

Photonic and Plasmonic Crystals: Nanostructured Platforms for Controlling Light- Matter Interaction

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U.S. DEPARTMENT OF
ENERGY



Office of
Basic Energy Sciences

Director:

Jerry Simmons

Co-Director:

Mike Coltrin

Chief Scientist:

Jeff Tsao

Thrust Leaders

Mary Crawford

George Wang

Art Fischer

- **Duration:** Aug 2009 – Jul 2014
- **Budget:** \$3.6M/year for 5 years
- **Staffing :** Sandia: > 20, External Partners: 9 (\$325K/year)



Senior Staff

Andy Armstrong

Normand Modine

Weng Chow

Dan Koleske

Ken Lyo

Jianyu Huang

Francois Leonard

Jim Martin

Lauren Rohwer

May Nyman

Igal Brener

Willie Luk

Ganesh Subramania

Eric Shaner

Qiming Li

Post-Docs and

Students

Jeremy Wright

Business Staff

Rene Sells

Jessica Hobbs

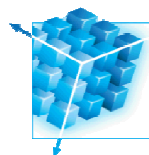
Denise LaPorte

Luz Tirado

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



PHILIPS



**SSLS
EFRC**
SOLID STATE LIGHTING SCIENCE
ENERGY FRONTIER RESEARCH CENTER



Sandia
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SSL EFRC Thrust Areas

Thrust 1: Competing Radiative and Non-Radiative Processes (M.Crawford)

Achieve a microscopic understanding of the competition between e-h-pair recombination via radiative pathways that produce light and via non-radiative pathways that produce heat.

Thrust 2: Beyond-2D (G.T. Wang)

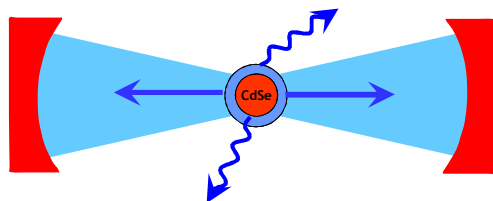
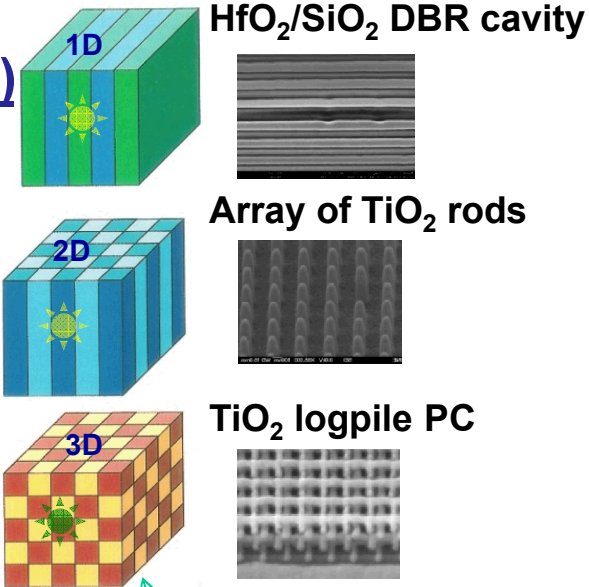
Explore the use of non-planar nanoscale structures to modify energy conversion routes so that they may be (a) isolated and better understood, and (b) engineered and optimized.

- Nanowires, Nanoparticles, Non-polar GaN substrate growth

Thrust 3: Beyond Spontaneous Emission (A. Fischer)

Manipulate environment around the emitter to achieve emission properties beyond conventional light sources

- Photons in structured environment (1D, 2D and 3D PCs, Plasmonics) – Spontaneous emission suppression/enhancement
- Exciton -Polaritons in microcavities - Purcell effect, Strong coupling, Polariton condensates (Nitride systems - important)
- Novel non-classical sources : Single photon, Polariton lasers



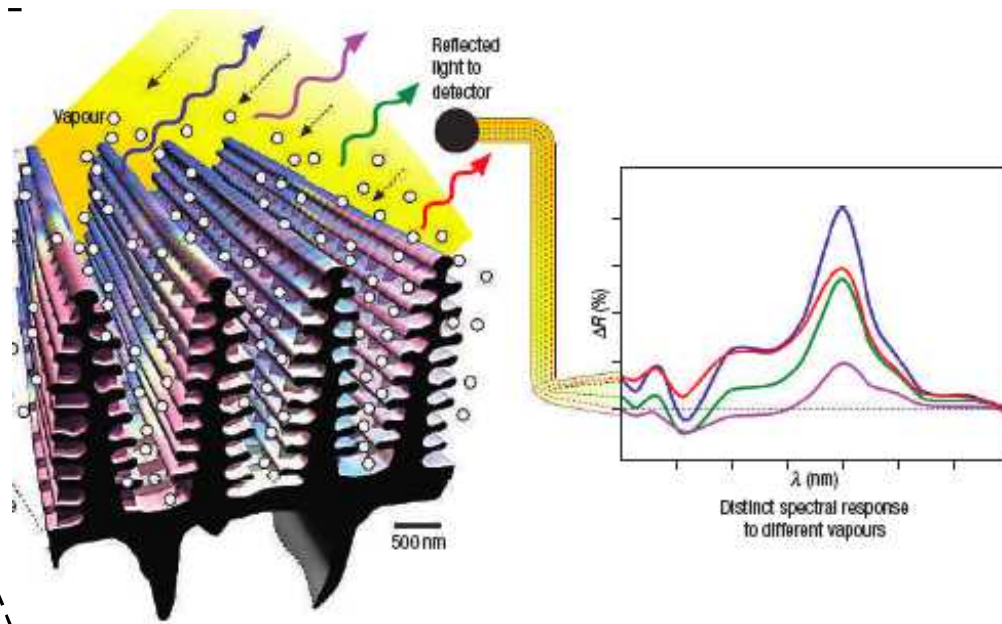
**Optical
Cavity**

Cartoon images courtesy: " Photonic Crystals", John D. Joannopoulos et. al..

Example of Light Control in Nature Via Nanostructuring

Morpho Butterfly
(*M. Sulkowskyi*)

- Signals by giving off colors by strong reflection of sunlight : visible half mile away
- Color response highly sensitive to different vapors



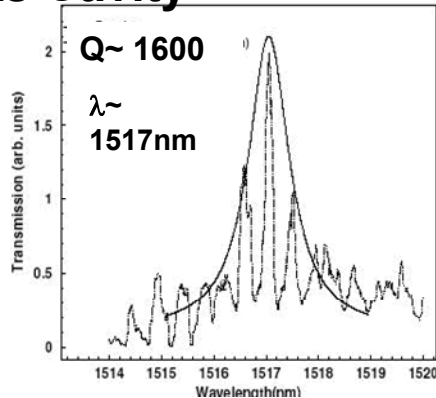
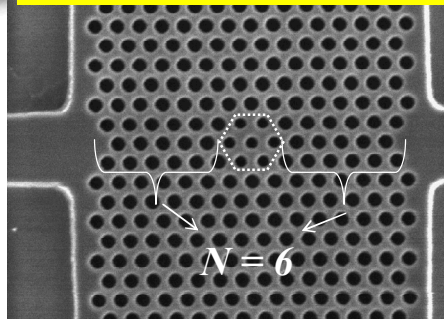
Periodic and Aperiodic Nanostructuring

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

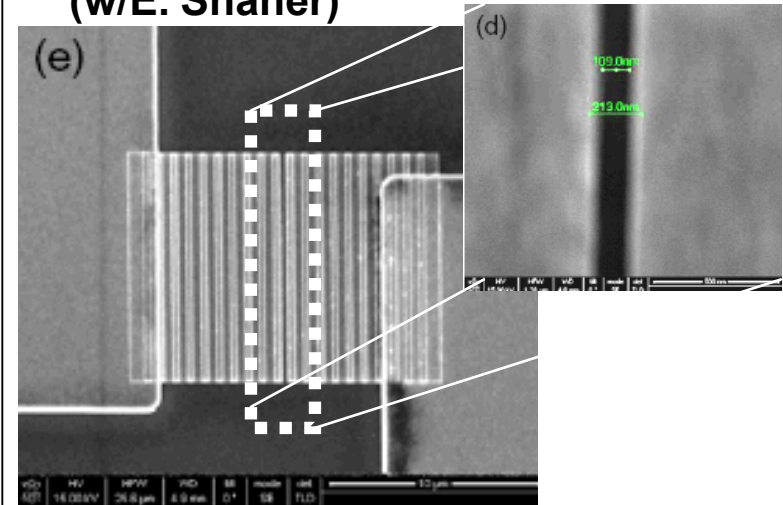
2DPCs for Light Matter Interaction

High Q GaAs Cavity

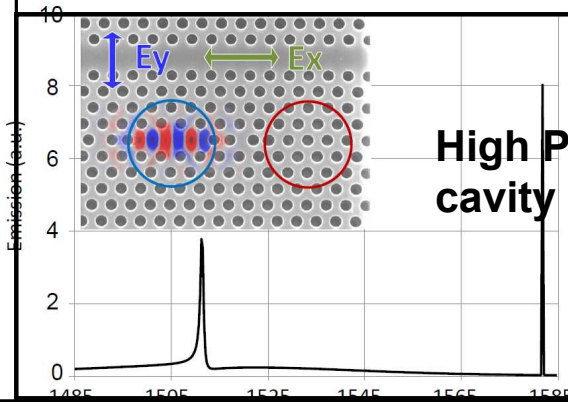
Super-defect cavity $d' = 195\text{nm}$



Surface plasmon Auston Switch (w/E. Shaner)



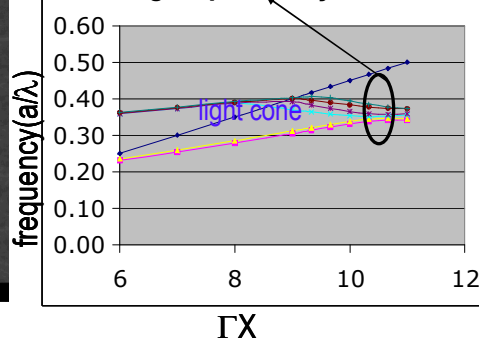
High Purcell factor SOI cavity (w/ T.S. Luk)



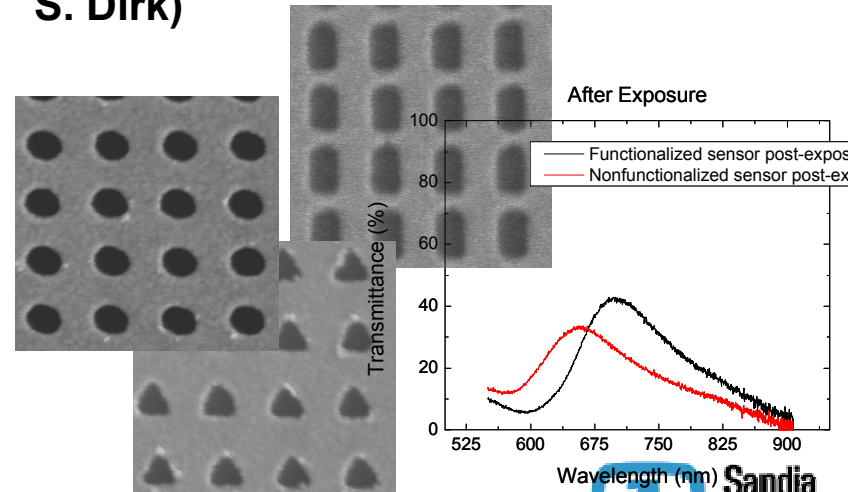
Slow group velocity mode lasing

2D array of TiO₂ rods

Slow group velocity modes

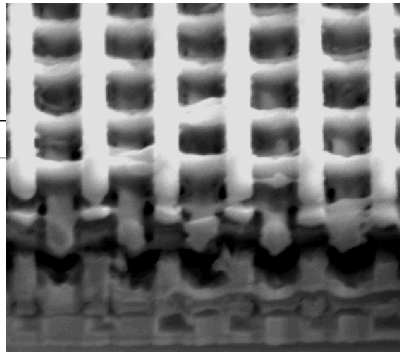
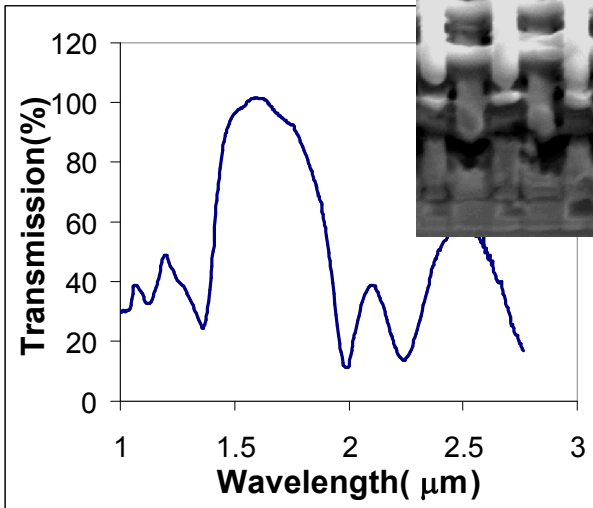


Nanohole EOT based sensors (w/I. Brener, S. Dirk)

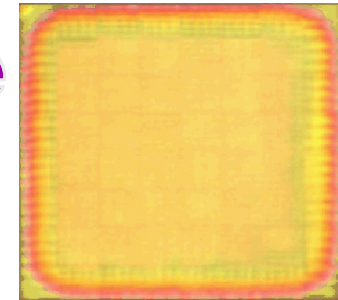
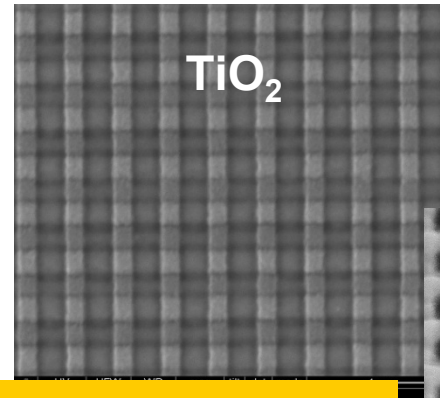


3DPCs for Light- Matter Interaction

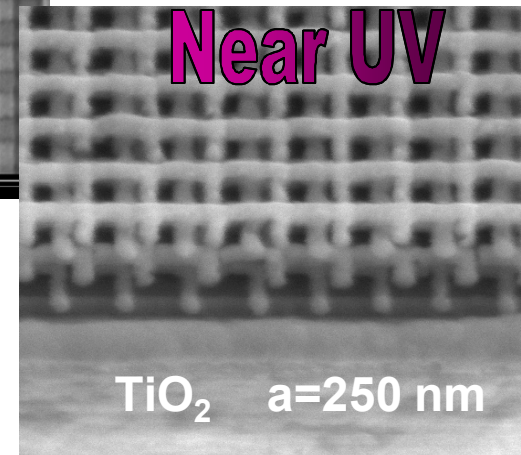
Si near-IR



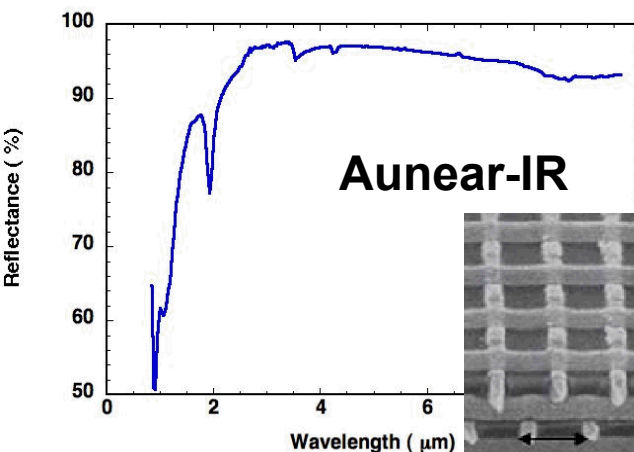
Visible



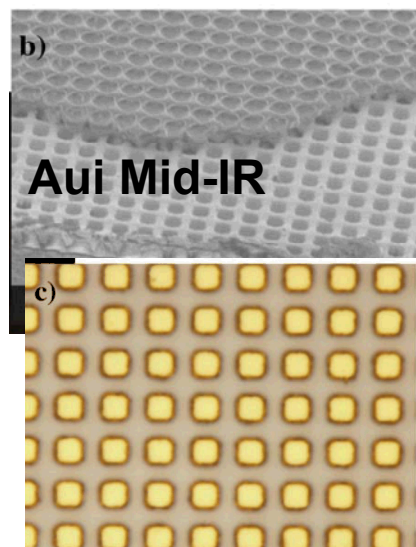
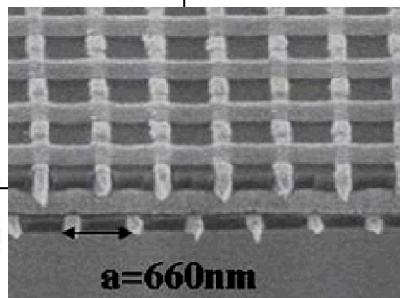
Near UV



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

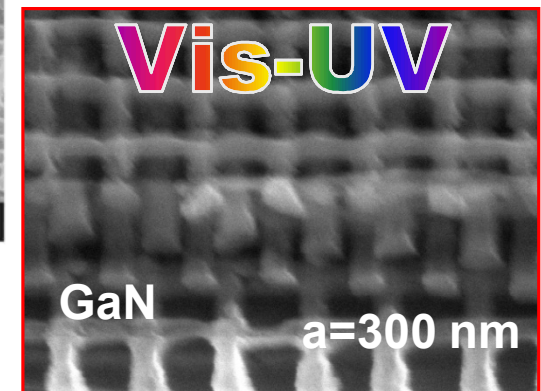


Au near-IR

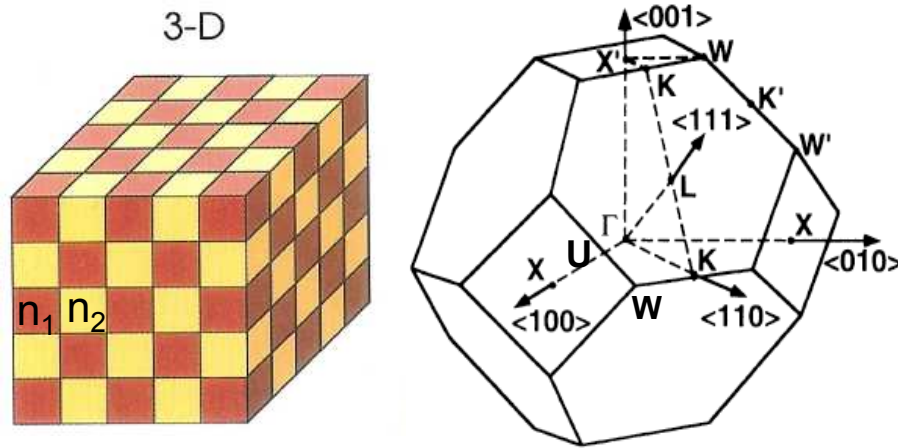


Au Mid-IR

Vis-UV



Photonic crystal: A class of Sub-wavelength Structured Material



Maxwell's Eqns. In Real space

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

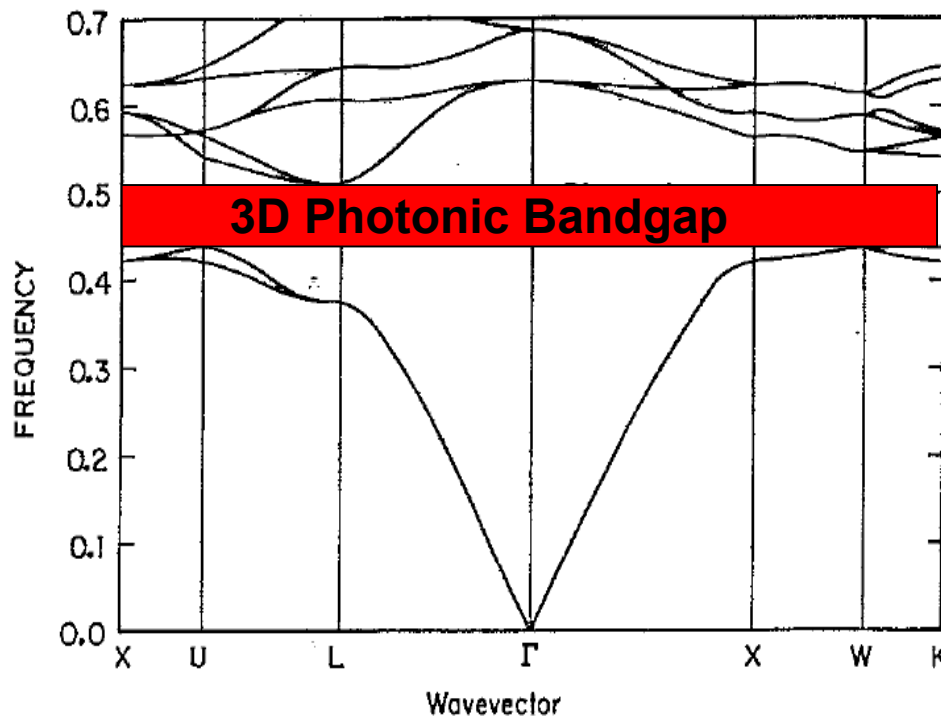
$$H(r, t) \propto e^{-i\omega t}$$

$$\nabla \times E(r) = i\mu_0 \omega H(r)$$

$$\nabla \cdot [\varepsilon(r) E(r)] = 0$$

$$\nabla \times H(r) = -i\varepsilon_0 \varepsilon(r) \omega E(r)$$

$$\nabla \cdot H(r) = 0$$



$$\varepsilon(r + R) = \varepsilon(r) \rightarrow E, H(r + R) = E, H(r)$$

Reciprocal (K) space

$$\varepsilon(r) = \sum_G \bar{\varepsilon}(G) e^{iG \cdot r}$$

$$G \cdot R = 2\pi n$$

$$E, H(r) = \sum_G \bar{E}, \bar{H}(G) e^{-i(-k+G) \cdot r}$$

Eigen value equation

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



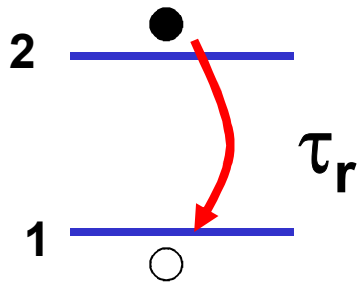
Photonic Crystal Band Structure

- **Dispersion control**
 - Negative refraction, Self-collimation, Light trapping
- **Defect control**
 - Waveguiding, Microcavities
- **Photon Density of States control**
 - Emission modification, exciton-photon coupling

While Maxwell's equations are inherently frequency independent the material properties $[\epsilon(\omega)]$ are not !

Spontaneous Emission

Spontaneous emission probability is also highly frequency dependent !



$$\frac{1}{\tau_r} = A = \rho(\omega) \hbar \omega B$$

Photon density of states (PDOS)

Related to absorption coefficient

Einstein Eqns:

$$A + B_{12}W(\omega) = B_{21}W(\omega)$$

In free space,

$$\rho(\omega) = \frac{\omega^2}{\pi^2 c^3} \rightarrow A \propto \omega^3$$

☞ Spontaneous emission dominant at higher frequencies

☞ Ability to control spontaneous becomes important

Spontaneous Emission Control

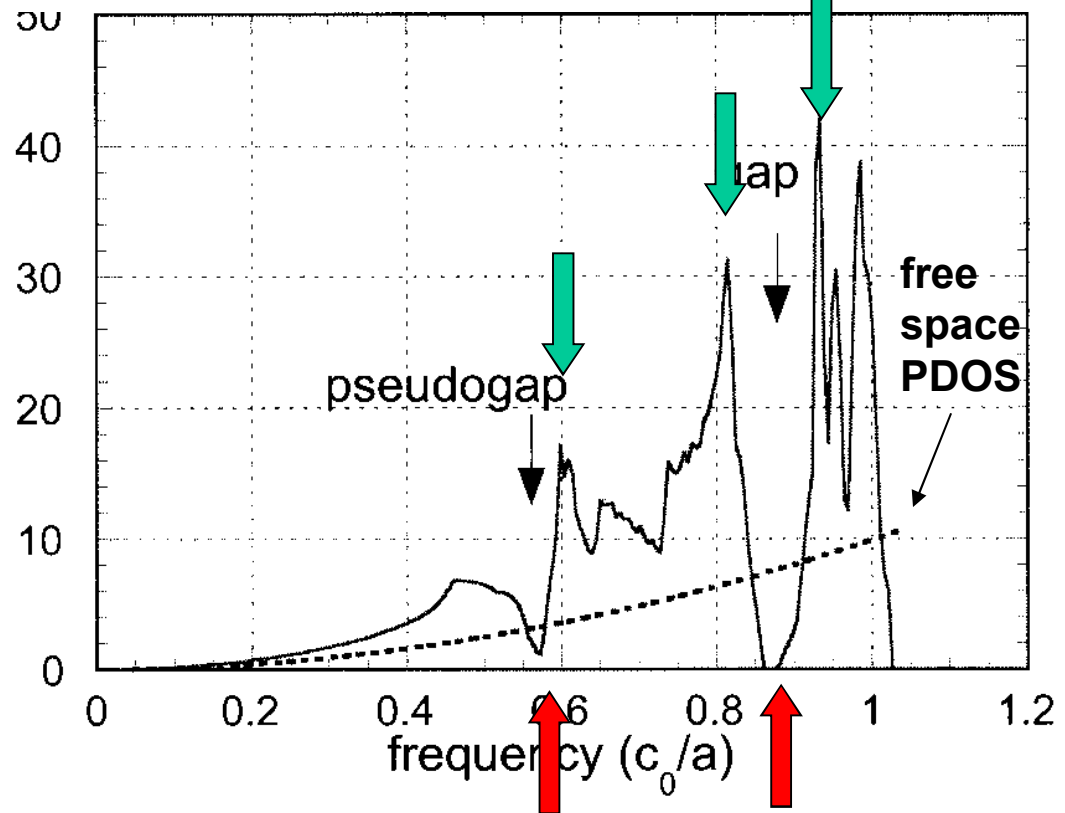
Photonic Crystal

Emitting dipole in an EM field
(Fermi's Golden Rule)

$$\frac{1}{\tau_r} = \frac{\pi \omega \mu^2}{3 \epsilon_0 \hbar} \rho(\omega)$$

- **Suppression**
- **Enhancement**

PDOS for FCC PC with $n = 3.1$

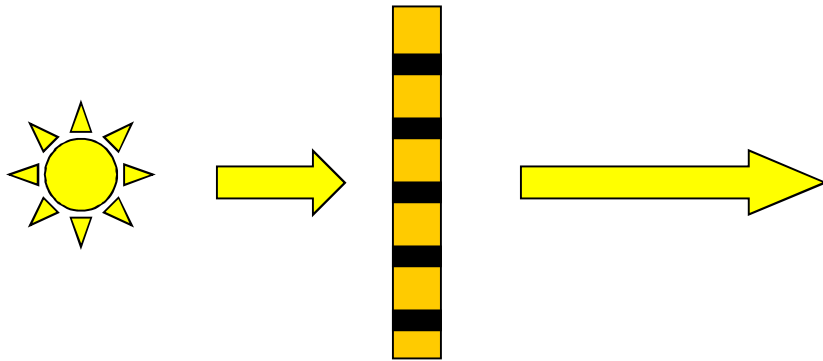


Near-IR , Visible regime of Practical Interest → Spontaneous emission control is important → PC fabrication

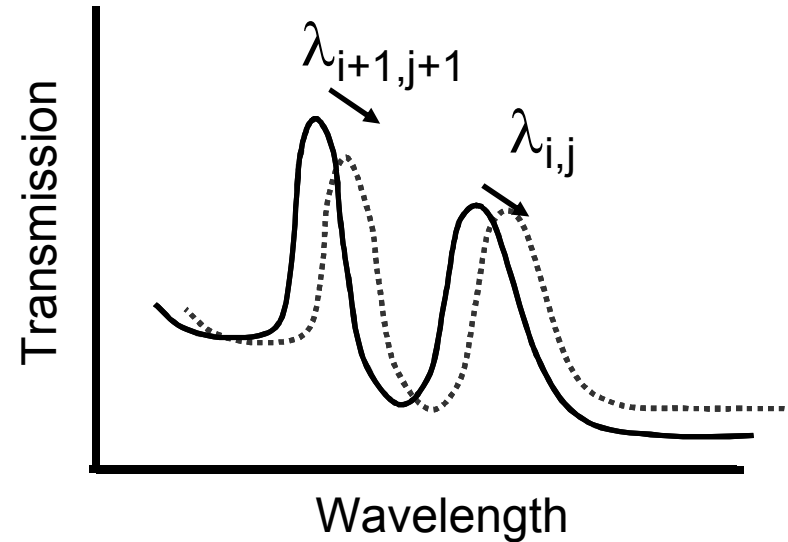
Extraordinary Transmission through Metal Nanoholes

T. W. Ebbesen, H. J. Lezec, H. F. Ghaemi, T. Thio, P. A. Wolff, *Nature* **1998**, 391, 667

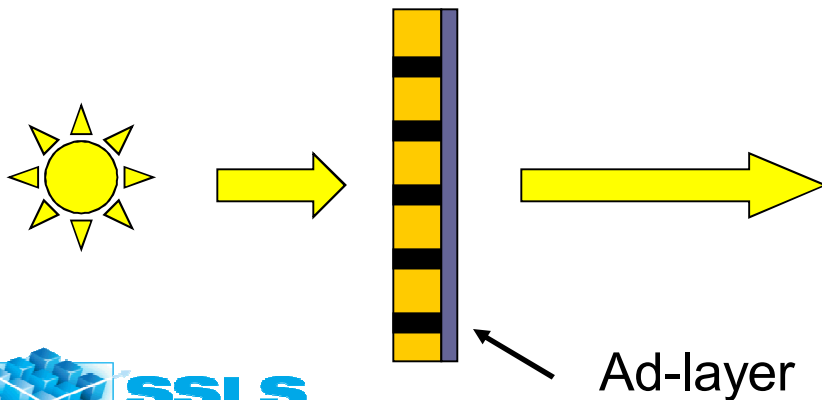
EOT of metallic nanohole arrays



$$\lambda(i, j) = \frac{a}{\sqrt{i^2 + j^2}} \sqrt{\frac{\epsilon_m \epsilon_d}{(\epsilon_m + \epsilon_d)}}$$

