

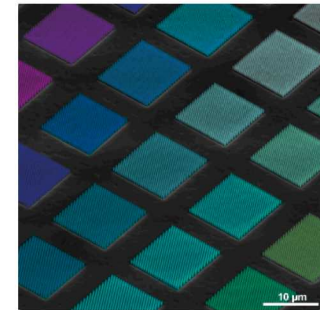
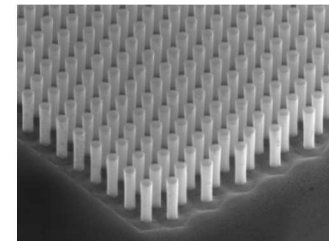
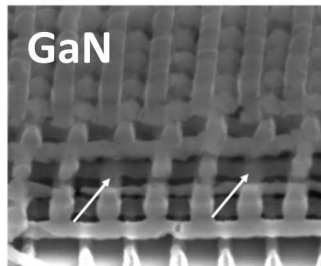
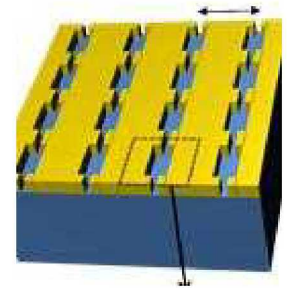
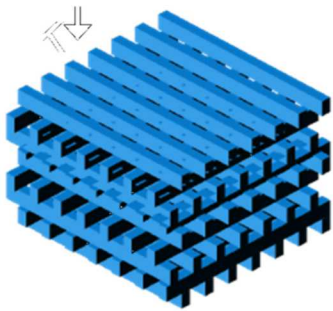
Nanophotonics for Tailoring Propagation, Emission and Topological behavior of Light

Ganapathi Subramania

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Sandia National Laboratories, Albuquerque, NM

OSI-ISO 2018

IIT, Kanpur, India 19-22 Sep, 2018



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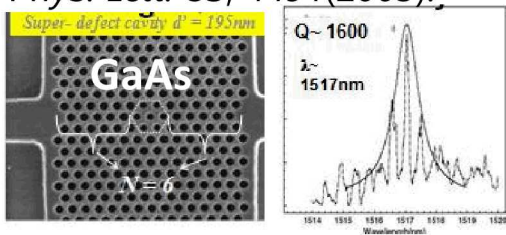
Nanophotonics Activity

Integrated Photonics, Nanoscale lasing, Emission control, Solid State lighting, Energy conversion, Non-classical light sources, Subwavelength light control, Detection, Sensing , Nanocircuitry

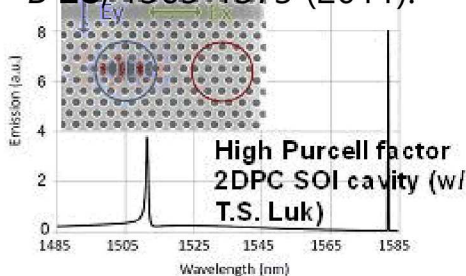
2D PC

3D PC

Subramania, G., et. al., J. M. App. PhyS. Lett. **83**, 4491(2003).

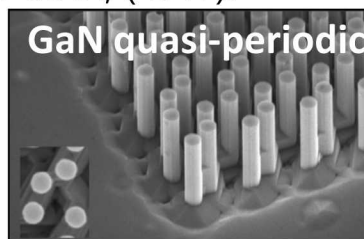
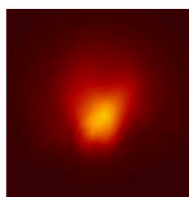


Luk, T. S. et al. J. Opt. Soc. Am. B **28**, 1365-1373 (2011).

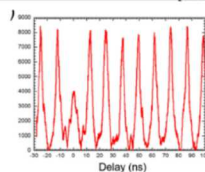


Photonic
Nanostructures

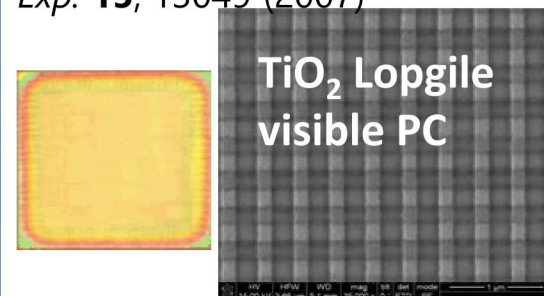
Anderson, P. D. et. al. Opt. Mat. Exp. **7**, 3634-3642, (2017).



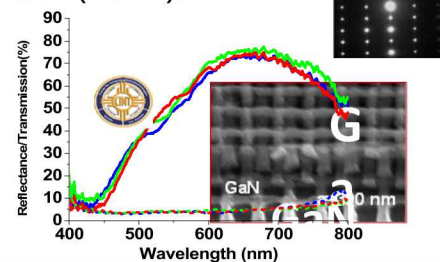
Fischer, A. J. et. al, . ACS Phot. **4**, 2165, (2017).



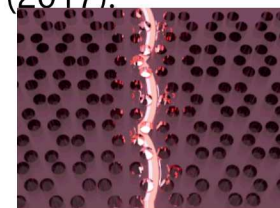
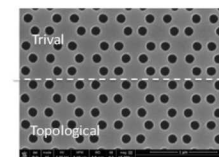
Subramania, G. et. al, Opt. Exp. **15**, 13049 (2007)



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



P. D. Anderson and G. Subramania, Opt. Exp. **25**, 23293 (2017).

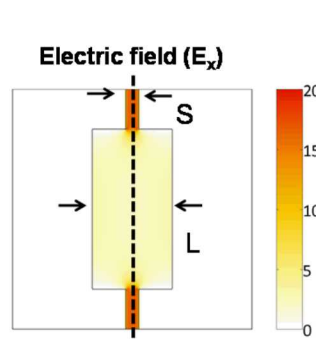
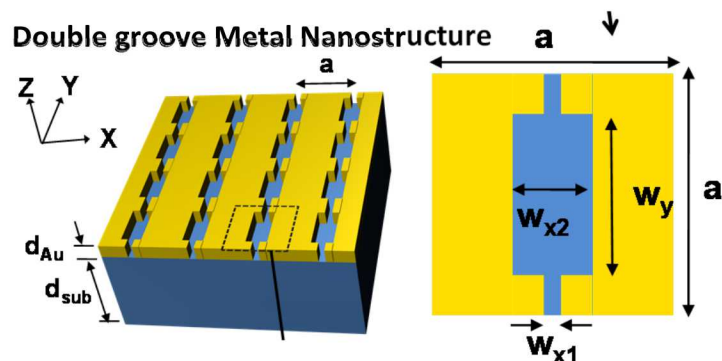


Topological Photonics

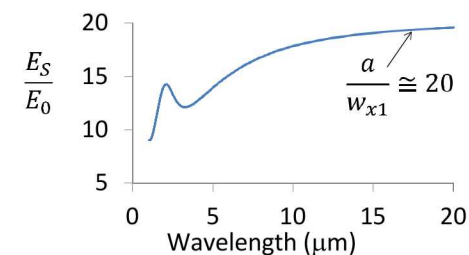
Nanophotonics Activity

Metal optics and Metamaterials

Non-resonant Broadband Ultra-subwavelength Light confinement

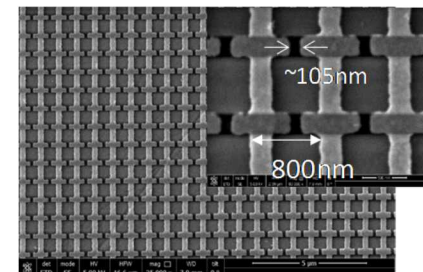


Electric field enhancement in the small gap

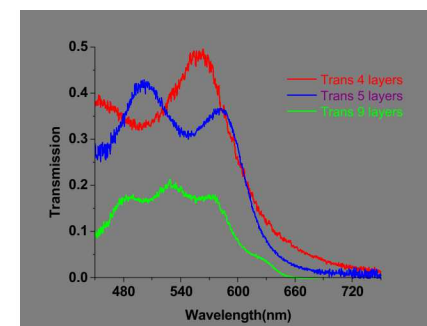
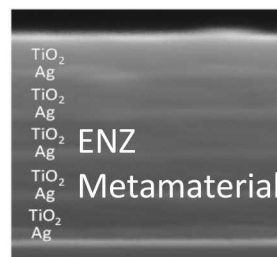
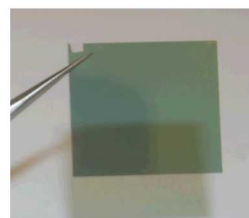
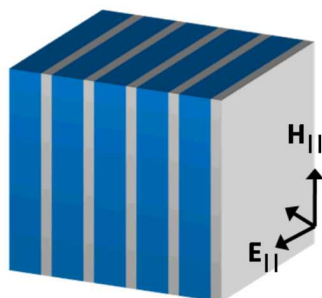


- Broadband transmission and electric field enhancement
- Extreme subwavelength confinement : $(\lambda/250)^2$

G. Subramania, S.Foteinopoulou and I. Brener, PRL. 107, 163902(2011).



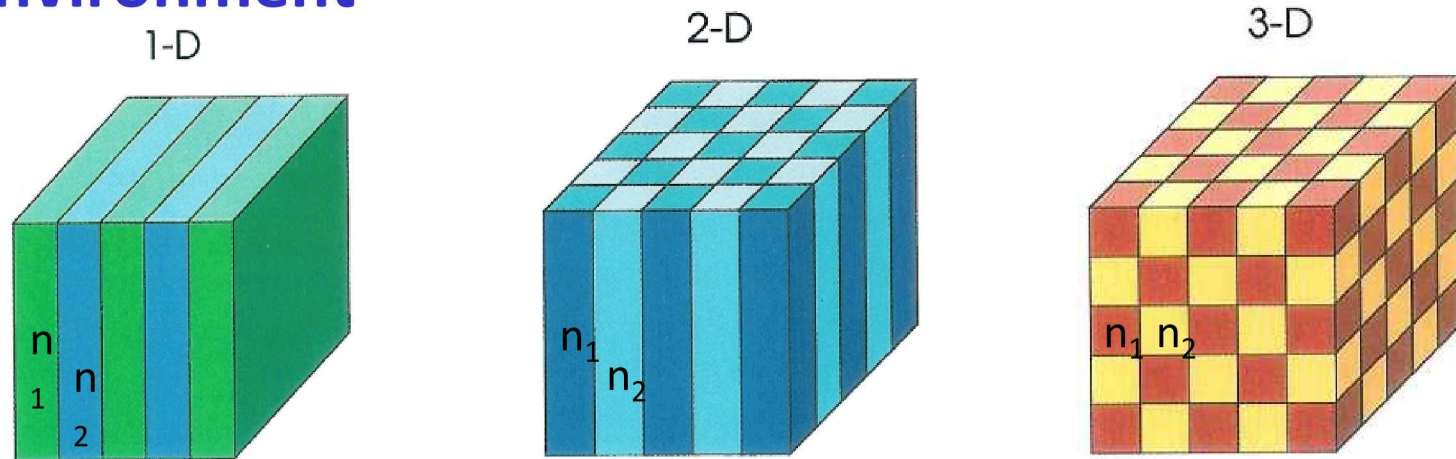
Metal dielectric composite for Epsilon-near-zero in the visible



G. Subramania, A. J. Fischer, T. S. Luk , Appl. Phys. Lett. , 101, 241107(2012)

3D TiO₂ Photonic crystal

Photonic Crystals: Nanostructured Electromagnetic Environment



Control of light propagation

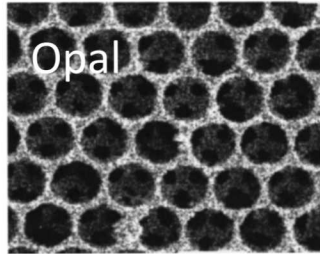
- Guiding, bending and splitting
- Negative refraction
- Self-collimation
- Localization
- Slow light
- Cloaking

Control of light emission

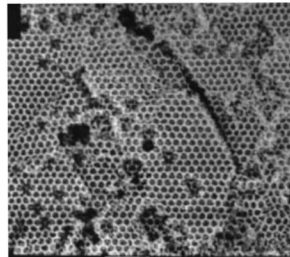
- Spontaneous emission enhancement
- Strong-coupling (Photon – Atom Bound states, Non-Markovian emission process)
- Non-classical light sources

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

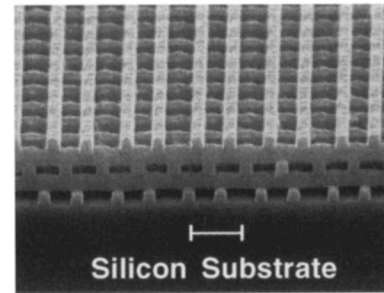
Examples of 3D Photonic Crystals



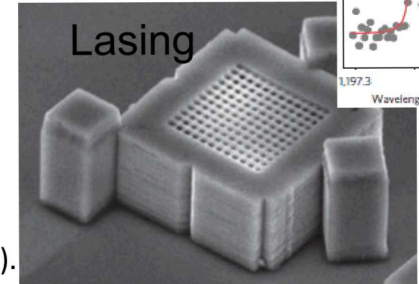
G. Subramania et. al., *Appl. Phys. Lett.* **74**, 3933 (1999).



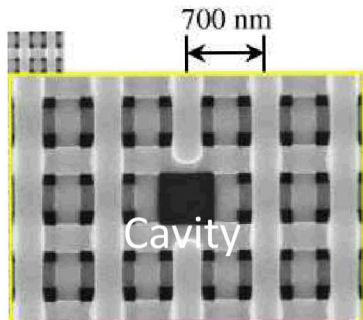
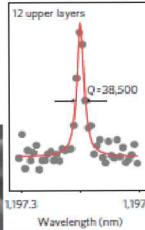
J.E.G. Wijnhoven et. al. *J Science* **281**, 802(1998),



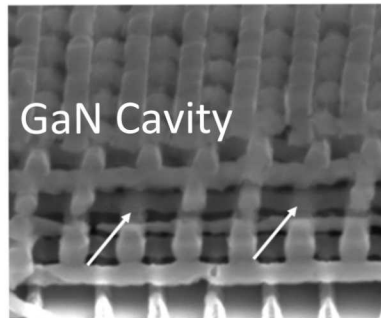
S.Y. Lin & J.G. Fleming, *JLWT*, **17**, 1944 (1999).



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

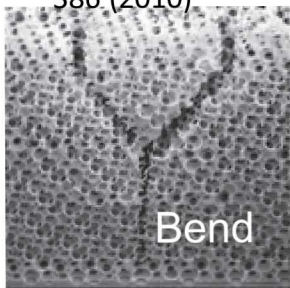
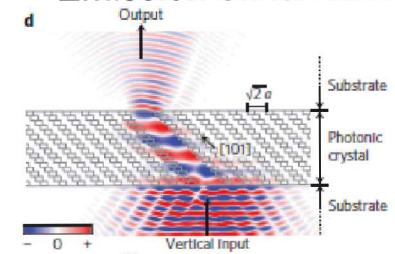


S. Kawashima et. al., *Opt. Exp.* **18**, 386 (2010)

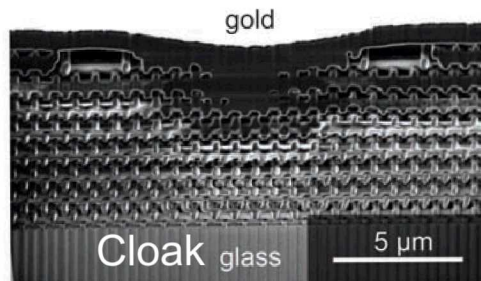


G. Subramania et. al, *Nano Lett.* **11**, 4591 (2011).

Emission enhancement

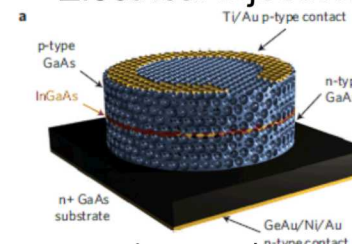


S.A. Rinne et. al., *Nat. Phot.* **2**, 52(2008)

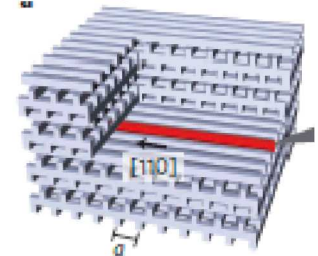


T. Ergin et. al., *Science* **328**, 337 (2010)

Electrical Injection



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

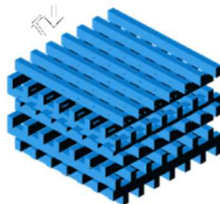


Ishizaki et.al., *Nat. Phot.*, **7**, 133 (2013)).

Spontaneous Emission Control using PC

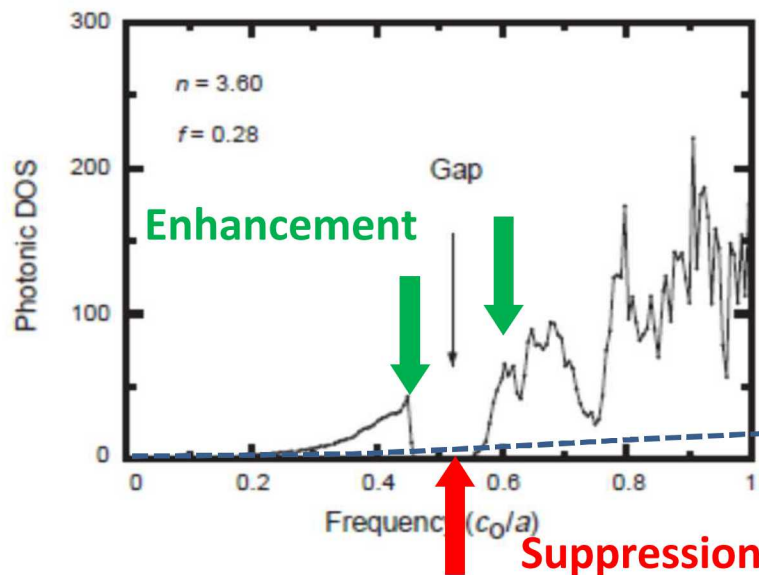
Radiative rate of an emitting dipole in an EM field
(Fermi's Golden Rule)

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

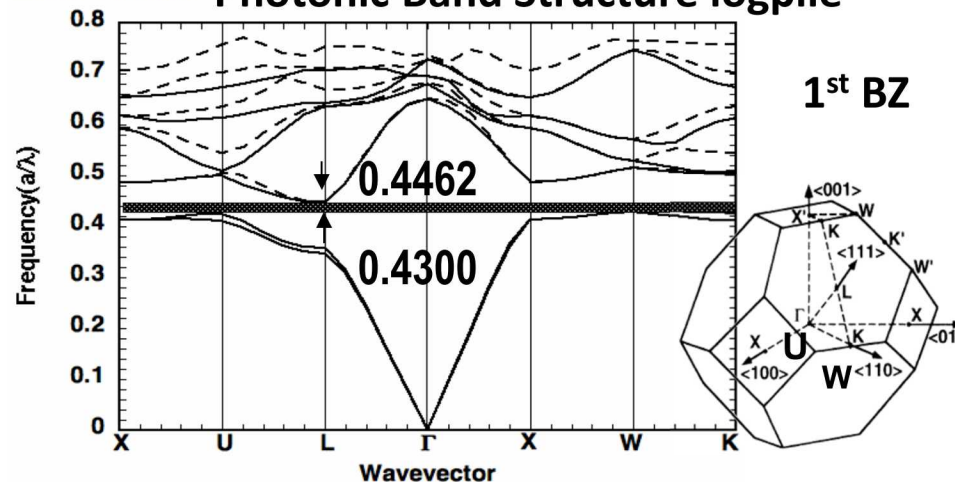


Photonic Density of States (PDOS)

$$\rho_f(\omega) = \frac{\omega^2}{\pi^2 c^3} \quad \leftarrow \text{in free space}$$



Photonic Band Structure logpile



Radiative rate
modification

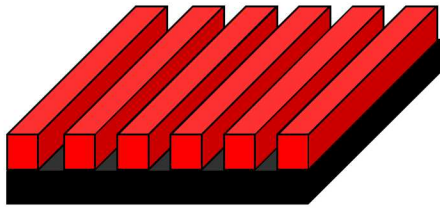
$$\frac{\Gamma_{r_PC}(\omega)}{\Gamma_{r_free}(\omega)} = \frac{\rho_{PC}(\omega)}{\rho_f(\omega)}$$

Local Photonic Density of States (LDOS)

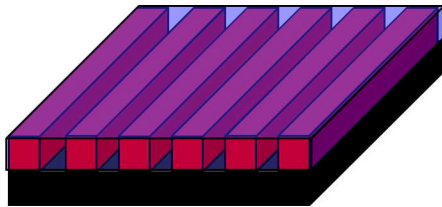
$$\rho_L(\mathbf{r}, \omega) = \sum_n \int_{1stBZ} d^3k |\bar{\boldsymbol{\mu}} \cdot \mathbf{E}_{n,k}(\mathbf{r})|^2 \delta(\omega^2 - \omega_{n,k}^2)$$

PC fabricated one layer at a time.

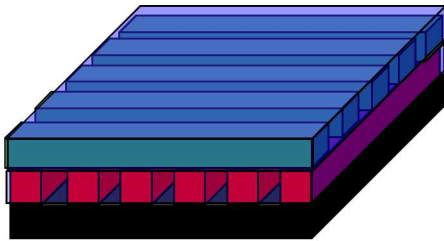
1. Fabricate first level



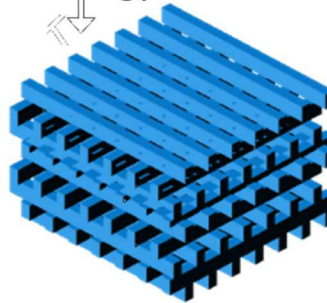
2. Fill and planarize



3. Make next level

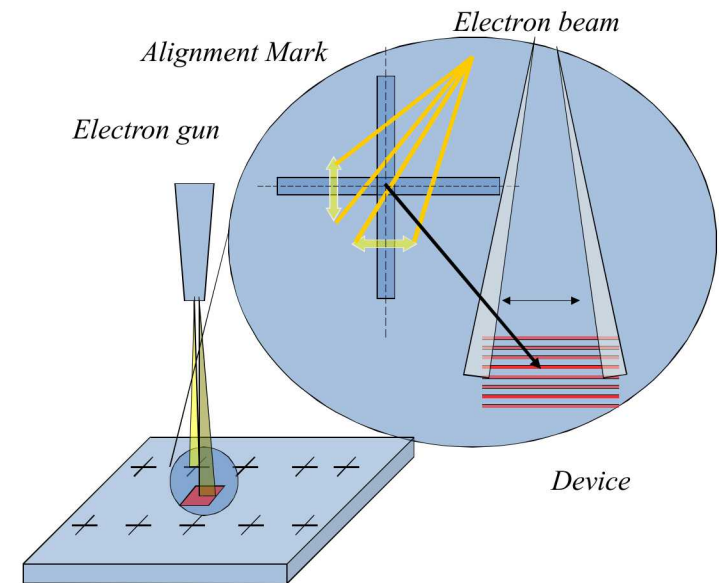


Logpile



Alignment

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



- Alignment
- Planarization

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

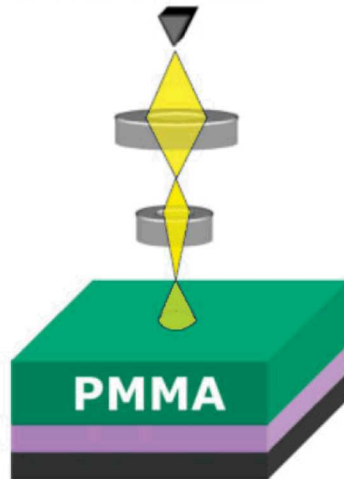
TiO₂ Logpile PC Fabrication Procedure

Single Layer Fabrication

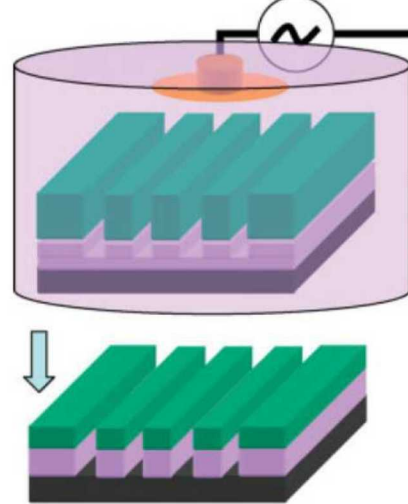
1. Deposit SiO₂



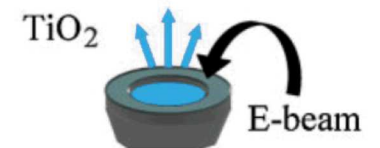
2. E-beam Write



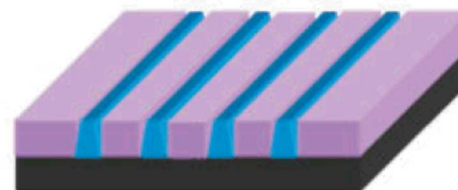
3. Reactive-ion Etch



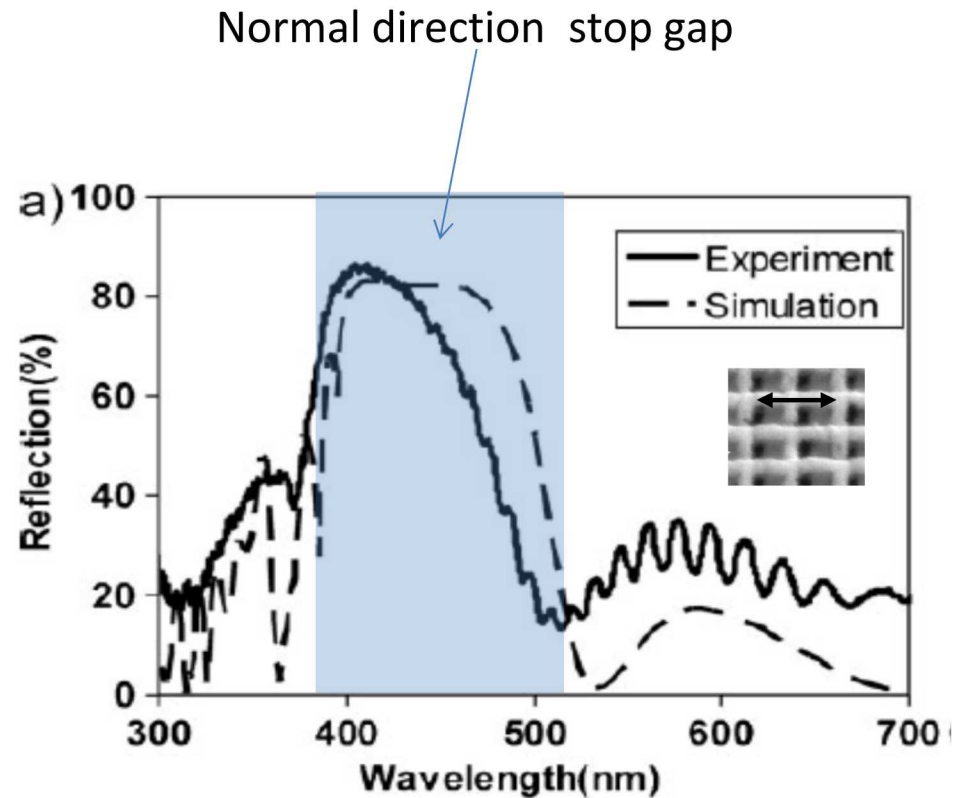
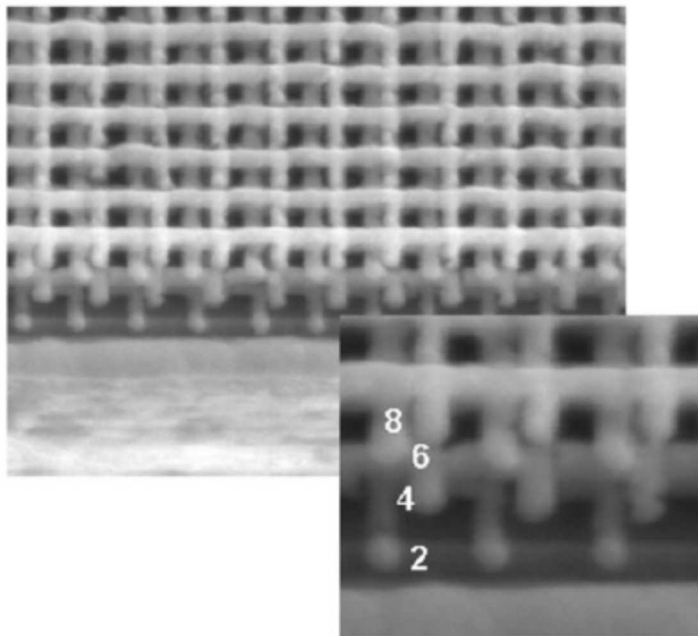
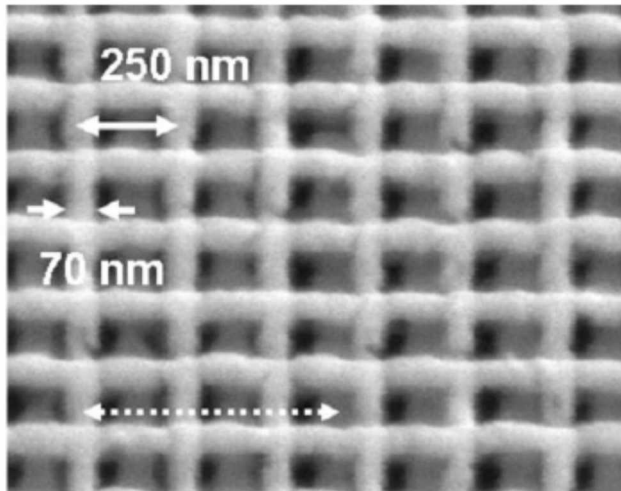
4. E-beam evaporation of TiO₂



5. Post lift-off



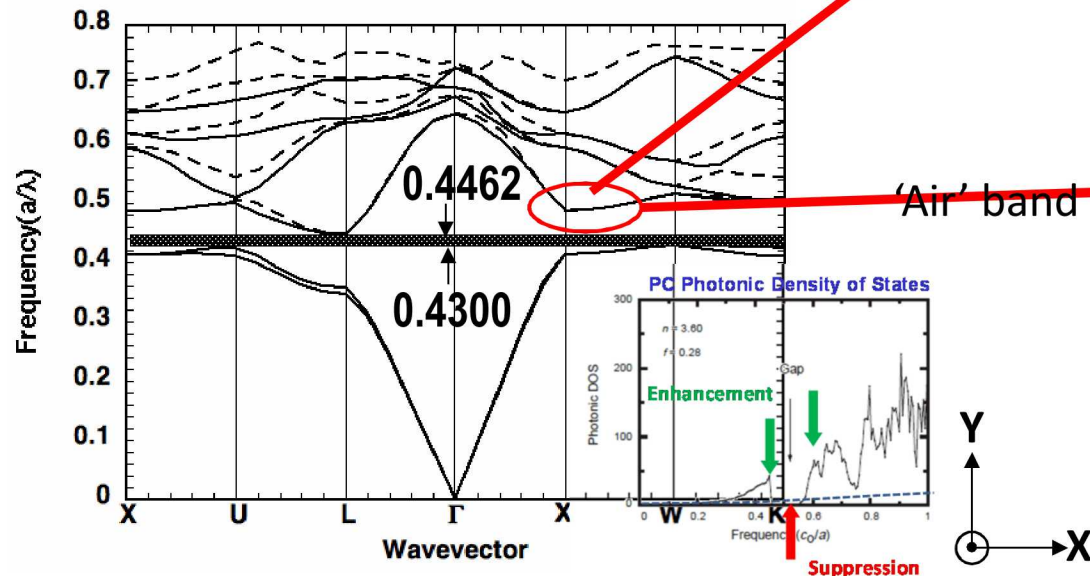
TiO₂ Logpile- Visible 3D PC



Emission Modification in TiO_2 Logpile

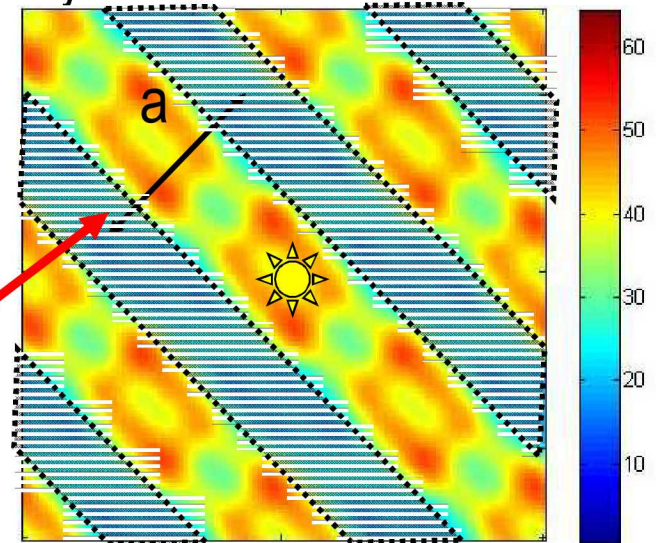
Dielctric band vs. air band emission control

- 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

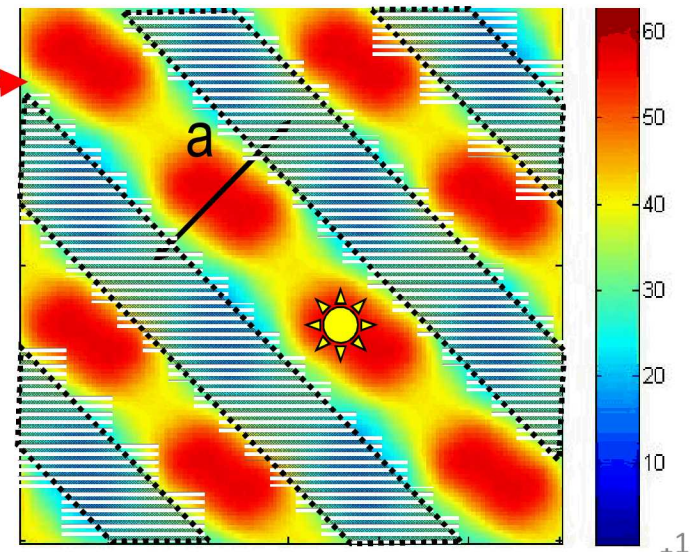


Field Distribution for the 'air band' using PWE method

E_y field distribution at Xpt



E_z field distribution at Xpt



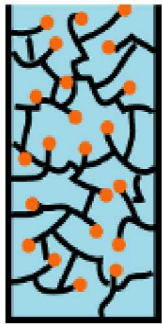
Requirements for Accessing the 'Air' Void Region of the PC

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

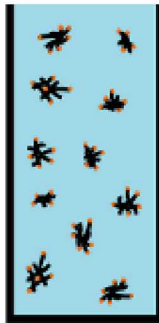
Room temperature Spin Coatable Aerogel

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

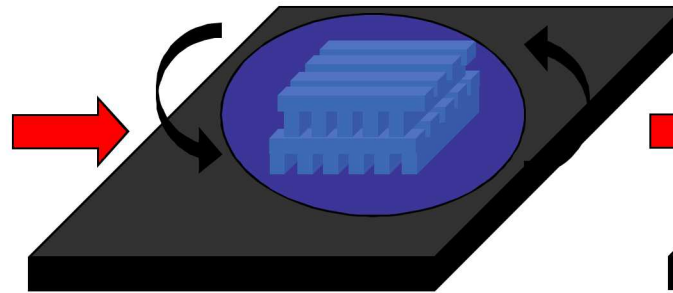
Age and
cap gel



Disperse by
sonication

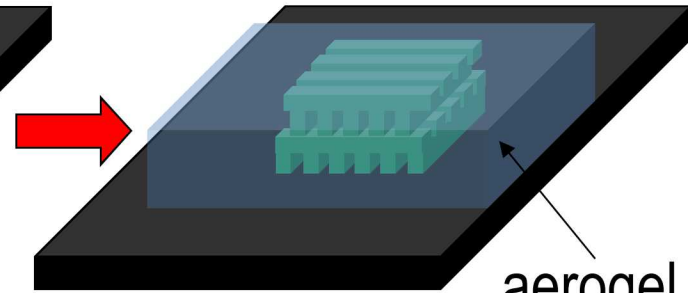


Spin coat



Logpile PC

dry at RT



Logpile PC

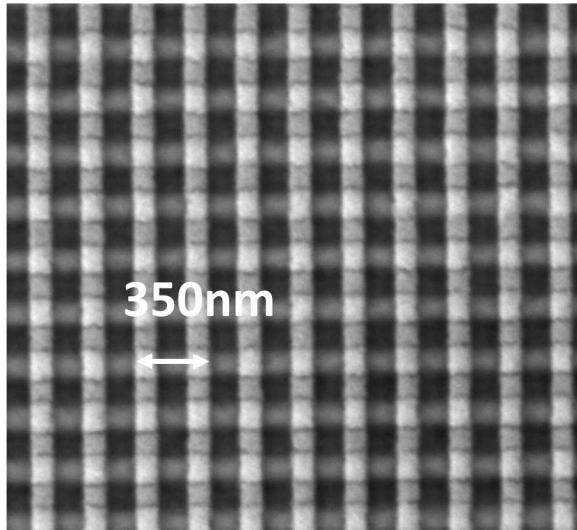
aerogel

Introduce QDs through chemical attachment (3-mercaptopropyltrimethoxysilane chemistry)

