Photonic Crystal-Based Optical Devices

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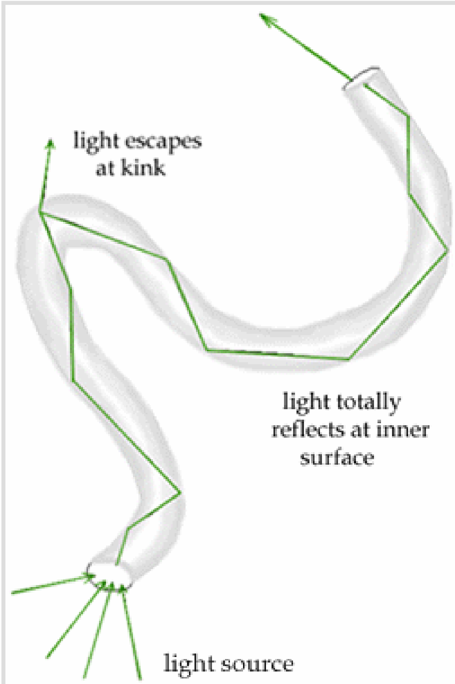
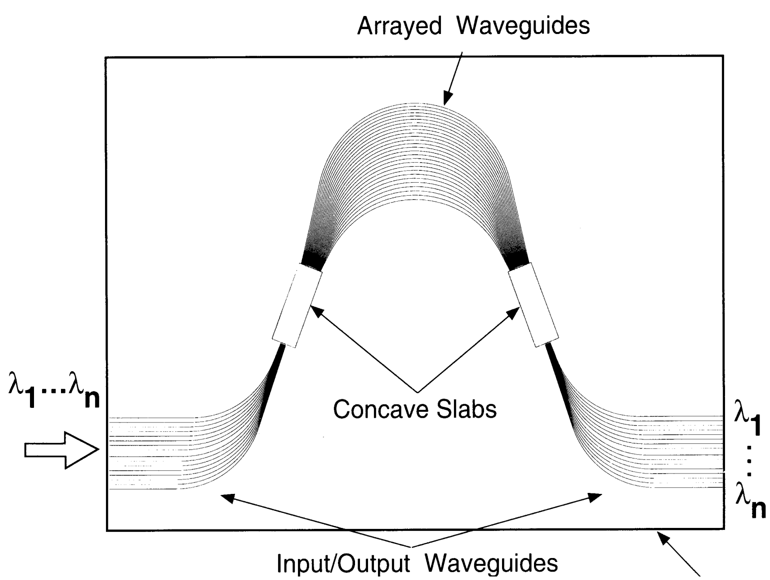
June 2004

Funding: NSF, DOE, ARO – MURI, Beckman Foundation, 3M

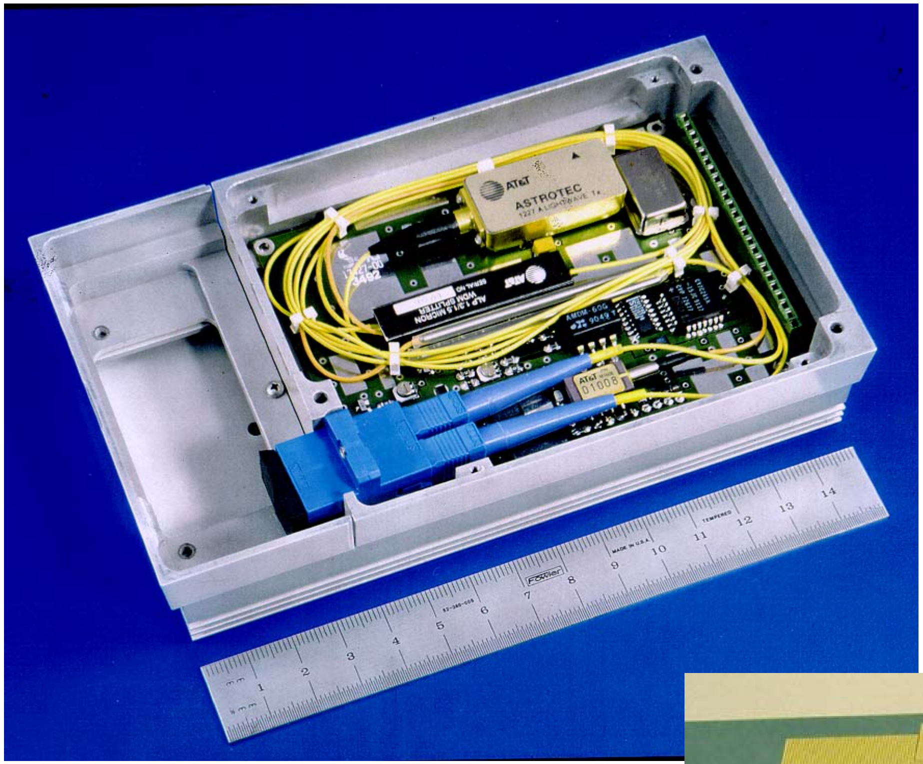
Photonics Today: Interesting, but Exciting?

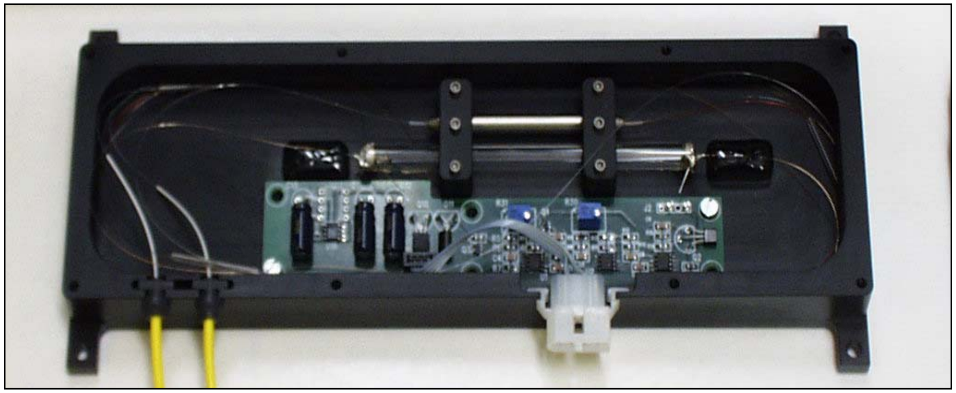


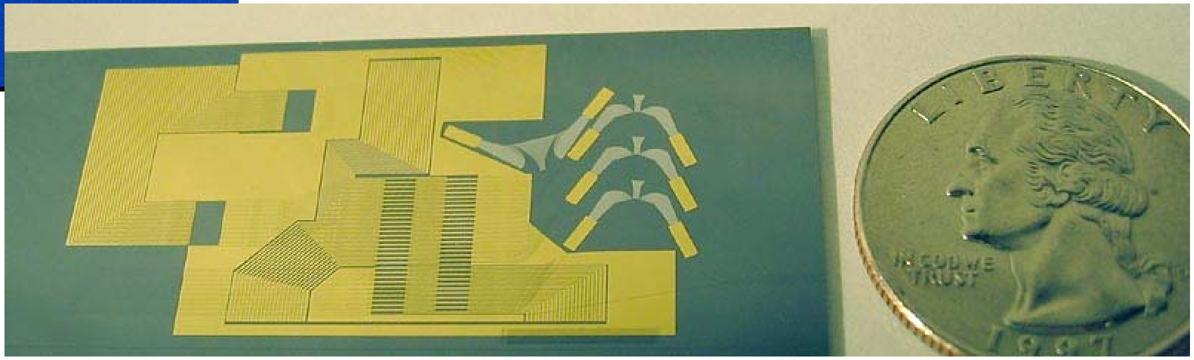


It's hard to get excited about 2-D

Current 2-D Optical Network Devices





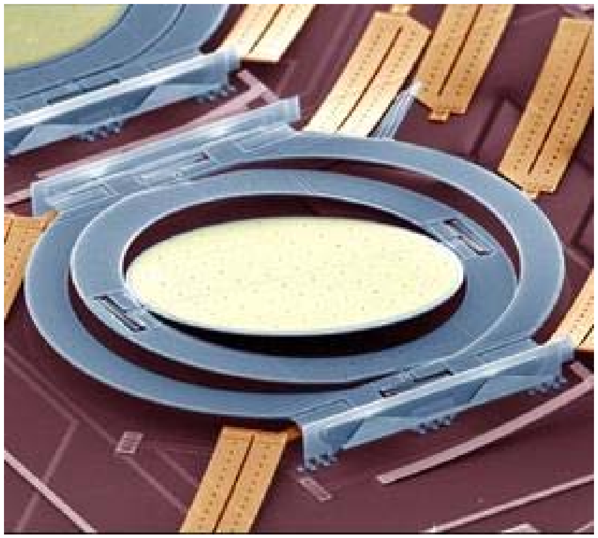


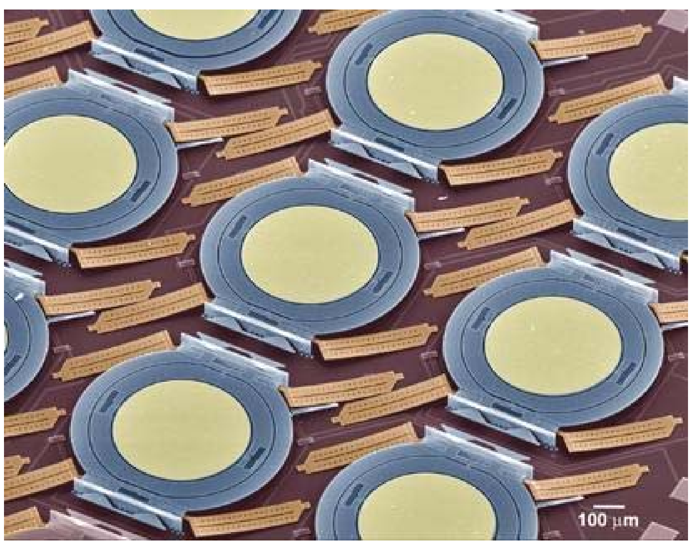
"Innovate to manipulate photons in a flexible, compact way."

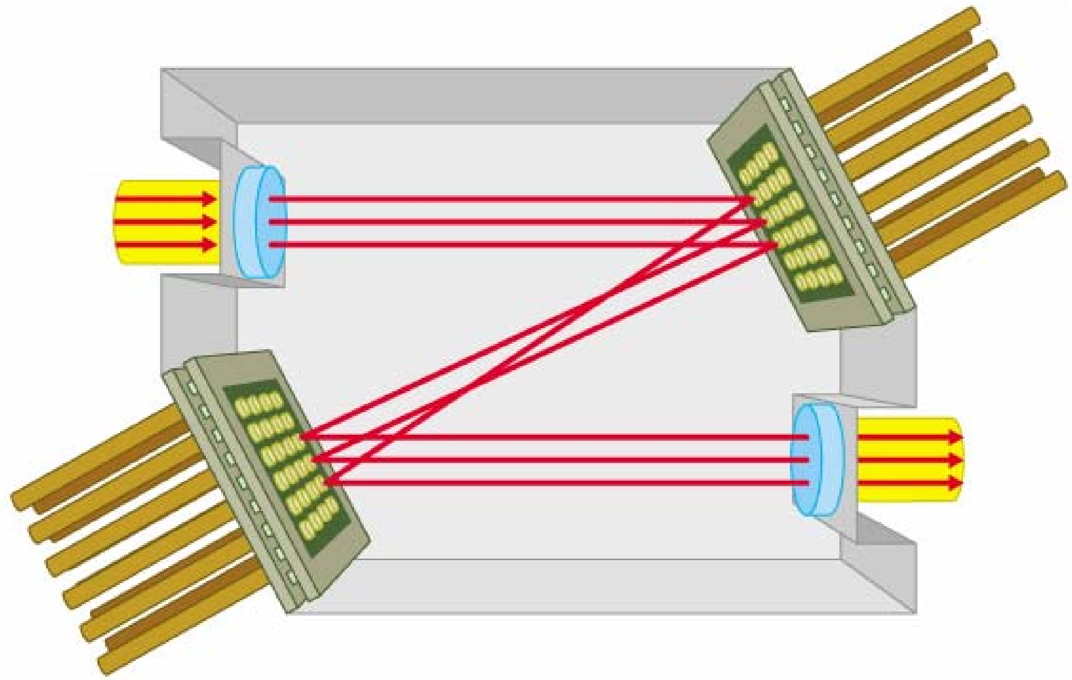
Lucent's (canceled) WaveStar™ LambdaRouter

2.5 dimensional?

Close-up of single mirror.



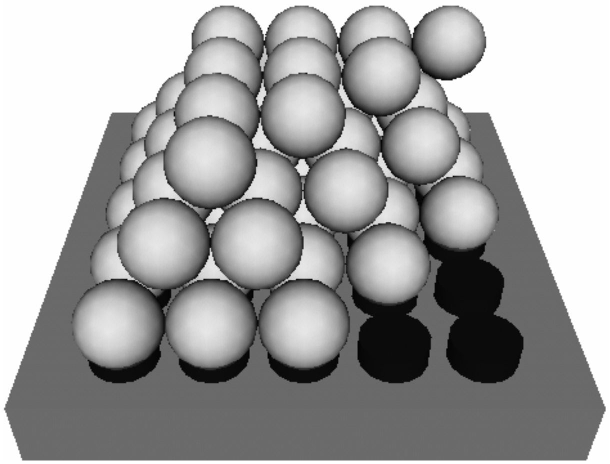




Array of microscopic mirrors, each able to tilt in various directions, to steer light.

