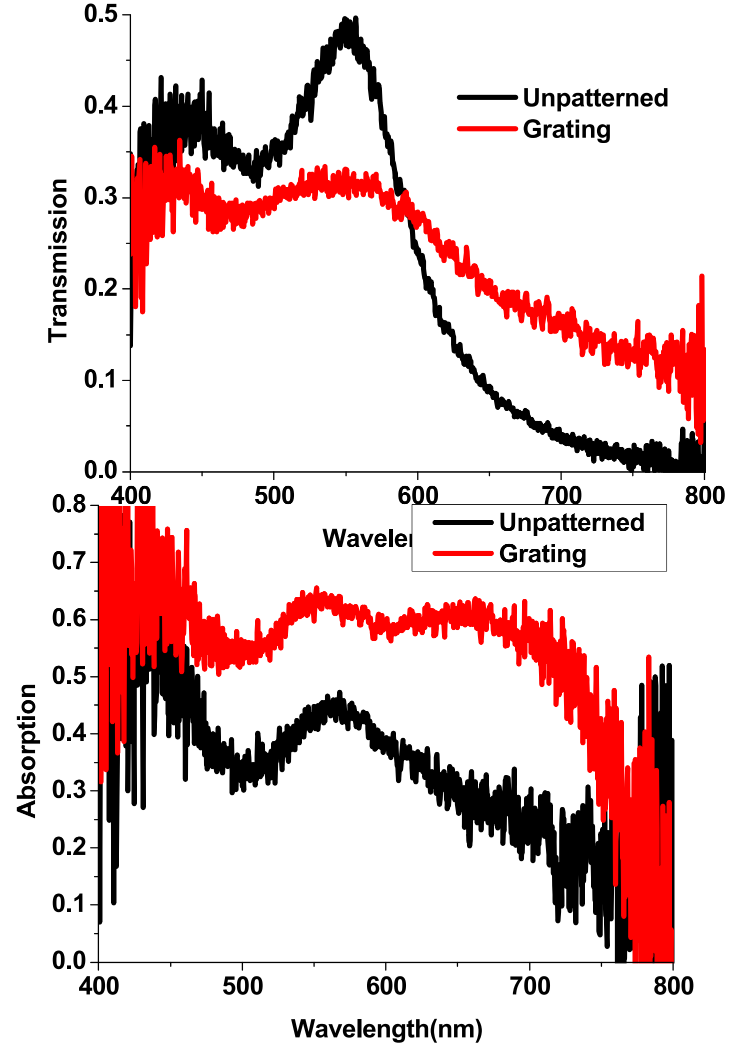
G. Subramania, Y.-J. Lee, A. J. Fischer, and D. D. Koleske, Advanced Materials **22**, 487-491 (2010)

Fabrication - Characterization



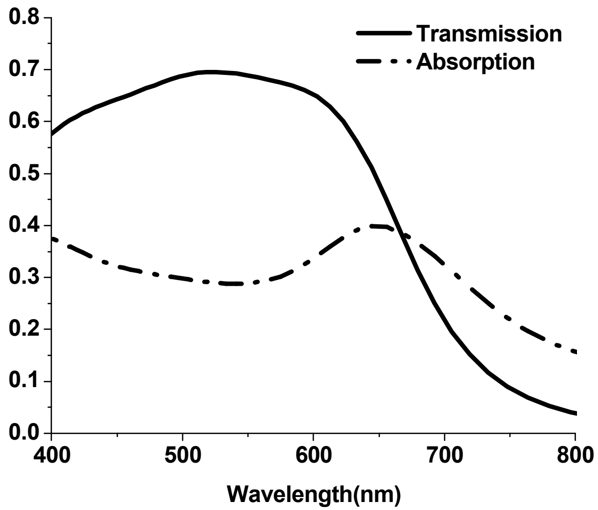


Experiment



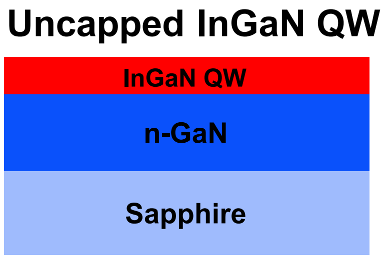
- Fabrication using Focused Ion Beam (FIB)

