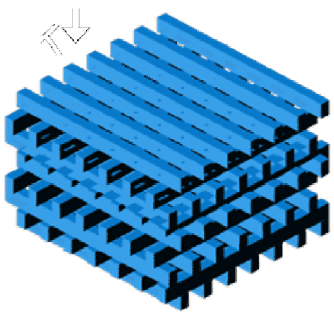
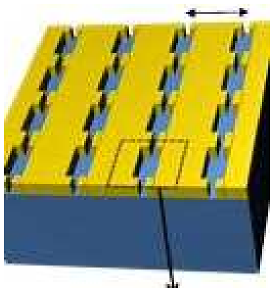
SAND2013-6423P

Nanophotonic Structures for Control of Light-matter Interaction

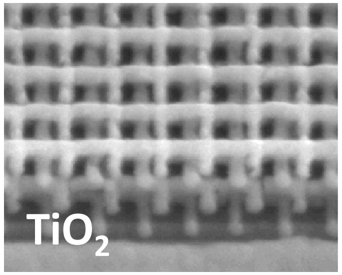


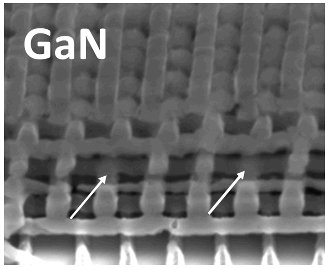


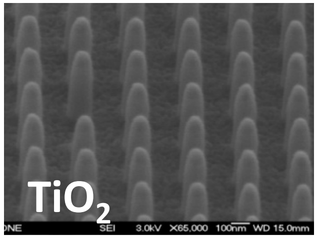
Ganapathi Subramania

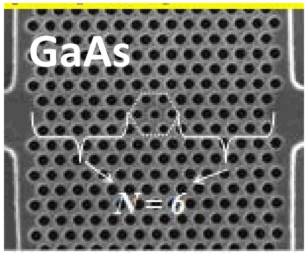
Advanced Material Science 01126
Sandia National Laboratories, Albuquerque, NM

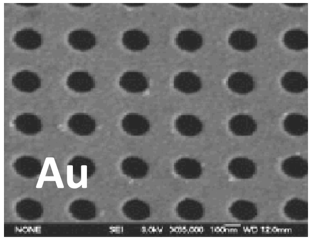
Indian Institute of Technology, Kanpur, India
August 16-17, 2013











Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

Acknowledgements

Sandia National Laboratories

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- Doug Pete
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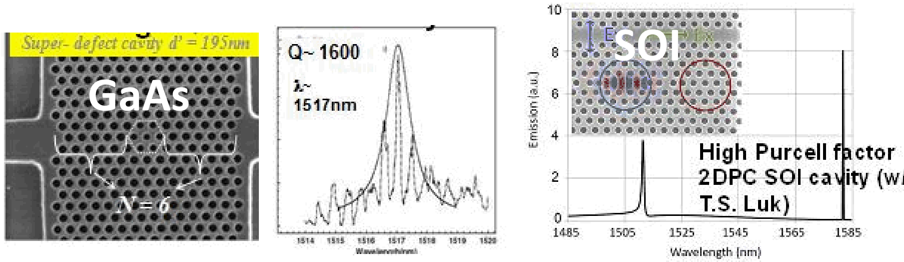
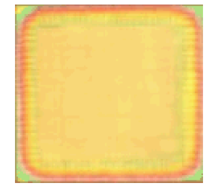
- Bob Biefeld
- Jerry Simmons

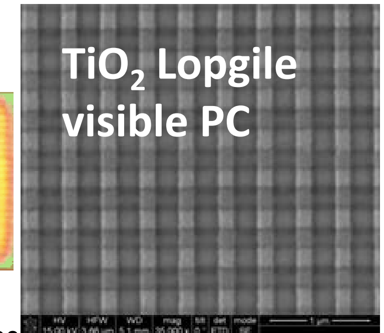
Nanophotonics Activity

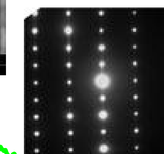
Sandia National Laboratories

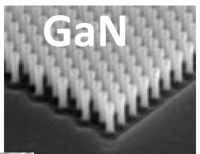
Integrated Photonics, Nanoscale lasing, Strong coupling, Full 3D emission control, Thermal control, Solid State lighting, Energy conversion



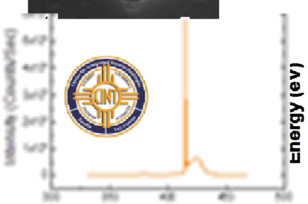


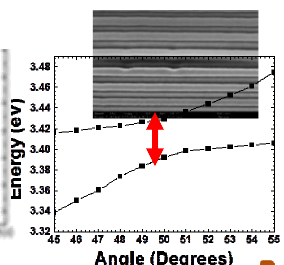






Strong coupling (w/A. Fischer)



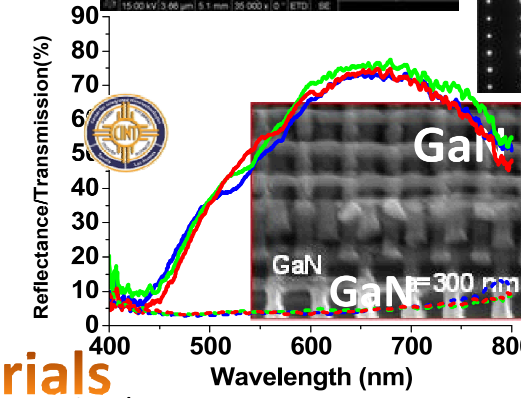


GaN 2DPC laser w/ G. Wang, I. Brener

1,2D PC

Photonic Nanostructures

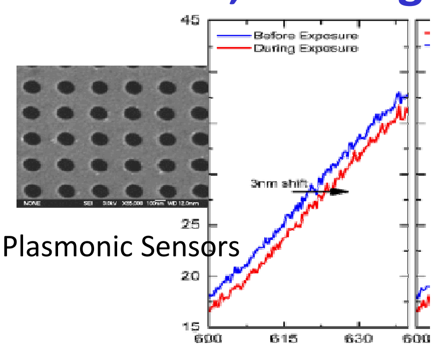
3D PC



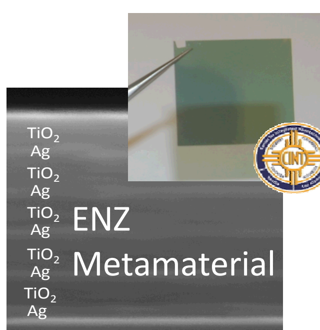
(w/ G.Wang, A. Fischer, D. Koleske)

Metal optics and Metamaterials

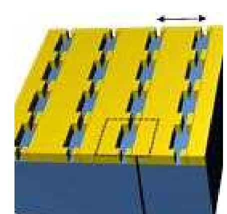
Ultrasubwavelength light control, Detection, Sensing , Nanocircuitry



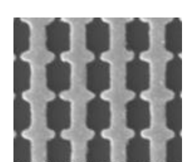
Plasmonic Sensors

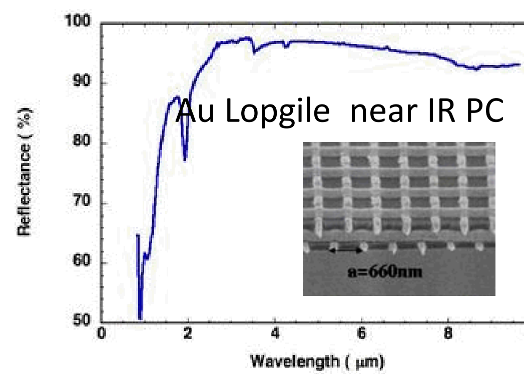


ENZ Metamaterial



Double groove Metal Nanostructure





Au Lopgile near IR PC

Energy Frontier Research Center for Solid-State-Lighting Science

SSLS EFRC
SOLID-STATE LIGHTING SCIENCE
ENERGY FRONTIER RESEARCH CENTER

- **Duration: Aug 2009 – Jul 2014**
- **One of 46 EFRC centers nationwide**
- **Budget: $3.6M/year for 5 years**

Director:
Mike Coltrin
Chief Scientist:
Jeff Tsao

Los Alamos NATIONAL LABORATORY · Northwestern University · PHILIPS · UMASS · The University of New Mexico · Rensselaer Polytechnic Institute · Yale University

Senior Staff
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Business Staff
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Luz Tirado

EFRC Web: http://science.energy.gov/bes/efrc/centers/

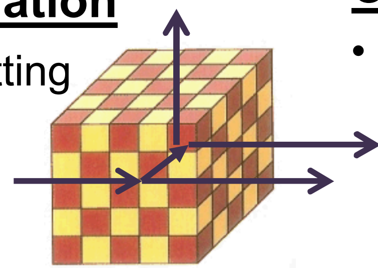
Website: http://ssls.sandia.gov/

3D PC: A Great Platform for Light Manipulation

Sandia National Laboratories

Control of light propagation

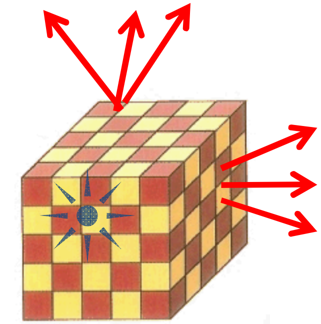
- Guiding, bending and splitting
- Negative refraction
- Self-collimation
- Localization
- Slow light
- Cloaking



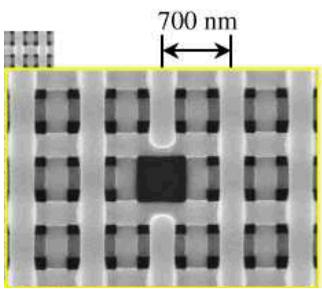
Control of light emission

- Full 3D confinement effect
  - Photon – Atom Bound states,

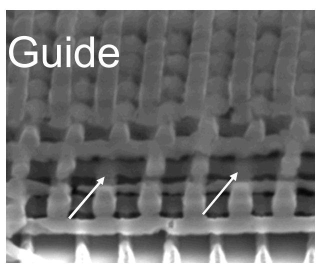
  Non- Morkovian emission process



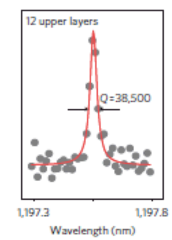
- Photonic Density of States effect
  - Spontaneous emission enhancement

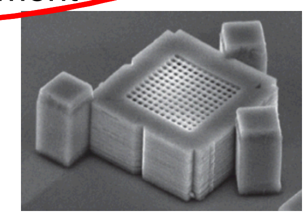


S. Kawashima et. al.., Opt. Exp. **18**, 386 (2010)

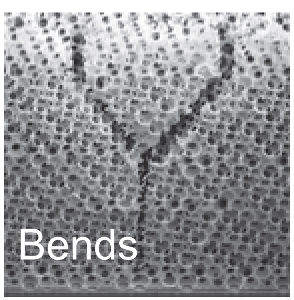


G. Subramania et. al, Nano Lett. **11**, 4591 (2011).

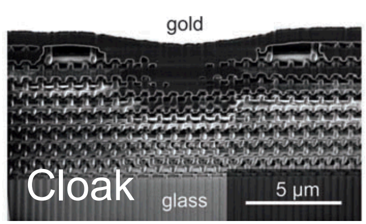




A. Tandaechanurat et. al., Nat Photon **5**, 91 (2011).

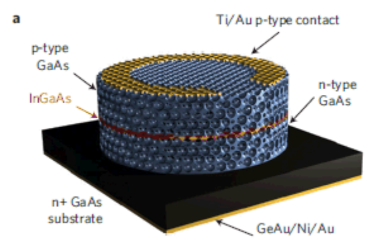


S.A. Rinne et. al., Nat. Phot. **2**, 52(2008)



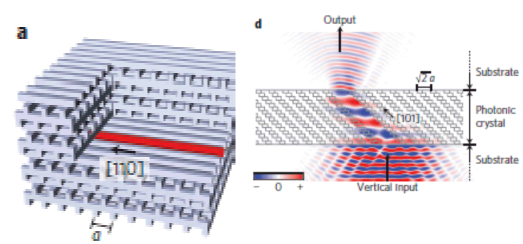
T. Ergin et. al.,Science **328**, 337 (2010)

Electrical Injection



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

Emission enhancement

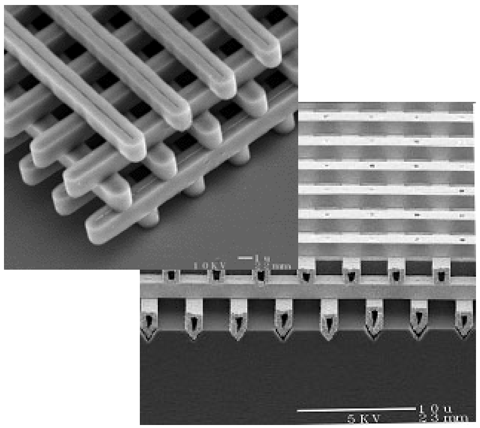


K. Ishizaki et.al. , Nat. Phot.,**7**, 133 (2013)).

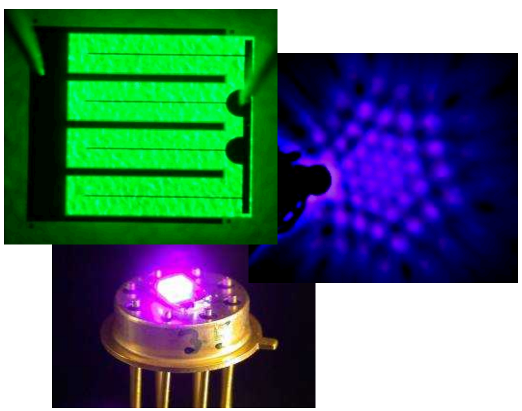
Objective : Understand Spontaneous Emission Control to Benefit SSL

- Sandia has strong capabilities in 3DPC and Nitrides
- Merge InGaN LED research with 3D photonic crystal research.

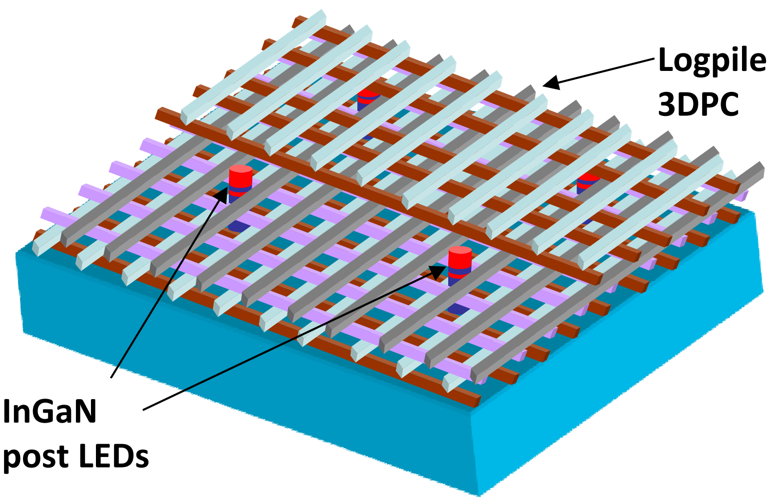
3D photonic crystals



InGaN LEDs



InGaN LED array incorporated into a 3DPC



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

Spontaneous Emission Control using PC

Sandia National Laboratories

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

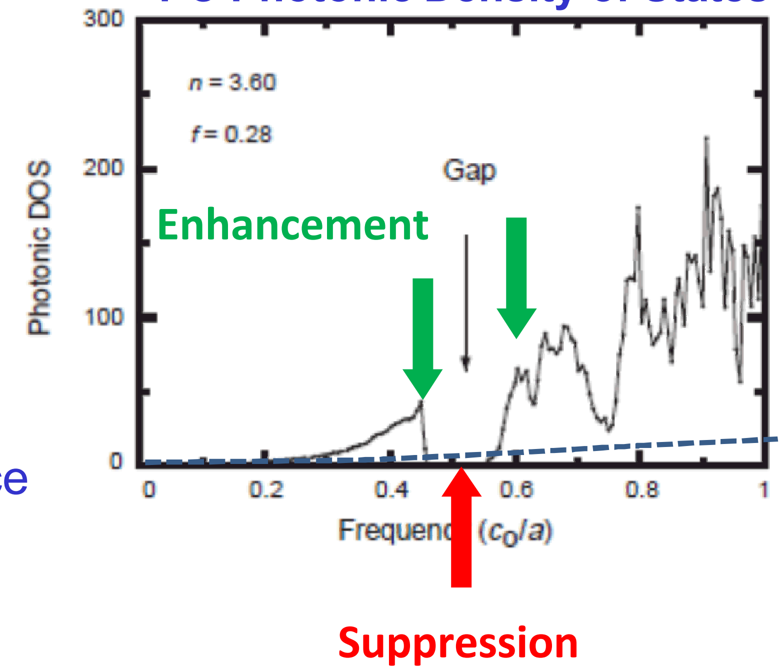
Radiative rate modification

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

Local Photonic Density of States (LDOS)

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

PC Photonic Density of States



Also Important :

- Where the emitters are located in the unit cell
- The orientation of the emitter dipole w.r.t to the eigenfield

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

Visible Frequency Logpile Photonic Crystal

Sandia National Laboratories

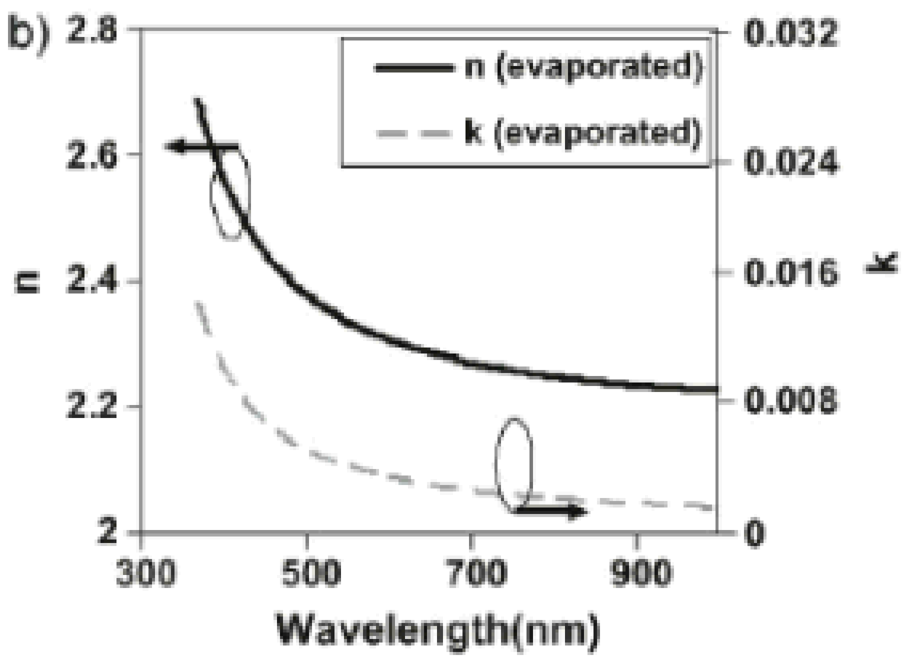
Material Choice : TiO_2

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

Method of fabrication:

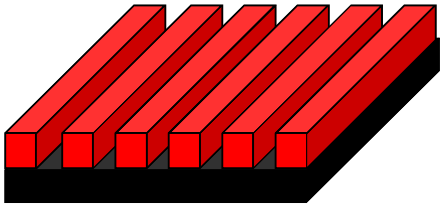
- **Nanofabrication based on electron beam lithography**



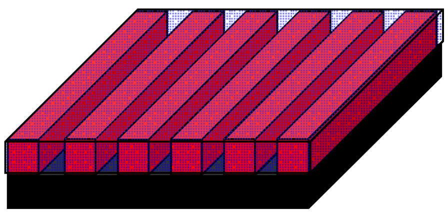
Multilevel E-beam Fabrication Process

PC fabricated one layer at a time.