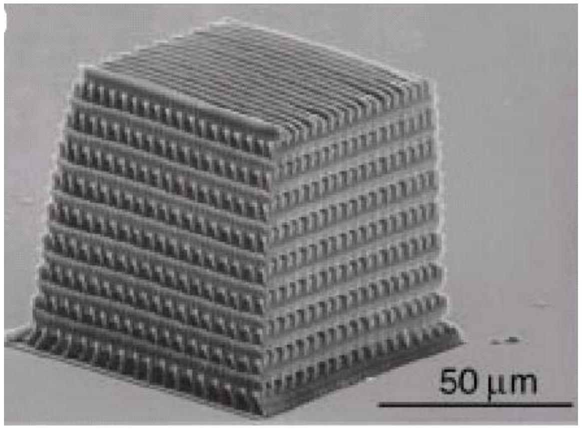
So, how to get to 3-D?

Colloidal self-assembly



Ref: many, many groups!

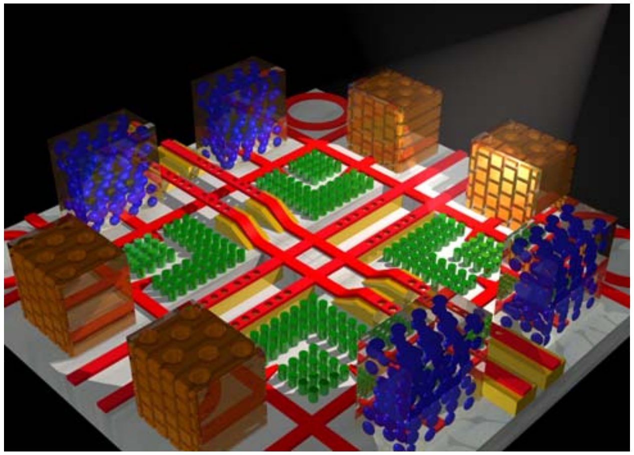
Multiphoton polymerization



Cumpston et al. *Nature* **1999**, *398*, 51.

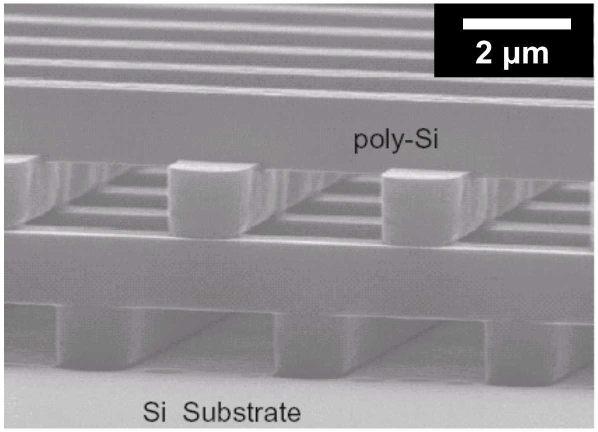
3-D Applications

- Low-loss waveguides
- Optical cavities
- Zero-threshold microlasers
- Light-emitting diodes
- All-optical transistors
- Improved photoreactors
- Tunable filters



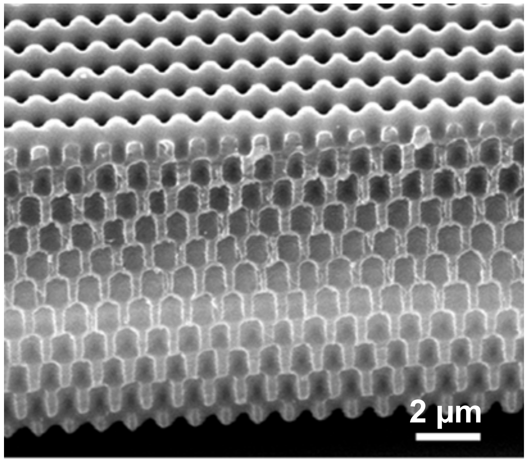
Prof. John Joannopoulos
http://ab-initio.mit.edu/photons/index.html

Lithography



S. Y. Lin, et al. *Nature* **1998,** *394*, 251.

4-beam holography

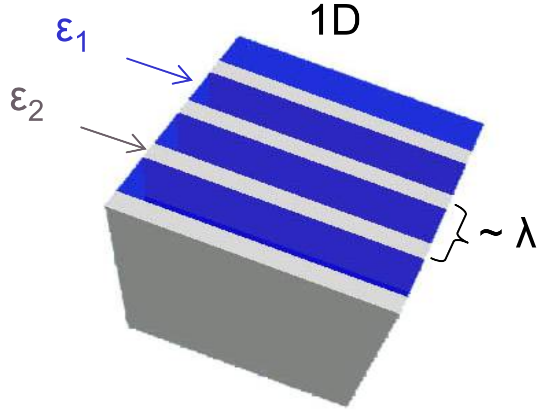


Turberfield A. J., *et al.*, *Nature* 2000
Wiltzius, P. *et al., Chem. Mater.* **2002**

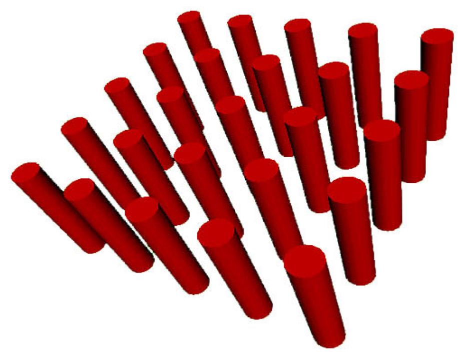
Photonic Crystal Primer

Requirements for a Photonic Crystal: 1) Periodicity in the dielectric constant; 2) Domain sizes ~ λ

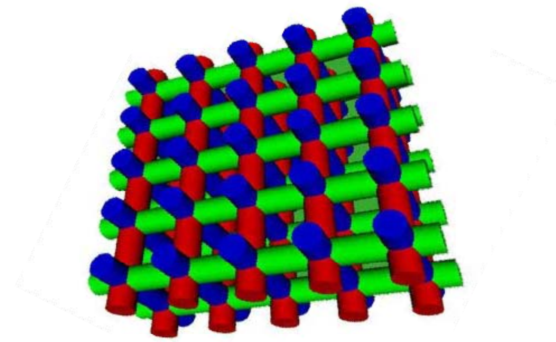
1D



2D



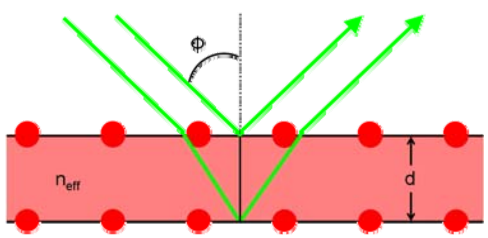
3D



Figures modified from: http://www.elec.gla.ac.uk/groups/opto/photoniccrystal/Welcome.html

Properties of a Photonic Crystal:

Bragg Diffraction



$$m\lambda = 2\,d\,(n_{eff}^2 - \sin^2 \Phi)^{1/2}$$

Light Modulation

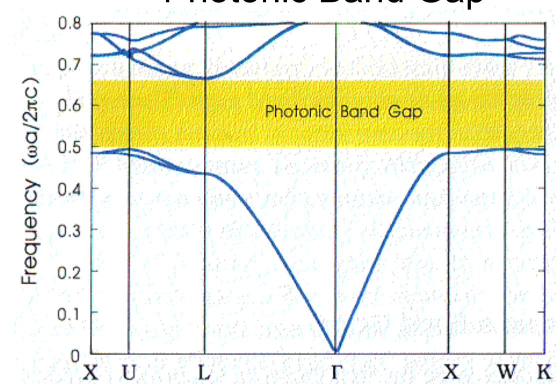
weak → strong

↑ index contrast

→ appropriate geometry

J. Joannopoulos et al. *Photonic Crystals,* 1995, p. 82

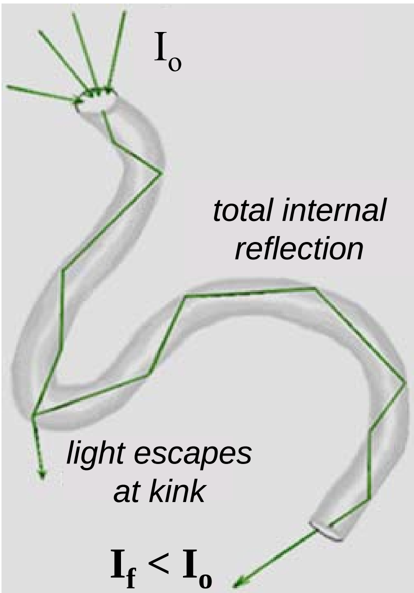
Photonic Band Gap



Example PBG Application: Waveguiding

Current Principle:

Total Internal Reflection



Inherent losses typically > ~ 0.2 db / km

+

Cannot tolerate bend radii < 5 cm

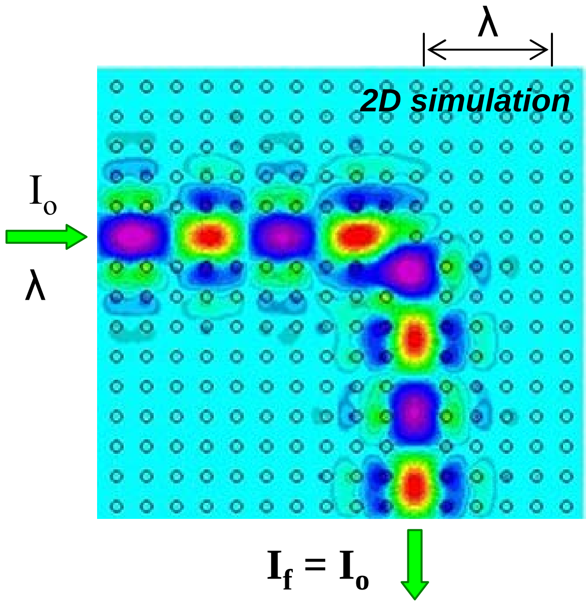
⇩

Require periodic amplification of signal

Not suitable for small bend radii

PBG-Based:

Frequency Confinement



Defects create states in the bandgap

⇩

Forbidden frequencies are confined within defects

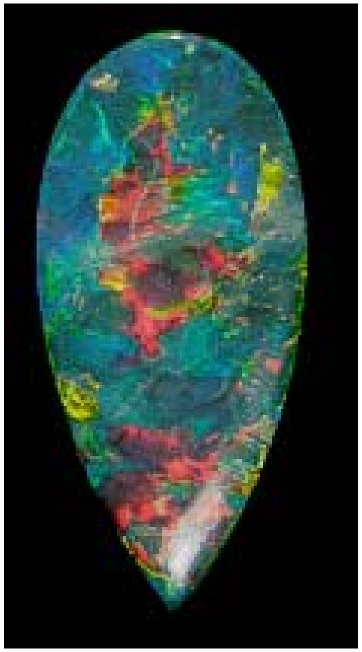
⇩

100% transmission around bend radii ~ λ!