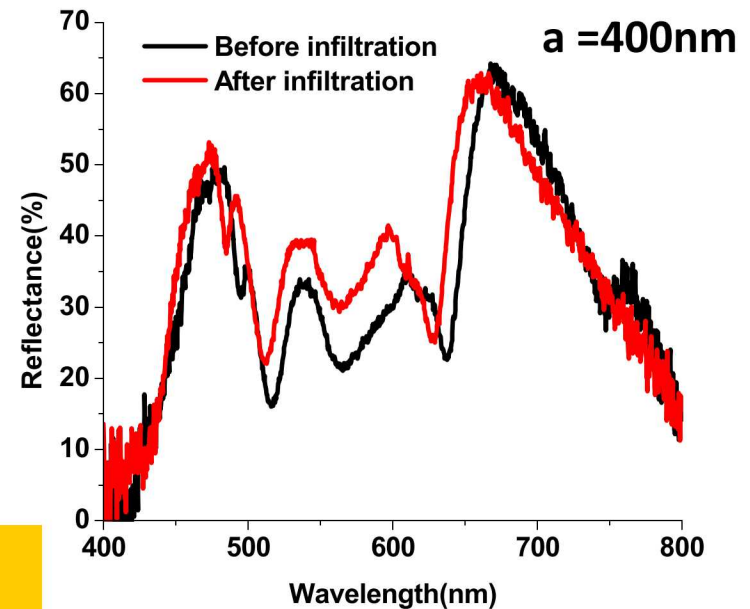
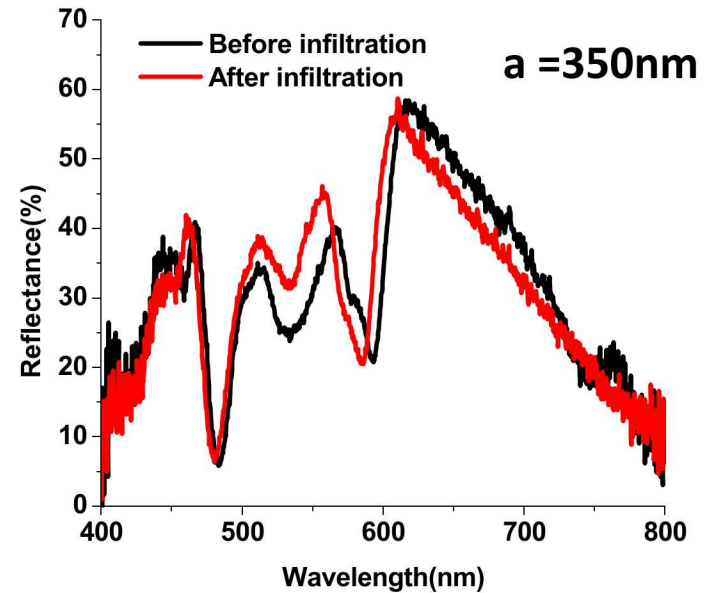
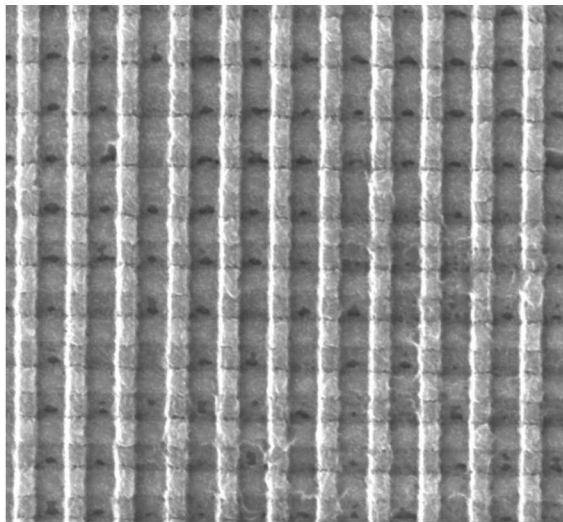
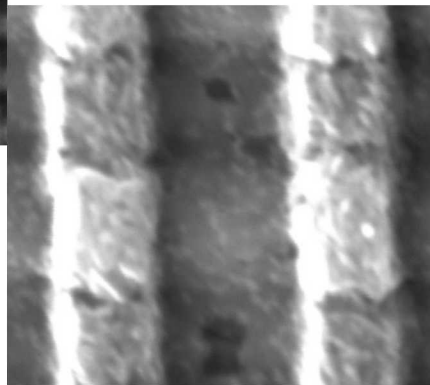
Developed by
Alex Lee



Effect of Aerogel and CdSe QD infiltration

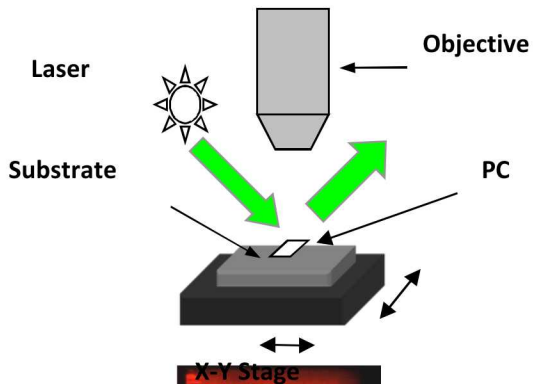


Aerogel Ref. index
~1.05-1.1



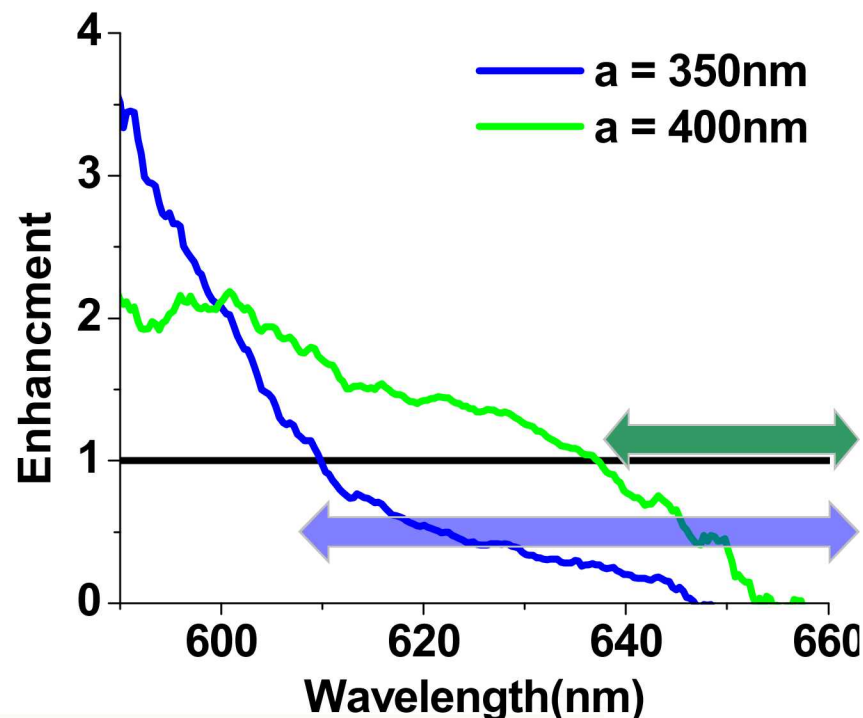
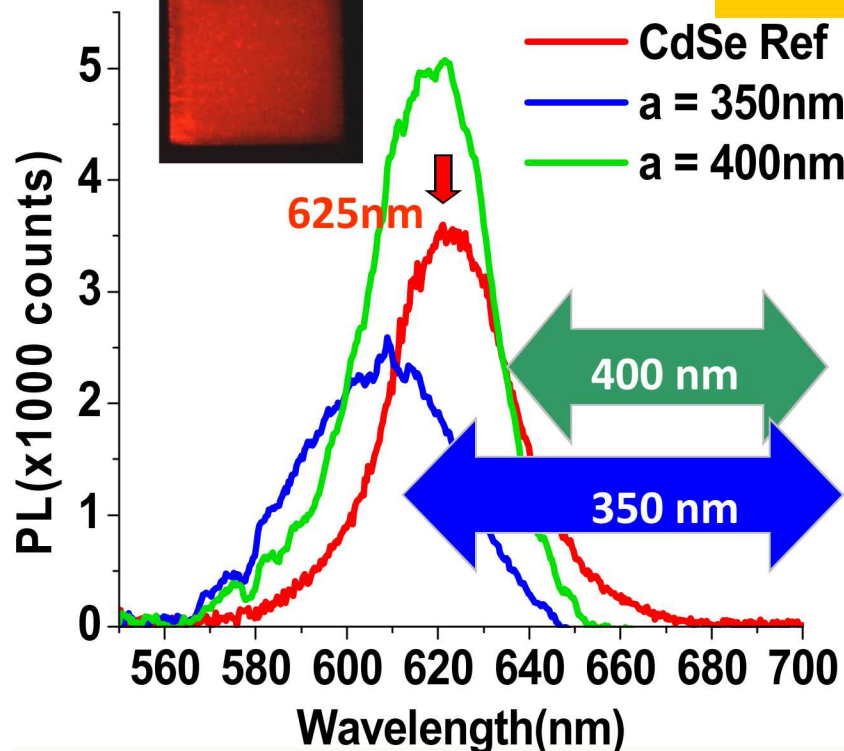
Aerogel and CdSe QD infiltration has negligible effect on the bandgap!

Spontaneous Emission Modification



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

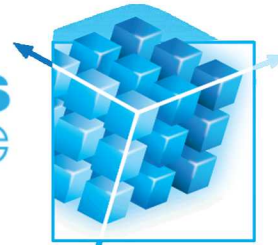
Light emission suppression inside the bandgap and enhancement at the band edge



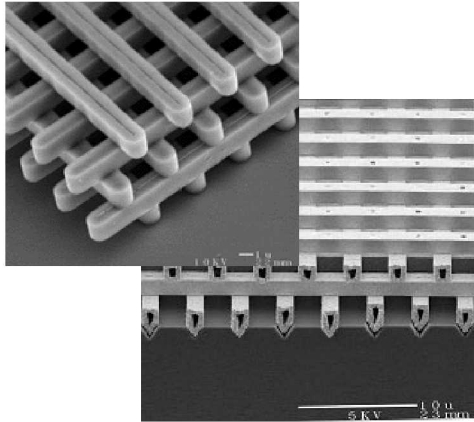
G. Subramania, Y. J. Lee, A. J. Fischer, T. S. Luk, C. J. Brinker, D. Dunphy, Appl. Phys. Lett., **95**, 151101(2009)

GaN 3D Photonic crystals

**SSLS
EFRC**

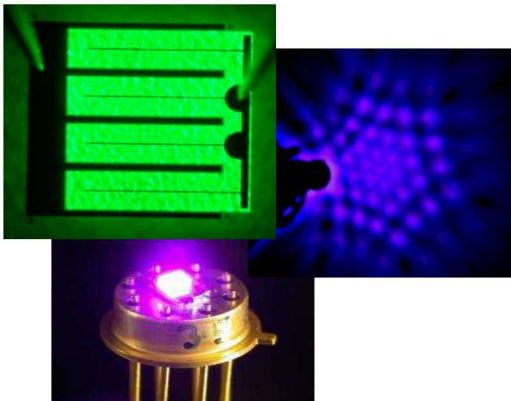


3D photonic crystals

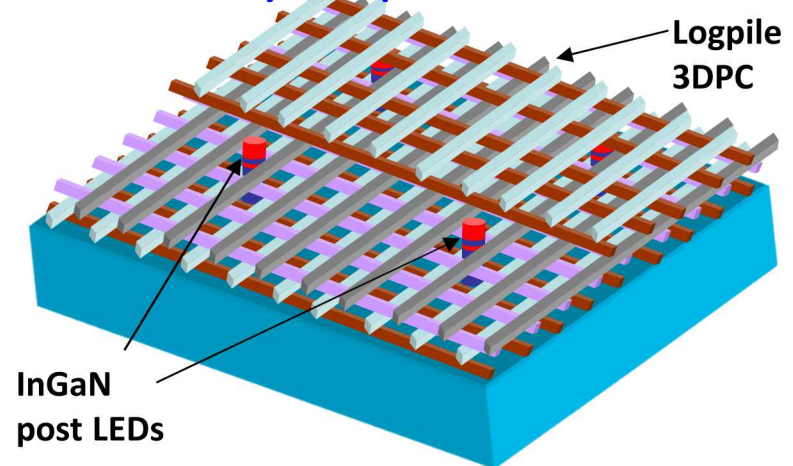


- Full 3D gap LEDs can achieve ultimate emission control
- Sandia has strong capabilities in 3DPC and Nitrides
- Merge InGaN LED research with 3D photonic crystal research.

InGaN LEDs

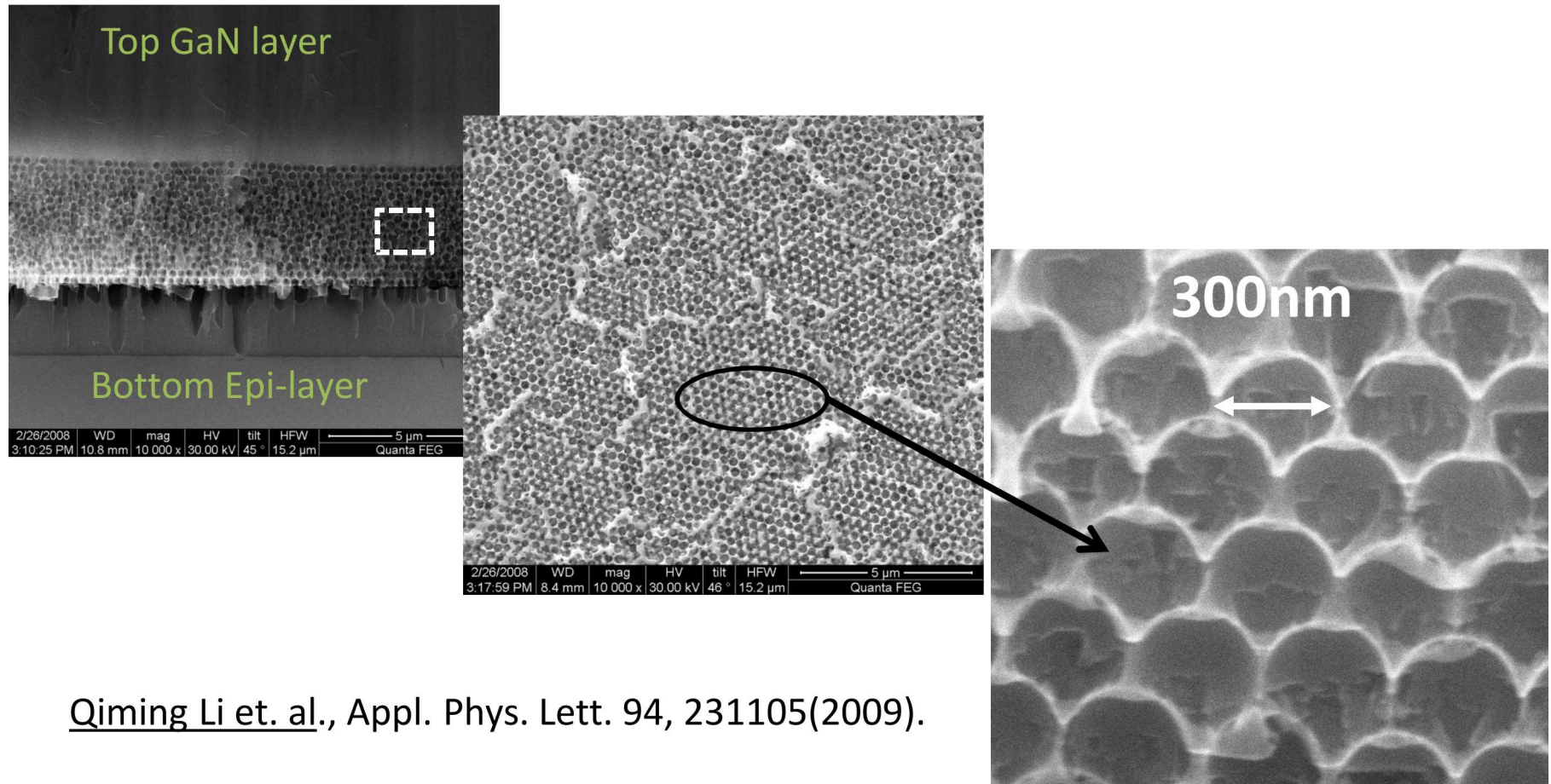


InGaN LED array incorporated into a 3DPC



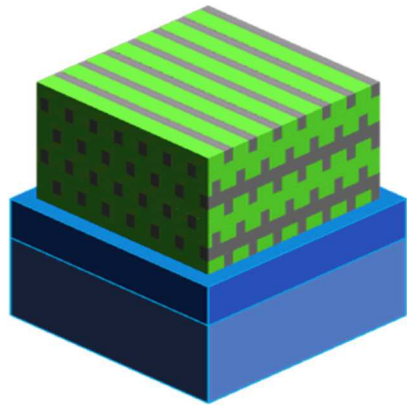
Improving InGaN LED efficiency enhancements will benefit SSL – e.g. Green emission.

Epitaxial GaN grown though nanostructured template reduces dislocation density

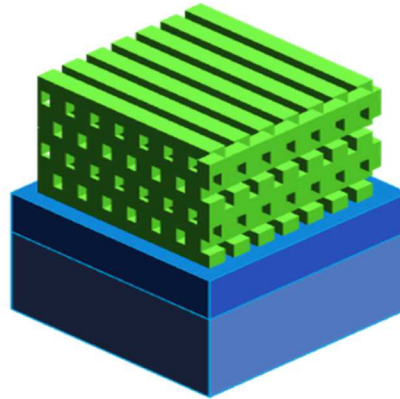


Qiming Li et. al., Appl. Phys. Lett. 94, 231105(2009).

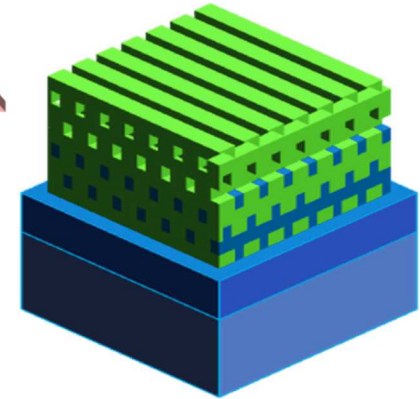
GaN growth through logpile template



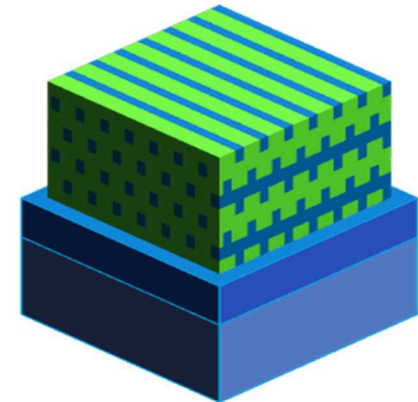
1. Si/SiO₂ logpile PC



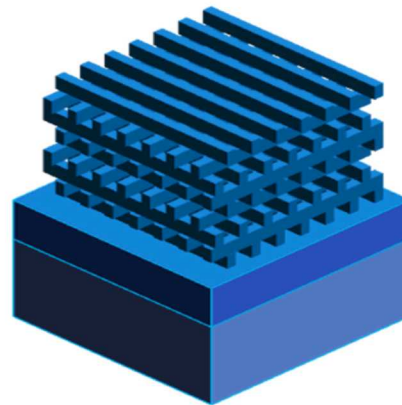
2. After Si is removed with KOH.



3. MOCVD GaN growth through SiO₂ template



4. After complete GaN infiltration into SiO₂ logpile template



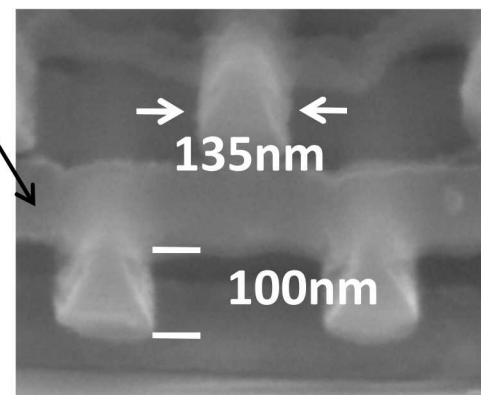
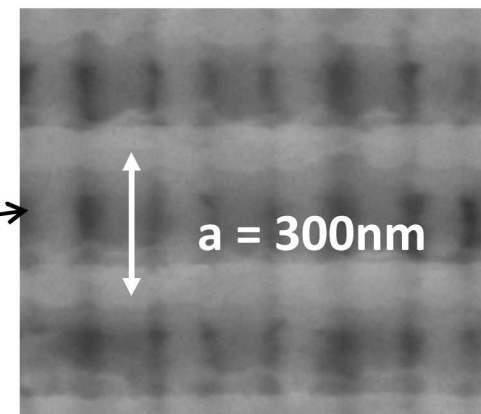
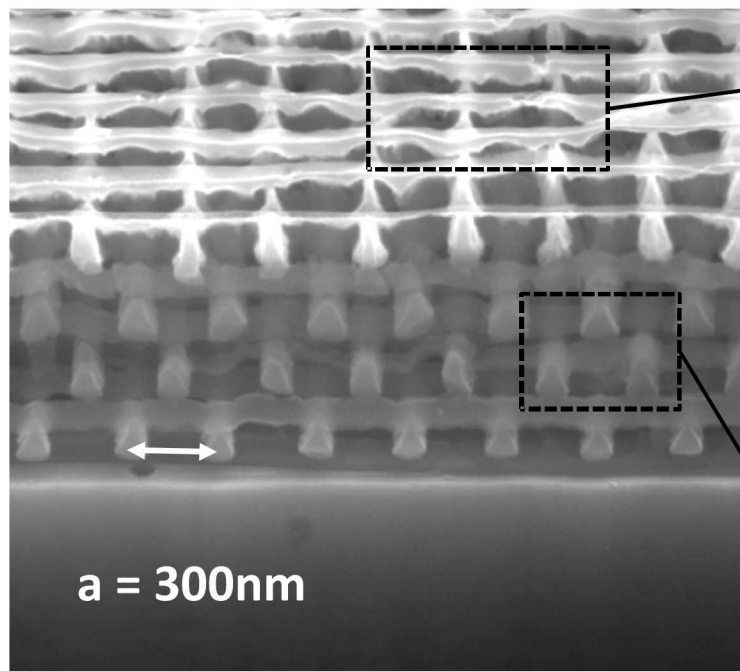
5. GaN logpile PC after SiO₂ logpile template removal



With optimized growth conditions ...

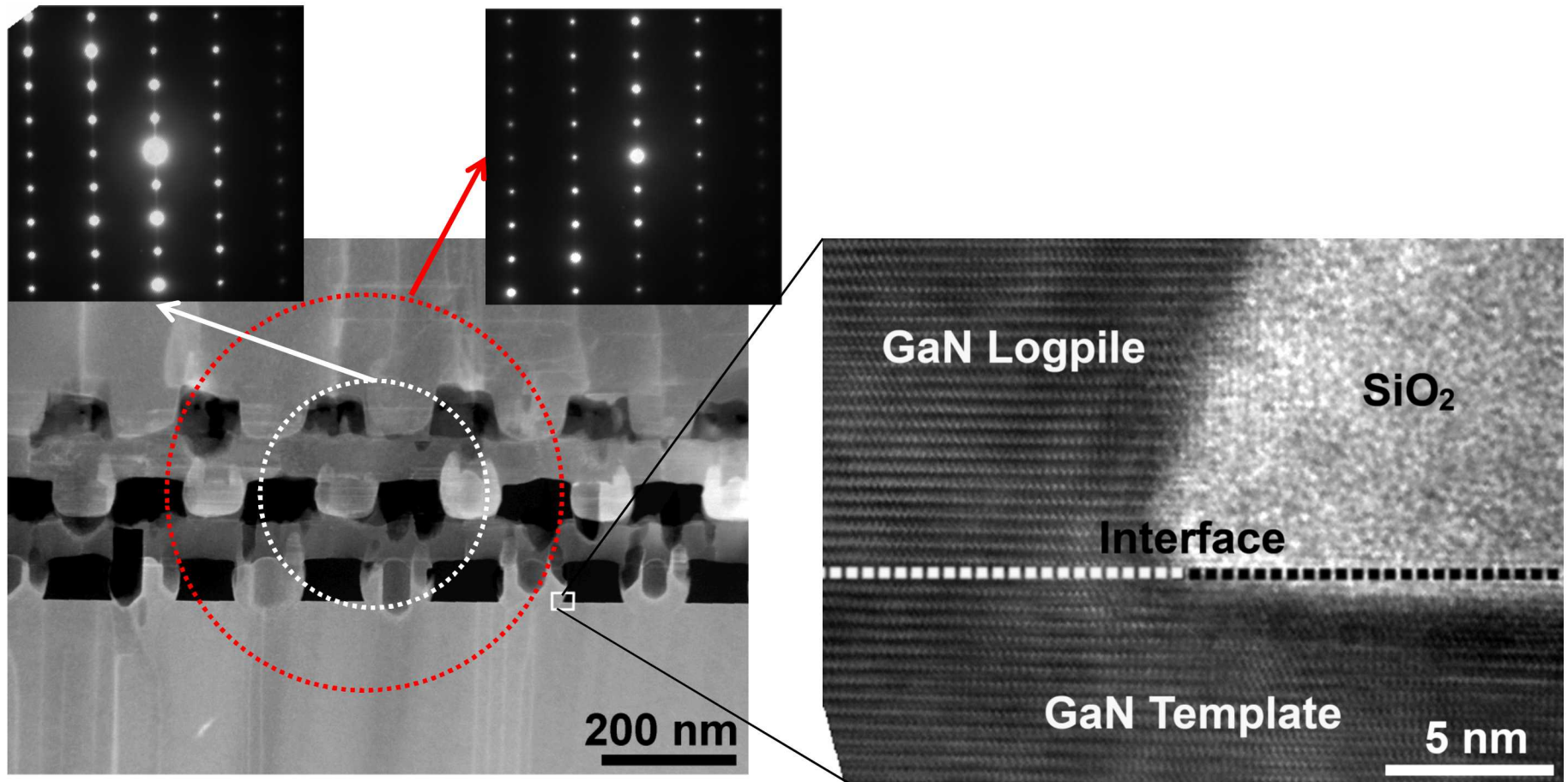
Optimize Growth conditions

- Gas mixture:
TMGa, NH₃ (~ 4 SLM), H₂,
and N₂ (~ 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).

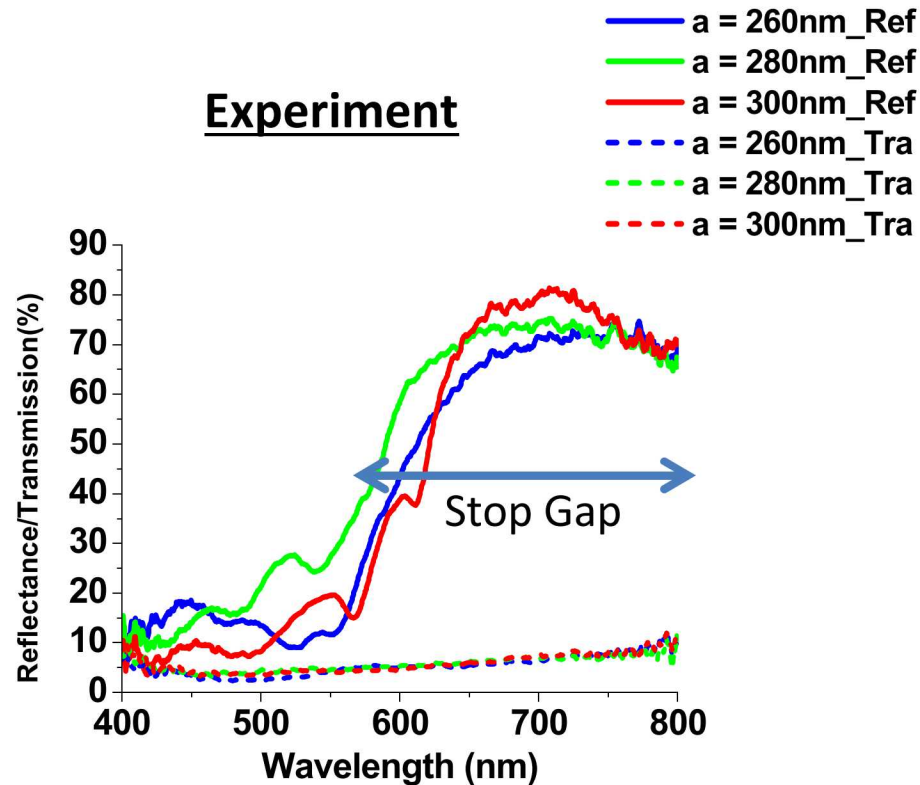
Bottom-up epitaxial growth of crystalline GaN



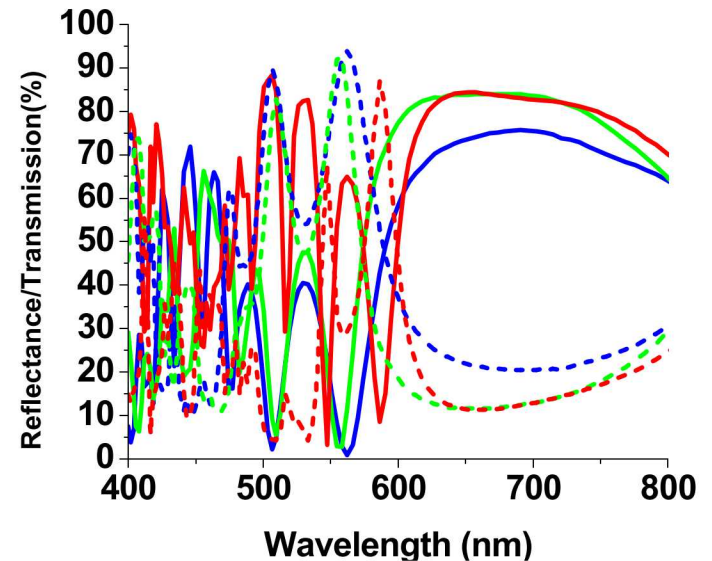
G. Subramania et. al. , Nano Lett. **11**, 4591 (2011).

Optical Response

Experiment



FDTD Simulation

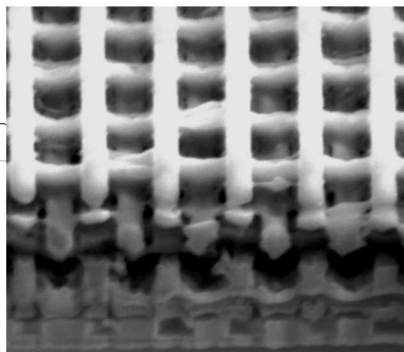
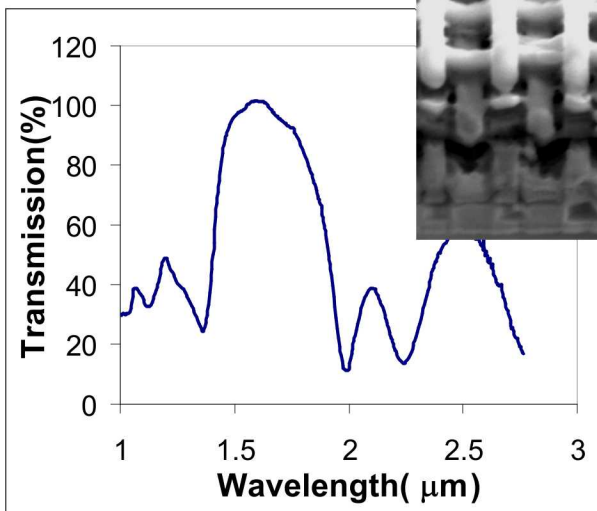


G. Subramania et. al. , Nano Lett. **11**, 4591 (2011).

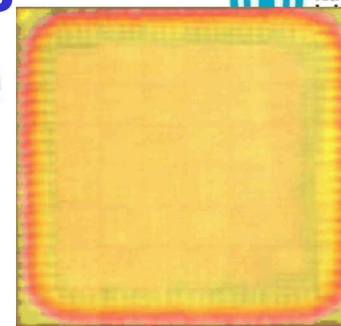
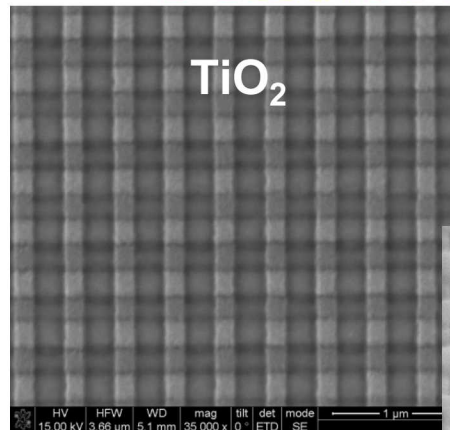
3DPCs: Wavelength, Materials

Visible

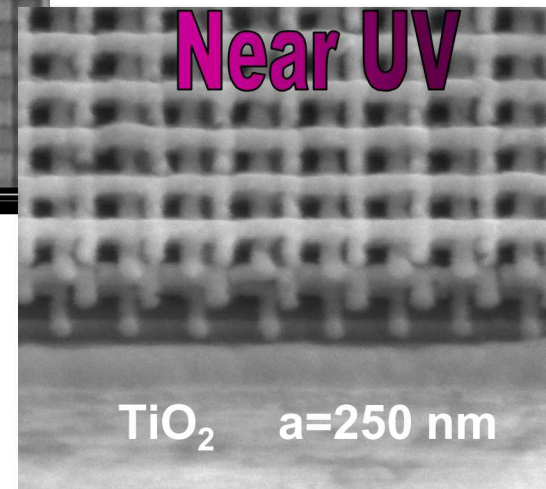
Si near-IR



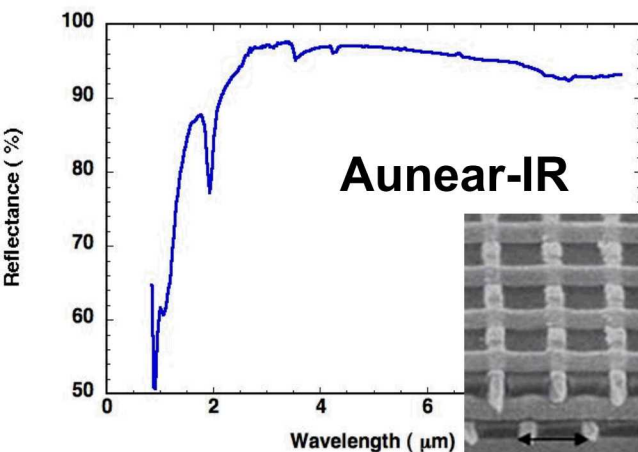
TiO₂



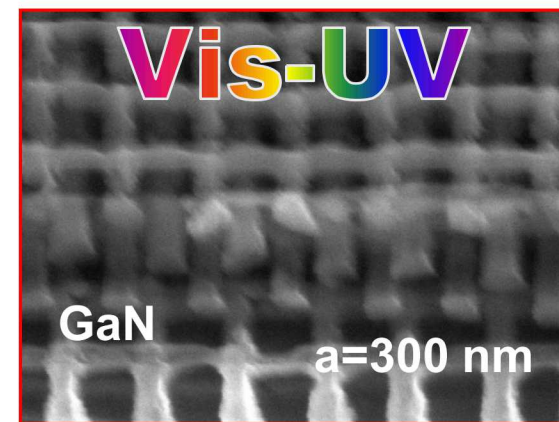
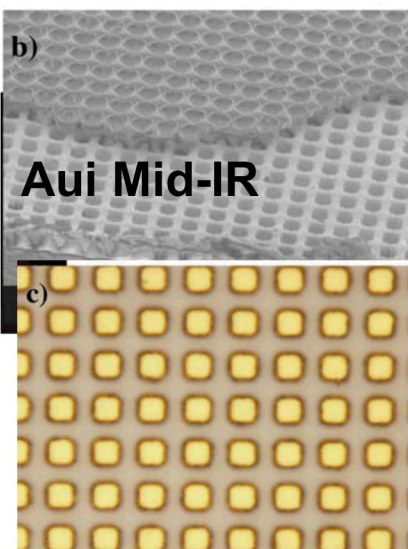
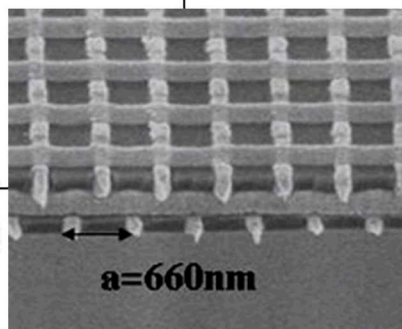
Near UV



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

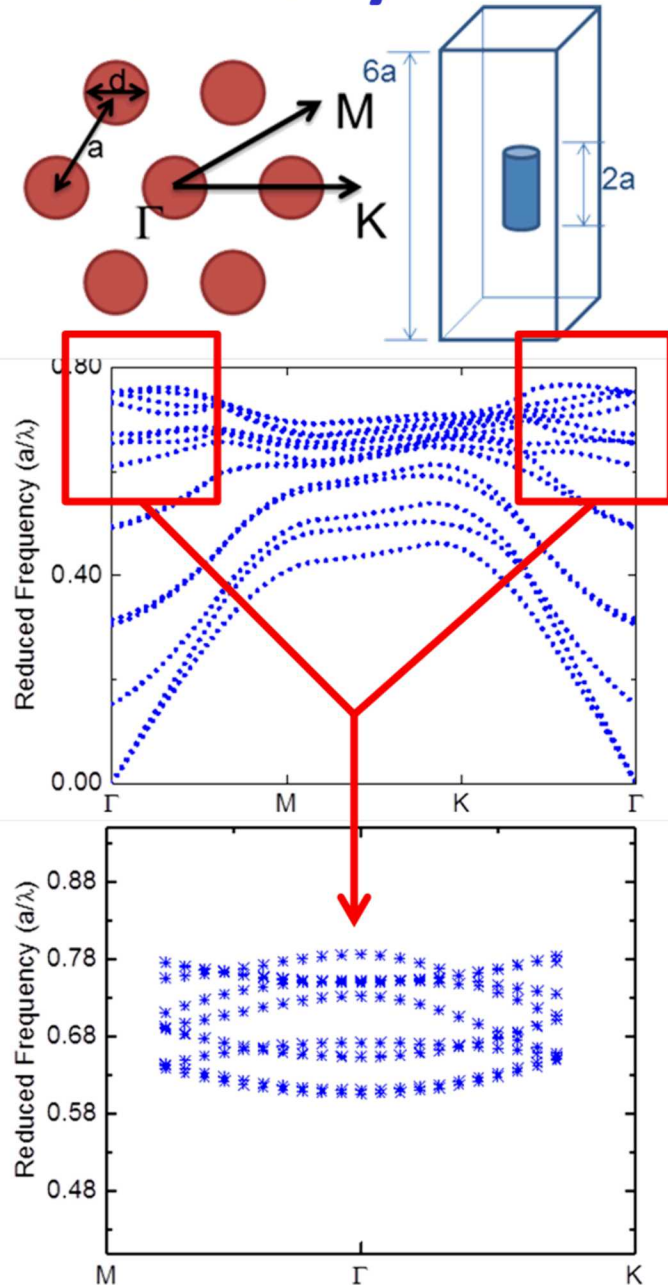


Au near-IR



GaN 2D Photonic crystals

Vertically emitting photonic crystal lasers - Theory

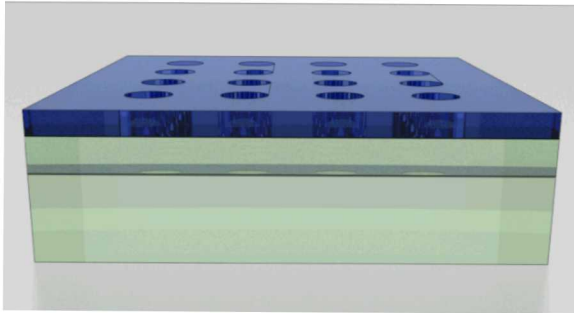


- *Low lasing threshold*
 - *Increase interaction of light with the gain region*
 - *Enabled by 'Low group velocity modes' in photonic crystal**
- *Vertical Emission*
 - *At higher bands there are low group velocity modes near the Gamma point*
 - *Near the Gamma point the in-plane wave vectors are small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

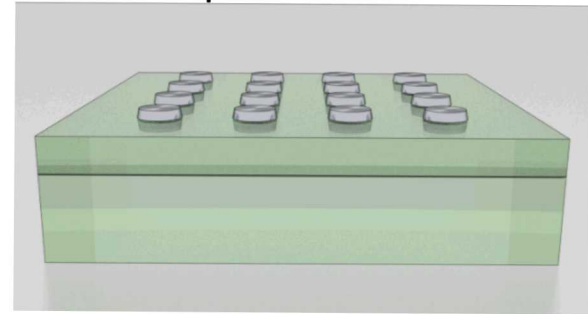
*Sakoda, K. *Optical Properties of Photonic Crystals*. (Springer-Verlag, 2001).