FDTD Simulation

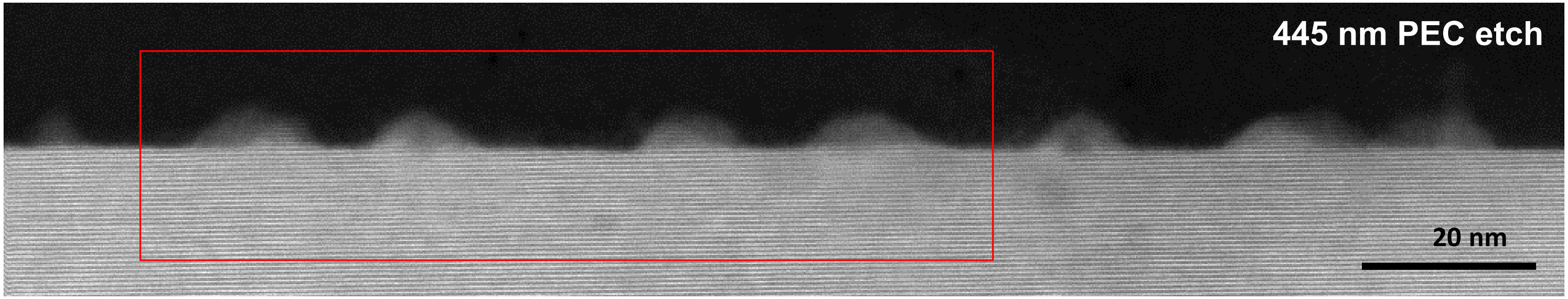


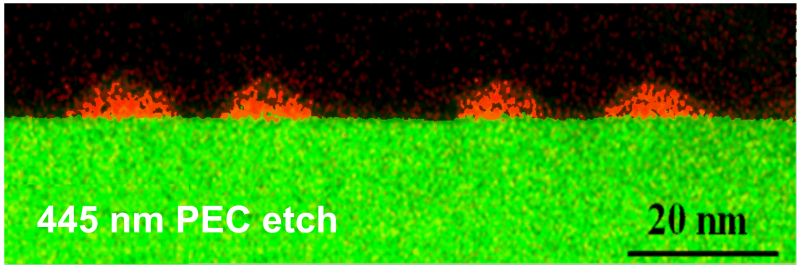
G. Subramania, A. J. Fischer, T. S. Luk – Submitted to Appl. Phys. Lett.

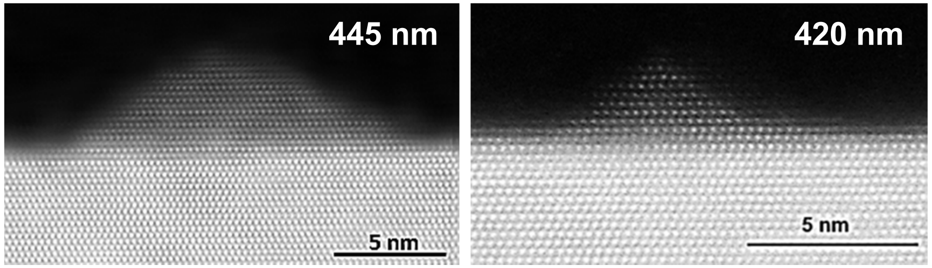
Transmission Electron Microscope (TEM) Images



- High-angle annular dark-field (HAADF) TEM images
- Samples etched at 420 nm and 445 nm
- Energy dispersive x-ray mapping
  - QDs on surface are InGaN
  - Red = indium, green=gallium
- InGaN QDs are epitaxial to the underlying GaN
- No underlayer, no cap → PL is not very bright