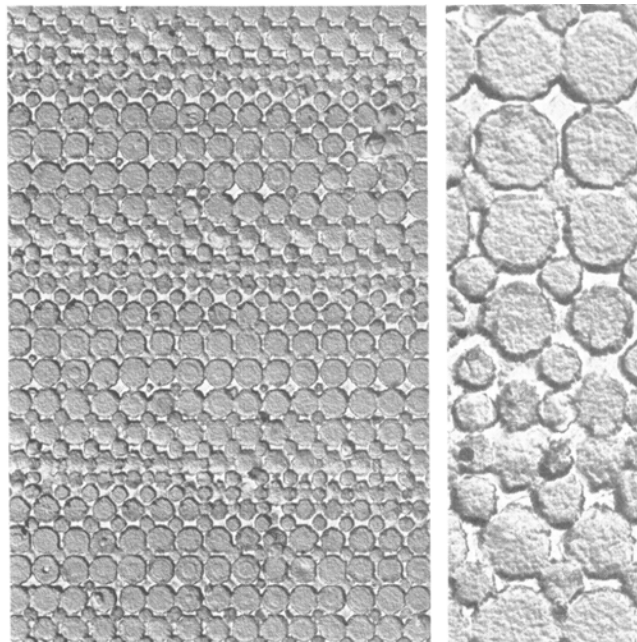
http://ab-initio.mit.edu/photons/index.html

3-D Self-Assembly: Colloidal Crystals (Opals)

Opal

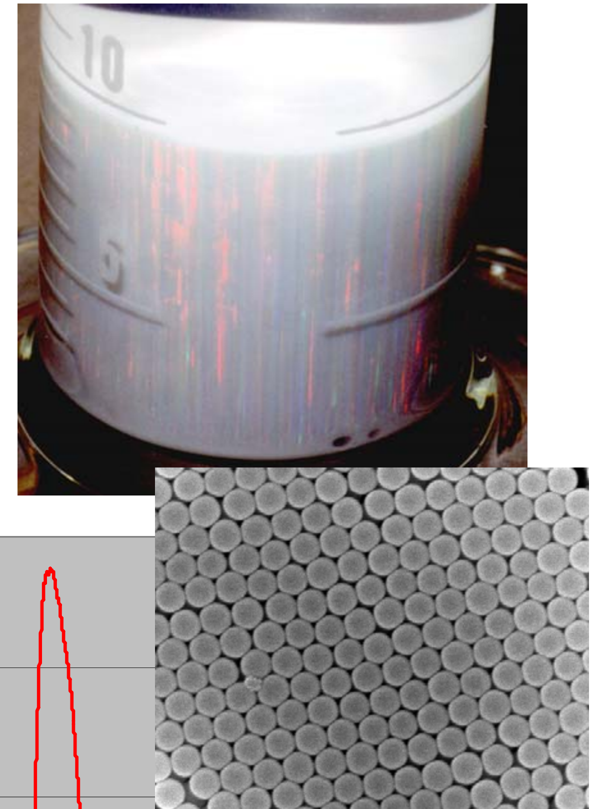


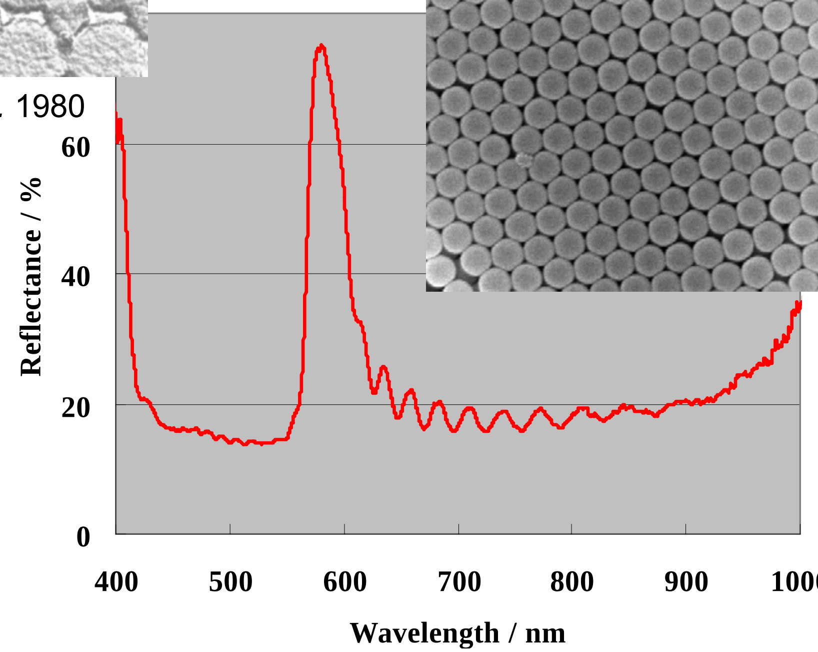
SEM of opal cross-section



J.V. Sanders, *Phil. Mag. A.* 1980

synthetic “opal”
formed from ~500 nm silica spheres



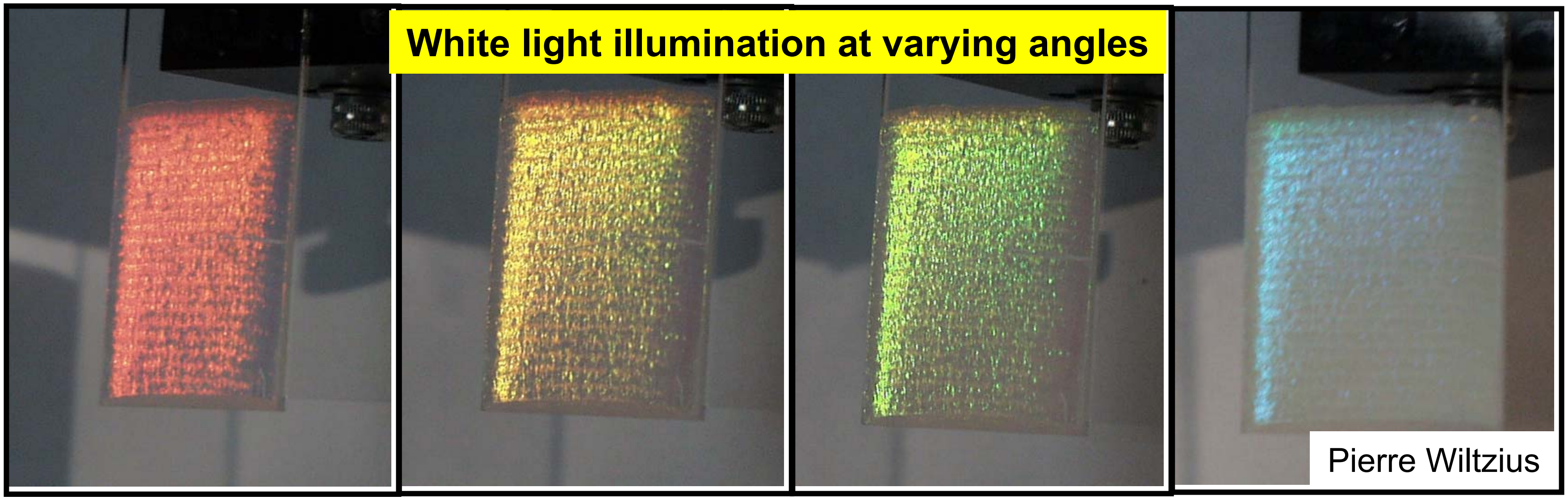


- Natural Opals consist of periodically arranged silica spheres in a matrix

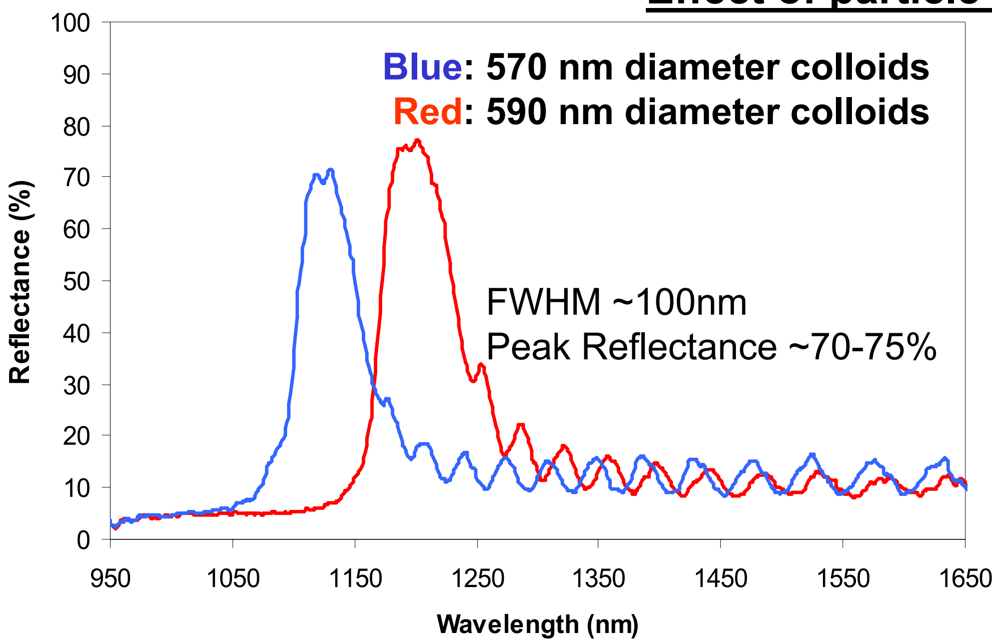
- The colors of an opals are due to Bragg diffraction of light by planes of silica spheres

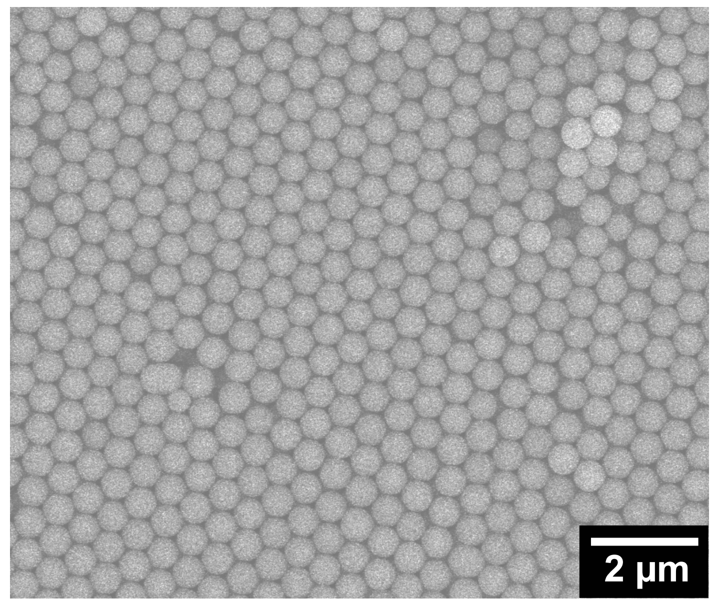
- Synthetic Opals are formed by careful assembly of silica spheres from solution

Colloidal Crystals – Diffraction Yields Color



Effect of particle diameter





Defects in Colloidal Crystals?

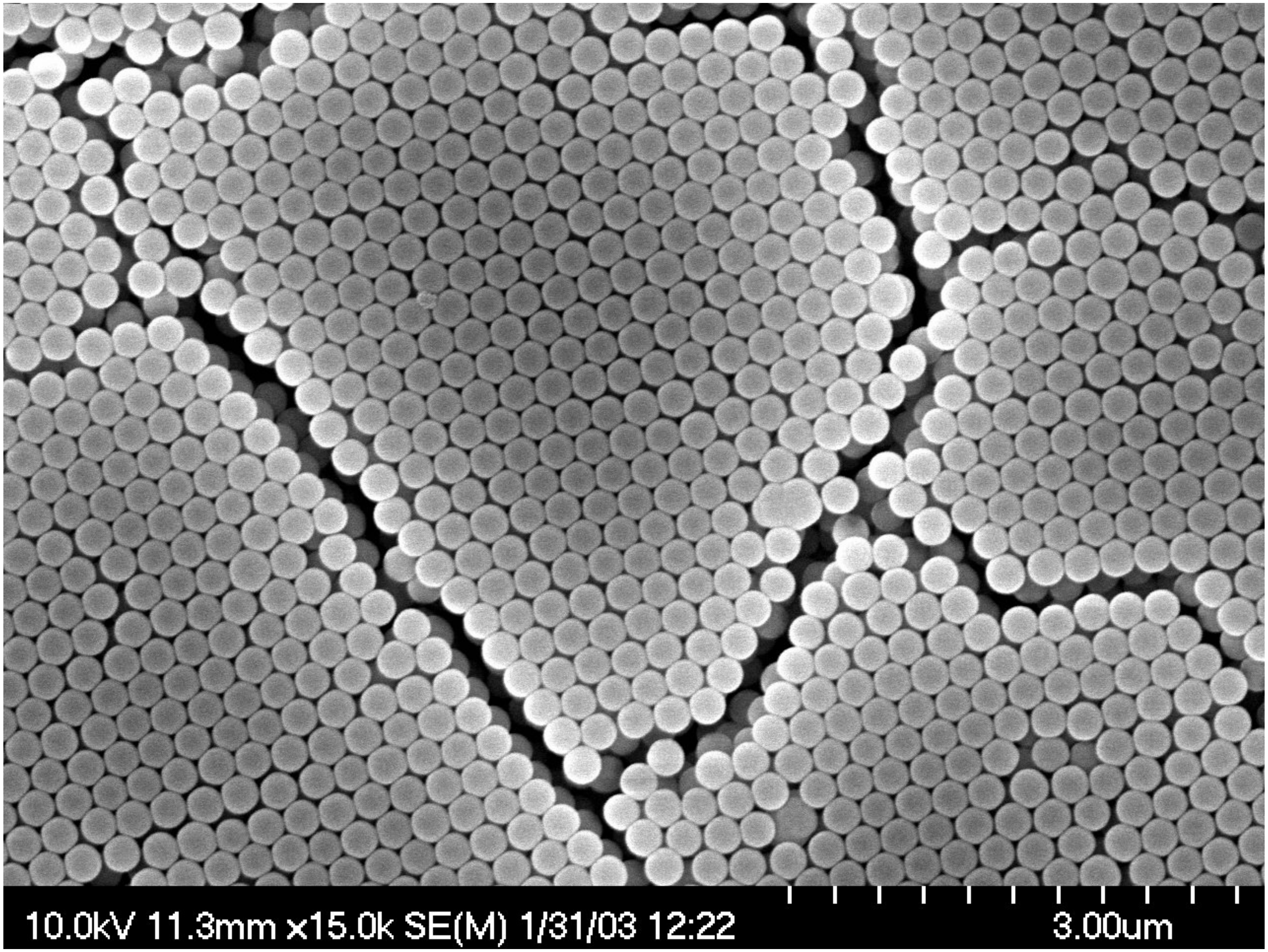
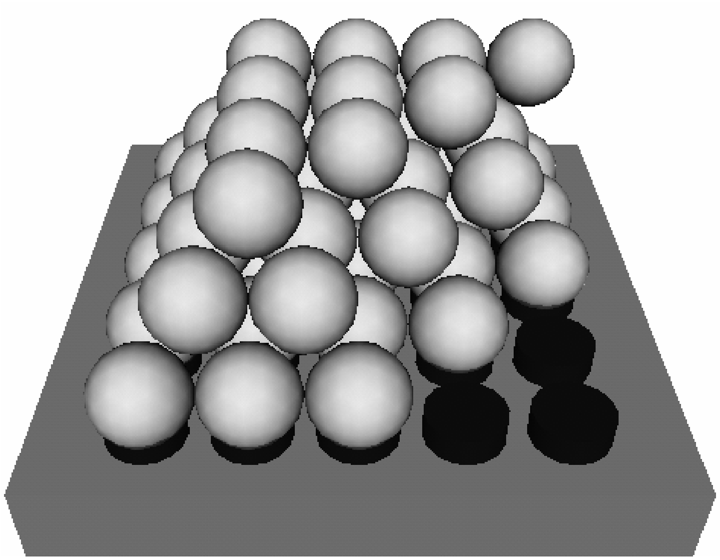
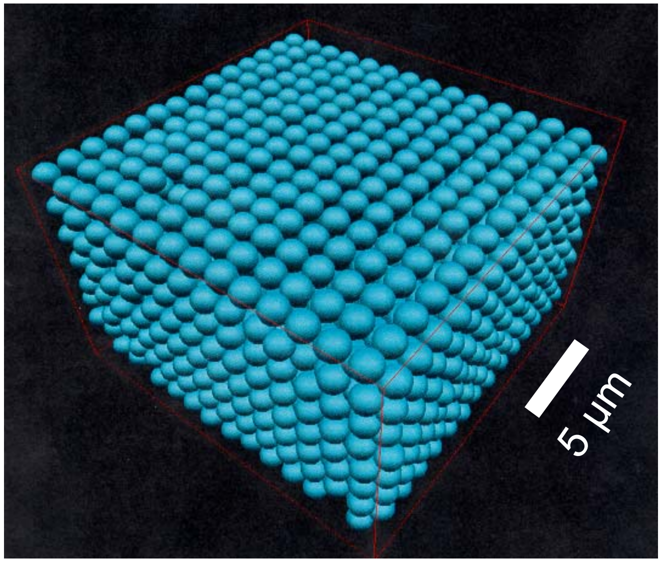