Fabrication of III-N nanowire laser array

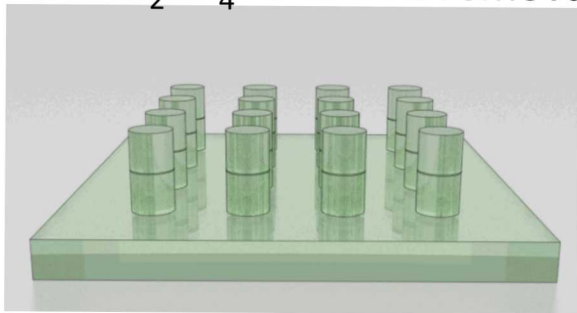
EBL pattern in PMMA



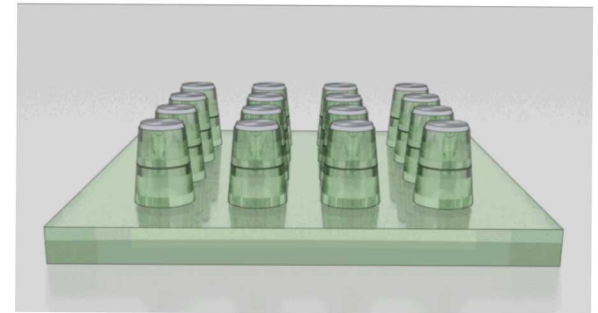
Ni evaporation and lift-off



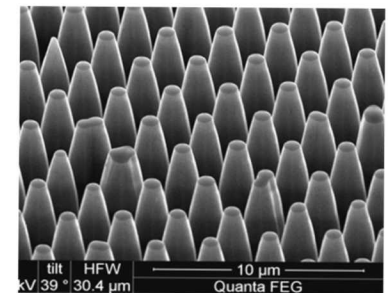
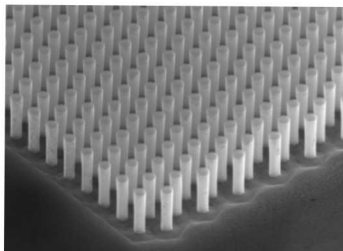
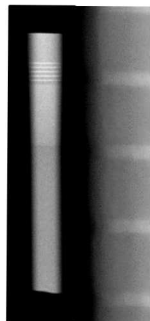
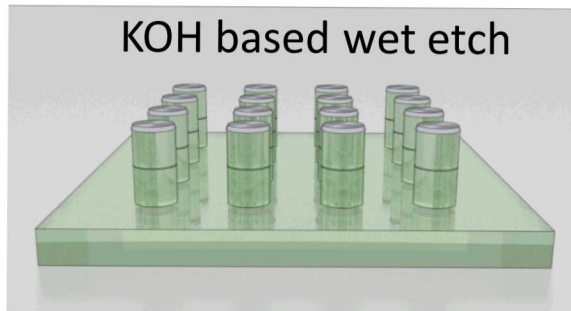
H₂SO₄-based Ni removal



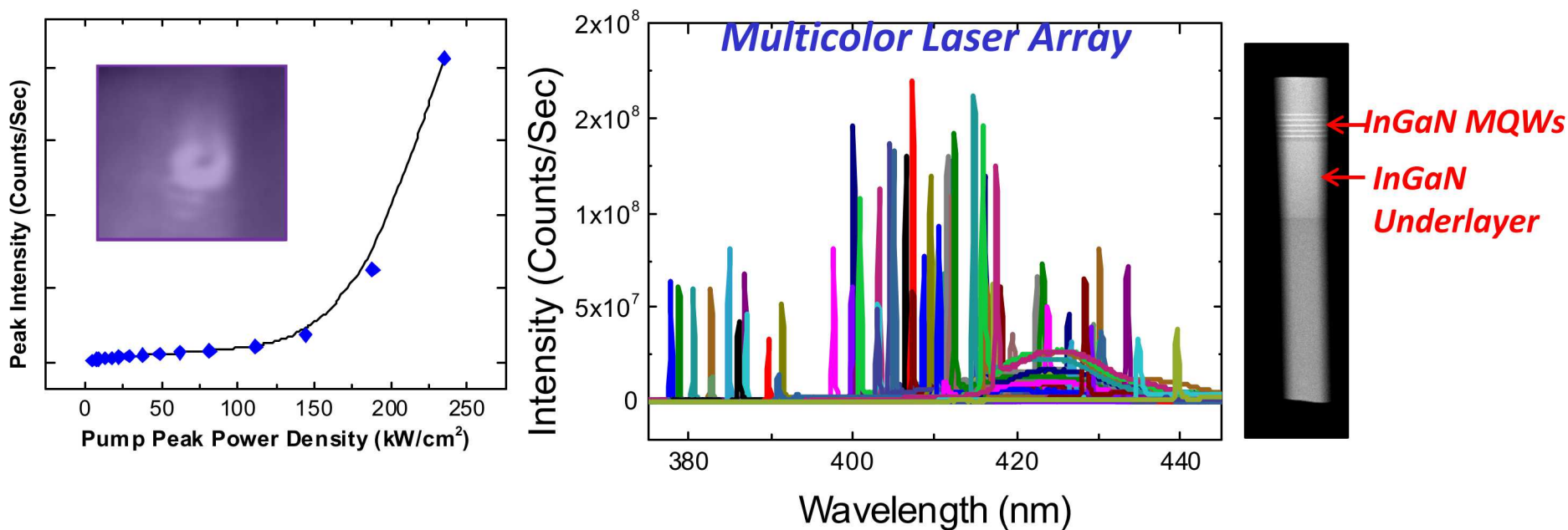
Cl₂ based dry etch



KOH based wet etch



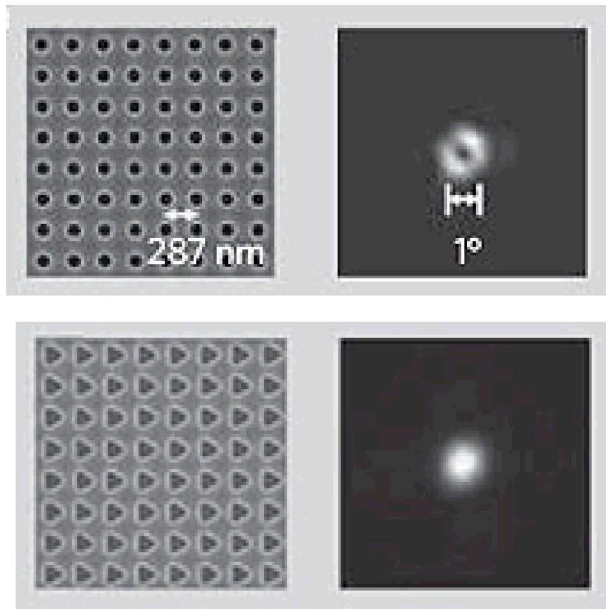
Optical response – low threshold lasing



- *A low lasing threshold is achieved with $< 500 \text{ kW/cm}^2$ for all PC lasers fabricated.*
- *Wavelength tunability (lattice constant and nanowire diameter).*
- *Multiple color laser emission on a single epitaxial wafer covering a spectral range from 380-440nm.*
- *Multiple gain regions can simultaneously lase*
- *Pathway for enhancing the available lasing spectral range*

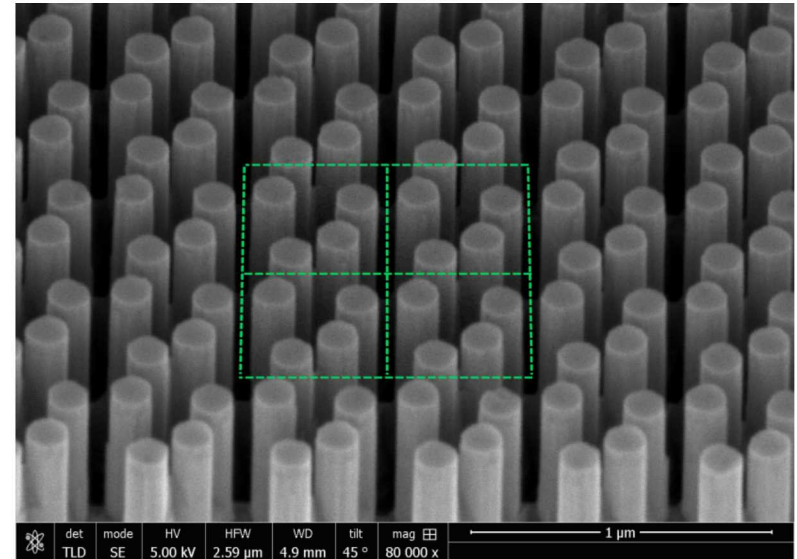
Improving light extraction with Quasiaperiodic structures

Method 1: change **shape** of emitters



Miyai, E., et al., *Nature*, 441, 946 (2006)
Noda Group

Method 2: change **position** of emitters



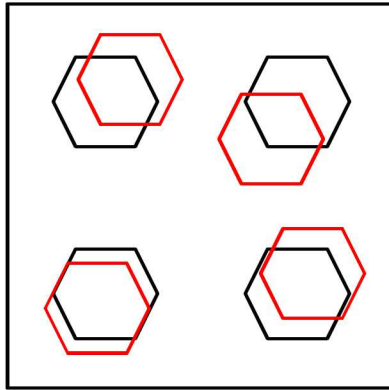
Present Work



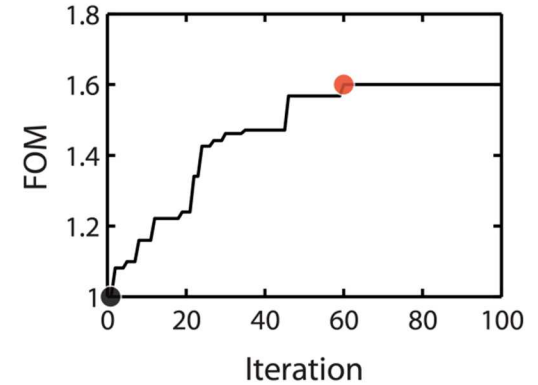
***Possible to improve extraction without sacrificing emission enhancement**

*Anderson et al., *Opt. Lett.* 40:2672 (2015)

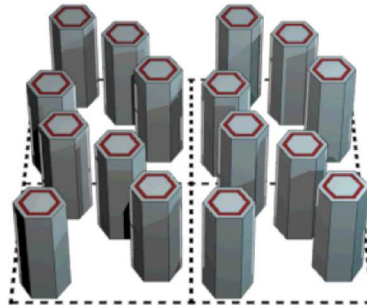
Extraction optimization using Quasi-periodic array



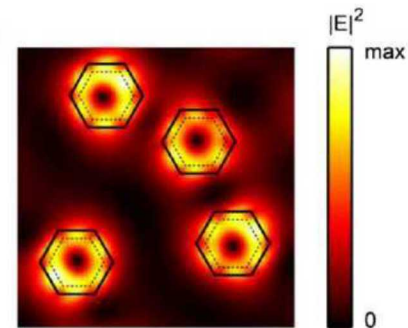
$$\text{F.O.M.} = \frac{\int_{\omega_0 - \Delta}^{\omega_0 + \Delta} |\vec{E}|_{Ap}^2 d\omega}{\int_{\omega_0 - \Delta}^{\omega_0 + \Delta} |\vec{E}|_P^2 d\omega}$$



Optimized geometry:

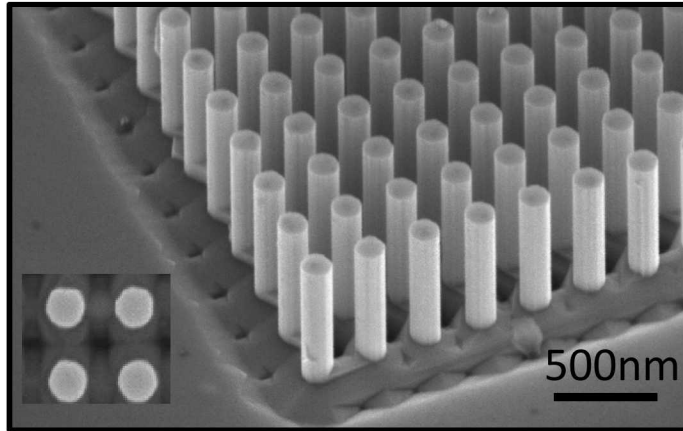


Breaks mirror symmetry

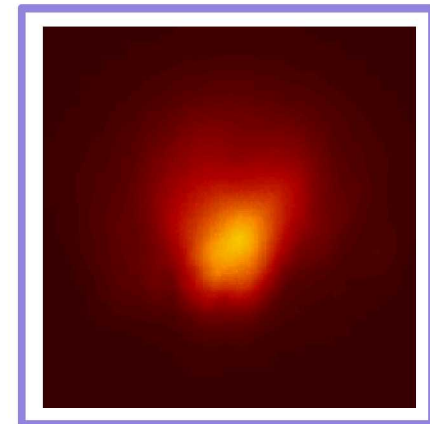
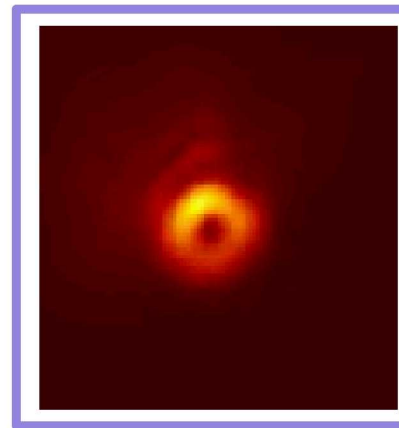
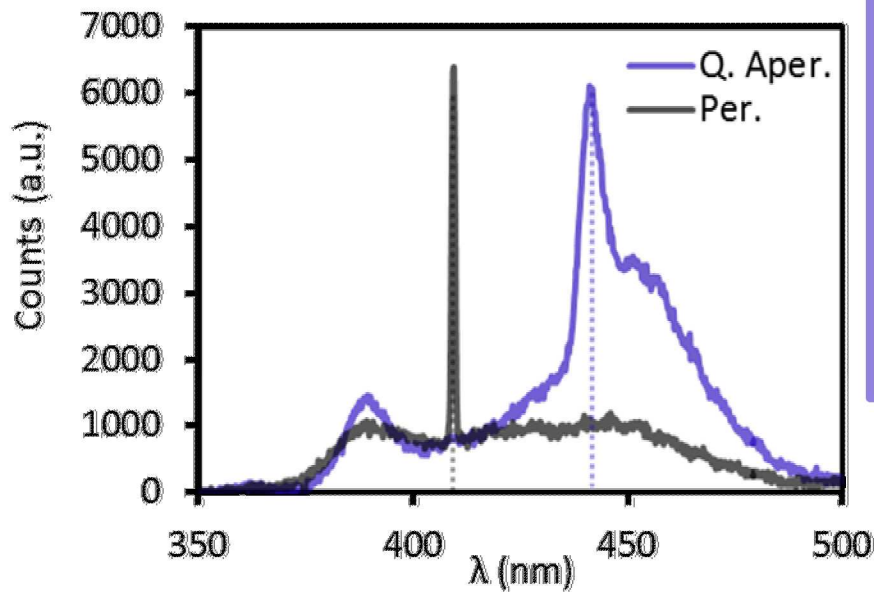
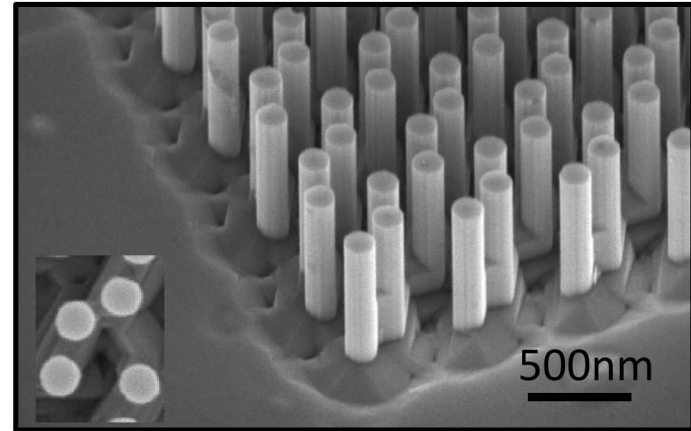


Photoluminescence response

Periodic



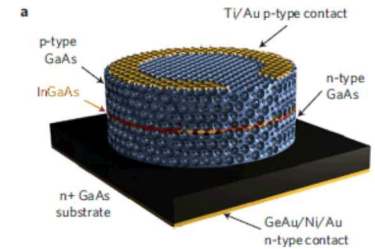
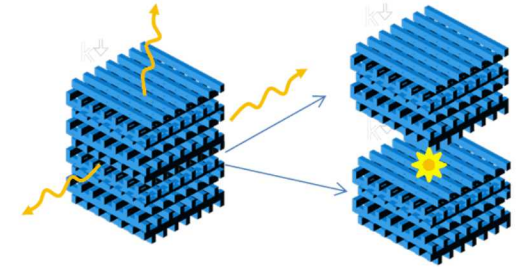
Quasi Periodic



Summary/Possibilities

3D

- 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)

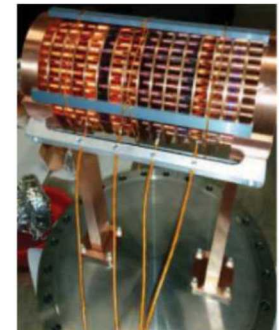


E. C. Nelson, et al., Nat Mater
10, 676 (2011)

2D

- Electrical injection
 - Large area scaling
 - Wavefront / angular momentum control
- Particle acceleration

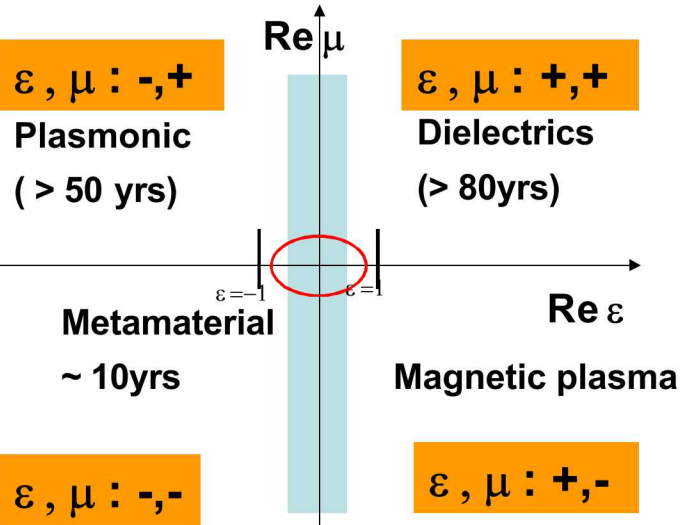
Simakov, E. I. et al., Phys. Rev. Lett. **116**, 064801 (2016).



Metal Nanostructure Photonics

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.

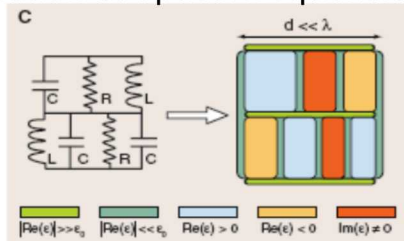
- $\underline{D} = \epsilon \underline{E} \sim 0$ for $\epsilon \sim 0$
- $V_p \rightarrow \infty$; No phase variation
- DC behavior at optical frequencies

Properties

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

Optical Nanocircuits

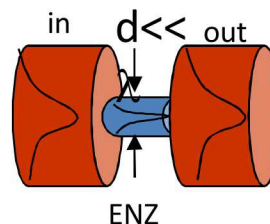
Vacuum light guiding, electrical isolation at optical frequencies



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

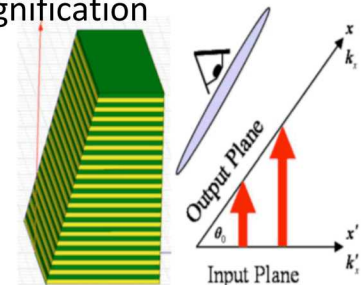
Supercoupling

Light squeezing through sub-wavelength channels



Subdiffraction Imaging

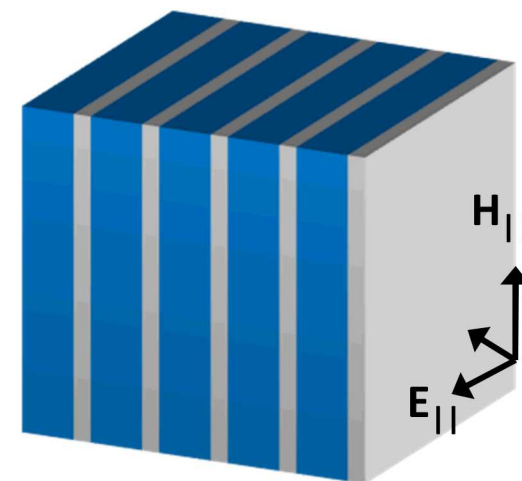
Far field subwavelength magnification



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

Effective Medium Approach to ENZ

$$\epsilon_{\text{effective}} = f\epsilon_{+}^{\leftarrow \text{dielectric}} + (1-f)\epsilon_{-}^{\leftarrow \text{metal}}$$



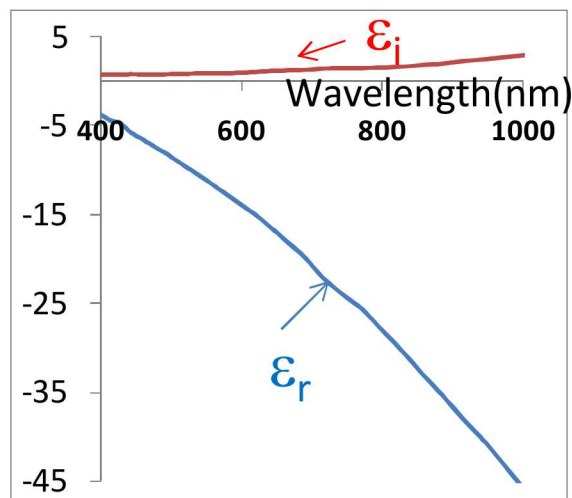
Goals

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

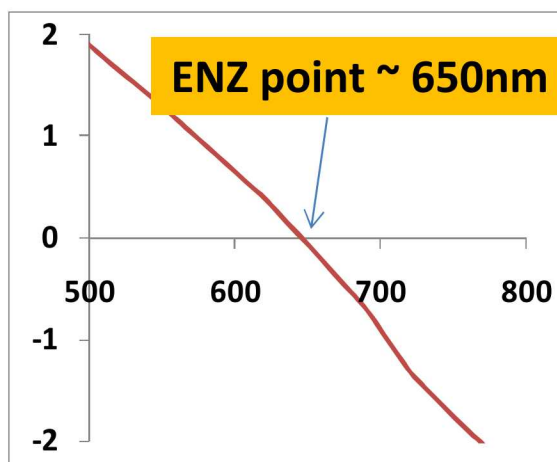
Materials Choice ϵ_{-} : Ag and ϵ_{+} : TiO₂

Ag (23%) + TiO₂ (77%)

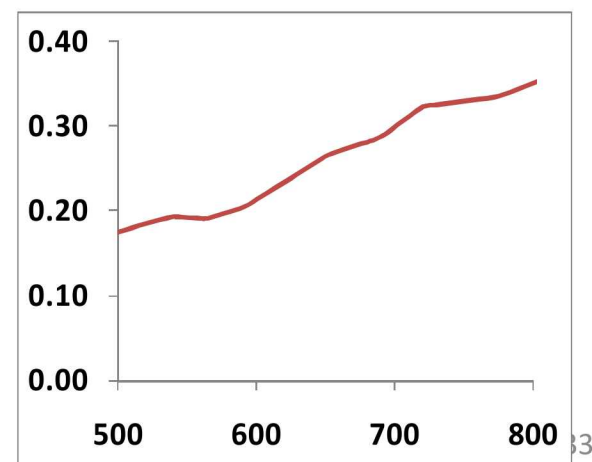
Silver(Ag)dispersion (Palik)



Composite- ϵ_{real}



Composite- ϵ_{imag}

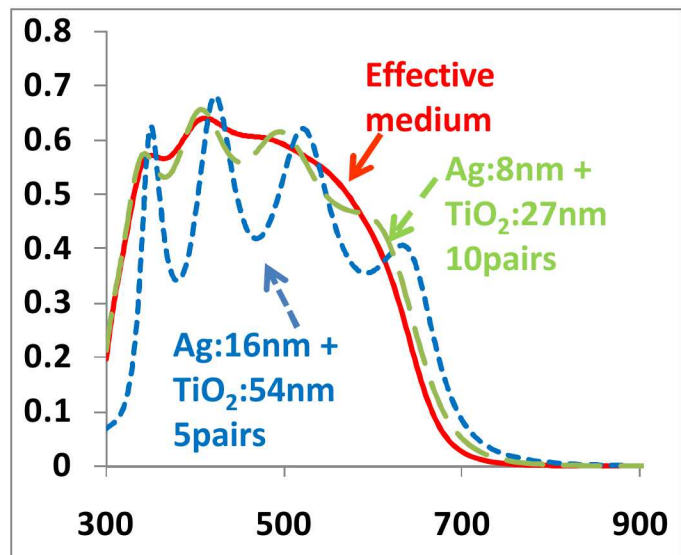


Effective Medium Multilayer Comparison

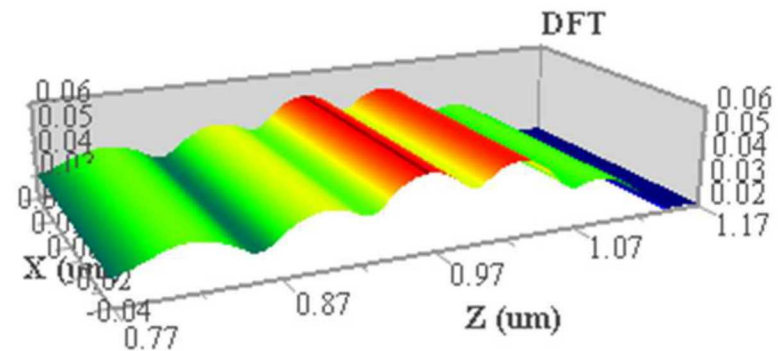
Finite Difference Time Domain Simulation



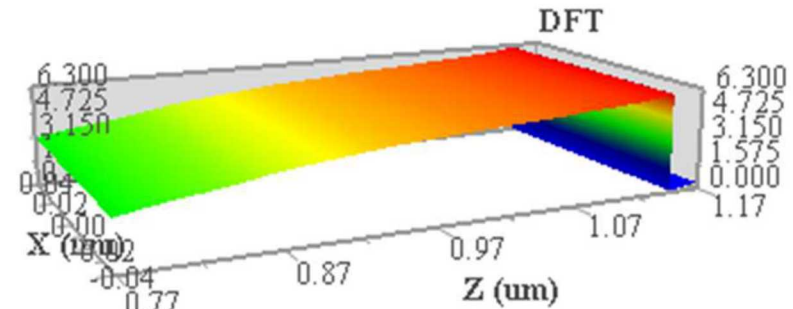
Ag/TiO₂ Composite
Ag = 16nm (23%); TiO₂ = 54nm (77%)



E field amplitude at $\sim 653\text{nm}$, ENZ point



E field phase at $\sim 653\text{nm}$, ENZ point



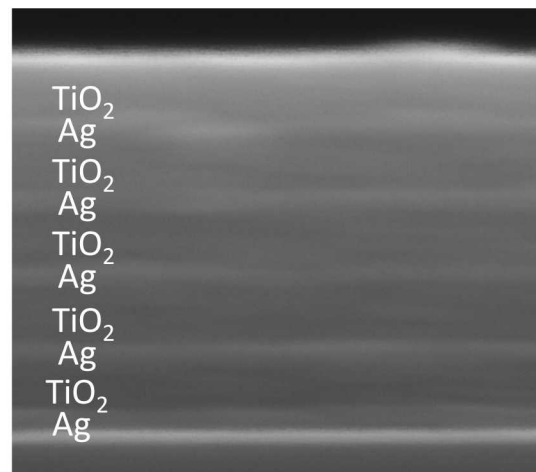
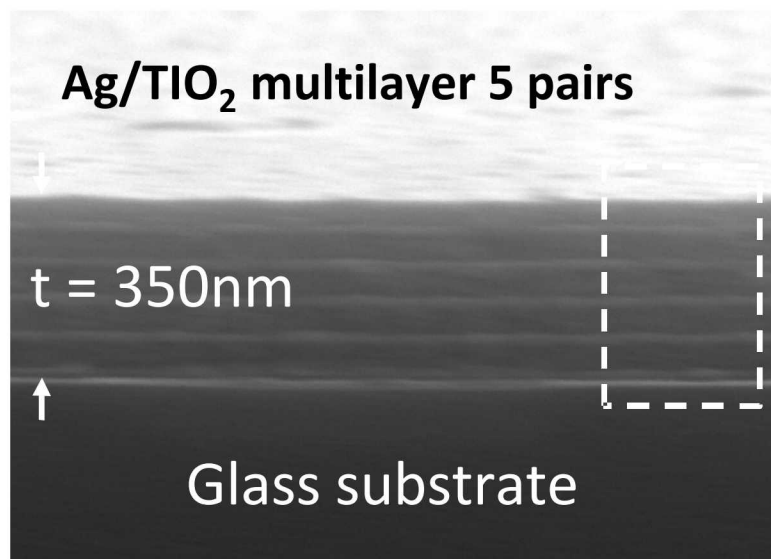
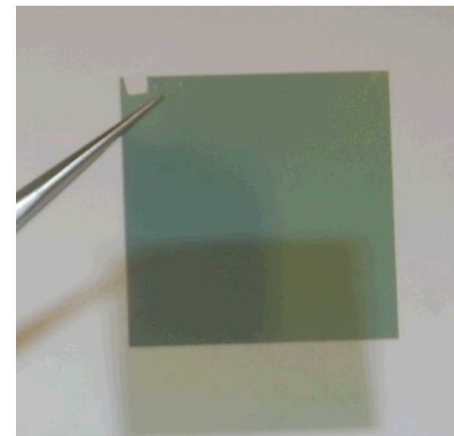
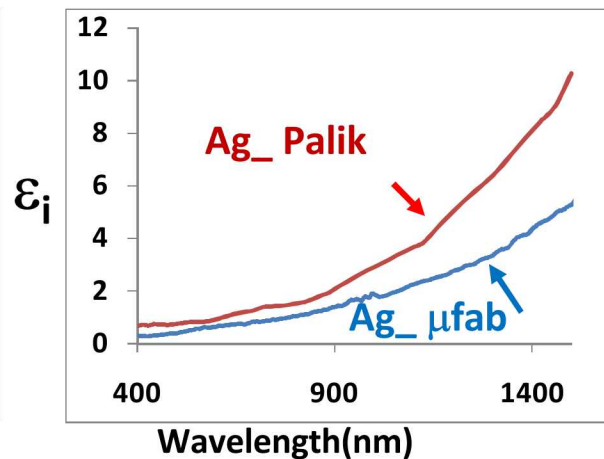
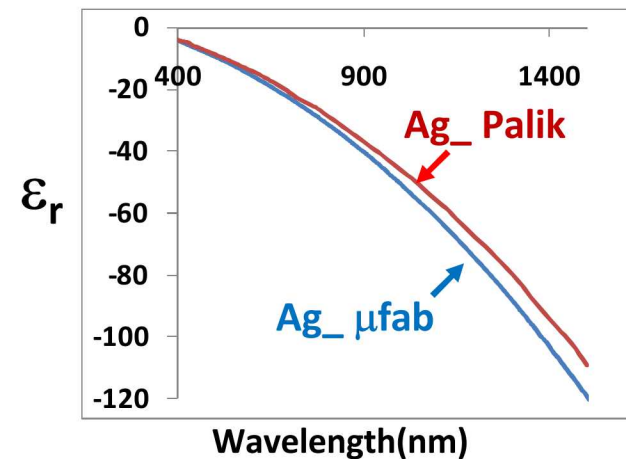
Small
Phase
Change

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

G. Subramania, A. J. Fischer, T. S. Luk , Appl. Phys. Lett. , 101, 241107(2012)

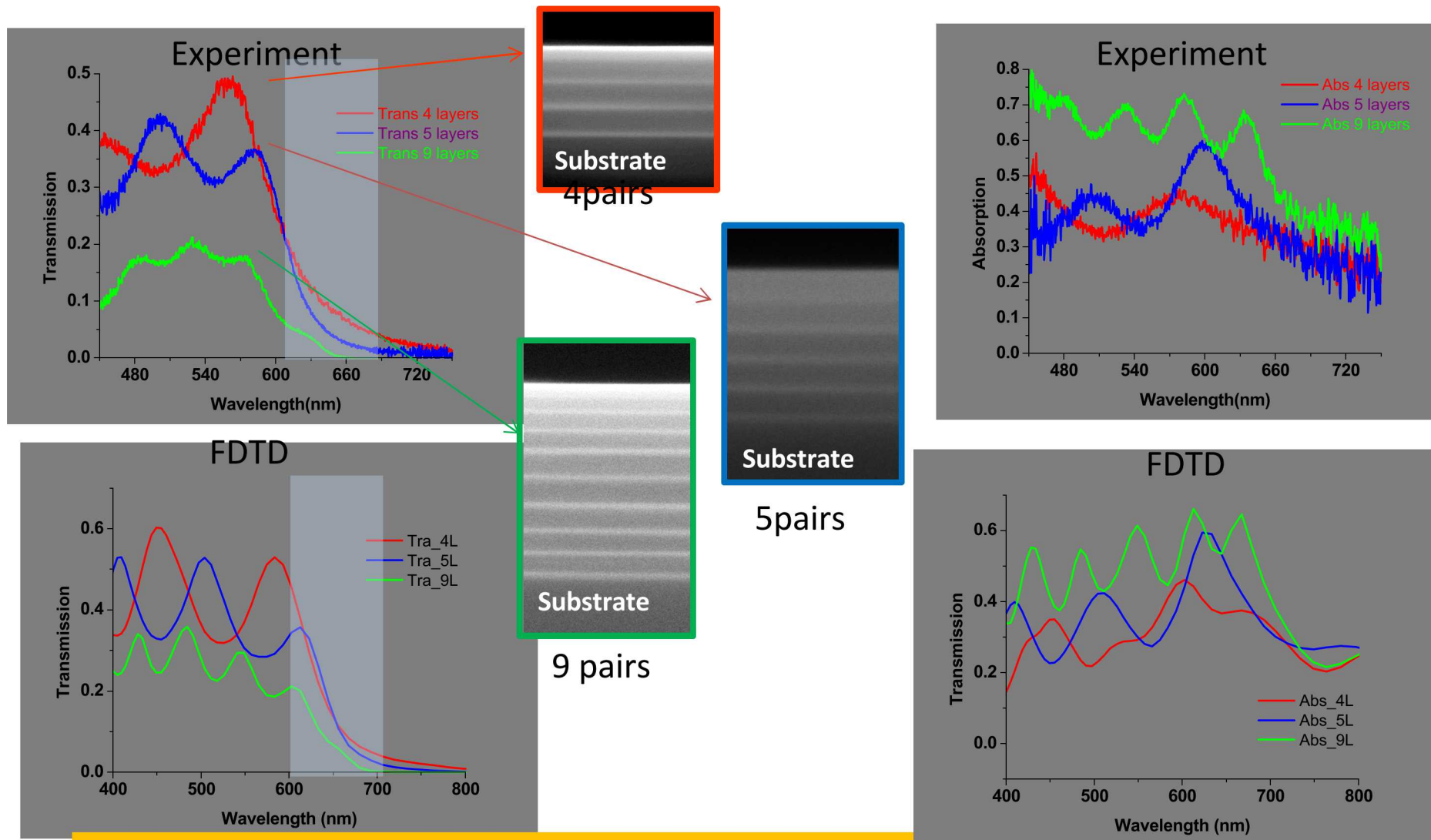
ENZ Sample Fabrication

Electron beam evaporation of alternating layers of Ag and TiO_2



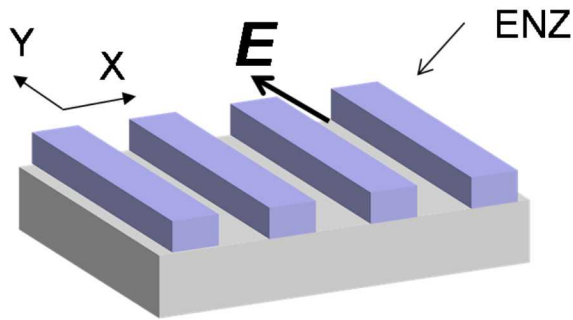
$\text{TiO}_2 = 54\text{nm}$
Ag = 16nm

Optical Characterization and FDTD Simulations



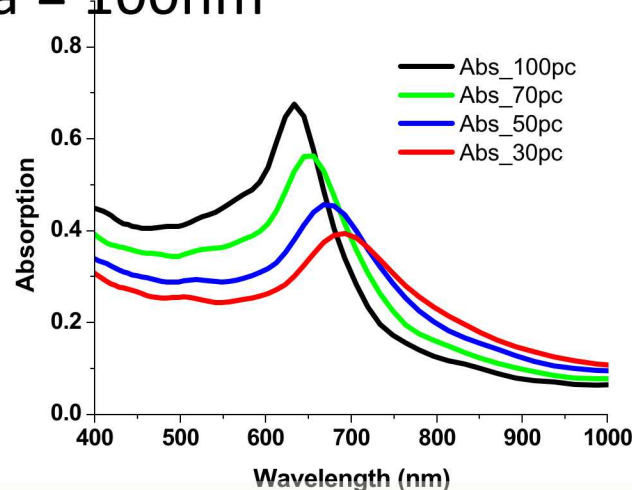
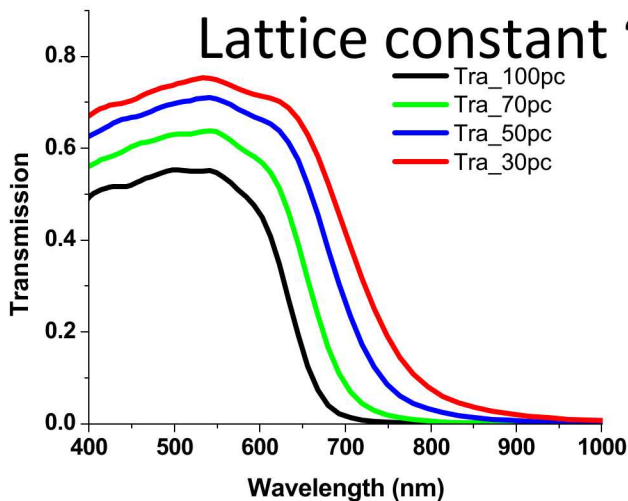
- Transmission reduces with increased number of pairs – Metal absorption
- Experimental absorption about 10% more than FDTD