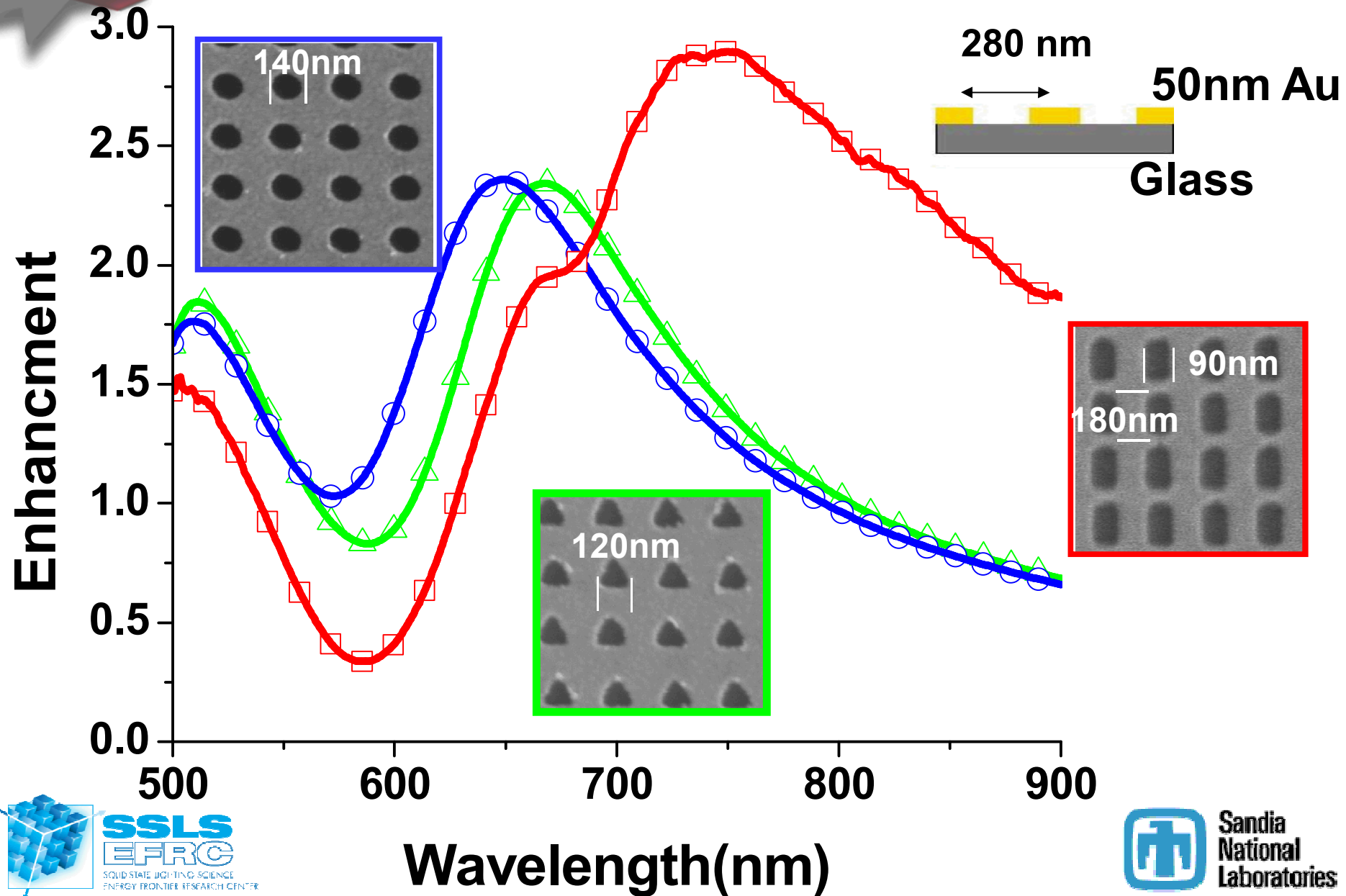


Nanohole array with an ad-layer



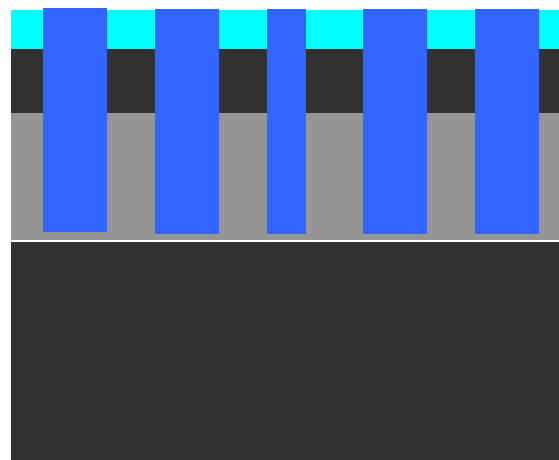
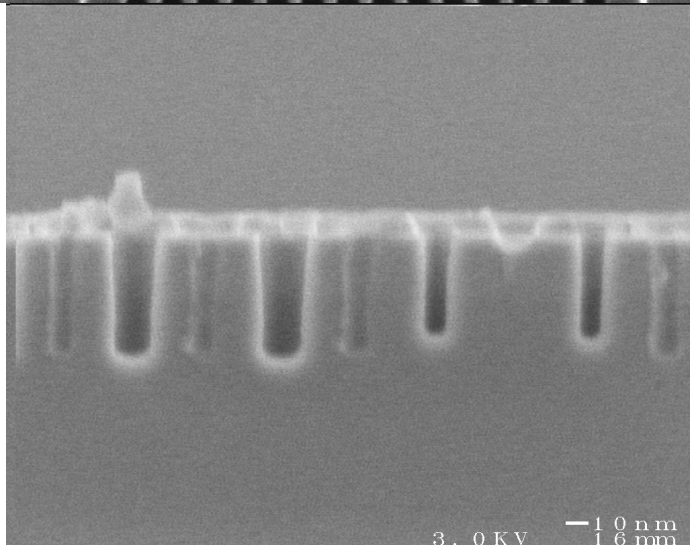
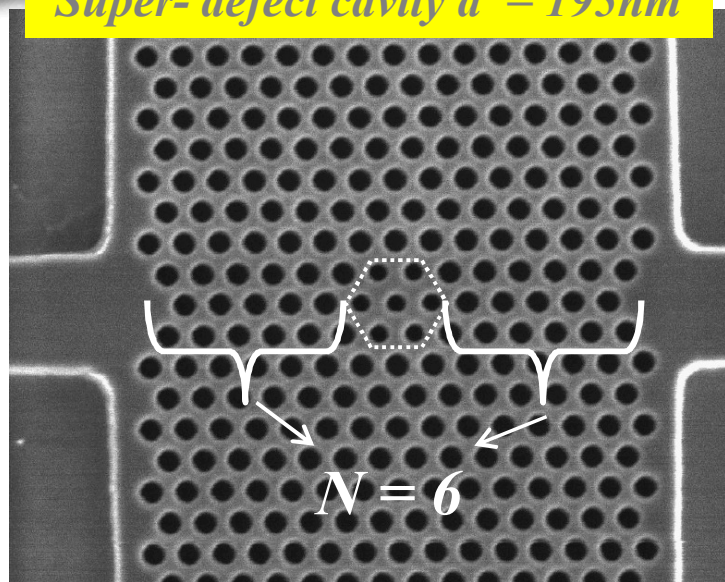
$$n_{eff} = \left(\frac{2}{I_d} \right) \int_0^{\infty} n(z) \exp(-2z / I_d) dz$$

Hole Shape Dependence of EOT



2D Slab PC Cavity: Simple System

Super- defect cavity $d' = 195\text{nm}$



SiO₂ mask (200nm)
Epi-GaAs (200nm)

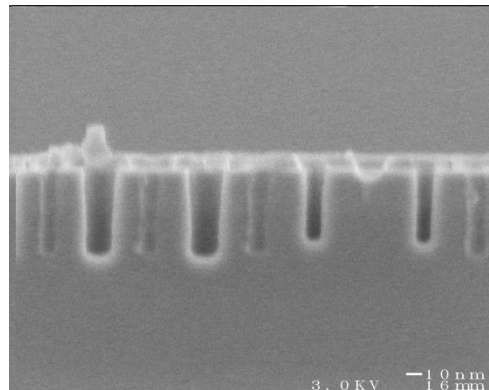
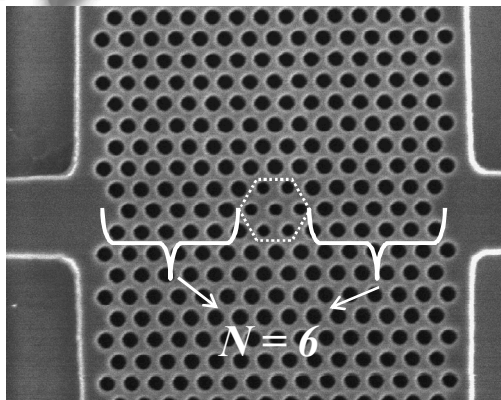
Al_xO_y (500nm)

GaAs Substrate

- Epitaxially grown GaAs/ $\text{Al}_x\text{Ga}_{1-x}\text{As}$ system
- E-beam direct patterning of holes ' $a = 400\text{-}460\text{nm}$ '; ' $d = 240\text{-}280\text{nm}$ ';
- Cl_2 based deep reactive ion beam etch (RIBE)
- $\text{Al}_x\text{Ga}_{1-x}\text{As}$ wet oxidized to Al_xO_y



Two-dimensional Photonic Crystal Cavity

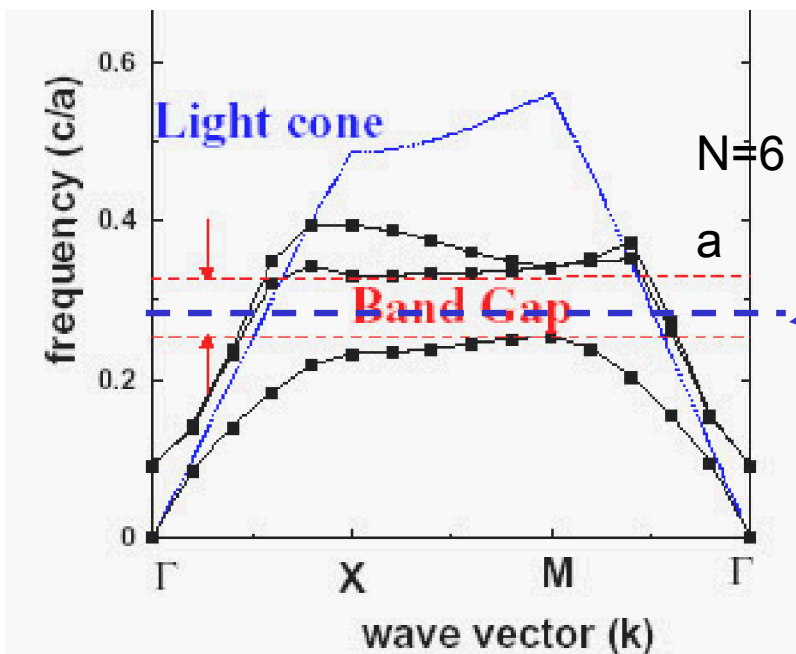


SiO₂ mask

Epi-GaAs(200nm)

Al_xO_y (500nm)

GaAs Substrate



Cavity mode

$$\lambda_{peak} = 1517 \text{ nm}$$

$$Q = 1600$$

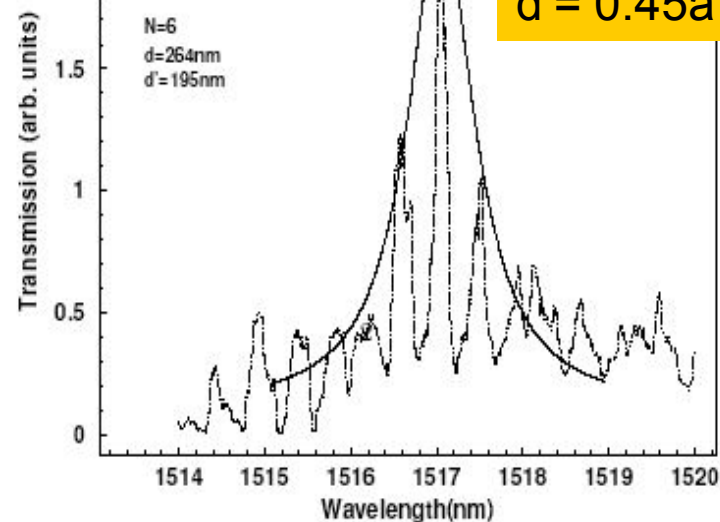
$$MV \sim 1.5(\lambda/n)^3$$

$$N=6$$

$$a = 440 \text{ nm}$$

$$d = 0.6a;$$

$$d' = 0.45a$$



Using 2D PC Cavities to Enhance Non-linearity

Pattern resist and deposit Pt bottom electrode

Spin coat & pyrolyze PLZT precursor

Pattern resist and deposit Pt etch mask

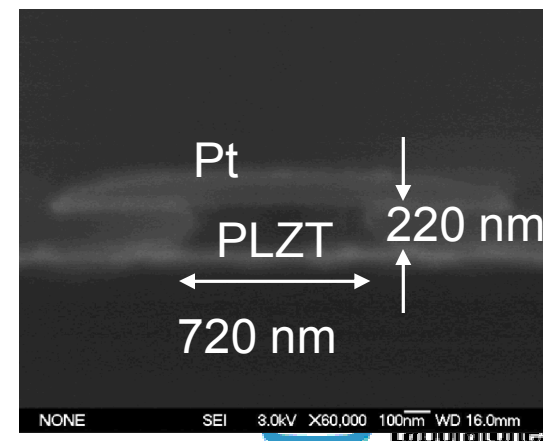
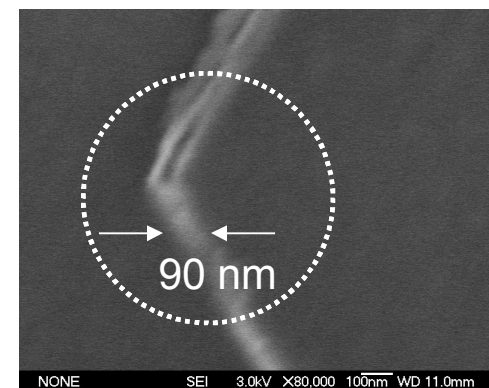
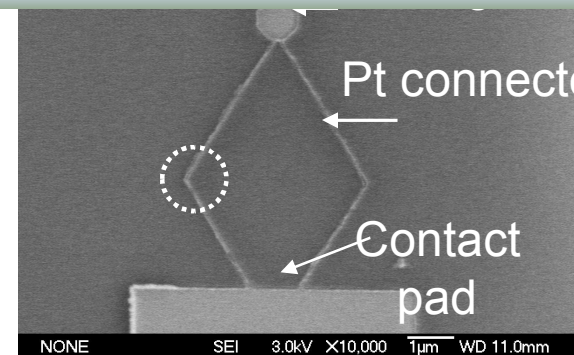
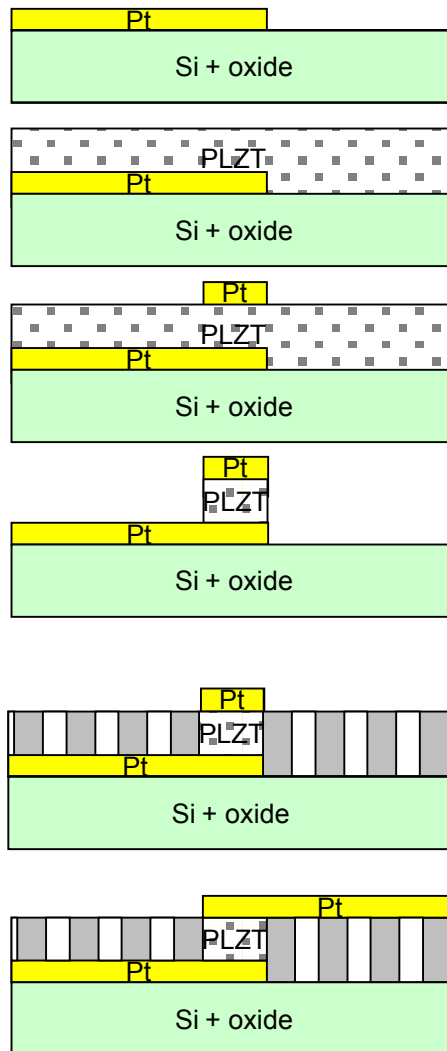
Wet etch PLZT (HCl) + anneal

PECVD Si

Pattern resist and dry etch Si

Pattern resist and deposit Pt top electrode

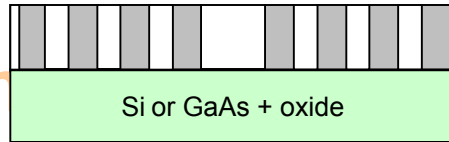
Test properties



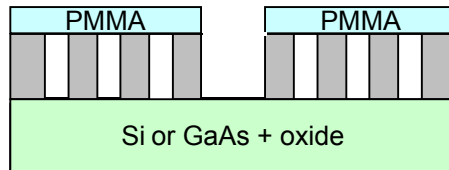
Achieve tunability/switching by applying electrical bias

Emission Modification of PbSe QDs by 2DPC Cavity

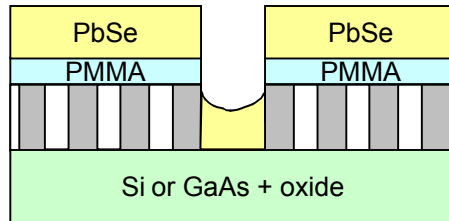
Fabricate PC cavity



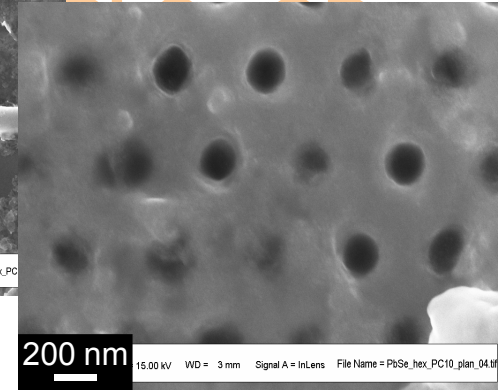
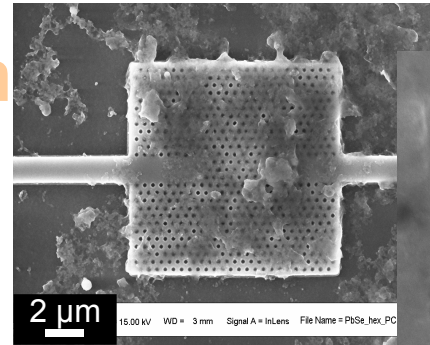
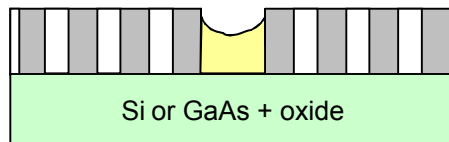
Deposit and pattern e-beam resist (PMMA)



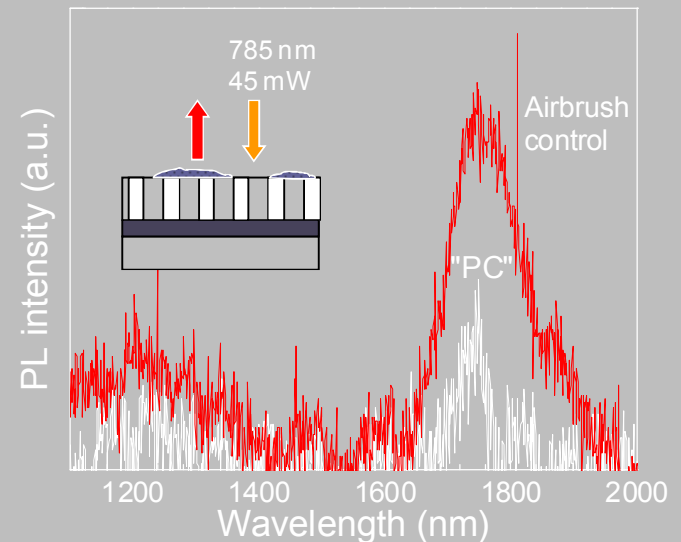
Deposit PbSe QDs



Test properties



PL of PbSe QDs



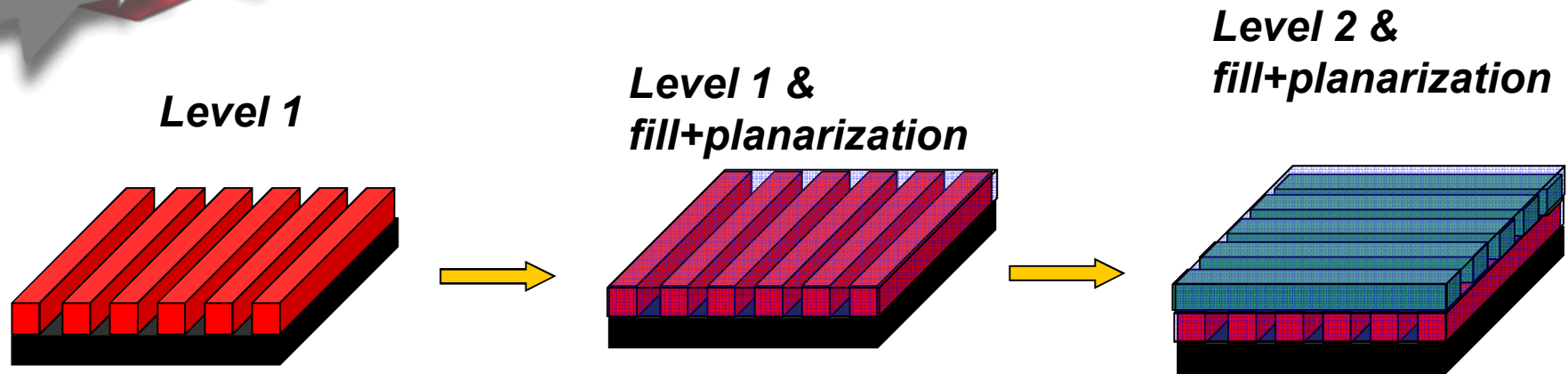
'Air brushing' does not provide sufficient control for incorporation of PbSe colloidal quantum dots

Y-J. Lee et.al., MRS proc., **939**, 2006



Fabrication

Layer-by-layer fabrication of 3D photonic crystals

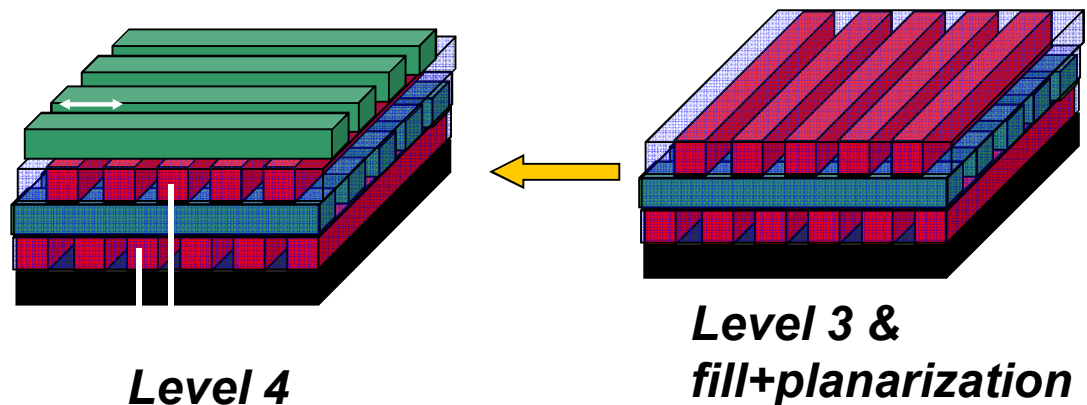


Near-infrared and Visible PC : < 500 nm periodicity

➤ **No Optical Lithography except CMOS fab**

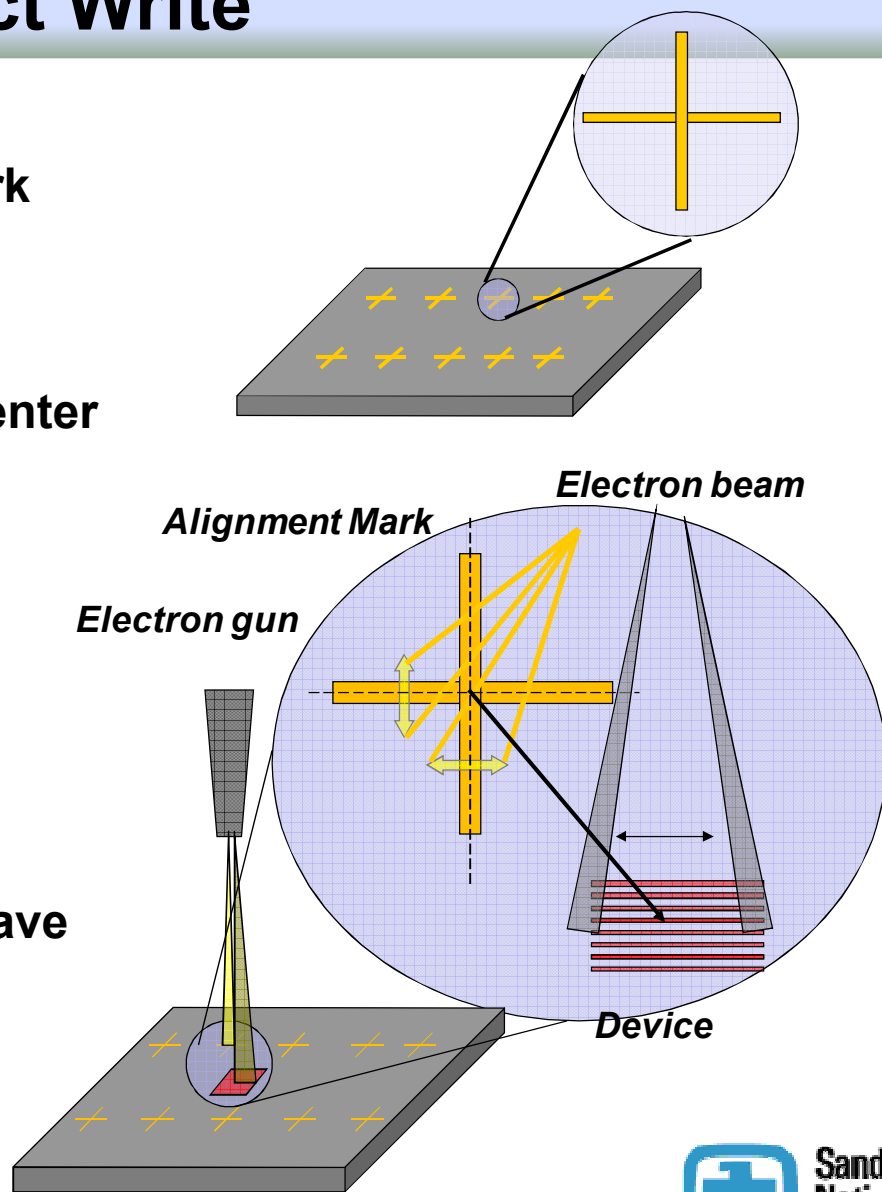
➤ **Alignment**

➤ **Planarization**



Alignment: Multilevel Layer-by-Layer Electron beam Direct Write

- Pattern a set of gold alignment mark
- Device is written at specified coordinates w.r.t alignment mark center
- Machine level alignment accuracy can be achieved ($\sim \pm 20$ nm)
- Alignment marks with ultra sharp edges
- Alignment mark material should have high electron backscatter (e.g. Au)



Fill and Planarization in 3D Multilevel Structures

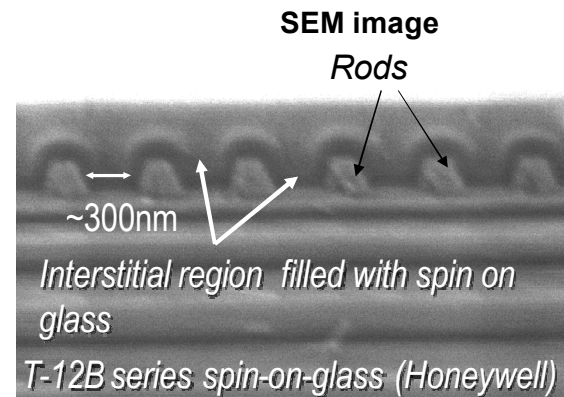
Need for Fill and Planarization

- Minimization of transfer of feature topography
- Increased process yield
- Reduction of resist non-uniformity
- Elimination of step coverage concerns (reduce scattering in optical measurements)

Chemical mechanical planarization (CMP)

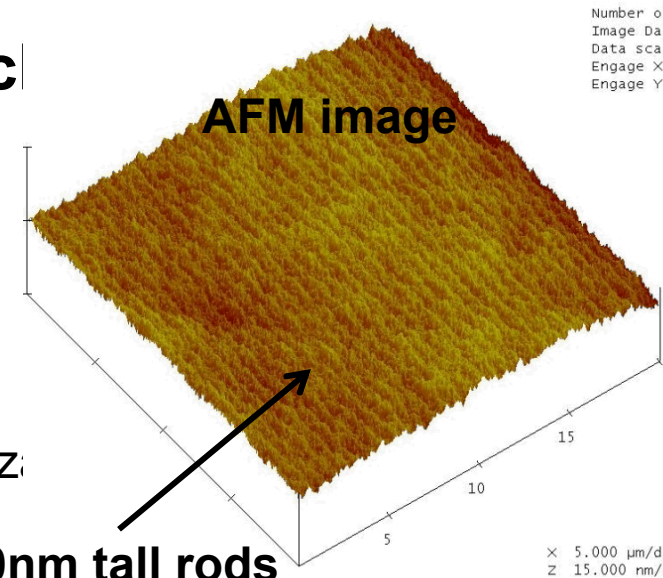
- **Excellent for commercial application-**
Robust , Large area processing, Good process yield
- **Unsuitable for research level –**
Difficult to implement, material dependent, complex set of 20+ parameters

Spin on dielectric + Etch back



- Simple
- Suitable for small wafers
- Excellent via filling (~ 100nm)
- High degree of '**local**' planariz:

Surface roughness < 1 nm for ~ 230nm tall rods



$$DOP_L(\%) = (1 - 1/230) \times 100 = 99.5\%$$

Photonic crystal fabrication: Etch approach

Film deposition (e.g. TiO_2 , Si)



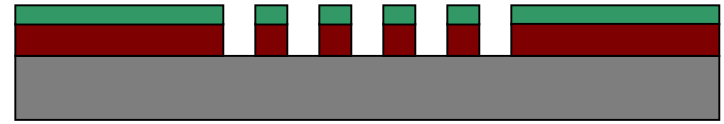
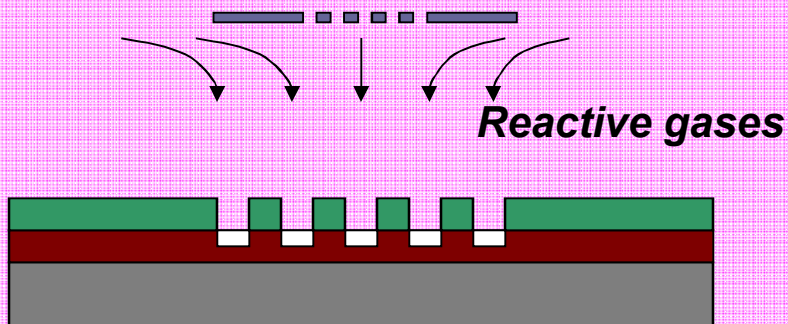
Resist Patterning (e-beam write)



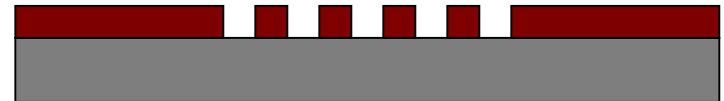
Resist development



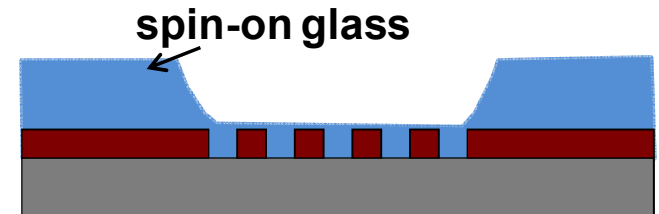
Dry etch



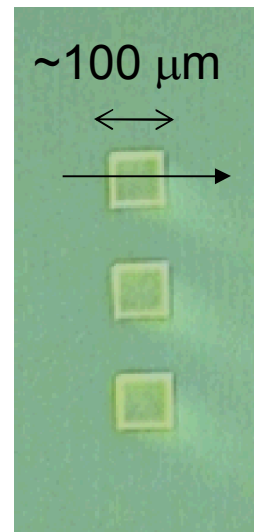
Soak in solvent (e.g. acetone)