Image courtesy of Satoshi Takeda, Pierre Wiltzius

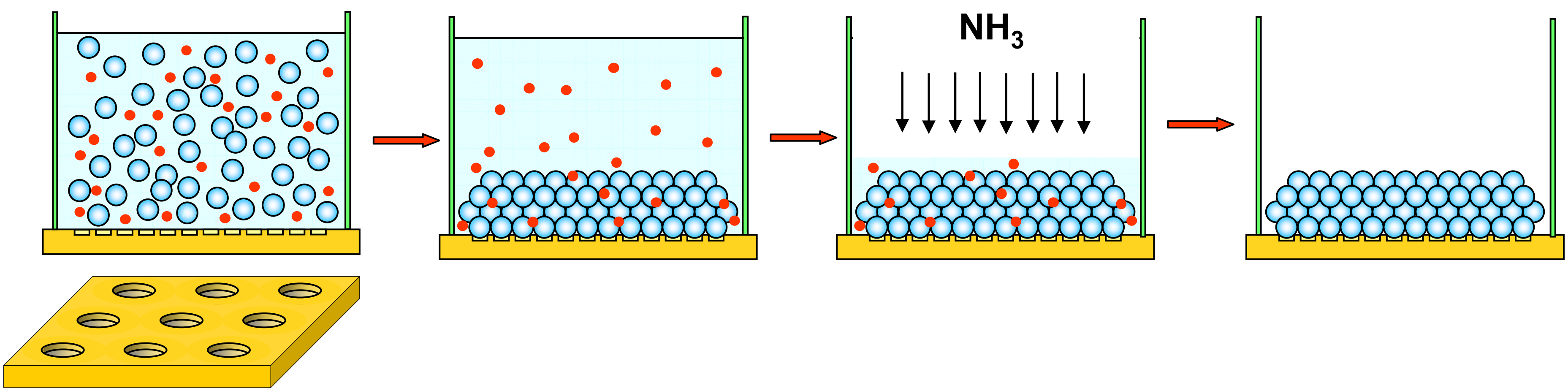
A Better Colloidal Crystal – Nanoparticle Mediated Colloidal Epitaxy



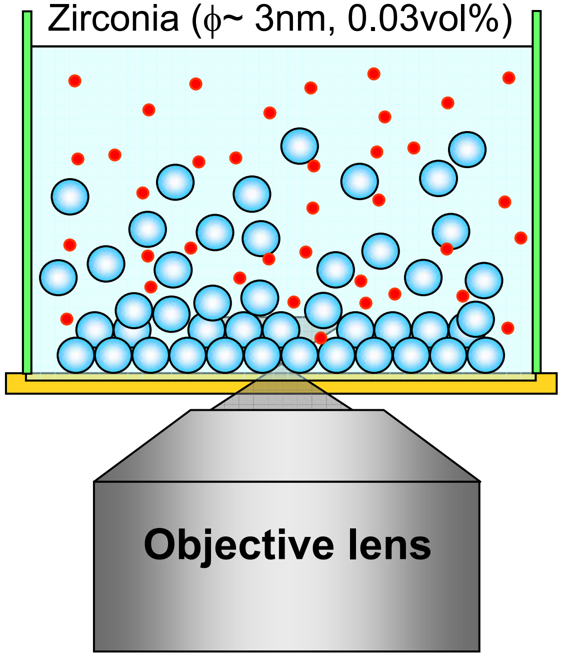


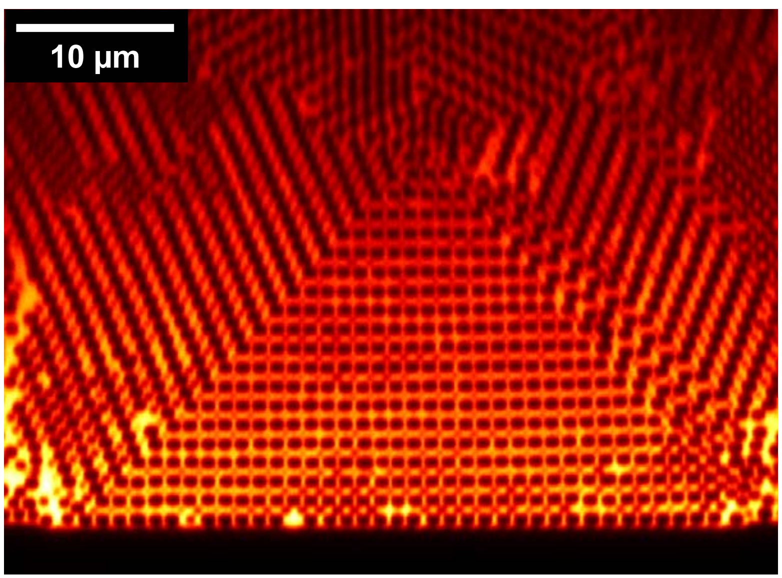
A. van Blaaderen, R. Ruel, P. Wiltzius, *Nature* **1997**, *385*, 321.

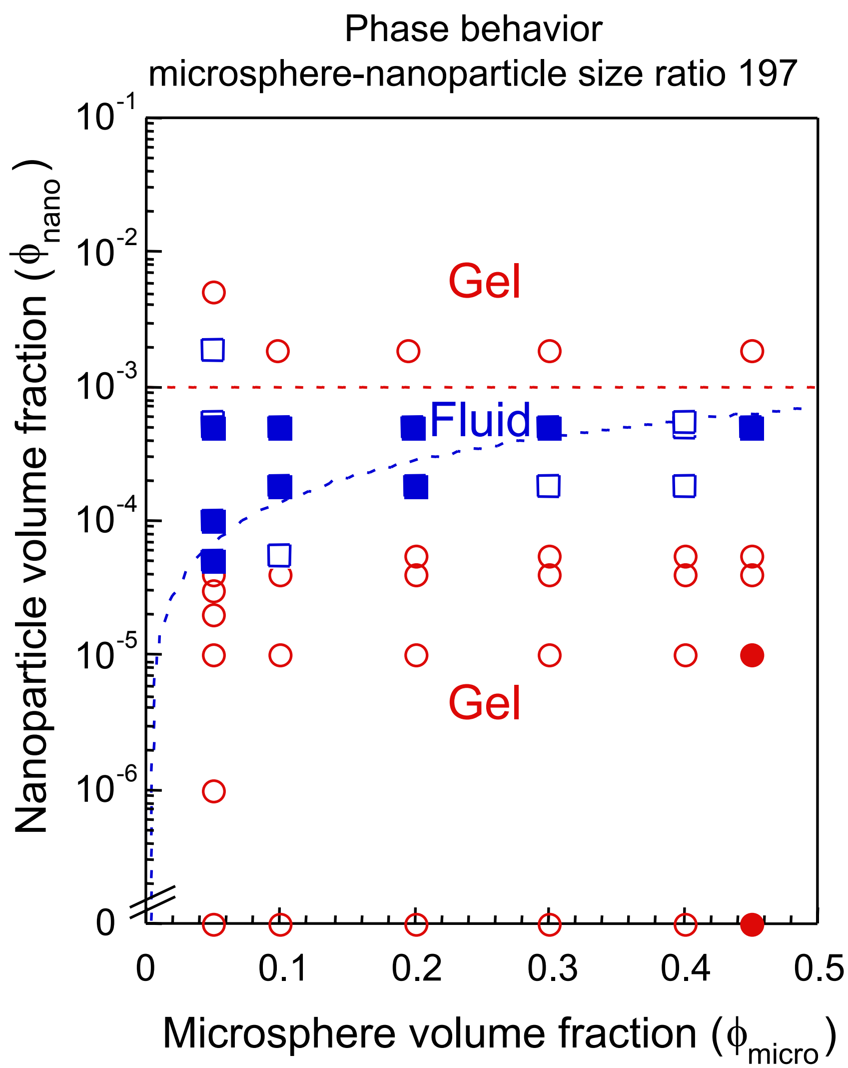
Colloidal epitaxy → low defect density & defined orientation with respect to the substrate