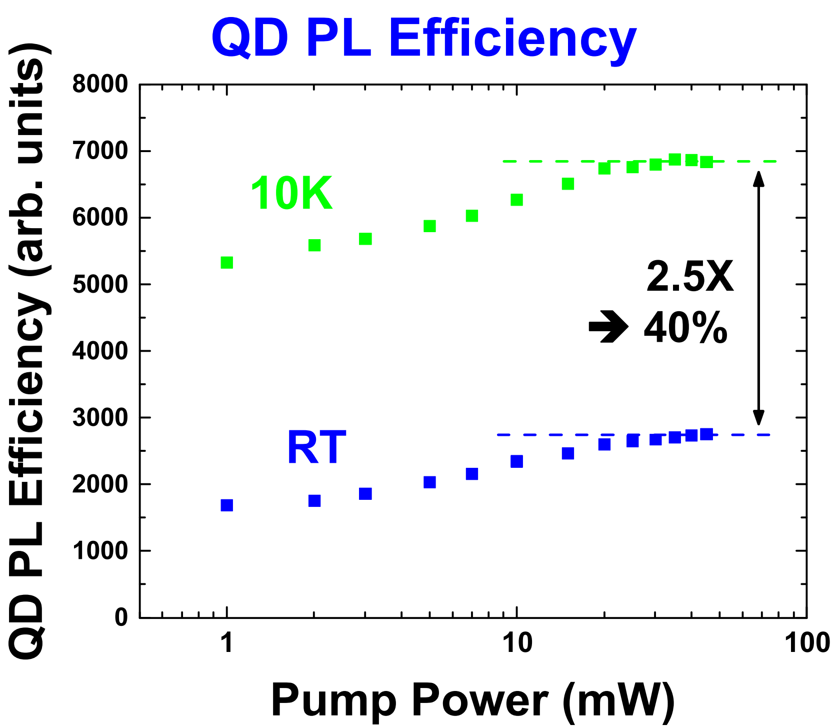


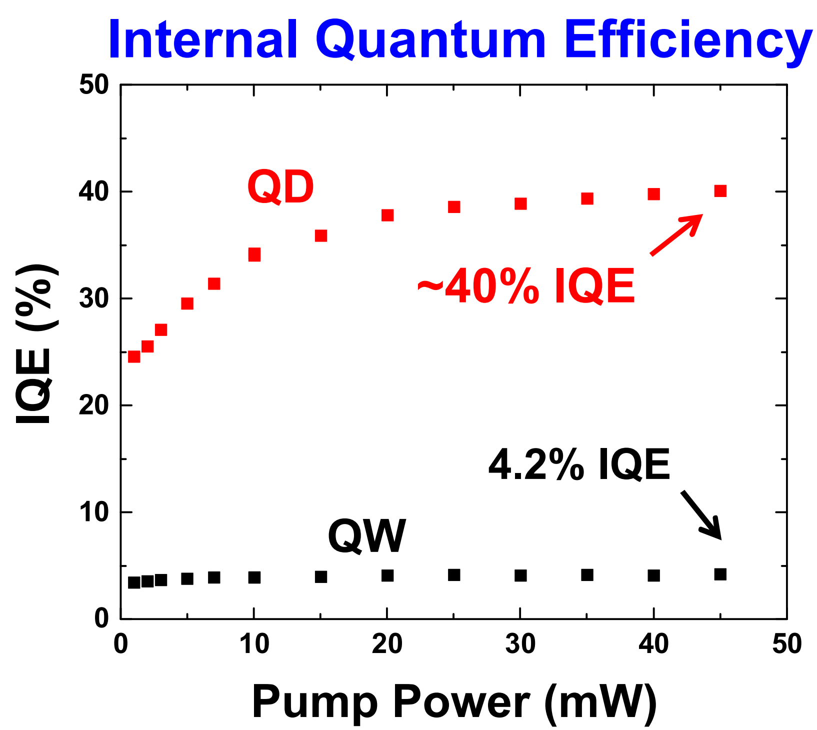


InGaN QD internal quantum efficiency

Capped InGaN QW

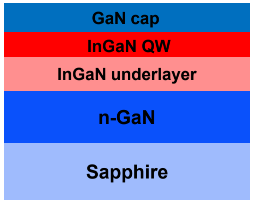
- Compare 10K and RT PL efficiency
- Assumes 10K PL is 100% efficient
- PL Intensity drops by >100X after QD etching
- IQE goes up by almost 10X after QD etching
- QDs are expected to have better IQE