Fill and planarize

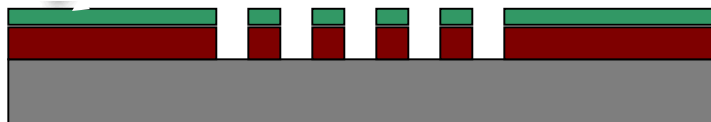


**'Locally' planarized but not
'globally' planarized**

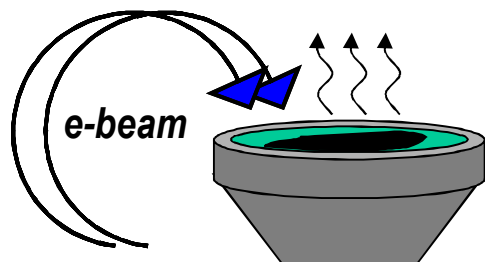
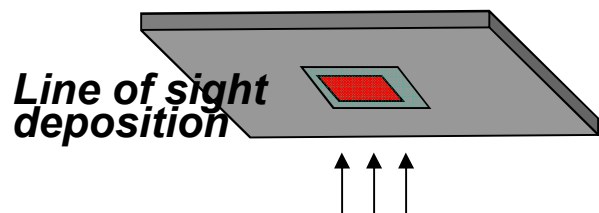


Pre-fill and etch back : total planarization

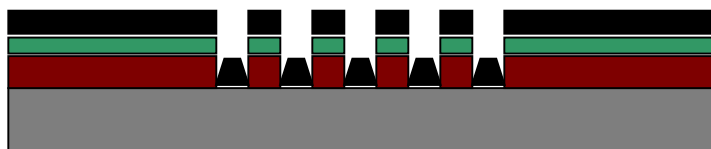
Residual resist after etch



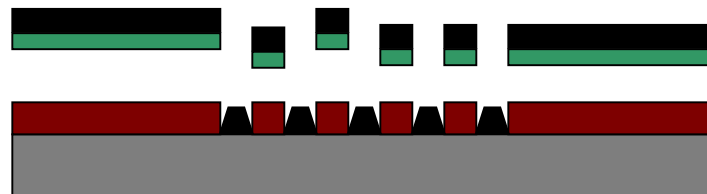
E-beam or thermal evaporation



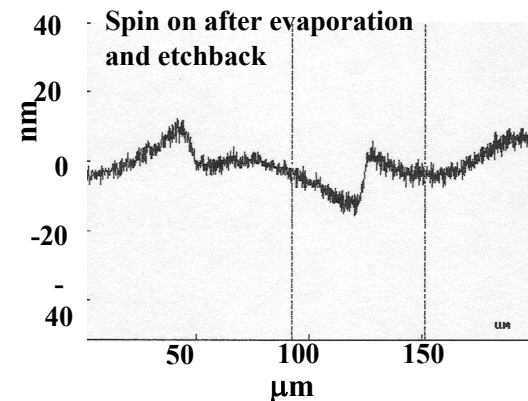
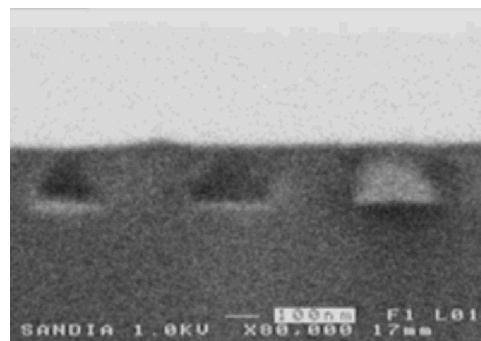
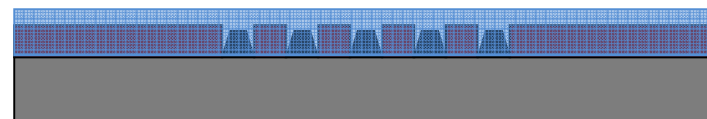
After Evaporation



Soak in solvent for lift-off



Fill and planarize

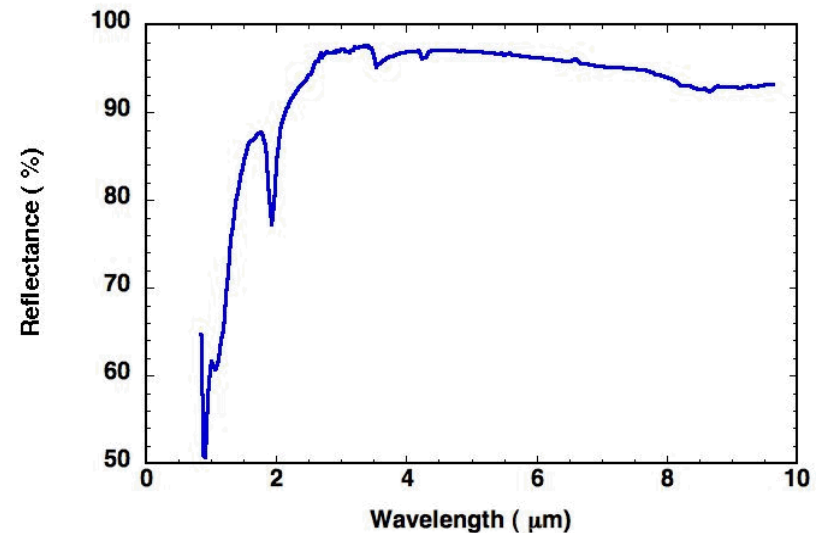
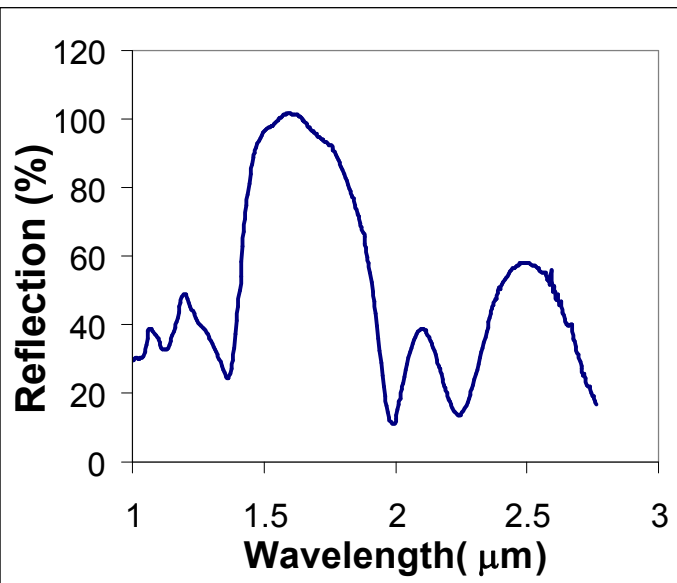
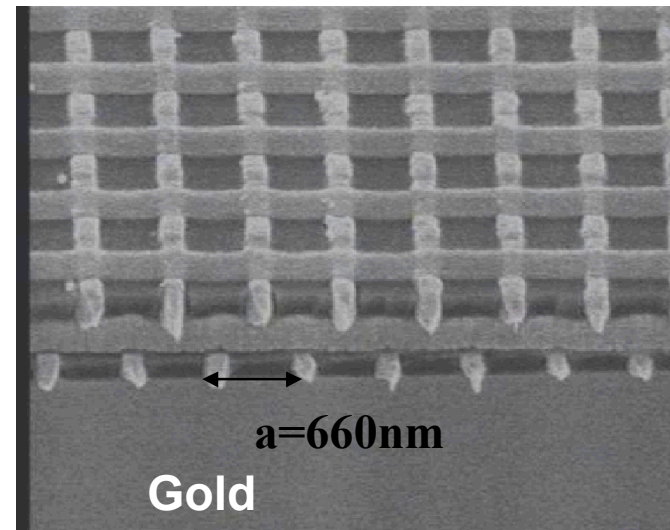
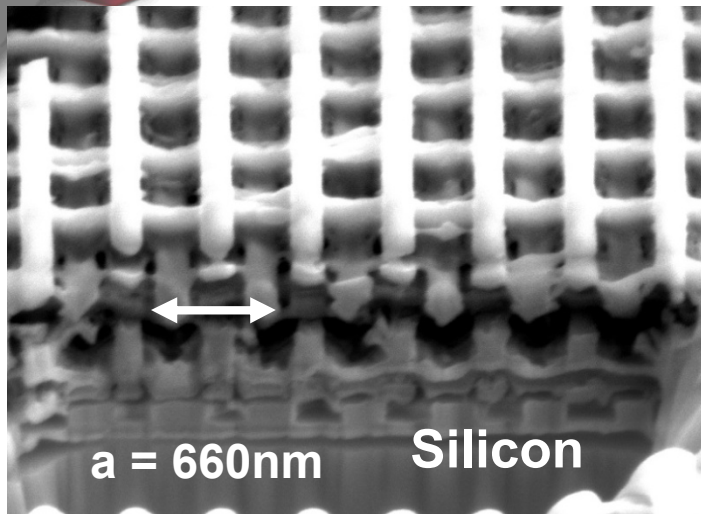


'Total' planarization can be achieved



Three dimensional Logpile PCs from Near-IR to Near UV

Near-IR bandgap Logpile: Silicon and Gold



3DPC for Visible Light Control: TiO₂ Logpile

- TiO₂ is an excellent material for visible PC

[1. G. Subramania, et. al., Adv. Mat. **13**, 443-446 (2001).]

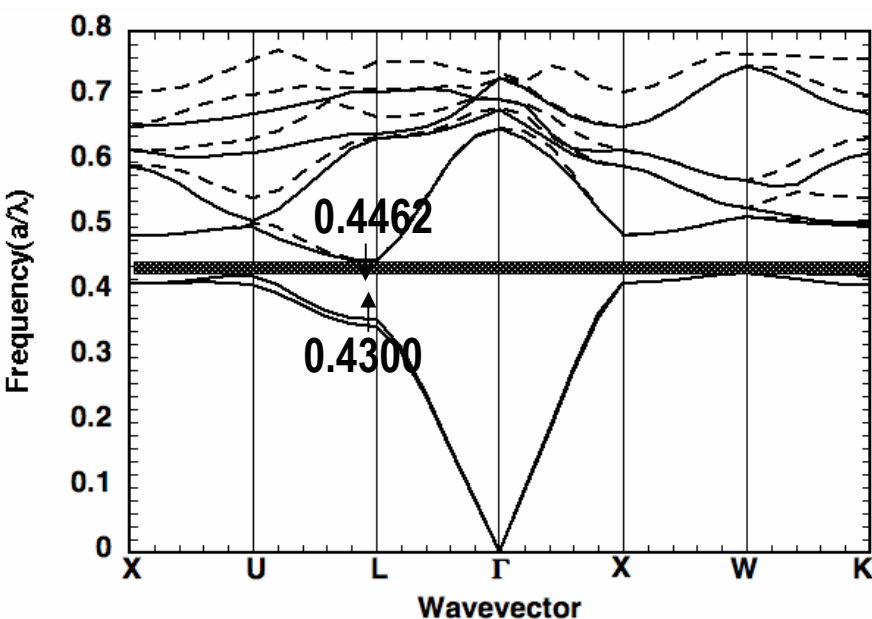
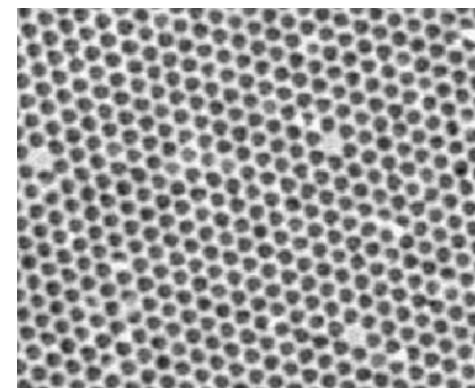
- Low loss high index (2.3-2.7)

- Easy to deposit

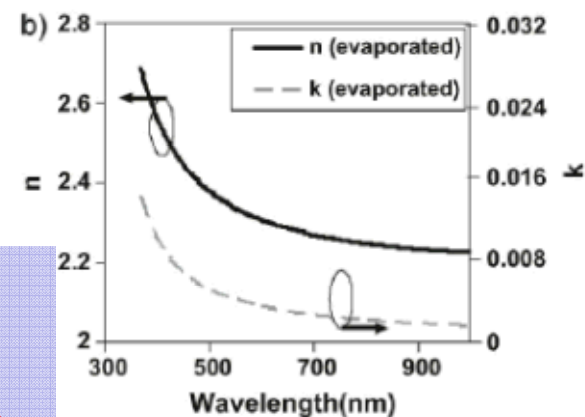
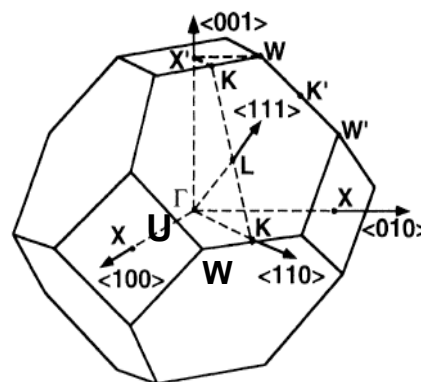
- Sputtering, evaporation, solgel, Atomic Layer Deposition

- Refractive index not high enough for full bandgap with opal² → Need logpile

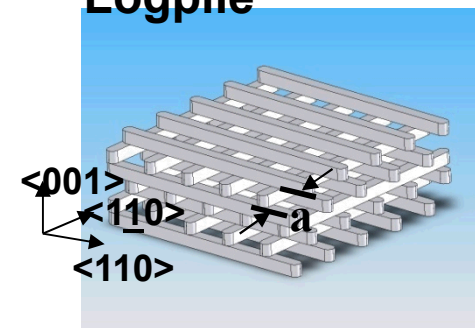
[R. Biswas, et. al. , Physical Review B **61**, 4549 (2000)]



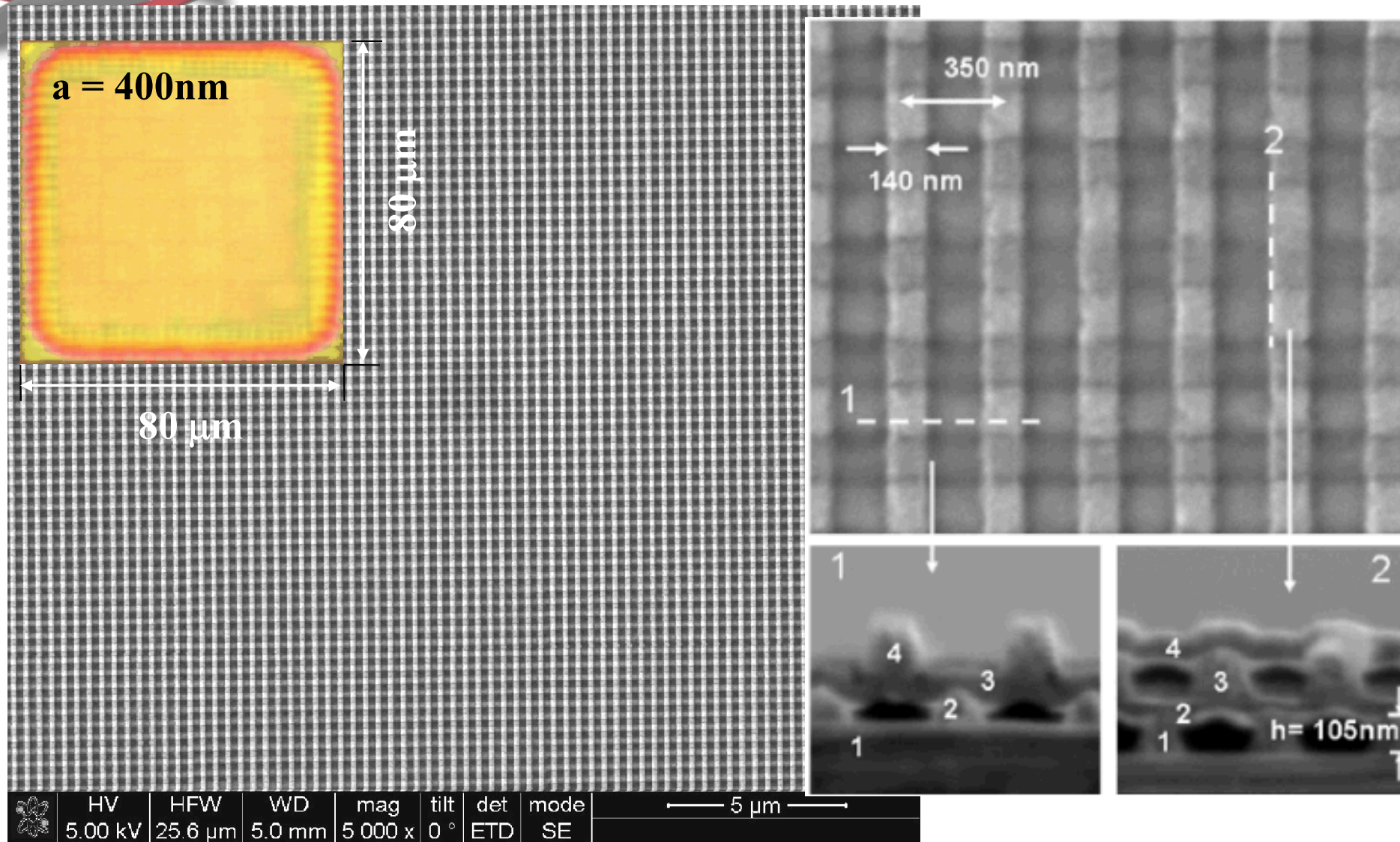
- $n \sim 2.3$
- 4% bandgap
- $\sim 20\text{nm @ } 500\text{nm}$



Logpile

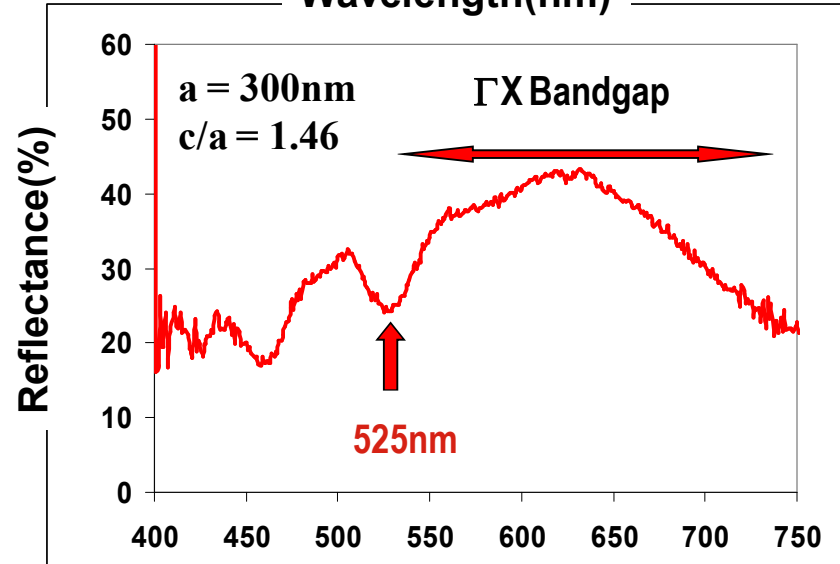
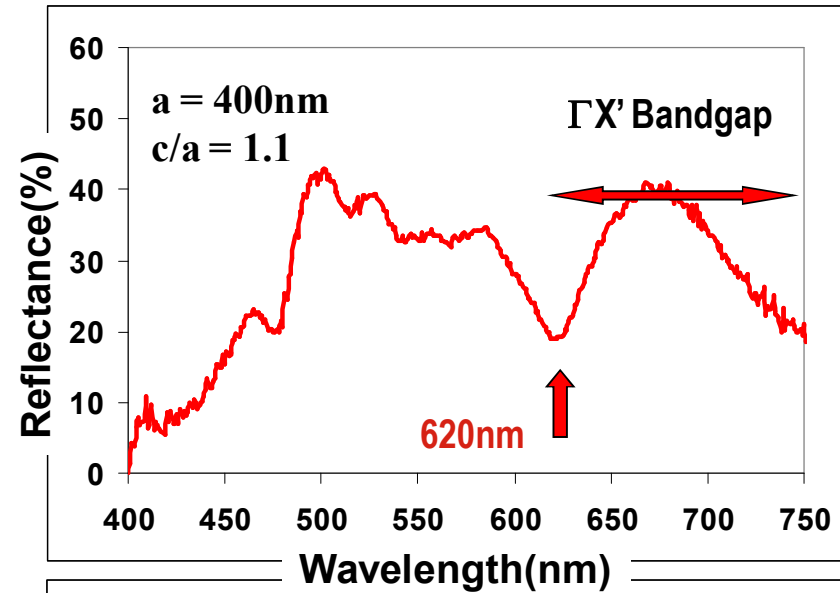
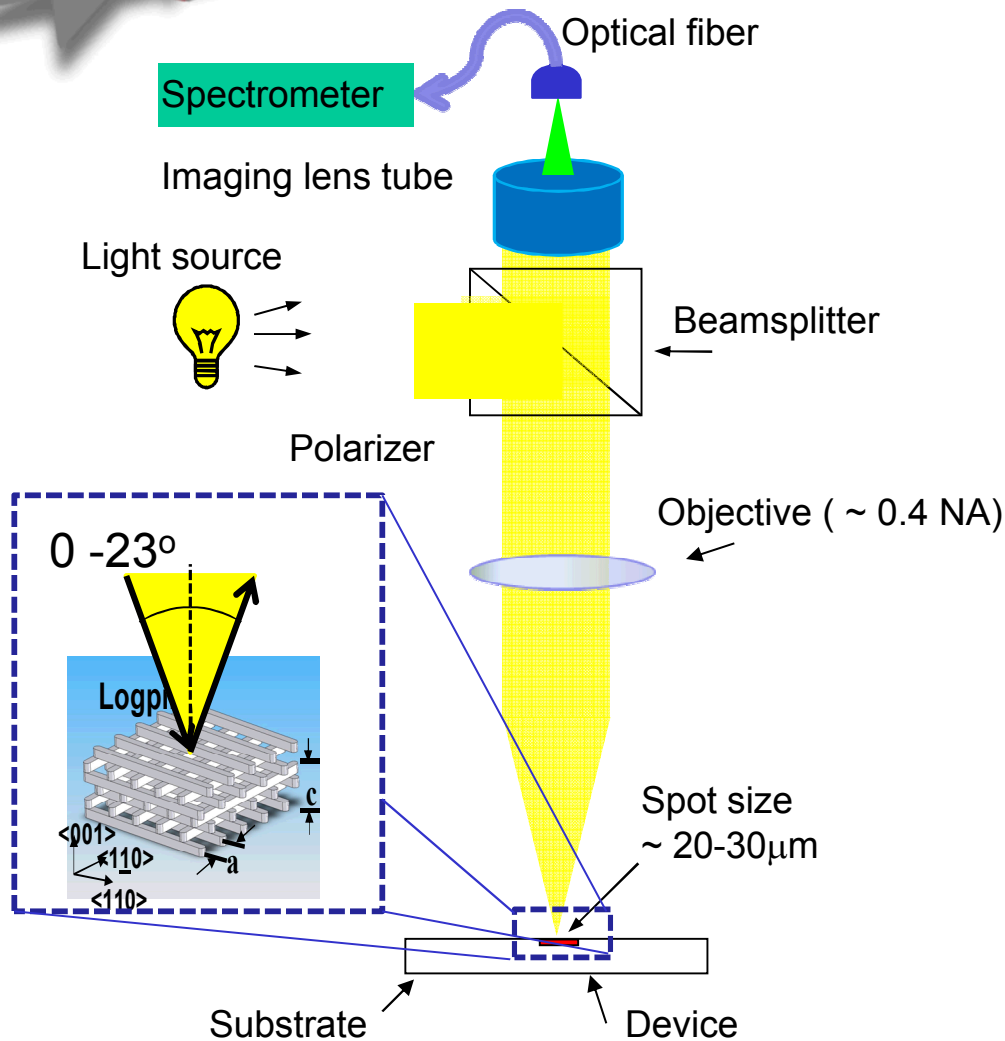


Four Layer Visible Titania Logpile

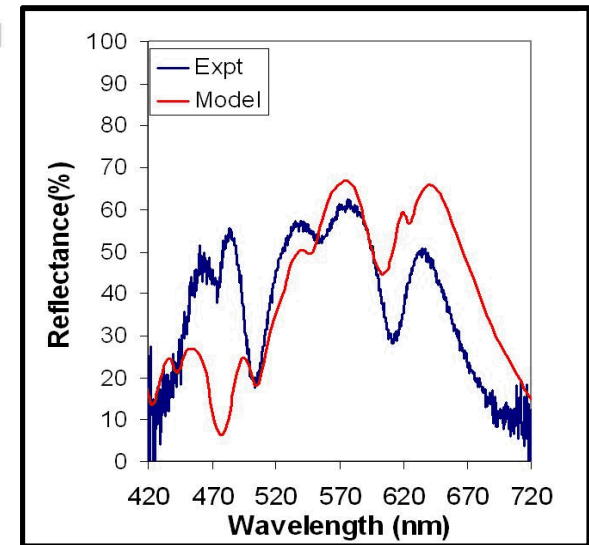
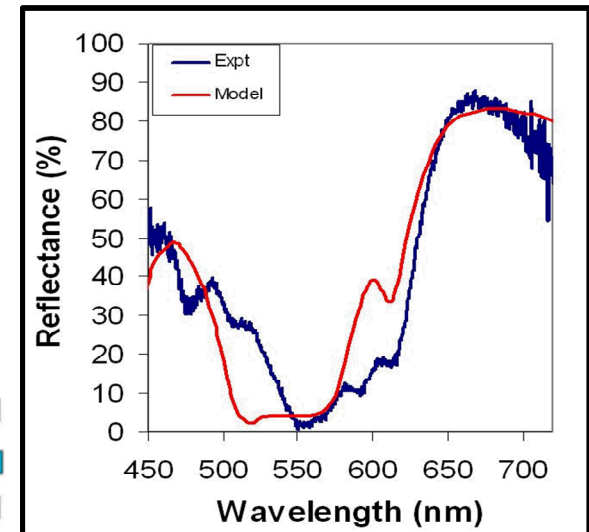
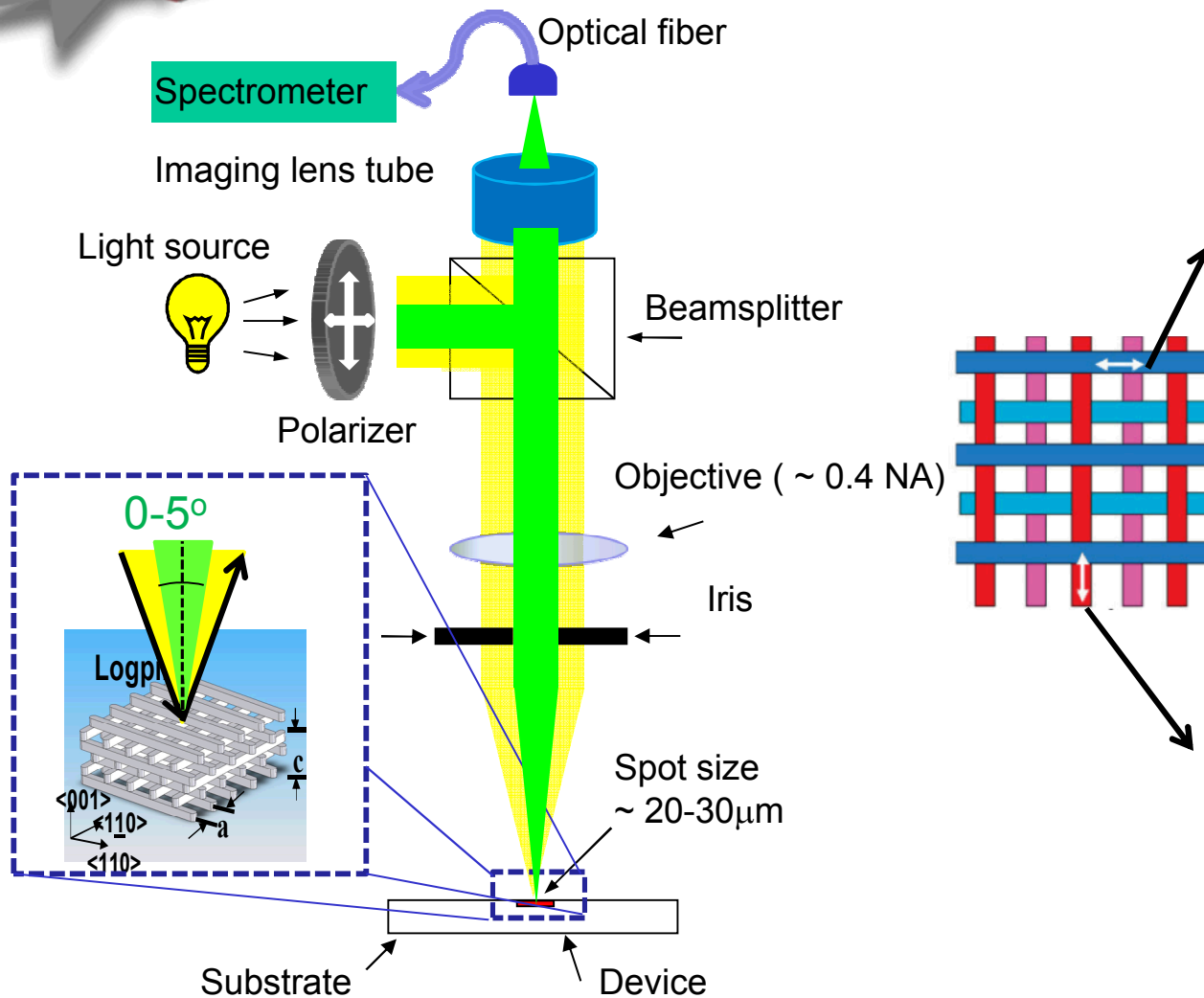