Gravity Driven Nanoparticle Mediated Colloidal Epitaxy



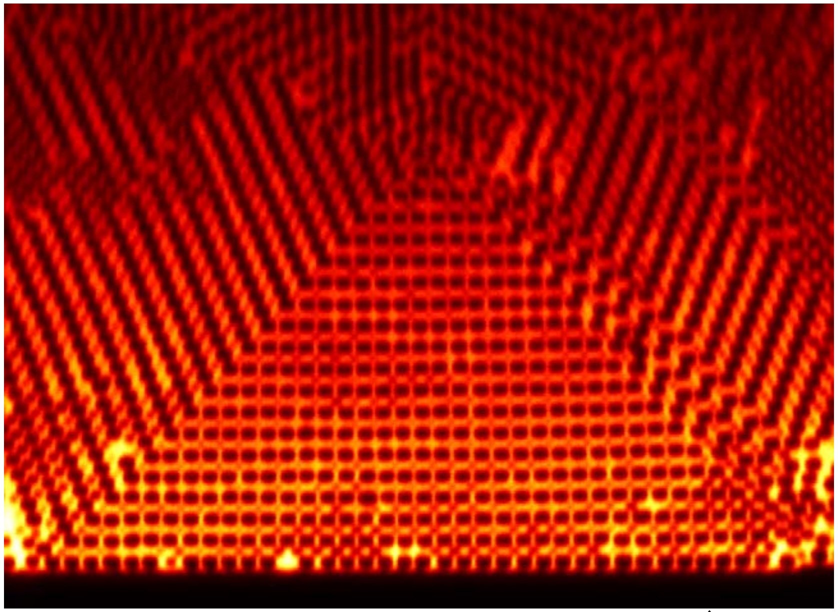


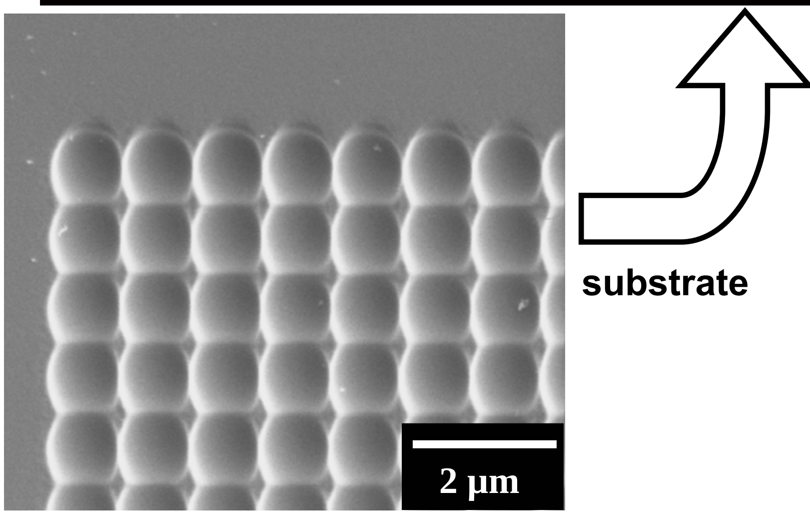


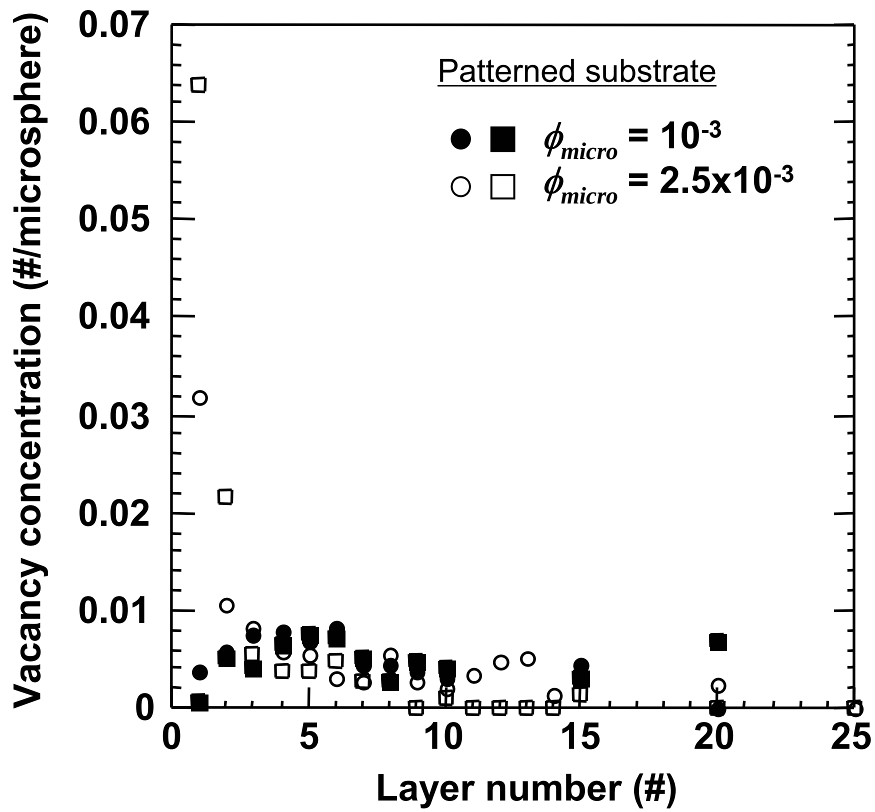
Tohver, V. *PNAS* **2001**, *98*, 8950
Tohver, V. *Langmuir* **2001**, *17*, 8414

Crystal Engineering through Substrate Engineering

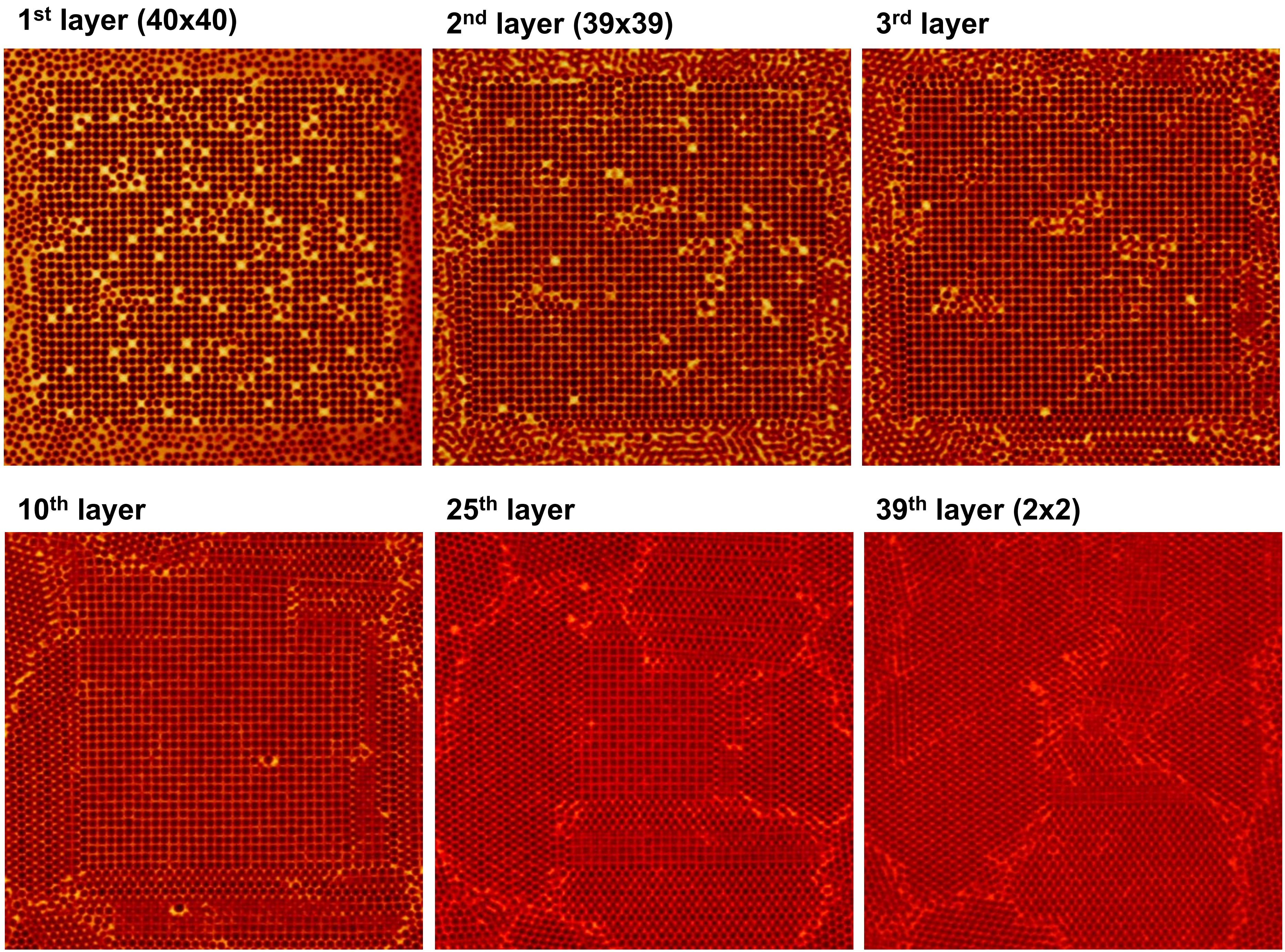
Vacancy concentration ~1 per 200 particles

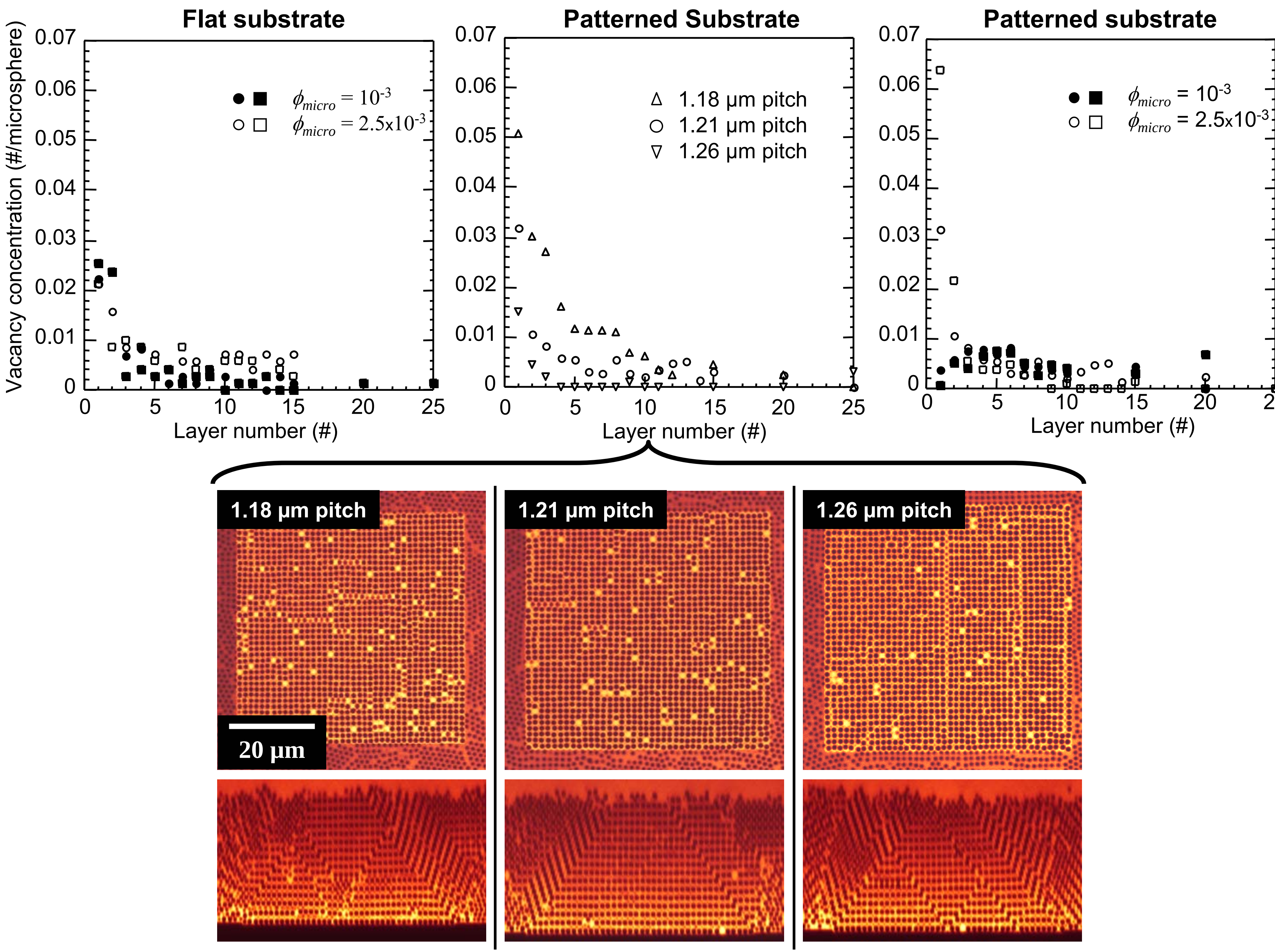






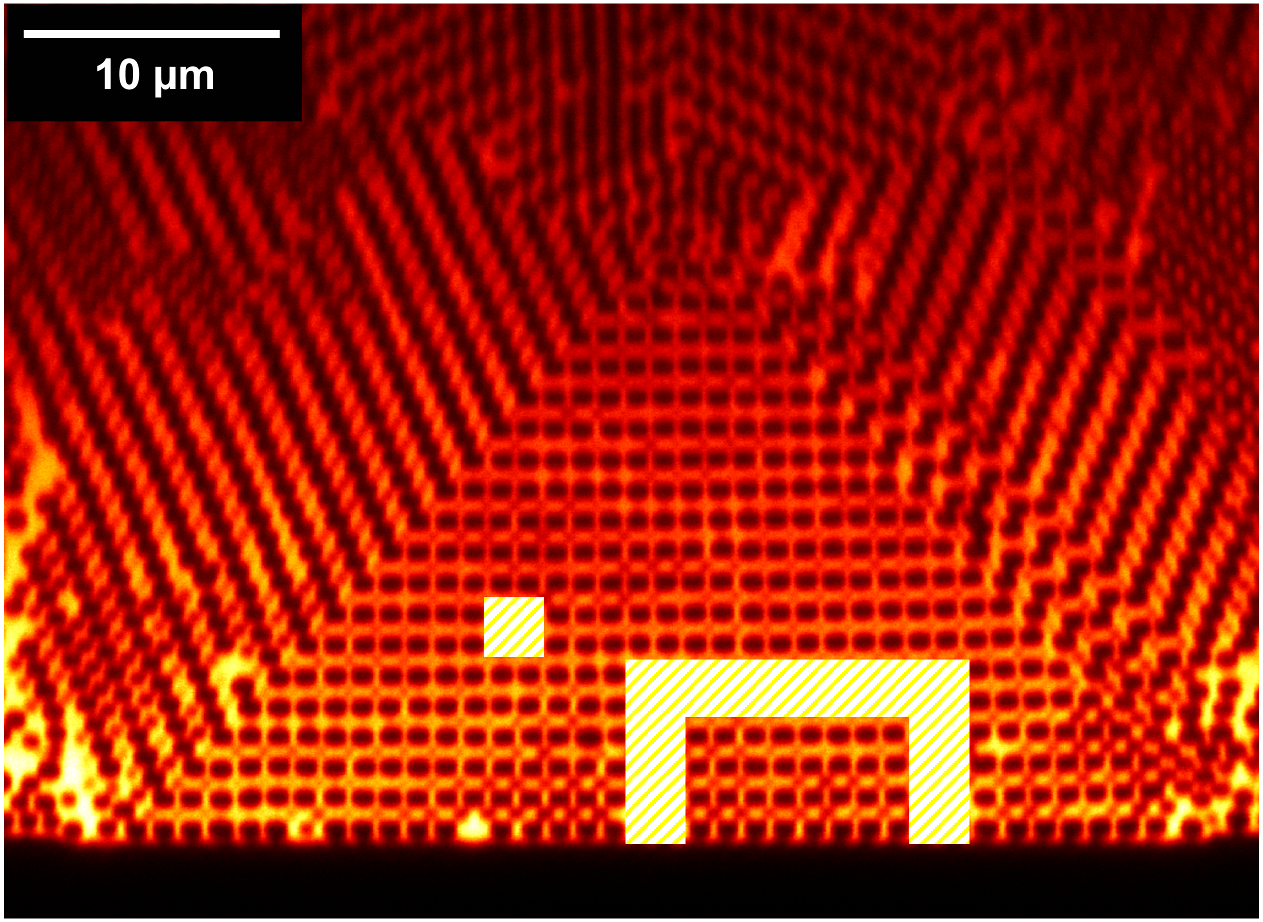
Langmuir, In press, 2004


1st layer (40x40)
2nd layer (39x39)
3rd layer
10th layer
25th layer
39th layer (2x2)