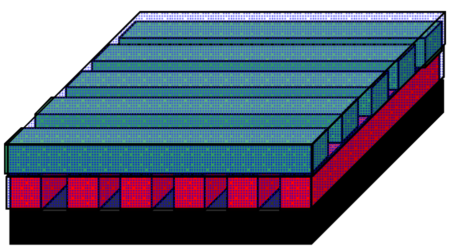
1.Fabricate first level



2. Fill and planarize



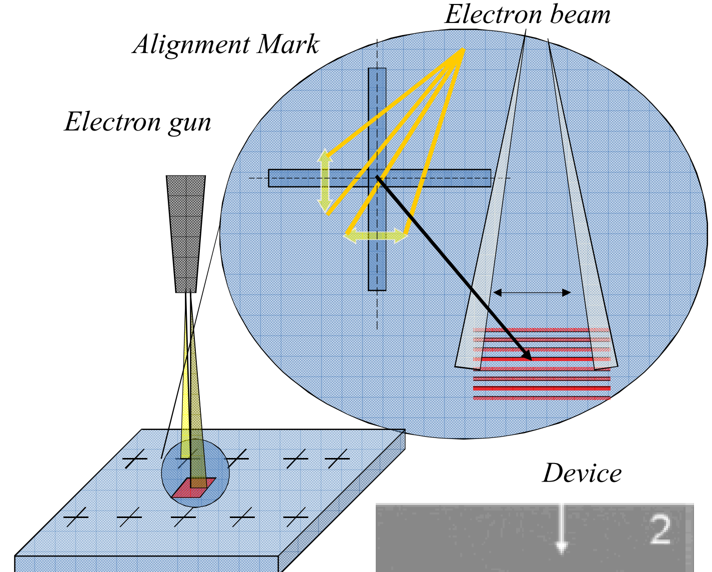
3. Make next level



4. Repeat process to make additional levels

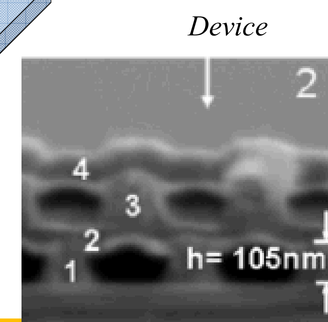
Alignment

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



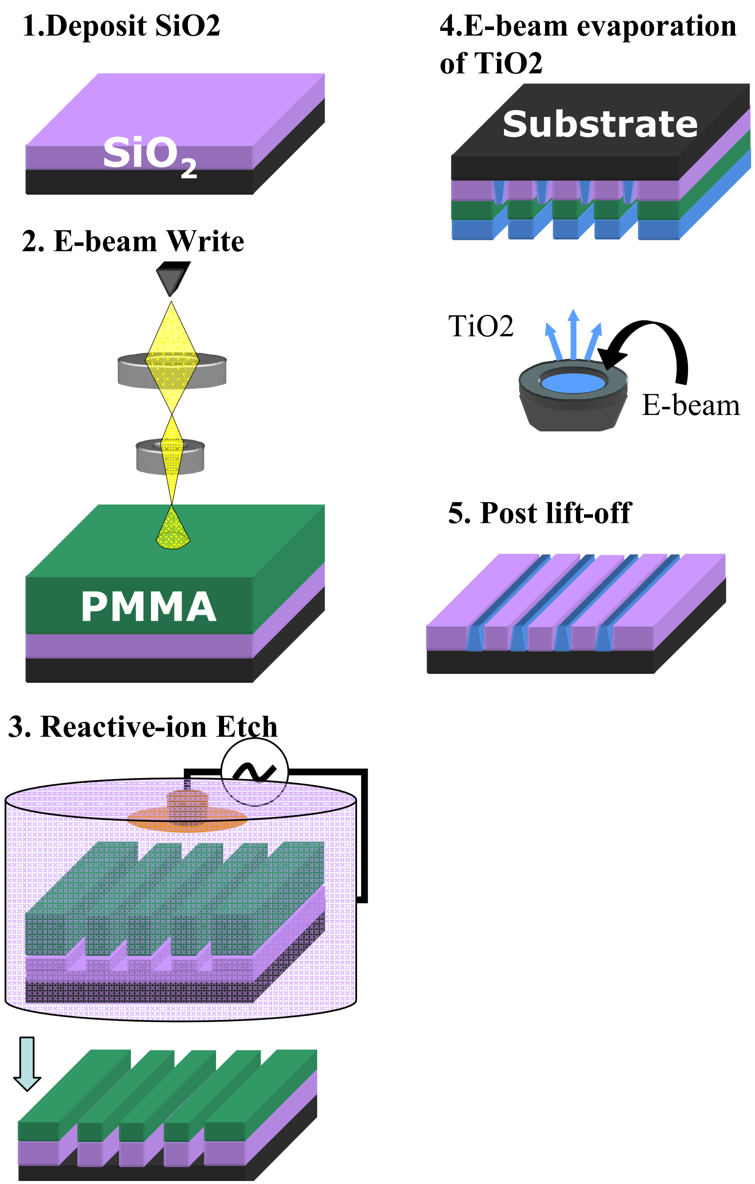
➢ Alignment
➢ Planarization

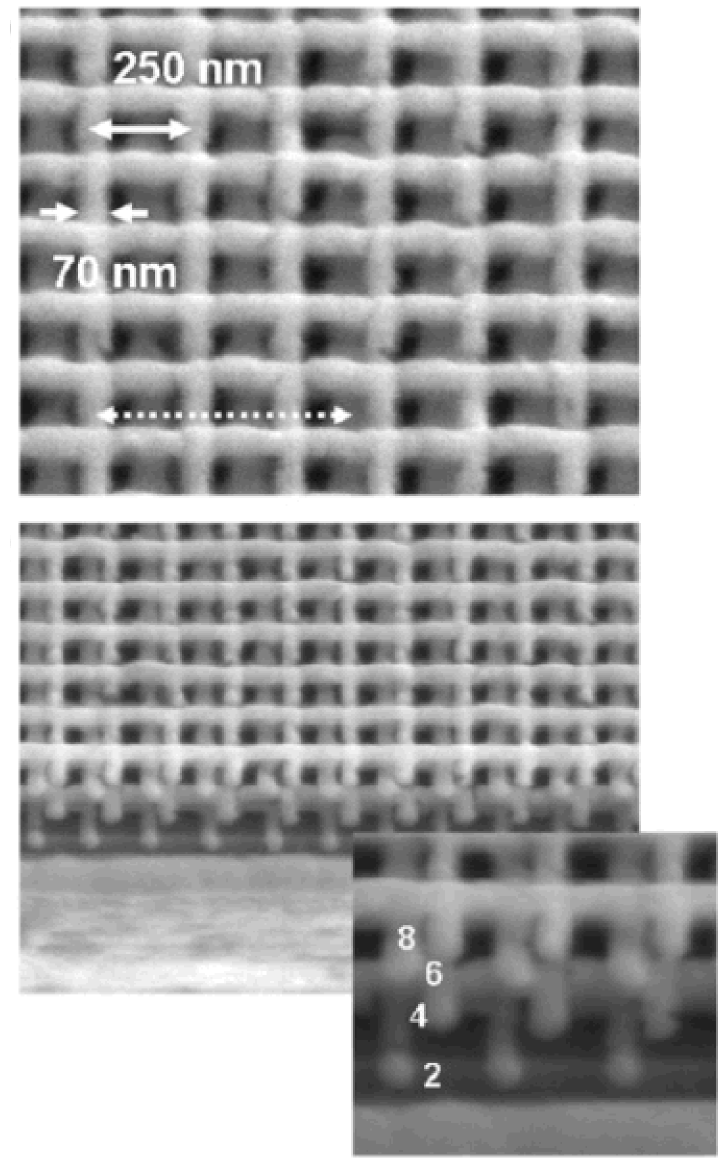
G. Subramania, Nanotechnology **18** , 035303 (2007).



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

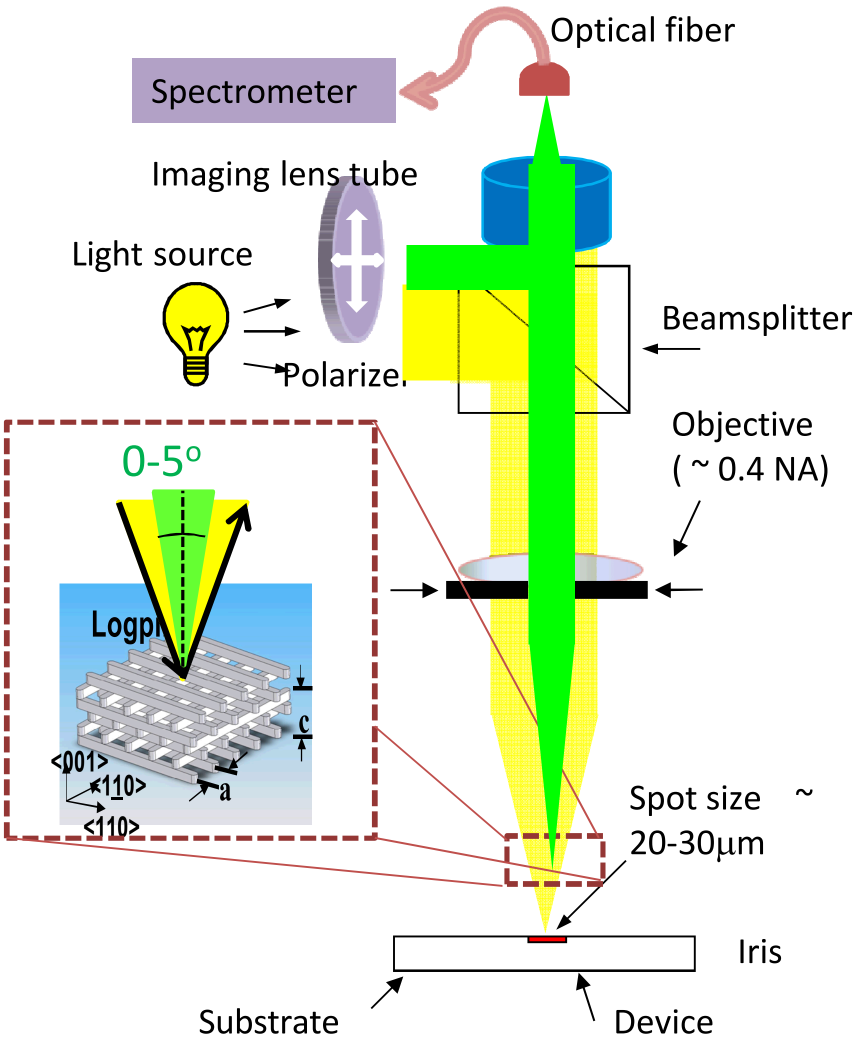
TiO_2 Logpile Photonic Crystal Fabrication Process

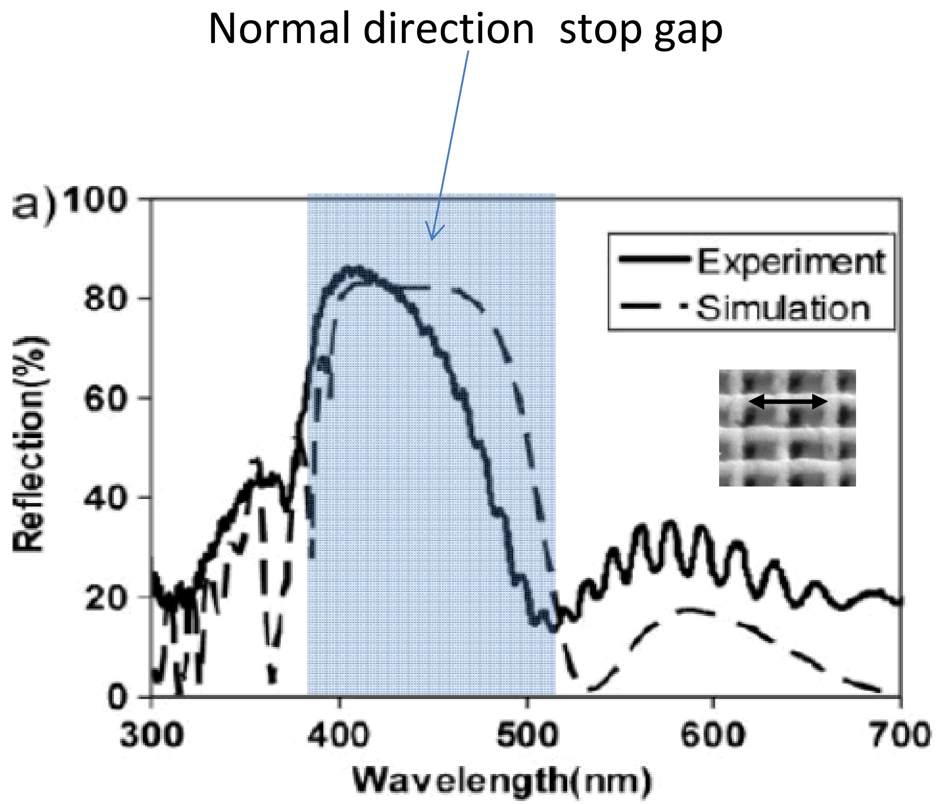




G. Subramania et. al., Adv. Mat. **22**, 487-491 (2010)

Visible- Near UV 9 Layer TiO_2 Logpile



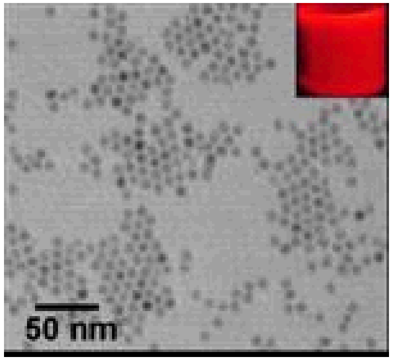


G. Subramania, Y.-J. Lee, A. J. Fischer, and D. D. Koleske, Advanced Materials **22**, 487-491 (2010)

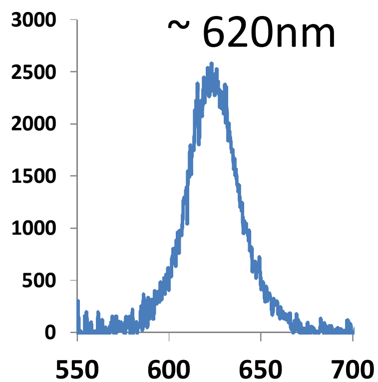
Emission Modification in TiO_2 Logpile

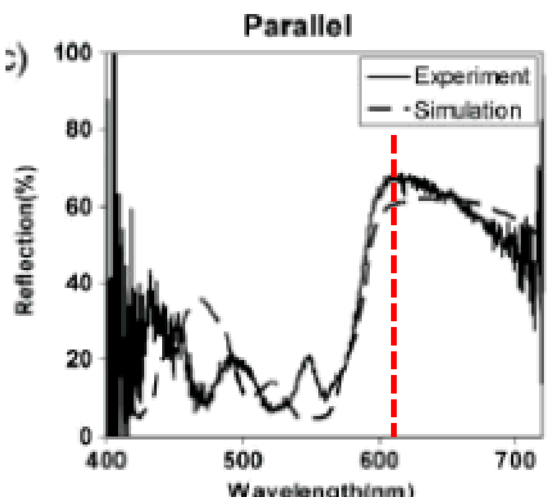
Sandia National Laboratories

CdSe red emitting quantum dots

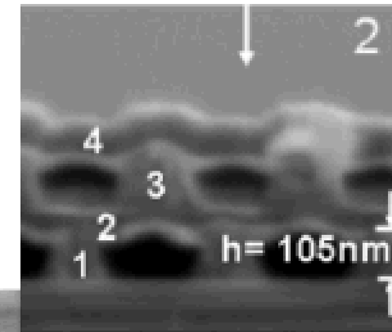


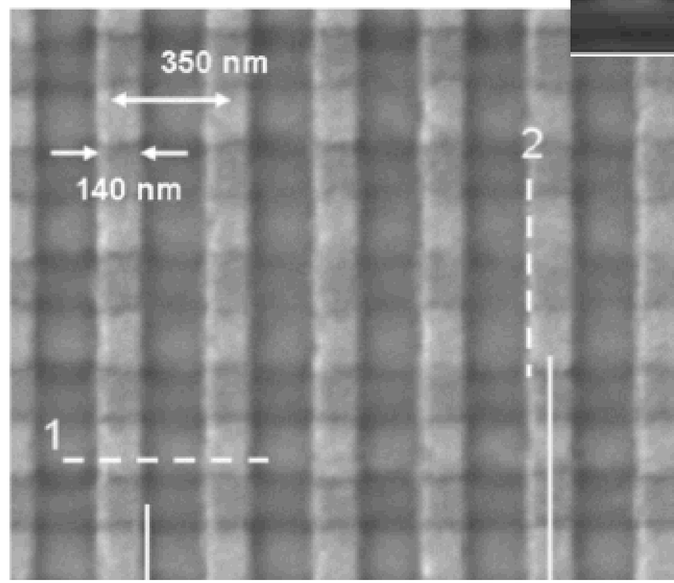
(www.nn-labs.com)





Larger lattice constants a= 350,400 with 4 Layers





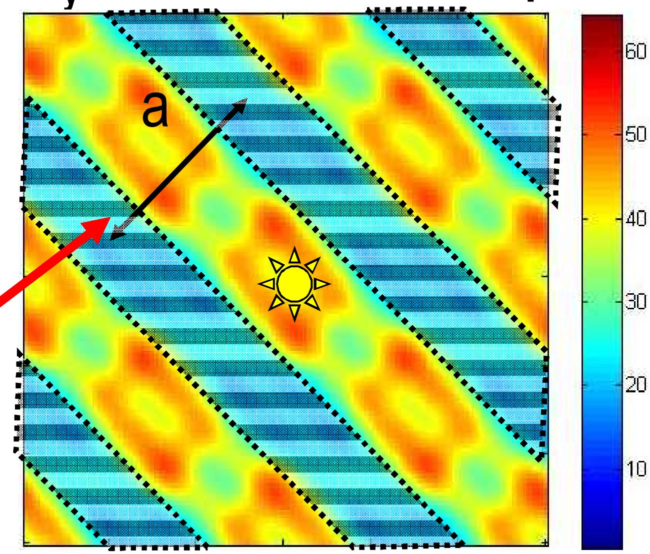
G. Subramania, Y. J. Lee, A. J. Fischer, T. S. Luk, C. J. Brinker, D. Dunphy, Appl. Phys. Lett. , **95**, 151101(2009)

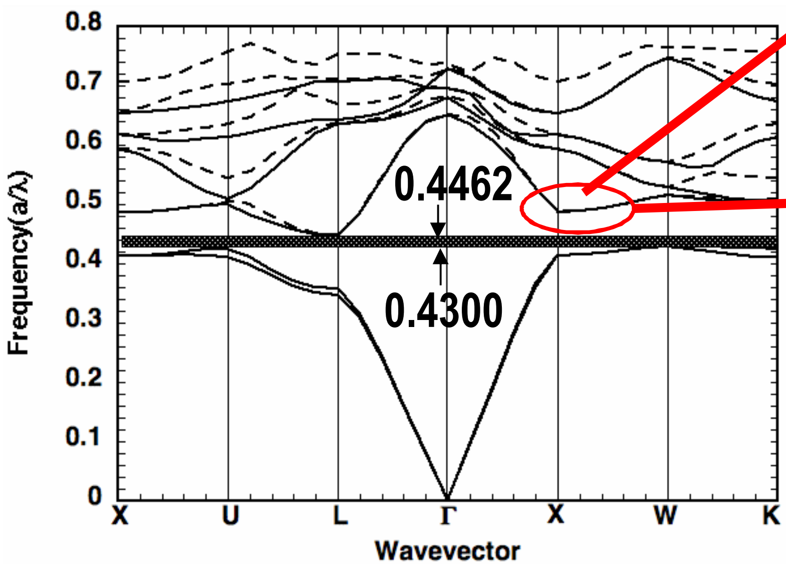
Effect of LDOS- Emitter Placement Inside the PC

Sandia National Laboratories

- Thus far emission control studies typically done for emitters in high index region – probing dielectric band
- 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

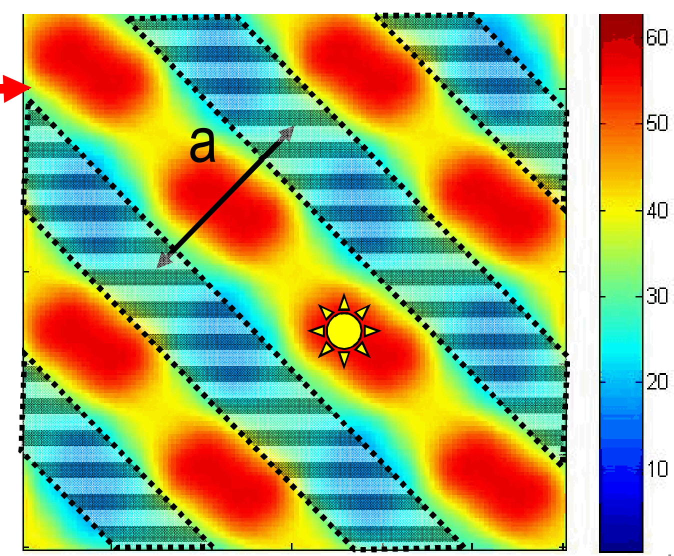
E_y field distribution at Xpt

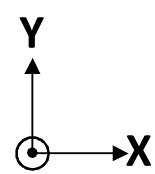




'Air' band

E_z field distribution at Xpt





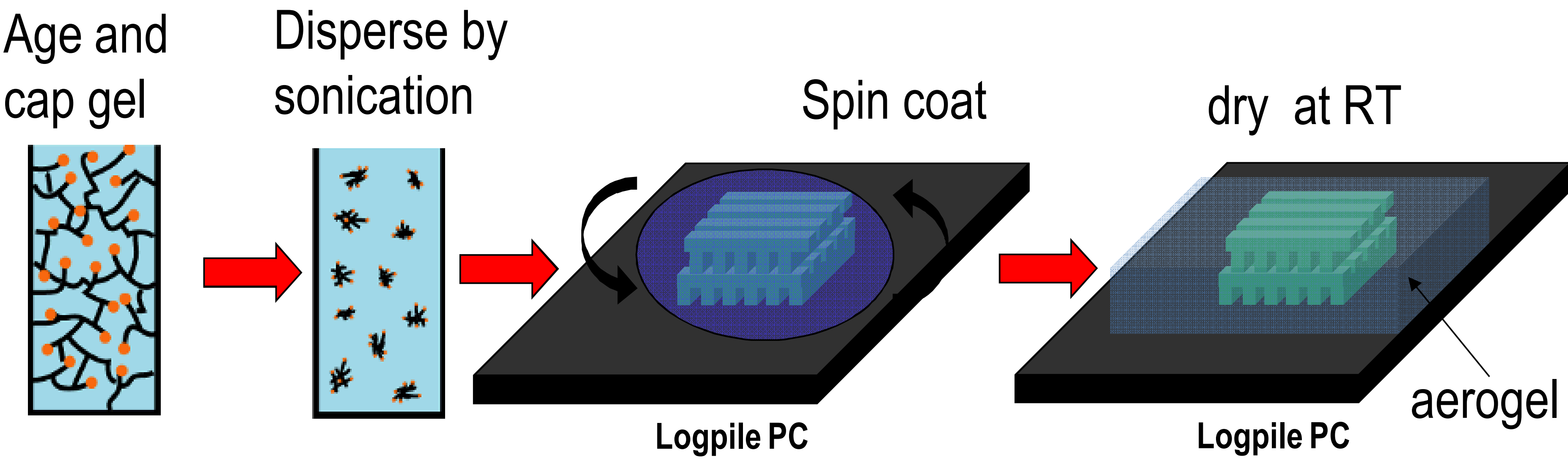
Field Distribution for the 'air band' using PWE method

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))

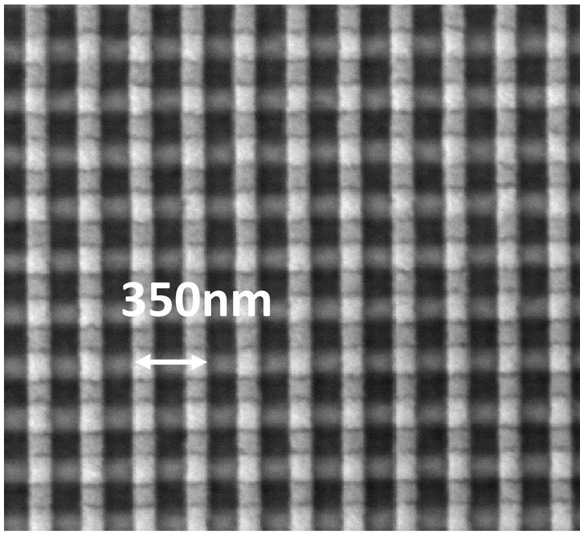


Introduce QDs through chemical attachment (3-mercaptopropyltrimethoxysilane chemistry)

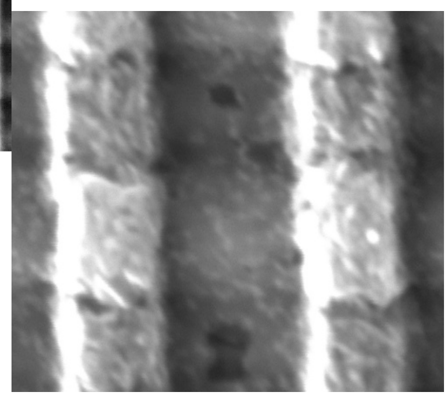
Developed by Alex Lee

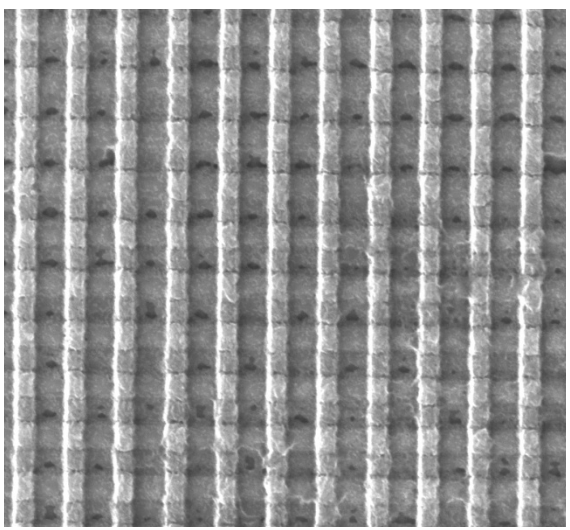
G. Subramania, Y. J. Lee, A. J. Fischer, T. S. Luk, C. J. Brinker, D. Dunphy, Appl. Phys. Lett. , **95**, 151101(2009)

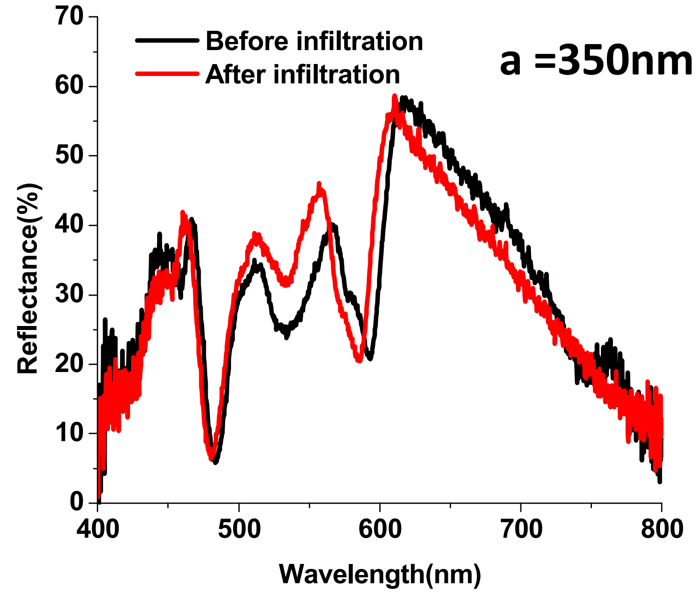
Effect of Aerogel and CdSe QD infiltration