G. Subramania, Y.-J. Lee, I. Brener, T. S. Luk, P. G. Clem,
Optics Express, **15**, 13049 (2007).

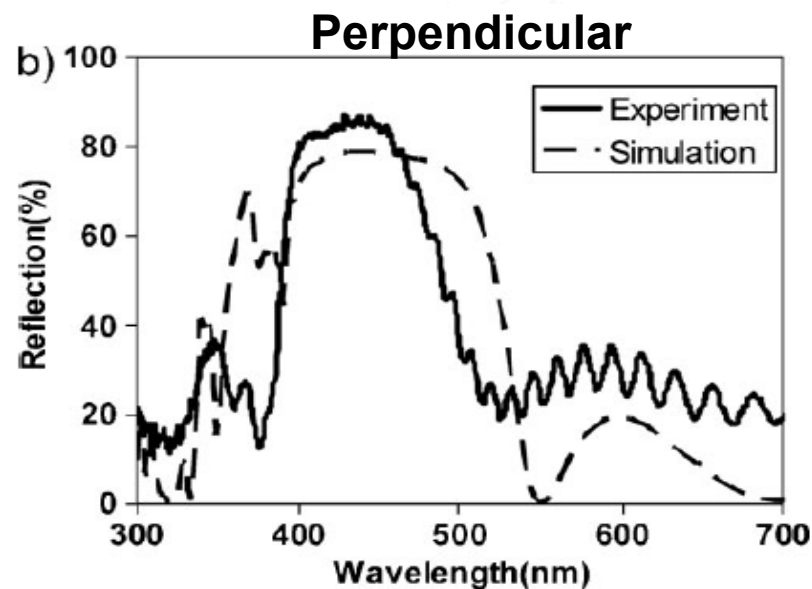
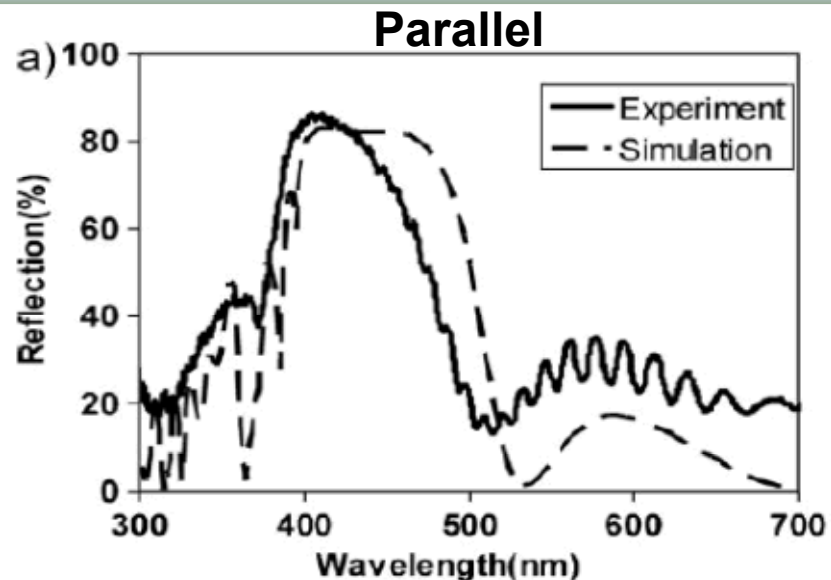
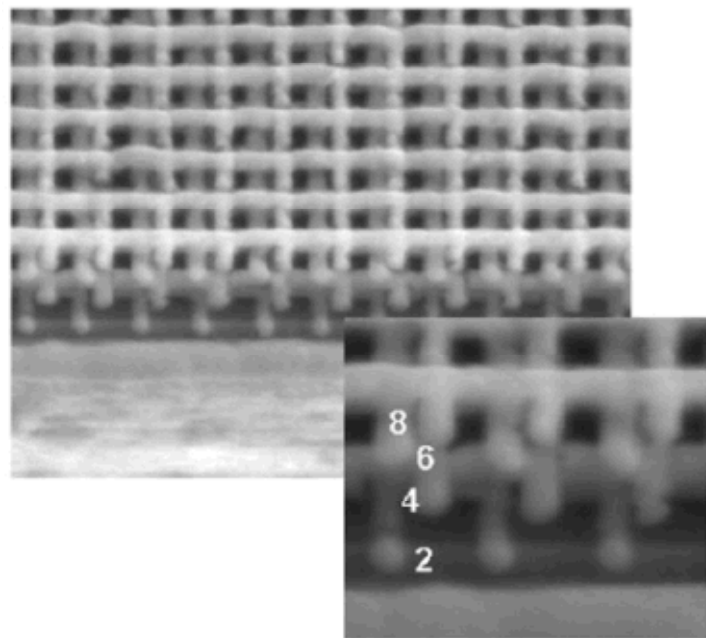
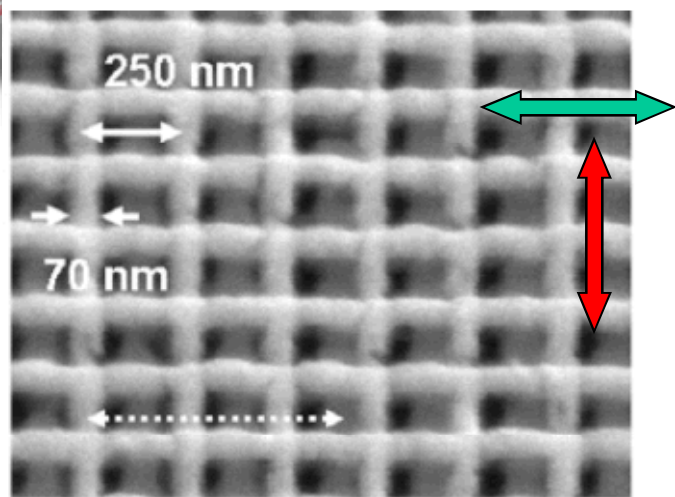
Optical Response : Microspot Spectrometry



Polarized Near-normal Response



Near UV 9 Layer Titania Logpile



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

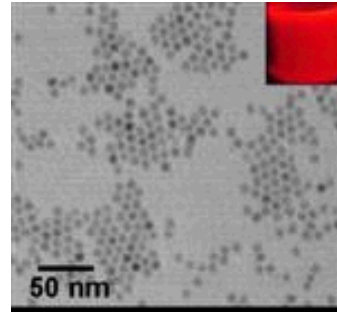


Emission Modification by Visible Logpile PC

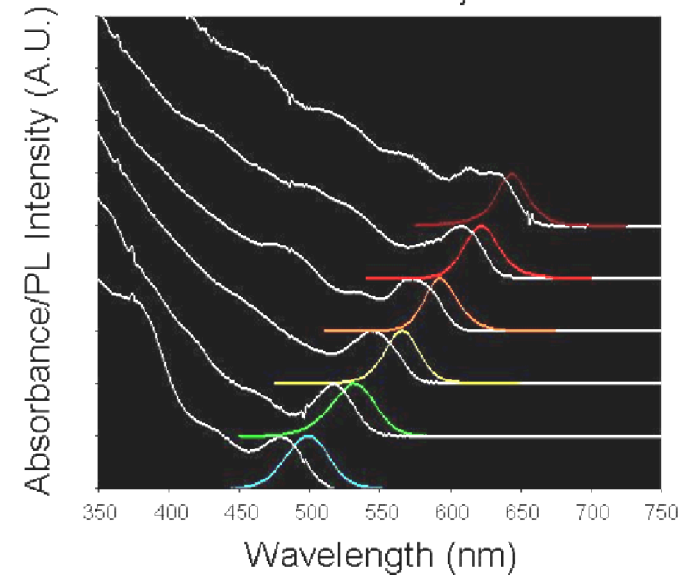
CdSe/ZnS Core-shell Quantum Dots in 3DPC



(www.nn-labs.com)



UV-Vis and PL spectra for CdSe/ZnS core/shell Nanocrystals

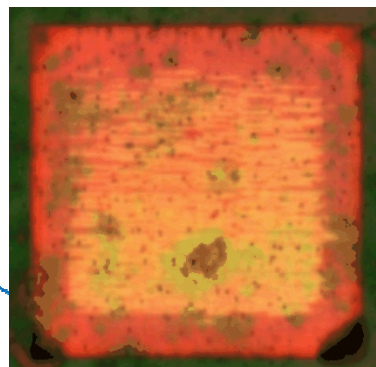


❖ Commerically available with emission over the entire visible range (520-640nm)

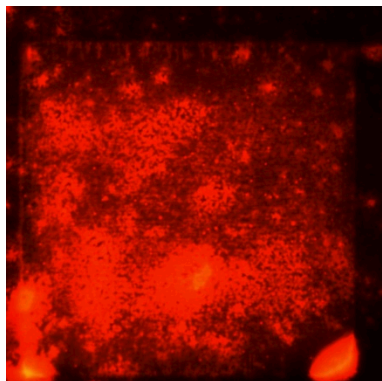
❖ Stable, with potential for surface treatment

❖ Uniform sized with strong photoluminescence(PL) profile (28-35nm)

Optical image



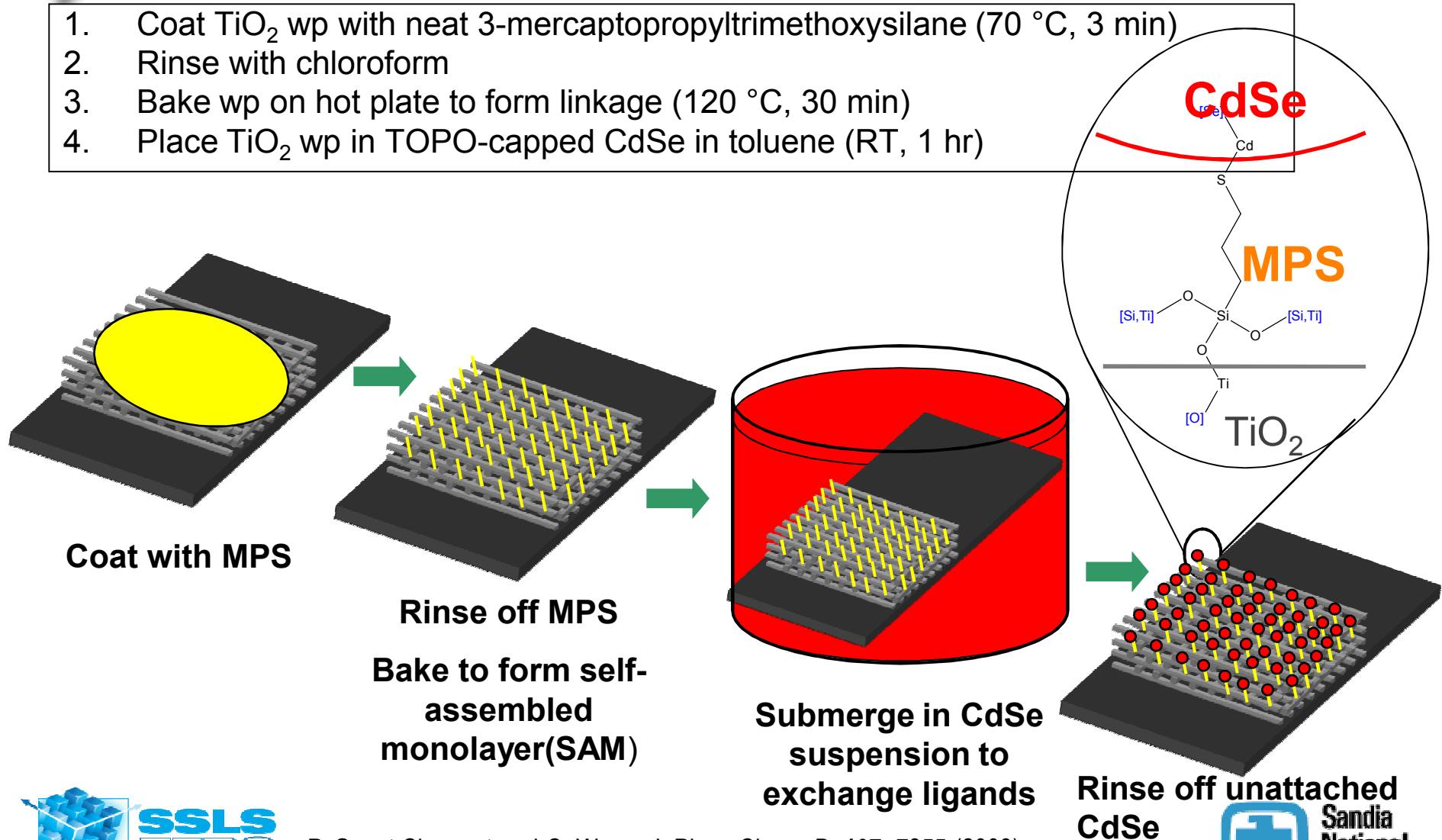
PLImage



- Simple dropcasting is unsuitable method of infiltration
- Non-uniform and destroys the bandgap
- A controlled infiltration approach is required

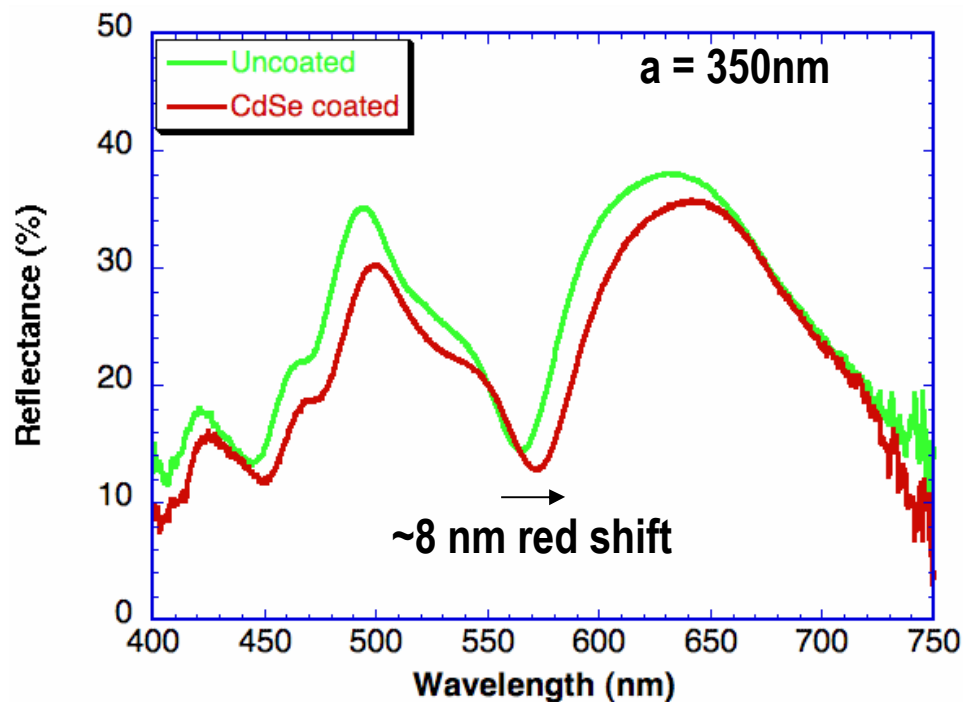
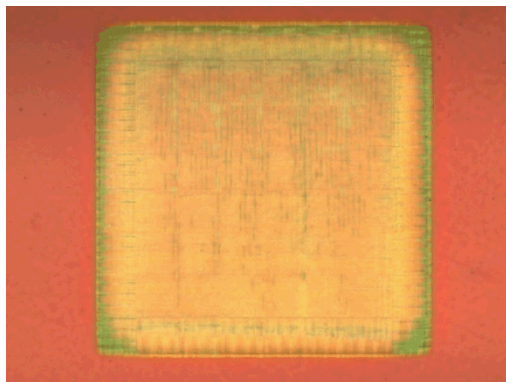
Controlled Coating of CdSe Self-assembled Monolayer on TiO₂ Rods of the Logpile

1. Coat TiO₂ 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 TiO₂ wp in TOPO-capped CdSe in toluene (RT, 1 hr)

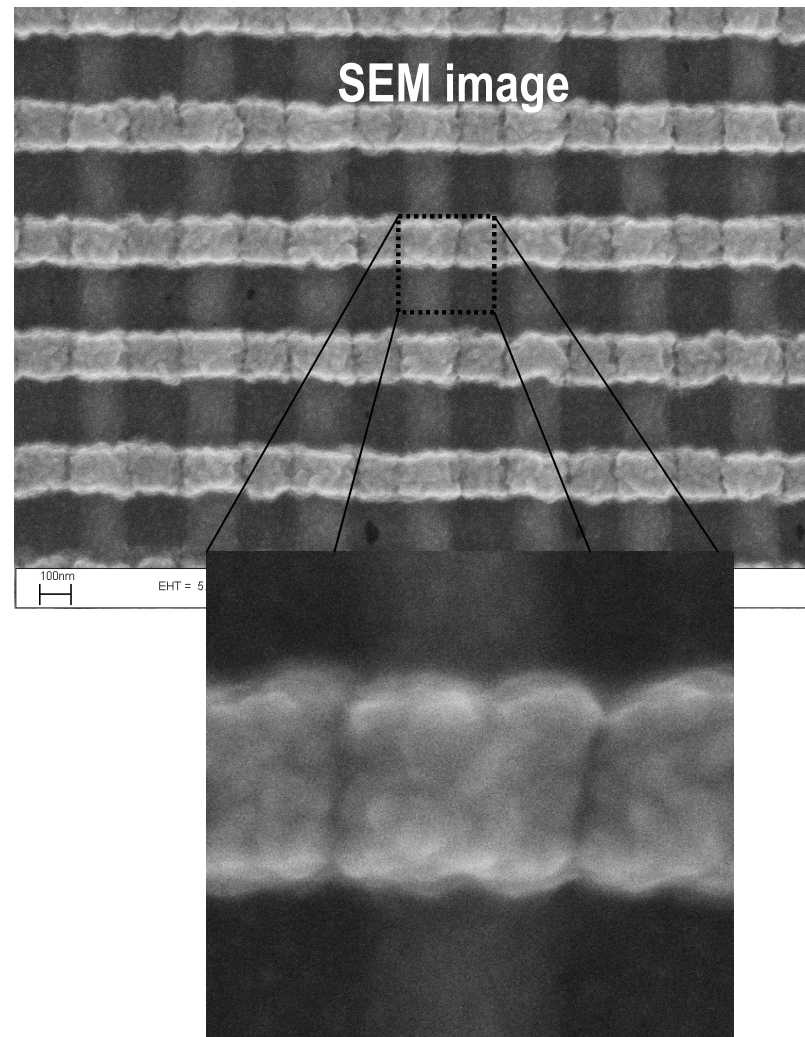


Characterization of CdSe SAM Coating

Optical image



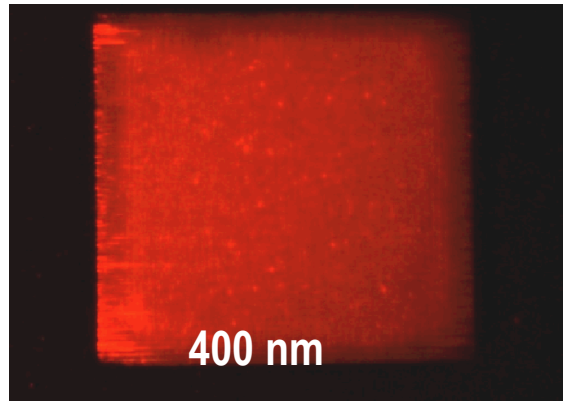
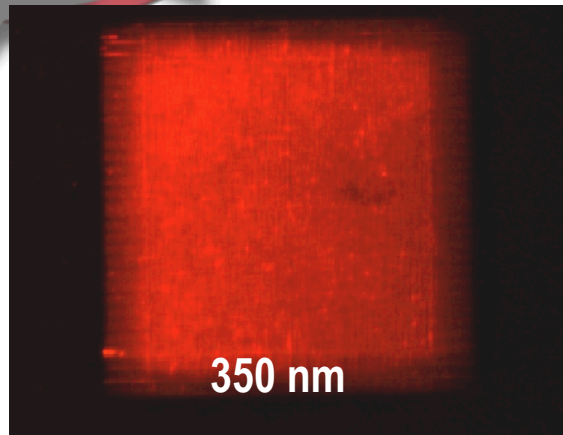
SEM image



CdSe infiltration has minimal effect on bandstructure

G. Subramania et. al. Photonics and Nanostructures, 6, 12-18 (2008)

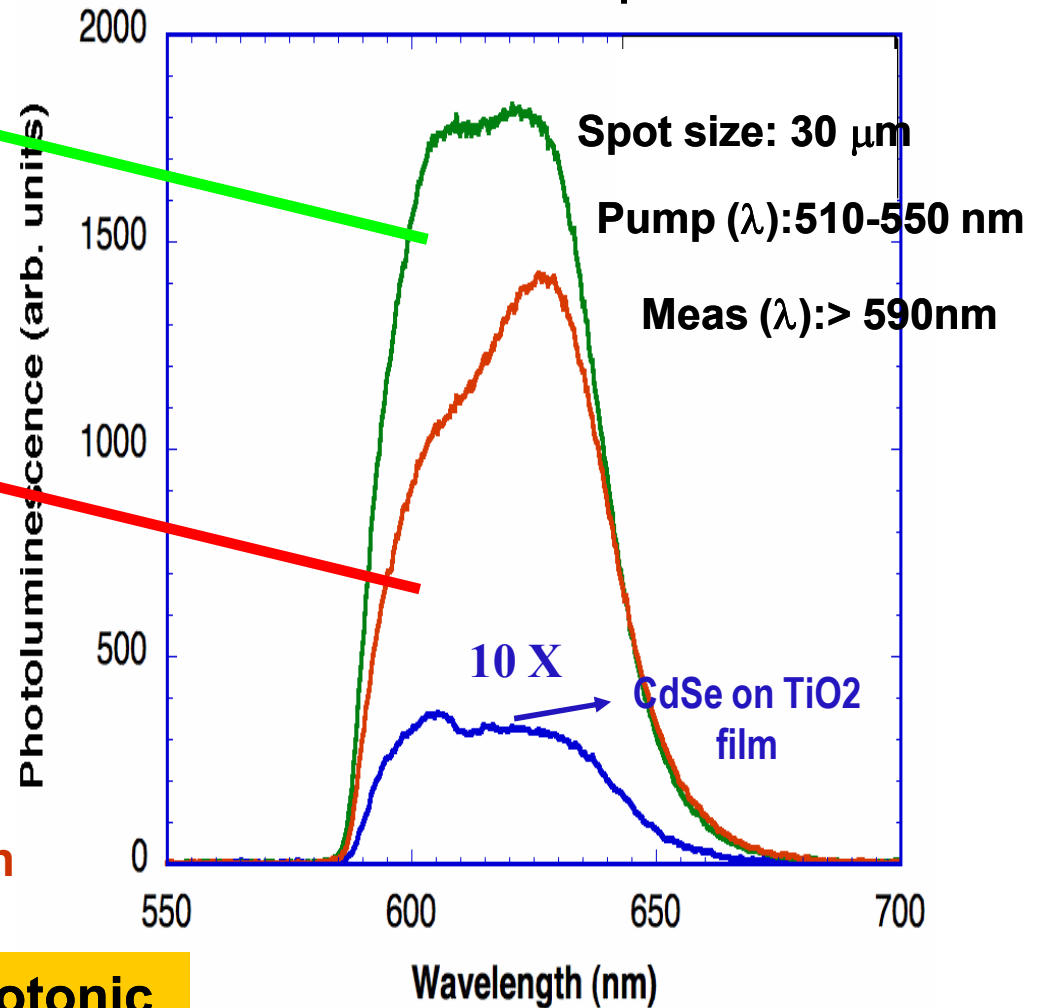
PL Spectra of CdSe SAM Coated PC



➤ PC emission 30X stronger than TiO₂ region

No noticeable effect due to photonic bandstructure was observed !

Unnormalized PL spectrum



Local Photonic Density of States (LPDOS)

In an engineered EM environment like a PC the Fermi golden rule needs to be cast more generally to account for the position of the emitter.

$$\frac{1}{\tau_r} = \frac{\pi \omega \mu^2}{3 \varepsilon_0 \hbar} \rho(\omega) \qquad \rho(\omega) \Rightarrow \rho_L(\mathbf{r}, \omega)$$

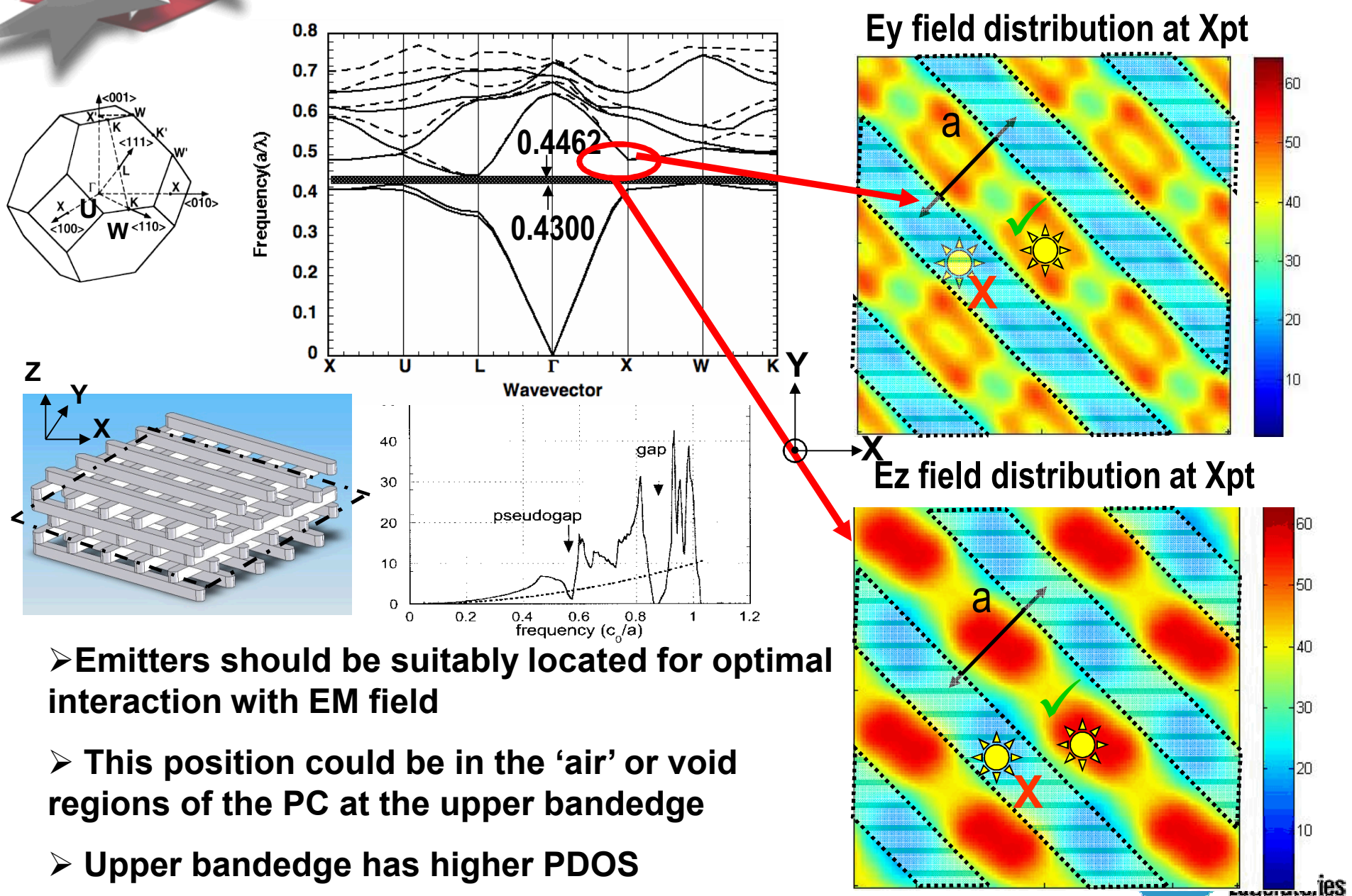
$$\rho_L(\mathbf{r}, \omega) = \sum_n \int_{1stBZ} d^3k \, |\bar{\boldsymbol{\mu}} \cdot \mathbf{E}_{n,k}(\mathbf{r})|^2 \delta(\omega^2 - \omega_{n,k}^2)$$

Where $\mathbf{E}_{n,k}(\mathbf{r})$ are the corresponding Bloch eigenfunctions

$$\rho(\omega) = \int_{WSC} d^3r \, \varepsilon(\mathbf{r}) \rho_L(\omega, \mathbf{r})$$

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

Local Photonic Density of States (LPDOS)



- Emitters should be suitably located for optimal interaction with EM field
- This position could be in the 'air' or void regions of the PC at the upper bandedge
- Upper bandedge has higher PDOS

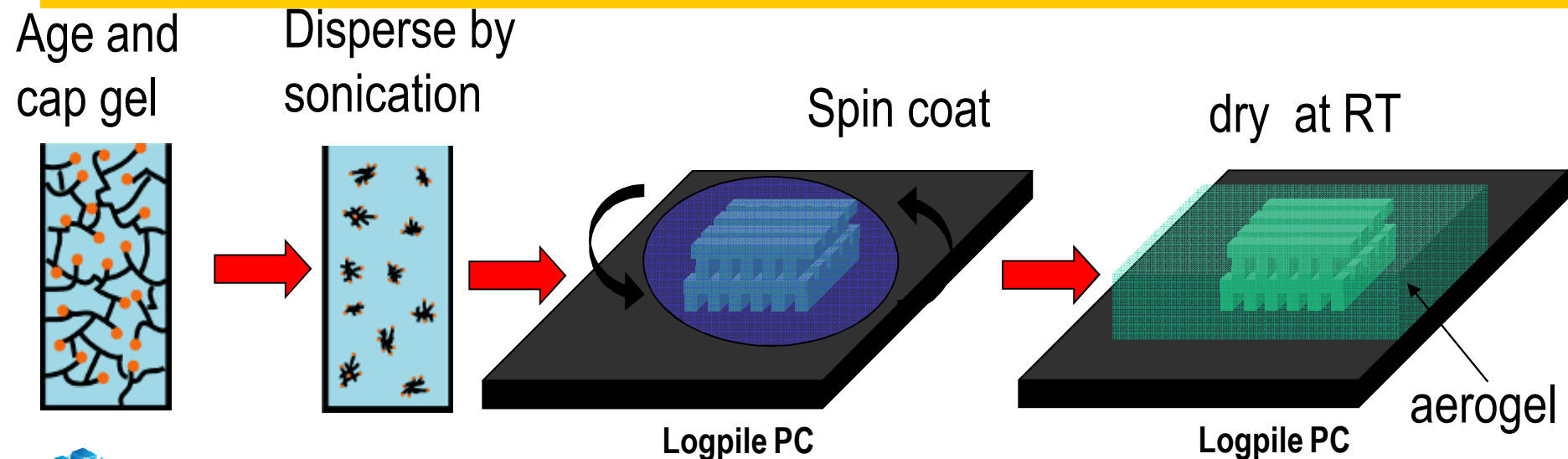
Accessing the 'Air' Void Region of the PC

- Provides physical access to the 'air' region
- Low refractive index: minimal disturbance of the underlying bandstructure of the PC
- Increased surface area for attachment of the QDs

Aerogel

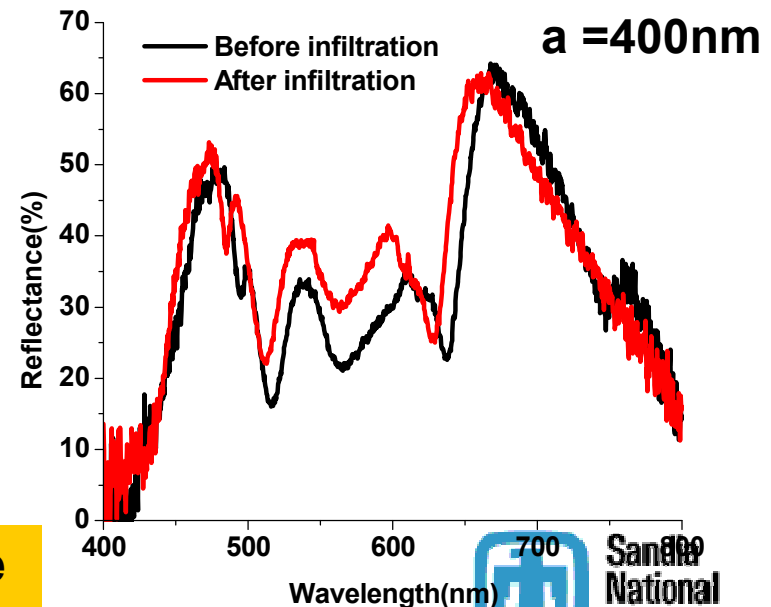
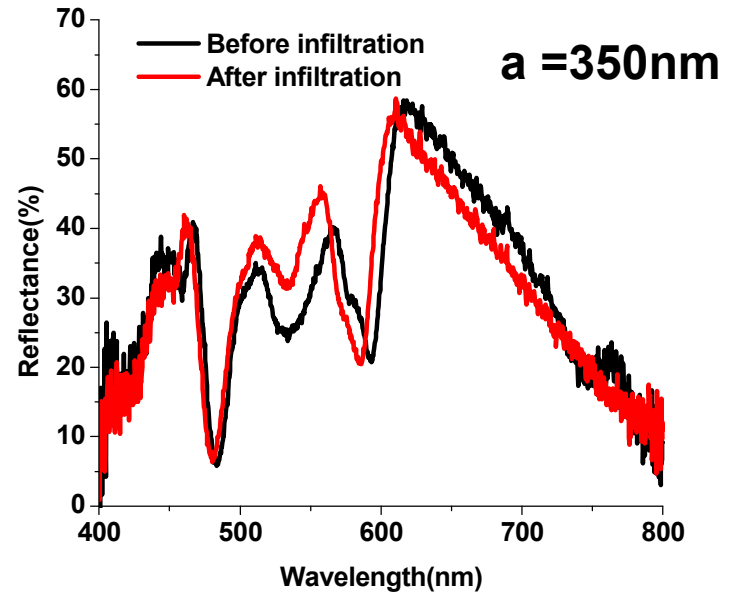
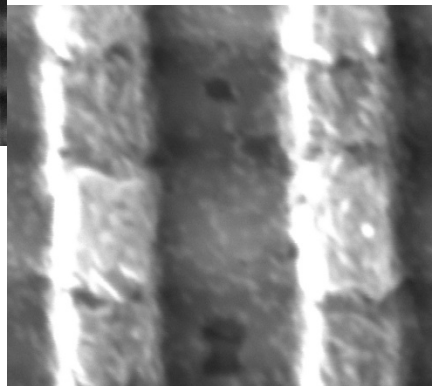
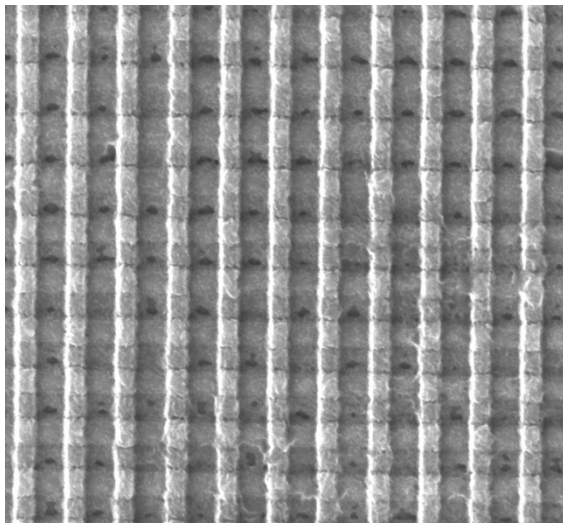
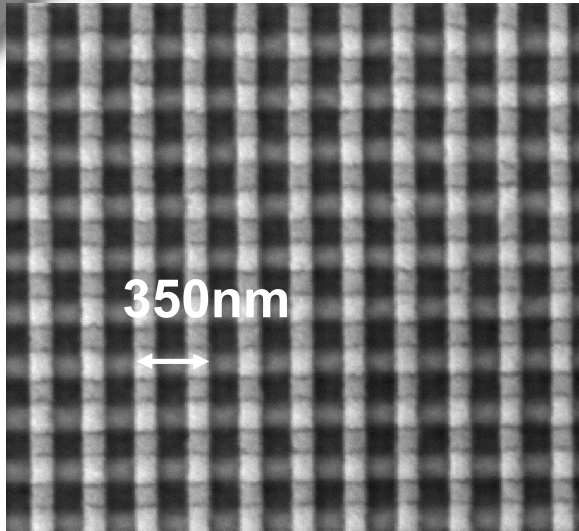
➤ Usually requires supercritical drying !