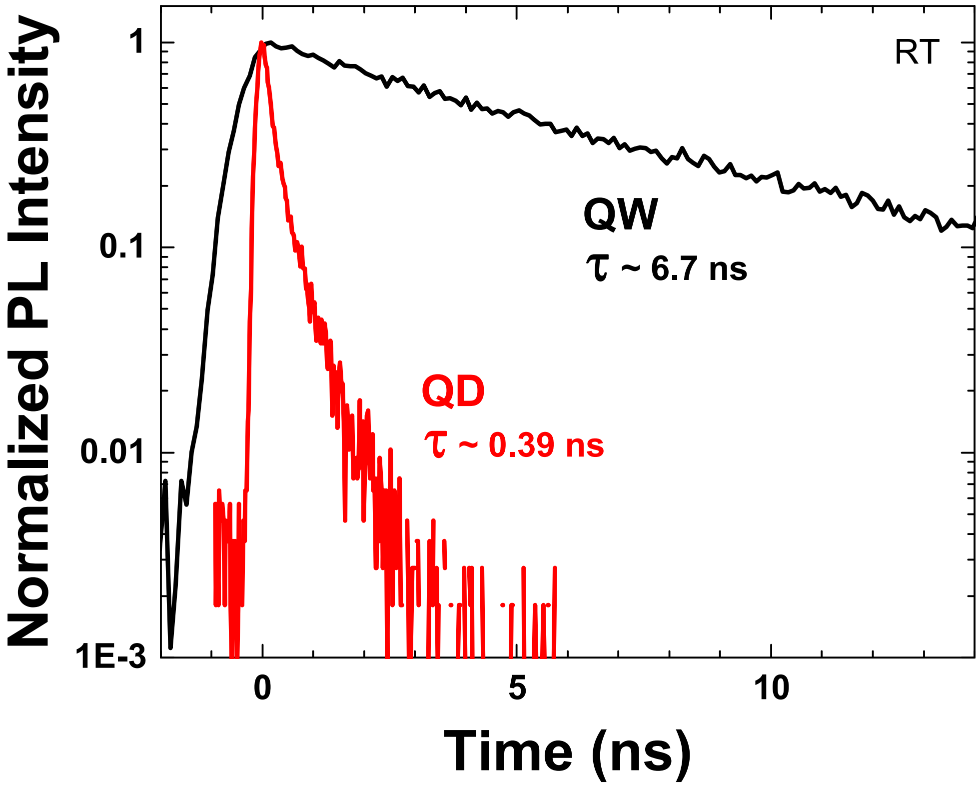




Time-resolved PL data from InGaN QDs

Capped InGaN QW

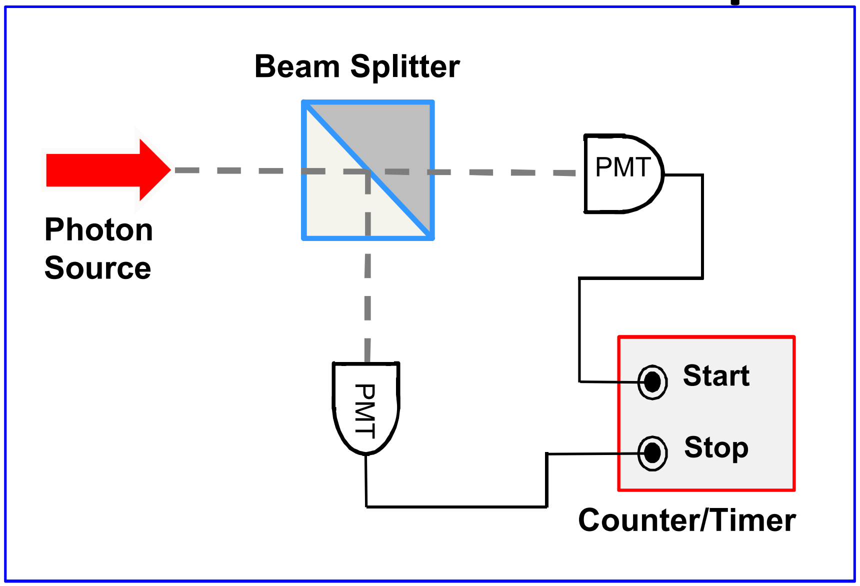


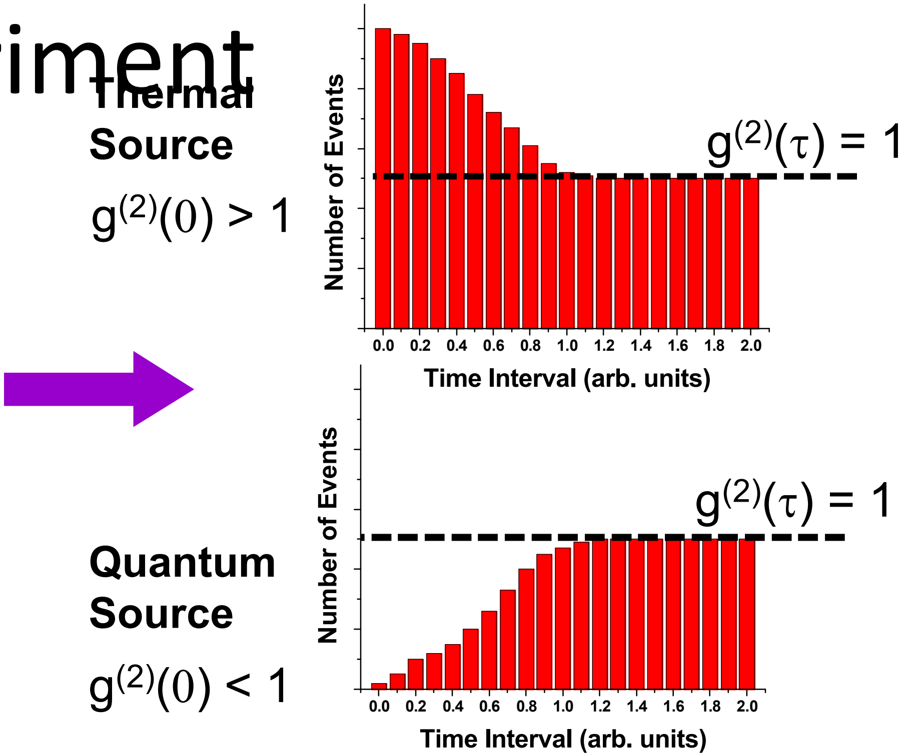


TRPL data:

- **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



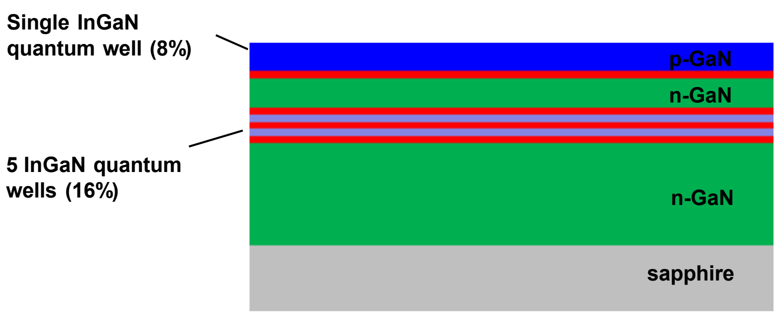


- Non-polarizing beamsplitter to split intensity between detectors
- Single photon counting required
  - Use PMTs or avalanche photodiodes
  - Single photon counting modules
- Measure correlation between detected photons
- Detectors: low QE, speed, and dark counts