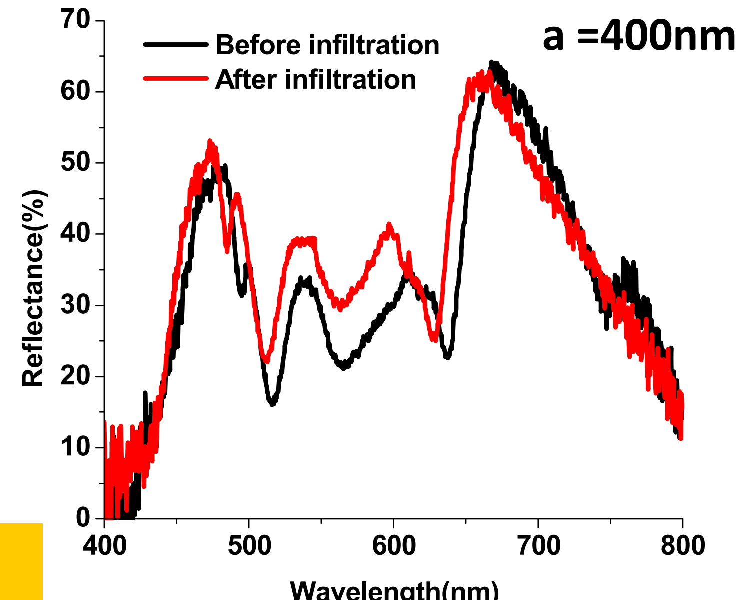


Aerogel Ref. index ~1.05-1.1



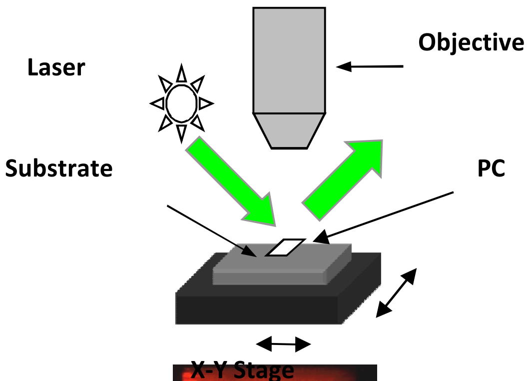






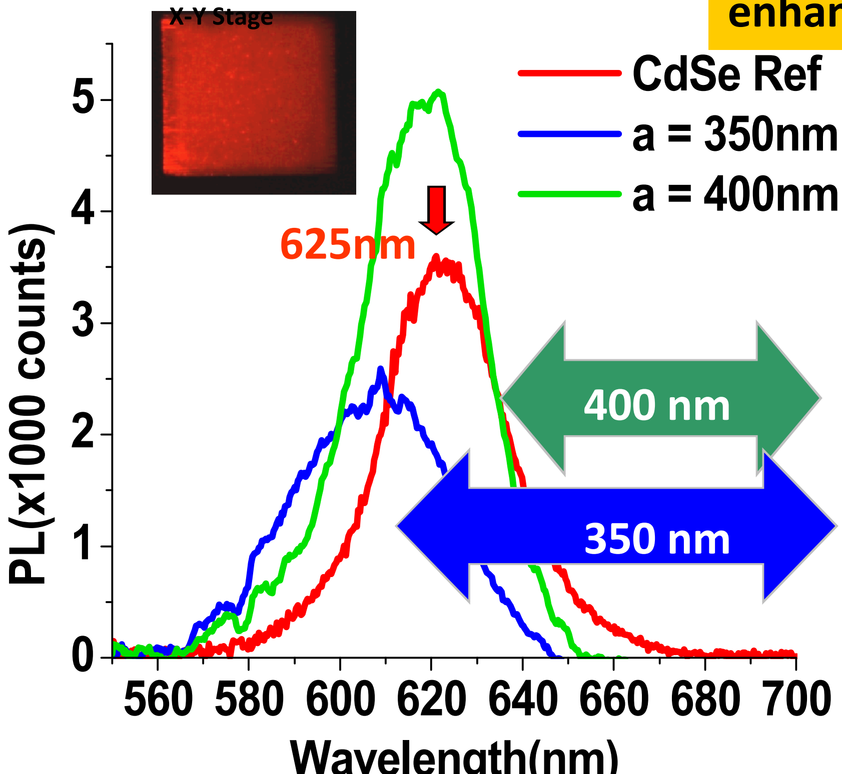
Aerogel and CdSe QD infiltration has negligible effect on the bandgap!

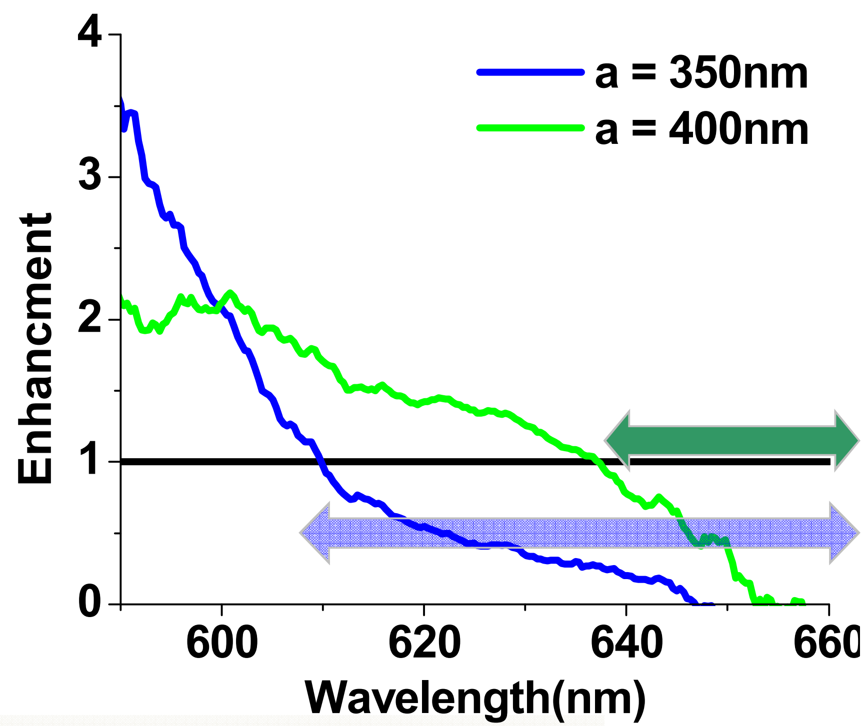
Spontaneous Emission Modification



- ❑ 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



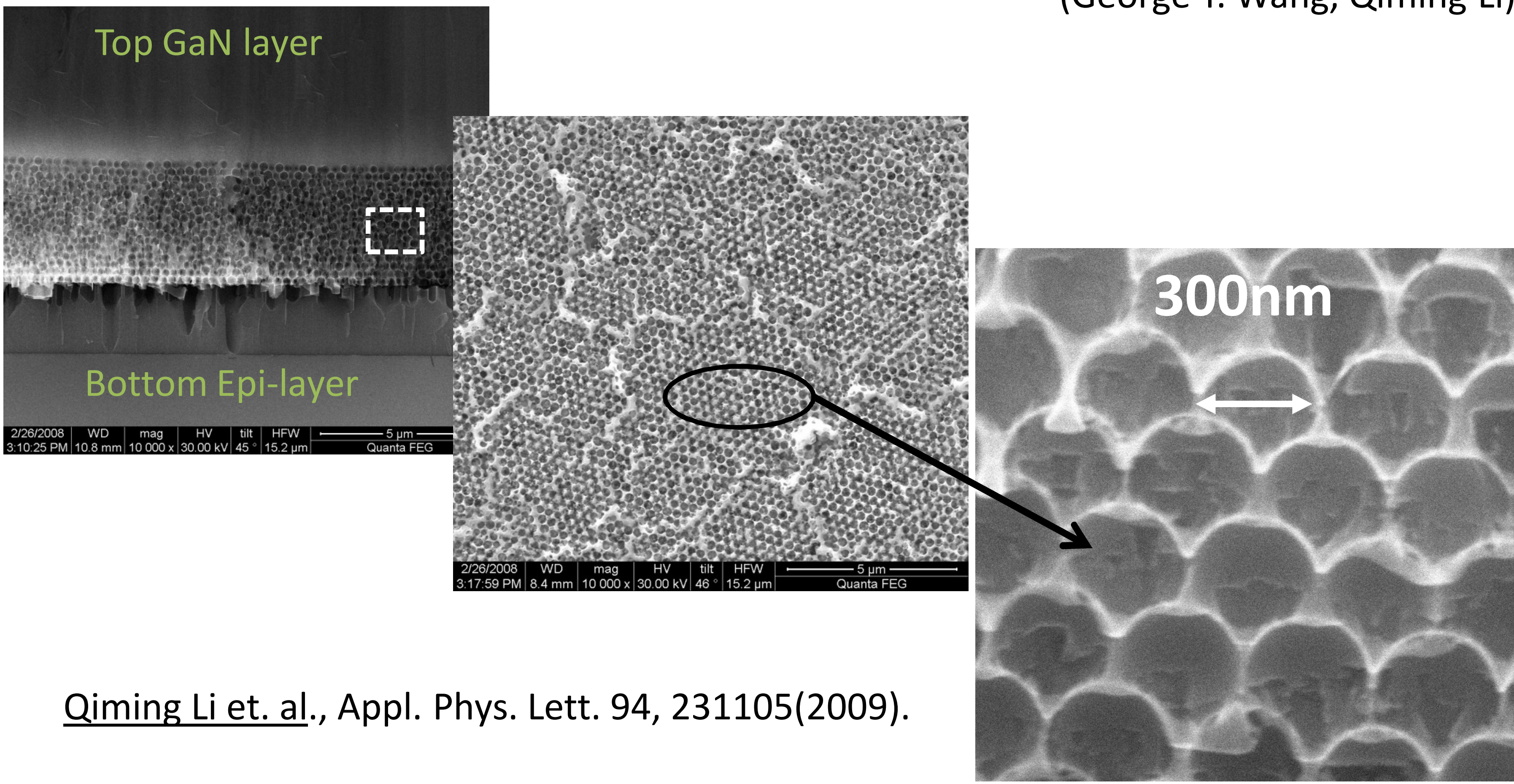


G. Subramania, Y. J. Lee, A. J. Fischer, T. S. Luk, C. J. Brinker, D. Dunphy, Appl. Phys. Lett. , **95**, 151101(2009)

All GaN Logpile Photonic Crystal

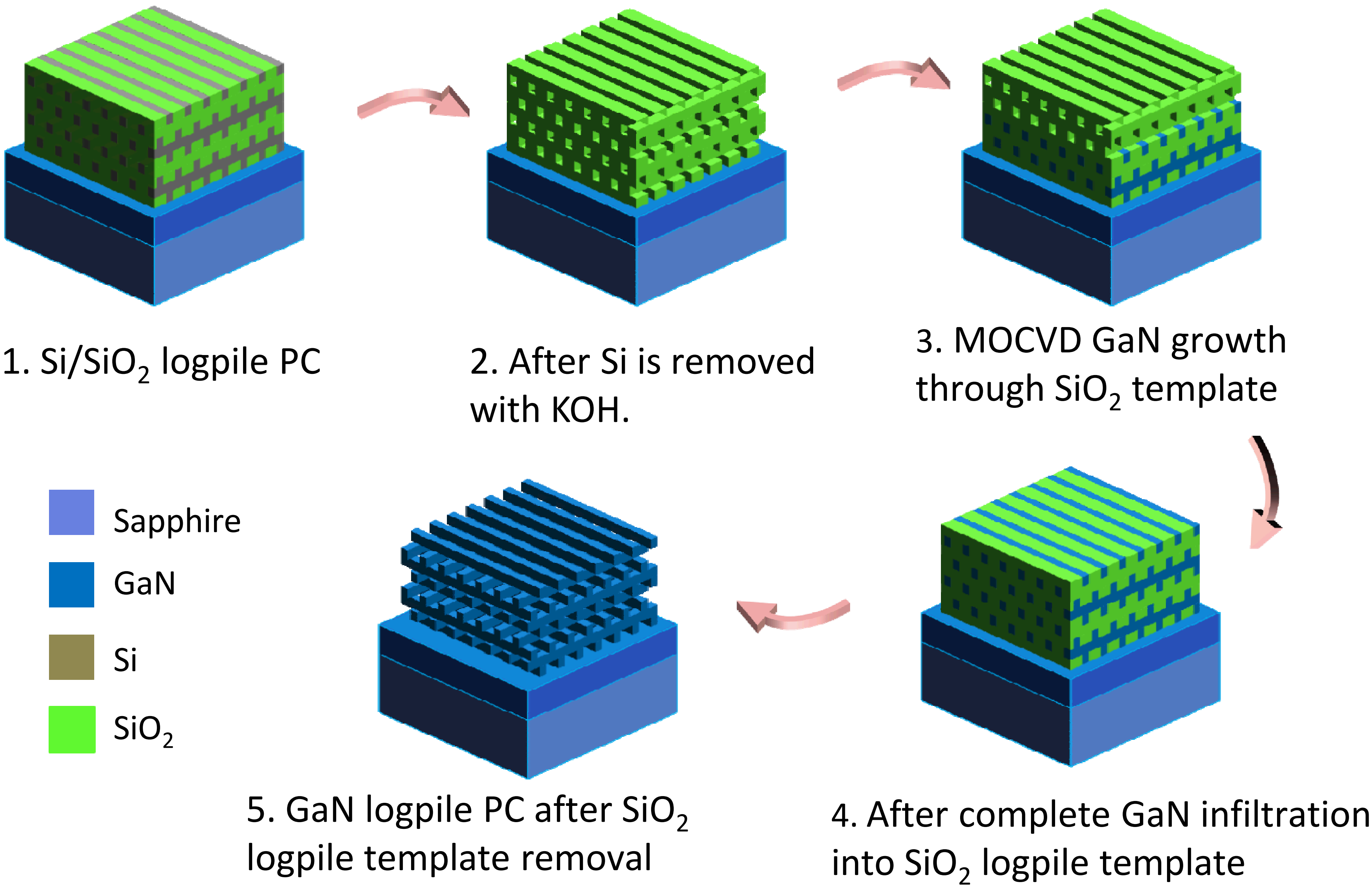
Epitaxial GaN grown though nanostructured template reduces dislocation density

(George T. Wang, Qiming Li)

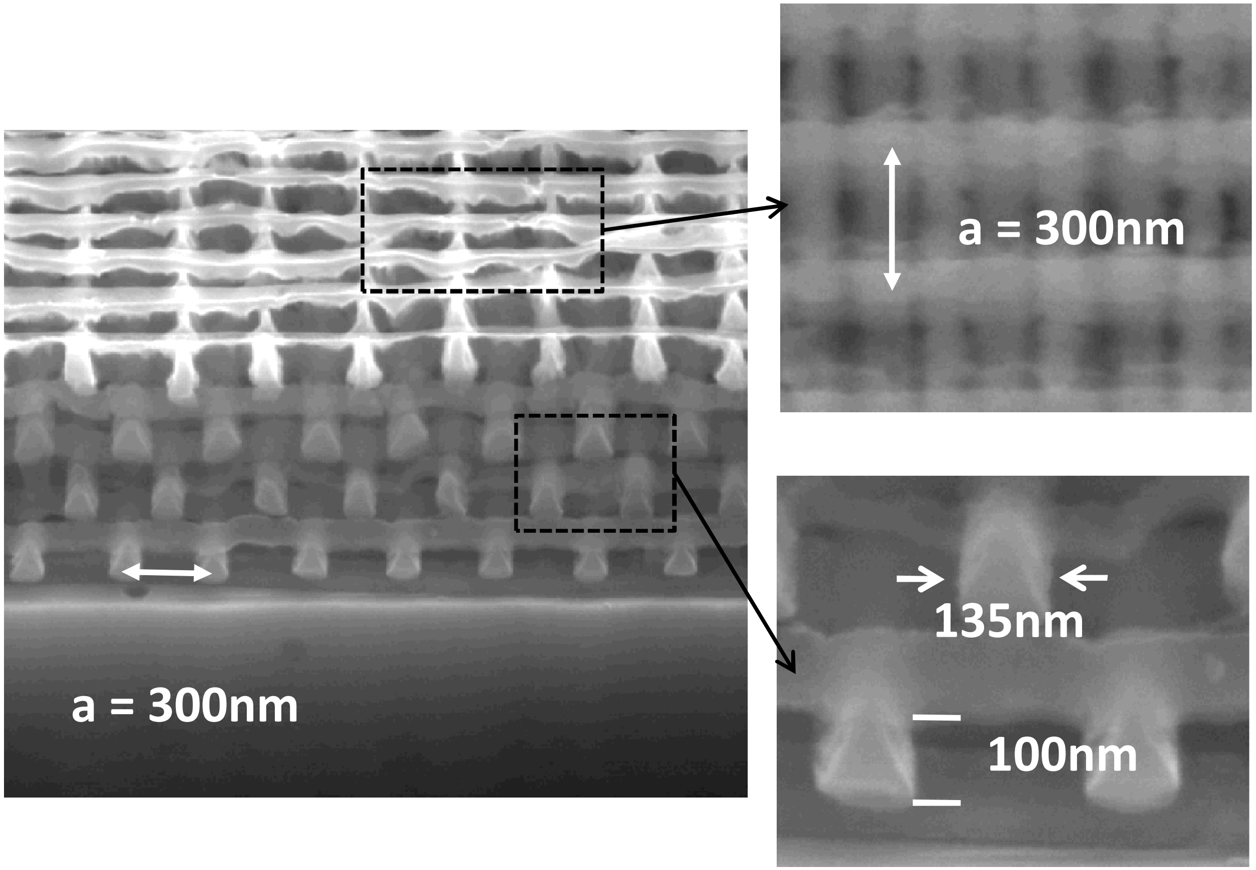


Qiming Li et. al., Appl. Phys. Lett. 94, 231105(2009).

GaN growth through logpile template

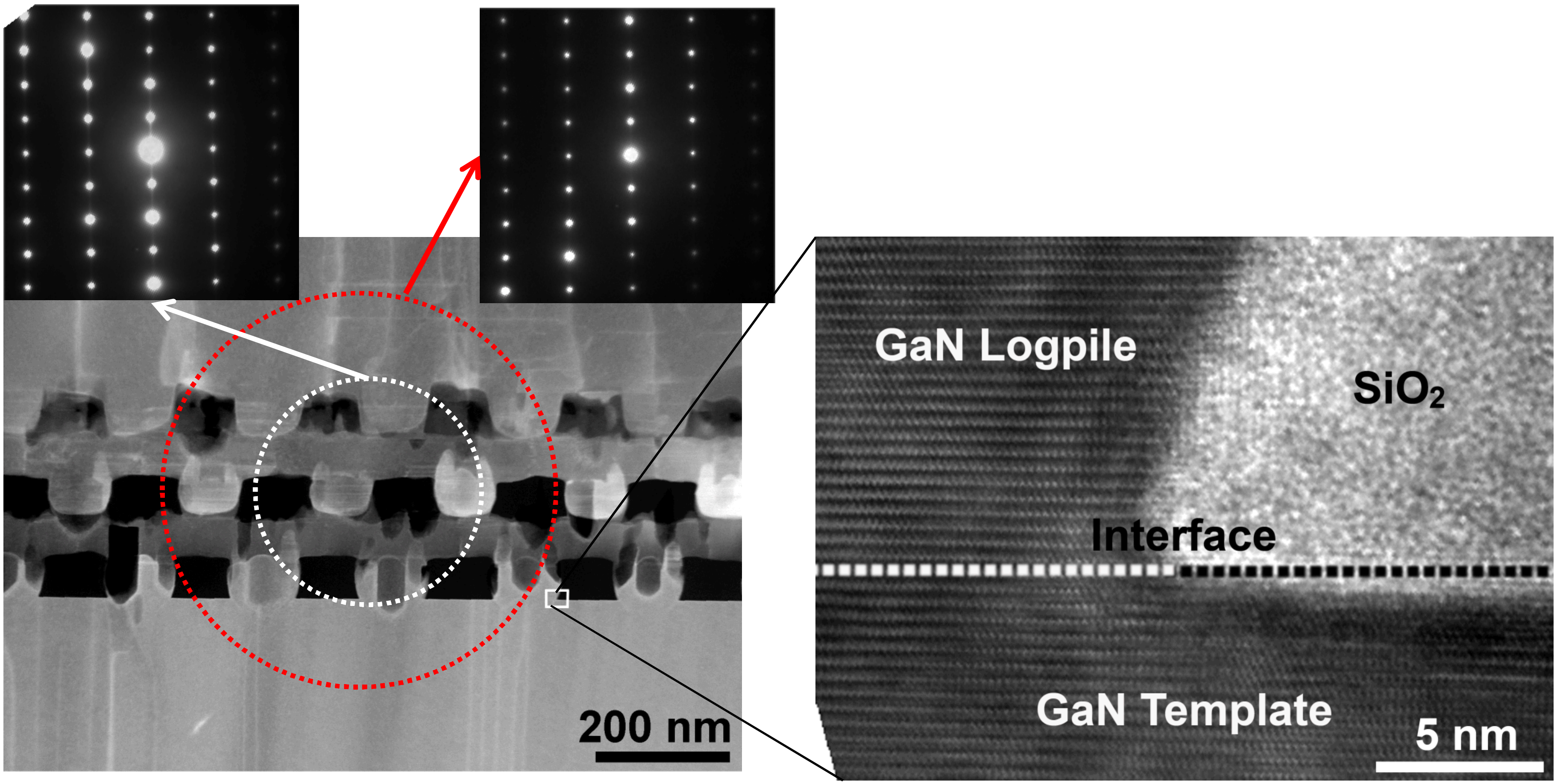


A nine layer all GaN logpile PC



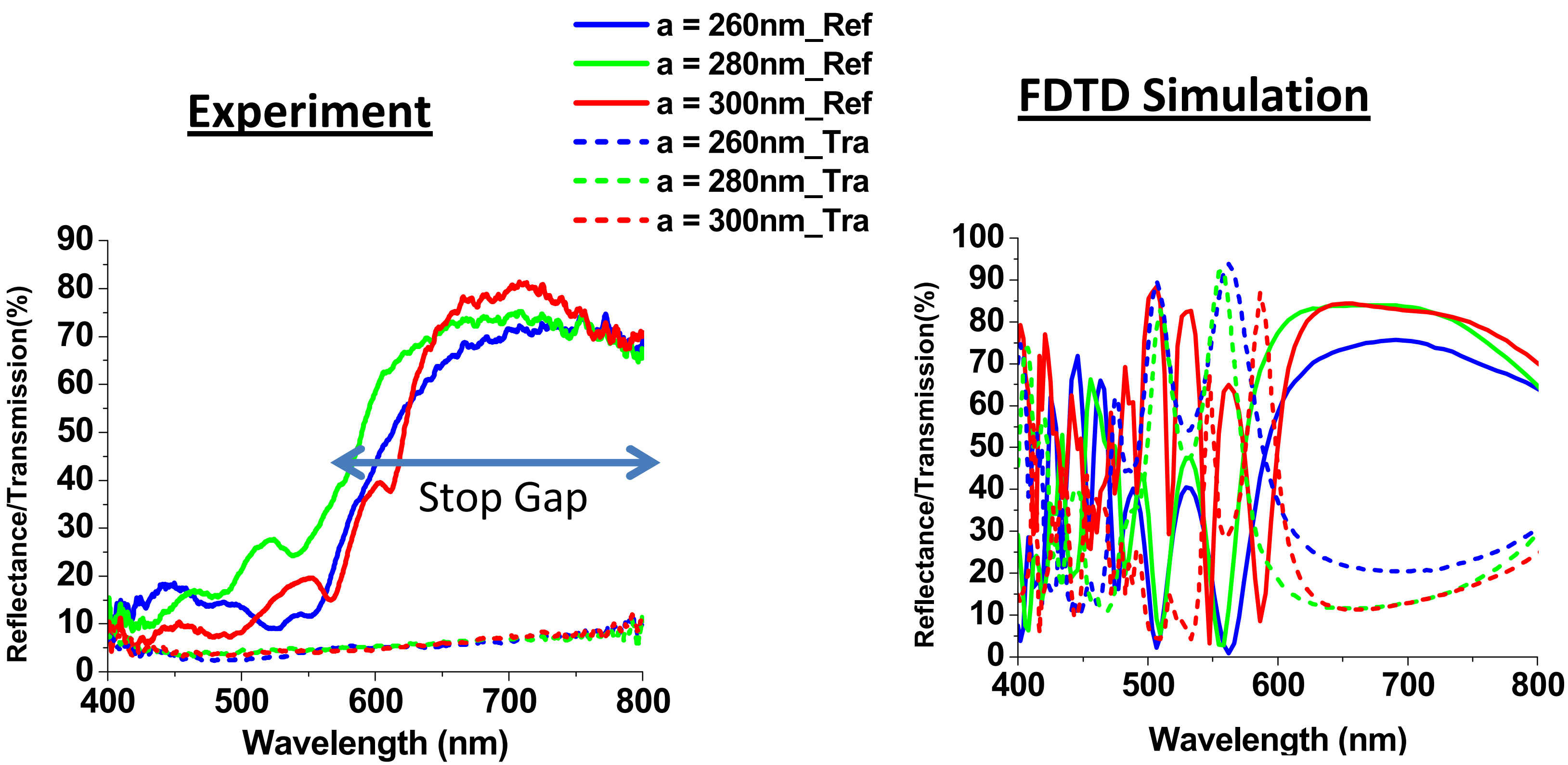
G. Subramania, Q. Li, Y.-J. Lee, J. J. Figiel, G. T. Wang, and A. J. Fischer, Nano Lett. **11**, 4591 (2011).