Room temperature spin-coatable aerogel (Brinker group) implies easier infiltration (S. S. Prakash et al., Nature 374, 439 (1995))



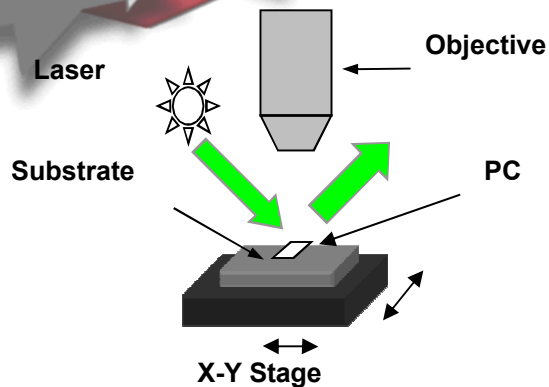
Introduce QDs through chemical attachment

Effect of Aerogel and CdSe QD infiltration



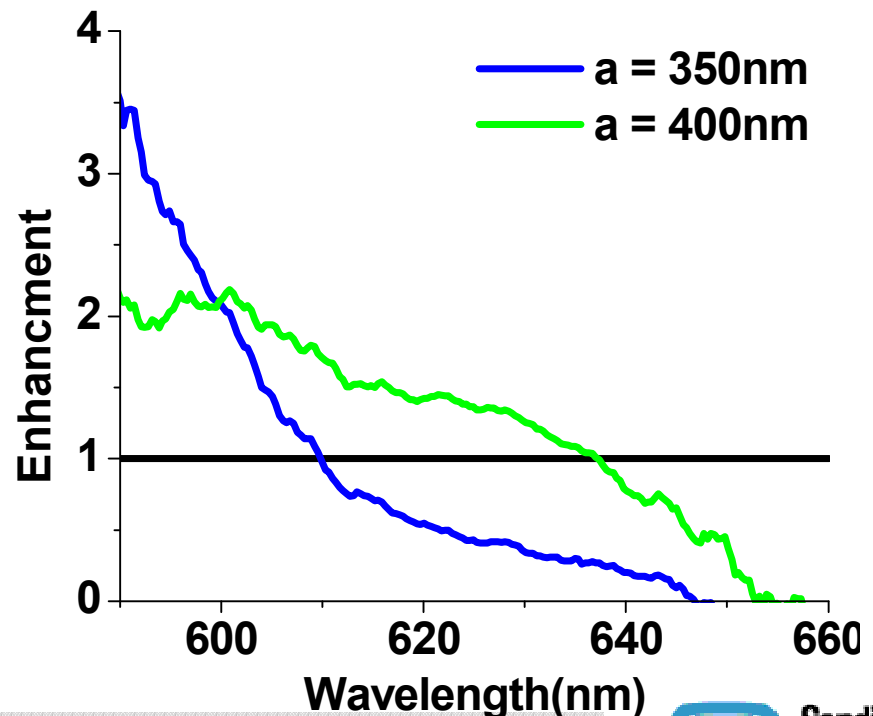
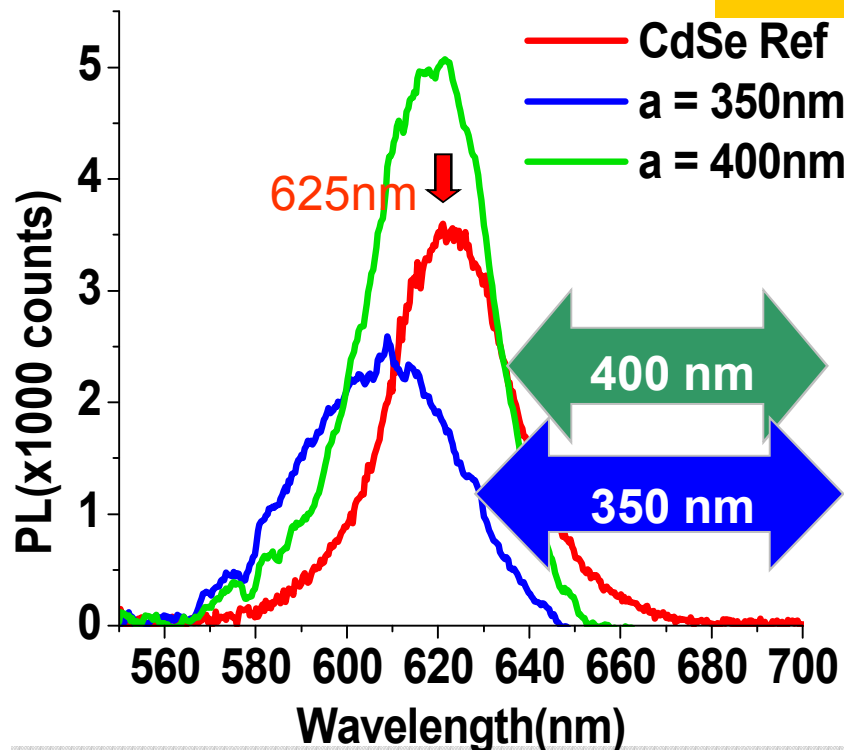
Aerogel and CdSe QD infiltration has negligible effect on the bandgap!

Spontaneous Emission Modification



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

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



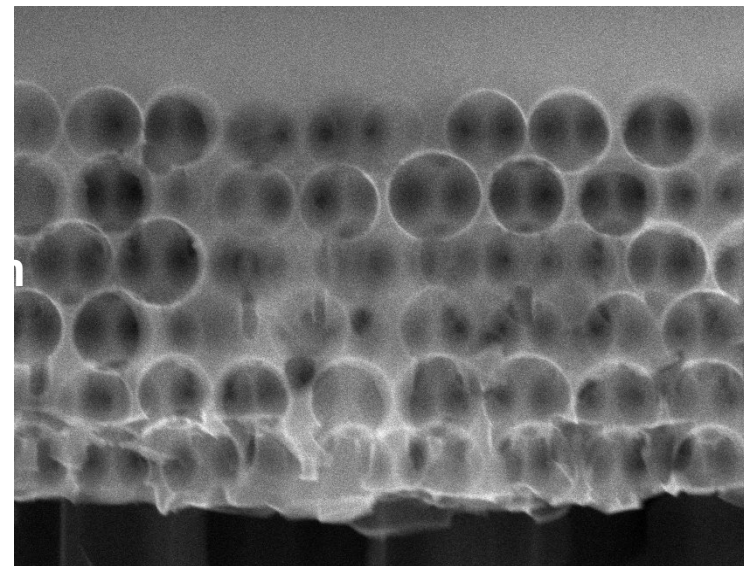
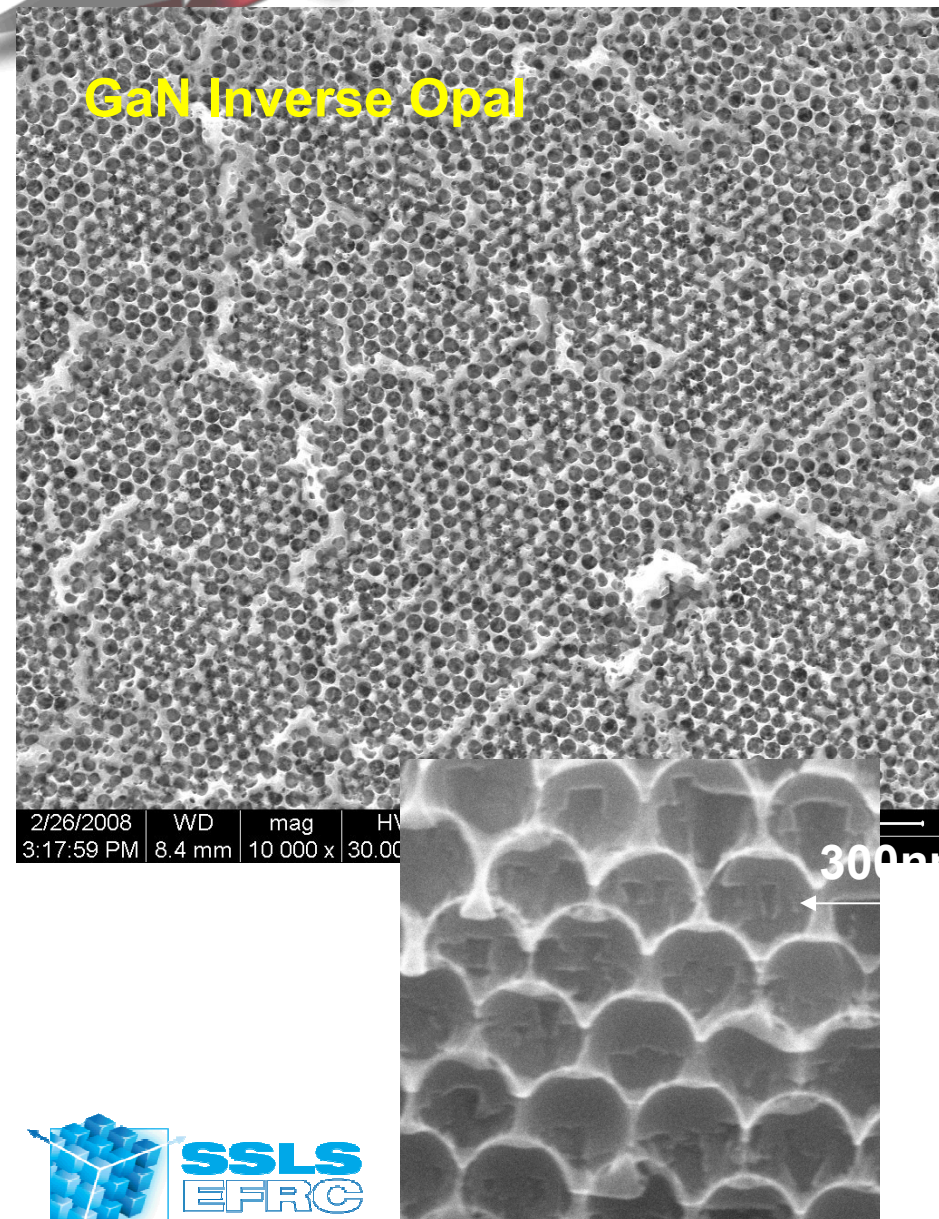


All GaN Logpile 3DPC

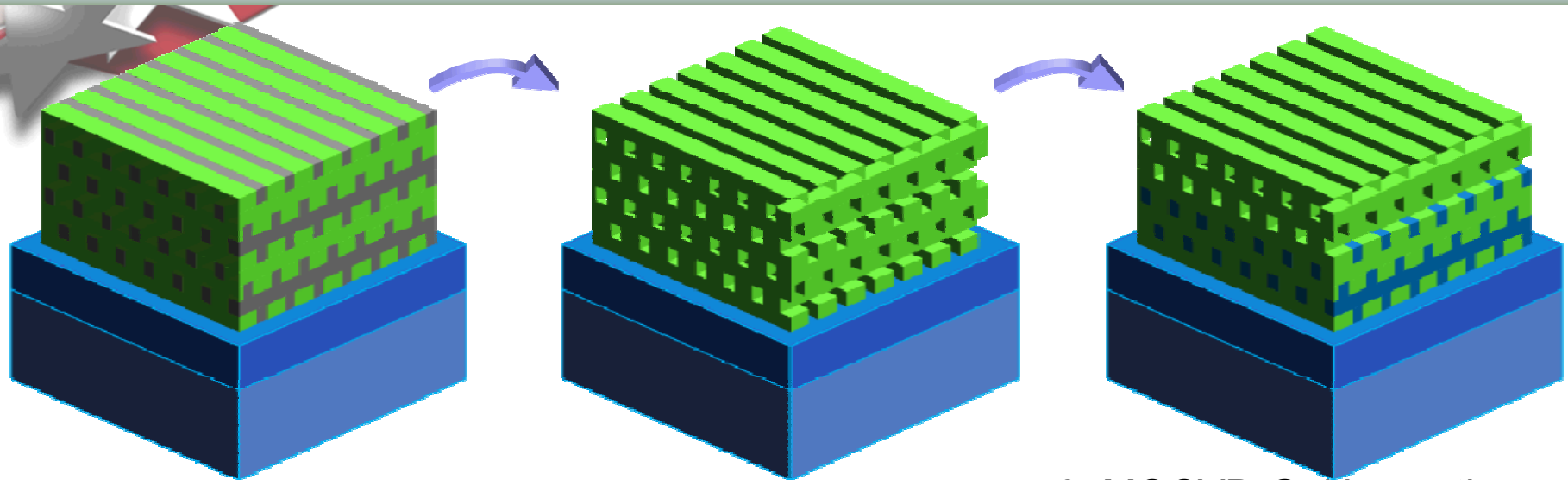
MOCVD Growth of GaN in Templated Nanostructures

GaN Inverse Opal

- GaN can be grown through a 3D nanostructure
- Approach used for reducing dislocation density in epitaxial GaN



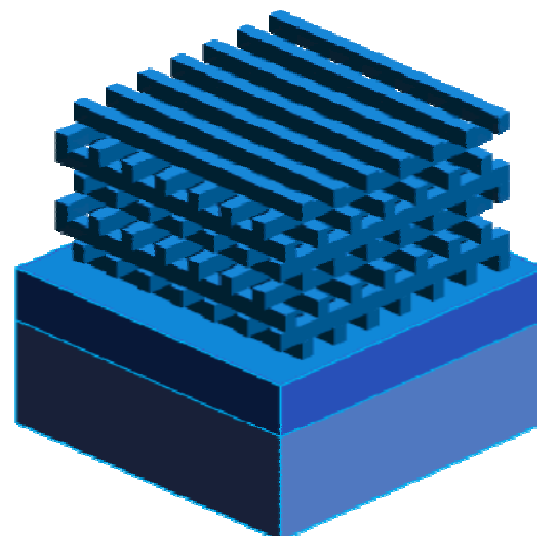
Schematic of GaN Logpile PC Fabrication



1. Si/SiO₂ logpile PC

2. After Si is removed

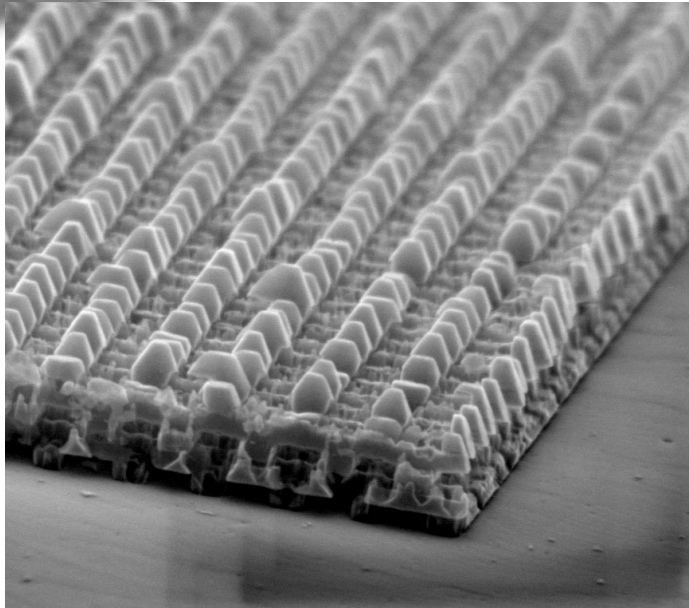
3. MOCVD GaN growth through SiO₂ template



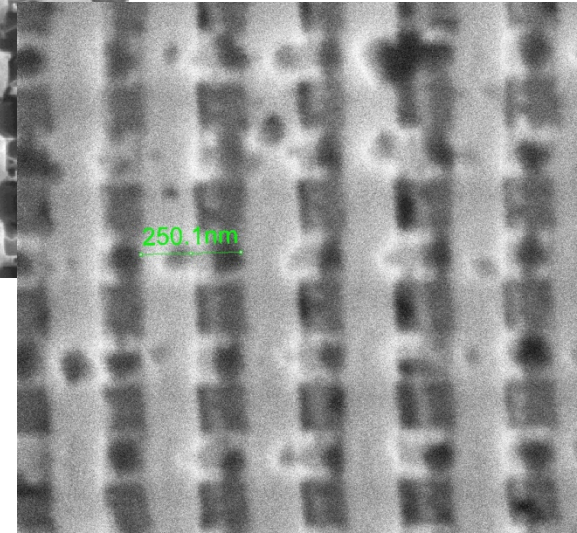
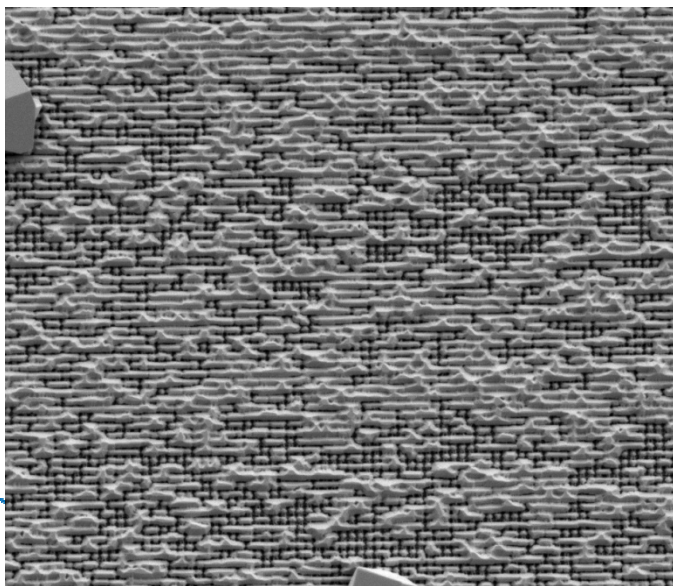
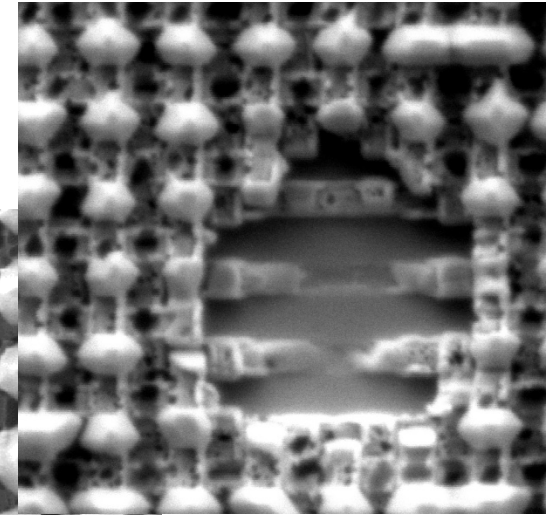
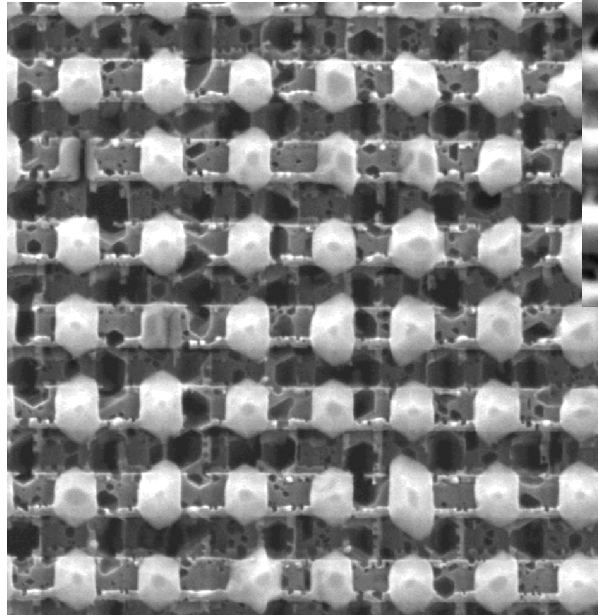
5. GaN logpile PC after SiO₂ logpile template removal

4. After complete GaN infiltration into SiO₂ logpile template

Potential Challenges in Template Growth



Lattice constants
'a' 250nm-300nm



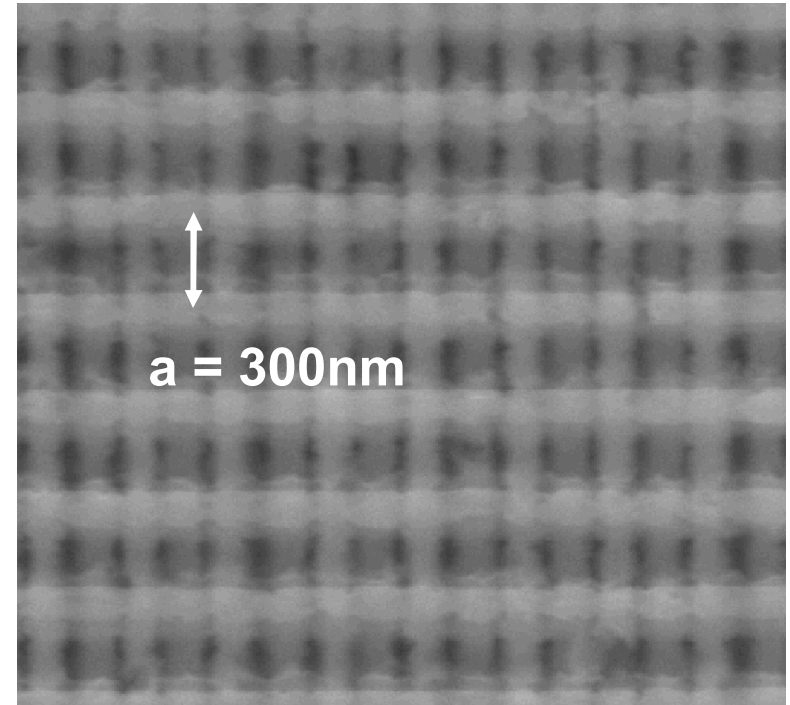
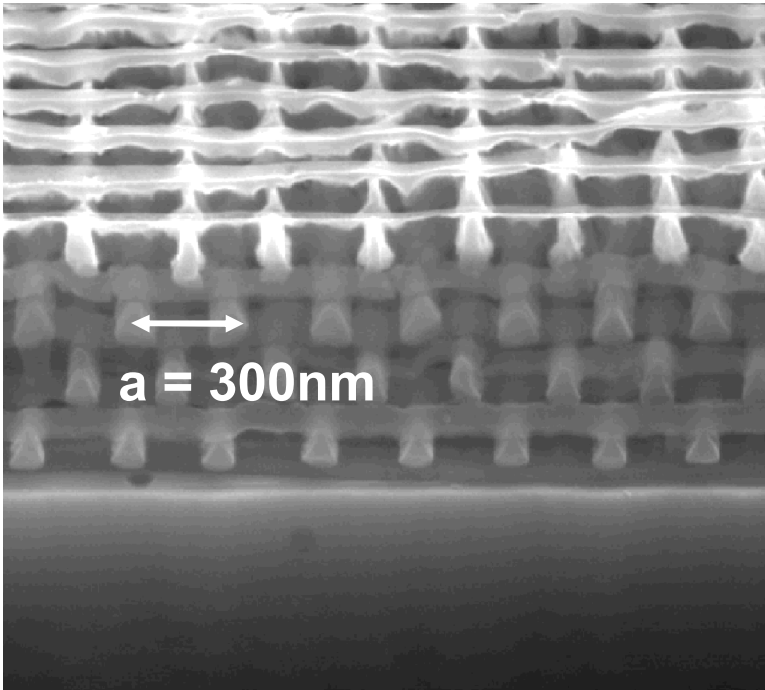
Challenges

- Non- Uniformity
- Controlling nucleation
- Porosity

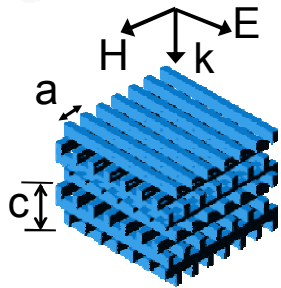
Nine Layer GaN Logpile

Optimize Growth conditions

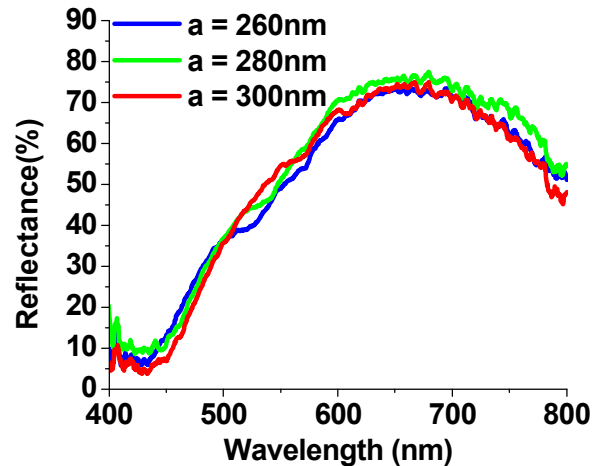
- Gas mixture: TMGa, NH₃, H₂, and N₂
- Temperature range: 1000C-1075C
- Pressure range: 15 torr-75 torr
- Lattice constants 'a' 260, 280, 300nm
- Rod widths 0.4- 0.45*a → 100-140nm
- Rod height ~100nm



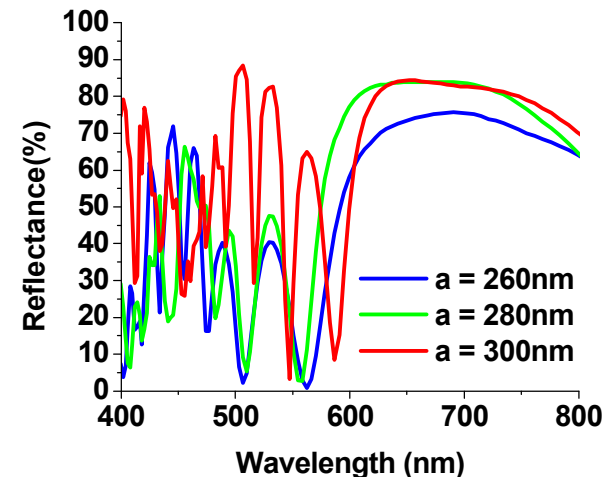
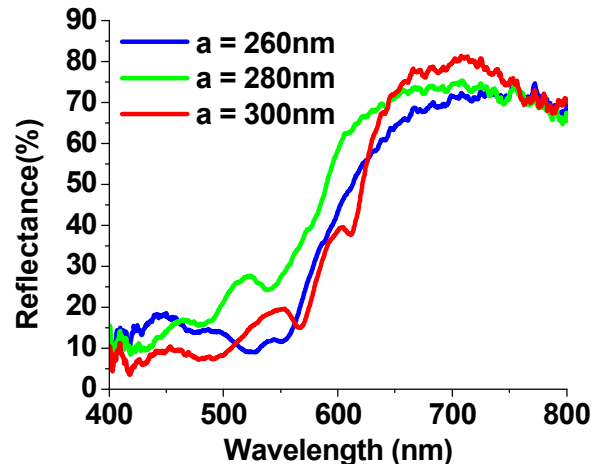
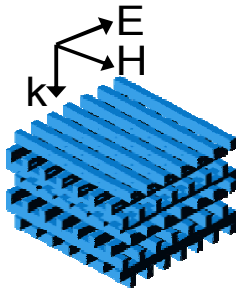
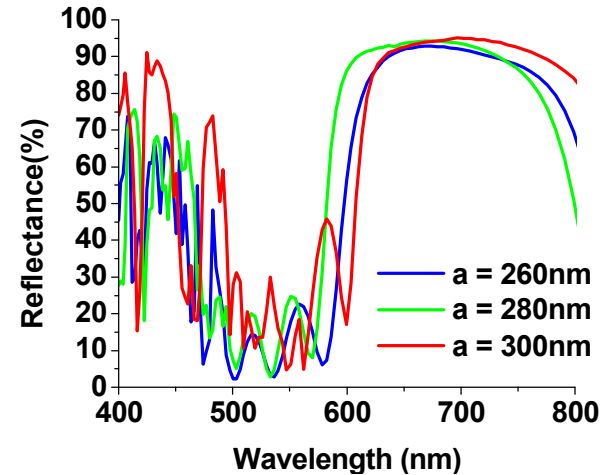
Normal Incidence Optical Response : Bandgap



Experiment

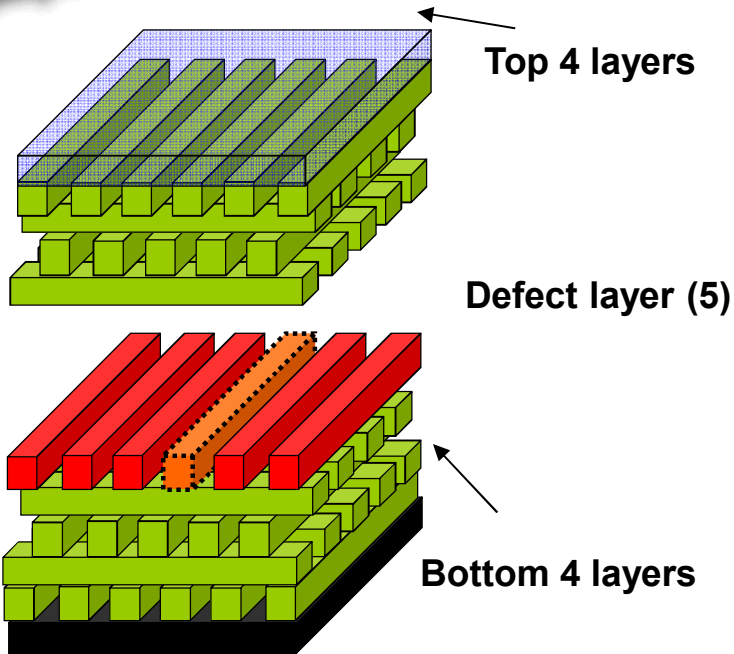


FDTD Simulation



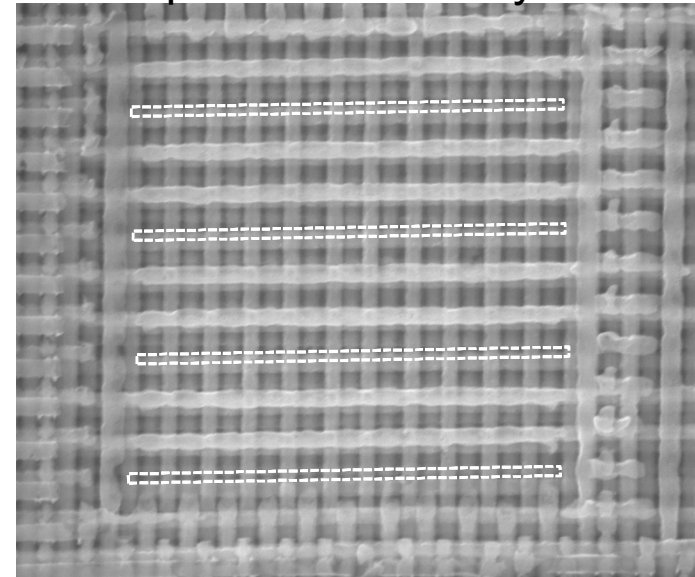
- Bandgap in the visible
- Spectral shift not proportional (c/a variation)
- Effects of scattering
- *Further growth and/or structure optimization*