Approach to Reducing Metal Absorption effects



$$\epsilon_{\text{effective}} = f \epsilon_{\text{dielectric}} + (1 - f) \epsilon_{\text{ENZ}}$$

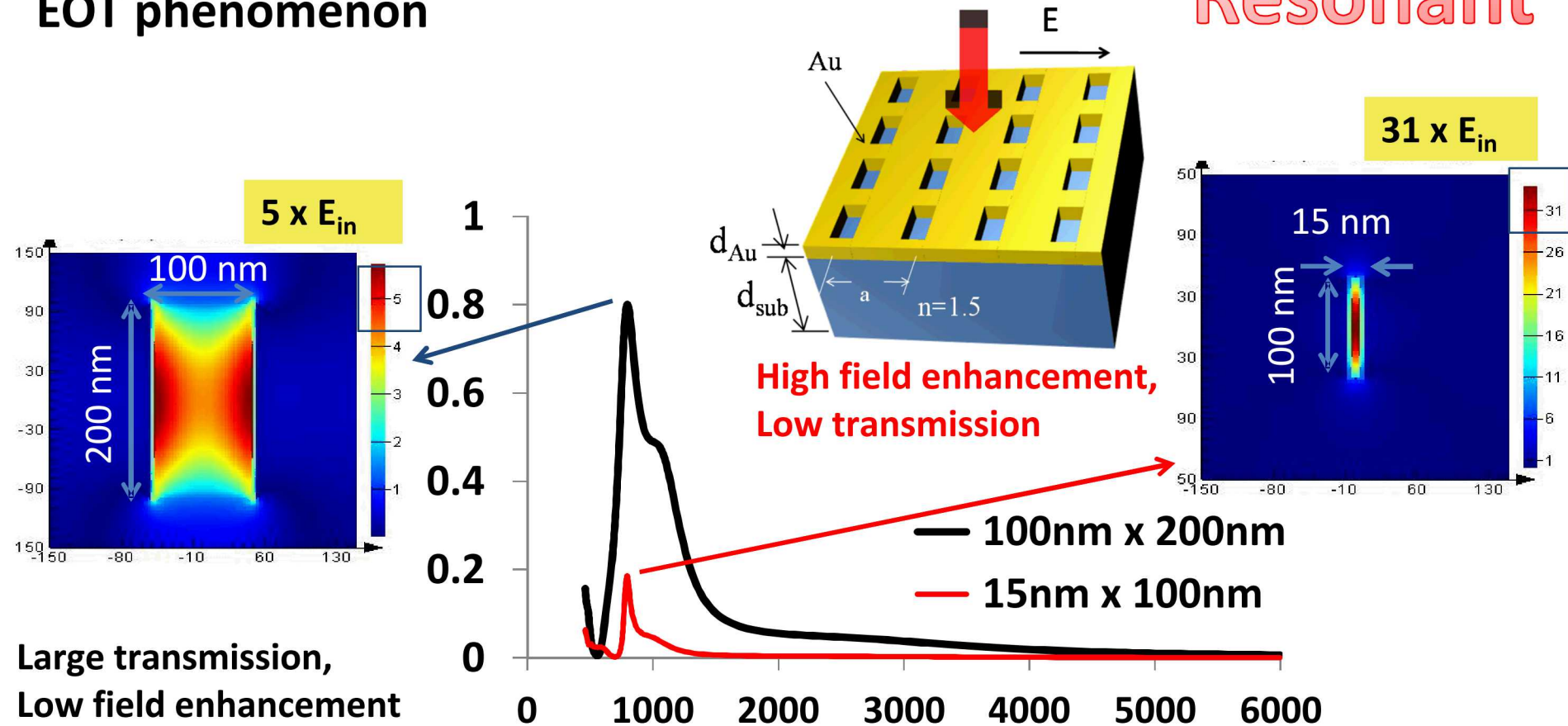
- Light polarized along the grating
- Ideally, grating period as small as possible for effective medium
- Increased transmission
- ENZ wavelength redshifts with grating duty cycle



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

Current approach : Surface plasmon based using EOT phenomenon

Resonant

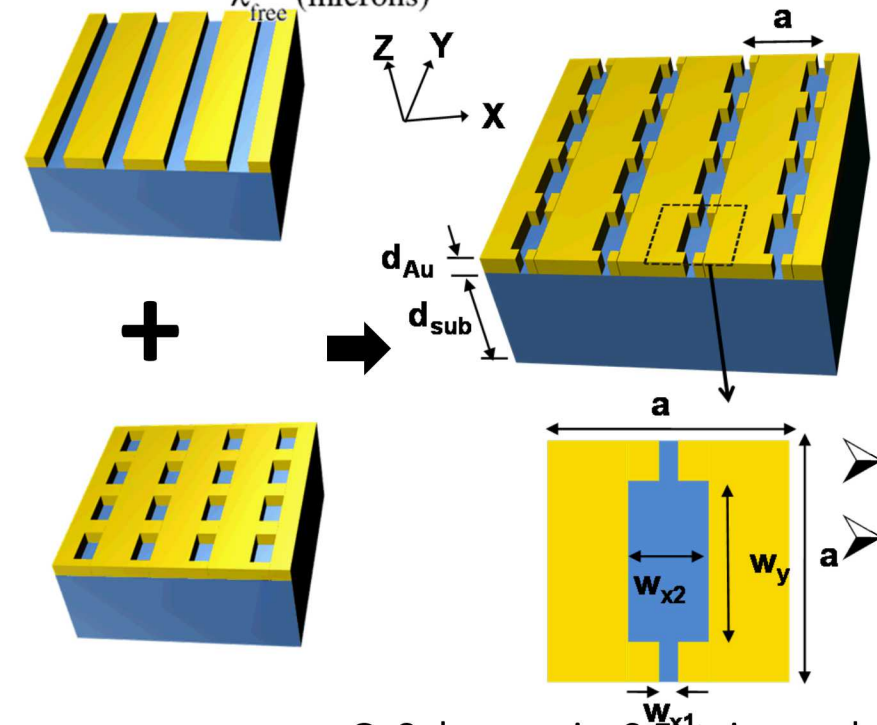
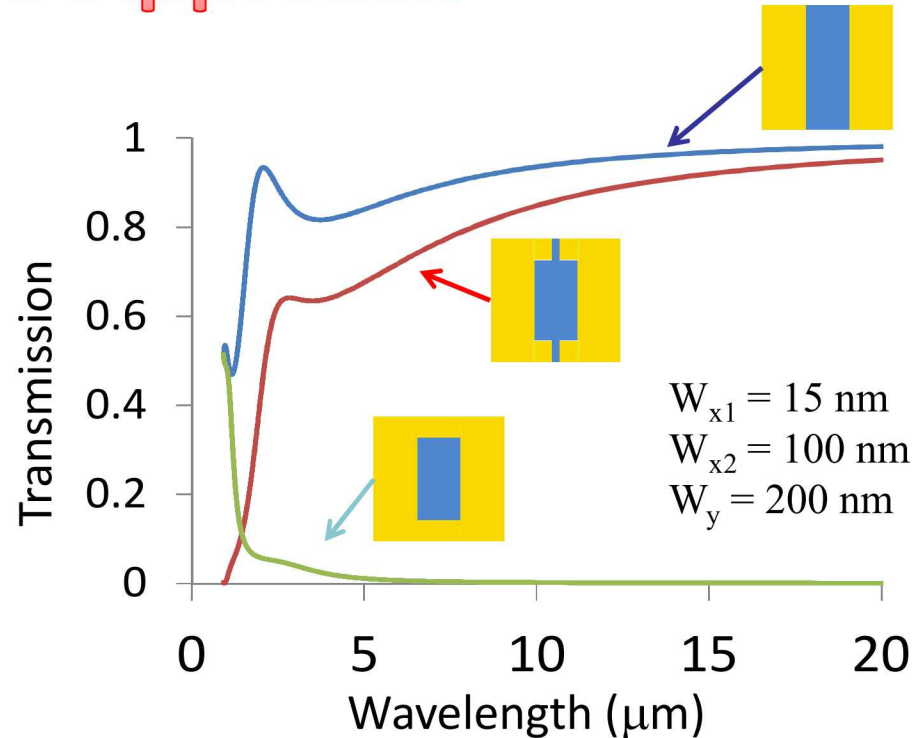
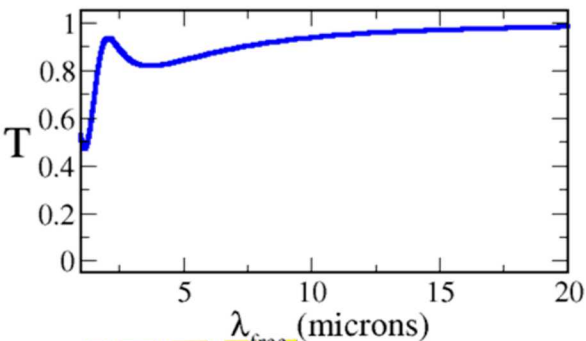


Can we achieve light confinement/field enhancement with broadband operation?

The Double-groove Structure

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

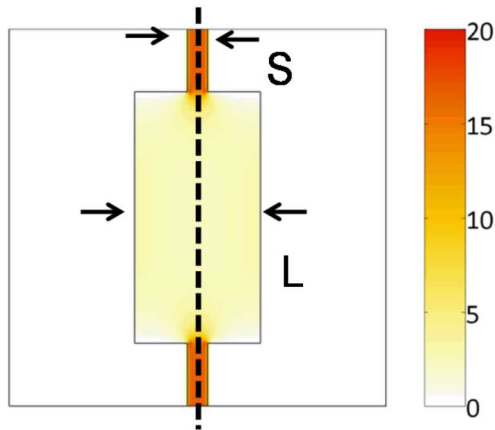
A: Non-resonant Approach



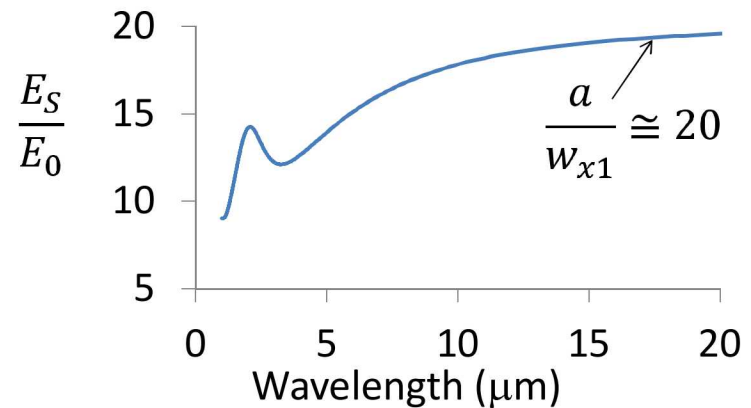
Broadband transmission
Large electric field enhancement and confinement

Key Results

Electric field (E_x)

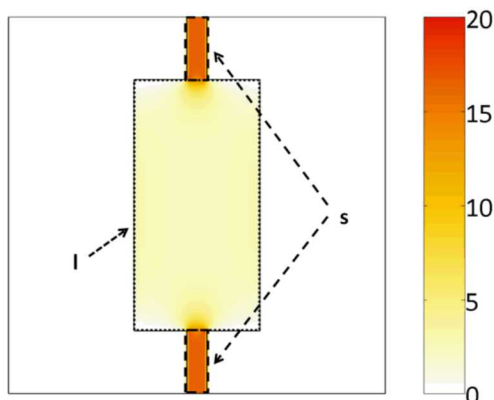


Electric field enhancement in the small gap

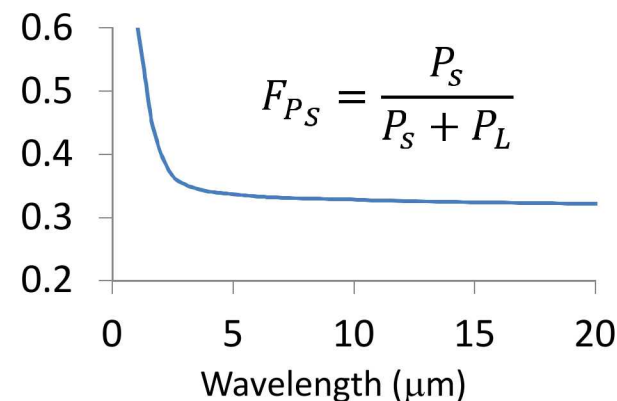


We can achieve large electric field enhancements in an ultra-subwavelength area ($\sim (\lambda/250)^2$) across broadband that can be controlled via structural geometry

Power Density (S_z)

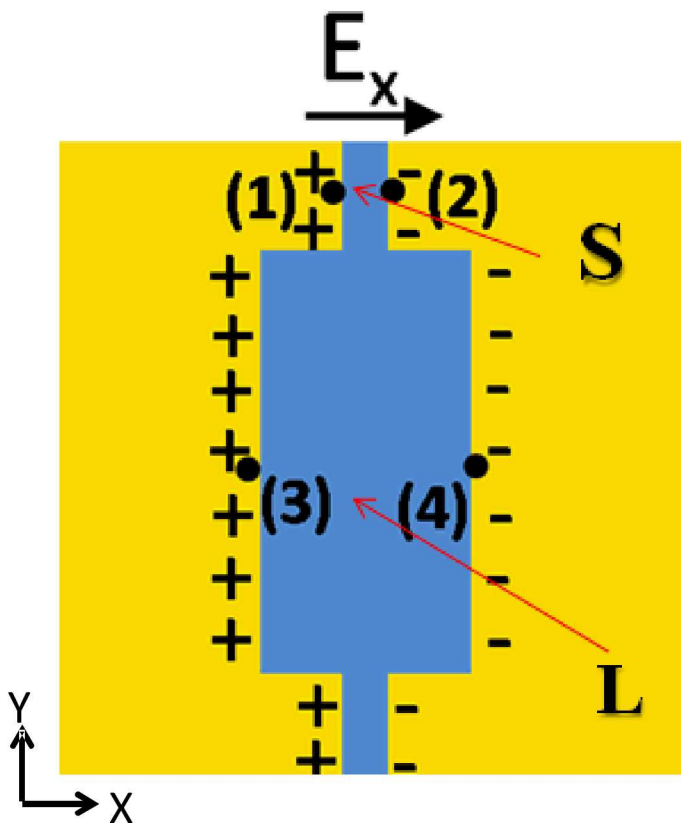


Power Fraction through the small gap



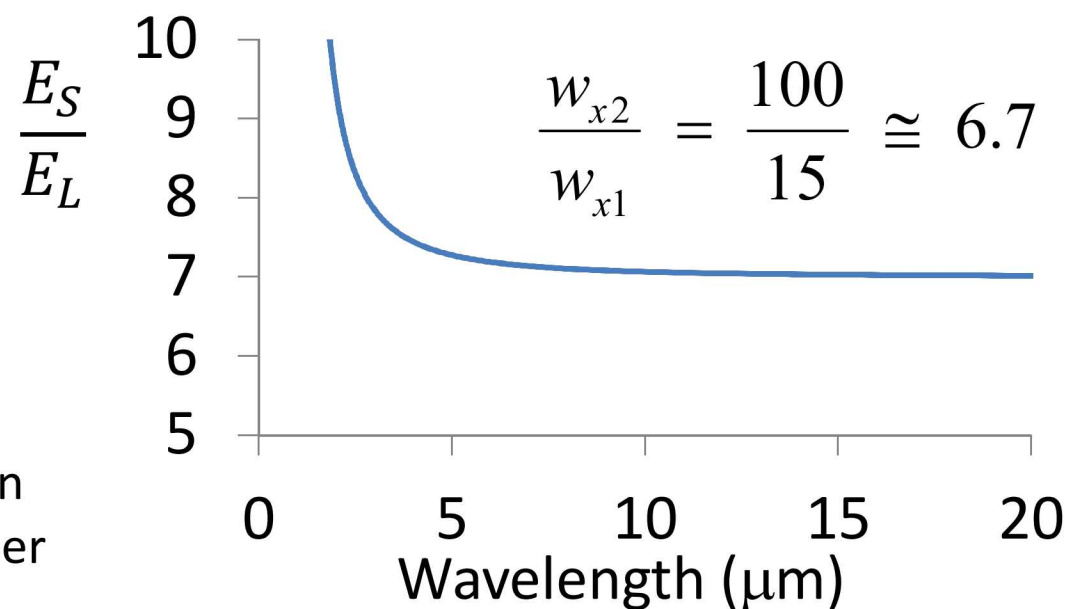
Surprisingly, nearly 30% of the transmitted power that is channeled through an area $\sim (\lambda/250)^2$ that is $1/60^{\text{th}}$ of the unit cell area.

Mechanism: Quasi-static response



- Voltage across the small and large gaps are nearly equal

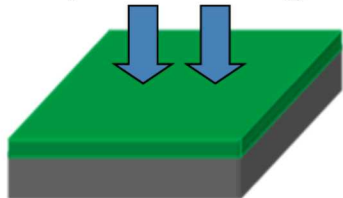
$$V_S \cong V_L \Rightarrow \frac{E_S}{E_L} = \frac{w_{x2}}{w_{x1}}$$



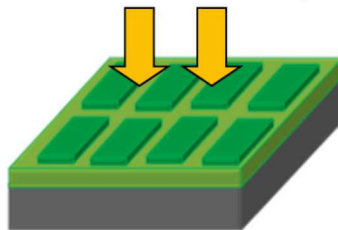
- Near-instantaneous response of charges even at mid-IR
- No effective current flow between small and large gap region on either side

Fabrication- Some recent results

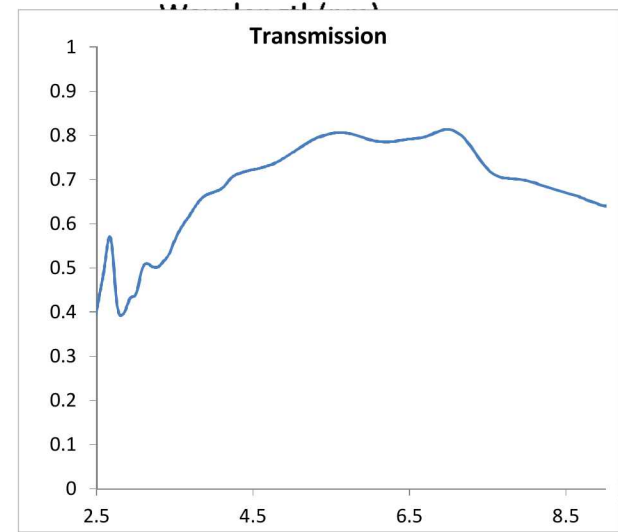
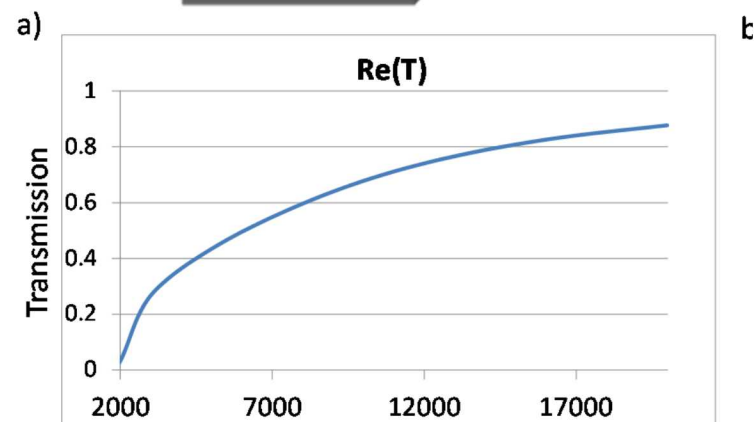
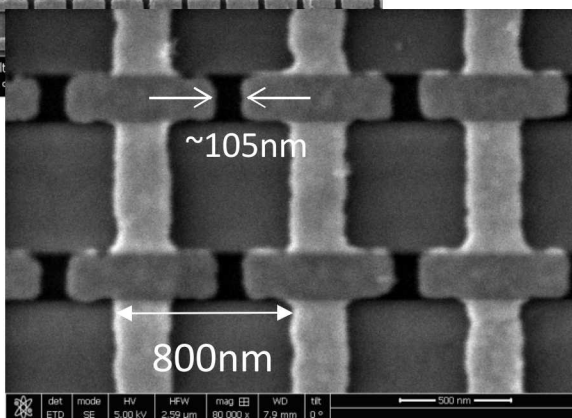
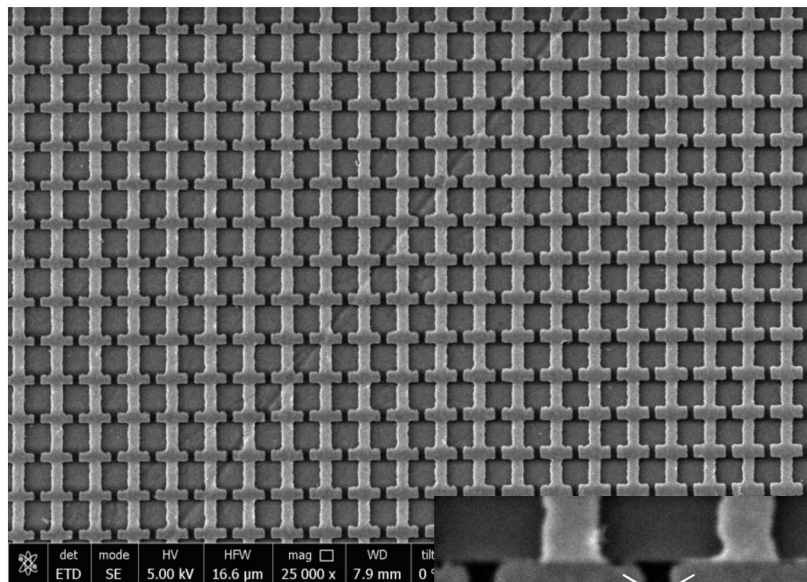
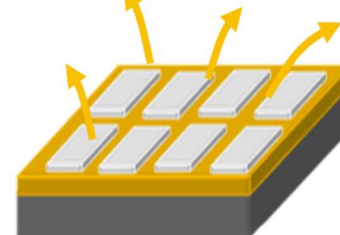
Electron beam
patterning of PC



Metal deposition



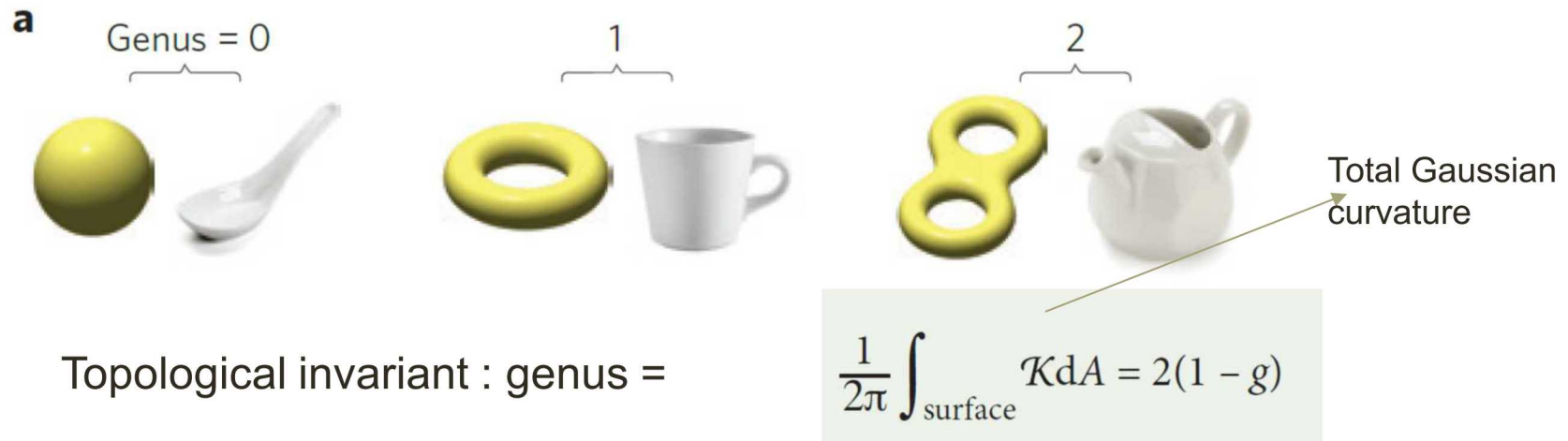
Metal Lift-off



Topological Photonics

Topological Protection

Topological Protection: Approaches that exploit topological properties of the phase space of a system can offer stability and robustness to the system of interest from external disturbances such as scattering, decoherence etc.



- Need to create a topological transition to affect the system.

➤ Non-trivial topological system can provide new ways of control in electronics and **photonics**. (Eg. Loss-less unidirectional, scatter-free transport)

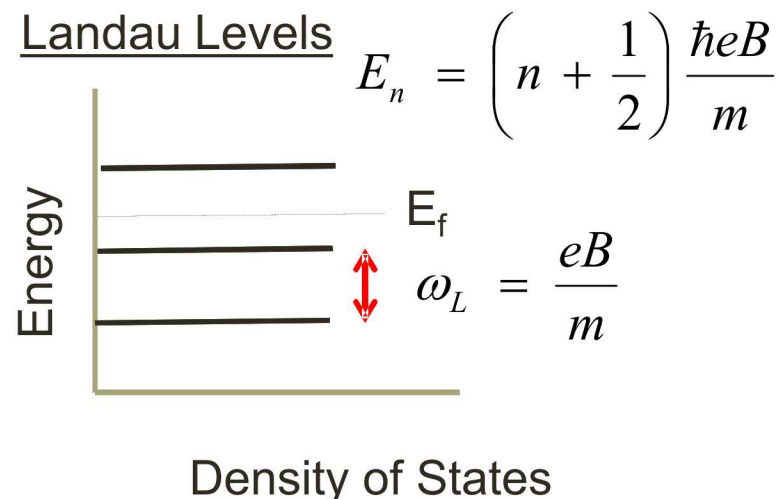
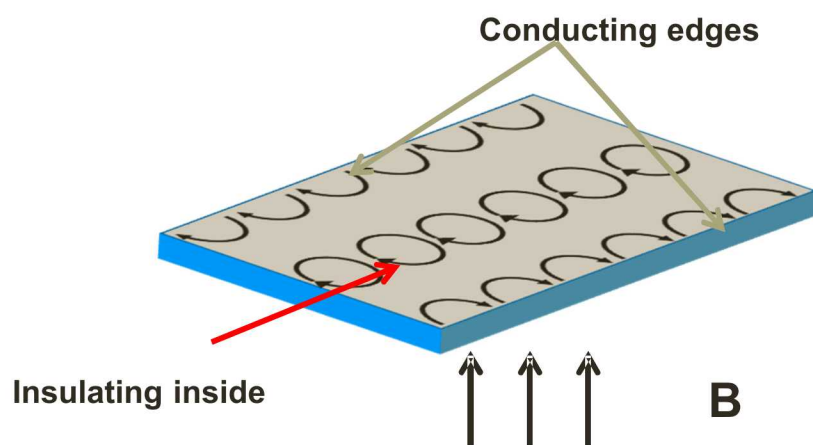
L. Lu, J. D. Joannopoulos, and M. Soljacic, "Topological photonics," Nat Photon **8**, 821-829 (2014).

Motivation: Topological Systems in Electronics

Electronic Topological Insulators : Systems exhibiting Quantum Hall Effect → 2DEGs

Time reversal symmetry is broken by applying magnetic (B) field

- Discrete highly degenerate Landau Levels
 - Conducting edge states within insulator gap
 - Topologically protected “one way” electronic transport
- *Needs high B fields*
 - *Low temperatures*

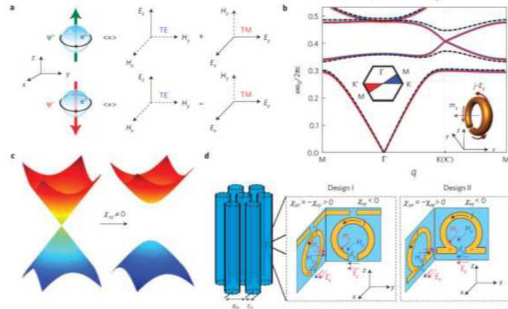


It turns out appropriately designed photonic structures can exhibit similar topological properties too!

F. D. M. Haldane and S. Raghu, Phys. Rev. Lett.
100 (1), 013904 (2008).

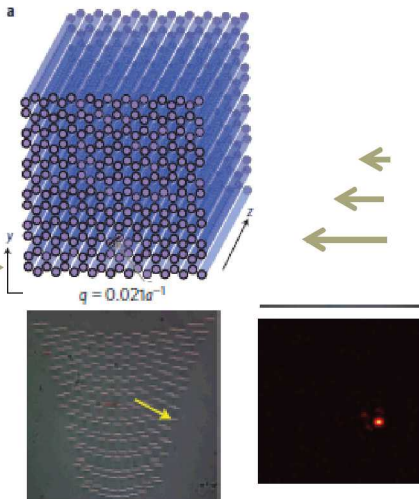
Topological Photonics Research Activities

Metamaterial Photonic Topological Insulator



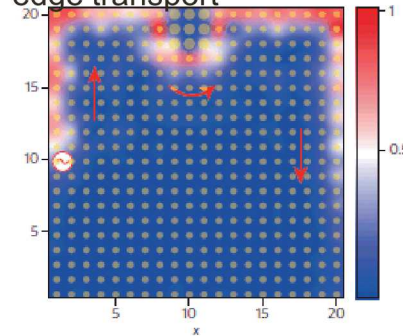
A. B. Khanikaev et.al. *Nat Mater* **12** (3), 233-239 (2013).

Strain induced pseud mag. field in optical fiber arrays and edge transport



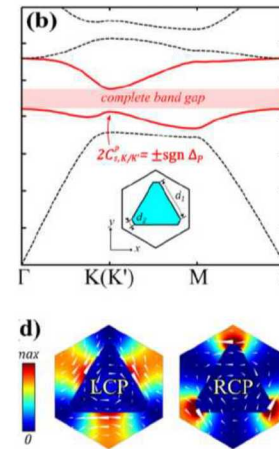
M.Rechtsman et.al. *Nat. Phot.* **7** (2013)

Simulation of Oneway edge transport



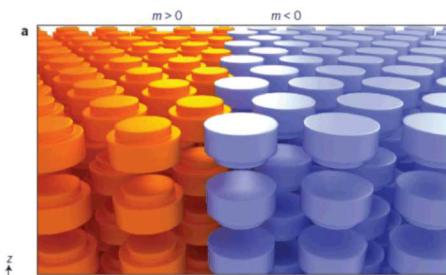
K.Fang, Z. Yu, S.H.Fan, *Nat. Phot.* **6**, (2012)

Valley hall Photonic Topological Insulator



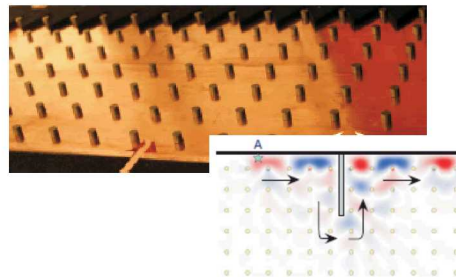
M. Tzuhsuan and S. Gennady, *New Jn. Phys.* **18** (2), 025012 (2016).

3D All dielectric PTI



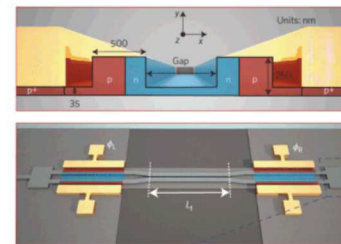
A. Slobozhanyuk, et.al., *Nat Photon* **11** (2), 130-136 (2017).

One- way scatter transport at microwave frequency ~ 4GHz in 2DPCs



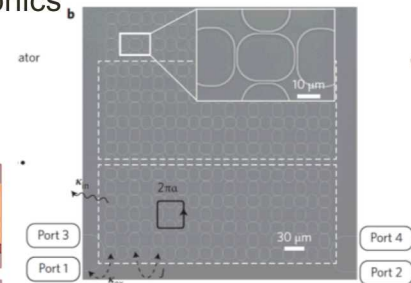
Z. Wang, Y. Chong, et.al., *Nature* **461**, 772 (2009).