Flat substrate
Patterned Substrate
Patterned substrate
Vacancy concentration (#/microsphere)
Layer number (#)
ϕ_{micro} = 10^{-3}
ϕ_{micro} = 2.5x10^{-3}
1.18 µm pitch
1.21 µm pitch
1.26 µm pitch
20 µm

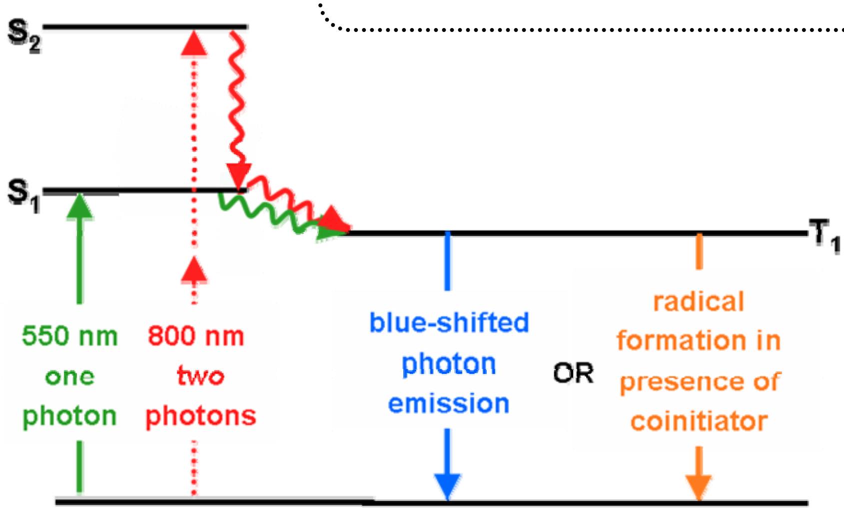
But, defined defects in colloidal crystals?



Optical cavities & Waveguides?

Two-Photon Polymerization (TPP)

Motivation: Need method for generation of embedded 3D defect features in self-assembled photonic crystals

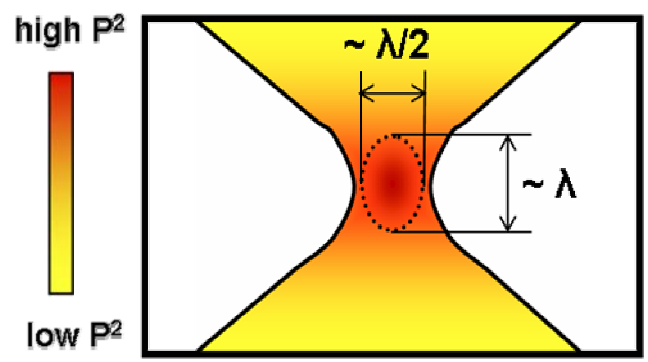


Absorption Probability $\alpha \; P^n$

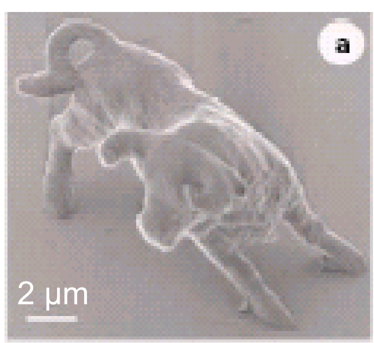
P = Laser intensity

n = Number of photons involved in the excitation process

Multi-Photon Excitation Volume $\alpha \; \lambda^3$



Photopolymerization of high-resolution three-dimensional free-form structures



S. Kawata, et al, *Nature* **2001**, *412*, 697.

System Characteristics

Beam:

Ti:Sapphire

Pulsed, mode-locked

λ = 780 nm

τ ~ 100 fs

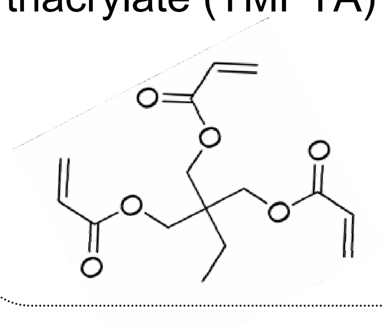
F = 82 MHz

P ~ 20-200 mW

N.A. ~ 1.32

Monomer:

Trimethylolpropane triacrylate (TMPTA)

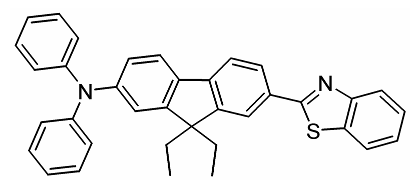


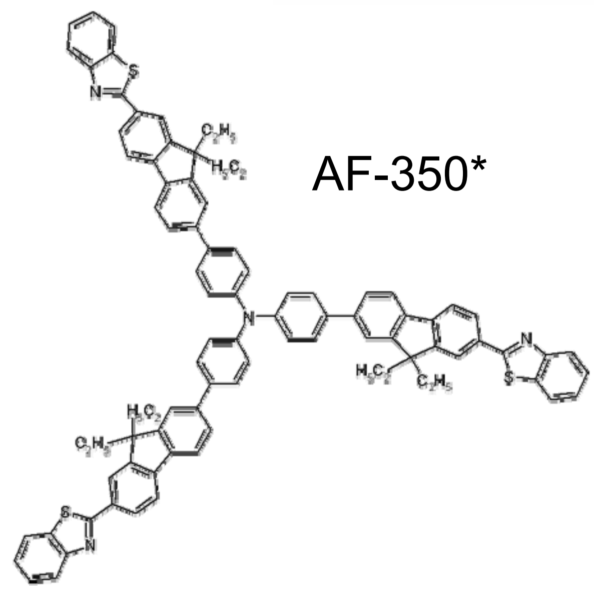
Intitiator:

σ ~ 9 x 10^{-47} cm^4 s / photon molecule

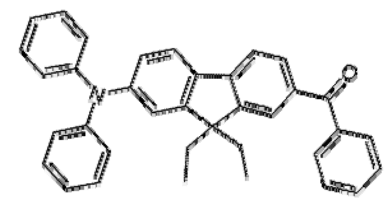
λ_{max} ~ 780 nm for two photon excitation

AF-240*





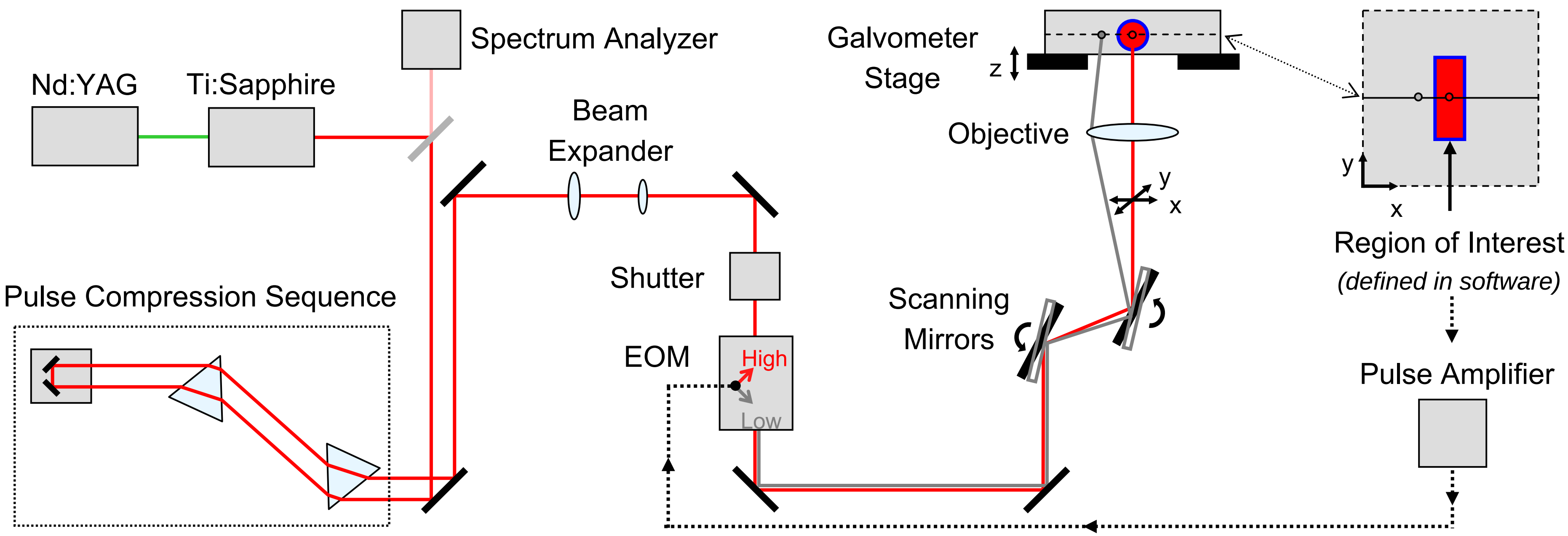
AF-350*



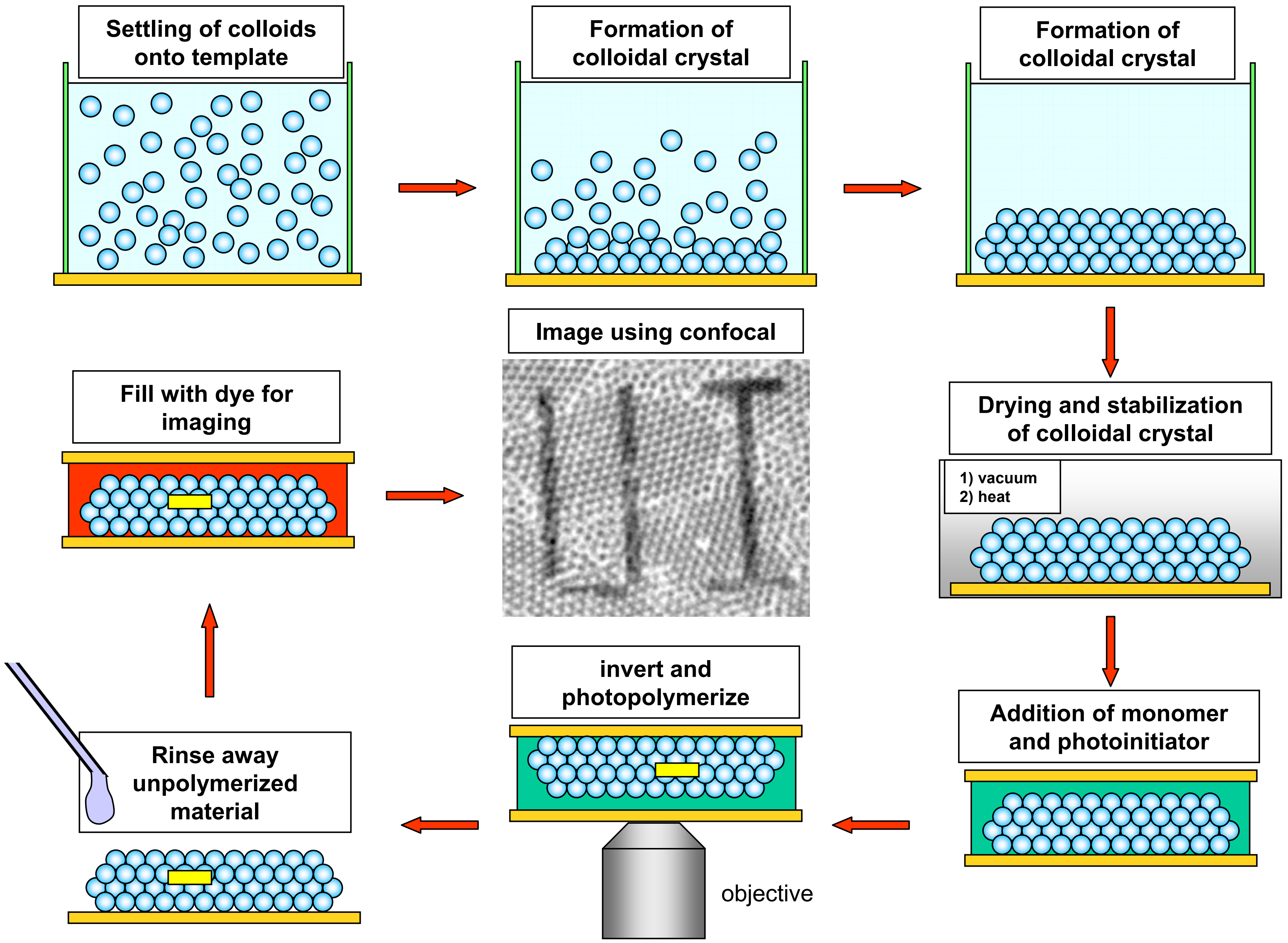
AF-270*

*Courtesy of Air Force Research Laboratory (e.g. R. Kannan et al. *Chem. Mater.* **2001**, *13*, 1896-1904)