GaN Logpile: Line- Defect Cavity

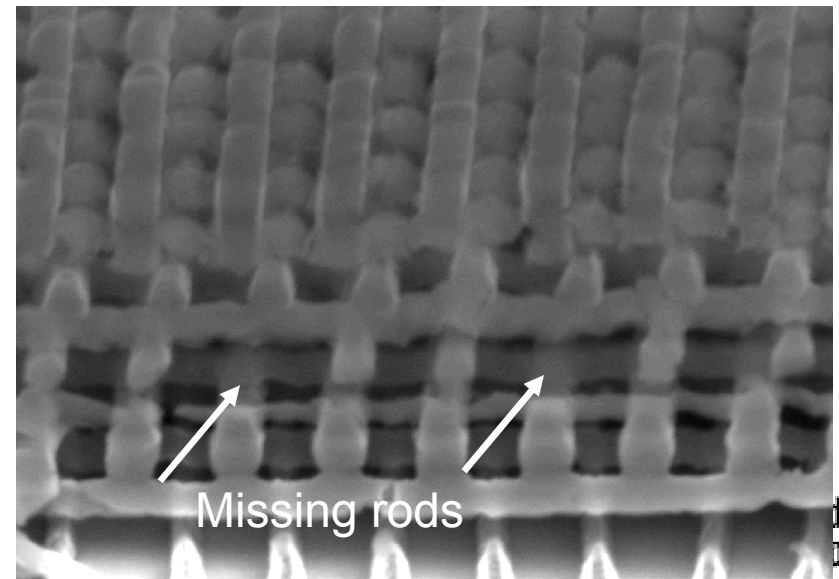


- Defect introduced in layer 5
- Every 3rd rod is removed
- Allows for emission control inside the bandgap

Top view SEM : Layer 5

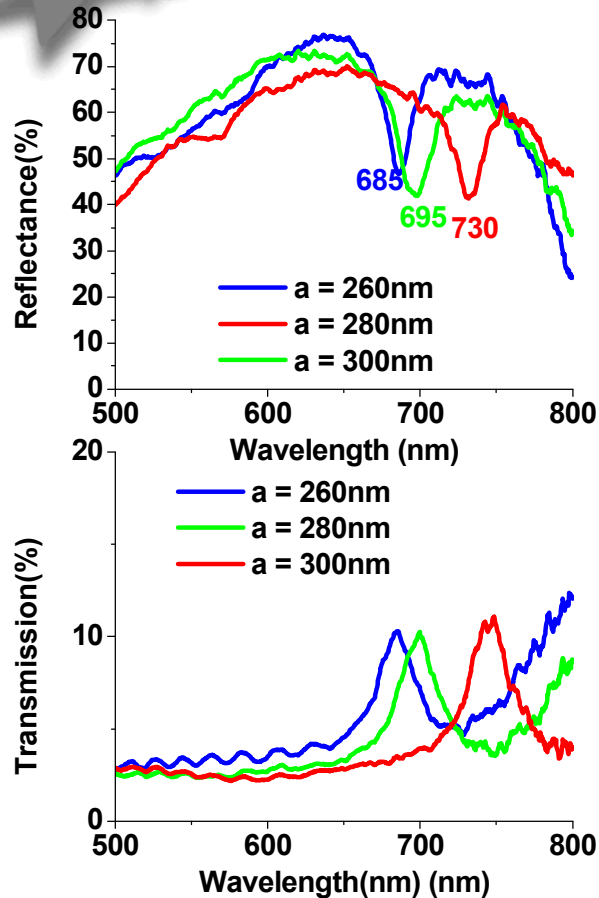


Cross-sectional View

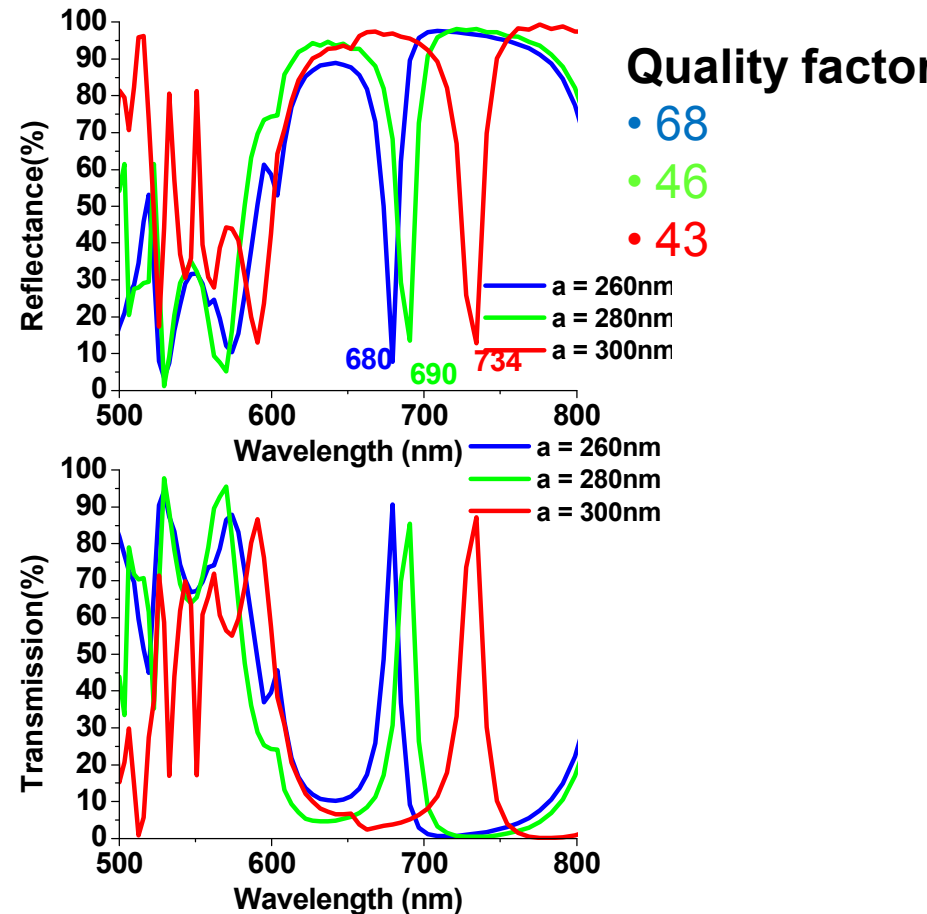


Optical Response of the Cavity

Experiment



FDTD Simulation



- Cavity mode is polarization dependent – couples best “E” is parallel to the rod
- Good matching of wavelength with FDTD simulation
- Q factor lower than expected

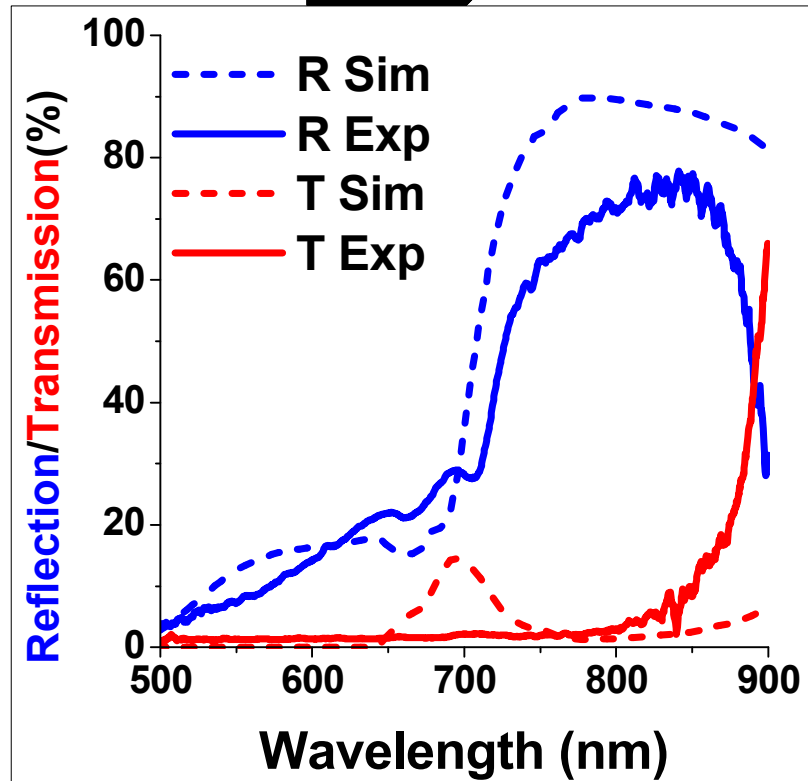
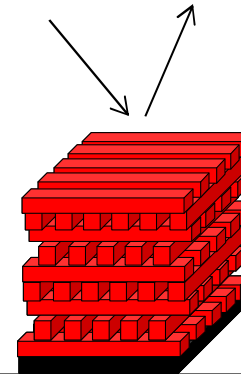
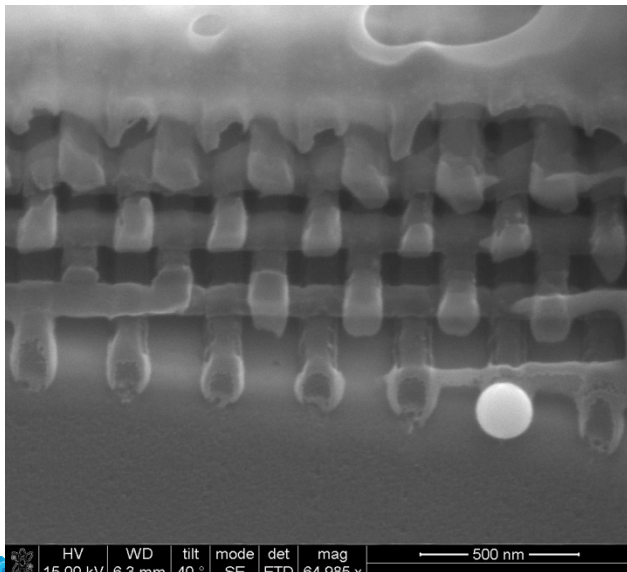
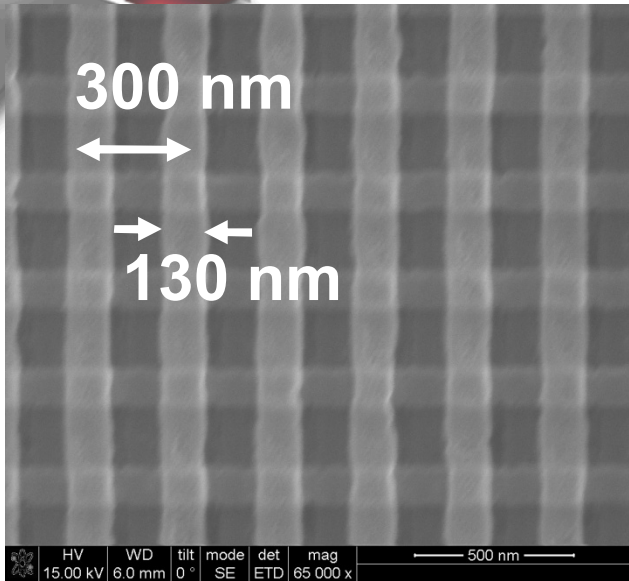
Future Directions for GaN Logpile

- **Electrically driven GaN logpile devices: P and N type doping**
 - Material growth, doping density
 - Electrical contact schemes
 - Carrier mobility issues
- **Tune and manipulate emission behavior**
 - Quantum well (InGaN)
 - Quantum dots, phosphors
 - Localizing phosphors
 - Cavity design



Silicon 3DPC in the Visible?

9Layer Silicon Logpile in the Near-Visible

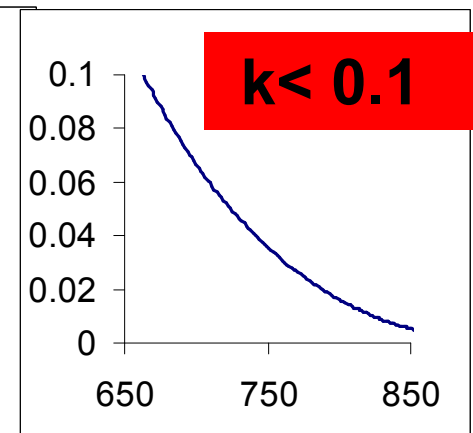
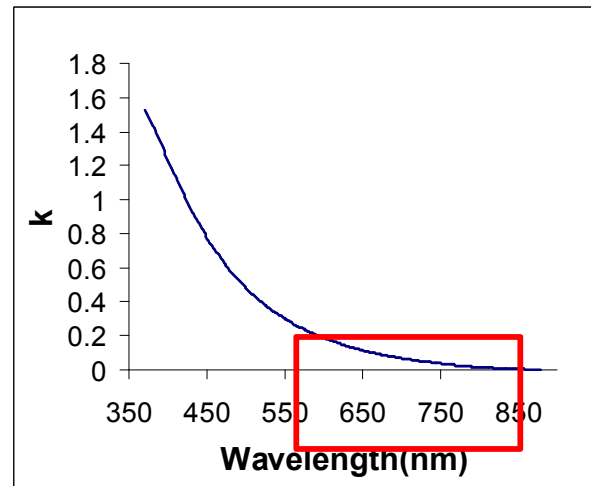
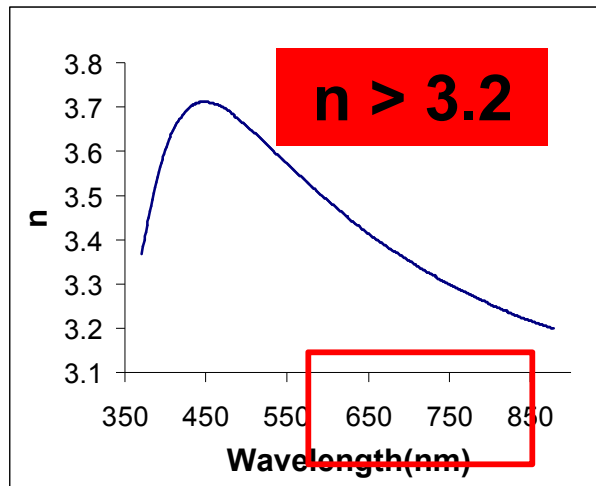


Silicon Logpile in the Near-Visible

What is going on?

Silicon is indirect bandgap semiconductor, so its imaginary part of the refractive index increases slowly.

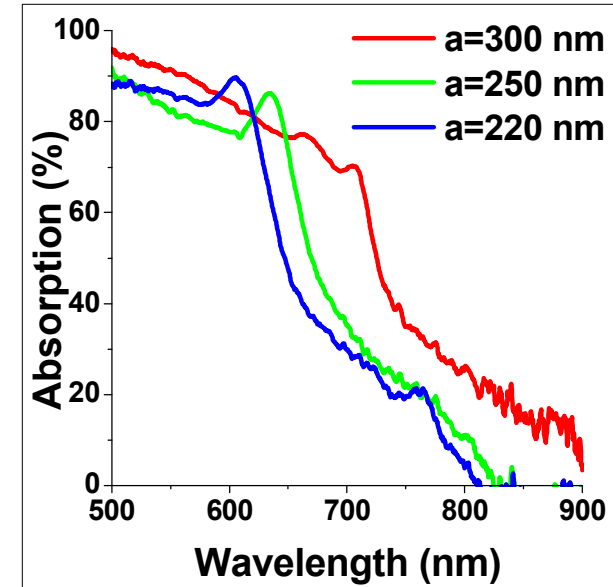
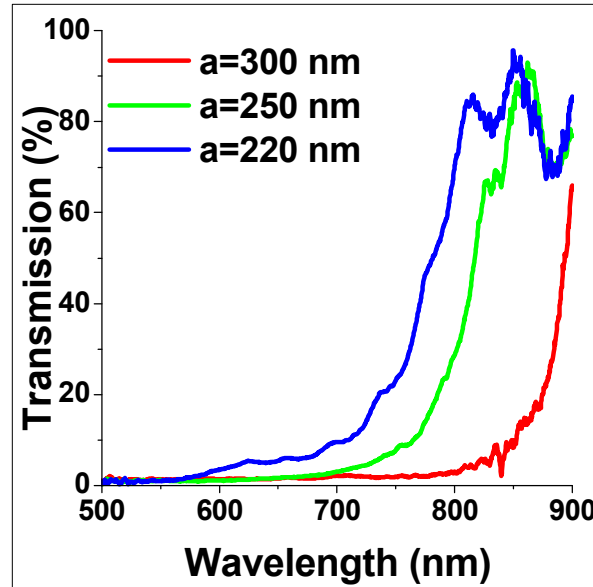
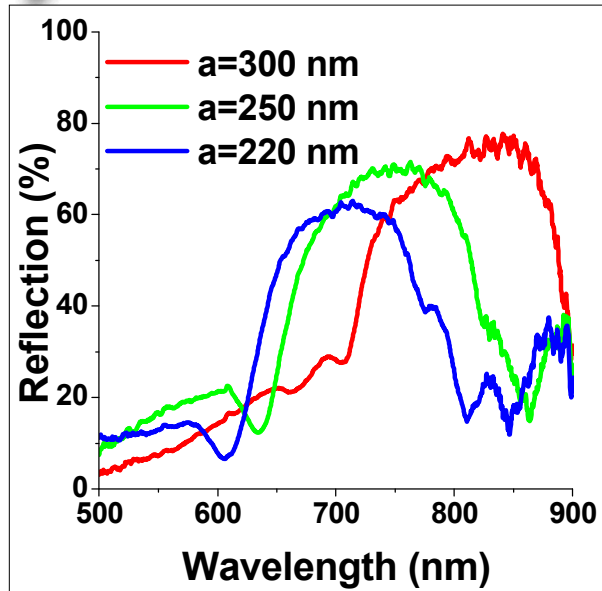
Ellipsometric data from electron beam evaporated silicon



Why is this interesting?

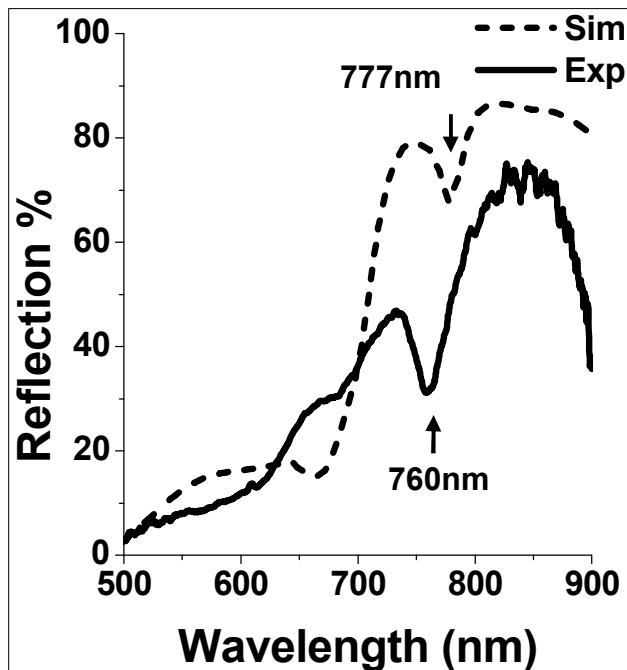
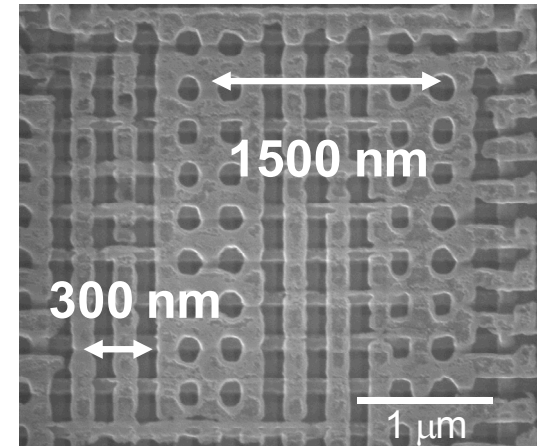
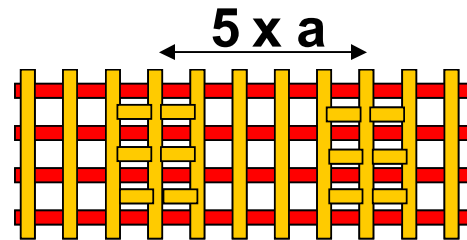
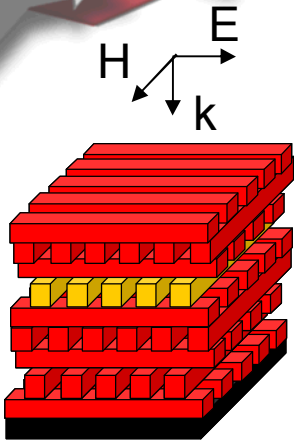
- ❑ Silicon has a much larger refractive index than visible materials like TiO_2 and GaN : ~ 3.3 vs $2.5 \rightarrow$ Wider complete 3D gap
- ❑ Compatible with electronics and large scale fabrication

Optical Response: Visible Band Gap

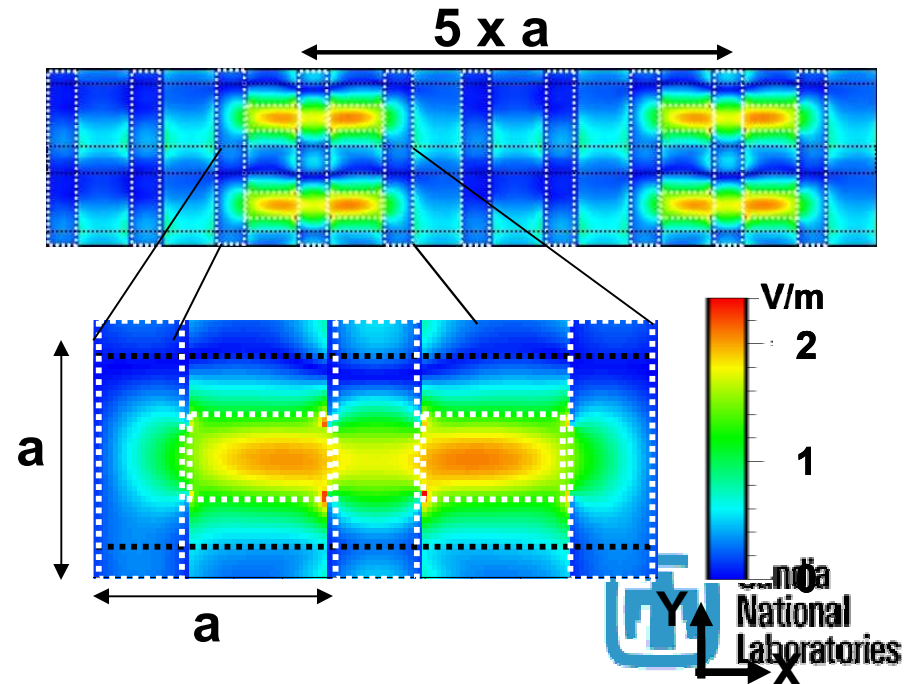


- Strong Photonic bandgap observed even down to 700nm
- Over 80% transmission at ~ 800 nm for $a = 220$ nm and 250nm
- Negligible absorption beyond ~ 800 nm for $a = 220$ nm and 250nm

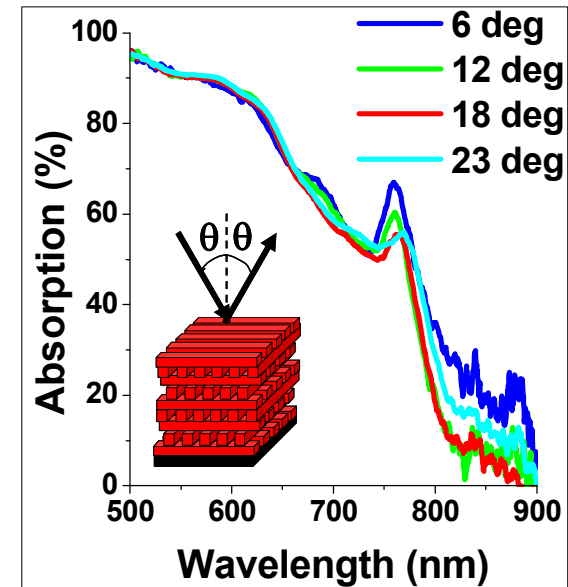
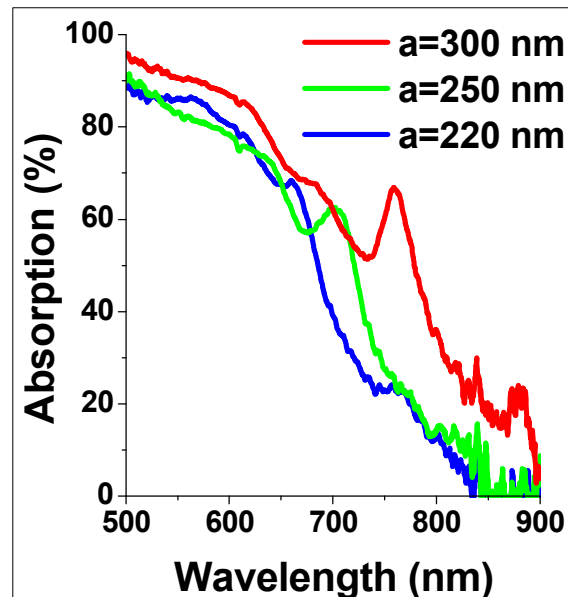
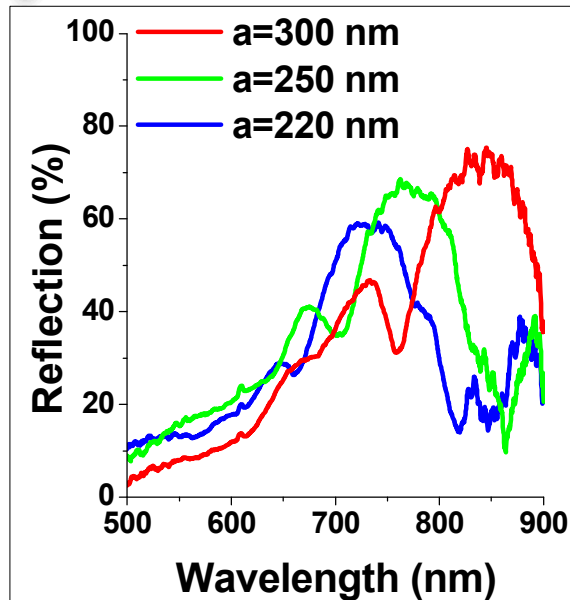
3DPC Cavity in Si logpile



Electric field (E_x) distribution



Cavity Response: Absorption Control



- Cavity mode becomes less prominent as lattice constant decreases
- Enhanced absorption at cavity mode : Slow group velocity
- Absorption wavelength relatively constant incidence angles upto 23°

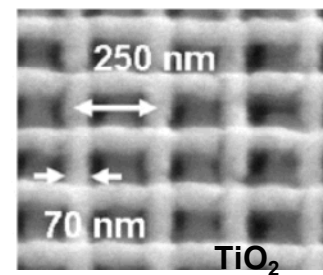
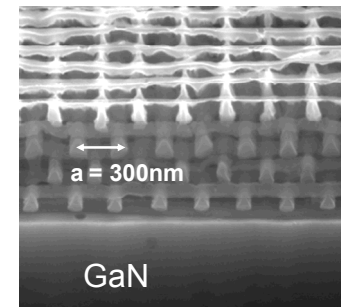
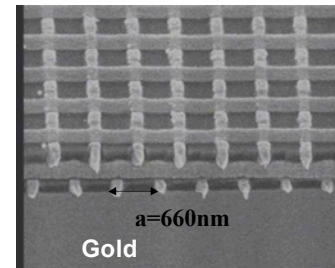
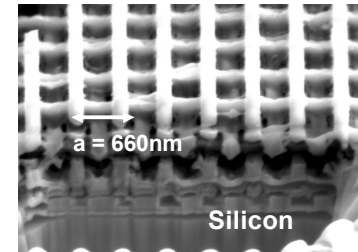
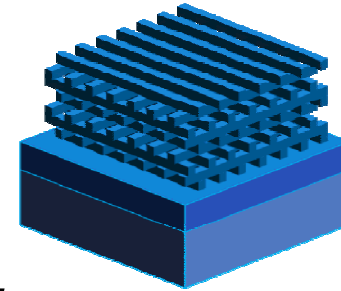
Summary

❑ **Multilayer e-beam direct write based fabrication**

❑ **Three dimensional Logpile PCs**

❑ *Near-IR to Near UV*

❑ *Various materials: Si, Au, TiO₂, GaN*



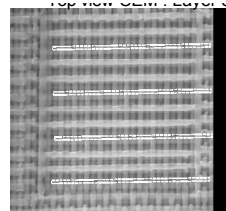
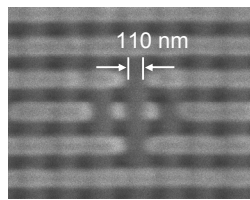
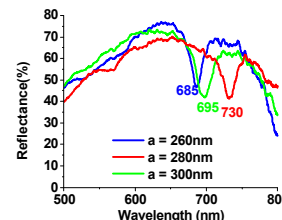
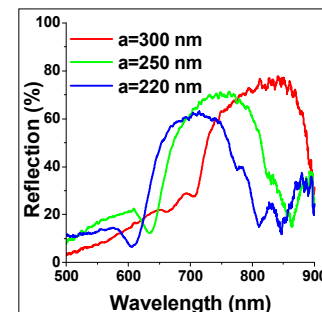
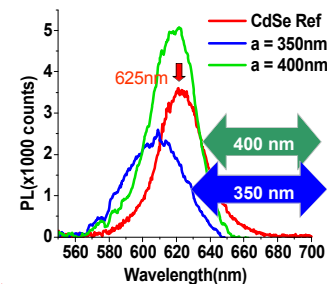
❑ **Emission Modification of CdSe QDs by Visible Logpile PC**

❑ *Accessing airband modes using aerogel*

❑ *Demo. of enhancement /suppression*

❑ **Fabrication and demonstration of 3D PC defect cavities**

❑ **Potential of silicon 3PDC in the visible**





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 - Jeff Figiel
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- Office of Basic Energy Science, USDOE
- Laboratory Directed Research and Development Office



U.S. DEPARTMENT OF
ENERGY



Office of
Basic Energy Sciences





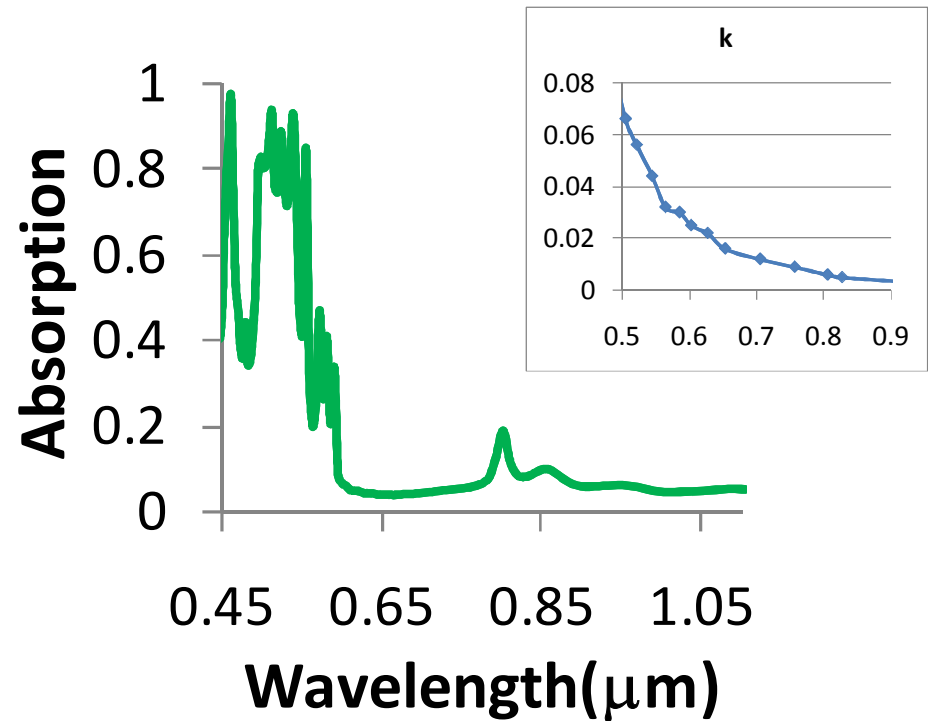
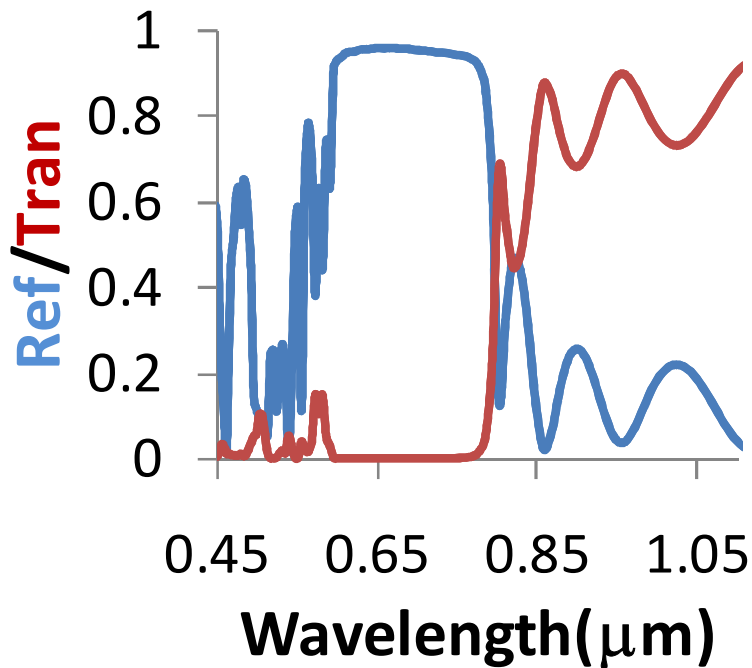
END



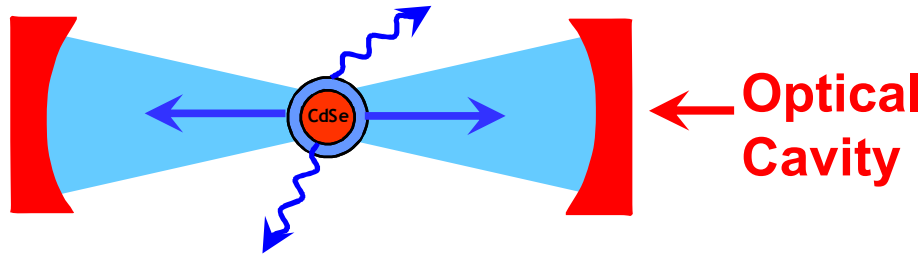
FDTD Simulation :16 layer Si logpile

$a = 250\text{nm}$

- ❑ rod width = $0.3a$; rod height = $0.35a$
- ❑ Silicon material data from Palik
- ❑ < 0.2 absorption for $\sim 0.8\text{ mm}$ ($< 350\text{nm}$ below Si abs. edge)



What is Strong Coupling?