Non-reciprocity in optical regime



L. D. Tzuang, et. al. *Nat Photon* **8** (9), 701-705 (2014).

Topological edge states in silicon photonics



S. Mittal, V. V. Orre and M. Hafezi, *Opt. Expr.* **24**, 15631(2016).

Topological Photonics Spin Hall in Dielectric PC

PRL 114, 223901 (2015)

PHYSICAL REVIEW LETTERS

week ending
5 JUNE 2015

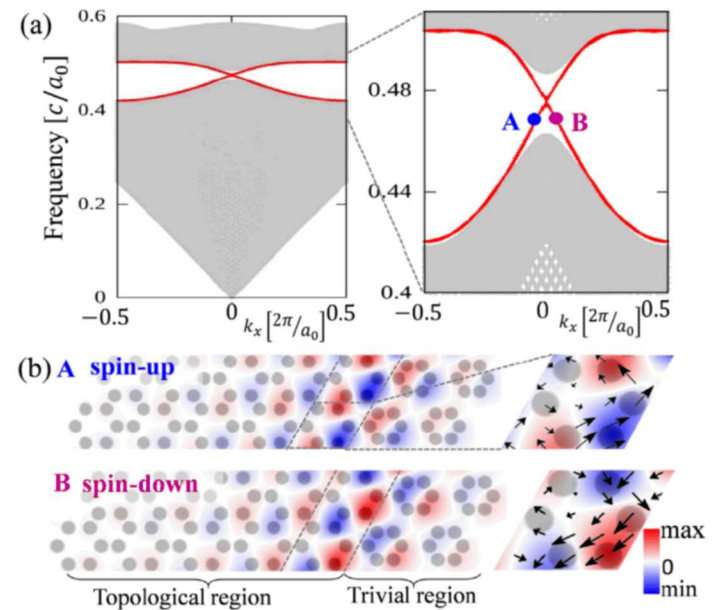
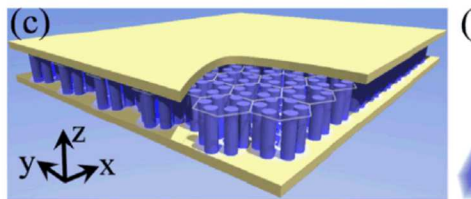
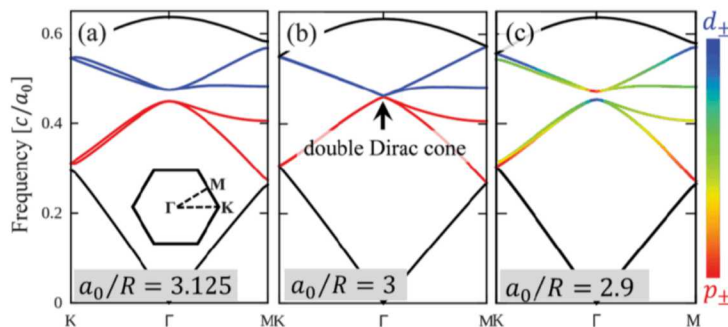
Scheme for Achieving a Topological Photonic Crystal by Using Dielectric Material

Long-Hua Wu and Xiao Hu*

*International Center for Materials Nanoarchitectonics (WPI-MANA), National Institute for Materials Science,
Tsukuba 305-0044, Japan*

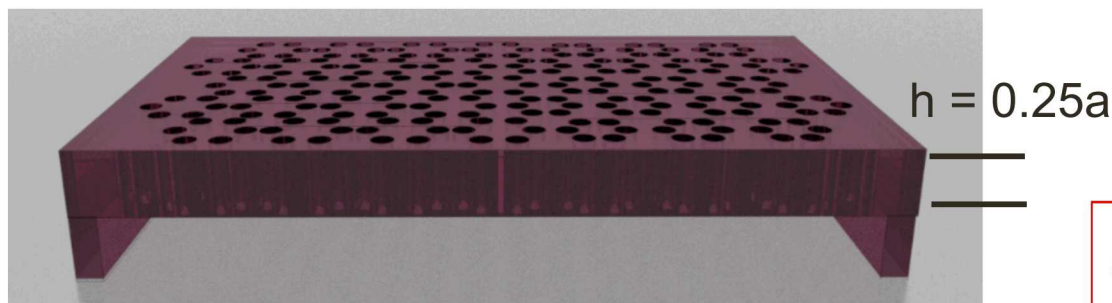
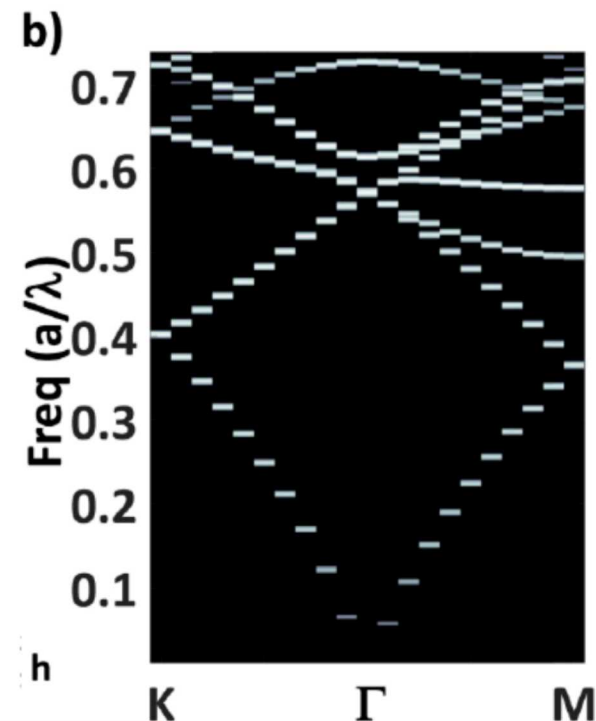
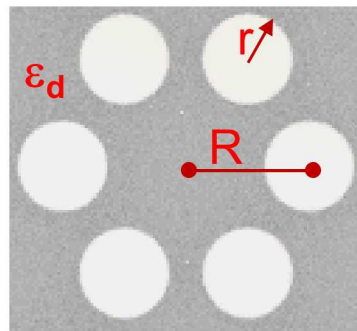
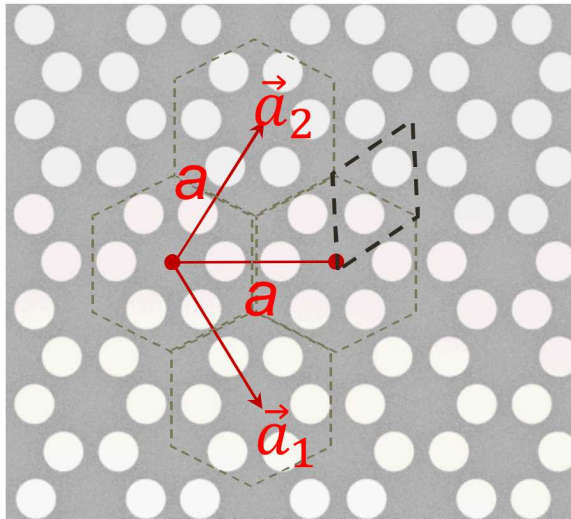
Graduate School of Pure and Applied Sciences, University of Tsukuba, Tsukuba 305-8571, Japan

(Received 10 February 2015; published 3 June 2015)



Modified honeycomb lattice of hexagonal cylindrical dielectric rods

Photonic Bandstructures Honeycomb Photonic Crystal



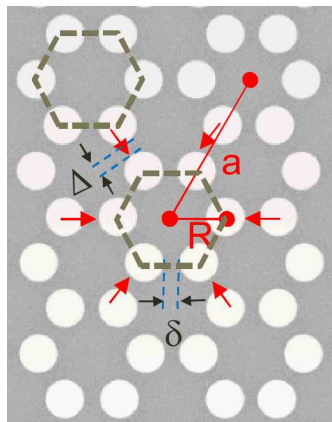
$$a/R = 3.0$$

$$r = 0.13a$$

Calculated with FDTD (Lumerical ®)

Circular Hole Array Honeycomb Lattice Photonic Crystal

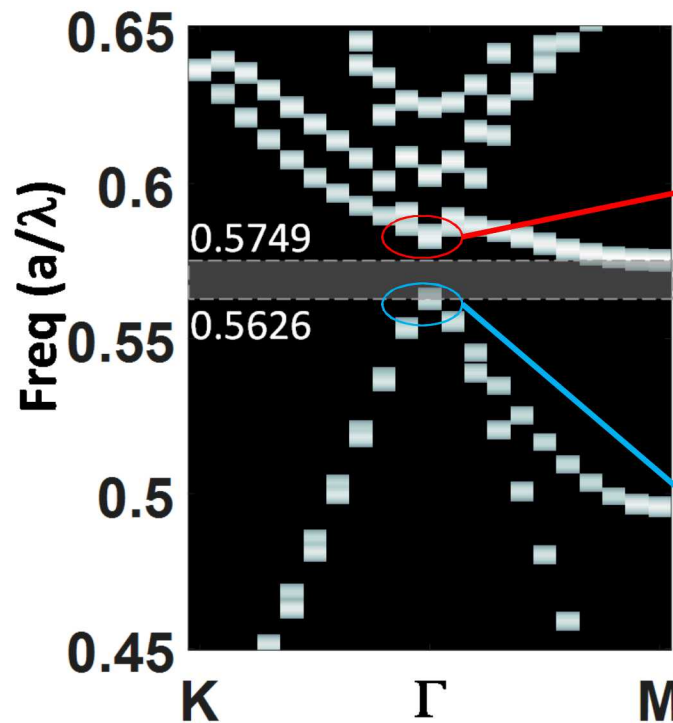
Compressed lattice $a/R = 3.1$



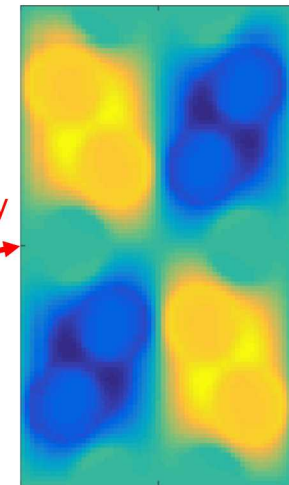
$$\Delta = a - 2(R + r)$$

$$\delta = R - 2r$$

Topologically Trivial PC



d_{xy}

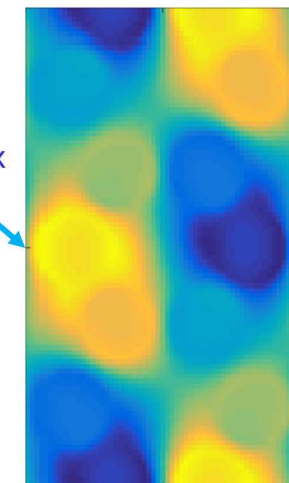


Re(Hz)

Max

Min

p_x

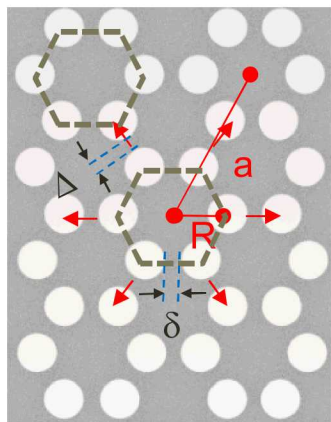


Max

Min

Circular Hole Array Honeycomb Lattice Photonic Crystal

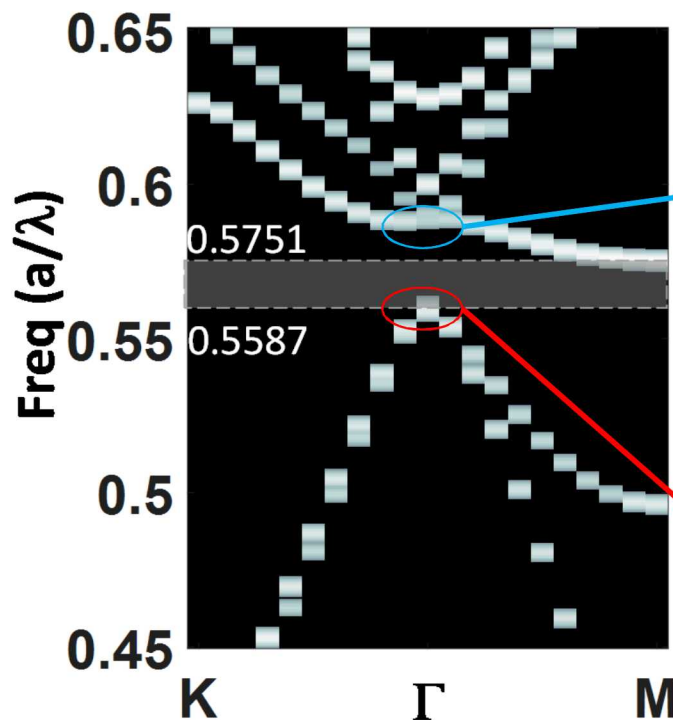
Expanded lattice $a/R = 2.9$



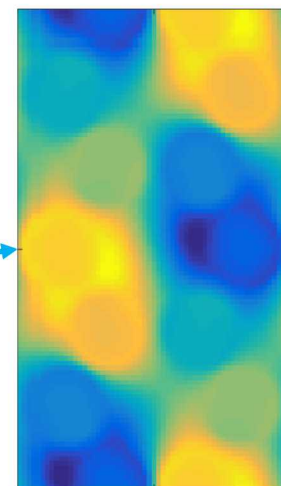
$$\Delta = a - 2(R + r)$$

$$\delta = R - 2r$$

Topologically Non-trivial PC



p_x

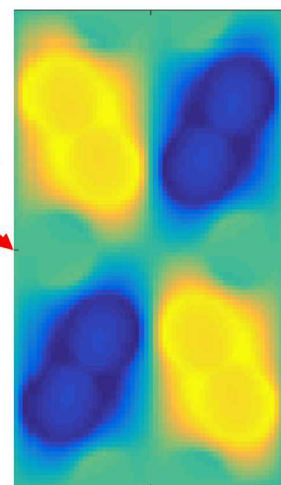


Re(Hz)

Max

Min

d_{xy}



Max

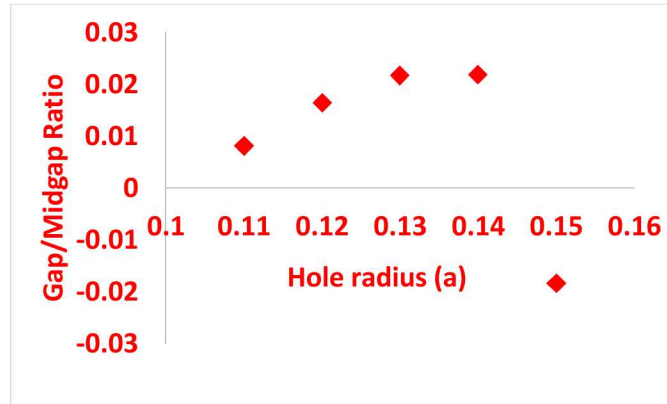
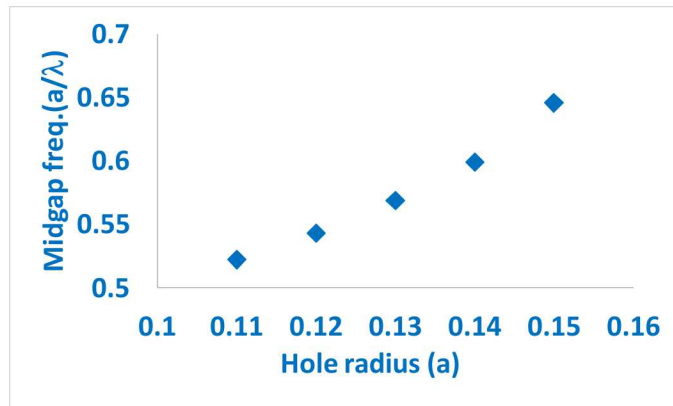
Min

Circular Hole Array Honeycomb Lattice Photonic Crystal

Hole radius 'r' dependence

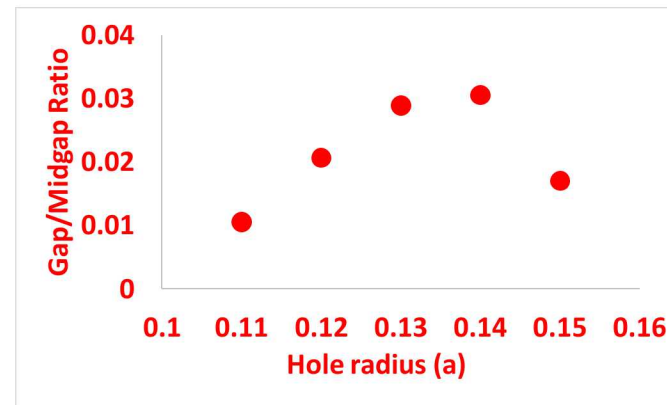
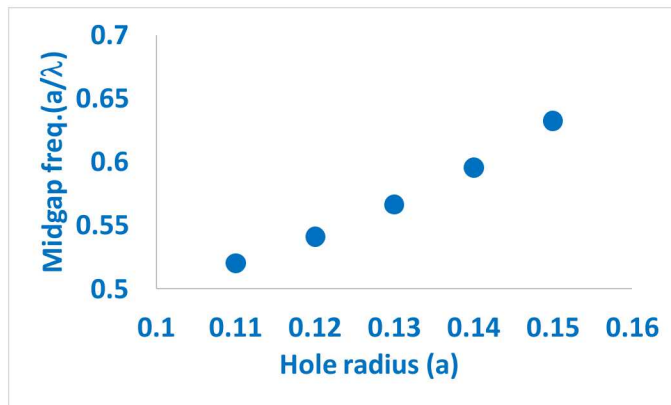
Compressed $a/R = 3.1$

Membrane thickness
'h' = $0.25a$



At $\lambda \sim 1500\text{nm}$
 $\Delta\lambda \sim 30\text{nm}$

Expanded $a/R = 2.9$

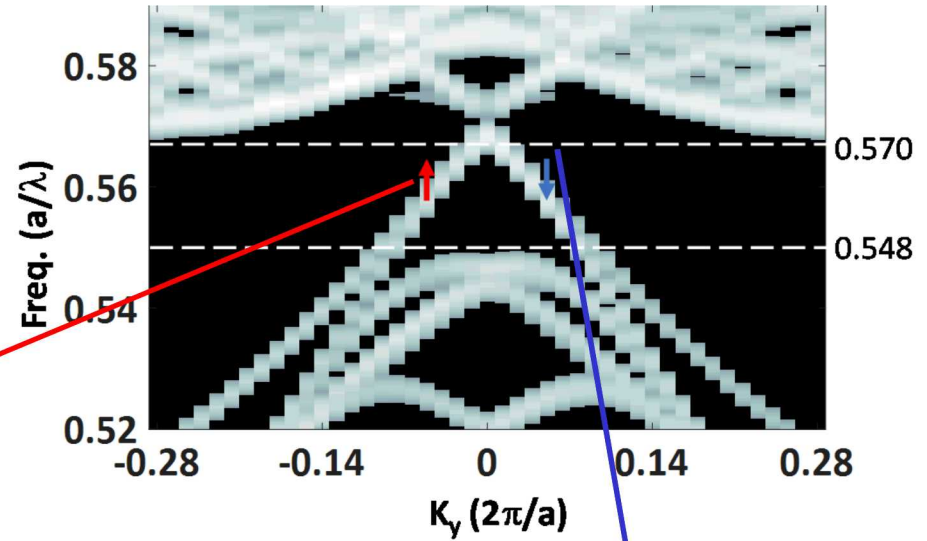
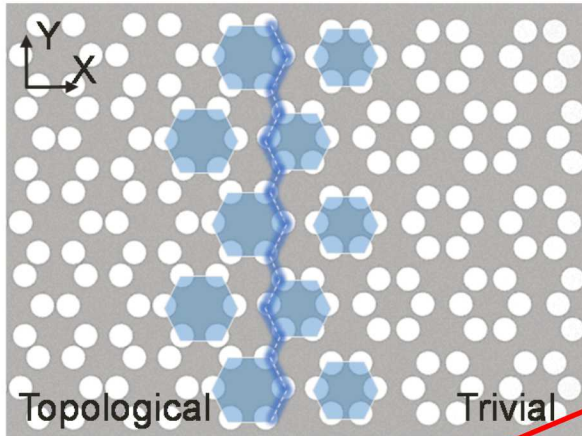


At $\lambda \sim 1500\text{nm}$
 $\Delta\lambda \sim 45\text{nm}$

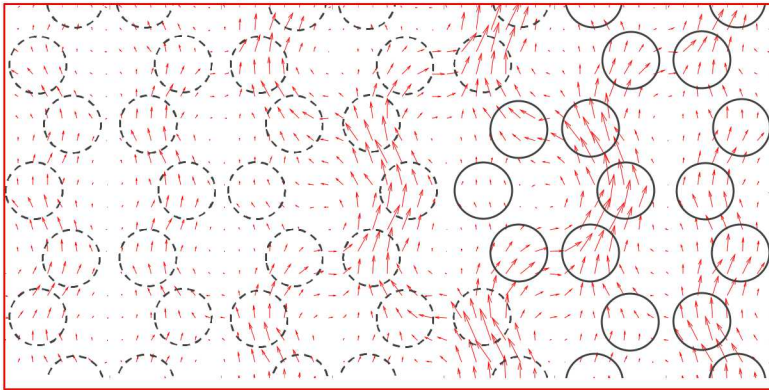
Reasonable operational bandwidth possible at the telecom frequencies

Unidirectional Edge State Propagation

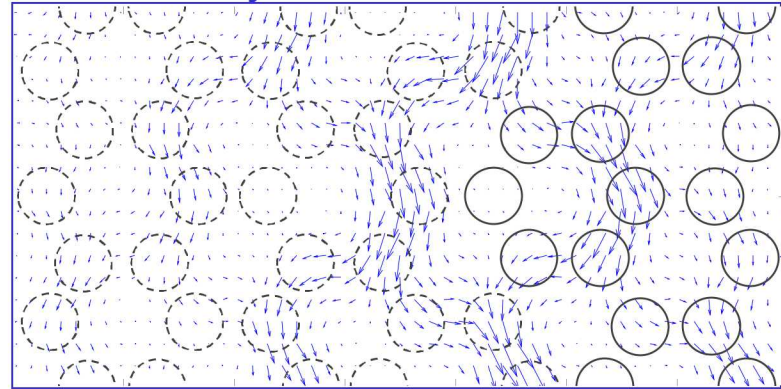
Zig-zag interface



$k_y = -0.05(2\pi/a)$



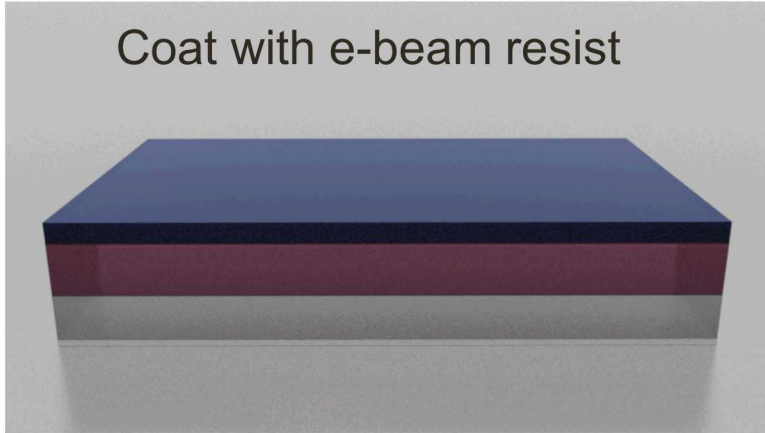
$k_y = 0.05(2\pi/a)$



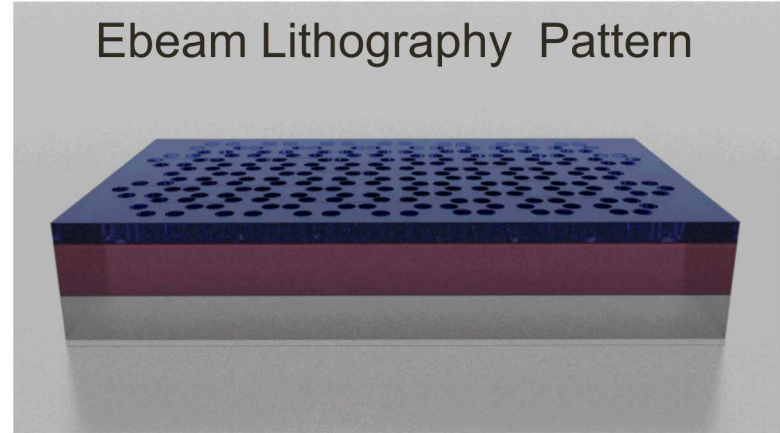
Next ...

Fabrication on Silicon on Insulator (SOI) - Membrane

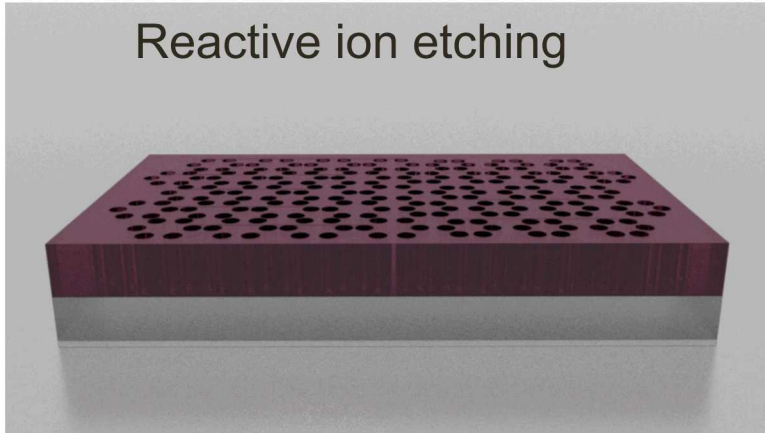
Coat with e-beam resist



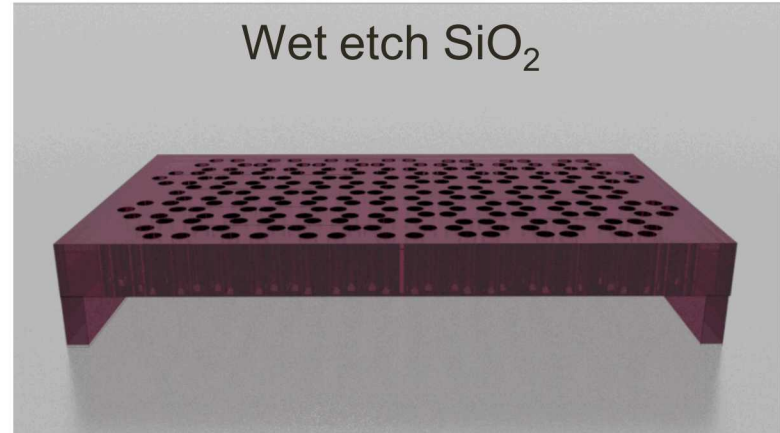
Ebeam Lithography Pattern



Reactive ion etching

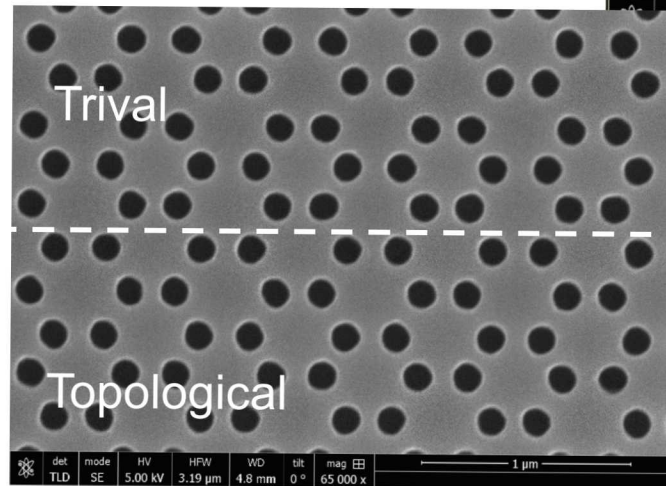
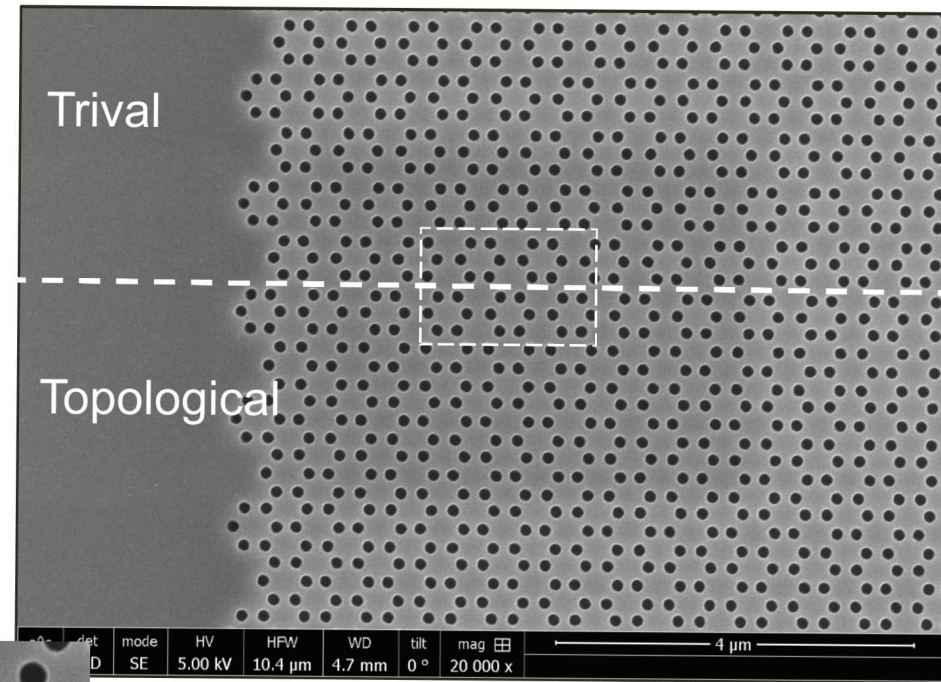
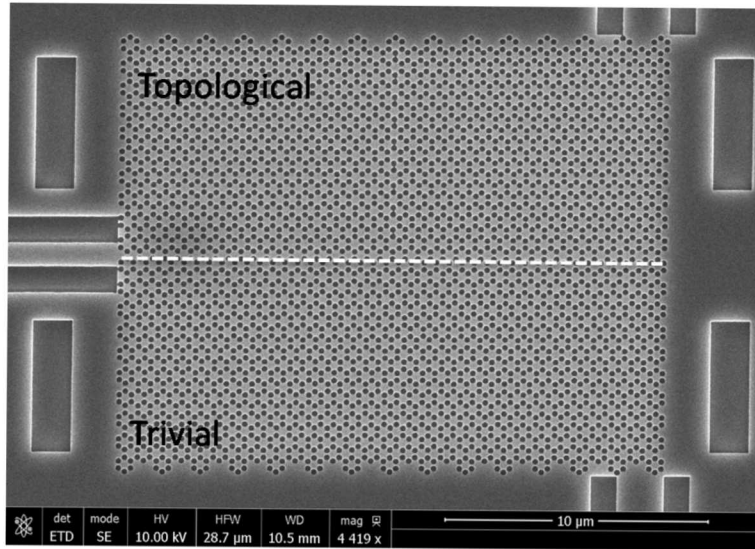


Wet etch SiO_2



Fabrication on Silicon on Insulator (SOI) - Membrane

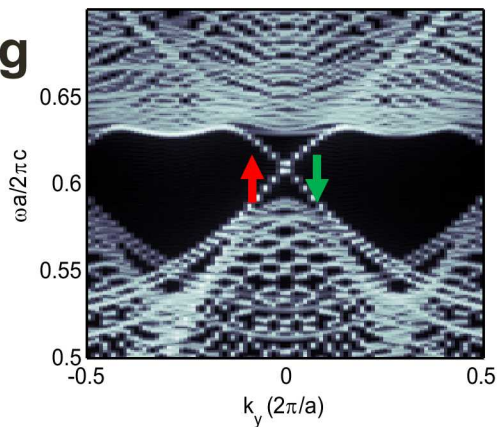
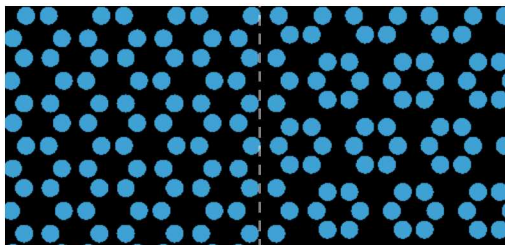
Topological/Trivial Interface structure



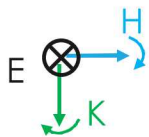
Measurement in progress ...

Topological edge state in III-Nitride Honeycomb Photonic Crystal Rods

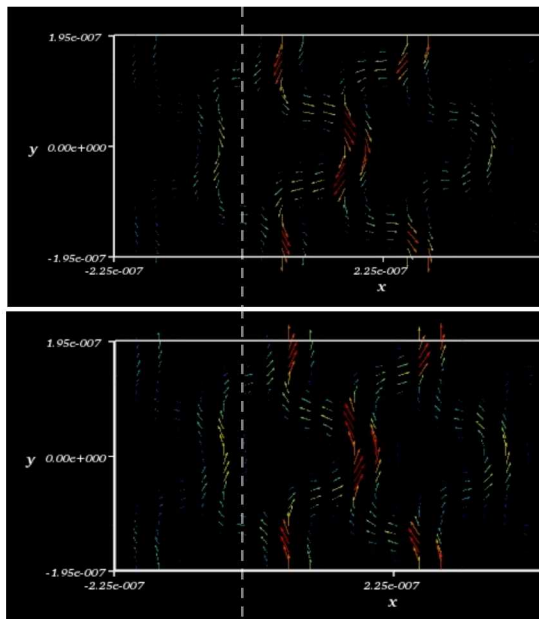
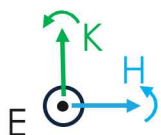
Modeling



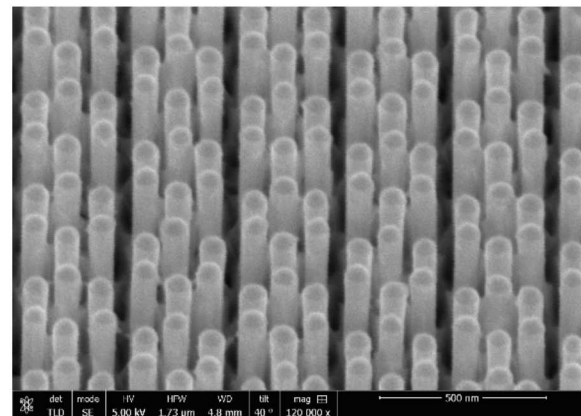
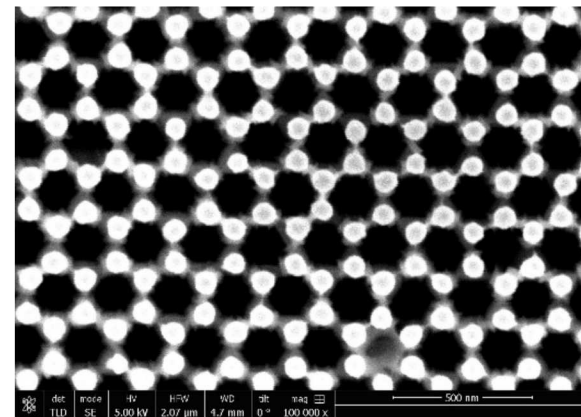
Spin-down state
 $a/\lambda = 0.618$



Spin-up state
 $a/\lambda = 0.60$

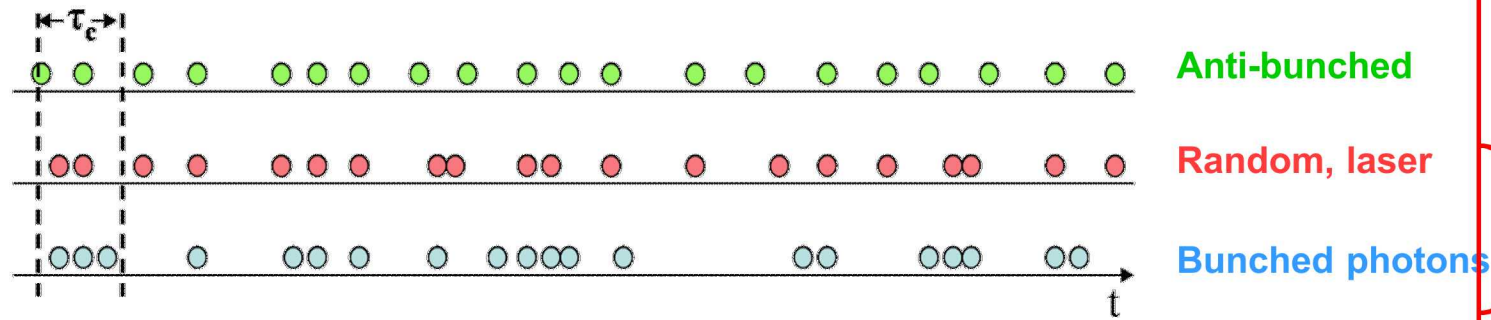


Structure in GaN



Quantum Dots for Single Photon Sources

Single Photon Source: Photon Statistics



Quantum

$g(2)(t=0) < 1$
e.g., SPS

Classical

$g(2)(t=0) \geq 1$
e.g., Thermal, LED, Laser

source: J.S. Lundeen

• Quantum communication

- High bit rates than attenuated laser
- Long distance secure comm.
- Quantum repeaters (with indistinguishability)

• Quantum metrology

- Measurement of low absorption
- Single molecule level detection (in combination with high efficiency SPD)

• Quantum computing

- Qubit operations
- 'flying' qubits

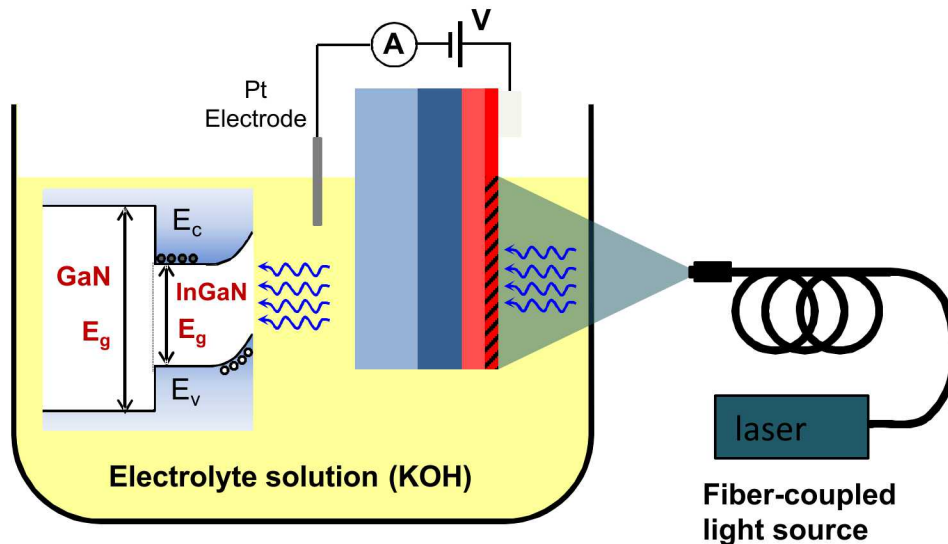
Desired properties of practical single photon sources (SPS)

- ❖ Near 100% probability of emitting single photon : $g_2(0) \sim 0$
- ❖ High single photon rates
- ❖ High extraction or collection
- ❖ Mode quality
- ❖ Room temperature operation
- ❖ Electrical injection
- ❖ $\sim 100\%$ indistinguishability

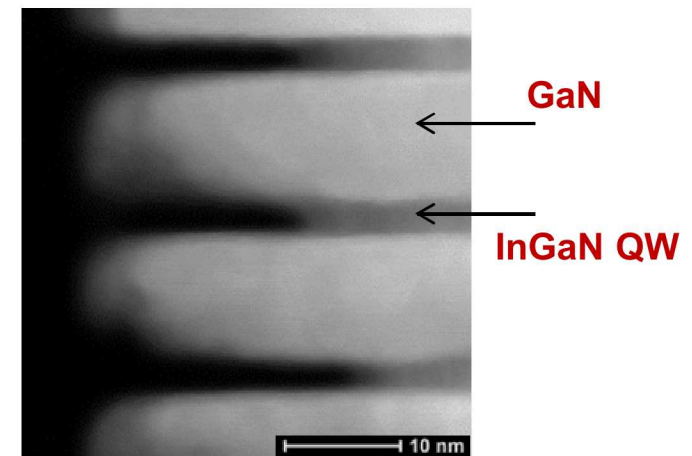
Motivation for InGaN Quantum Dot SPS

Room temperature, electrically-injected, chip-scale single photon source

- Large exciton binding energy so can enable room temp. operation
- Path to electrical-injection/chip-scale integration
- **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 ($\sim 0.1\text{M}$) typically used as electrolyte