Bottom-up epitaxial growth of crystalline GaN



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

Optical Response

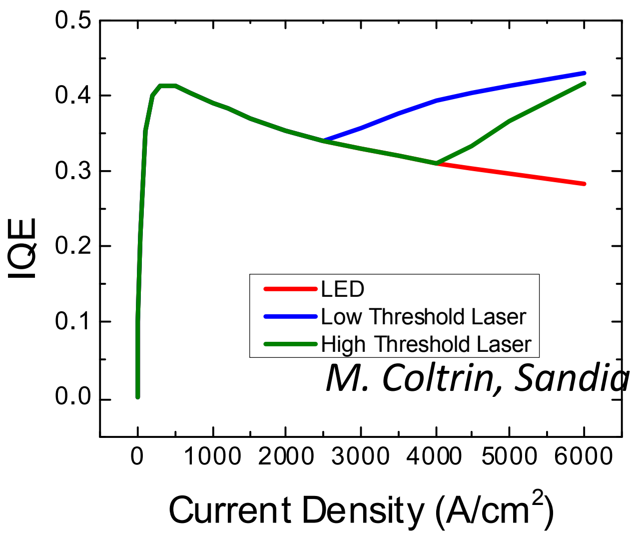


G. Subramania et. al. , Nano Lett. **11**, 4591 (2011).

Nanowire Photonic Crystal Lasers

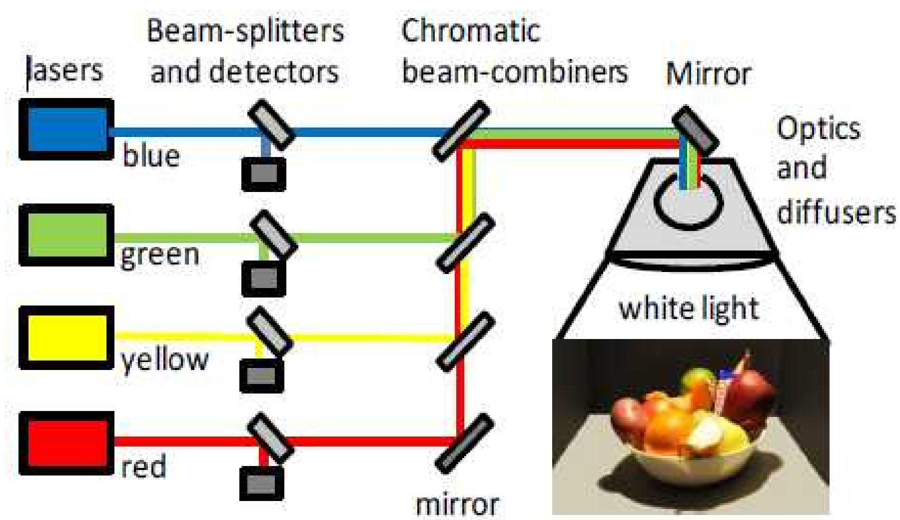
(Jeremy B. Wright, Sheng Liu, Alexander Benz, George T. Wang, Qiming Li, Daniel D. Koleske, Ping Lu, Huiwen Xu, Luke Lester, Ting S. Luk, Igal Brener)

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*

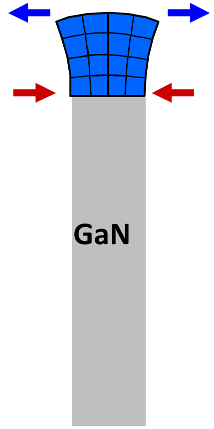


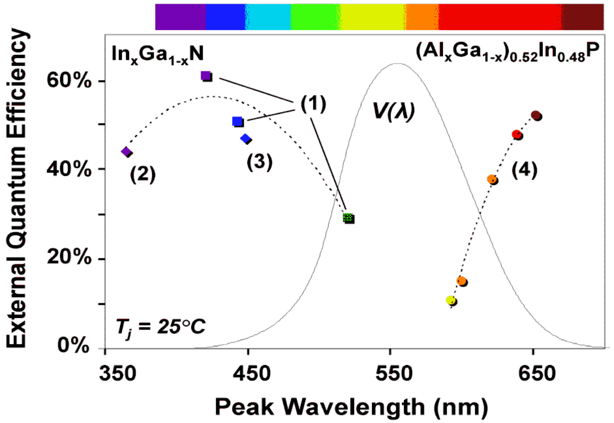
- ***4 color lasers suitably combined can achieve high color rendering***
- ***Lasers can potentially mitigate the efficiency droop problem !***

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

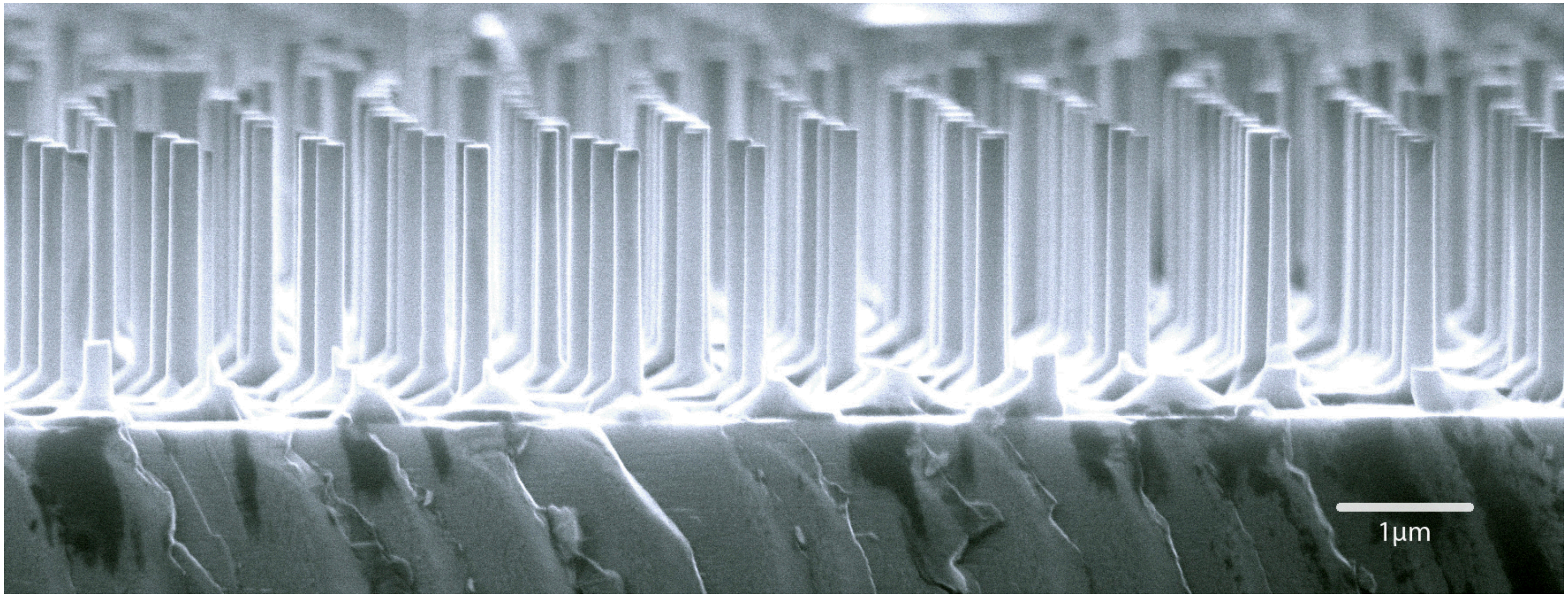
Why Nanowires for Lasing?

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

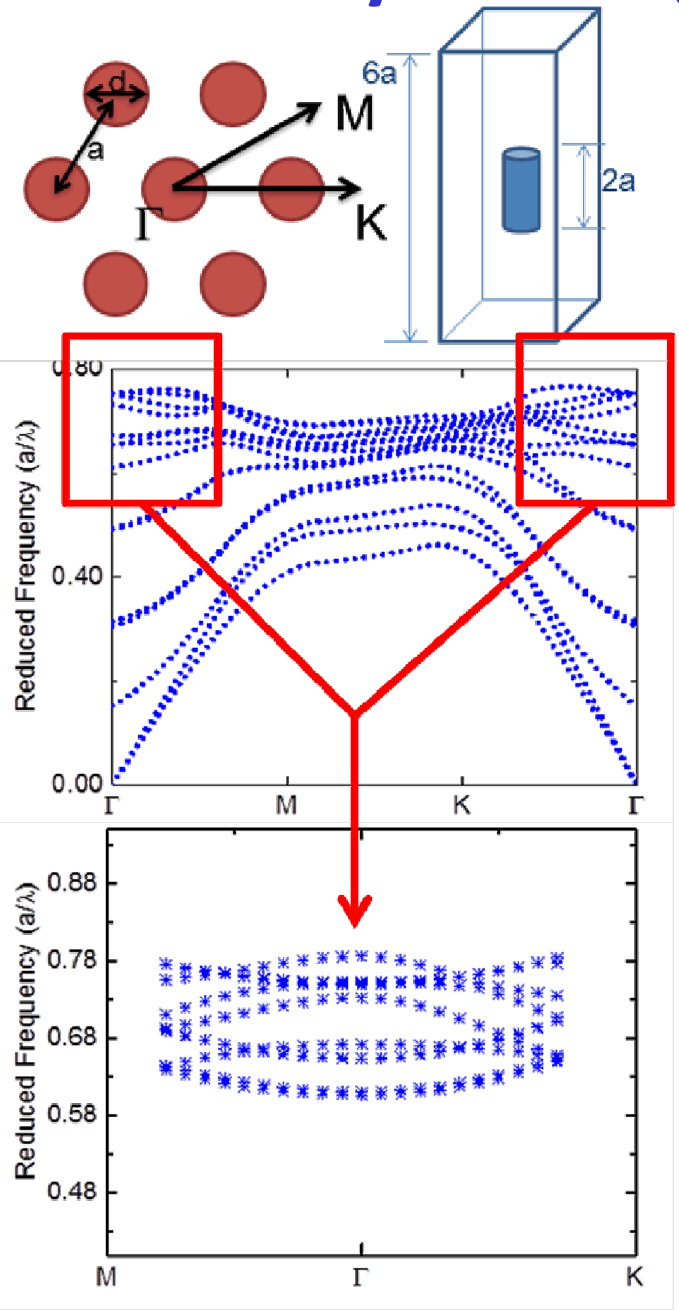




M. Krames, Philips Lumileds



Vertically emitting photonic crystal lasers - Theory

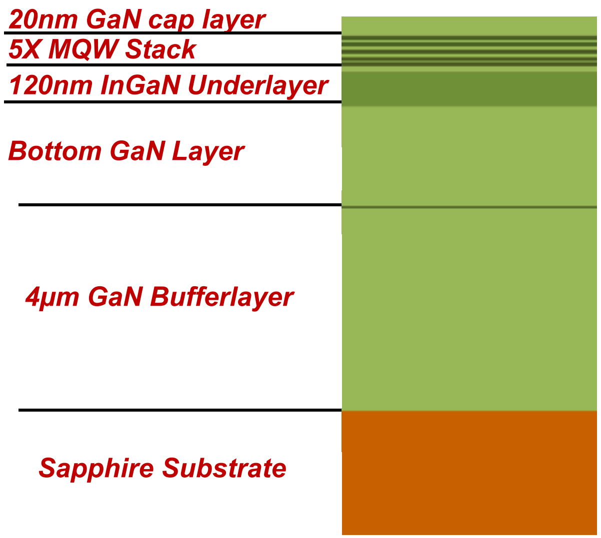


- ***Low lasing threshold***
  - ***Increase interaction of light with the gain region***
  - ***Enabled by 'Low group velocity modes' in photonic crystal***
- ***Vertical Emission***
  - ***At higher bands there are low group velocity modes near the Gamma point***
  - ***Near the Gamma point the in-plane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

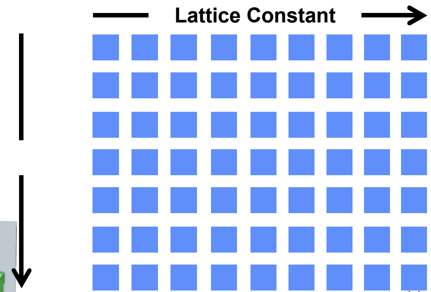
Fabrication of III-N nanowire laser array

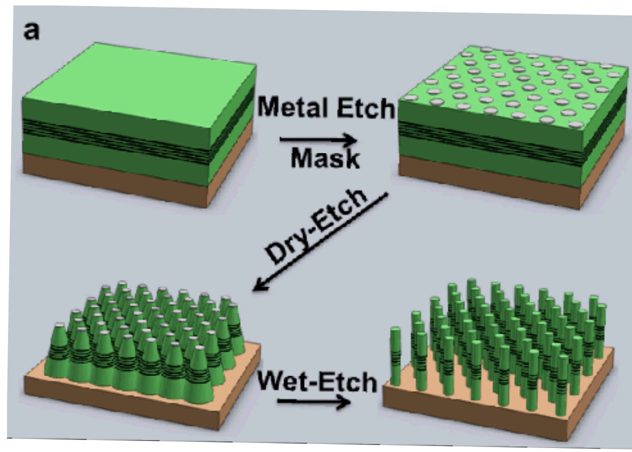
Sandia National Laboratories

Growth of III-N active material

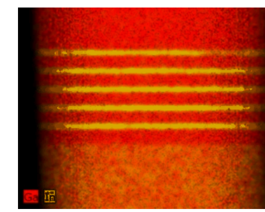


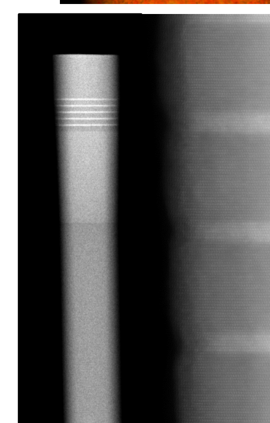
Patterning of 2DPC using e-beam lithography





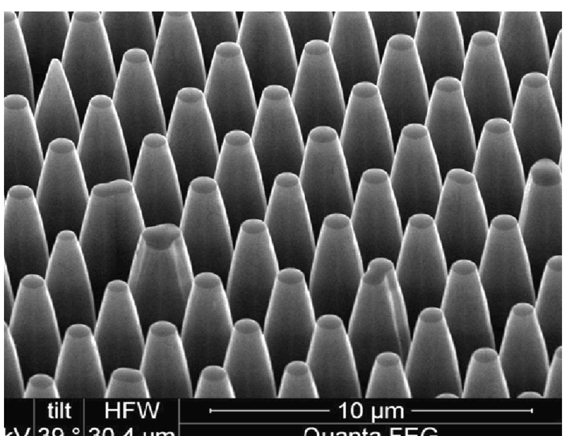
TEM images

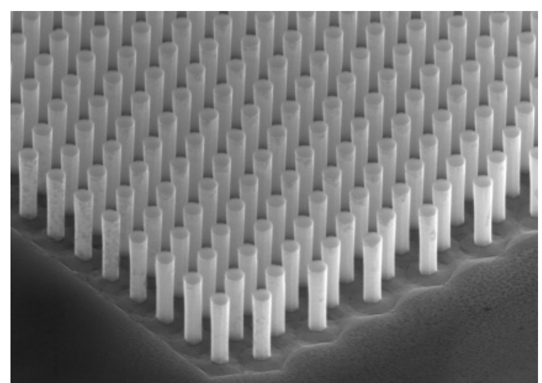




Ping Lu, Sandia

Inductively coupled plasma dry etch



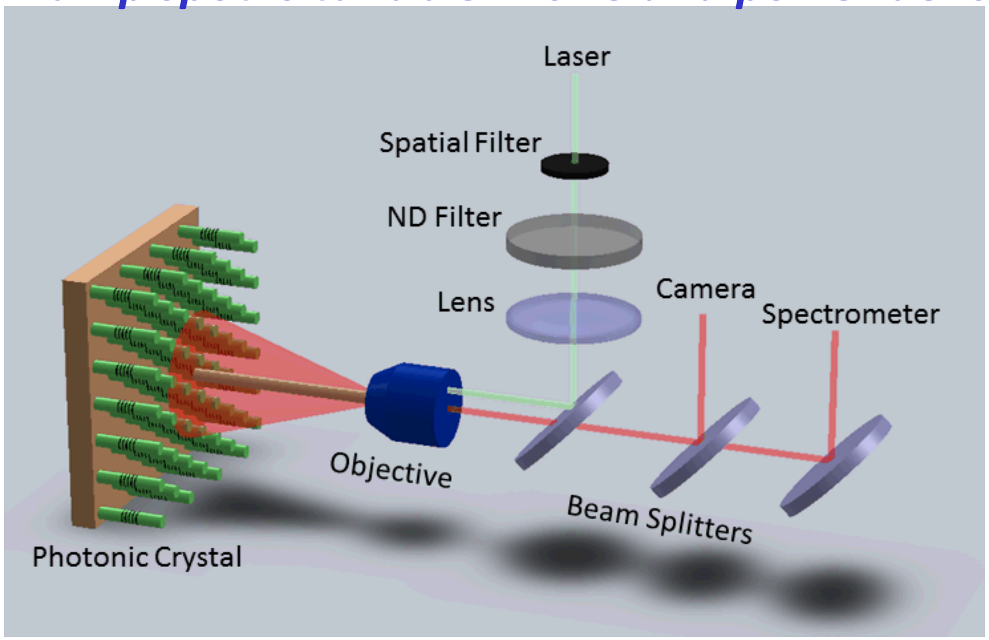


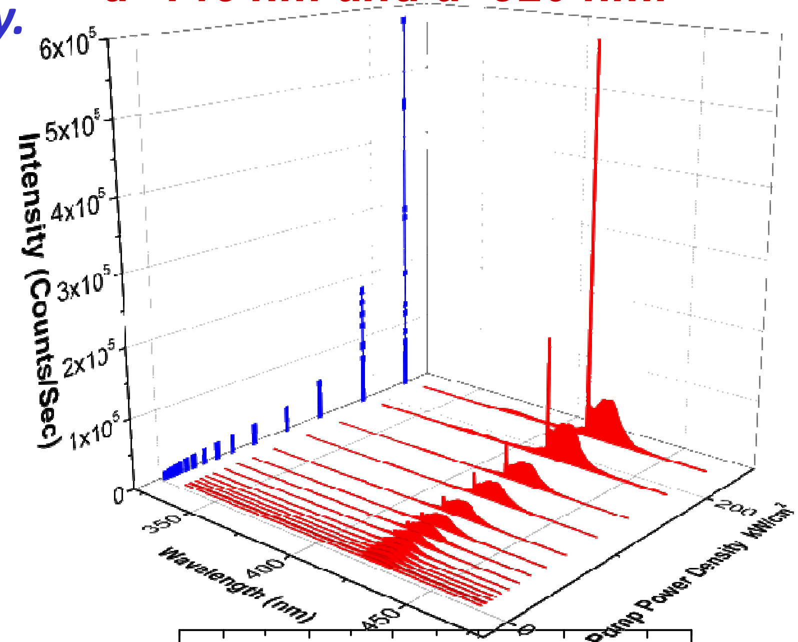
Wet etch using KOH process

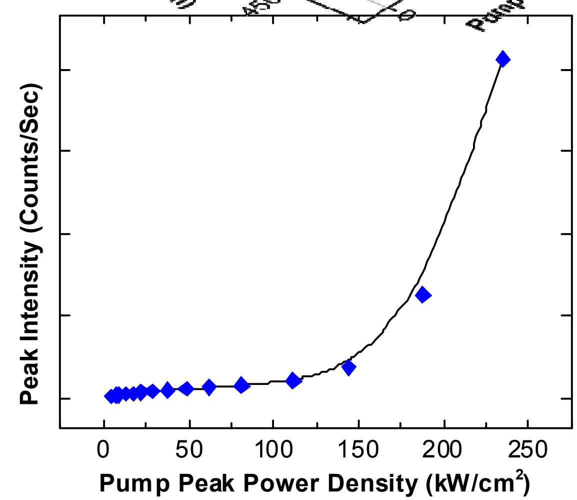
Optical response – low threshold lasing

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

Pump spot is tunable in size and power density.





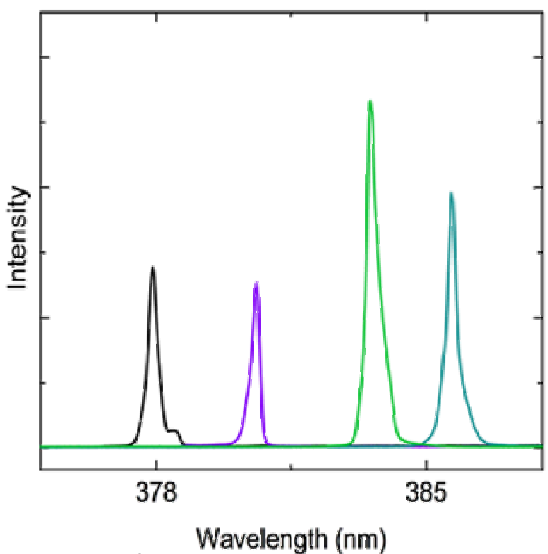


A low lasing threshold is achieved with < 500kW/cm2 for all PC lasers fabricated.