Coupling parameter

$$g = \frac{\mu}{\hbar} \sqrt{\frac{\hbar \omega}{2 \epsilon_0 V}}$$

Cavity decay rate

$$\gamma = \frac{\omega}{Q}$$

Atomic decay rate

$$\kappa = \frac{\omega^3 \mu^2}{3 \pi \epsilon_0 \hbar c^3} = \frac{\pi \omega \mu^2}{3 \hbar \epsilon_0} \times \frac{\omega^2}{\pi^2 c^3}$$

Free photon
density of
states

$$\rho(\omega)$$

Strong Coupling Condition: $2g \gg (\gamma, \kappa)$

Rabi Frequency

Goals:

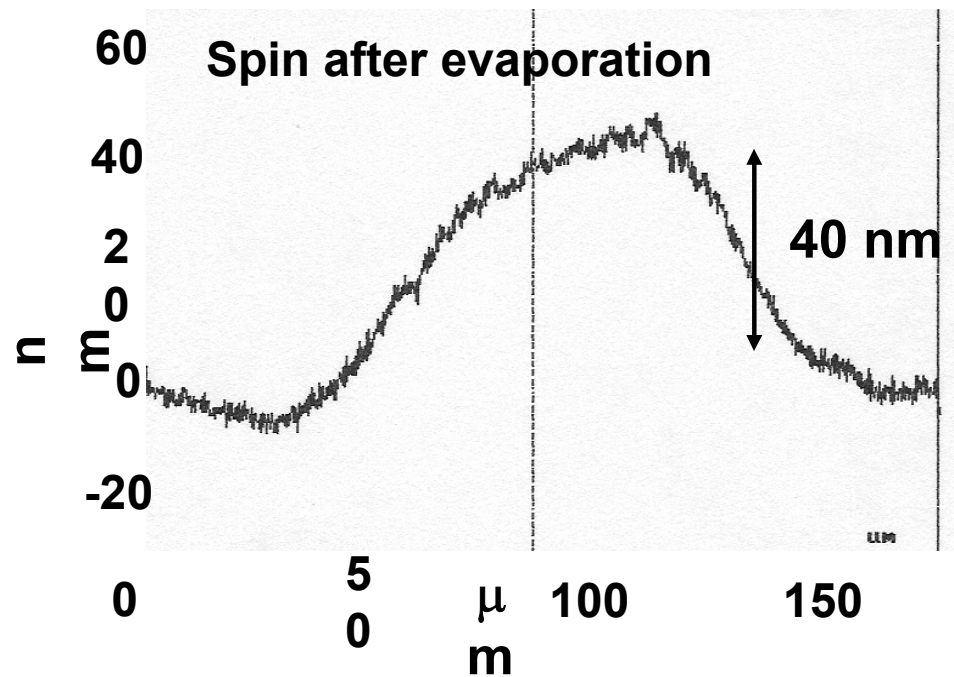
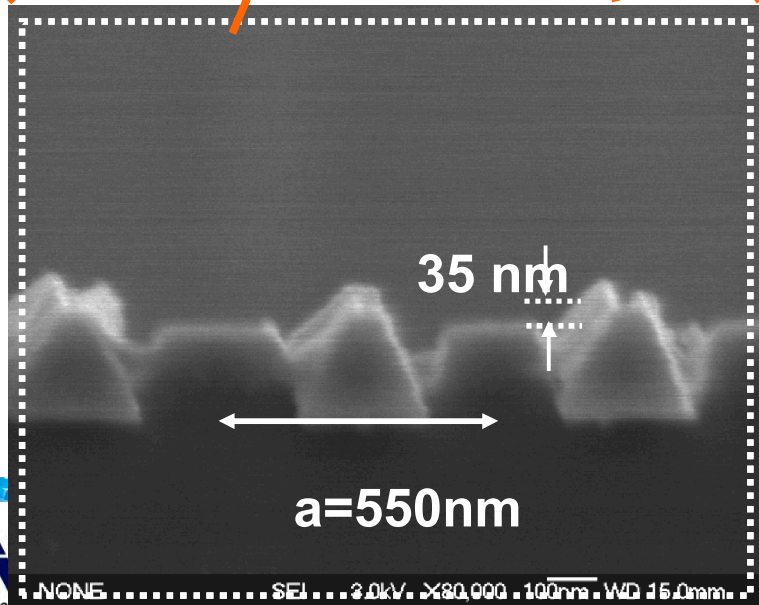
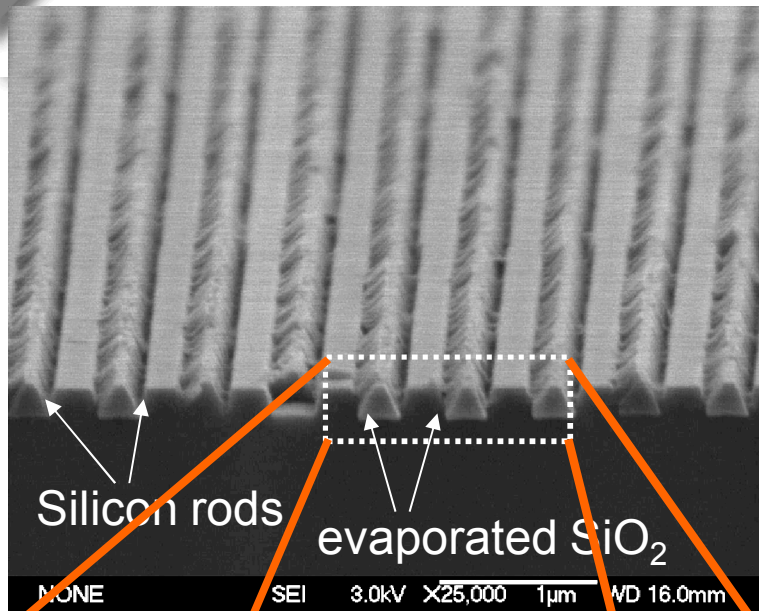
Q

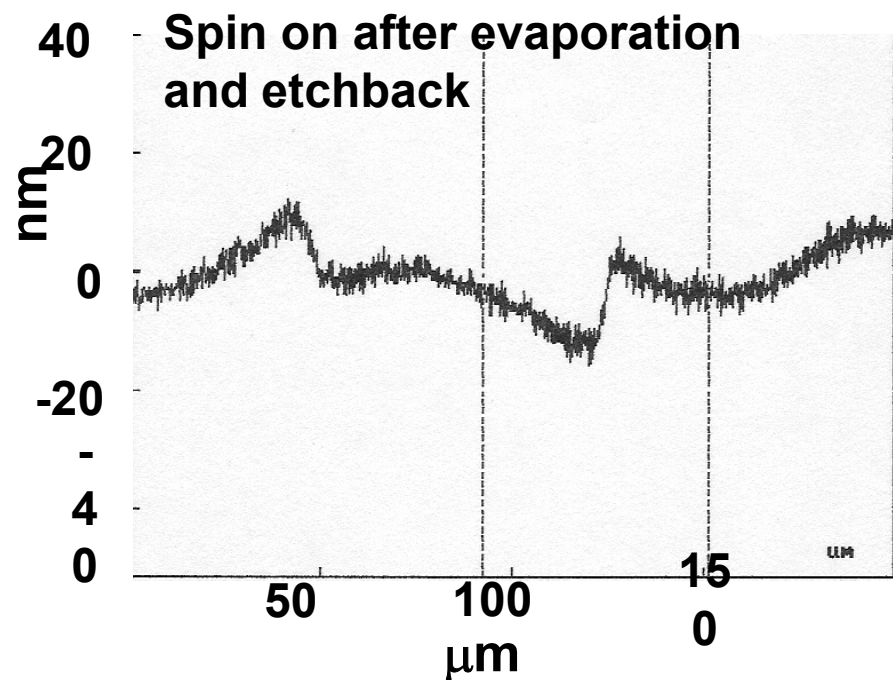
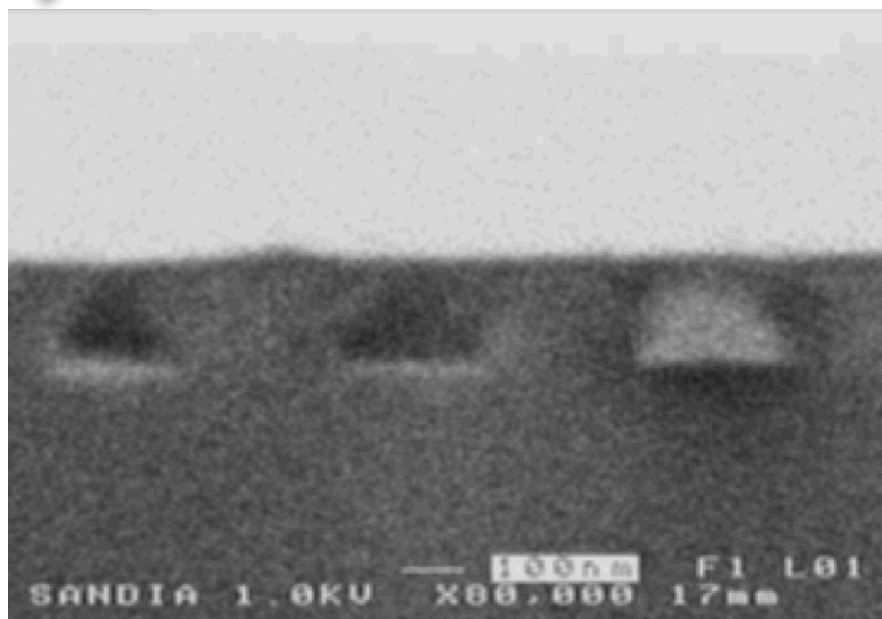


V



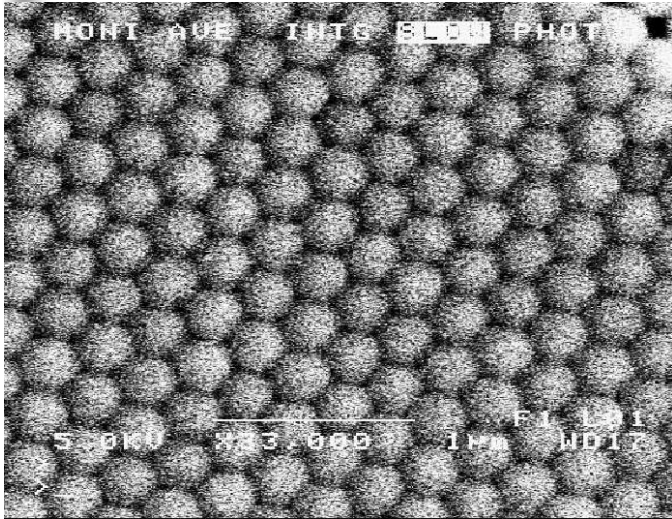
Improving





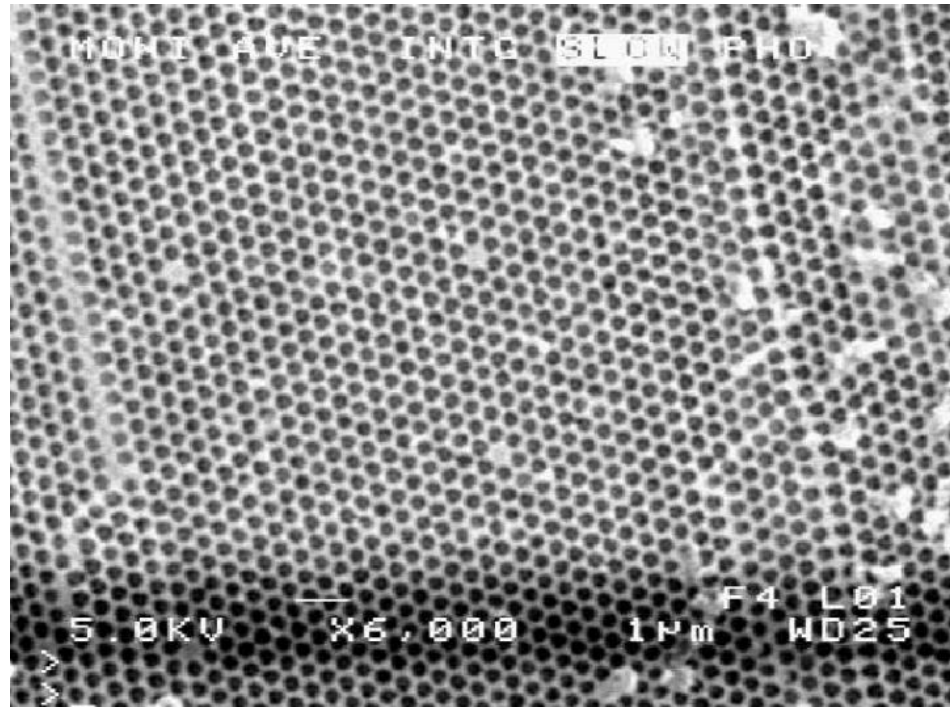
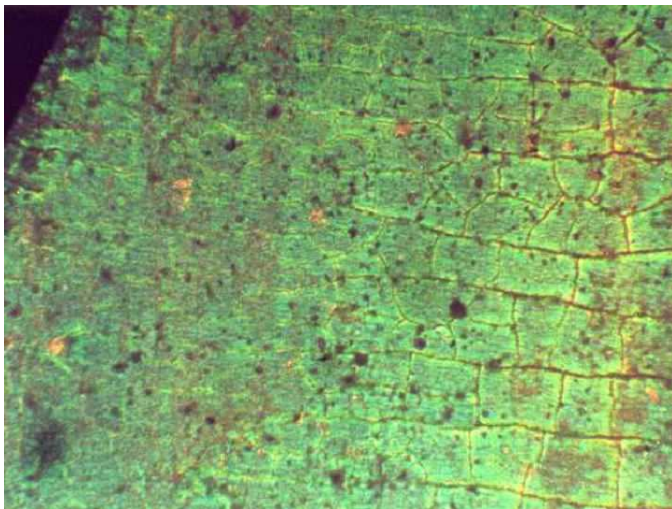
- *Uniformity of ~ 10nm is achieved*
- *Global degree of planarization achieved ~94 %*

Moving to the Visible Regime: Key Material TiO_2



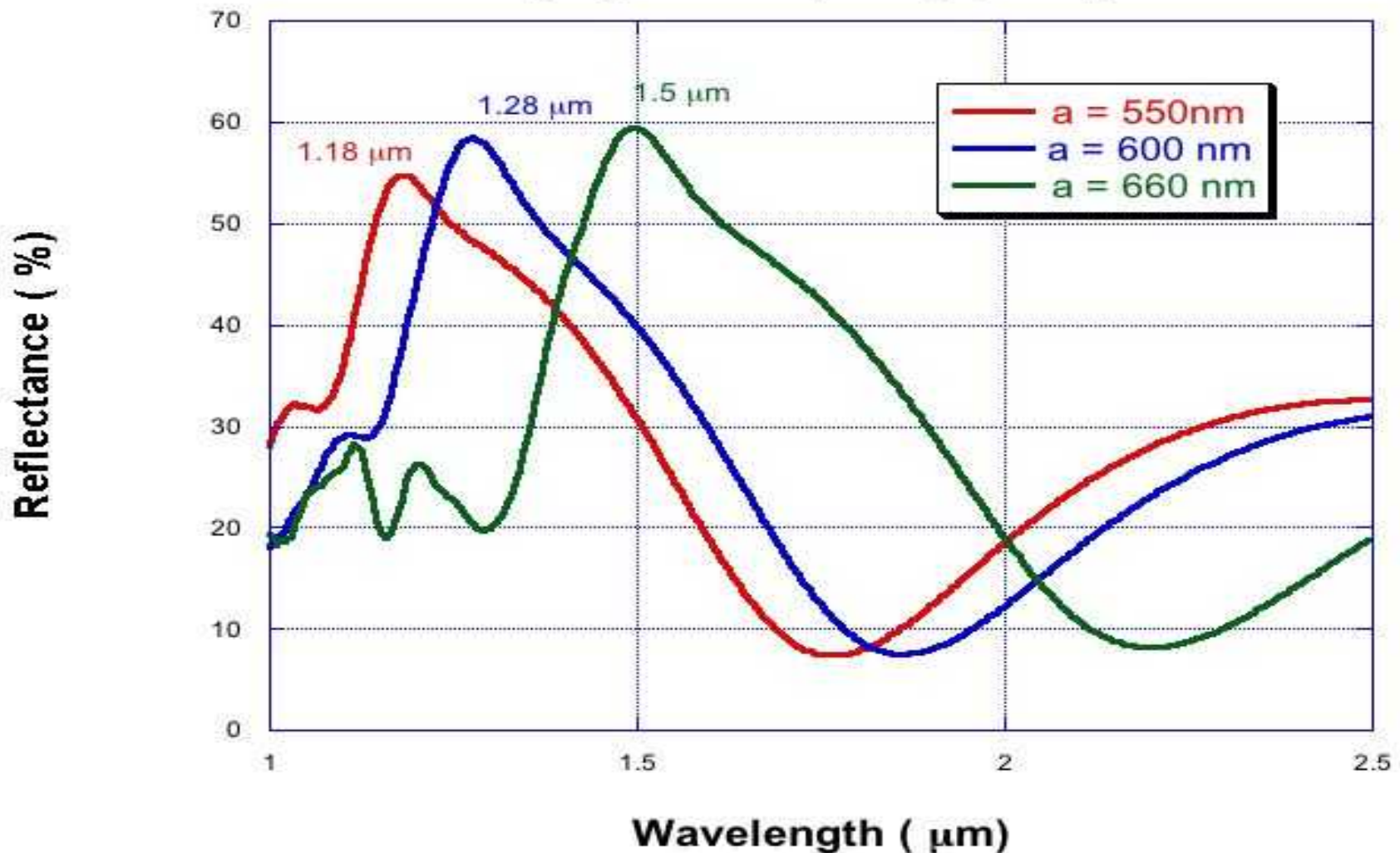
Periodicity achieved using close packed nanospheres -> FCC lattice

High index material: Titania (TiO_2)

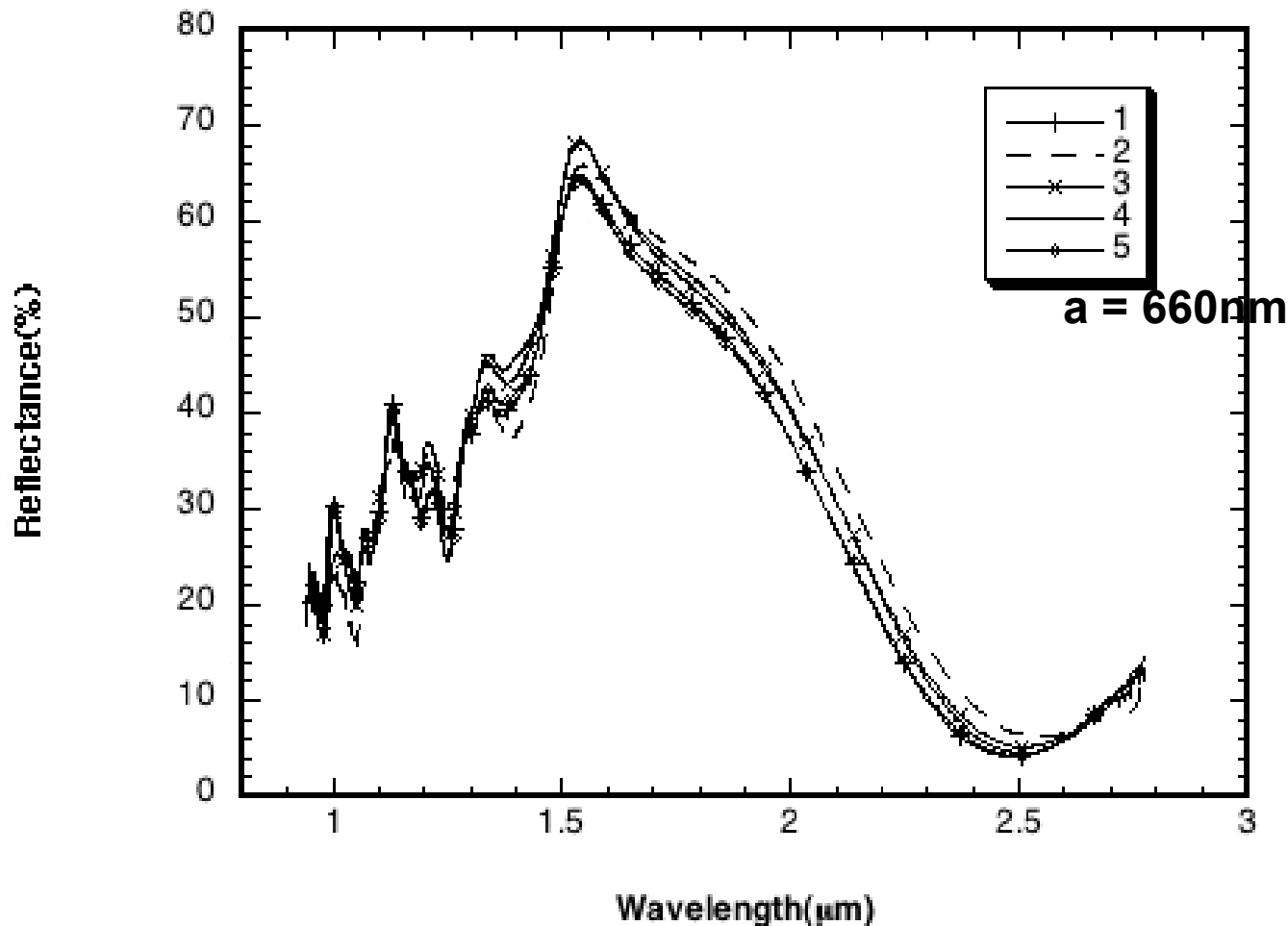


Peak shifts to shorter wavelengths with lattice constant

Varying lattice spacing , 4 Layers

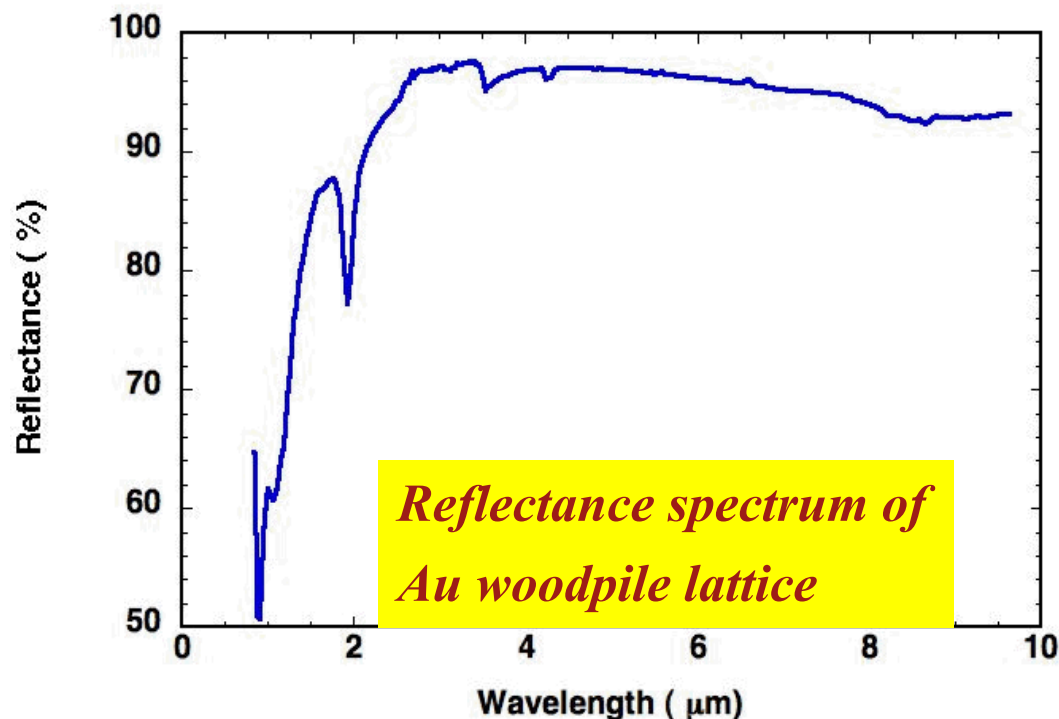
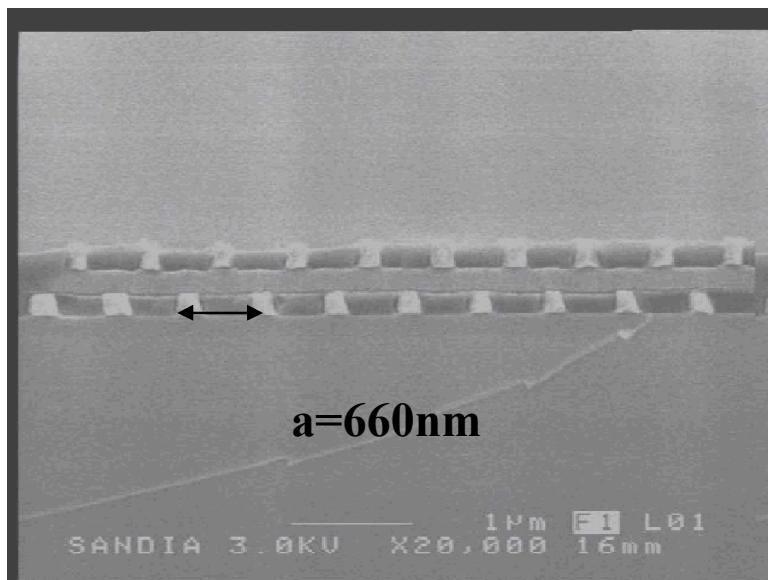
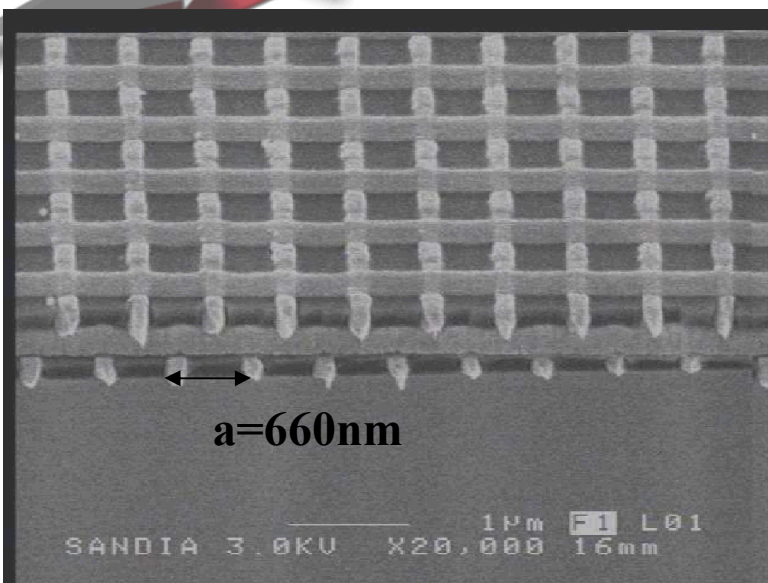