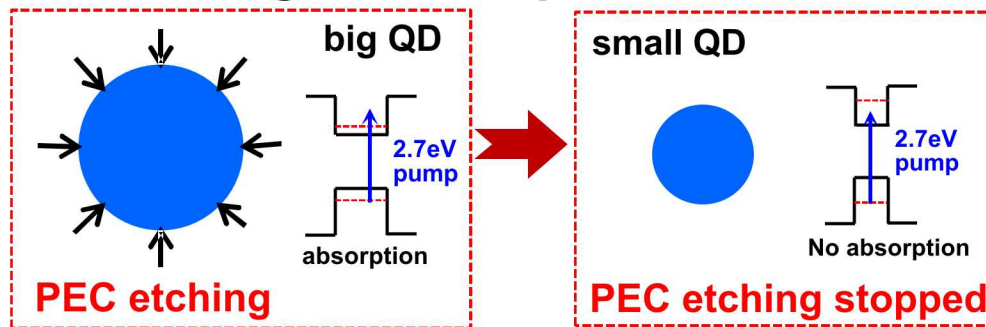
PEC etched InGaN/GaN QWS



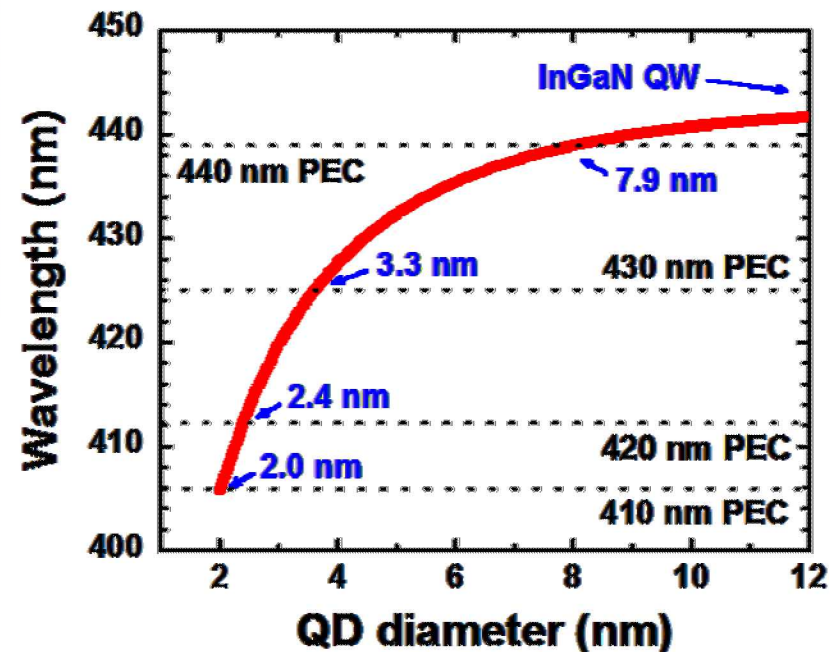
Fabrication of InGaN QDs via PEC etching

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 $E_g > E_{\text{photon pump}}$
- **Self-terminating etch process**
- **Band gap selective**
- **QD size depends on PEC wavelength**
- **Monodisperse QD distributions ??**



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

Transmission Electron Microscope Images

Capped InGaN QW

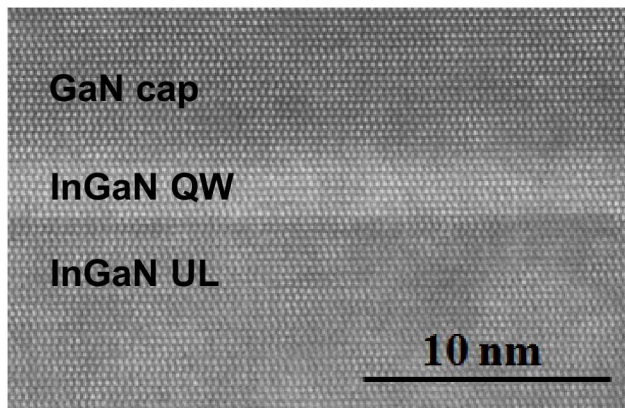


InGaN QD

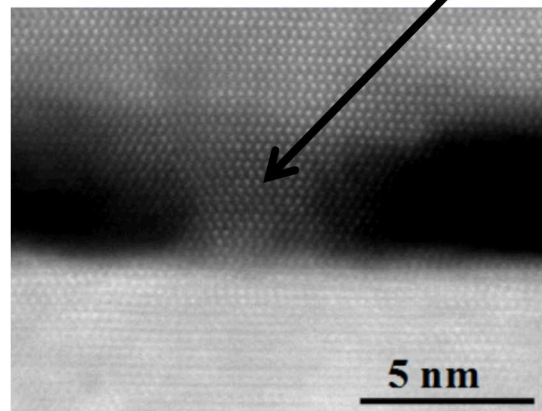


- High-angle annular dark-field (HAADF) TEM images
- Sample etched at 420 nm
- EDX mapping shows that dots are InGaN
- InGaN QDs are epitaxial to the underlying GaN
- 2% InGaN underlayer + GaN cap
- GaN cap provides partial passivation

before PEC etch

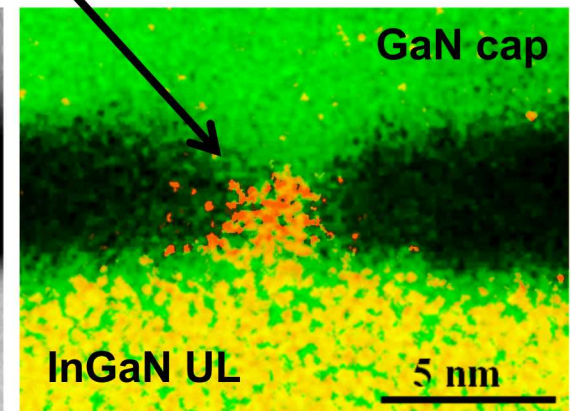


after PEC etch



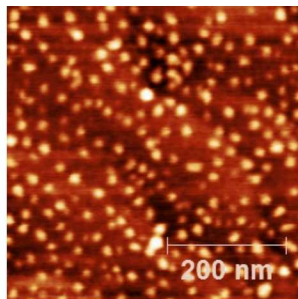
InGaN QD

after PEC etch



Photoluminescence from fabricated InGaN QDs

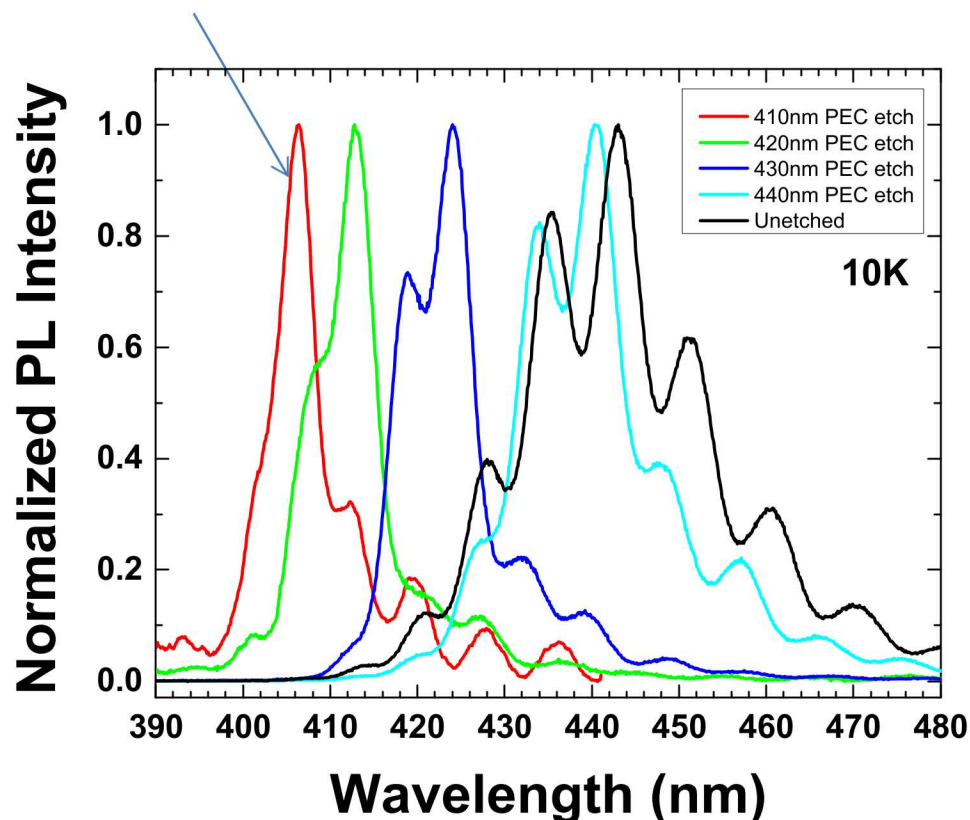
Capped InGaN QW



Photoluminescence (PL) data:

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

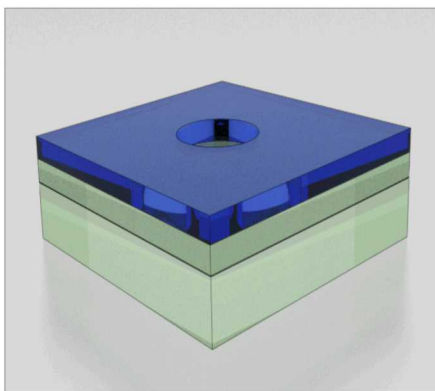
As narrow as **6 nm** FWHM is consistent with a narrowing of the QD size distribution



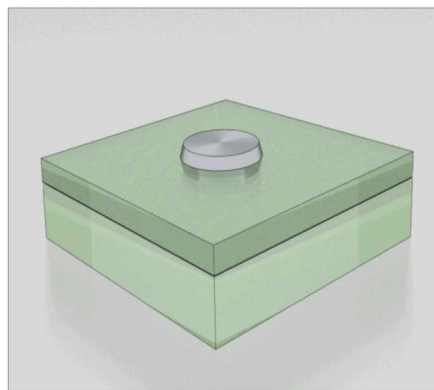
Patterned fabrication of InGaN QDs

➤ Deterministic placement

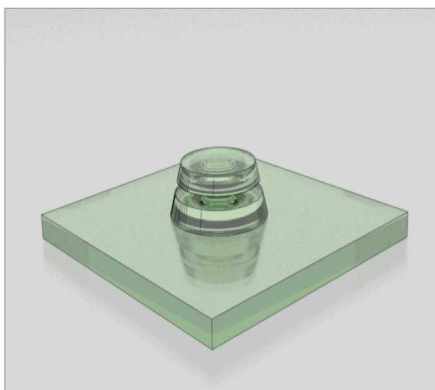
EBL Patterning



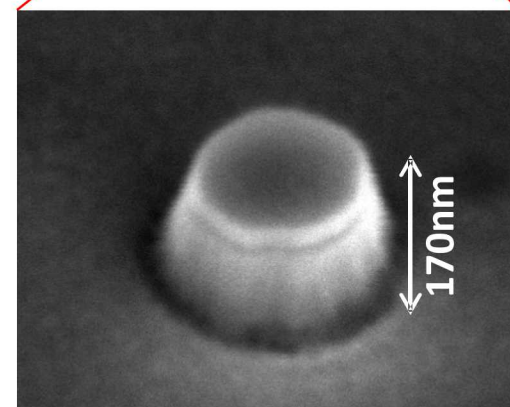
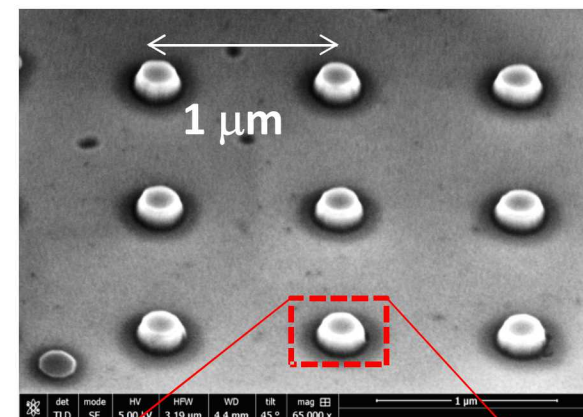
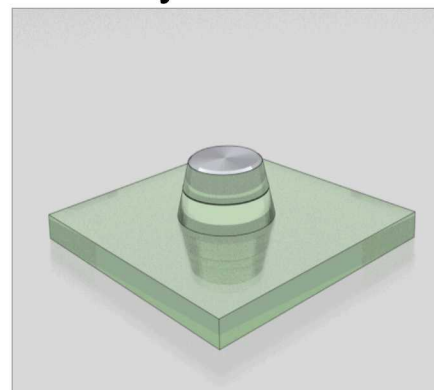
Metal Evaporation + Liftoff



Ni removal + PEC Etch



Dry Etch



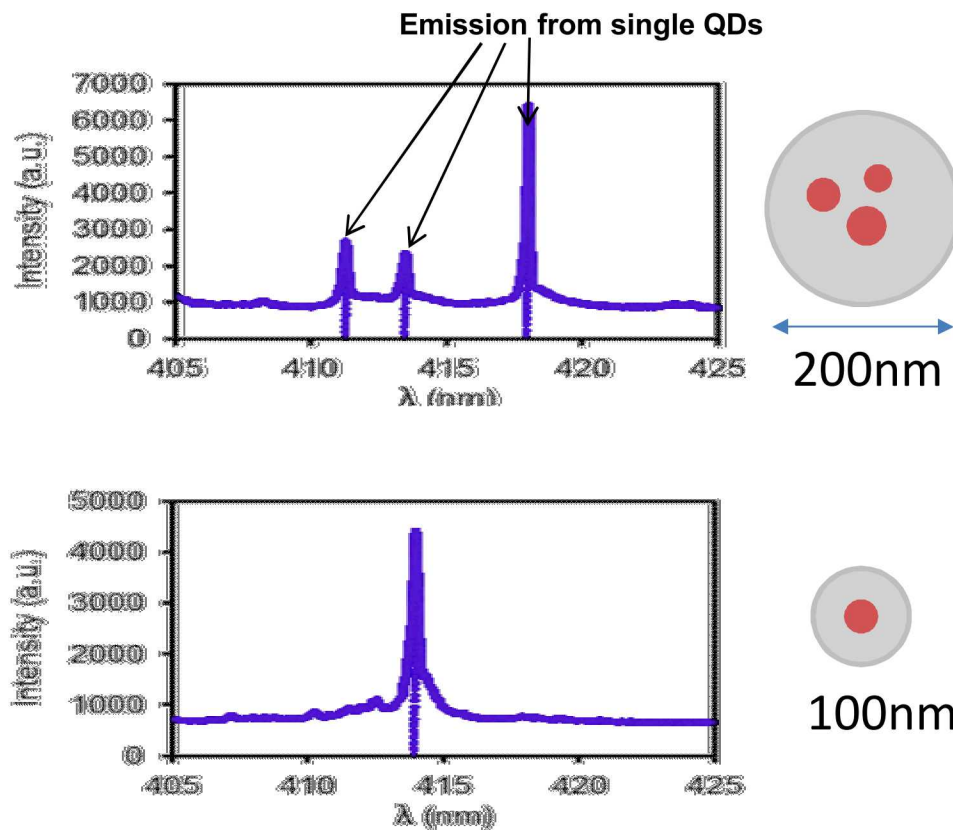
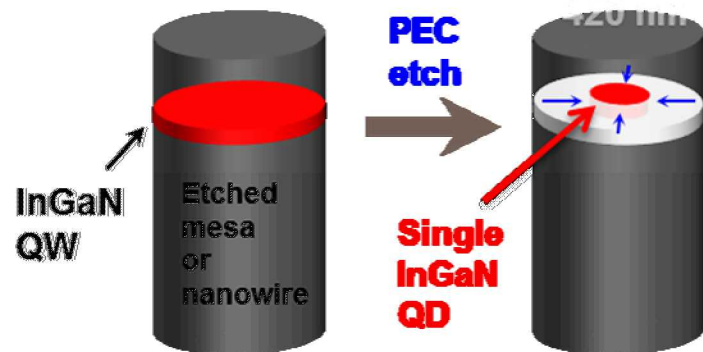
PL from InGaN QDs

Capped InGaN QW



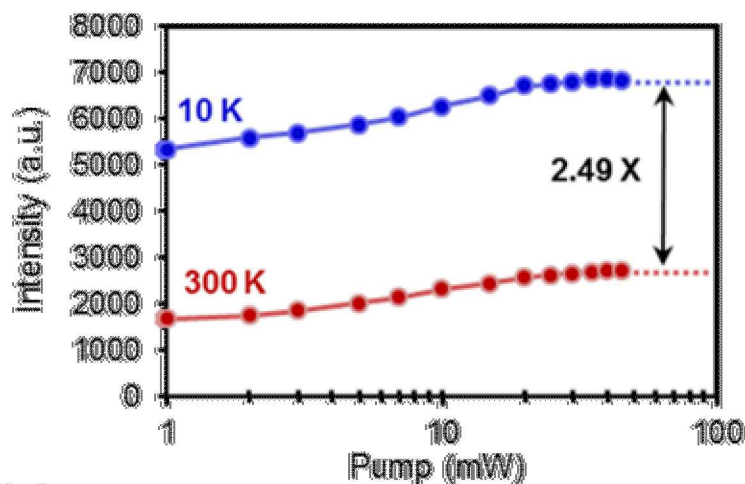
- Posts (150 – 200 nm) patterned with e-beam lithography
- **Thicker GaN capping layer (~ 30 nm)**
- Narrow PL emission (<1 nm FWHM) observed
- Better ratio of single QD mission to background

Fabrication of single InGaN QDs (methodology)

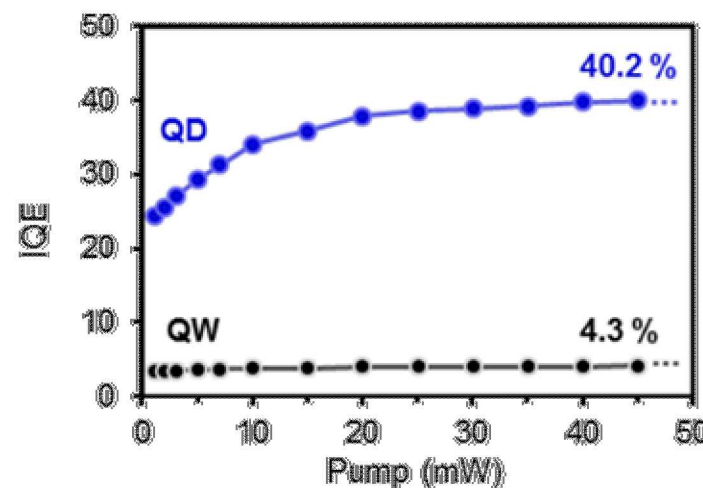


IQE from InGaN QW vs QDs

QD PL pump dependence



IQE QD vs QW

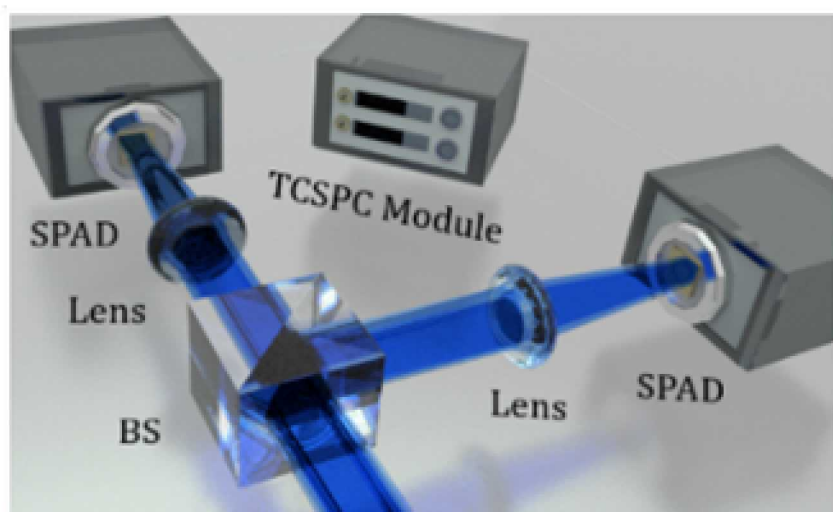


- Significant improvement in IQE between QW and QDs
- Cause: QDs are efficient emitters ; Also poor material etched away

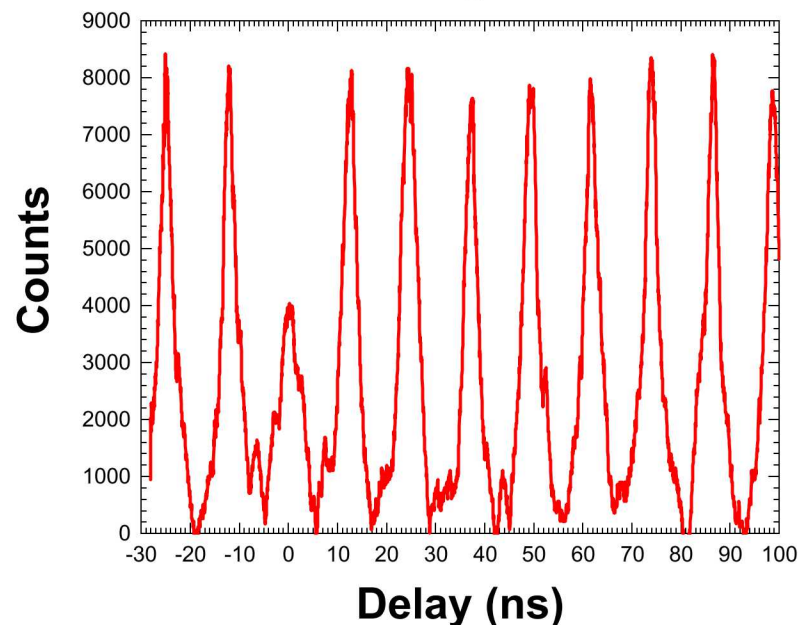
Single Photon Measurement: HBT experiment

- Observation of antibunching : $g_2 \sim 0.5$ for PEC-etched InGaN QDs
- Next steps:
 - Thicker GaN cap
 - Reduce nanowire radius
 - Emission rate enhancement
 - Enhanced light extraction

HBT Experimental Set-up

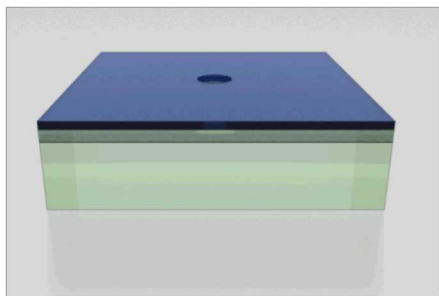


Pulsed g_2 data

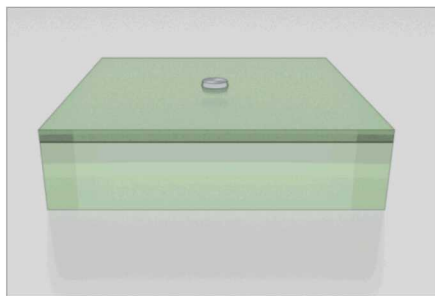


Next .. Incorporate in PC cavity

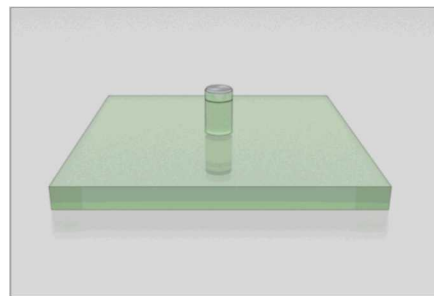
EBL Patterning



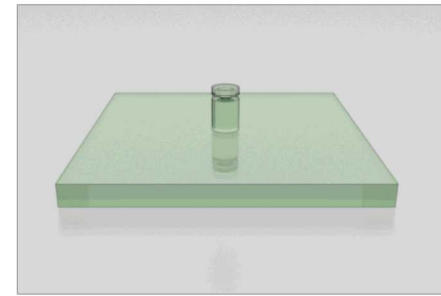
Metal Evap. + Liftoff



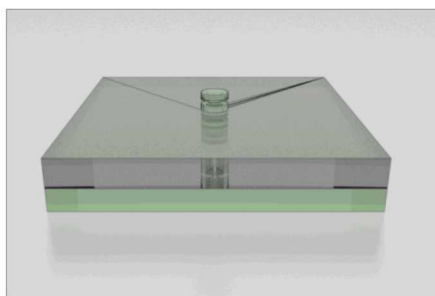
Dry + Wet Etch



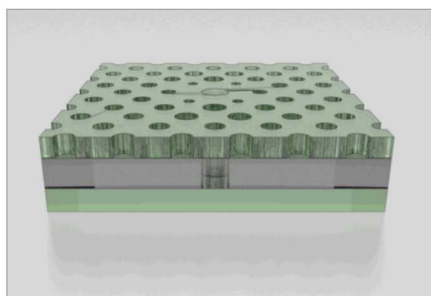
PEC Etch



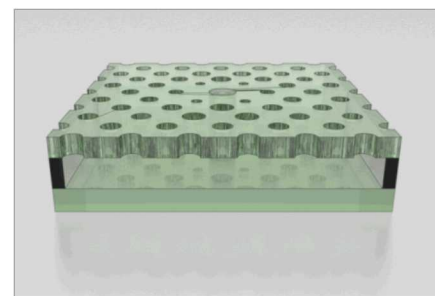
Spin-coat FOX16



TiO₂ dep. + EBL

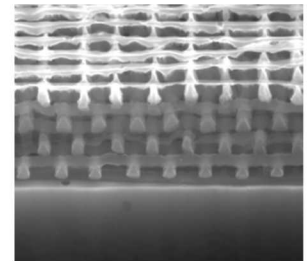
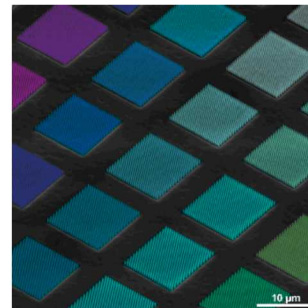
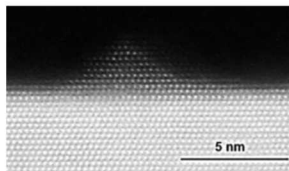
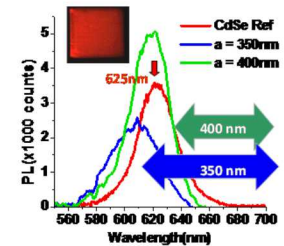
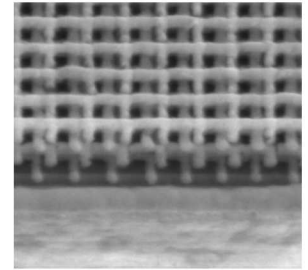


Membrane formation



Summary

- E-beam Litho based Logpile TiO₂ PC
- Spontaneous emission control in logpile TiO₂ PC
- Epitaxially grown GaN logpile PC
- Low-threshold multicolor nanowire lasers
- Far-field emission control Quasiperiodic structures
- PEC etched size controlled III-nitride quantum dots



Collaborators

- Art Fischer
- Dan Koleske
- Duke Anderson
- George Wang
- Yun -Ju (Alex) Lee
- Igal Brener
- Jeremy Wright
- Stavroula Foteinopoulou
- Jon Wierer
- Willie Luk
- Weng Chow
- Mike Coltrin
- Xiaoyin Xiao
- Jeff Tsao
- Joel Wendt
- Thomas Beechem
- Paul Clem
- Jeff Brinker
- Bernadette Sanchez
- John Nogan
- Ed Gonzales
- Cathy M
- Doug Pete
- Carlos Sanchez
- Tony Coley
- Travis Young

Thank you for your attention!

Back up slides

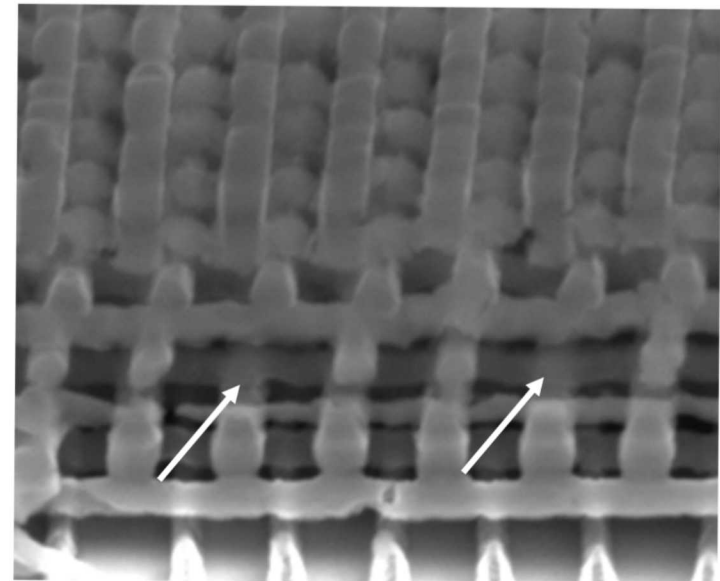
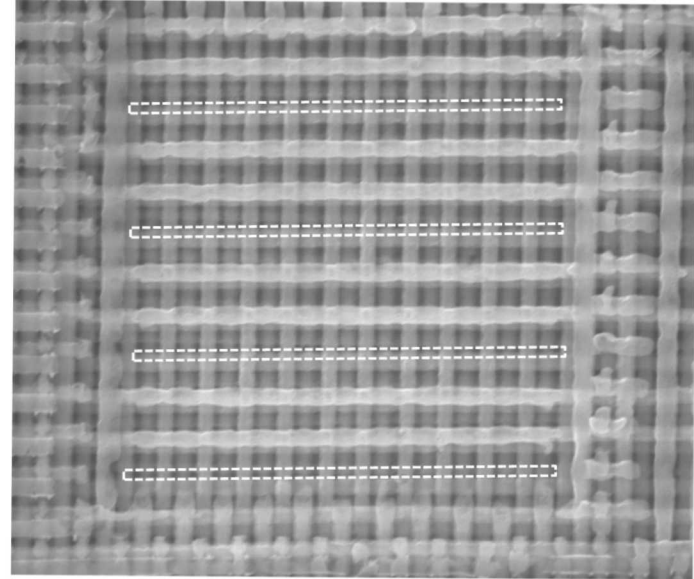
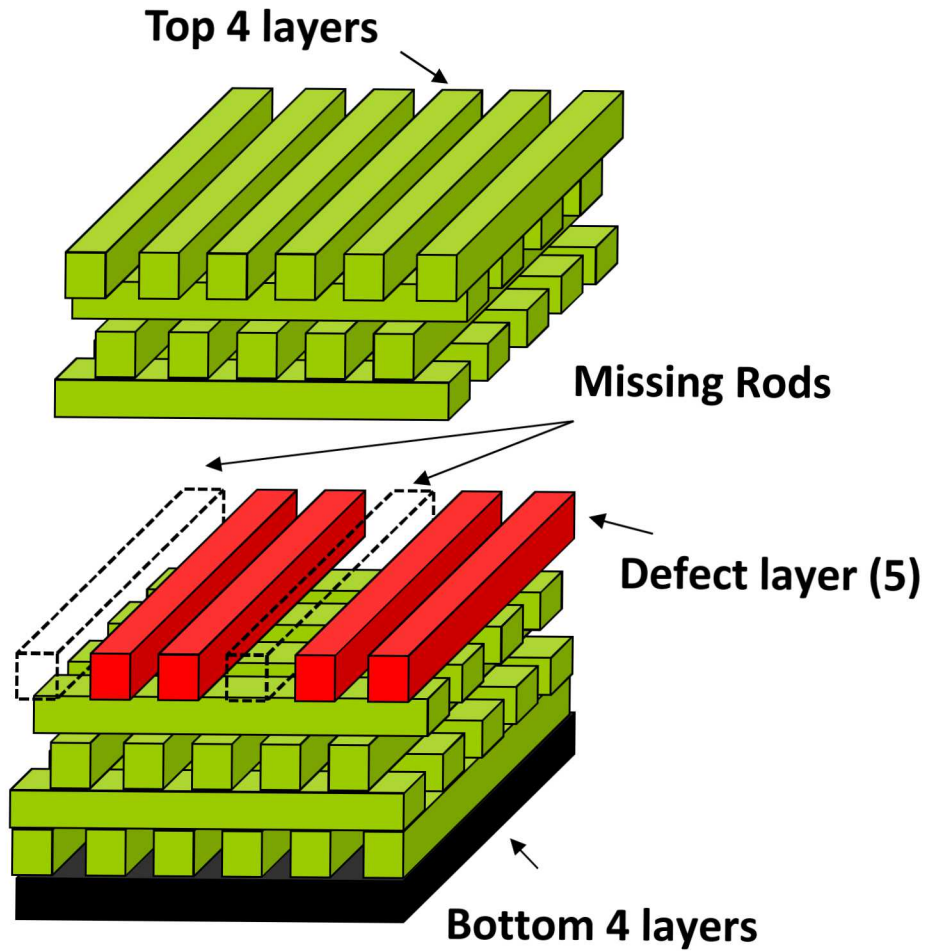
Summary of DG Structure properties

- Large field enhancement ($> 20\times$)
- Subwavelength confinement $\sim \lambda^2/500^2$
- Broadband transmission ($\lambda \sim 20 \mu\text{m}$ range)

Impact

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

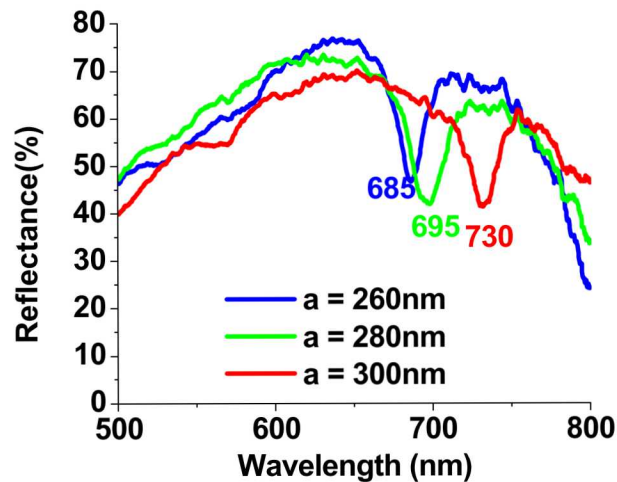
Logpile PC Cavity



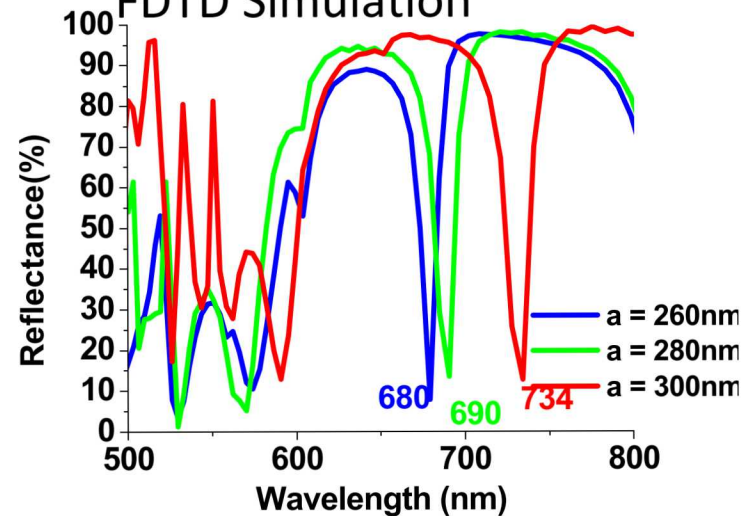
Logpile PC Cavity Optical Response

Reflection

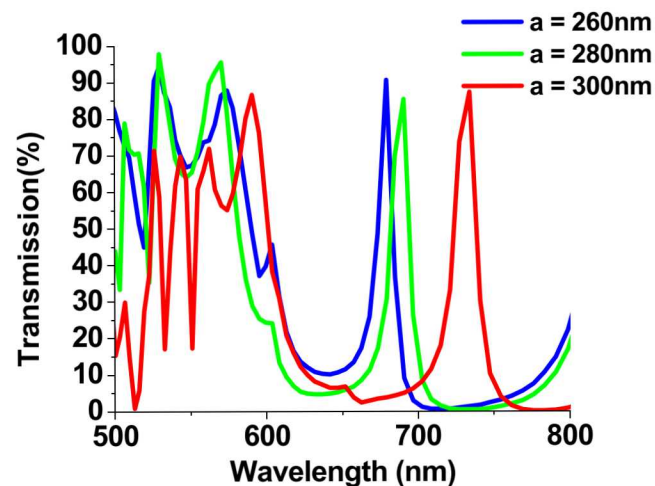
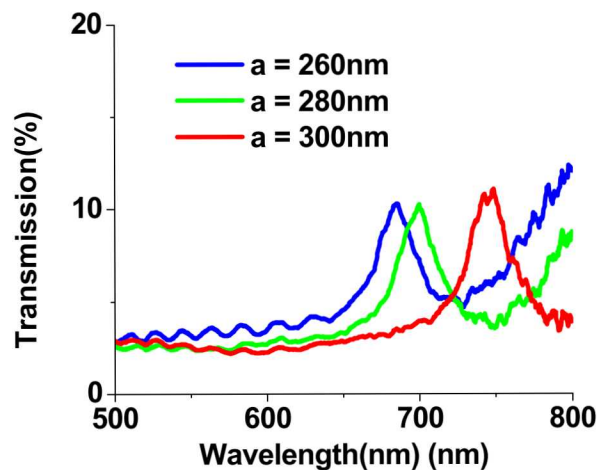
Experiment