Results

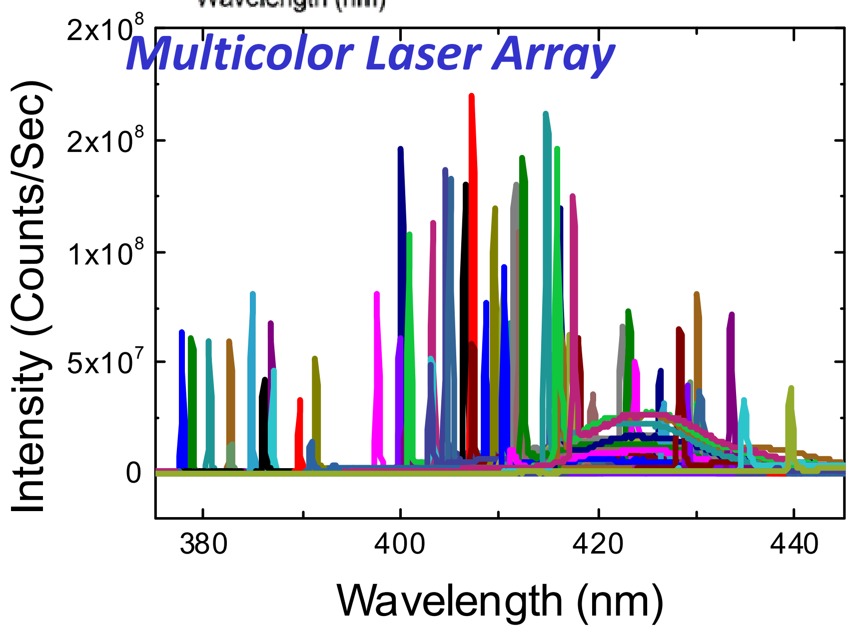
Sandia National Laboratories

Gain from multiple gain sections



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

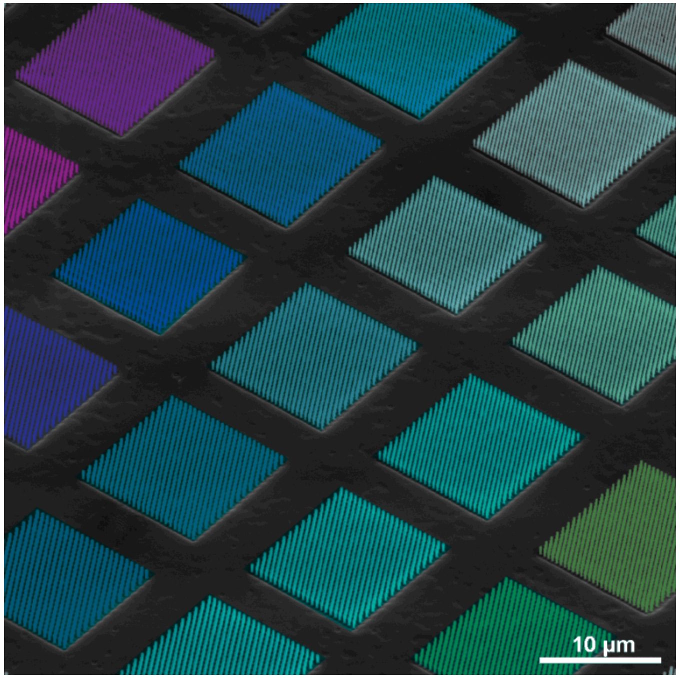
Multicolor Laser Array



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

Summary and Outlook

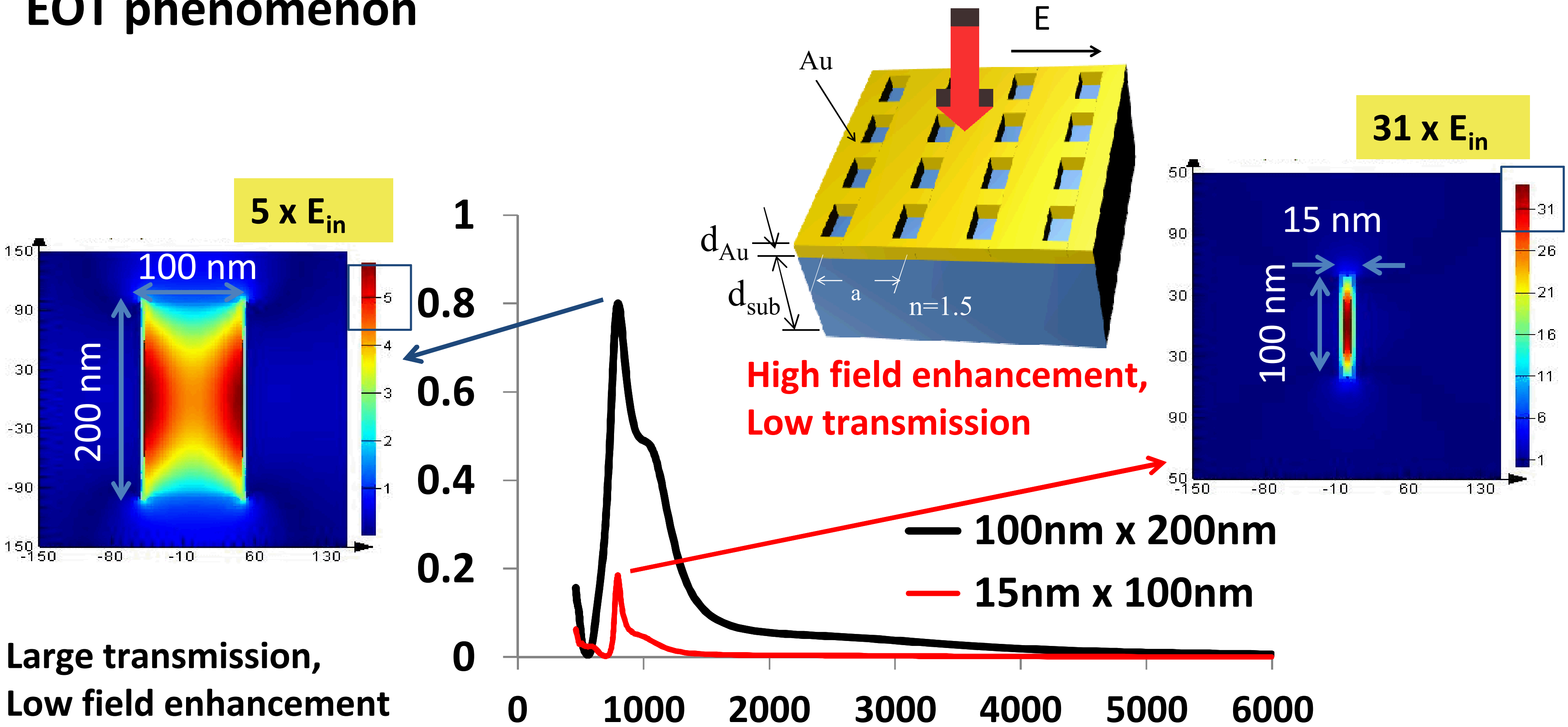
- ***Laser arrays that span a broad spectral range***
- ***Near-vertical single-mode emitters***
- ***Low thresholds with optical pumping with wavelength tunability***
- ***Possible to fabricate high density of emitters with a larger wavelength span***
- ***Potential extension of lasing spectral range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



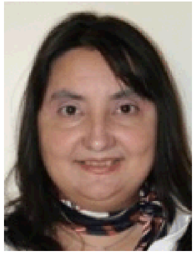
Energy Transport through Ultra Sub-wavelength Channels

Current approach : Surface plasmon based using EOT phenomenon

Resonant



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

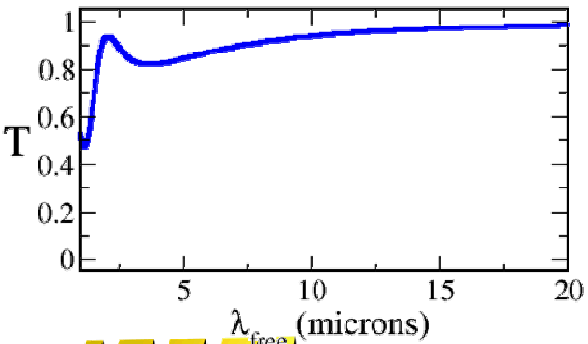


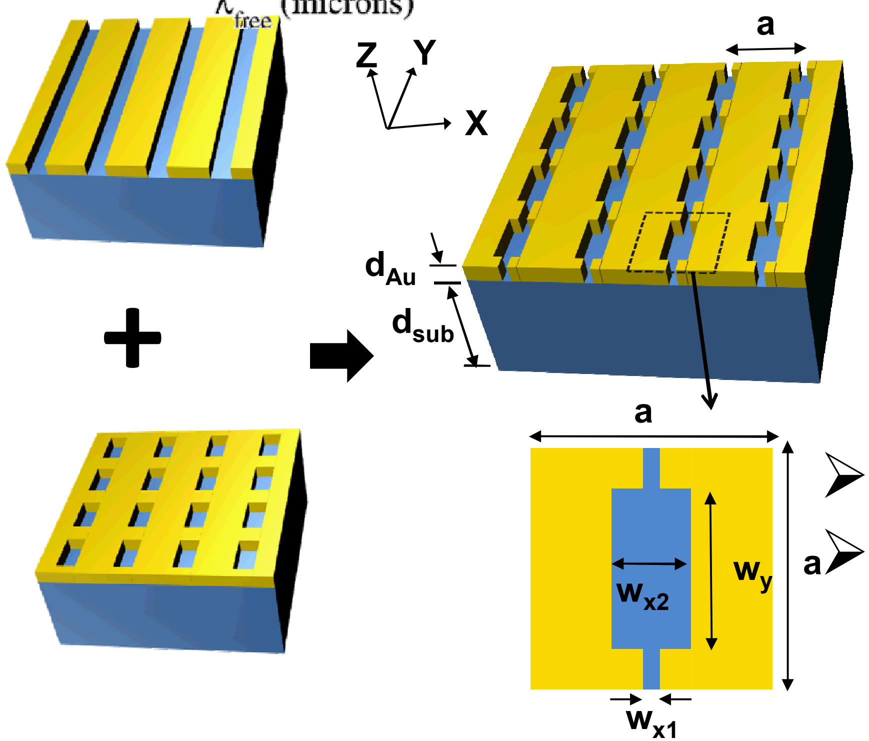
The Double-groove Structure

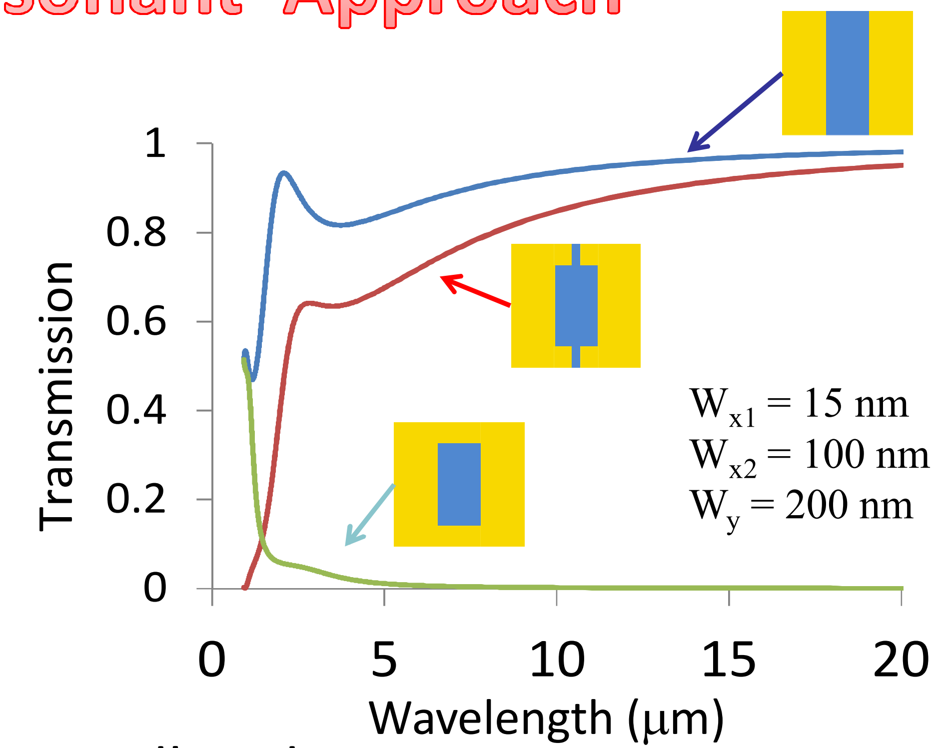
(In collaboration with S. Foteinopoulou- Univ. of Exeter, UK)

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

Non-resonant Approach

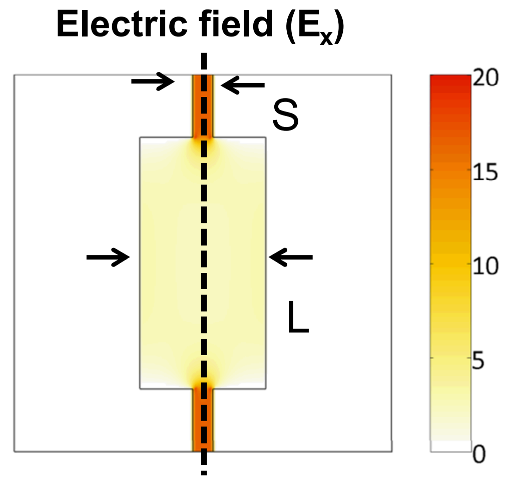


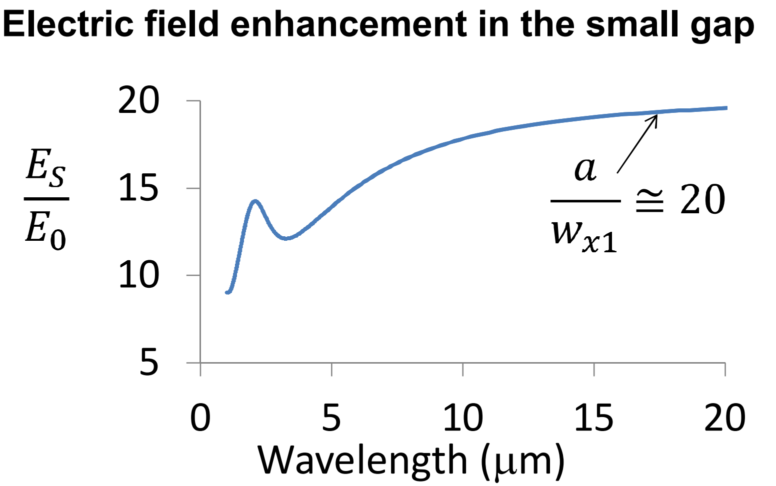




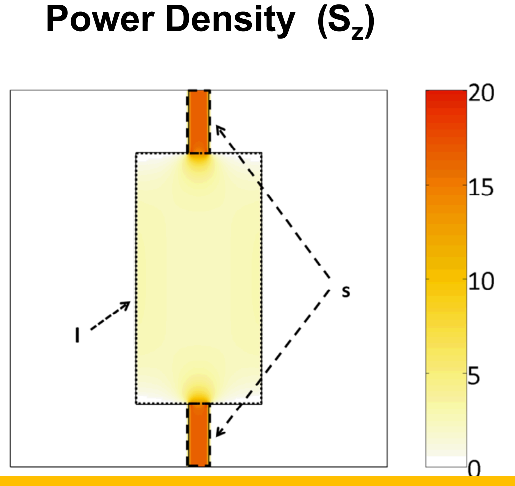
- Broadband transmission
- Large electric field enhancement and confinement

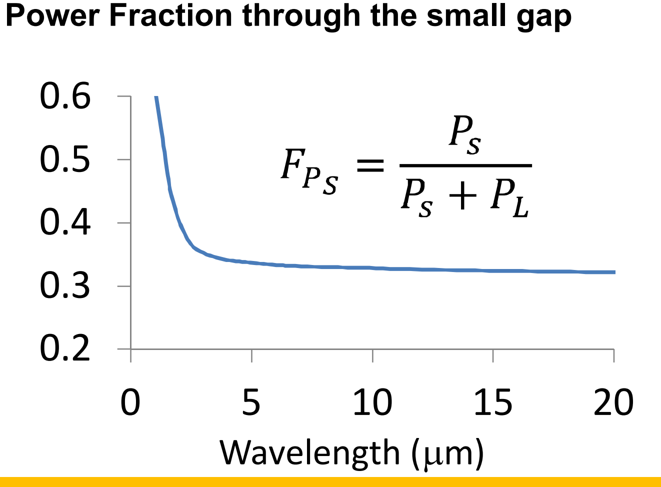
Key Results





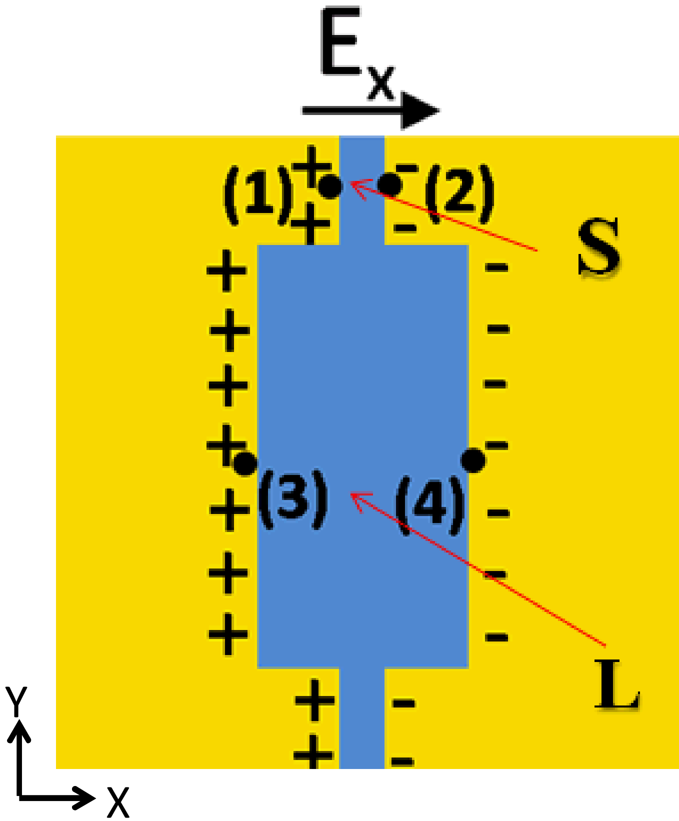
We can achieve large electric field enhancements in an ultra-subwavelength area (**~ (λ/250)^2**) across broadband that can be controlled via structural geometry





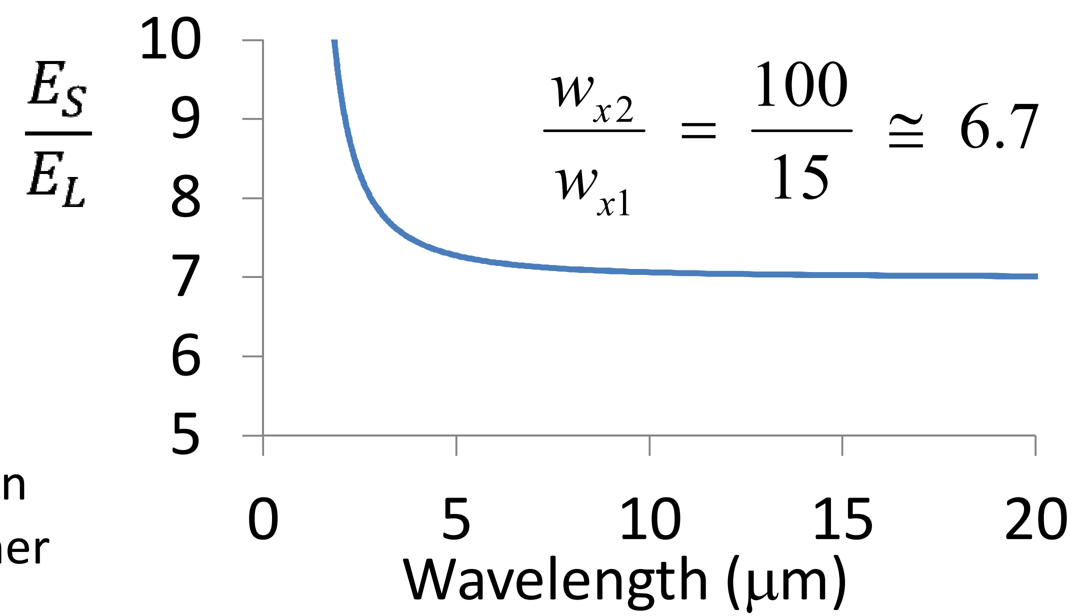
Surprisingly, nearly 30% of the transmitted power that is channeled through an area **~ (λ/250)^2** that is **1/60th** of the unit cell area.

Mechanism: Quasi-static response



- Voltage across the small and large gaps are nearly equal

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

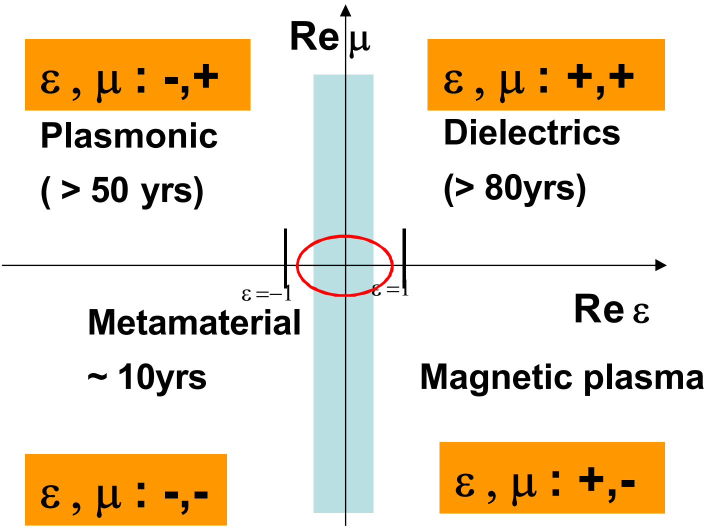


- Near-instantaneous response of charges even at mid-IR
- No effective current flow between small and large gap region on either side

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

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.