Optics for Multiphoton Polymerization



3-D Pattern Formation in Colloidal Crystals – Procedure

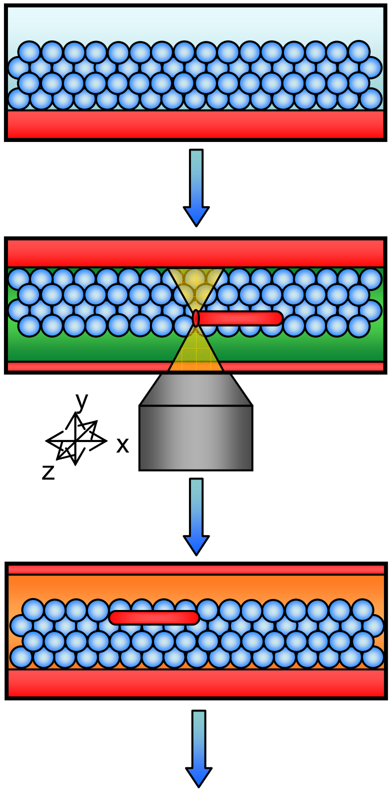


Imaging of Templated Multiphoton Written Polymers

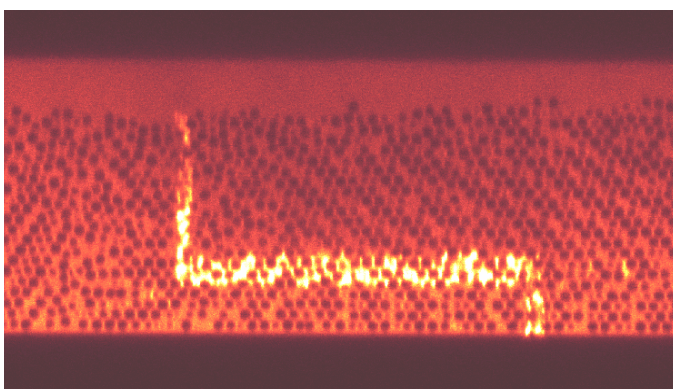
Sedimentation of colloidal crystal

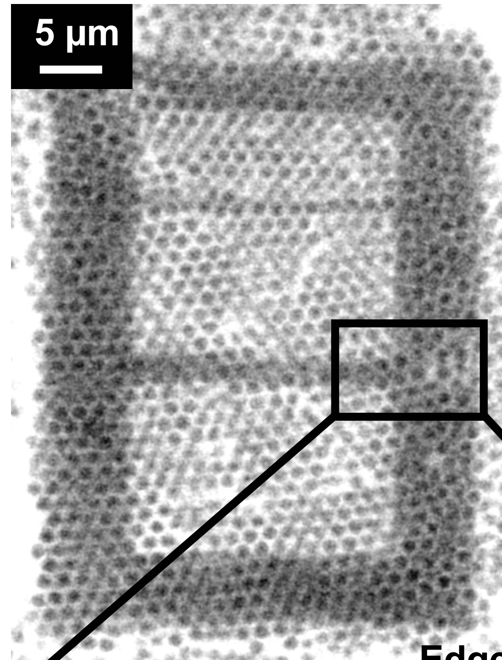
Multi-photon polymerization

Remove unpolymerized materials



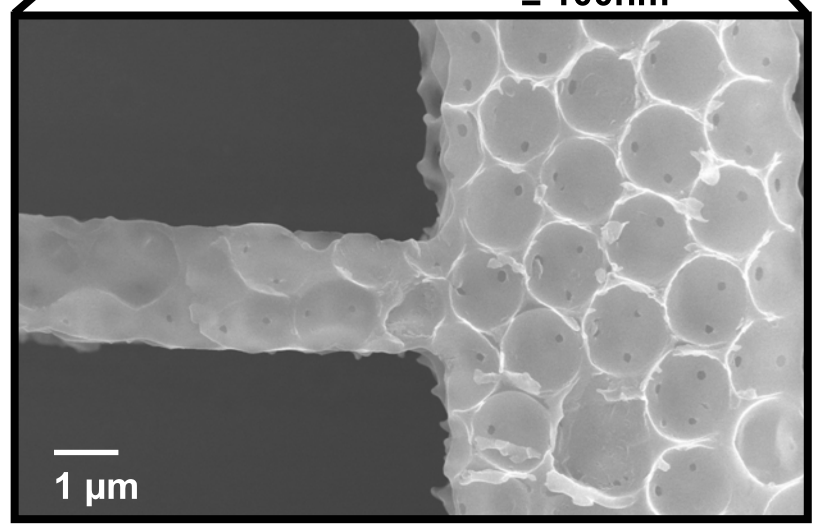
LSCM, side view





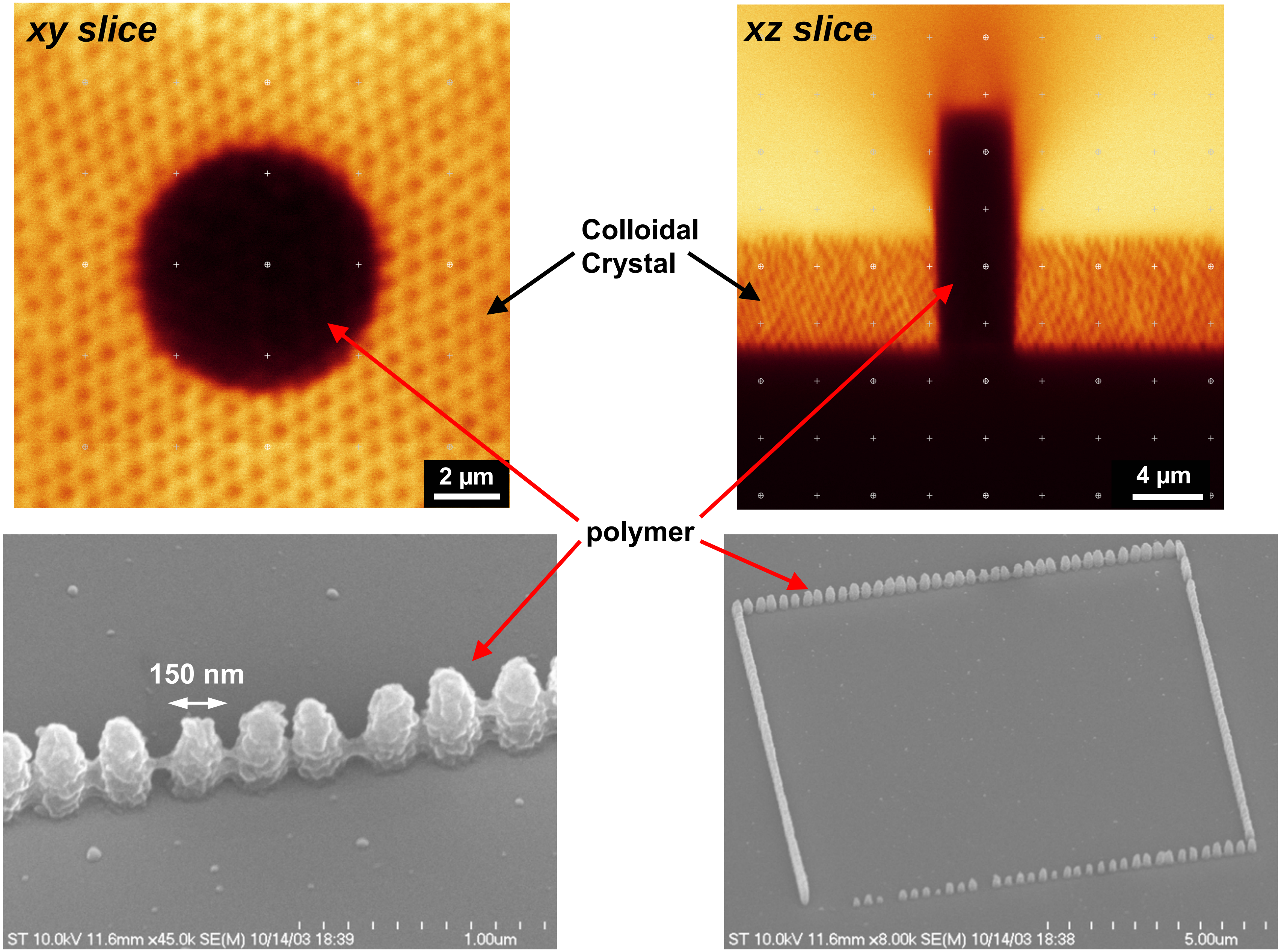
LSCM, top view

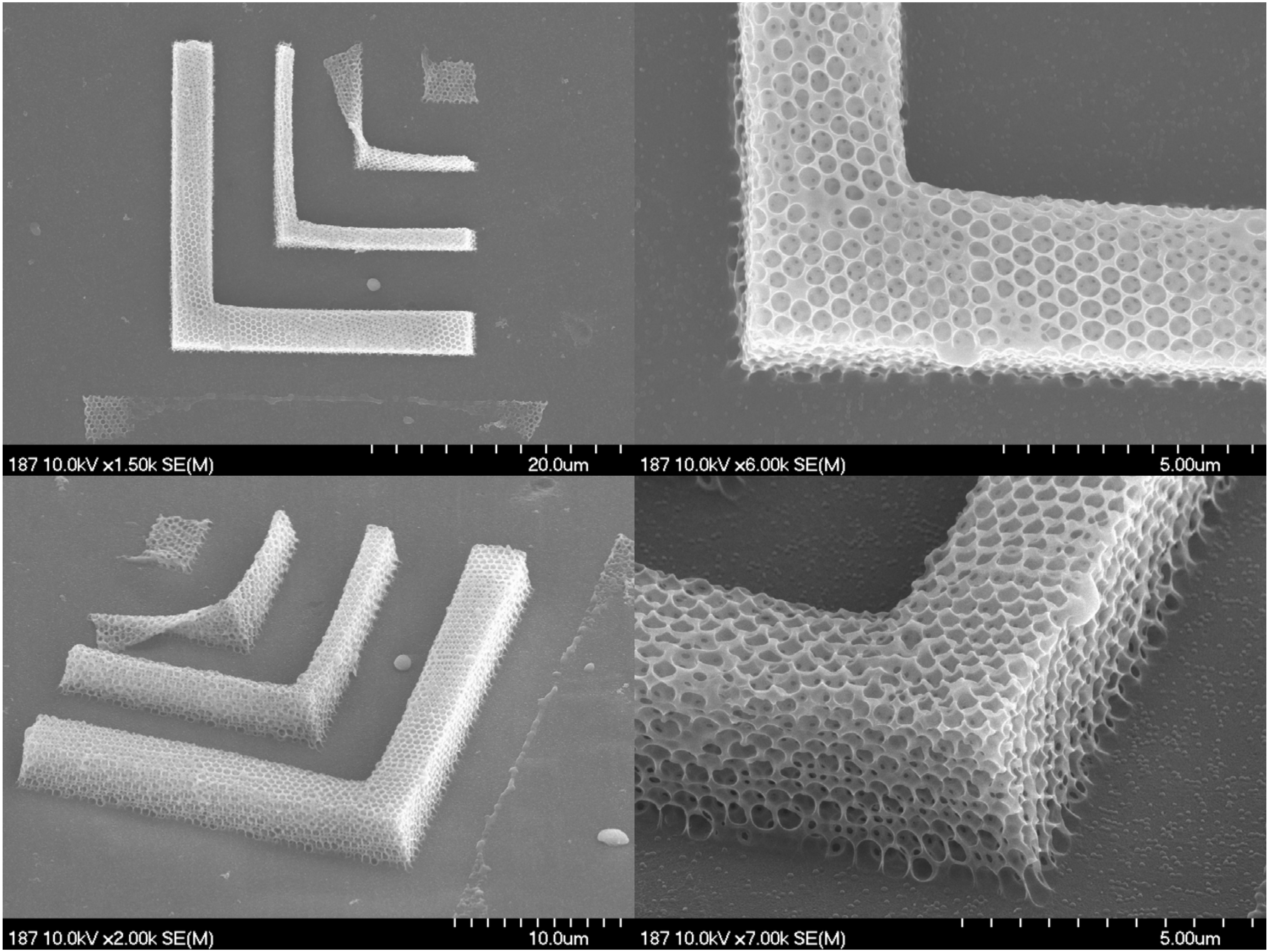
SEM
Edge resolution
≤ 100nm



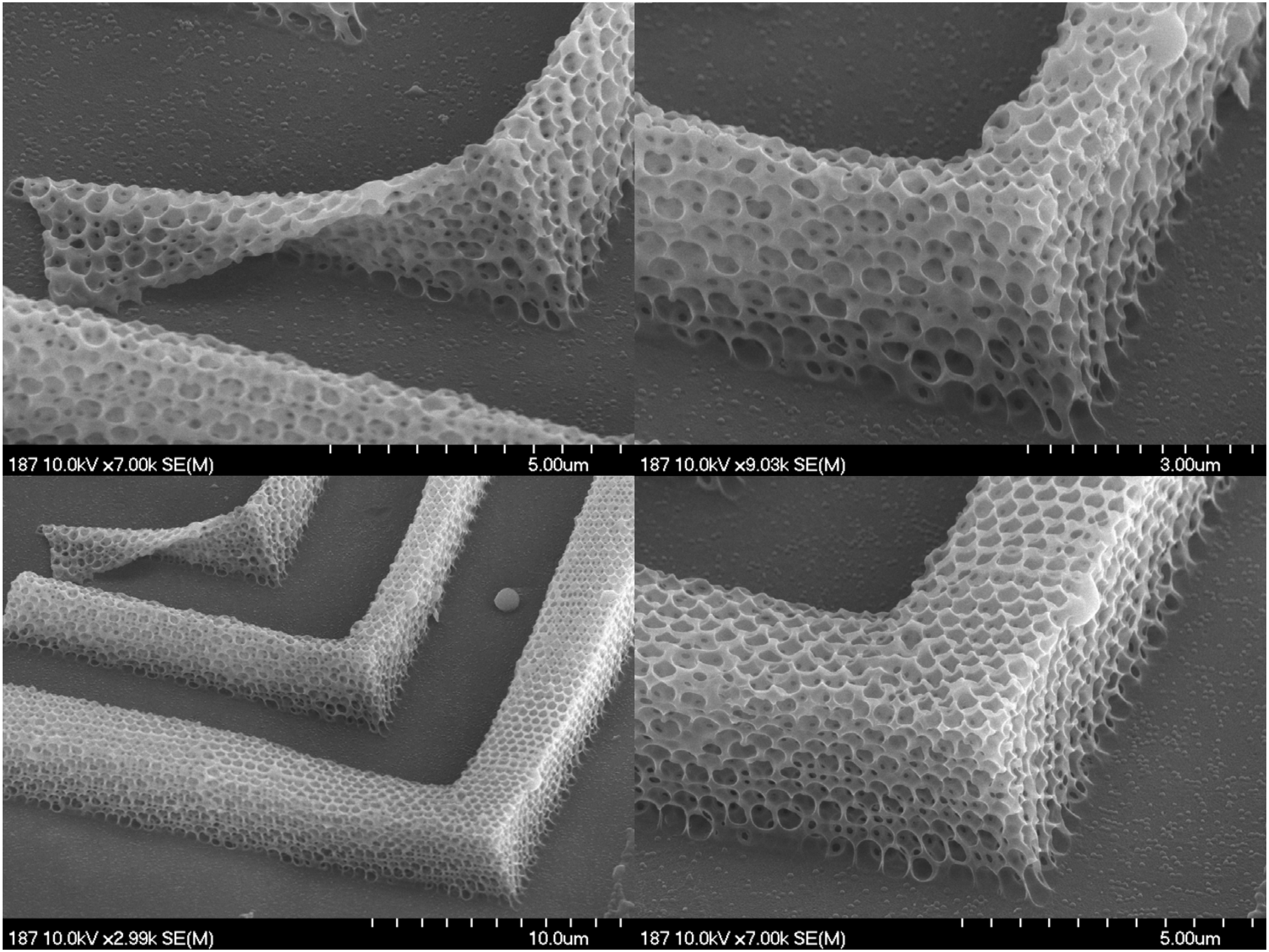
W. Lee, S. A. Pruzinsky, P. V. Braun,
Adv. Mater. **2002**, *14,* 271.

2-photon Polymerization in and out of Colloidal Crystals

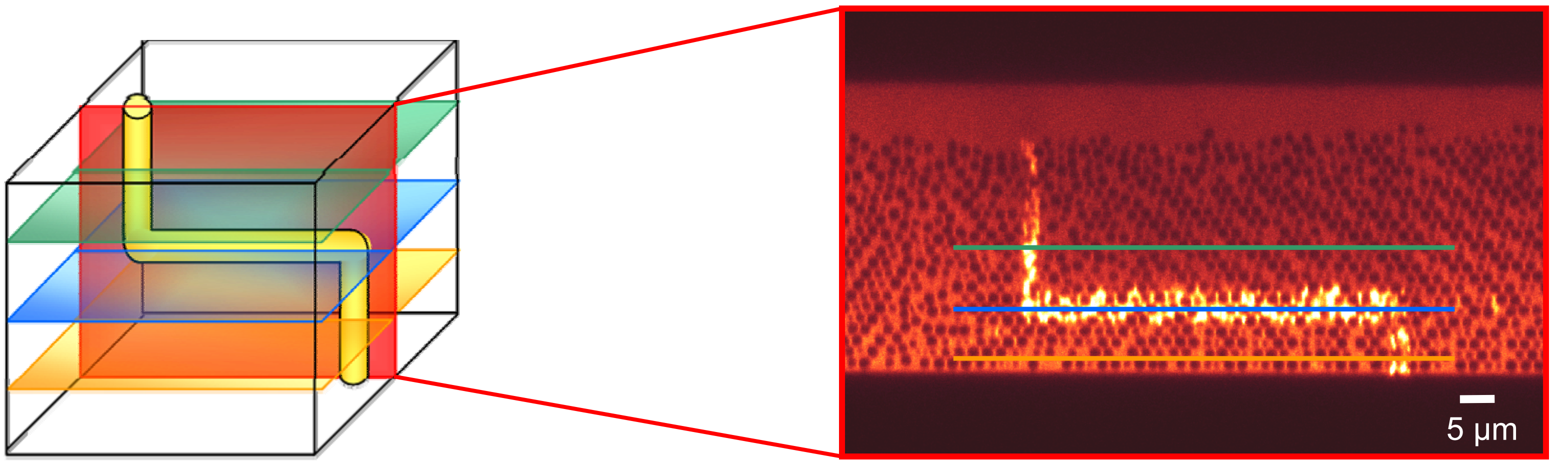


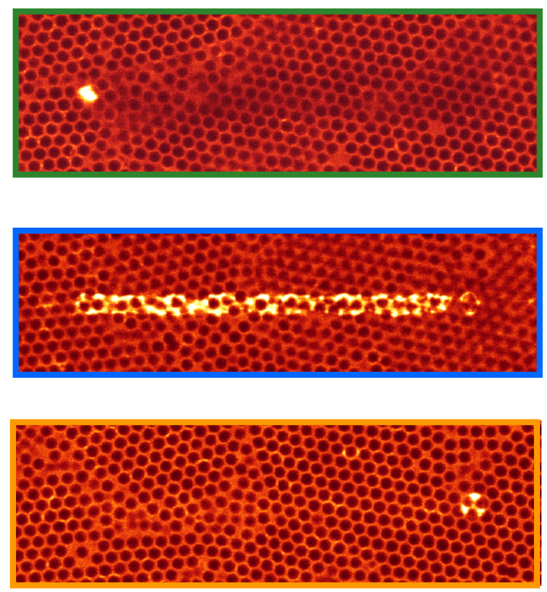


187 10.0kV x1.50k SE(M)
20.0um
187 10.0kV x6.00k SE(M)
5.00um
187 10.0kV x2.00k SE(M)
10.0um
187 10.0kV x7.00k SE(M)
5.00um


187 10.0kV x7.00k SE(M)
5.00um
187 10.0kV x9.03k SE(M)
3.00um
187 10.0kV x2.99k SE(M)