Deterministically Positioned InGaN QDs

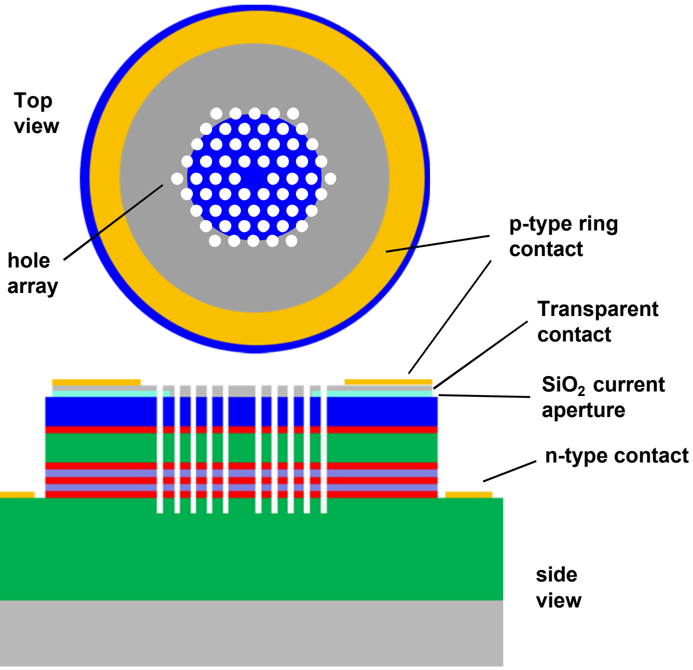
Standard III-nitride device fabrication

1.) Epitaxial layer structure



- Specially design epitaxial structure for PEC etching
- InGaN QWs with 8% and 16% indium

2.) Fabrication of device plus PhC etch

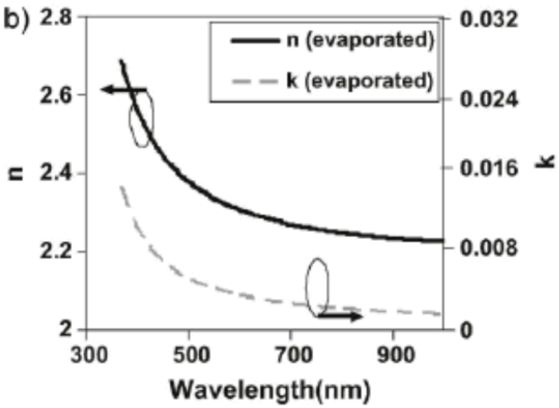


- Standard LED fabrication
- Etch PhC triangular array
- defect cavity at the center
- Requires current aperture
- Use transparent contact