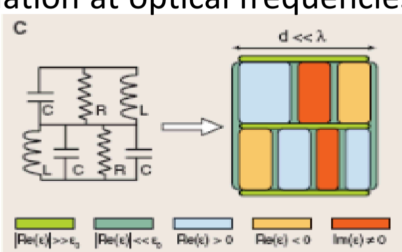
- $\underline{D} = \varepsilon\, \underline{E} \sim 0$ for $\varepsilon \sim 0$
- $V_p \rightarrow \infty$; No phase variation
- DC behavior at optical frequencies

Properties

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

Optical Nanocircuits

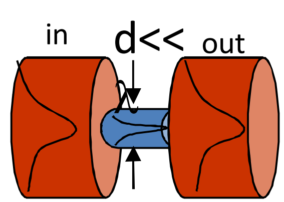
Vacuum light guiding, electrical isolation at optical frequencies



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

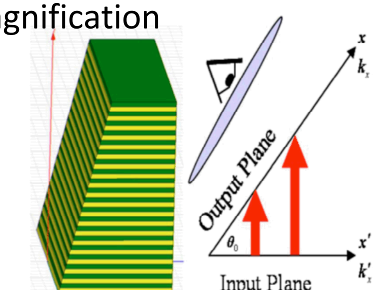
Supercoupling

Light squeezing through sub-wavelength channels



Subdiffraction Imaging

Far field subwavelength magnification



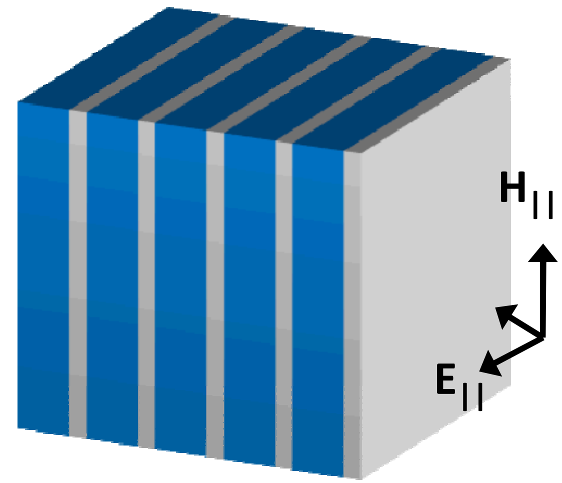
A. Salandrino and N. Engheta, Phys. Rev. B. 74, 075103(2006)

Effective Medium Approach to ENZ

Sandia National Laboratories

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

dielectric (ε_{+}), metal (ε_{-})



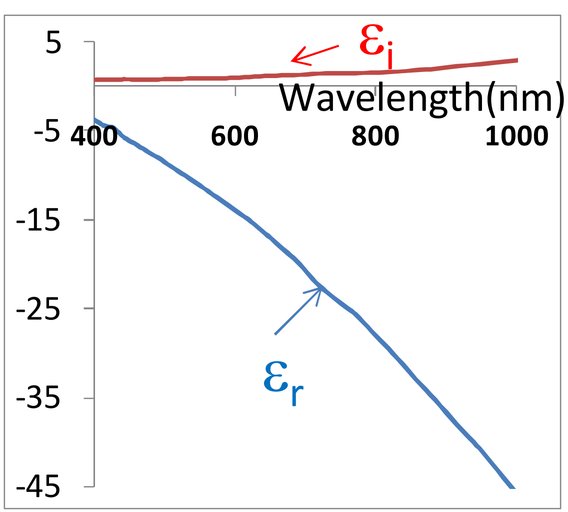
Goals

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

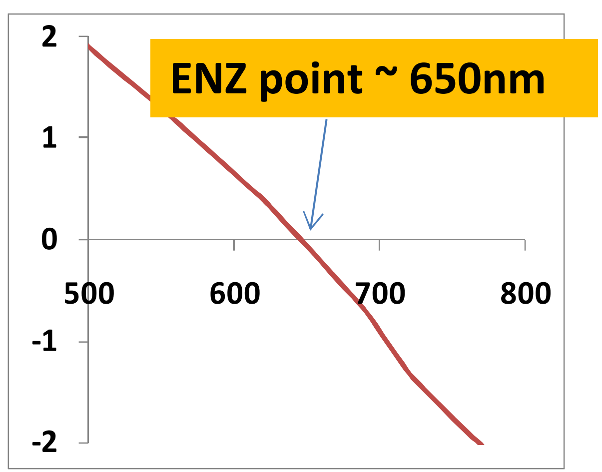
Materials Choice ε_{-} : Ag and **ε_{+} : TiO_2**

Ag (23%) + TiO_2 (77%)

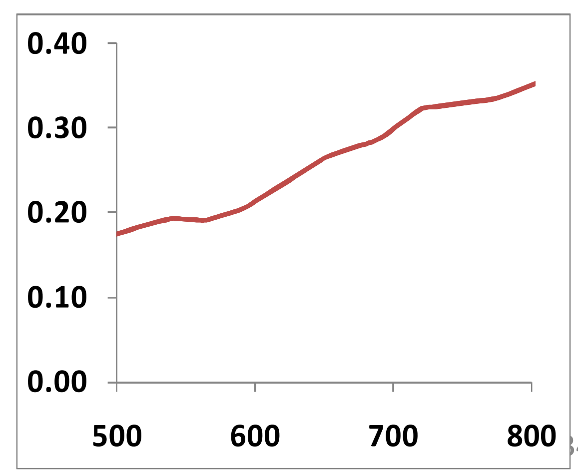
Silver(Ag)dispersion (Palik)



Composite-ε_{real}



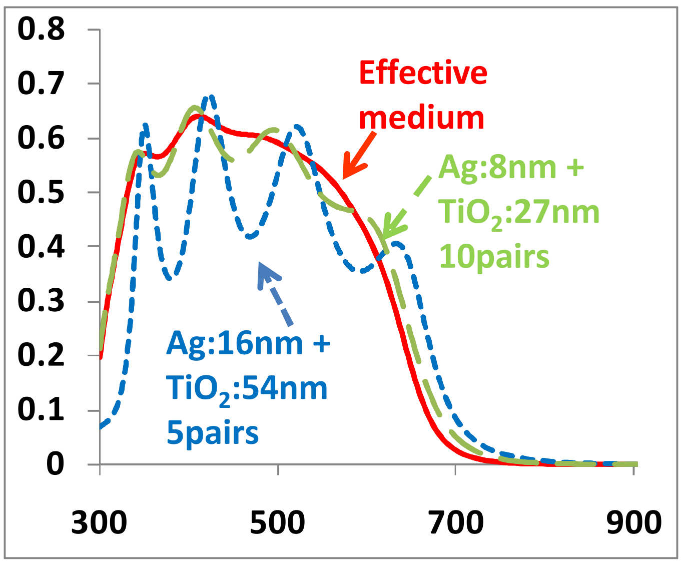
Composite-ε_{imag}



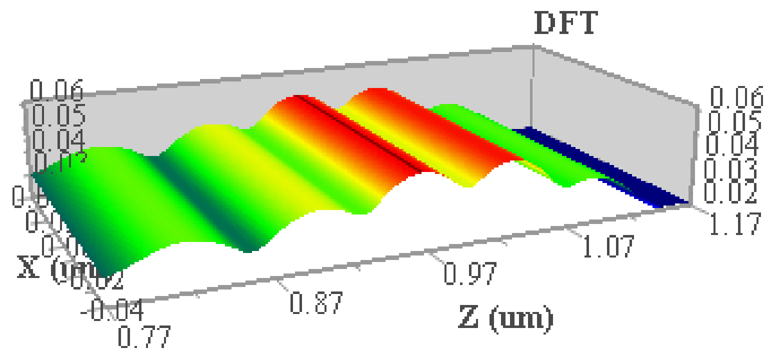
Effective Medium Multilayer Comparison

Finite Difference Time Domain Simulation

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

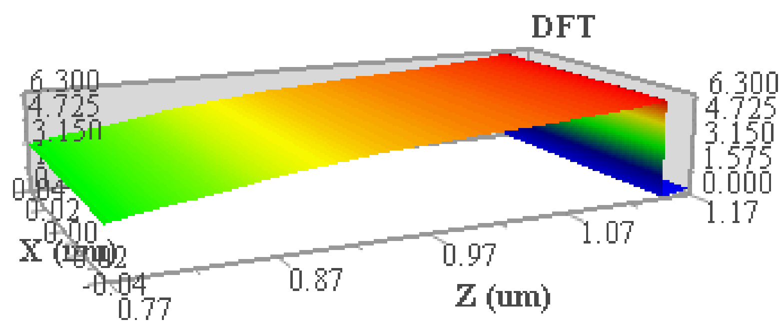


E field amplitude at ~ 653nm , ENZ point



E field phase at ~ 653nm , ENZ point

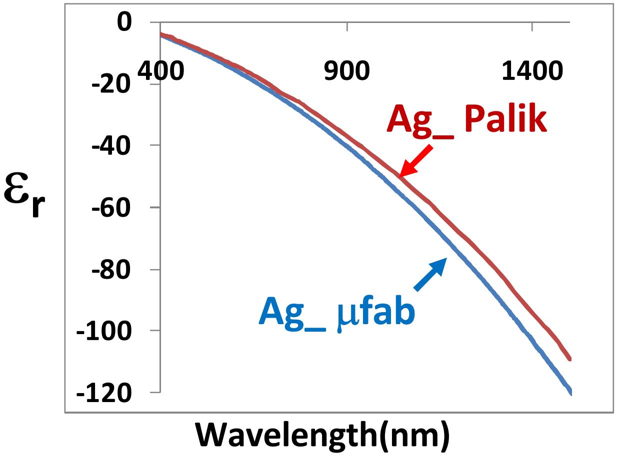
Small Phase Change

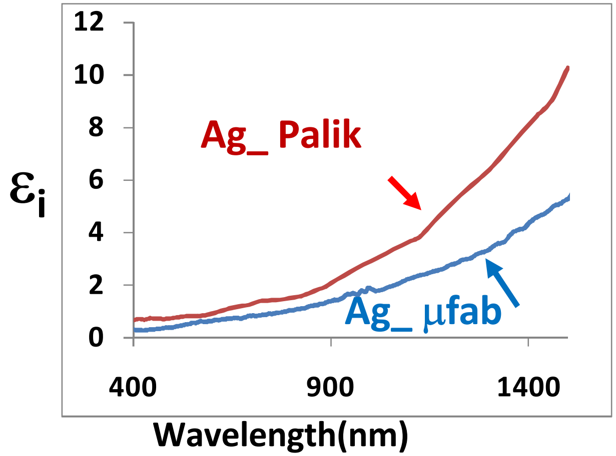


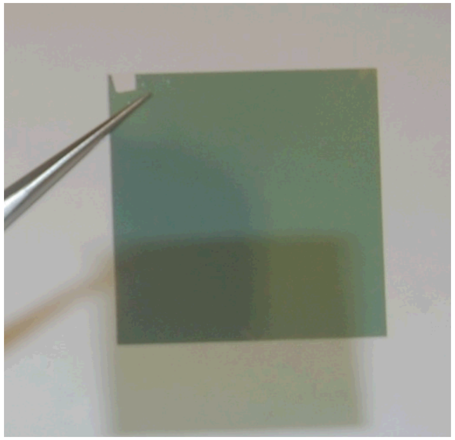
Ag thickness was chosen to be 16nm to obtain a continuous film using e-beam evaporation while remaining as thin as possible.

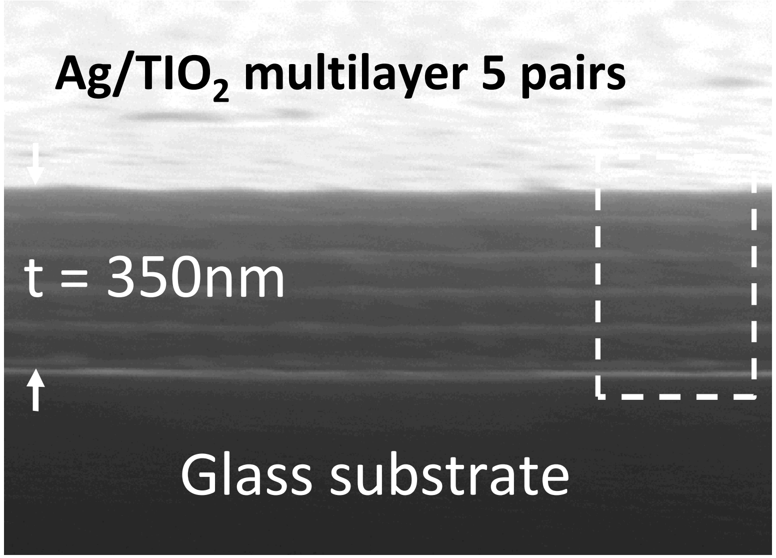
ENZ Sample Fabrication

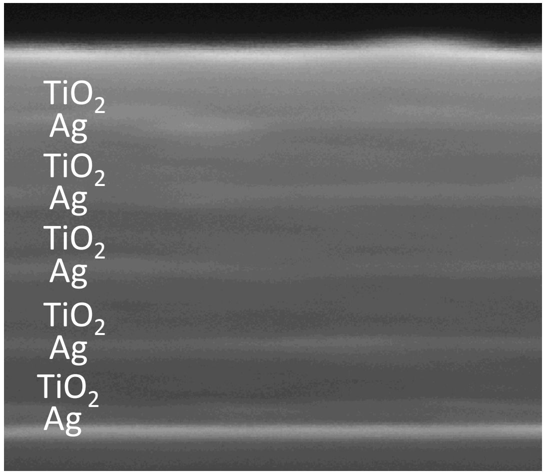
Electron beam evaporation of alternating layers of Ag and TiO_2









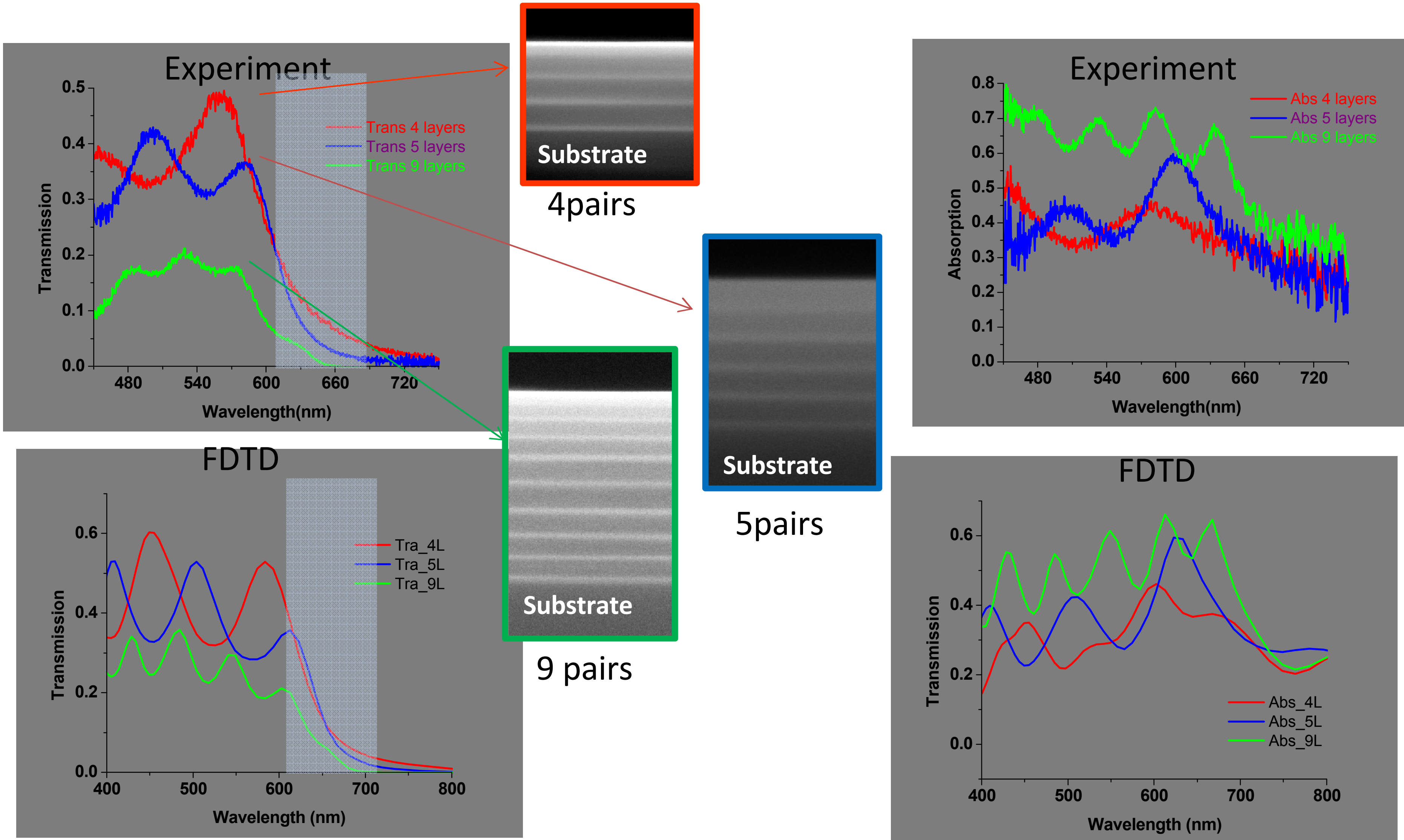


TiO2 = 54nm

Ag = 16nm

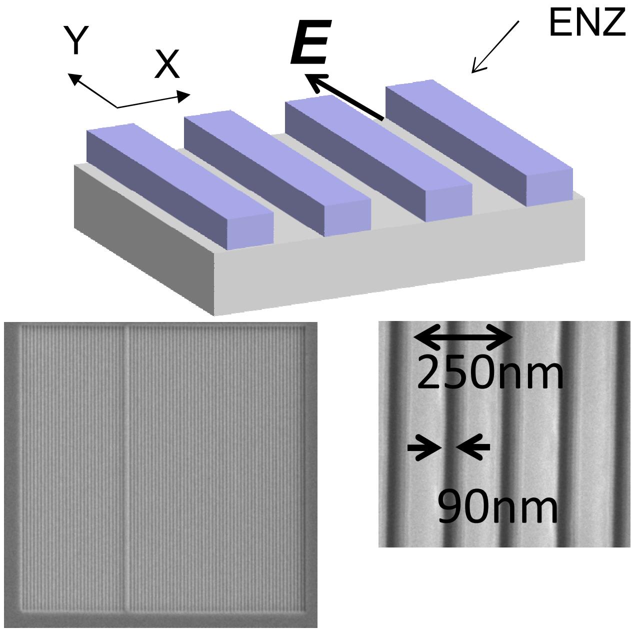
G. Subramania, A. J. Fischer, T. S. Luk – *Applied Physics Letters* **101**, 241107(2012)

Optical Characterization and FDTD Simulations



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

Approach to Reducing Metal Absorption effects

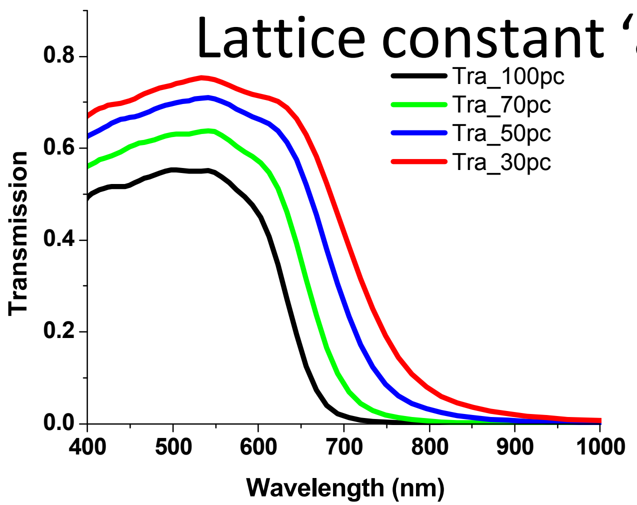


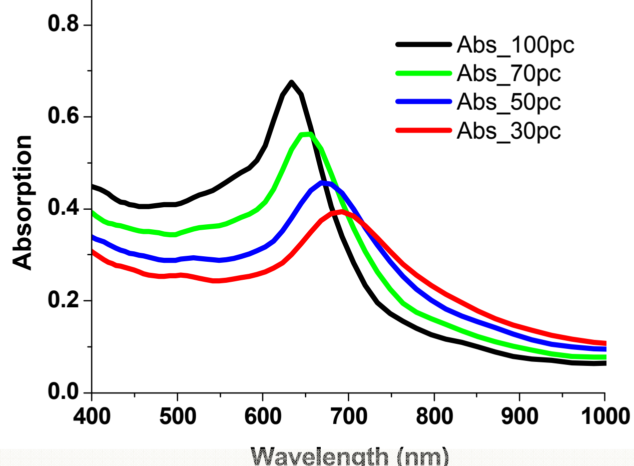
dielectric

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

- 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.

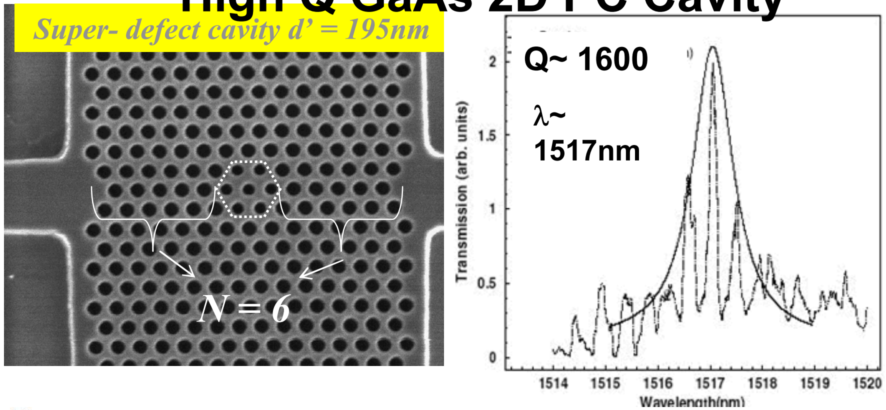
Thank you for your attention!

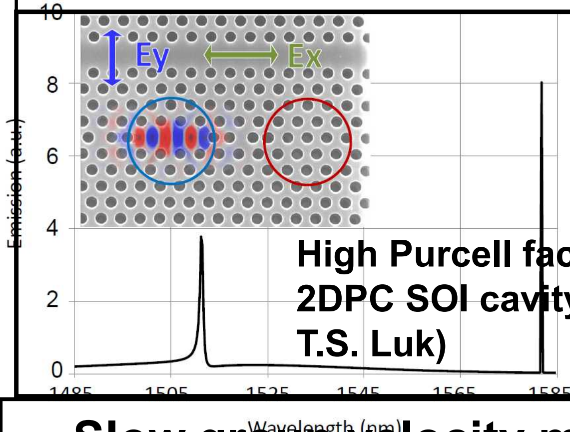
Backup slides

L-M Interaction in 2DPC

Sandia National Laboratories

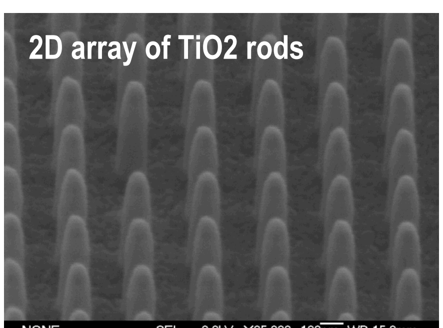
High Q GaAs 2D PC Cavity

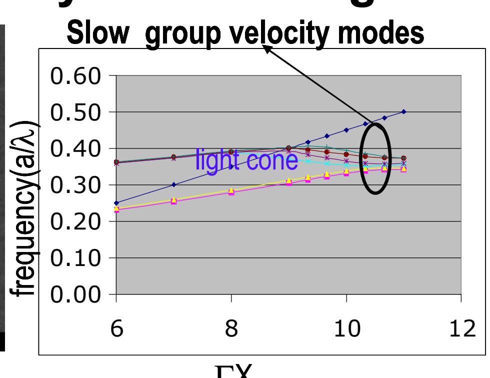




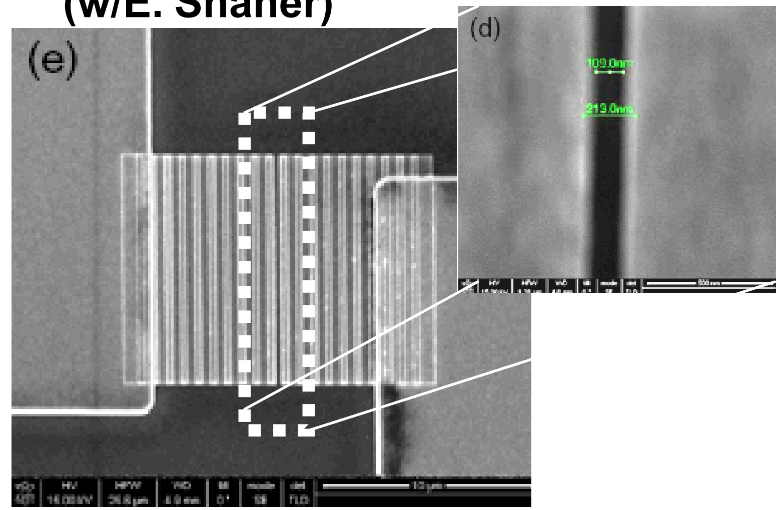
High Purcell factor 2DPC SOI cavity (w/ T.S. Luk)