FDTD Simulation



Transmission



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

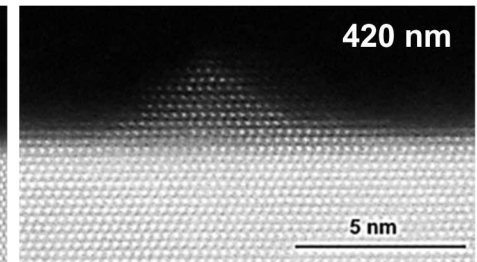
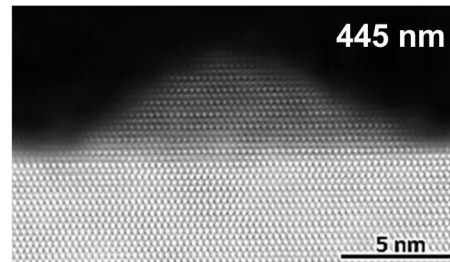
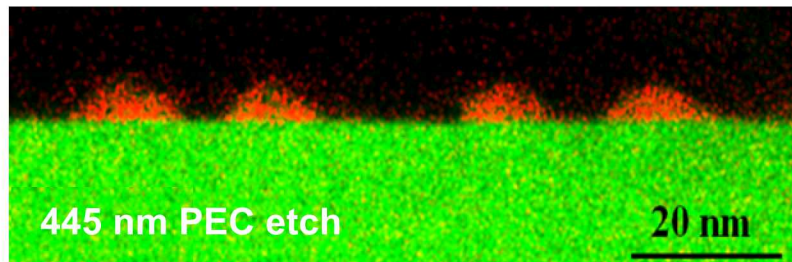
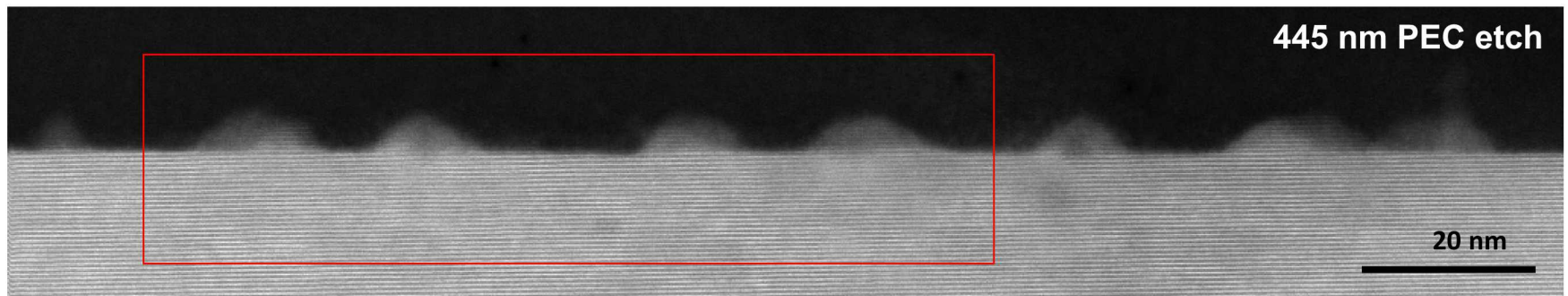
Transmission Electron Microscope (TEM)

Images

Uncapped InGaN QW



- 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

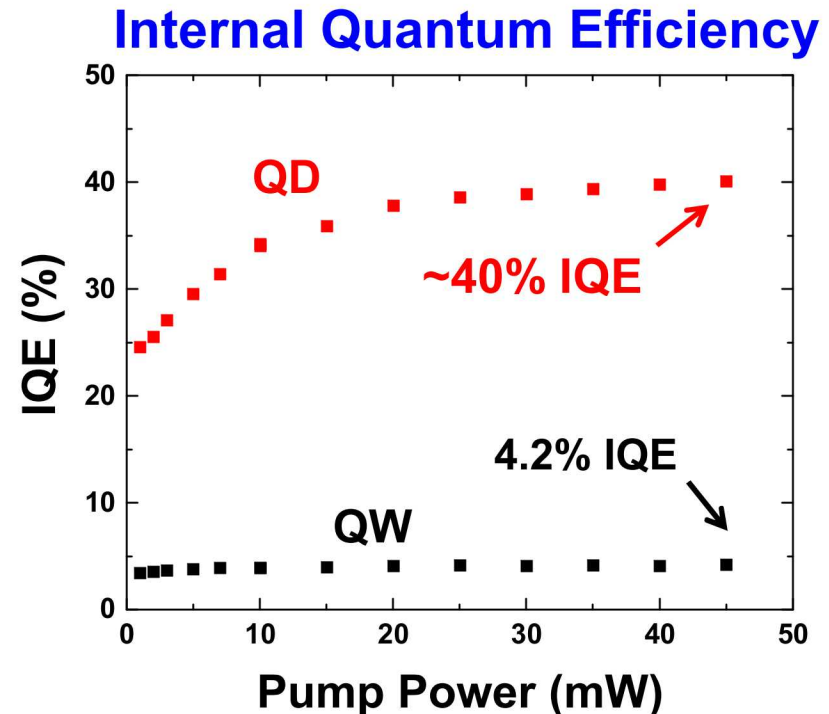
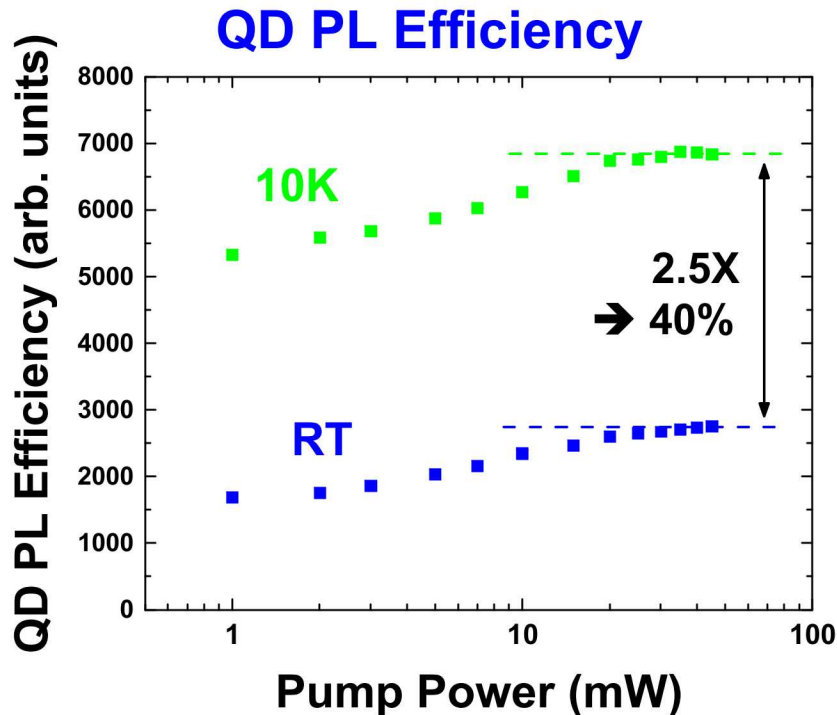


InGaN QD internal quantum efficiency

Capped InGaN QW

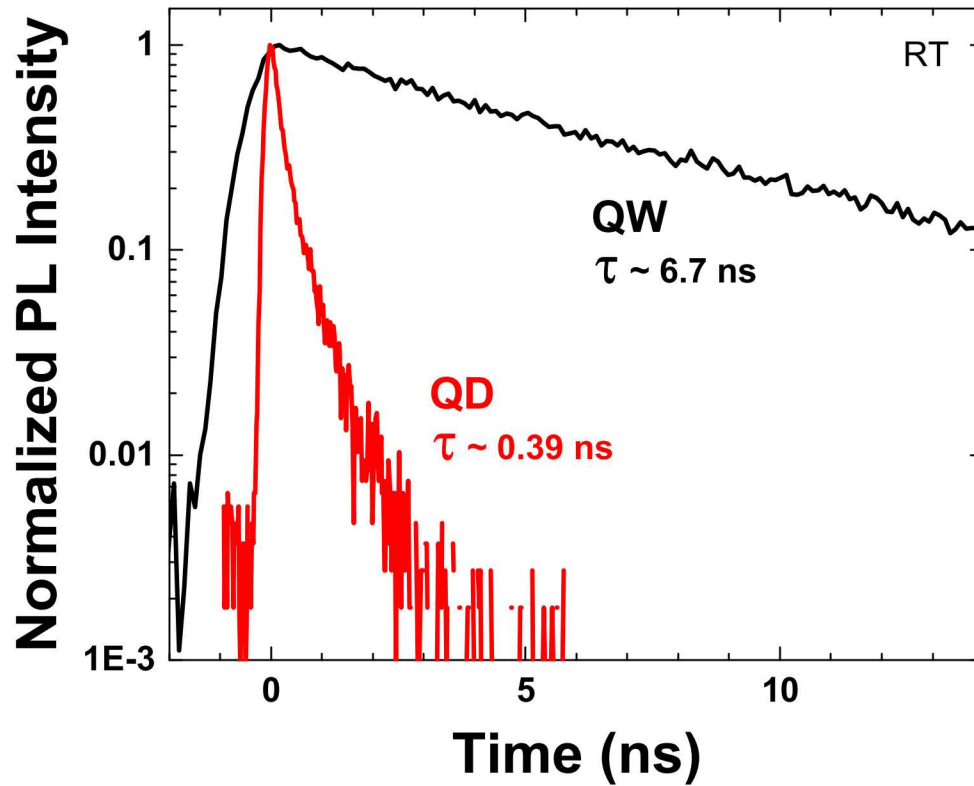


- Compare 10K and RT PL efficiency
- Assumes 10K PL is 100% efficient
- PL Intensity drops by >100X after QD etching
- IQE goes up by almost 10X after QD etching
- QDs are expected to have better IQE



Time-resolved PL data from InGaN QDs

Capped InGaN QW

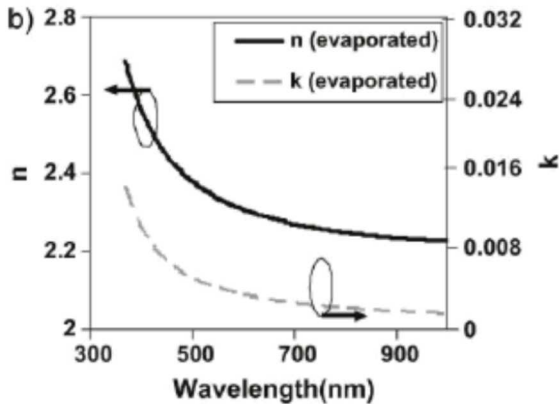


TRPL data:

- 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 $\rightarrow$ QDs

Visible Frequency Logpile Photonic Crystal

Choice : TiO_2



Requirements:

- High enough index with low loss in the visible :
 - $n \sim 2.3\text{-}2.4$ 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

$$\left\{ \begin{array}{l} E(\mathbf{r}, t) \propto e^{-i\omega t} \\ H(\mathbf{r}, t) \propto e^{-i\omega t} \end{array} \right.$$

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

In a periodic potential

$$\epsilon(\mathbf{r} + \mathbf{R}) = \epsilon(\mathbf{r})$$

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

Apply Bloch's Theorem

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

Plane Wave Expansion Method

Reciprocal (K) space

$$\varepsilon(\mathbf{r}) = \sum_{\mathbf{G}} \overline{\varepsilon(\mathbf{G})} e^{i\mathbf{G} \cdot \mathbf{r}}$$

$$\mathbf{E}, \mathbf{H}(\mathbf{r}) = \sum_{\mathbf{G}} \overline{\mathbf{E}}, \overline{\mathbf{H}}(\mathbf{G}) e^{-i(-\mathbf{k} + \mathbf{G}) \cdot \mathbf{r}}$$

Reciprocal Lattice vector

$$\mathbf{G} \cdot \mathbf{R} = 2\pi n$$

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

Eigen value equation

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

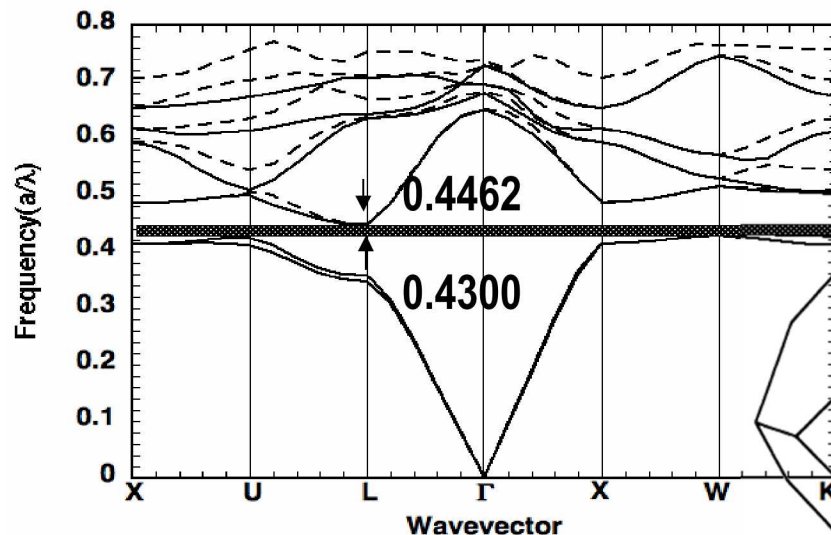


$$\mathbf{A} \overline{\mathbf{H}}_n(\mathbf{k}) = -\frac{a^2 \omega_n^2}{c^2} \overline{\mathbf{H}}_n(\mathbf{k})$$

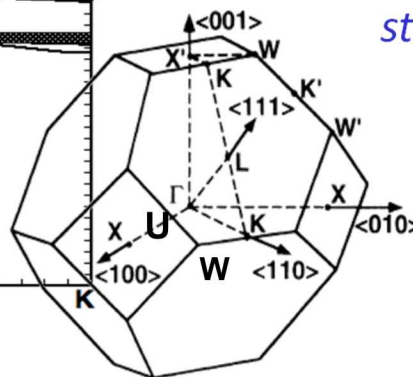
Photonic Band Structure for TiO₂ logpile

Band index

Wave vector within the first BZ



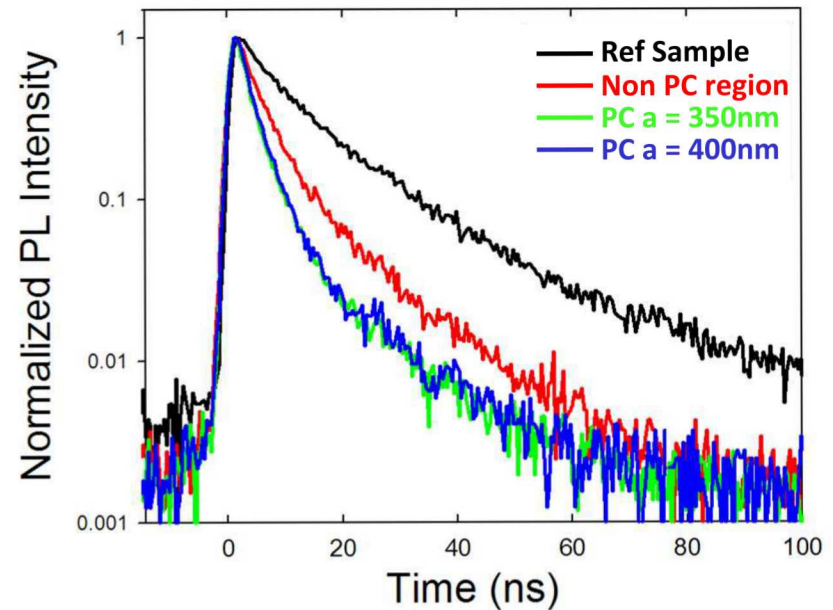
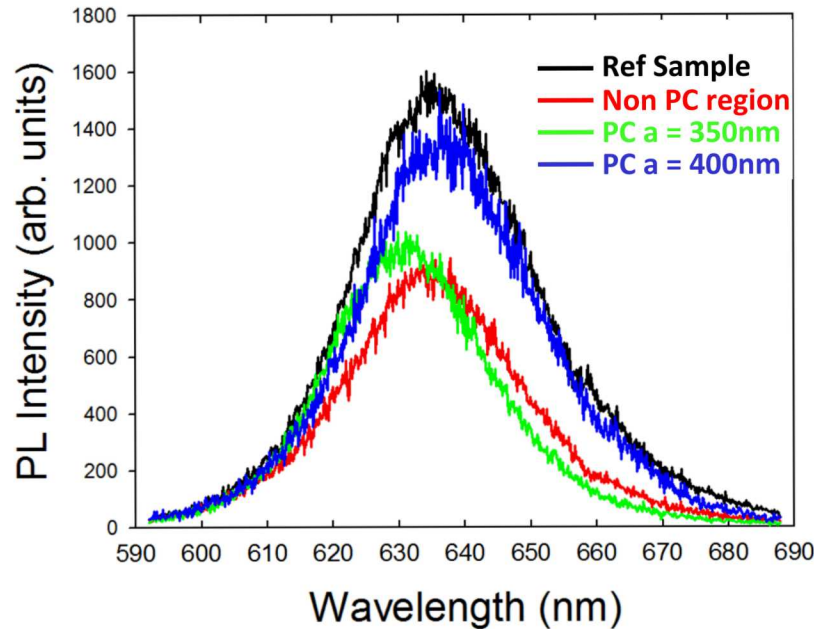
1st BZ



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

- $n \sim 2.3$
- 4% bandgap
- $\sim 20\text{nm @ } 500\text{nm}$

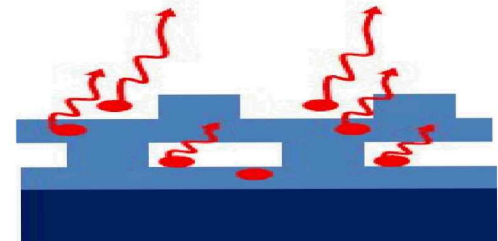
Emission Lifetime Measurements - TRPL



- Conditions: 380 nm pump, 4 MHz, 20 uW average power, 10 mm aperture
- Emitter wavelength $\sim 640\text{nm}$

- 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 $a = 350\text{nm}$) and shorter for outside ($a = 400\text{nm}$).



Possible reasons:

- Fewer layers of PC
- Surface QD emission

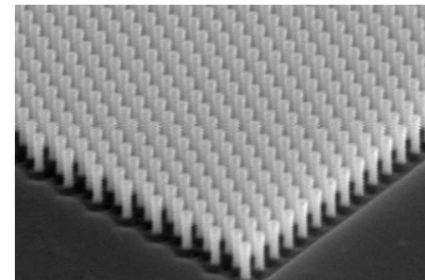
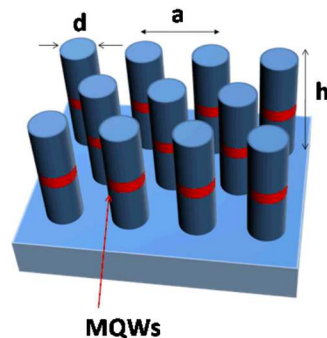
Summary / Future Possibilities

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 !

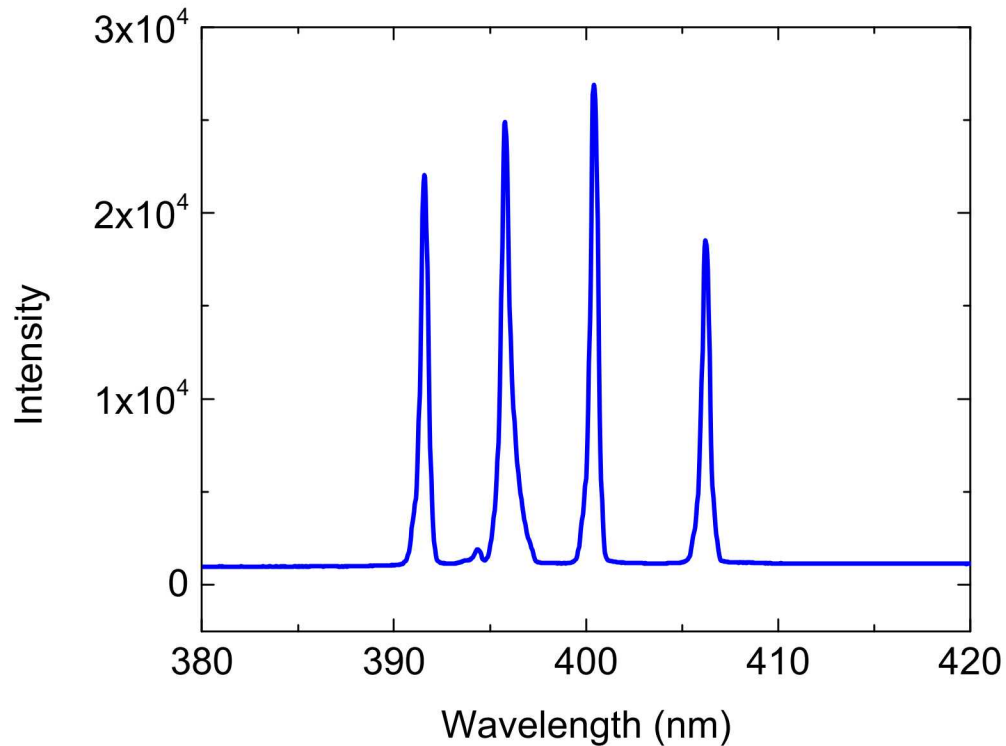
Investigating 2DPC GaN nanopillar array based light emission



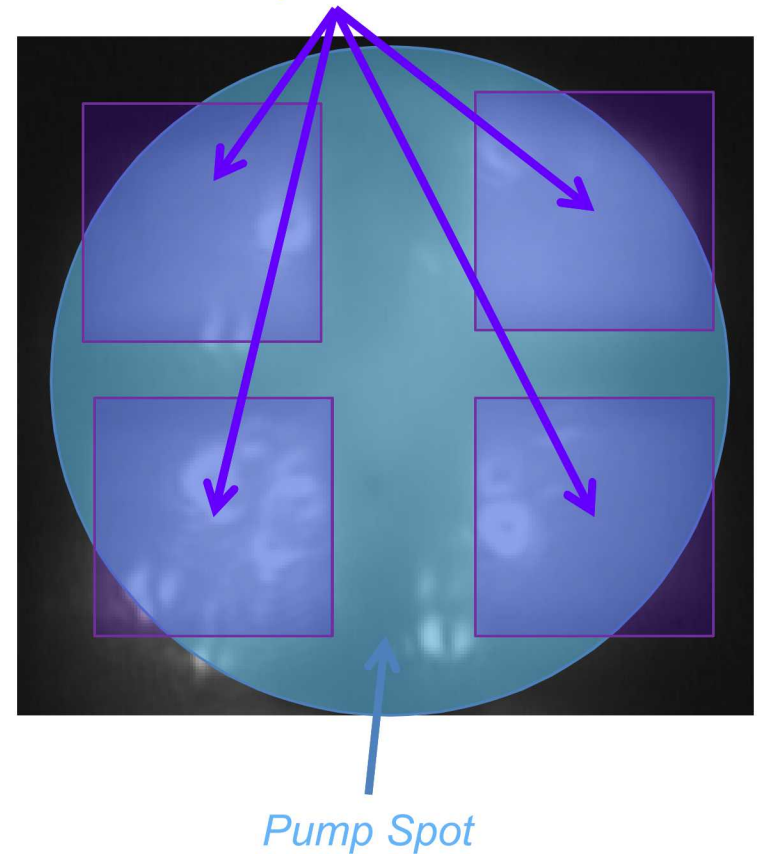
w/ G. Wang , I.
Brener, T.S. Luk

Multiple Laser Pixels Coexcited

Emission from 4 adjacent laser pixels.



Photonic Crystal Laser Pixels



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

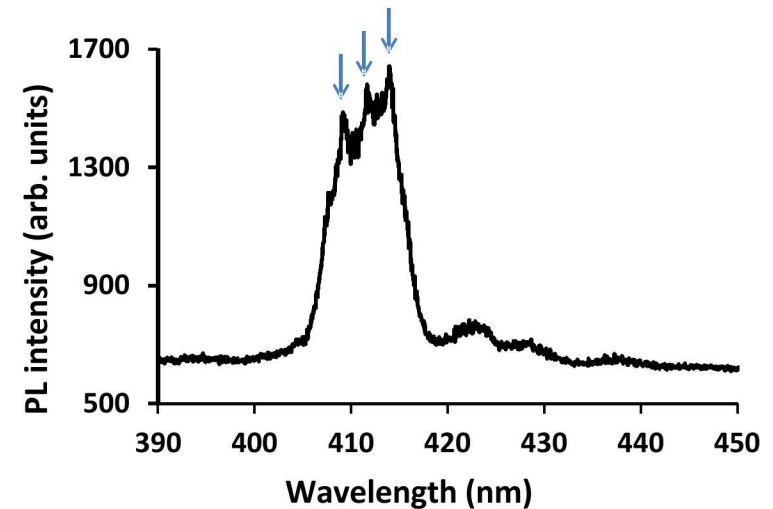
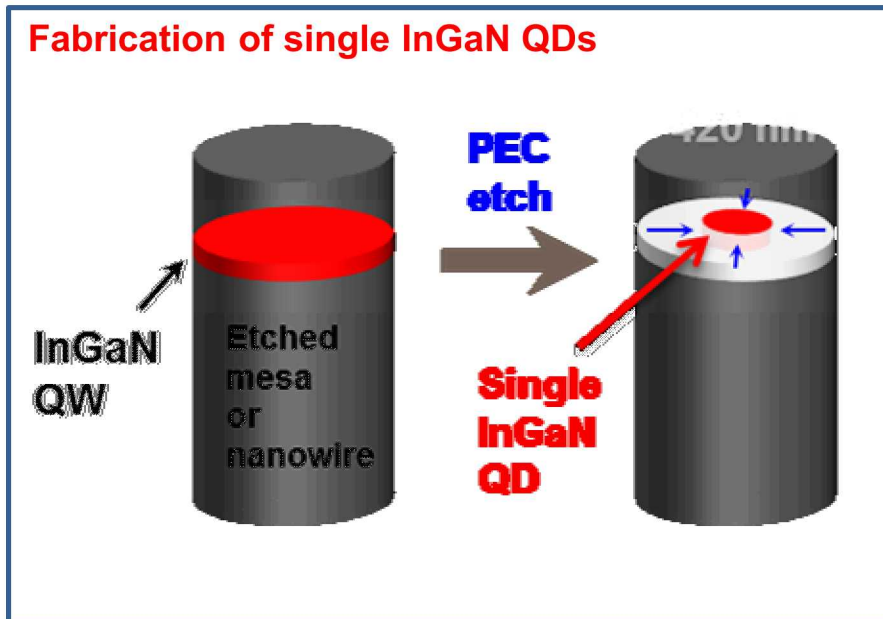
Emission from single InGaN QDs

Capped InGaN QW



- Posts (150 – 200 nm) patterned with e-beam lithography
- Fabricate InGaN QDs at deterministic locations
- GaN cap ~ 10nm
- Narrow peaks emerge revealing QD formation

Fabrication of single InGaN QDs

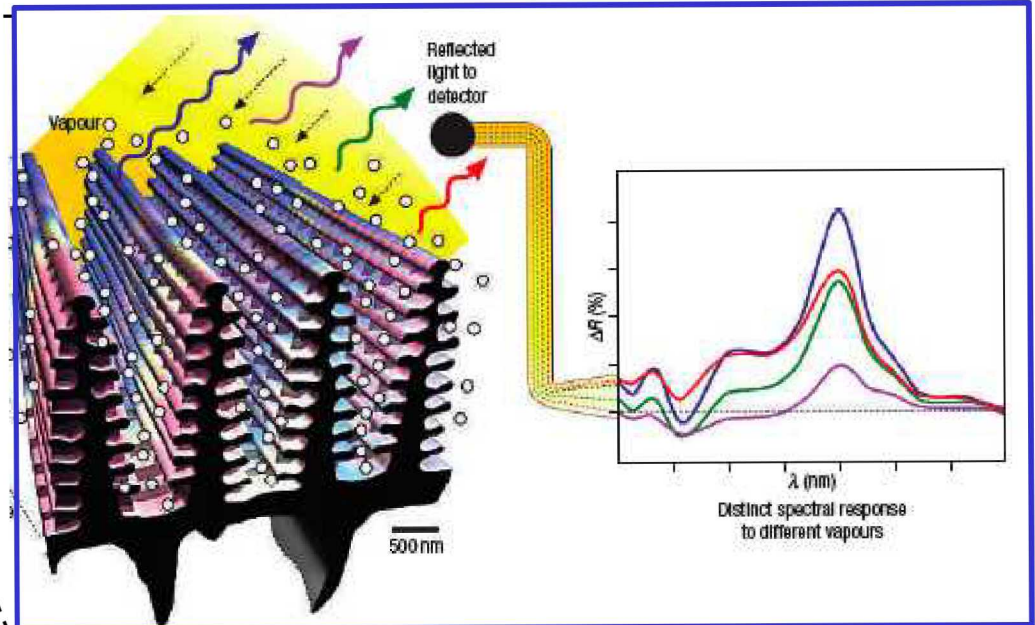


Light Control in Nature Via Nanostructuring

- Color response highly sensitive to different vapors

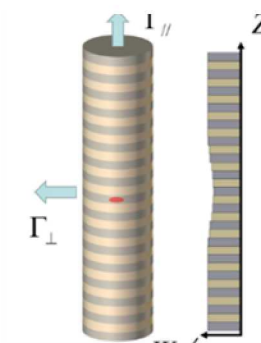
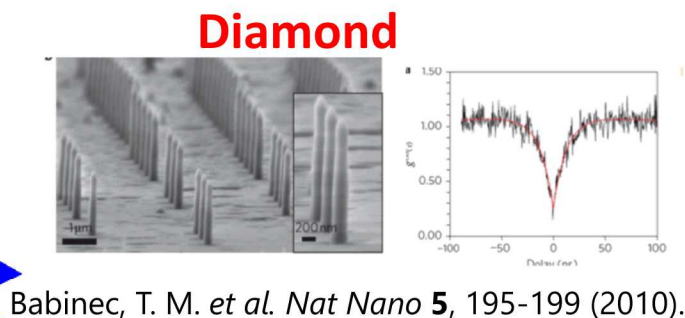
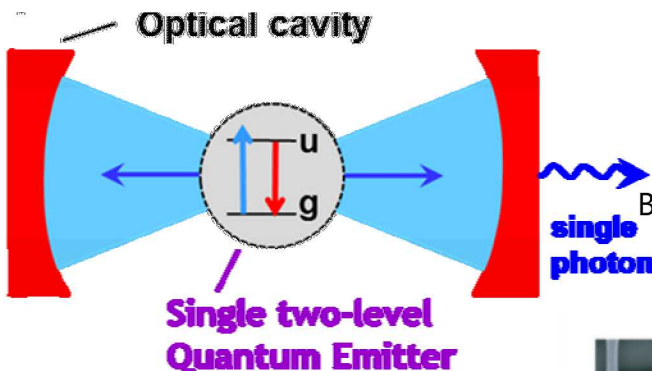


Morpho Butterfly
(M. Sulkowskyi)

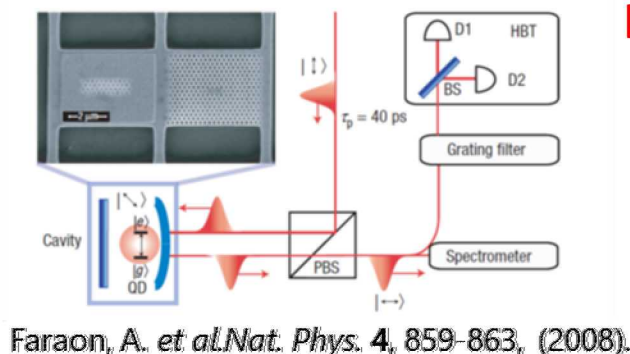
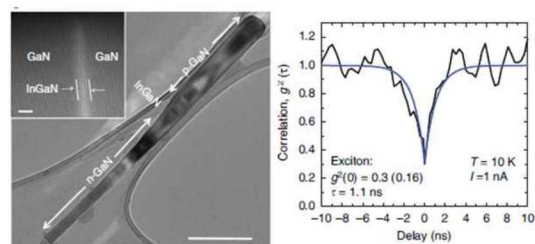


* R.A. Potyrailo et. al. , Nature Photonics , 1, 123(2007).

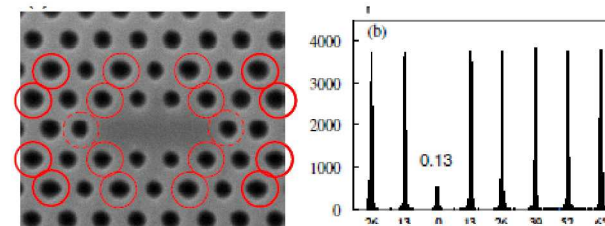
Single Photon Source based on Quantum Dots



Portalupi, S. L. et al. *Nano Lett.* **15**, 6290-6294, d (2015).

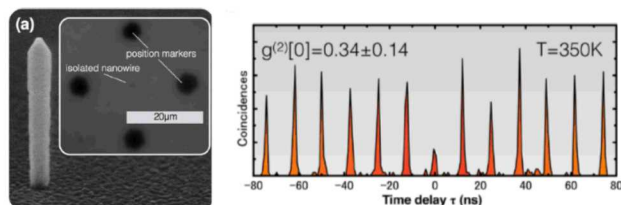


III-V

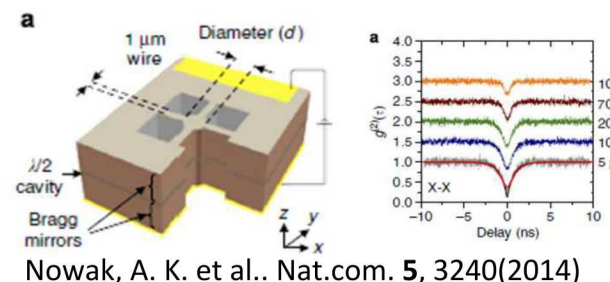


Deshpande, S., *Nat.com.* **4**, 1675(2013)

III-N

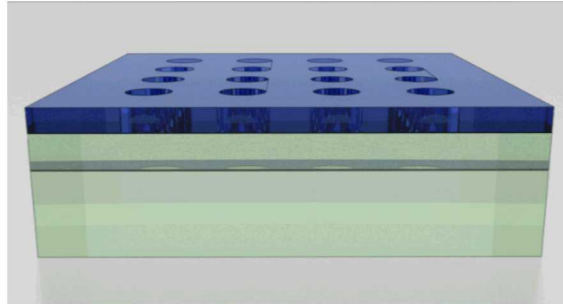


Holmes, M. J., et. al., *ACS Photonics* **3**, 543-546, (2016).