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

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

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

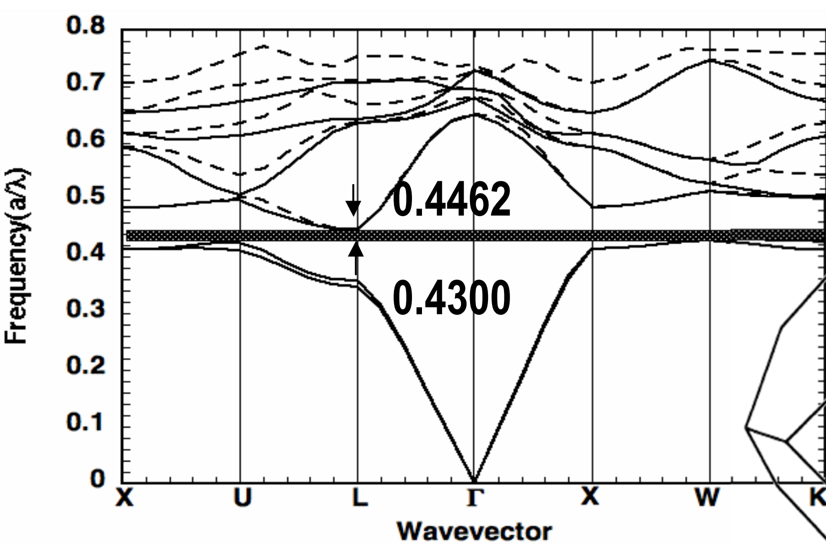
Eigen value equation

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

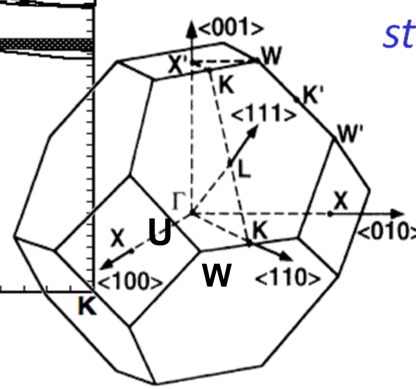
Band index

Wave vector within the first BZ

Photonic Band Structure for TiO_2 logpile



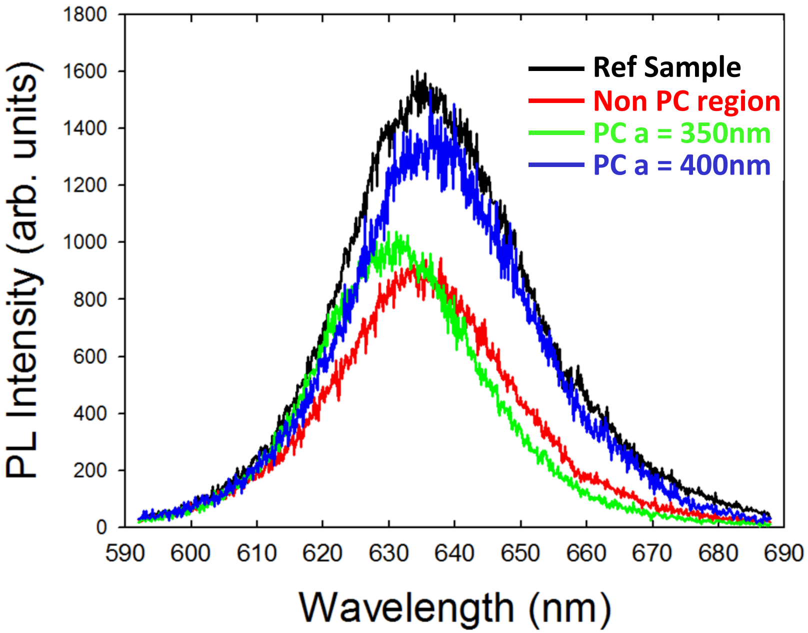
1st BZ

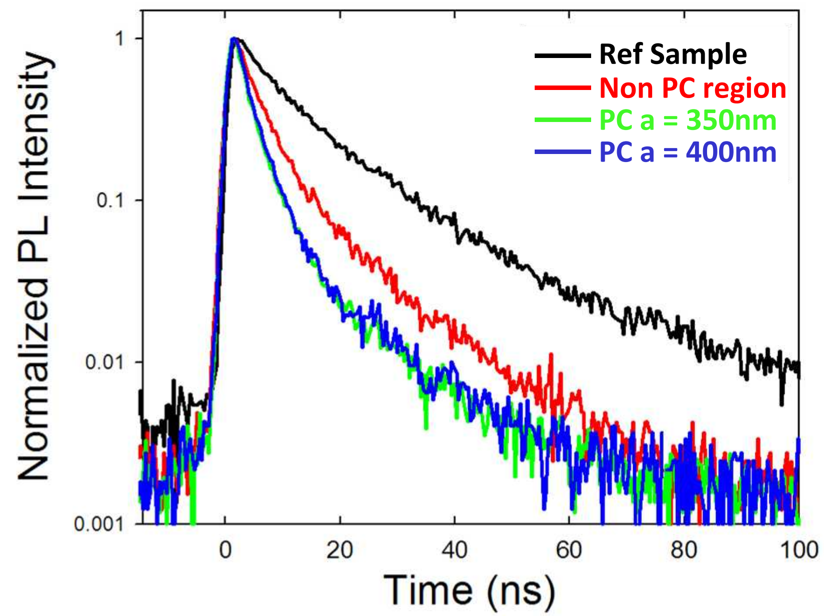


Eigen value equation becomes a matrix equation for which you can write a code and solve for band structure within the first Brillouin zone.

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

Emission Lifetime Measurements - TRPL

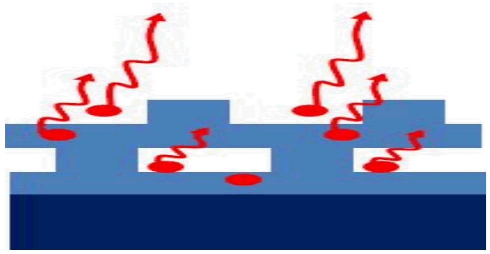




- **Conditions: 380 nm pump, 4 MHz, 20 uW average power, 10 mm aperture**
- **Emitter wavelength ~ 640nm**

- **Faster lifetime in PC vs. in the reference/ no PC**
- **Lifetime similar for both lattice constant PCs**

Ideally expect longer lifetime inside the gap (for a= 350nm) and shorter for outside (a = 400nm).