Slow group velocity mode lasing

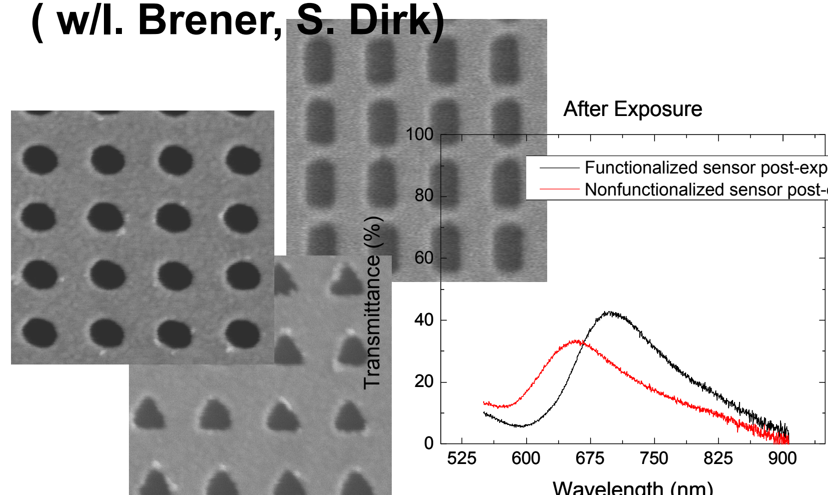




Surface plasmon Auston Switch (w/E. Shaner)

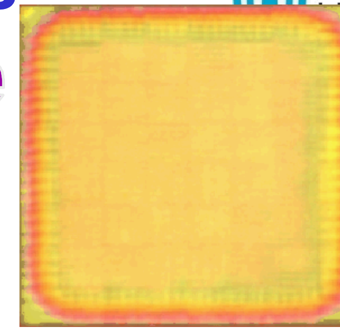


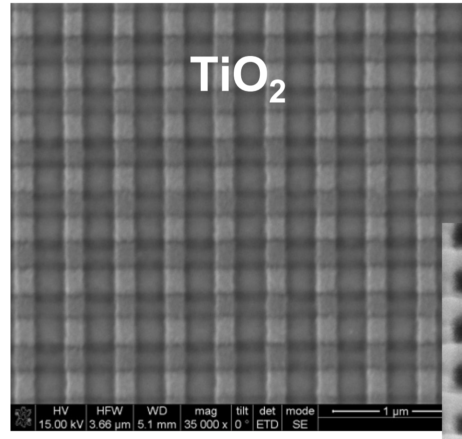
Nanhole EOT based sensors (w/I. Brener, S. Dirk)



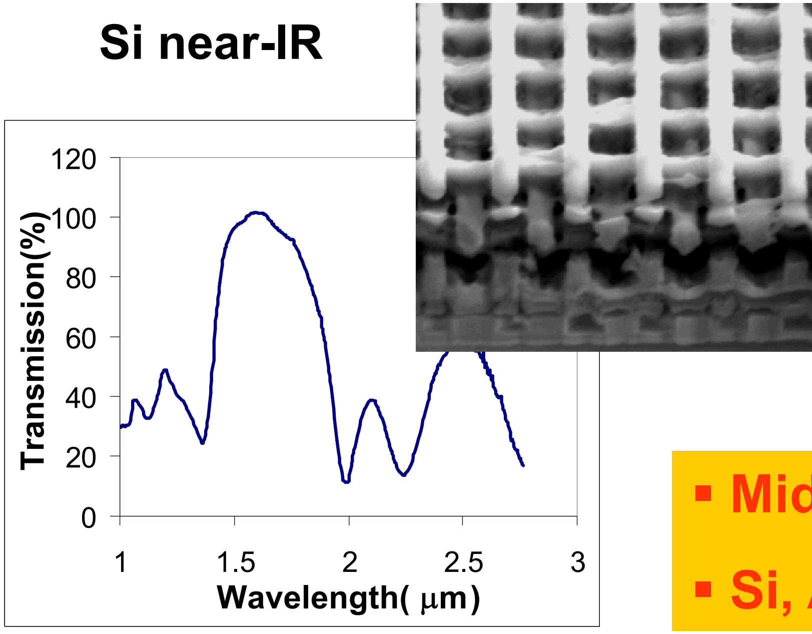
3DPCs: Wavelength, Materials

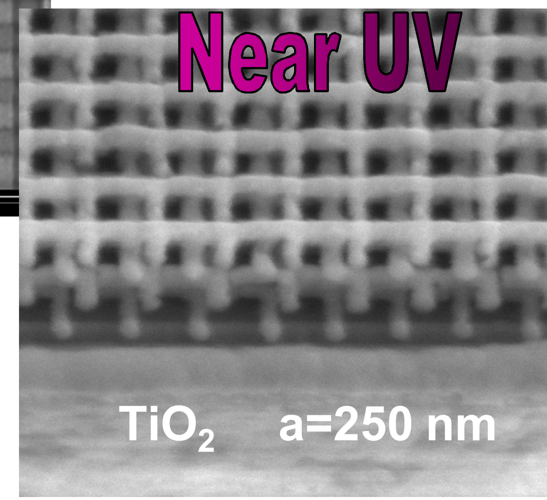
Visible



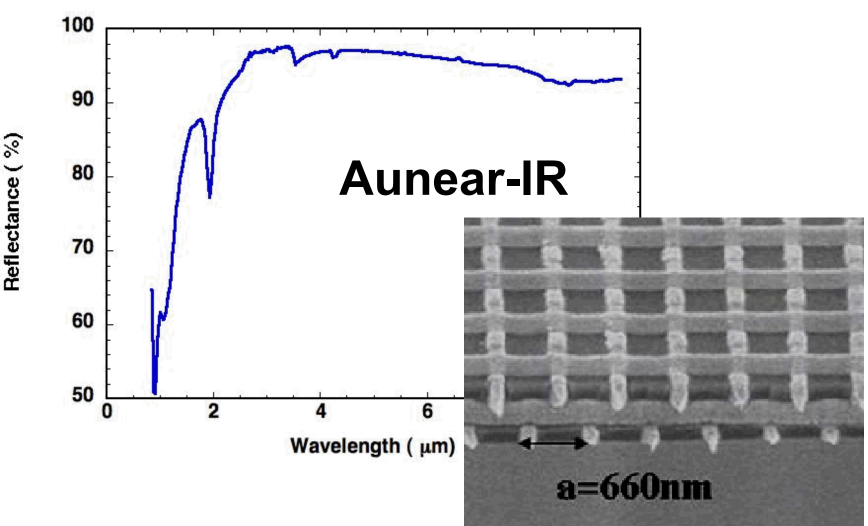


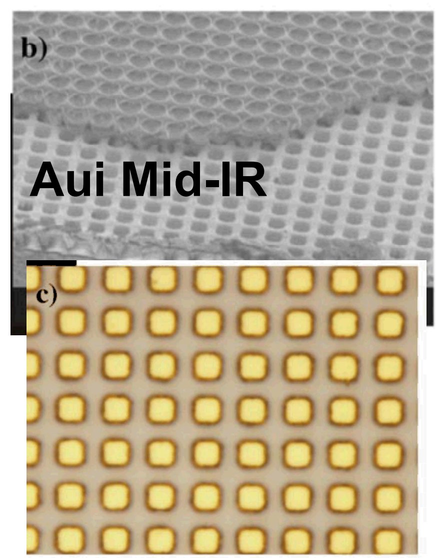
Si near-IR

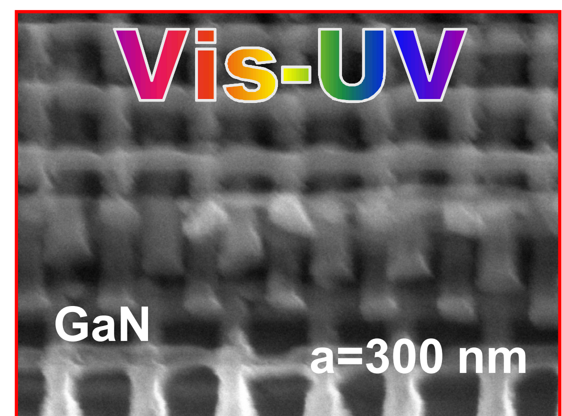




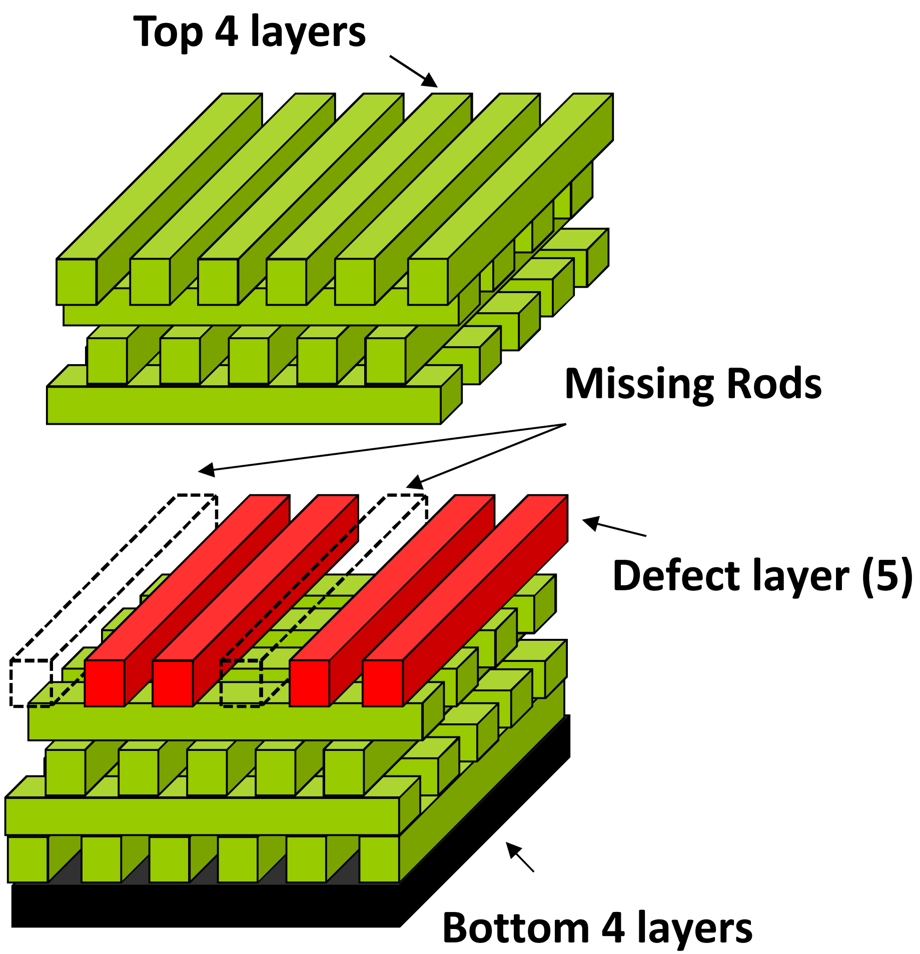
- **Mid IR to Near UV**
- **Si, Au, TiO2 and GaN**

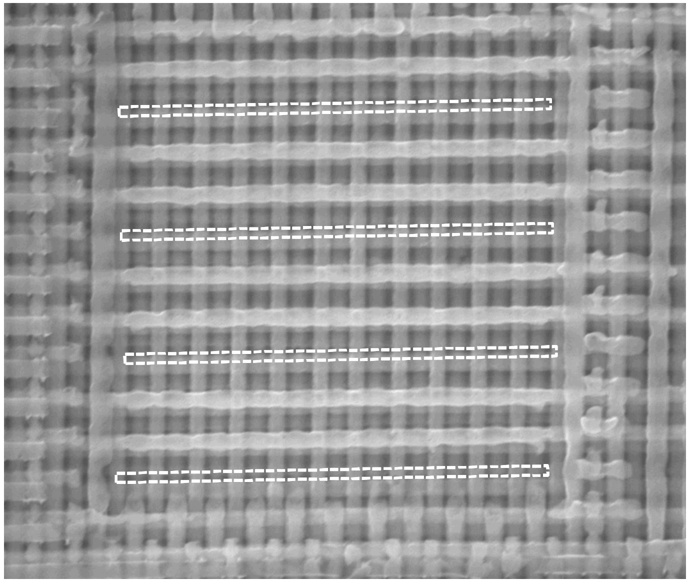


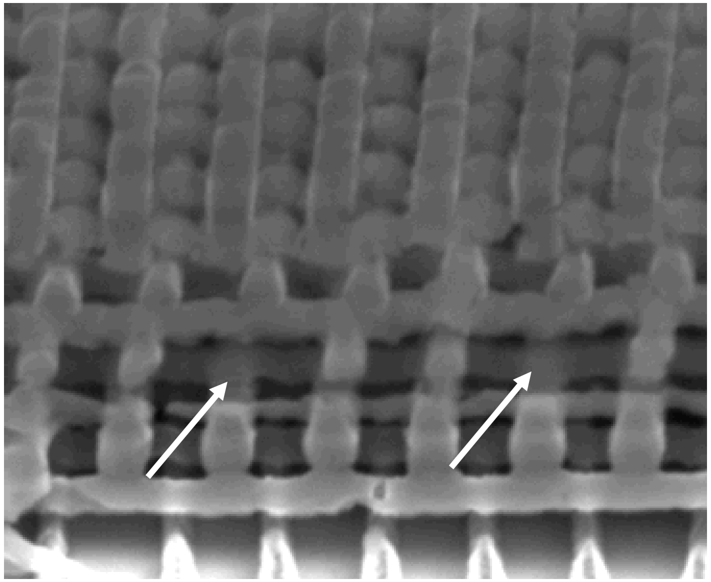




Logpile PC Cavity





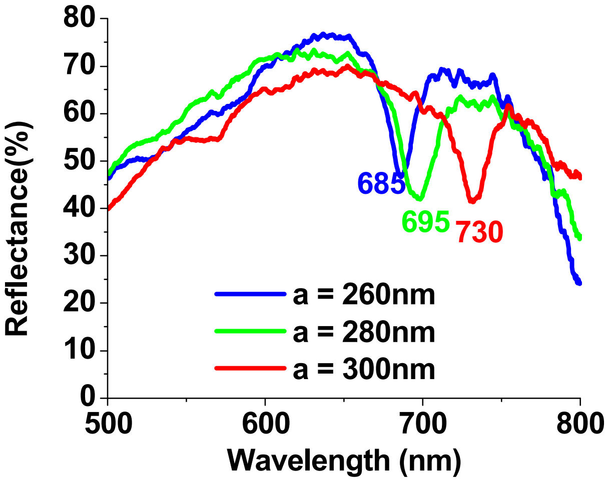


Logpile PC Cavity Optical Response

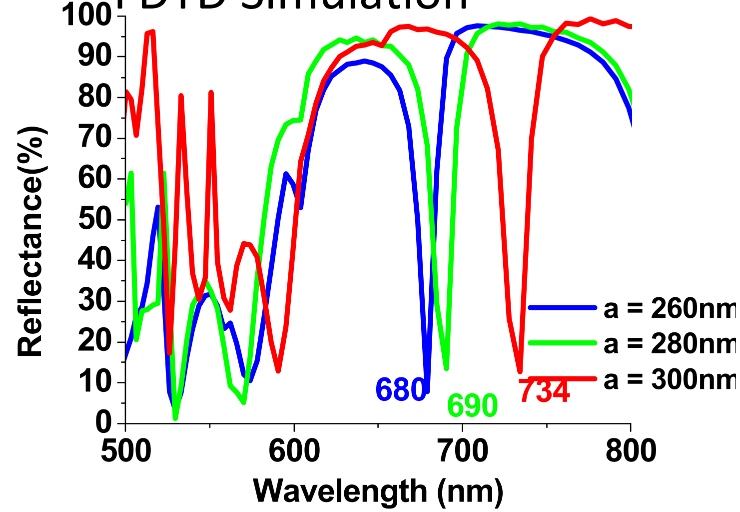
Sandia National Laboratories

Reflection

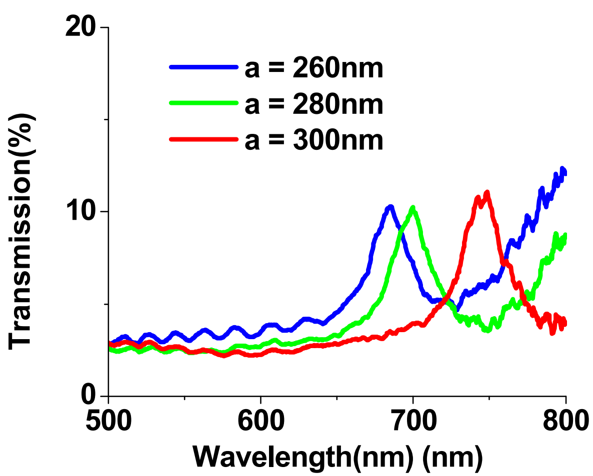
Experiment

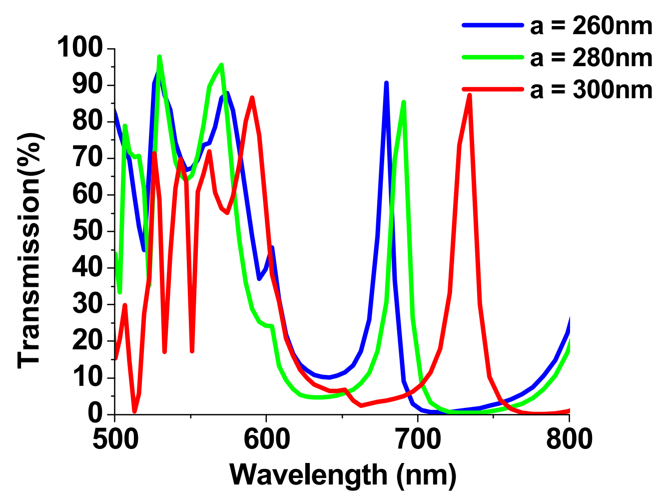


FDTD Simulation



Transmission

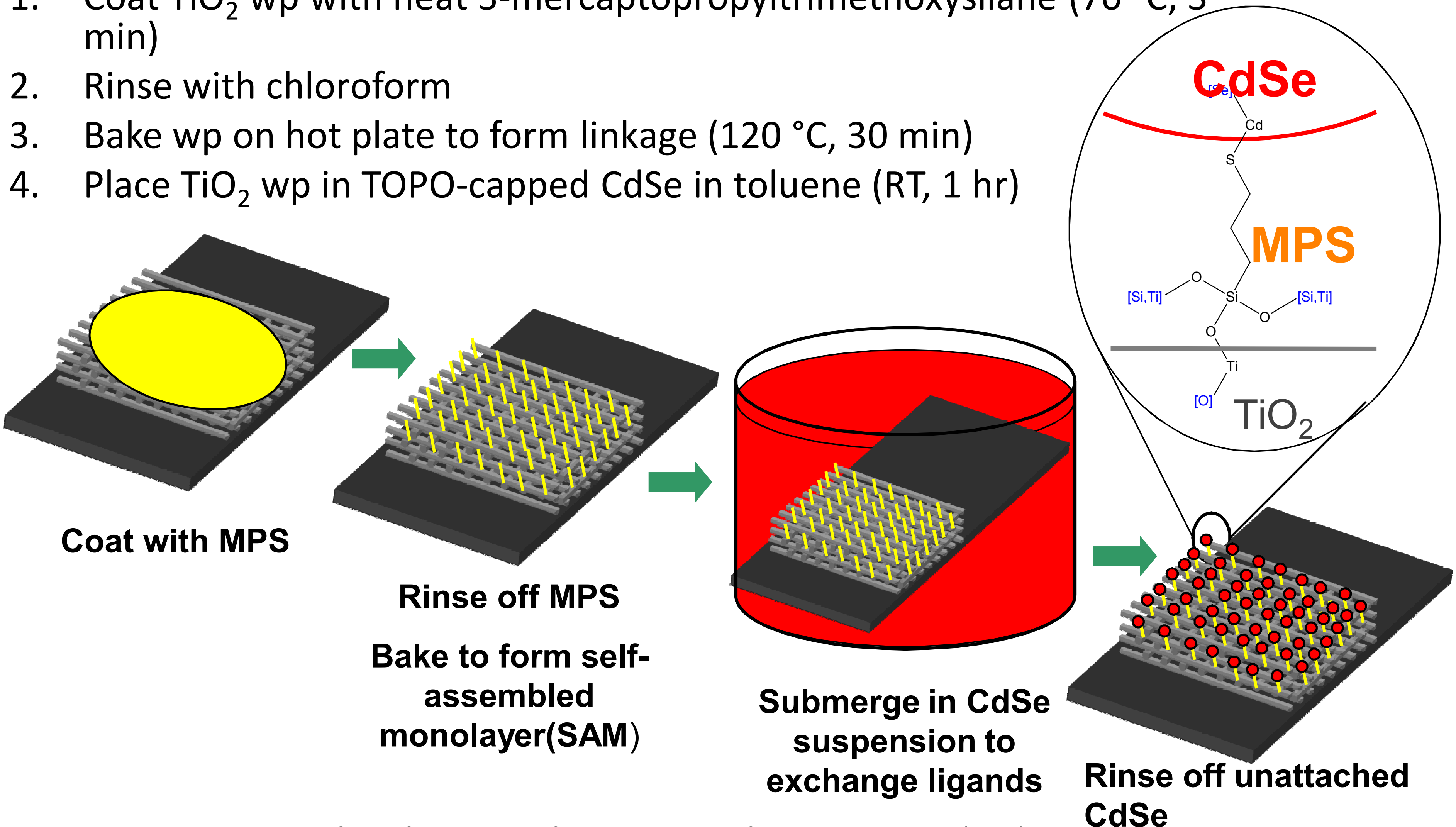




G. Subramania et. al. , Nano Lett. **11**, 4591 (2011).

Development of 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)

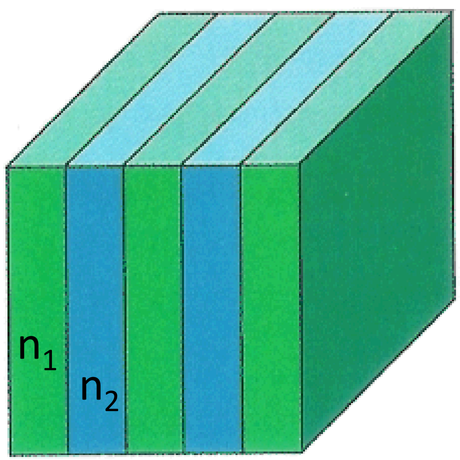


P. Guyot-Sionnest and C. Wang, J. Phys. Chem. B, **107**, 7355 (2003)
J. Pacifico, D. Gomez, and P. Mulvaney, Adv. Mater. **17**, 415 (2005)