Reflectance data from devices on different chips



Excellent uniformity in device response across wafer

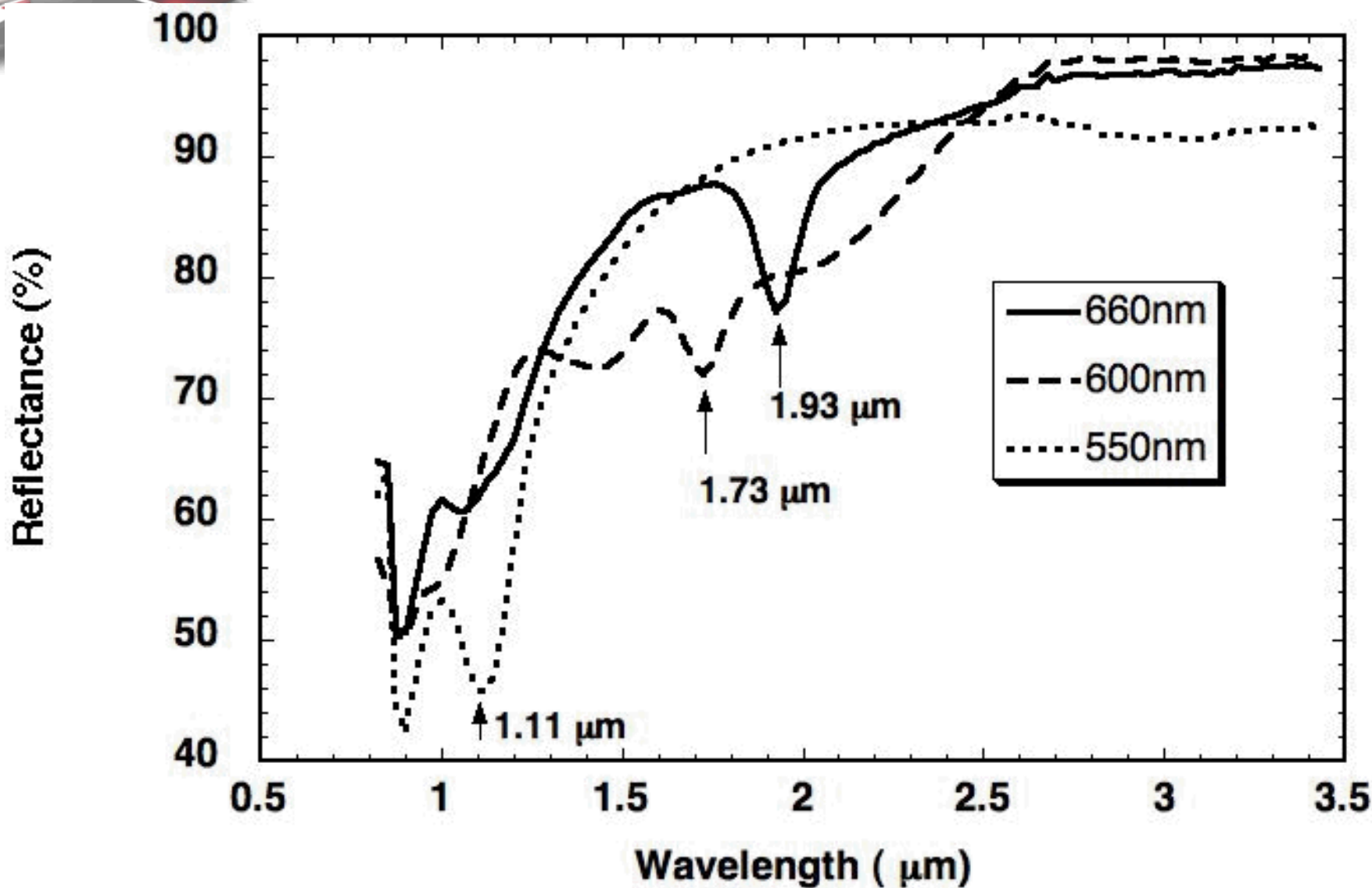
Gold Logpile Lattice



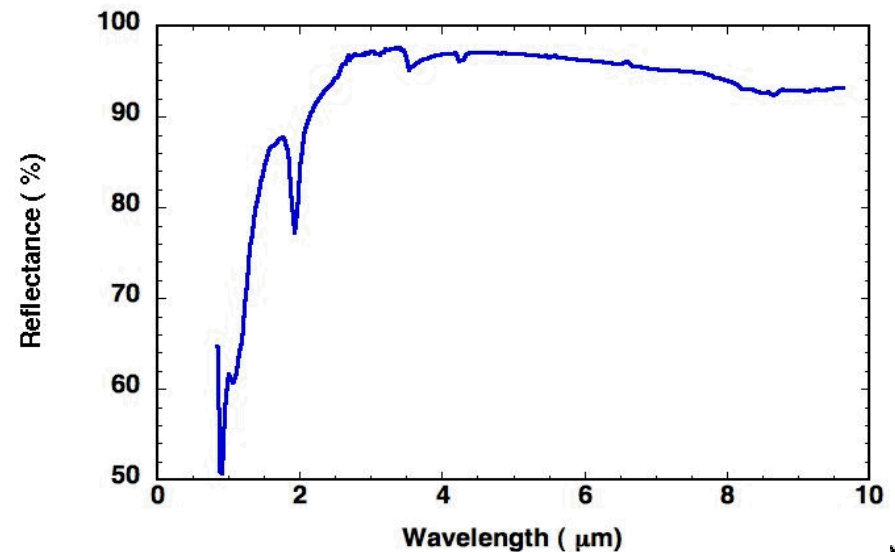
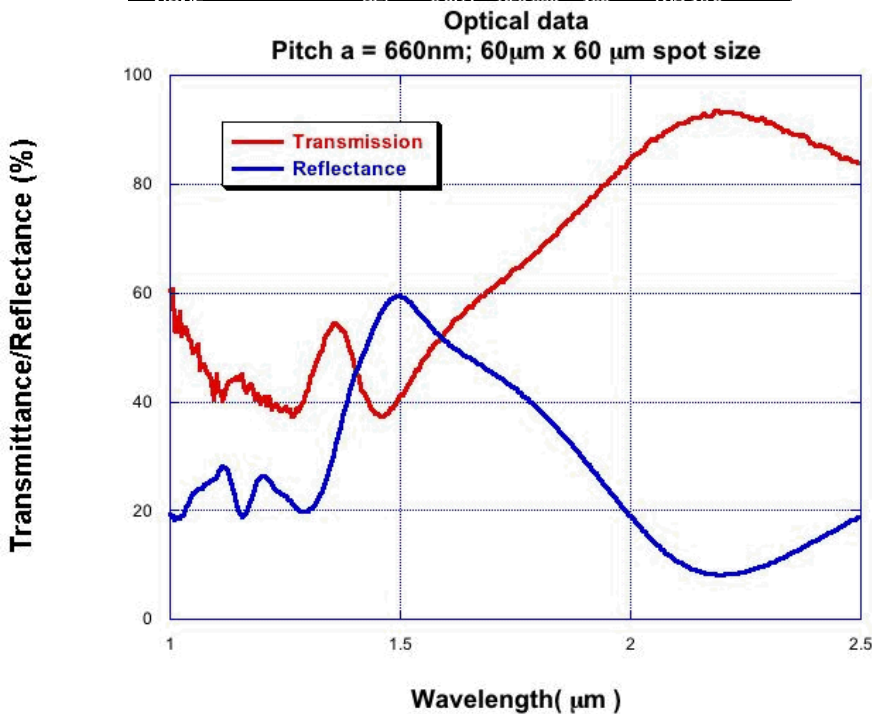
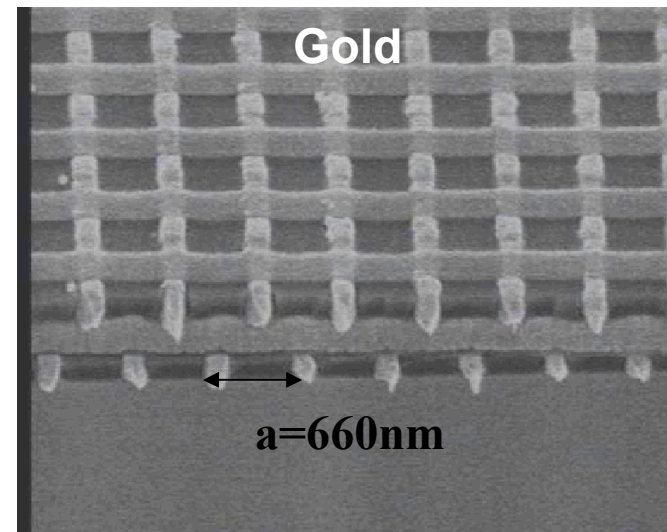
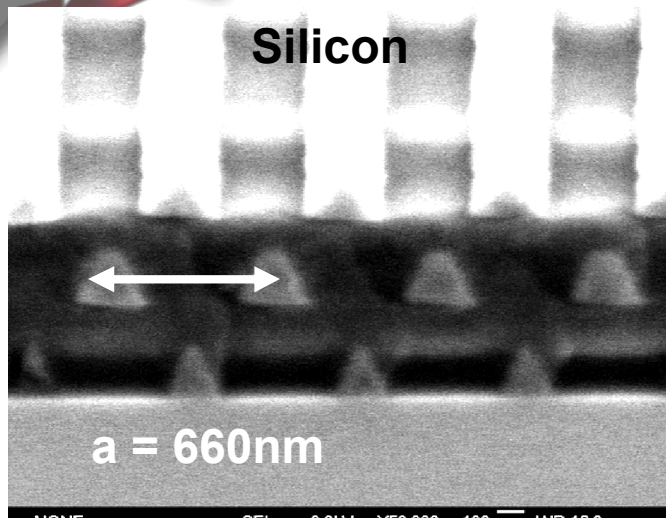
- Broad band reflectors, selective emitters
- Substrate for 3D SERS reproducible SERS sensor

G.Subramania, et.al., MRS. Symp. Proc. 846,DD12.3(2005)

Change Lattice Spacing : Band Edge Tuning

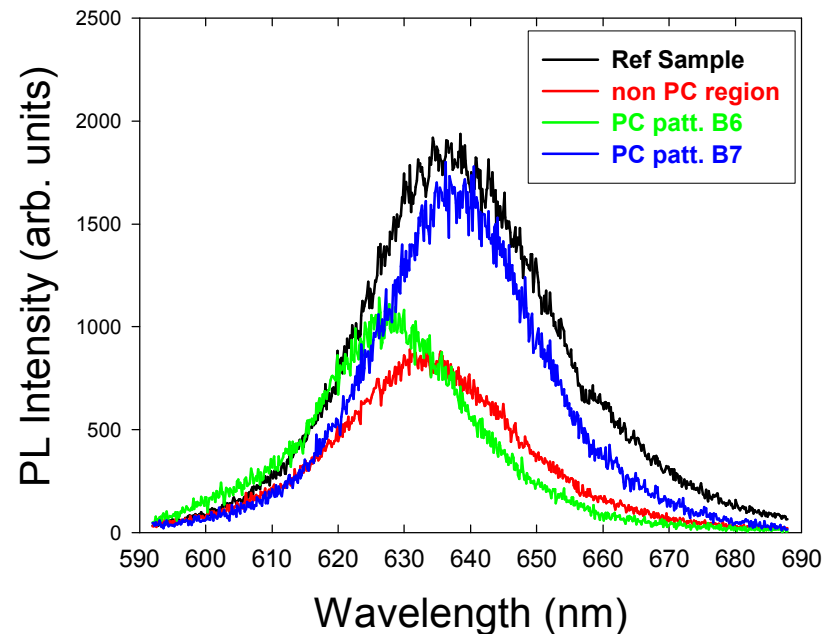
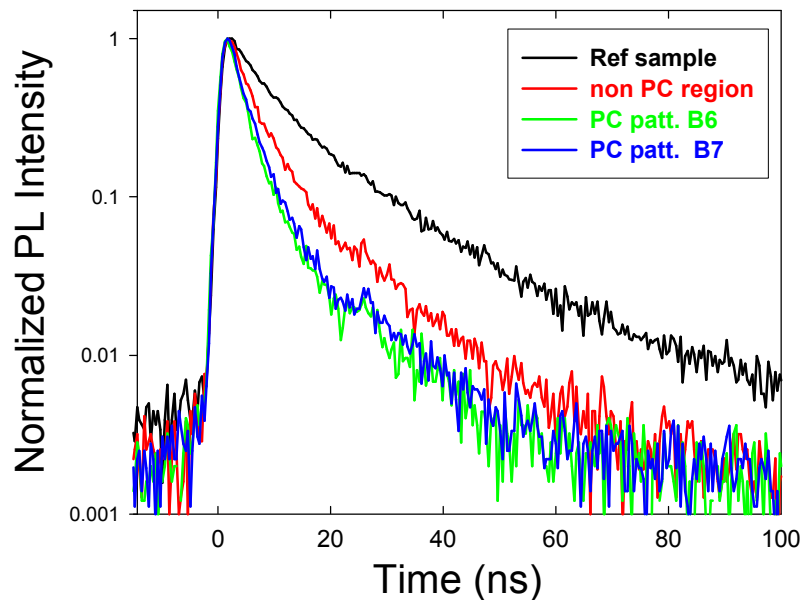


Near-IR bandgap Logpile: Silicon and Gold



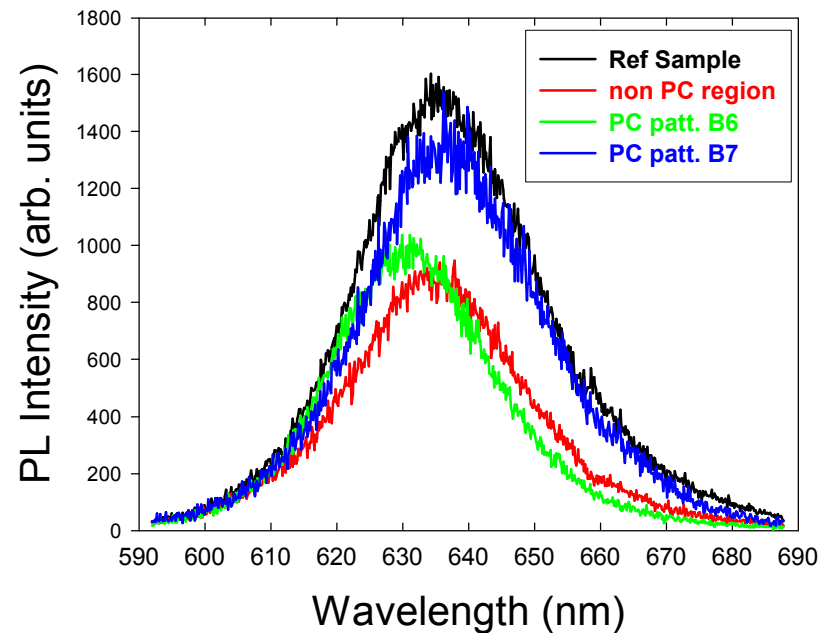
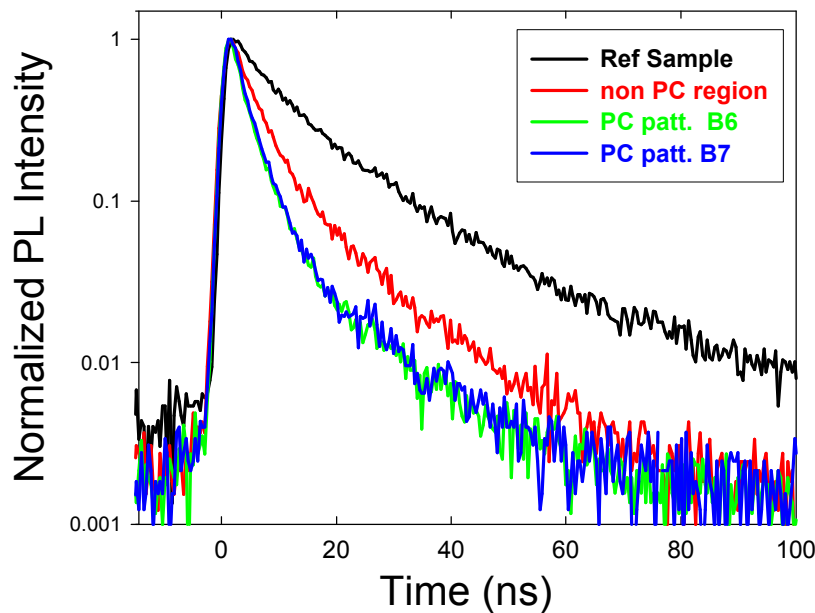
TRPL from Vis3-14A: vertical polarization

- 380 nm pump, 4 MHz, 20 μ W average power, 10 mm aperture
- Largest change between ref sample and PC patterns
- Small change between patterned and unpatterned region on PC sample
- No significant change between pattern B6 and B7



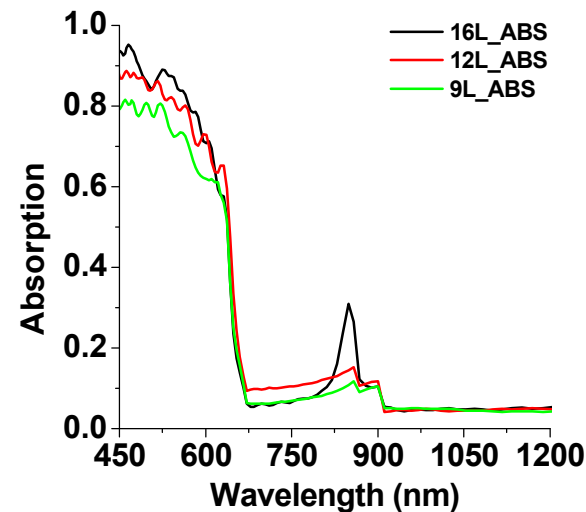
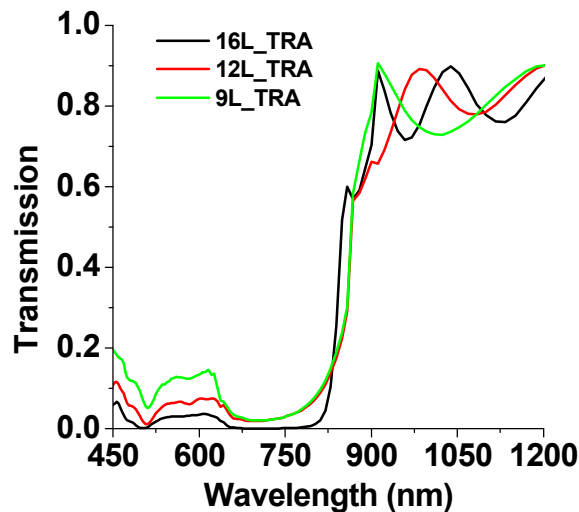
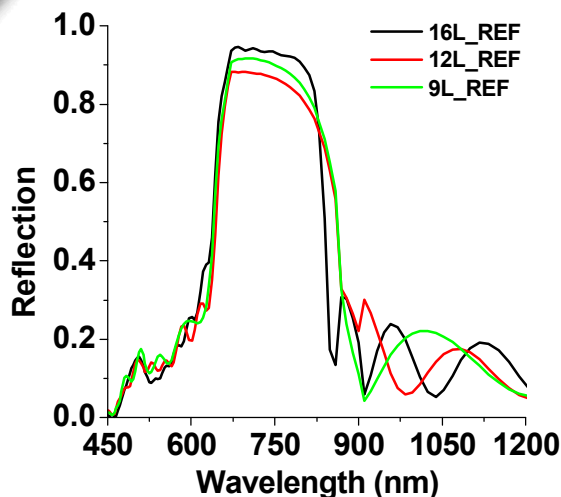
TRPL from Vis3-14A: horizontal polarization

- 380 nm pump, 4 MHz, 20 μ W average power, 10 mm aperture
- Small change between patterned and unpatterned region on PC sample
- No significant change between pattern B6 and B7

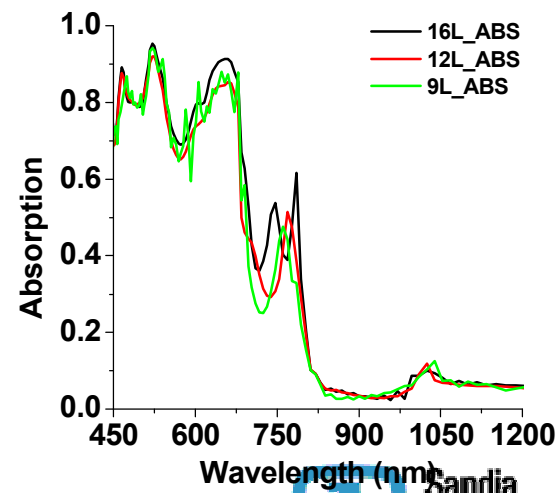
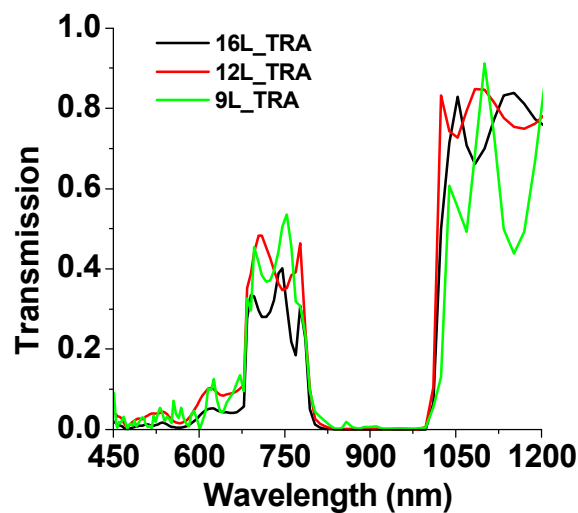
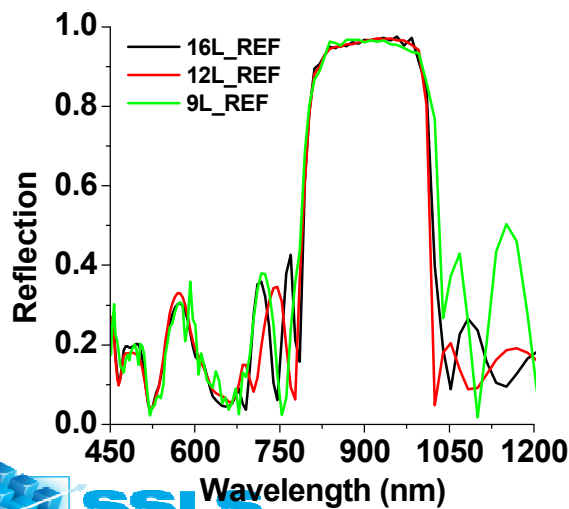


FDTD Simulations for Increasing Layers

$a = 250\text{nm}$



$a = 400\text{nm}$



Line defect Cavity in 9L logpile : TiO_2

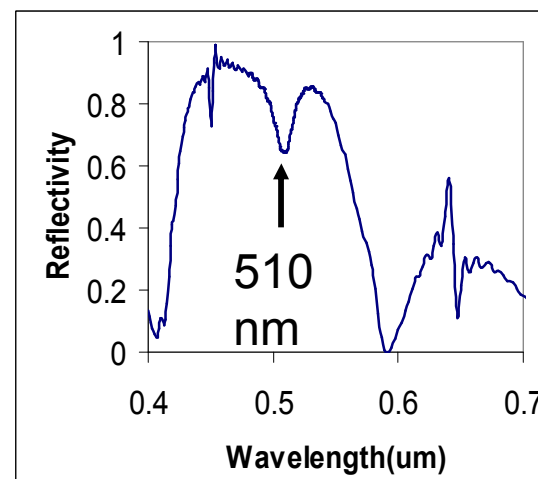
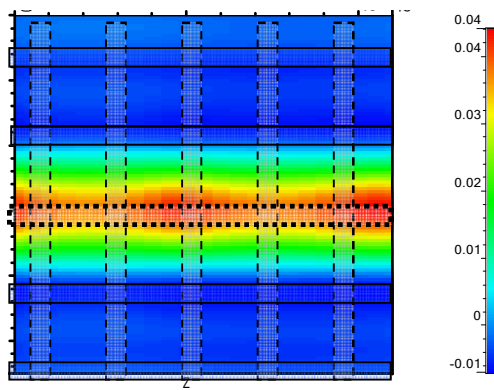
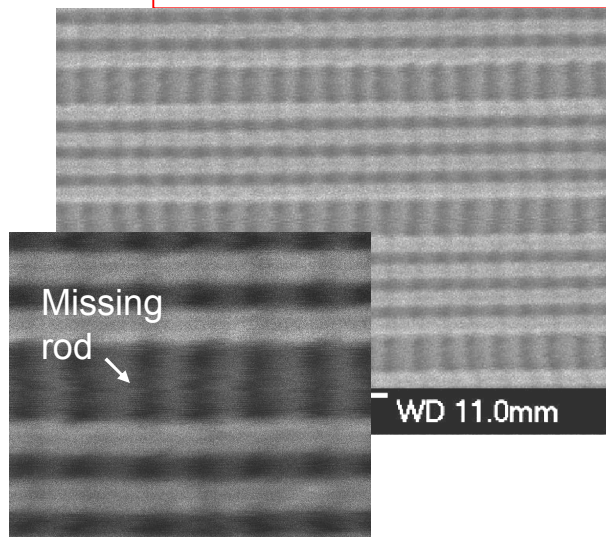
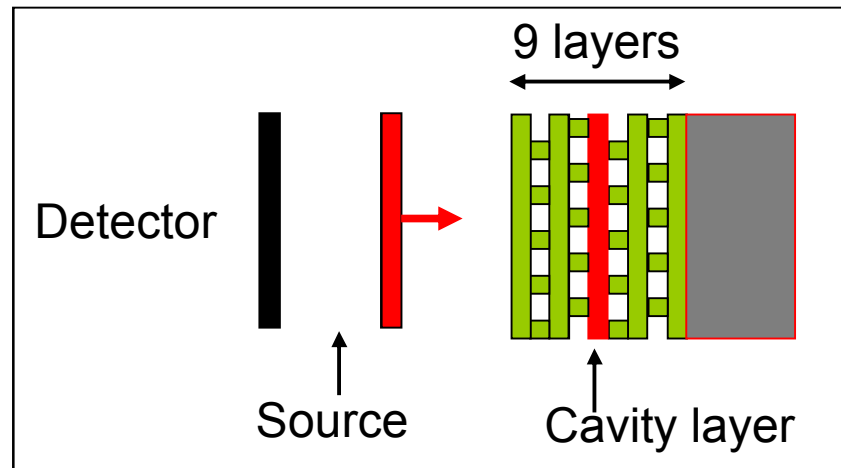
Finite difference time domain simulation of 3DPC cavities

FDTD conditions:

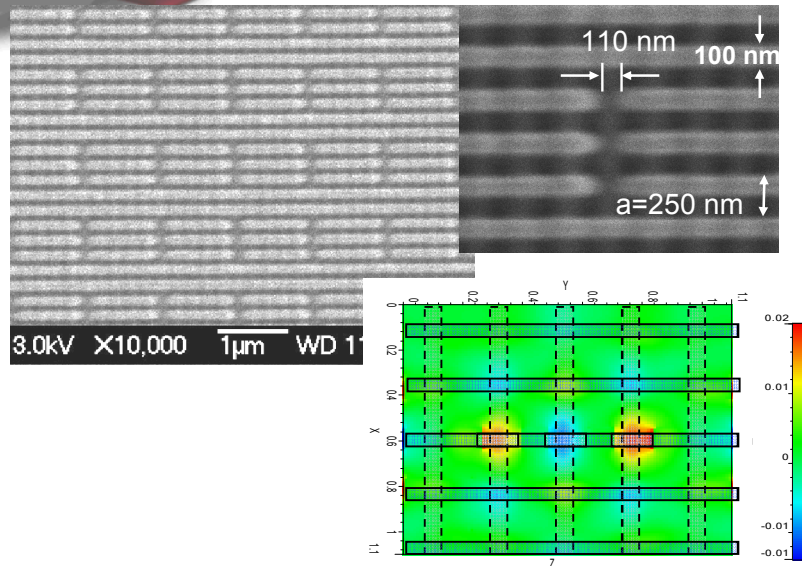
- Supercell: 5 unit cells
- Cavity defect periodic with 5 unit cells
- Periodic boundary conditions in the transverse
- Gaussian source

Cavity A: Every 5th rod removed

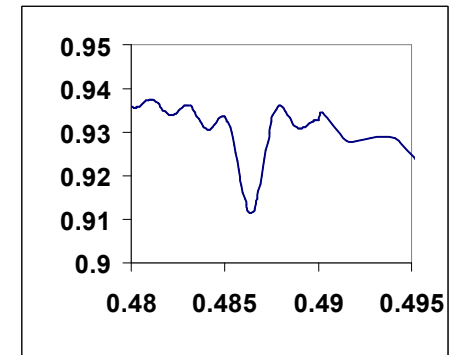
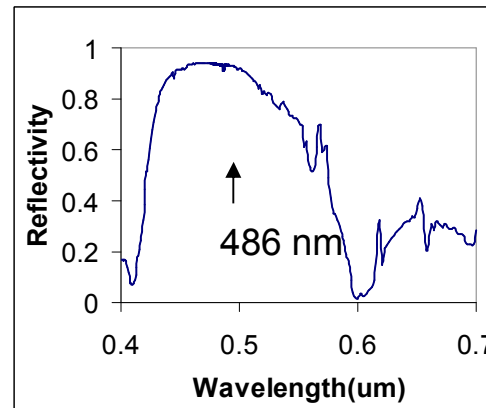
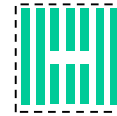
- Q factor ~ 30
- Mode volume : $2 \cdot (\lambda/n)^3$



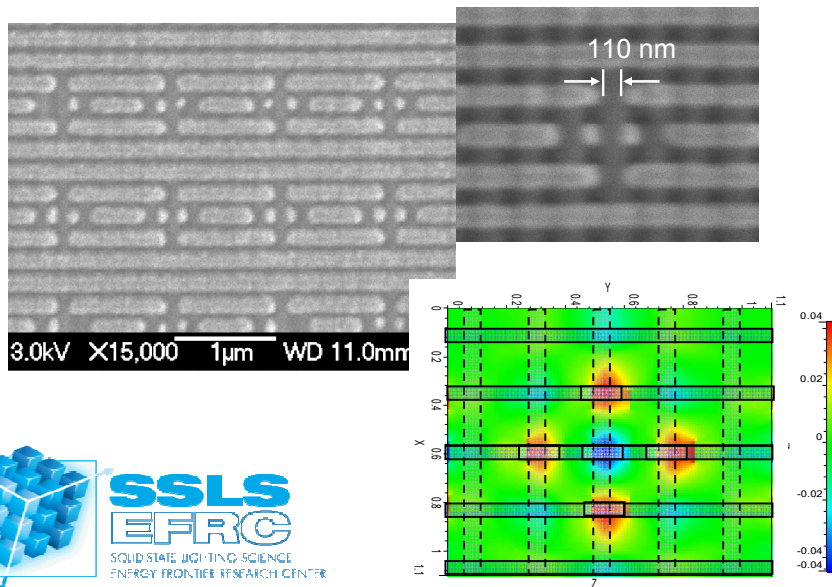
Point defect Cavity in 9L logpile : TiO_2



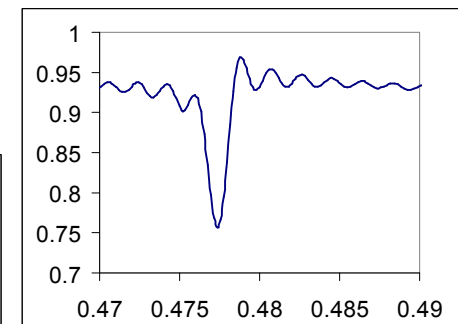
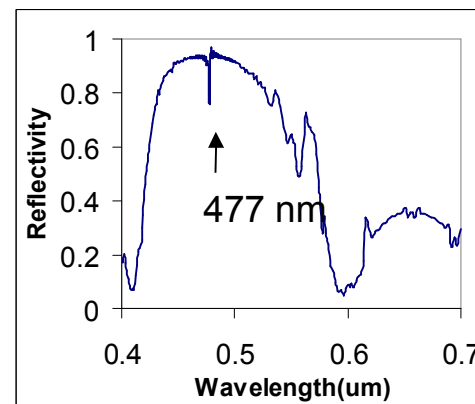
Cavity B: $\rightarrow$



- $Q \sim 250$
- $MV : 0.25(\lambda/n)^3$



Cavity C: $\rightarrow$



- $Q \sim 300$
- $MV : 0.42(\lambda/n)^3$

Polarized Near-normal Response