Possible reasons:

- **Fewer layers of PC**
- **Surface QD emission**

Summary / Future Possibilities

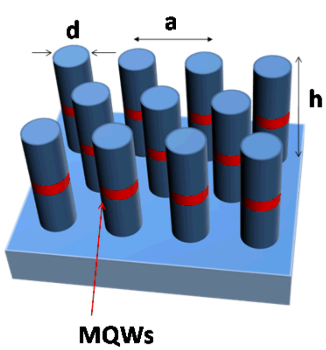
GaN

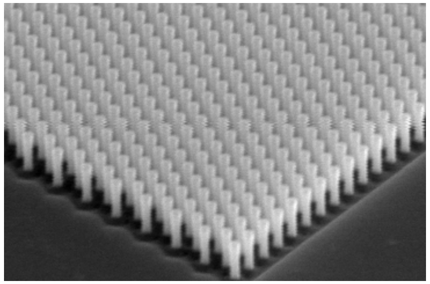
- Nanotemplated 3DPC growth possible (also demonstrated by UIUC group in GaAs)
- The GaN grows epitaxially maintaining crystallinity

- 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

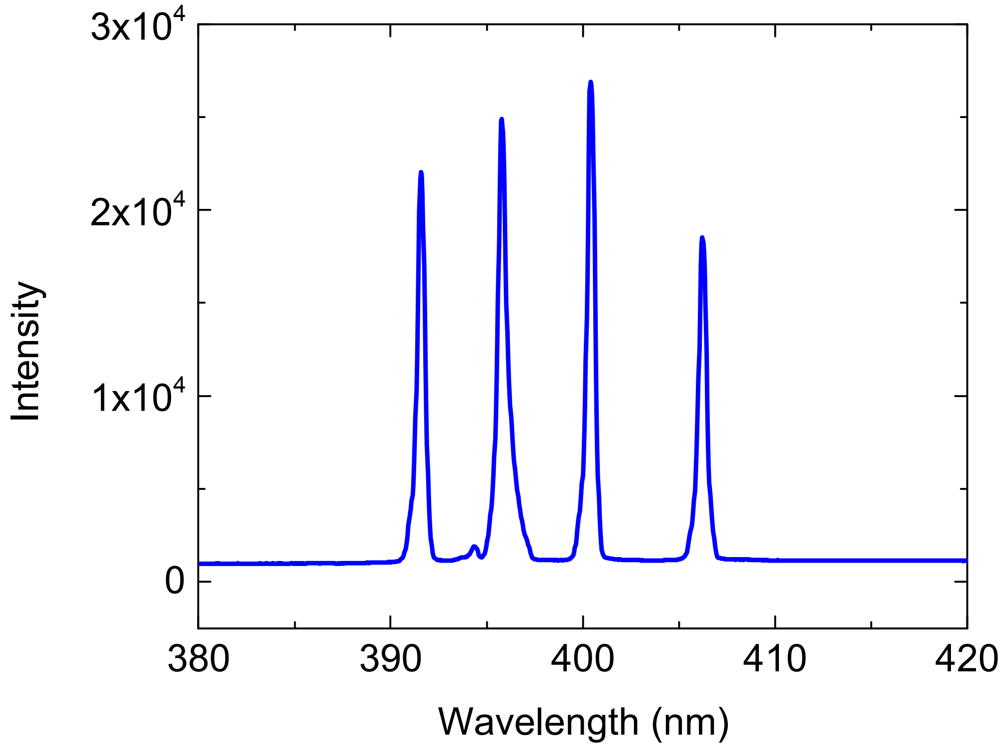


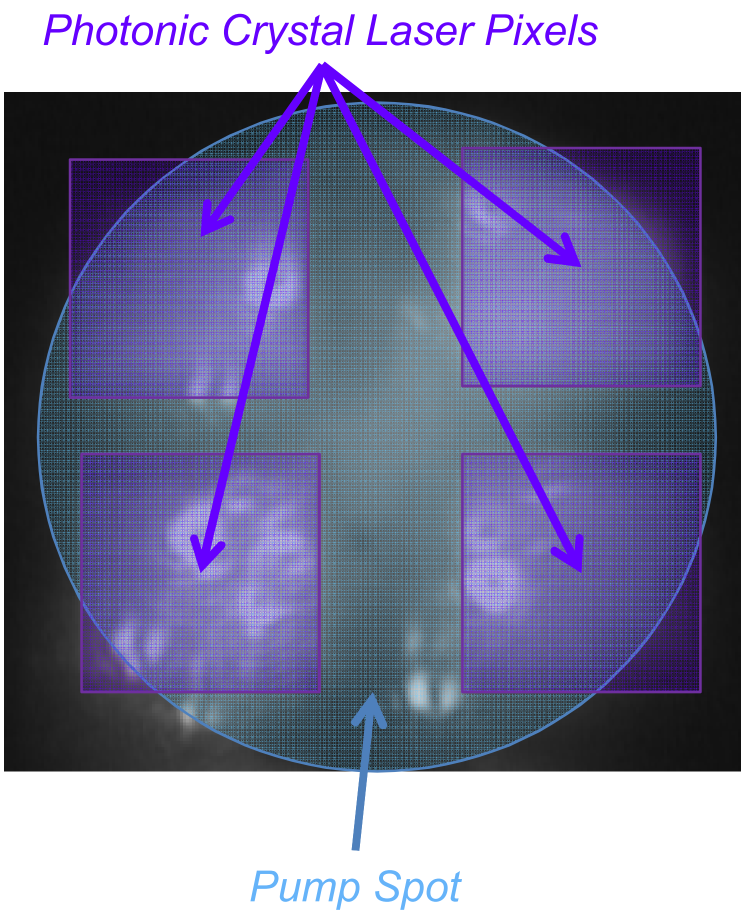


w/ G. Wang , I. Brener, T.S. Luk

Multiple Laser Pixels Coexcited

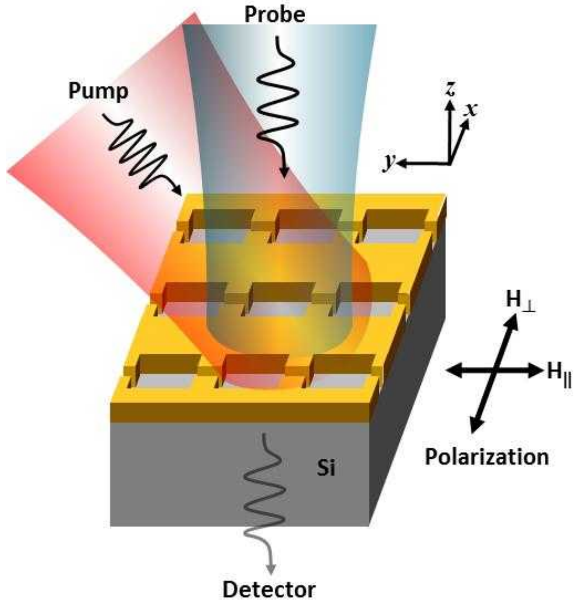
Emission from 4 adjacent laser pixels.





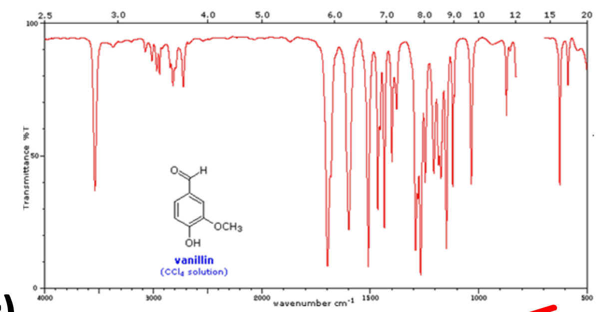