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

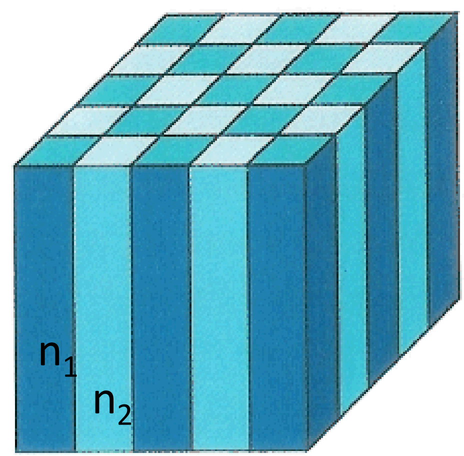
Sandia National Laboratories

1-D



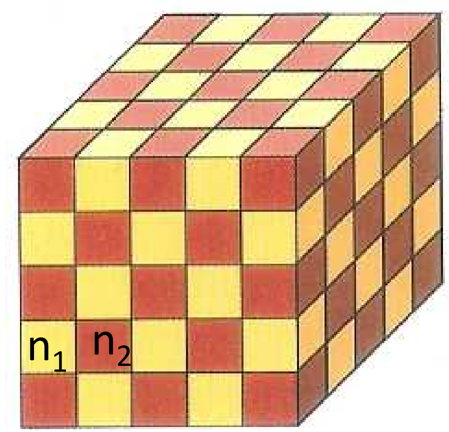
Periodic in 1 dimension

2-D

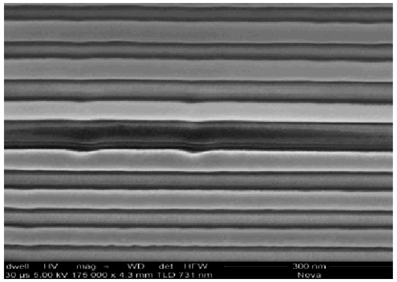


Periodic in 2 dimensions

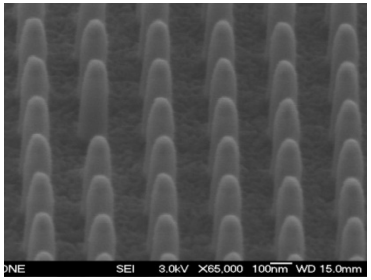
3-D



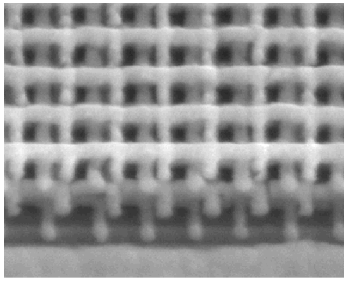
Periodic in 3 dimensions



HfO_2/SiO_2 DBR cavity

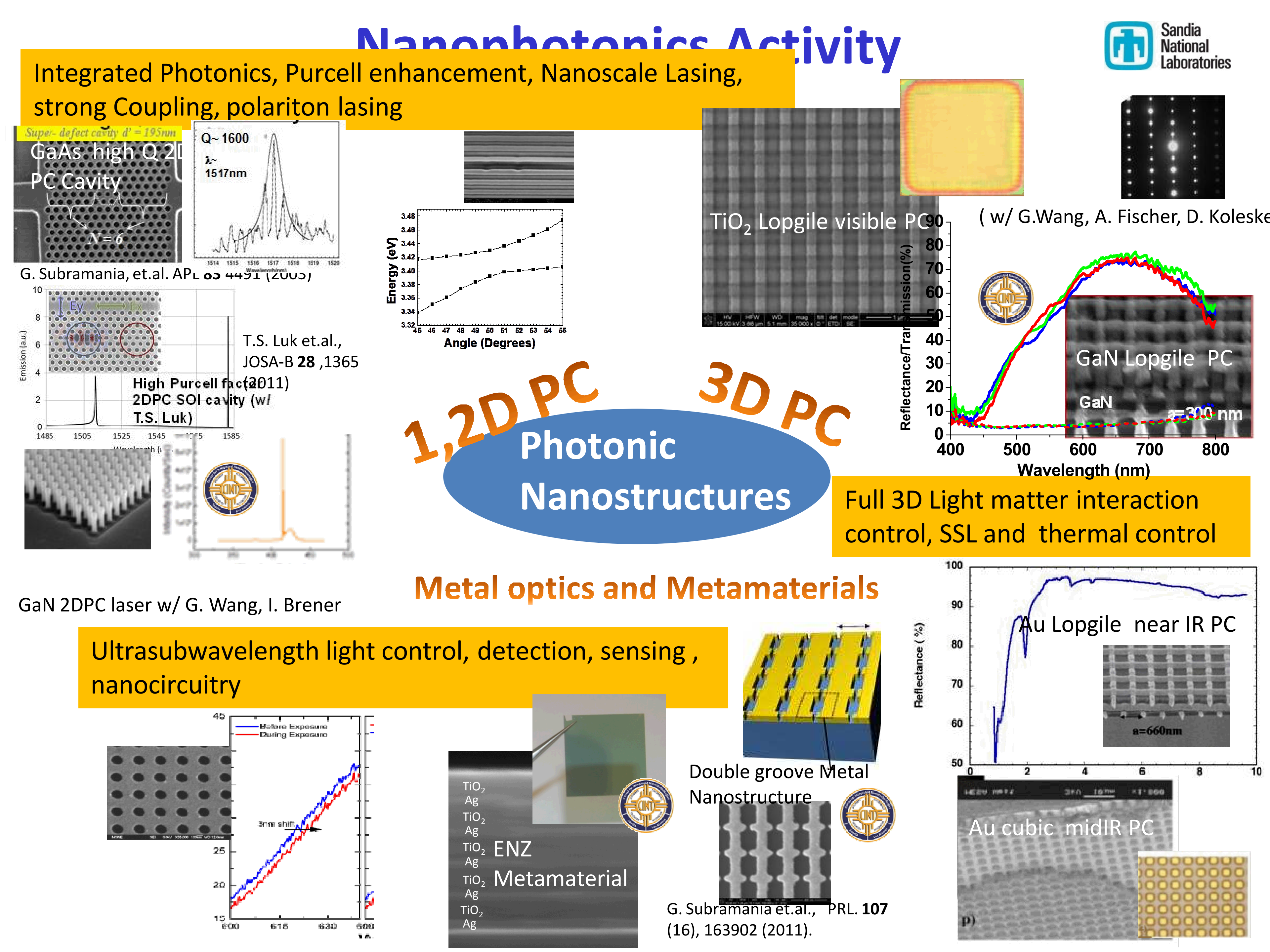


Array of TiO_2 rods



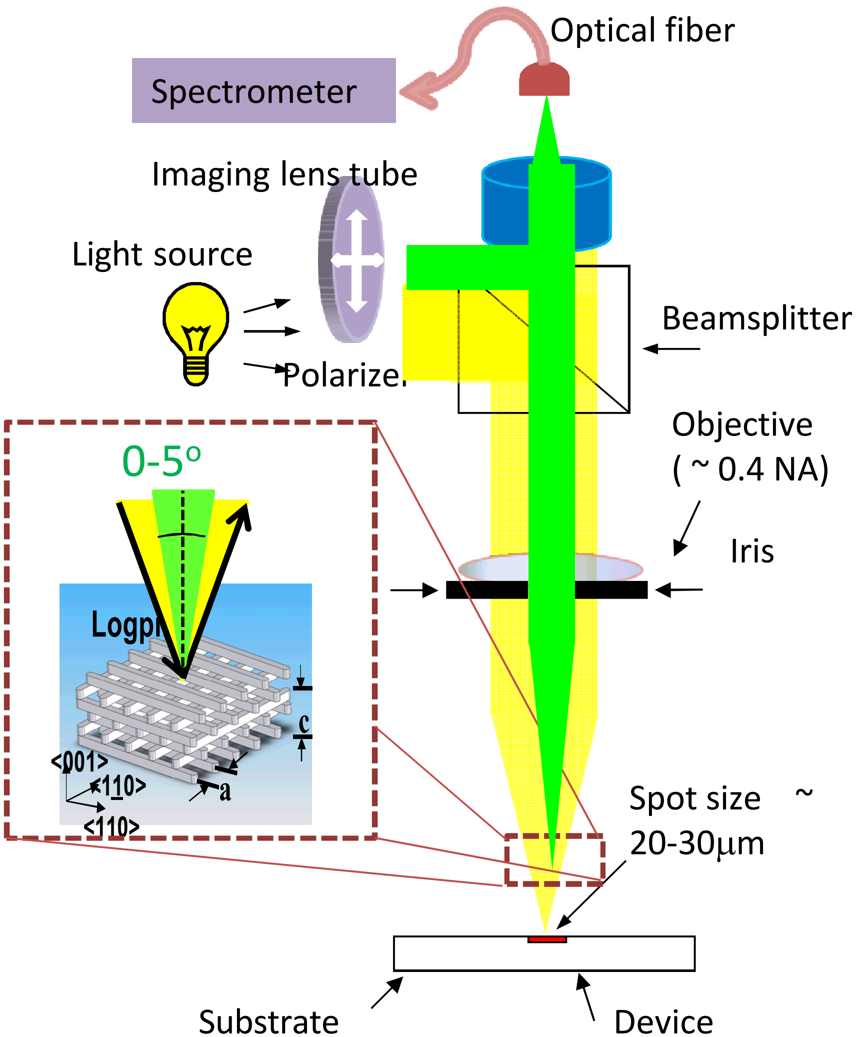
TiO_2 logpile PC

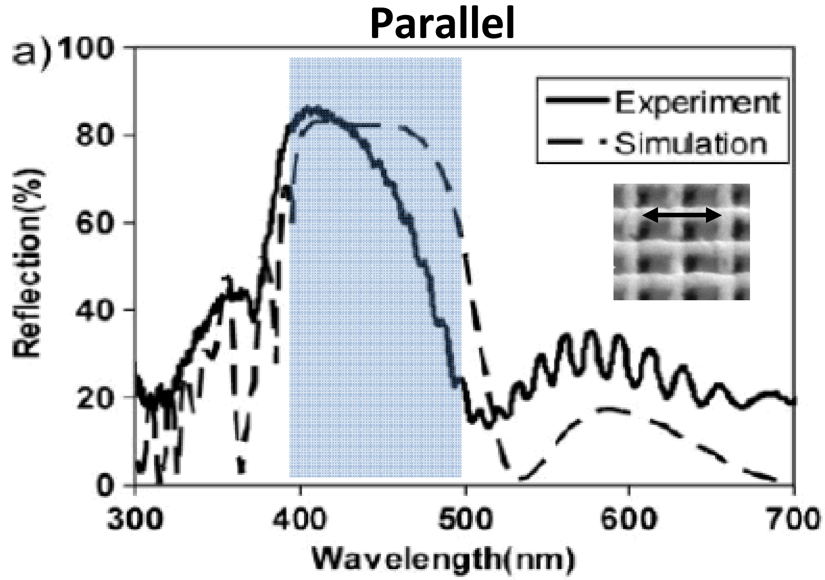
Reference: "Photonic crystals: Molding the flow of light", J.D. Joannopoulos, R.D. Meade, J. Winn, Princeton Univ.Press, NJ(1995)

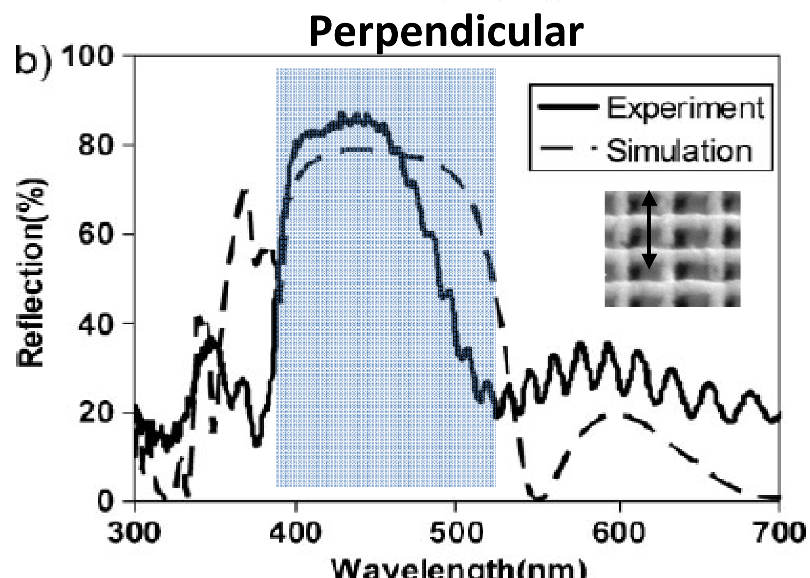


Nanophotonics Activity
Sandia National Laboratories
Integrated Photonics, Purcell enhancement, Nanoscale Lasing, strong Coupling, polariton lasing
Super- defect cavity d' = 195nm
GaAs high Q 2D PC Cavity
N = 6
Q~ 1600
λ~ 1517nm
G. Subramania, et.al. APL 83 4491 (2003)
Energy (eV)
Angle (Degrees)
TiO2 Lopgile visible PC
(w/ G.Wang, A. Fischer, D. Koleske
Ey
Ex
T.S. Luk et.al., JOSA-B 28 ,1365 (2011)
High Purcell factor 2DPC SOI cavity (w/ T.S. Luk)
Emission (a.u.)
1,2D PC
3D PC
Photonic Nanostructures
Reflectance/Transmission(%)
GaN Lopgile PC
GaN
a=300 nm
Wavelength (nm)
Full 3D Light matter interaction control, SSL and thermal control
GaN 2DPC laser w/ G. Wang, I. Brener
Metal optics and Metamaterials
Ultrasubwavelength light control, detection, sensing , nanocircuitry
Before Exposure
During Exposure
3nm shift
TiO2
Ag
ENZ Metamaterial
Double groove Metal Nanostructure
G. Subramania et.al., PRL. 107 (16), 163902 (2011).
Reflectance (%)
Au Lopgile near IR PC
a=660nm
Au cubic midIR PC

Visible- Near UV 9 Layer TiO_2 Logpile

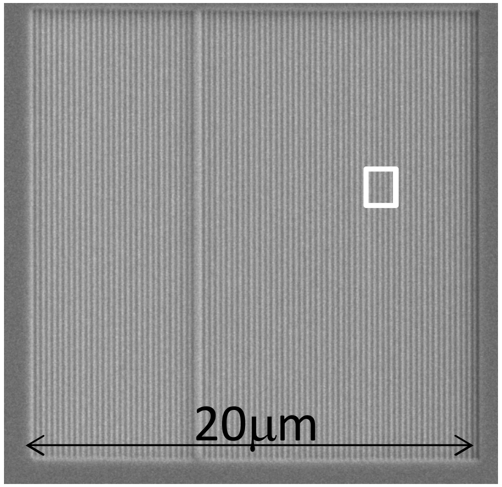


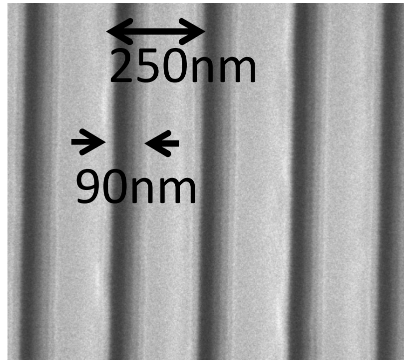




G. Subramania, Y.-J. Lee, A. J. Fischer, and D. D. Koleske, Advanced Materials **22**, 487-491 (2010)

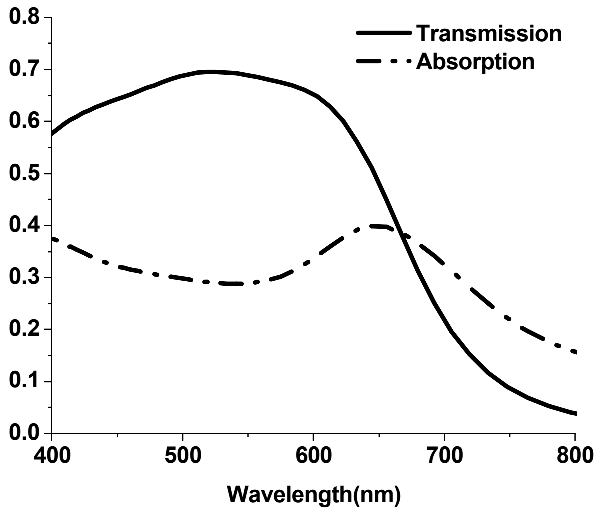
Fabrication - Characterization



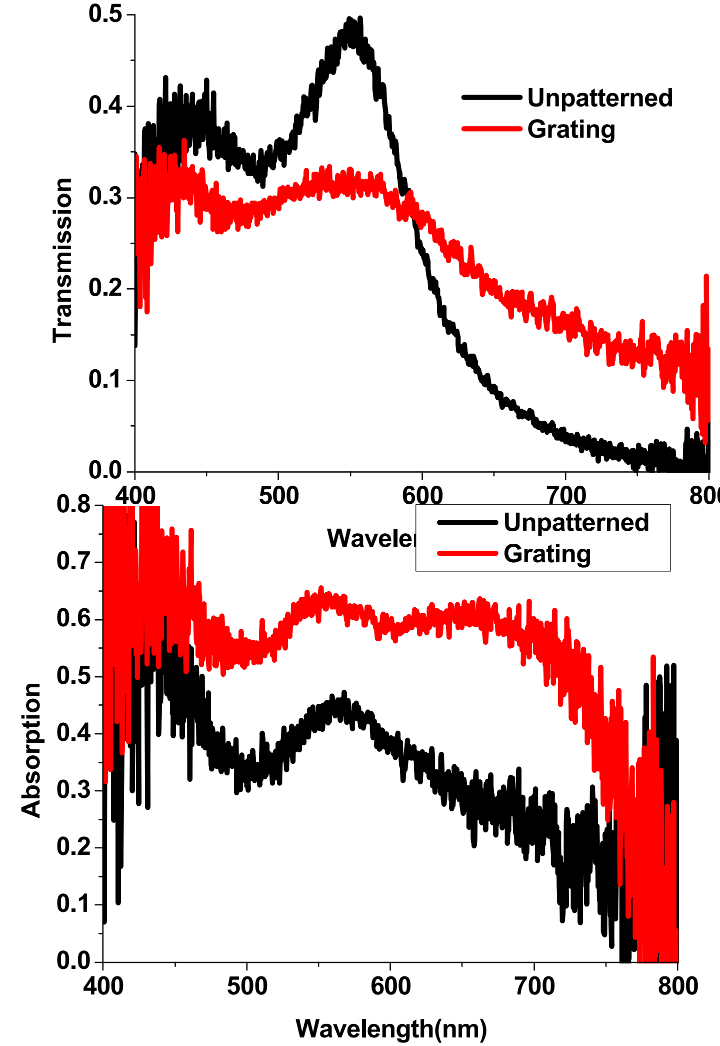


- Fabrication using Focused Ion Beam (FIB)

FDTD Simulation



Experiment



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

Band Structure Calculation

Solve Electromagnetic wave equation for Plane wave

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

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

In a periodic potential

$$\varepsilon(\boldsymbol{r} + \boldsymbol{R}) = \varepsilon(\boldsymbol{r})$$

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

Apply Bloch's Theorem

$$\boldsymbol{E}, \boldsymbol{H}(\boldsymbol{r} + \boldsymbol{R}) = \boldsymbol{E}, \boldsymbol{H}(\boldsymbol{r})$$

Plane Wave Expansion Method

Reciprocal (K) space

Reciprocal Lattice vector

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

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

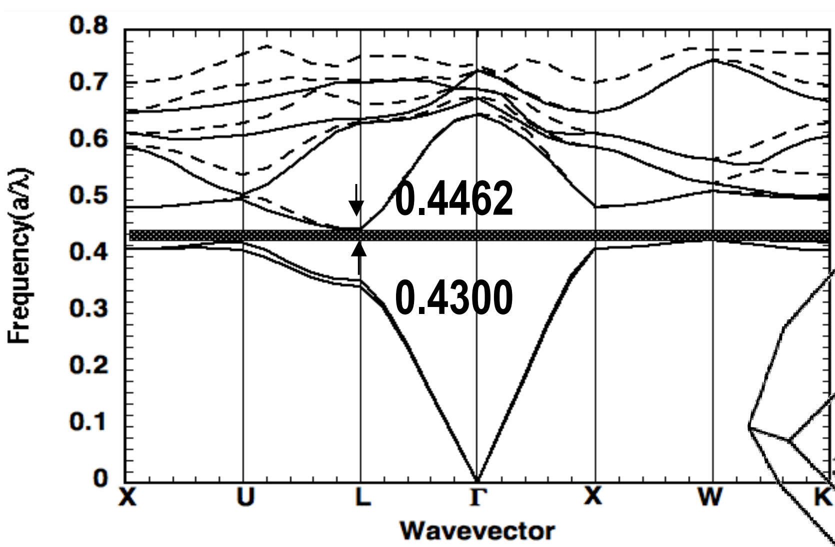
Eigen value equation

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

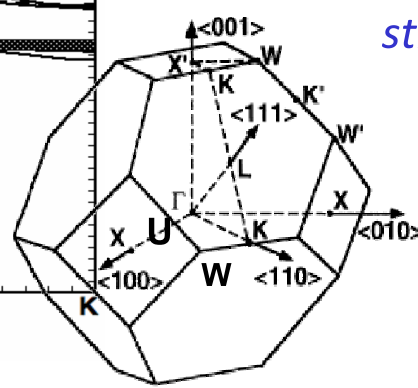
Band index

Wave vector within the first BZ

Photonic Band Structure for TiO_2 logpile



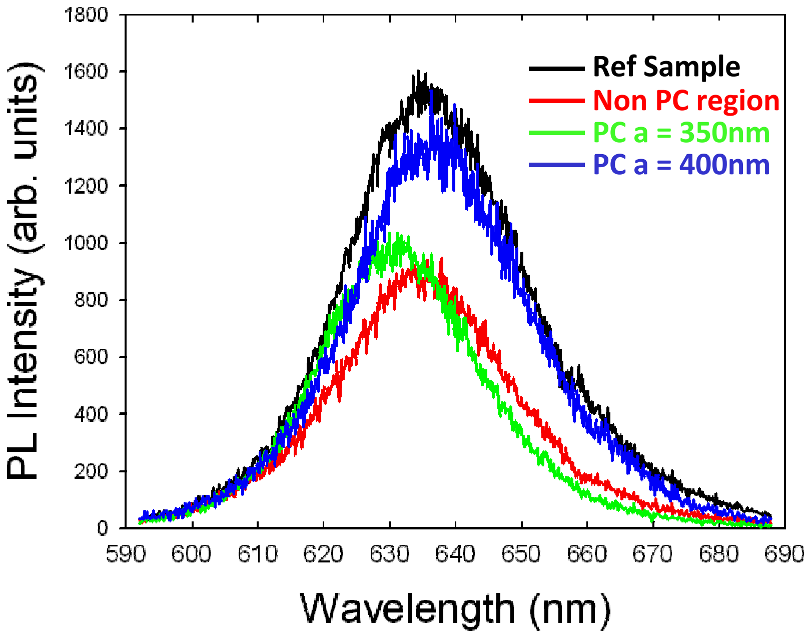
1st BZ

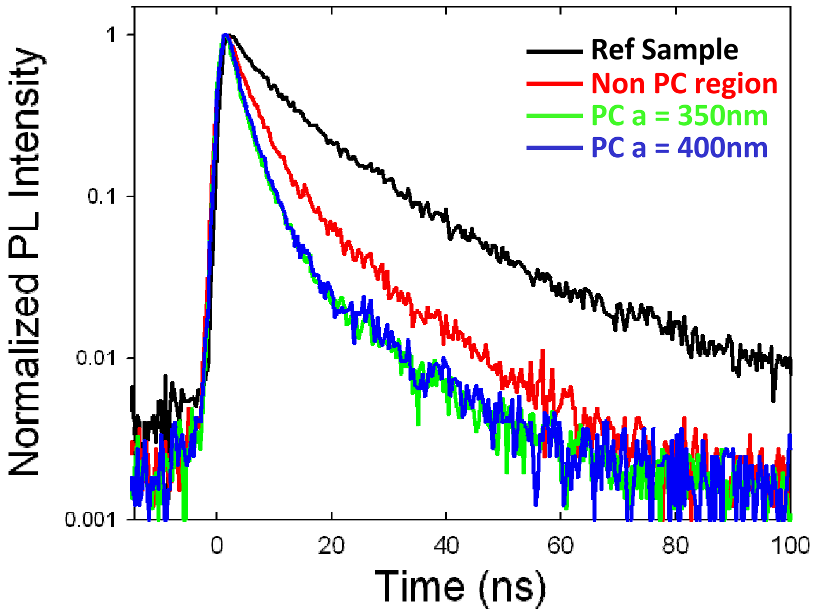


Eigen value equation becomes a matrix equation for which you can write a code and solve for band structure within the first Brillouin zone.

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

Emission Lifetime Measurements - TRPL

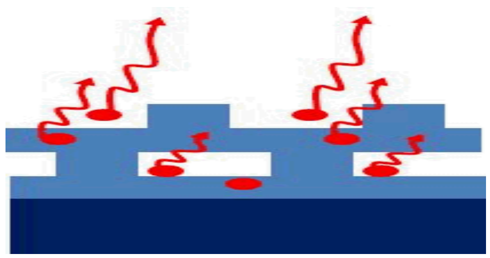




- Conditions: 380 nm pump, 4 MHz, 20 uW average power, 10 mm aperture
- Emitter wavelength ~ 640nm

- **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**