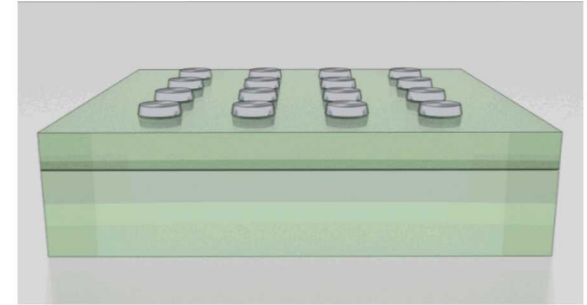


Fabrication procedure in GaN

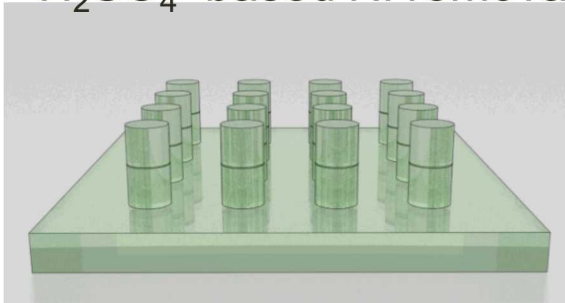
EBL pattern in
PMMA



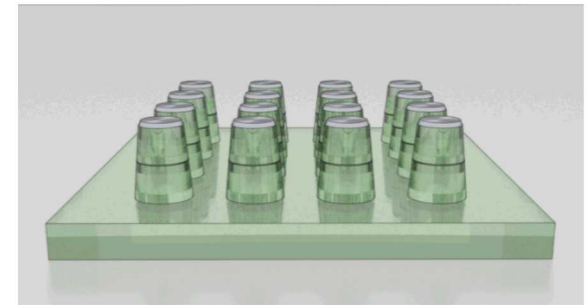
Ni evaporation and lift-off



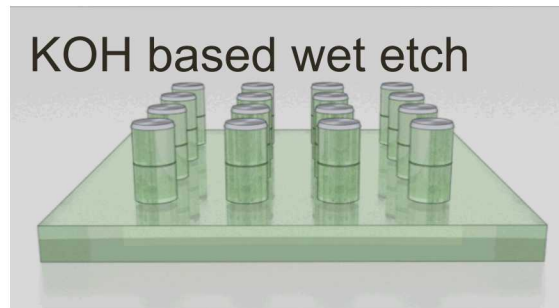
H_2SO_4 -based Ni removal



Cl_2 based dry etch

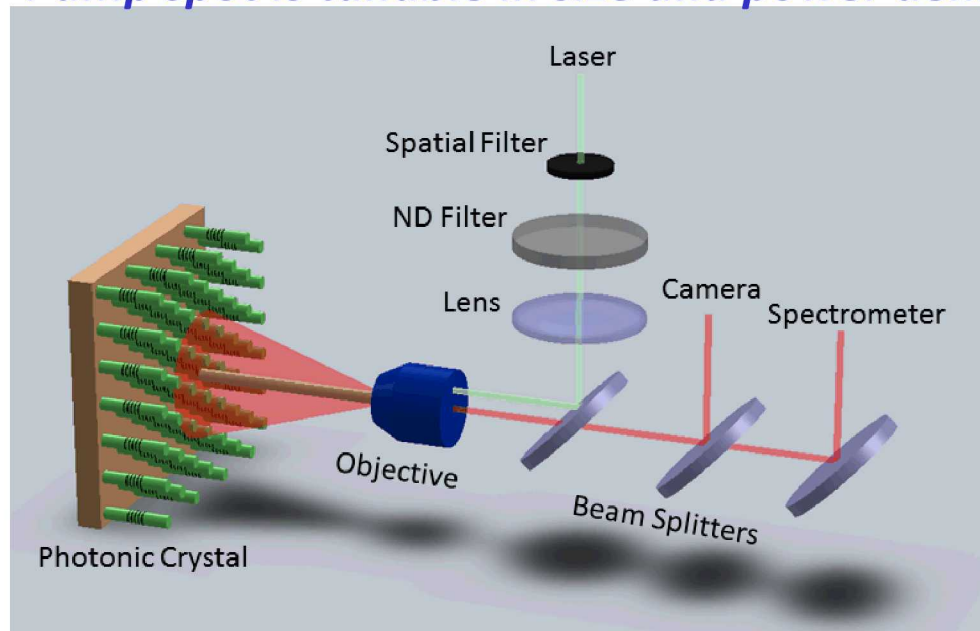


KOH based wet etch

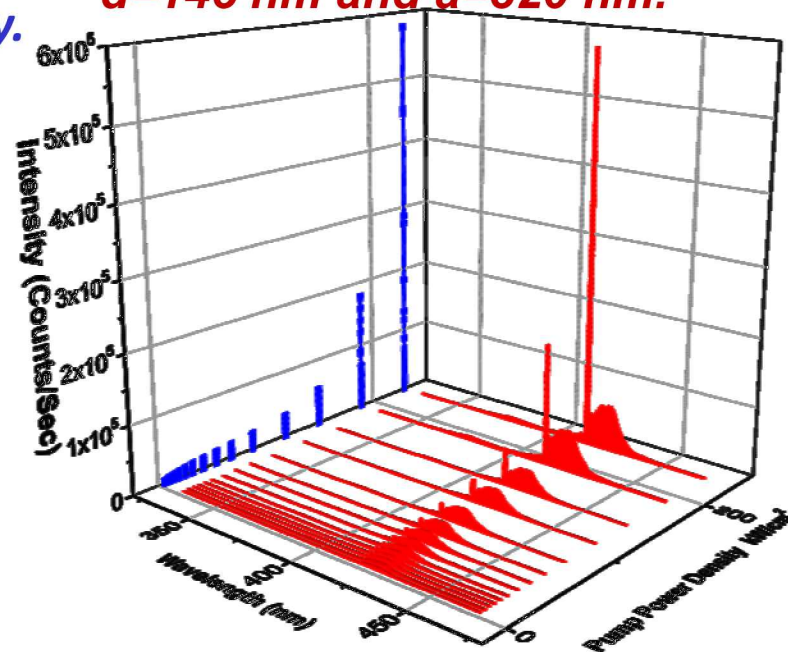


Optical response – low threshold lasing

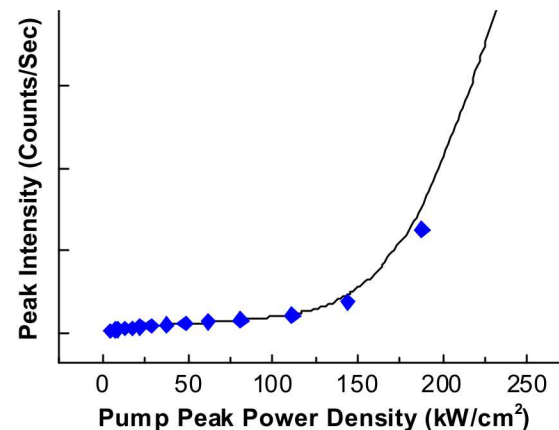
Pump spot is tunable in size and power density.



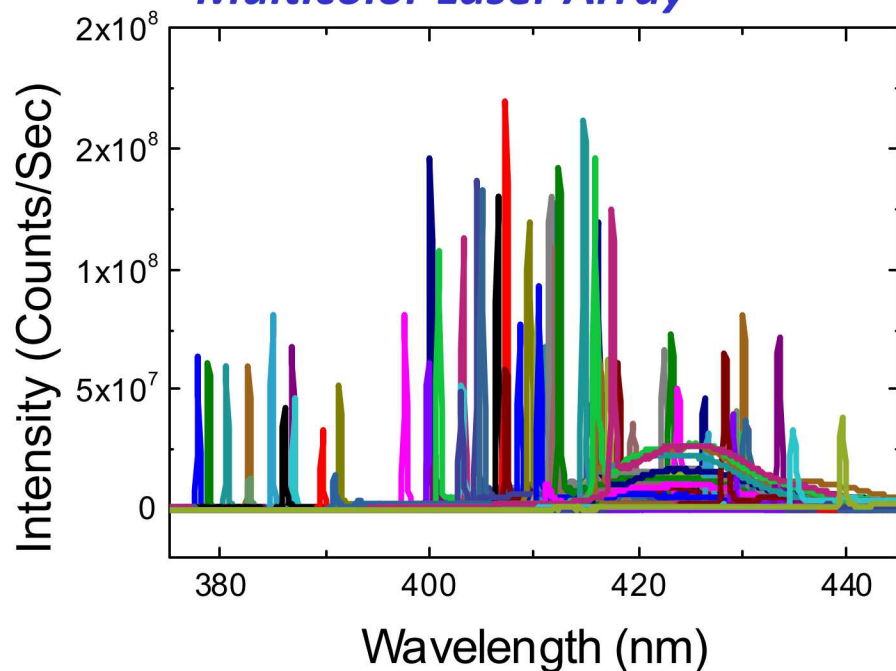
**Array Element Dimensions:
 $d=145\text{ nm}$ and $a=320\text{ nm}$.**



A low lasing threshold is achieved with $< 500\text{ kW/cm}^2$ for all PC lasers fabricated.

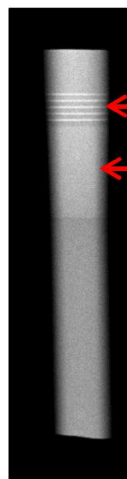
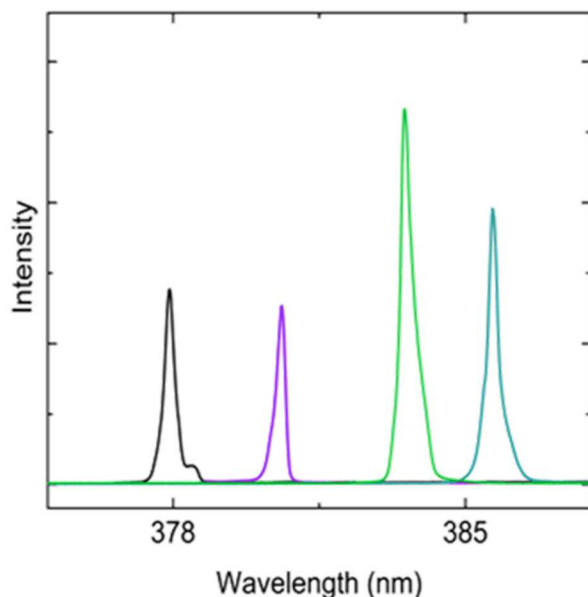


Multicolor Laser Array



- 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



- ← InGaN MQWs
- ← InGaN Underlayer

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

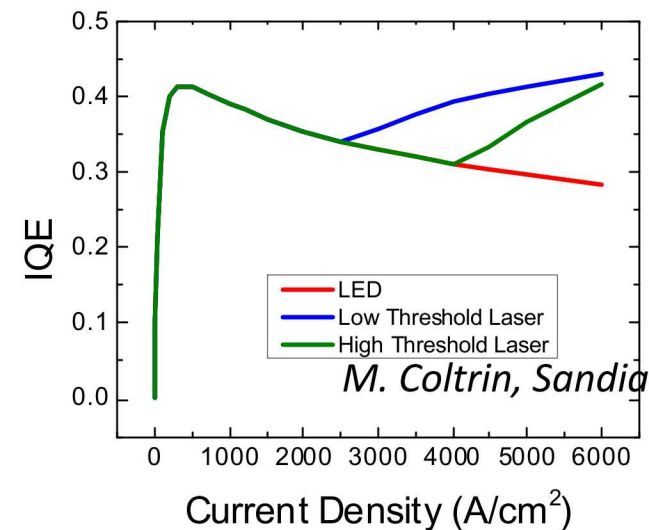
Nanowire Photonic Crystal Lasers

(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)

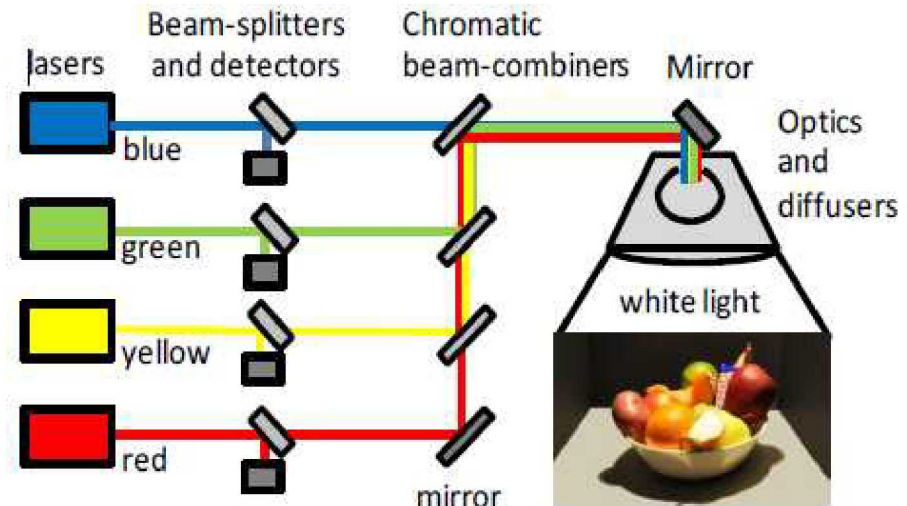
Why Lasers in Solid State Lighting?

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 !**

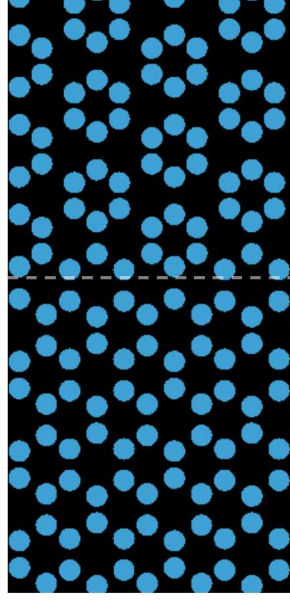


A. Neumann et al., "Four-color laser white illuminant demonstrating high color-rendering quality," *Opt. Express*, vol. 19, pp. A982-A990, 2011.

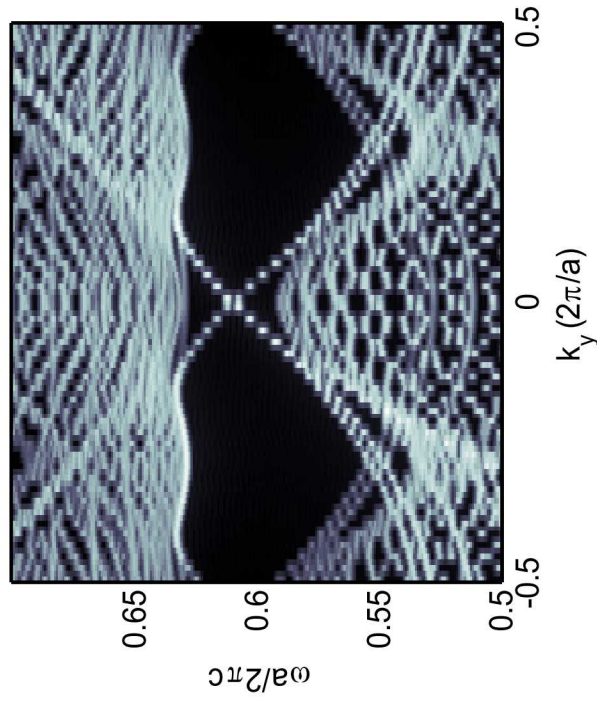
Crystal Rods

Topological edge state in III-Nitride Honeycomb Photonic

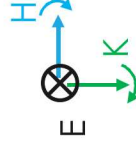
Modeling



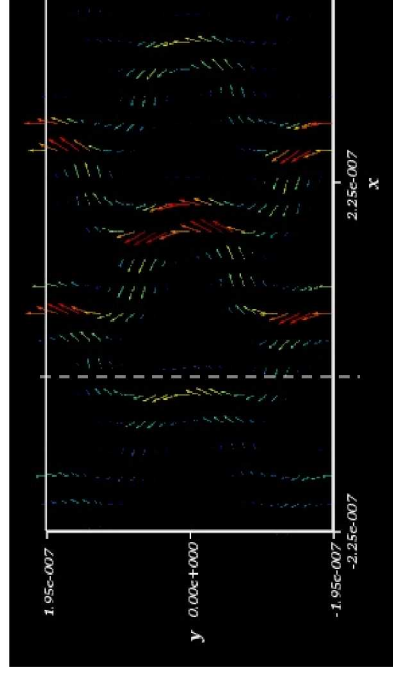
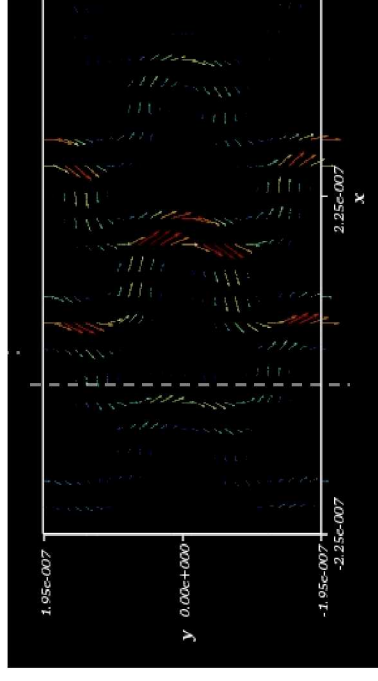
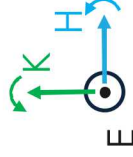
Band Structure



Spin-down state
 $a/\lambda = 0.618$



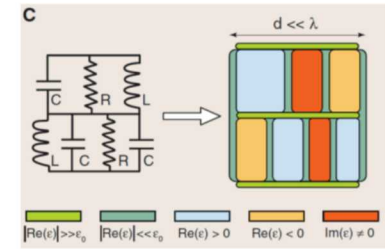
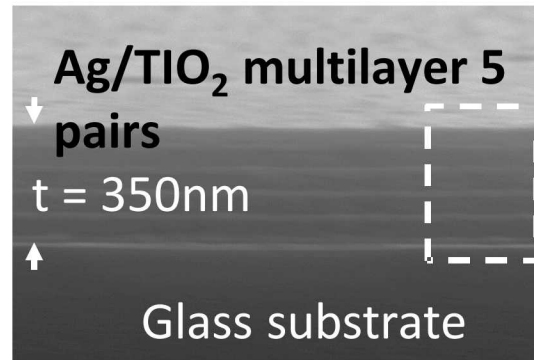
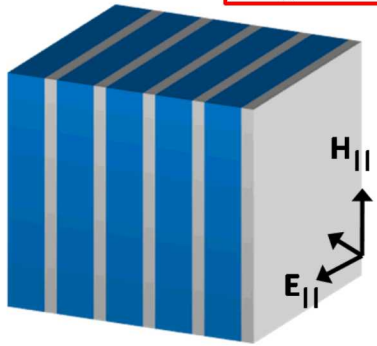
Spin-up state
 $a/\lambda = 0.60$



Metal-Dielectric Visible Epsilon Near Zero Metamaterial

Engheta, N. Circuits with Light at Nanoscales: Optical Nanocircuits Inspired by Metamaterials. *Science* **317**, 1698 (2007).

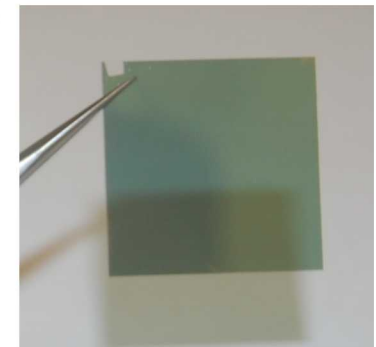
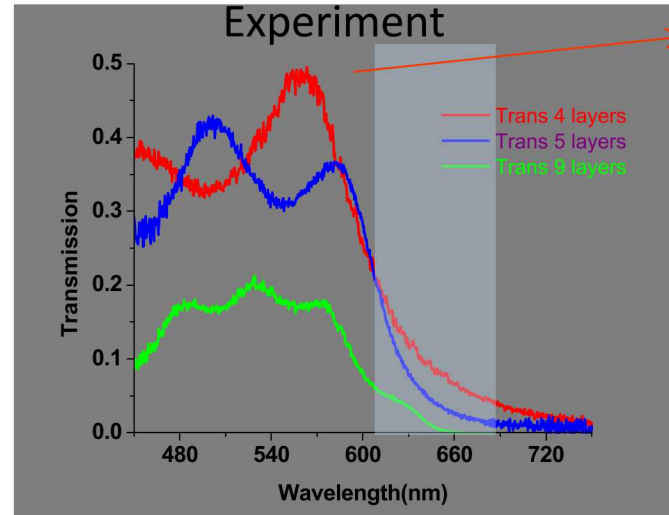
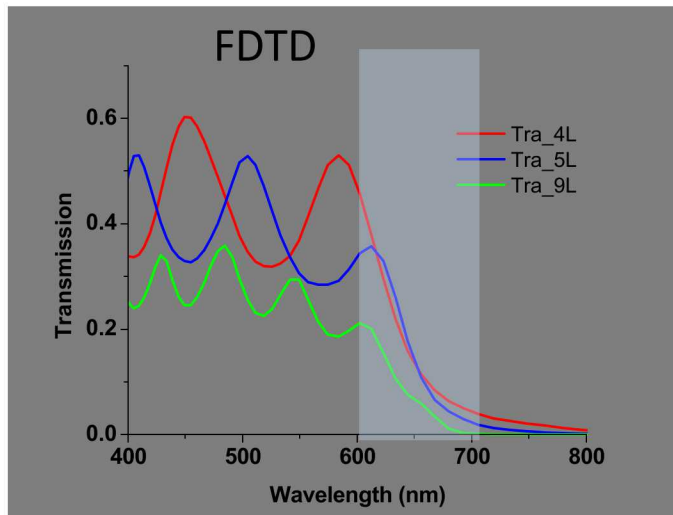
$$\epsilon_{\text{effective}} = f\epsilon_{+}^{\text{dielectric}} + (1-f)\epsilon_{-}^{\text{metal}}$$



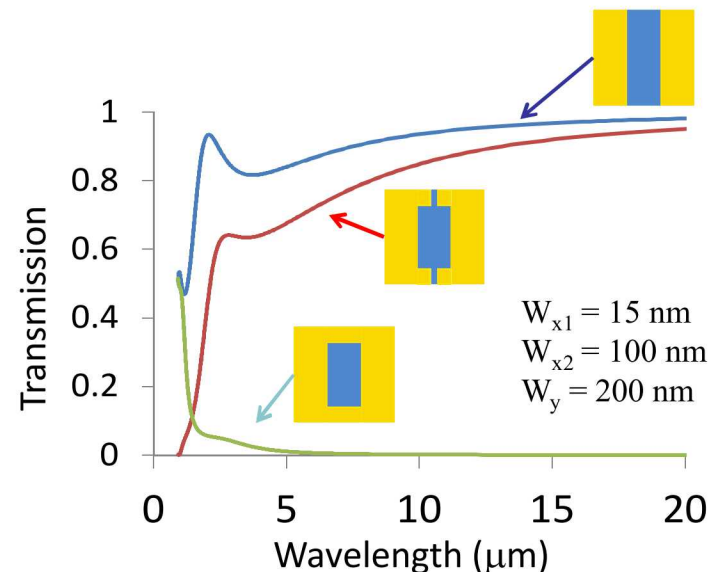
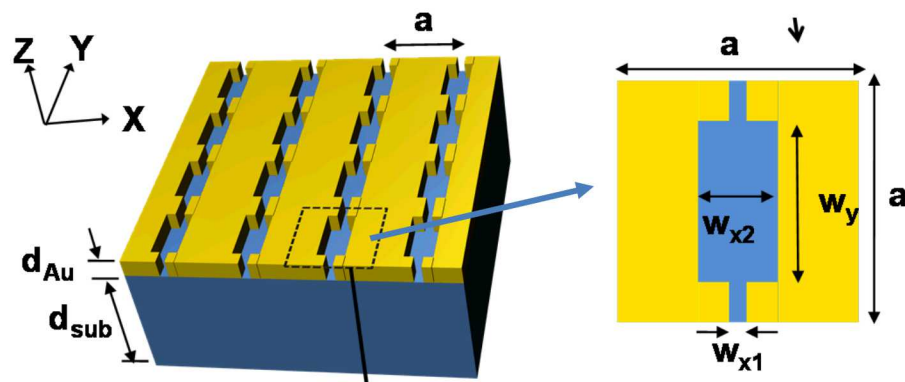
ENZ point $\lambda \sim 630\text{nm}$

Ag (23%) + TiO₂ (77%)

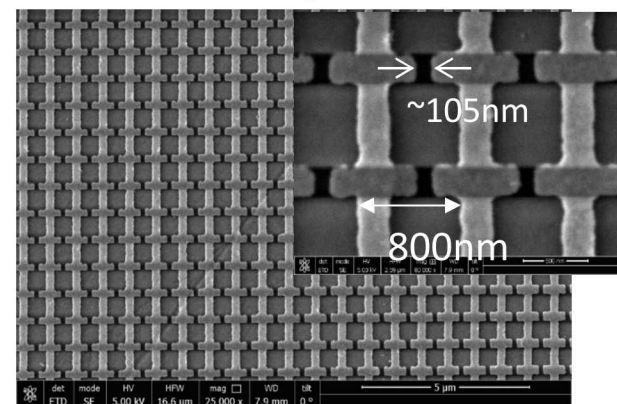
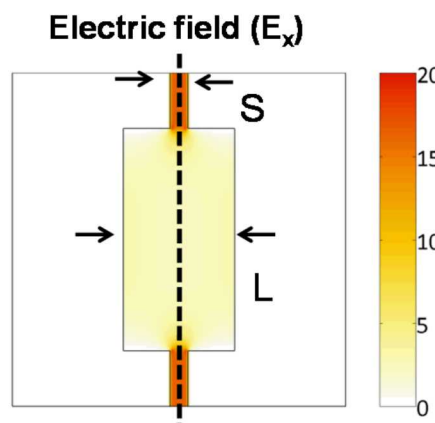
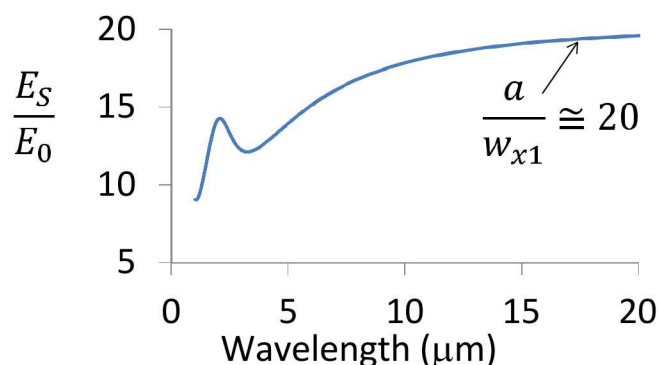
TiO₂ = 54nm
Ag = 16nm



Non-resonant Broadband Ultra-subwavelength Light confinement



Electric field enhancement in the small gap

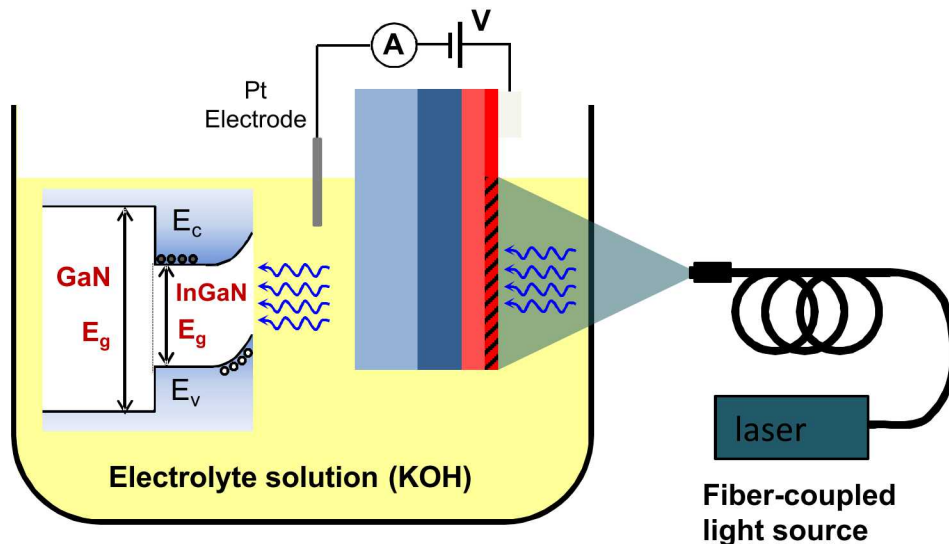


- Broadband transmission and electric field enhancement
- Ultrasubwavelength confinement : $(\lambda/250)^2$ (@ 10 μm)

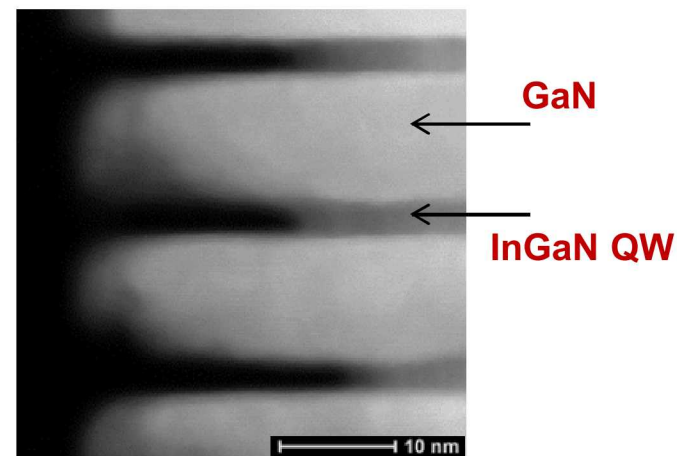
InGaN Photoelectrochemical (PEC) Etching

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 ($\sim 0.1\text{M}$) typically used as electrolyte

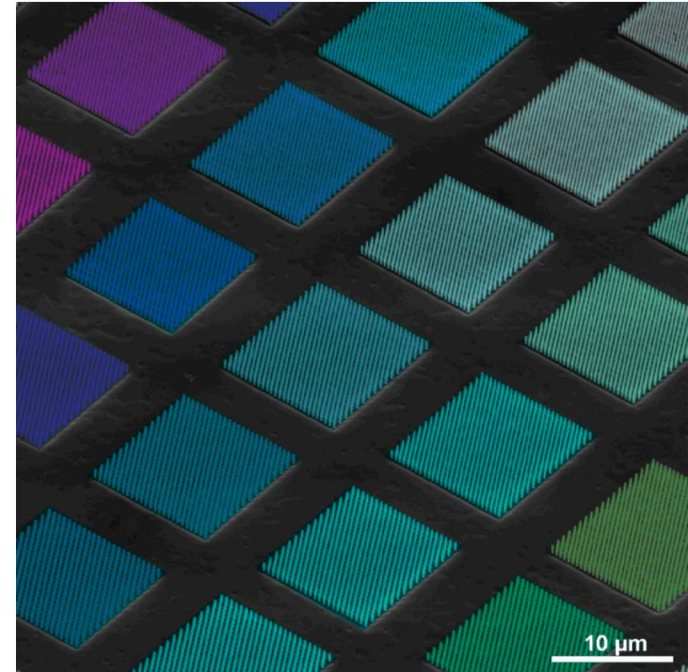


PEC etched InGaN/GaN QWS



Possibilities

- *Laser arrays that span a broad spectral range*
- *Near-vertical low threshold single-mode emitters*
- *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.*



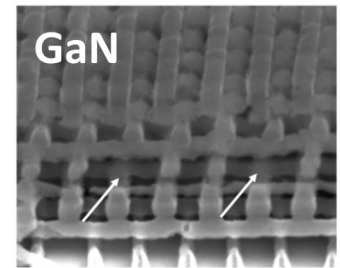
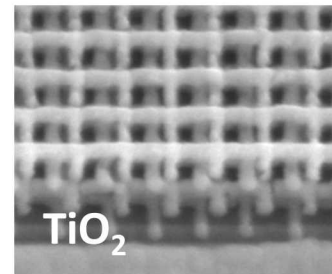
Wright, J. B. *et al.* Multi-Colour Nanowire Photonic Crystal Laser Pixels. *Sci. Rep.* **3**, 2982, doi:10.1038/srep02982

➤ Background and Motivation

➤ 3D logpile photonic crystals

➤ TiO_2

➤ GaN

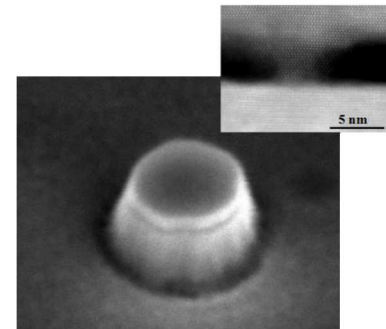
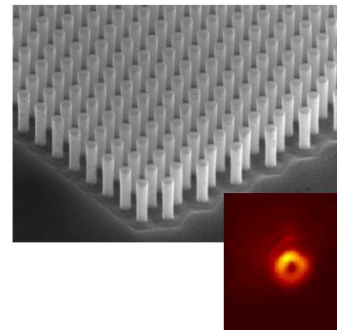
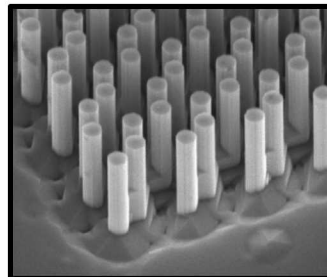


➤ 2D photonic crystals

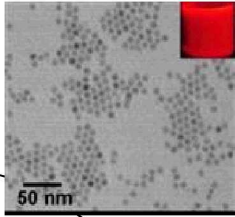
➤ GaN 2D PC lasing

➤ Topological PC structures

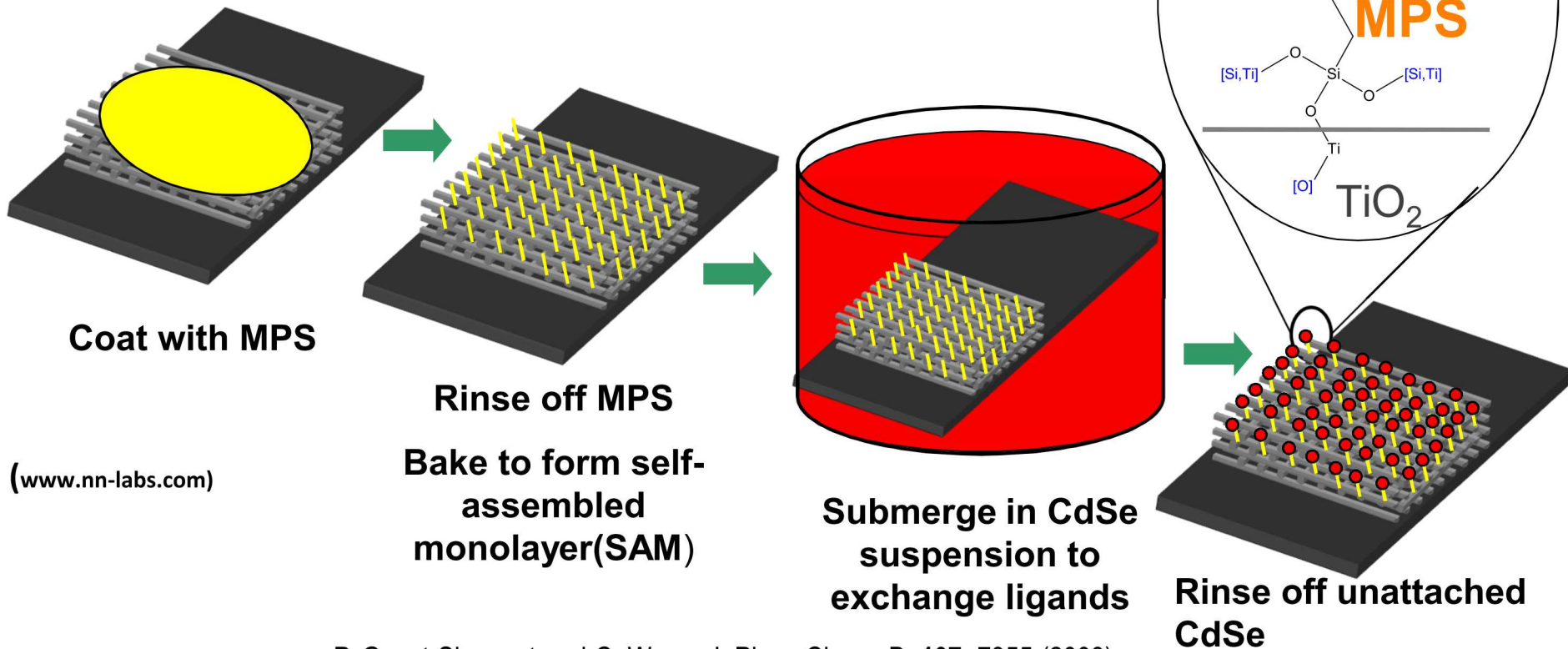
➤ GaN QDs for single photon sources



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)

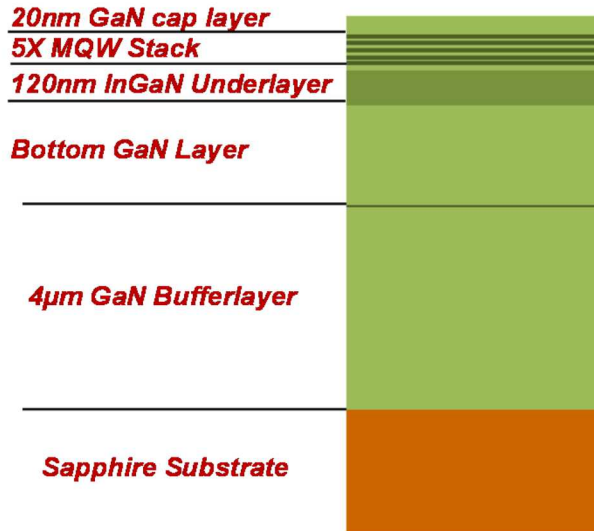


P. Guyot-Sionnest and C. Wang, J. Phys. Chem. B, **107**, 7355 (2003)

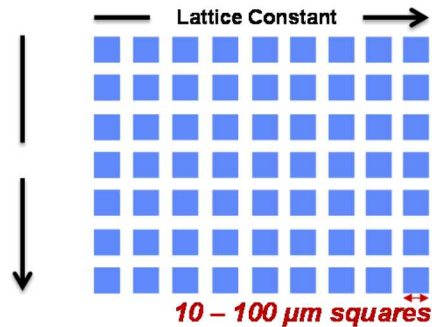
J. Pacifico, D. Gomez, and P. Mulvaney, Adv. Mater. **17**, 415 (2005)

Fabrication of III-N nanowire laser array

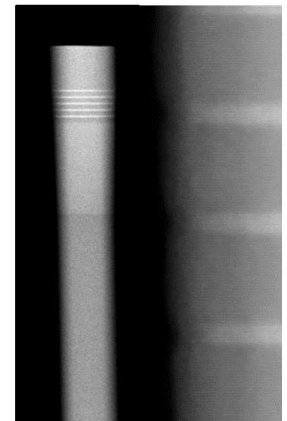
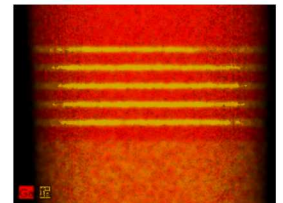
Growth of III-N active material



Patterning of 2DPC using e-beam lithography

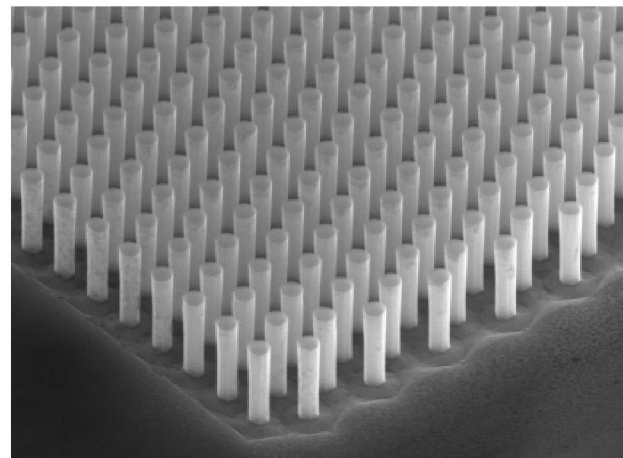
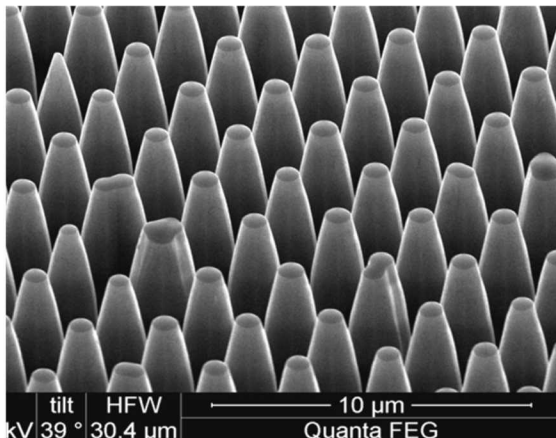


TEM images



Ping Lu,
Sandia

Inductively coupled plasma dry etch



Wet etch using KOH process