Wright, J. B. *et al.* Multi-Colour Nanowire Photonic Crystal Laser Pixels. *Sci. Rep.* **3**, 2982, doi:10.1038/srep02982

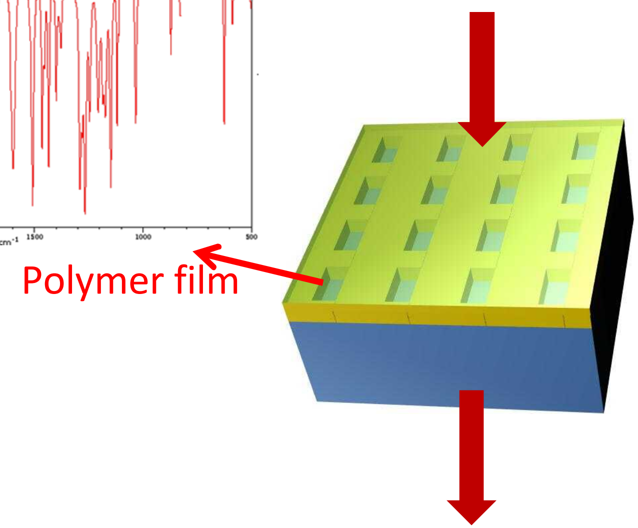
Experiments with Double groove Structure



Pump probe experiments (w/ Rohit Prasankumar-)

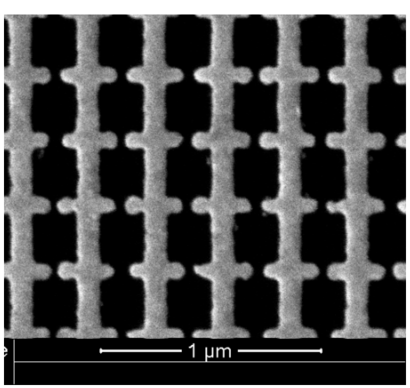
- Carrier based transmission control
- Fundamental understanding of quasistatic respose

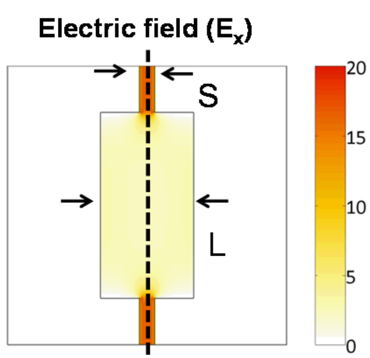




Low conc. Molecular detection (w/ Dale Huber)

- Uses high power confinement in nanoscale gap
- Uses broadband response





Near field measurement (w/ Prof. Glenn Boreman (UNCC)

- Experimental measurement of near-field intensity in subwavelength gaps using scattering NSOM