10.0um
187 10.0kV x7.00k SE(M)
5.00um

Embedded Waveguide Structure Fabrication





Successful fabrication of embedded waveguide structures in self-assembled photonic crystals!

Press Reports:

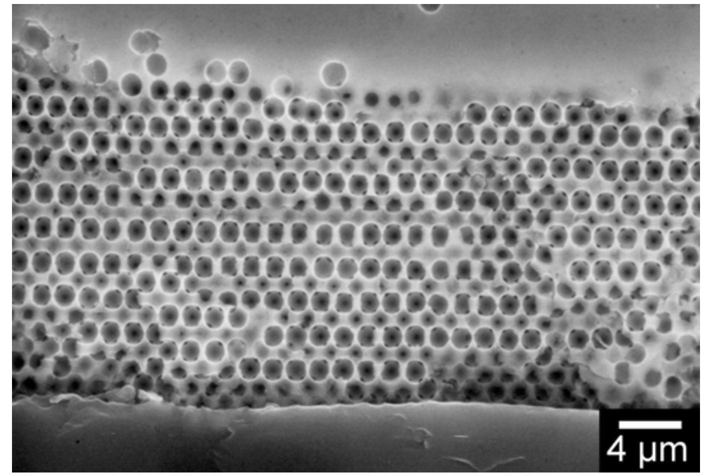
R.F. Service, *Science.* **2002**, *295*, 2399.

T.A. Taton, D.J. Norris, *Nature.* **2002**, *416,* 685.

W. Roush, *Technology Review.* **2002**, *105*, 22.

Selenium – a High Refractive Index Filler

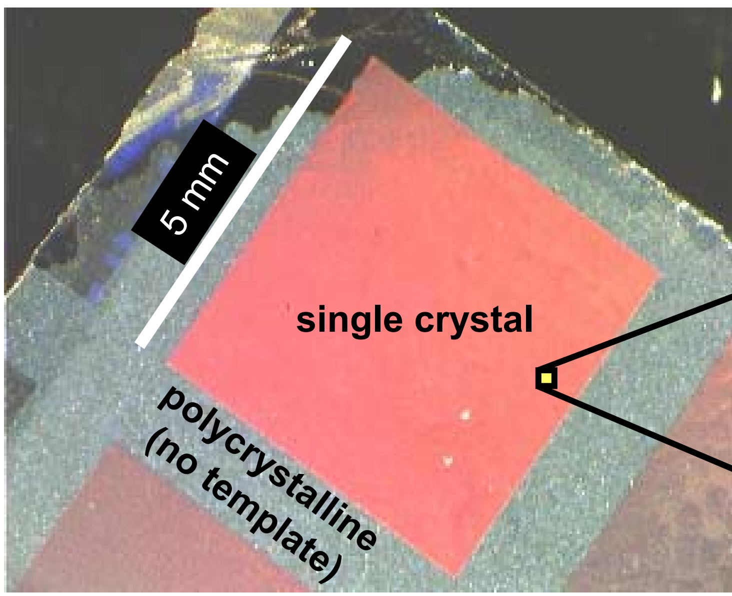
Selenium photonic crystal



011 face

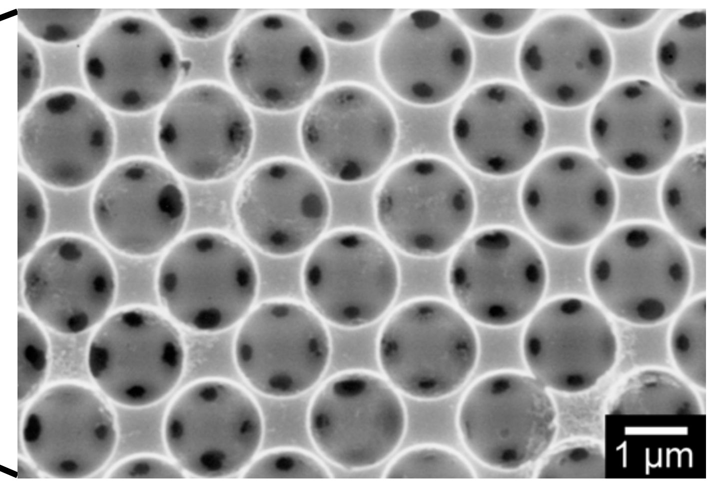
<u>Results in high refractive index contrast, highly oriented photonic band gap materials</u>

True fcc colloidal crystal created by settling on a patterned substrate. The colloidal crystal nucleates and grows perpendicular to the 001 face, therefore no stacking faults form.



1.6 µm silica colloid settled on a 1.66 µm template. Index matched with DMF (n ~ 1.43). White light illumination

After selenium imbibing and removal of colloidal template

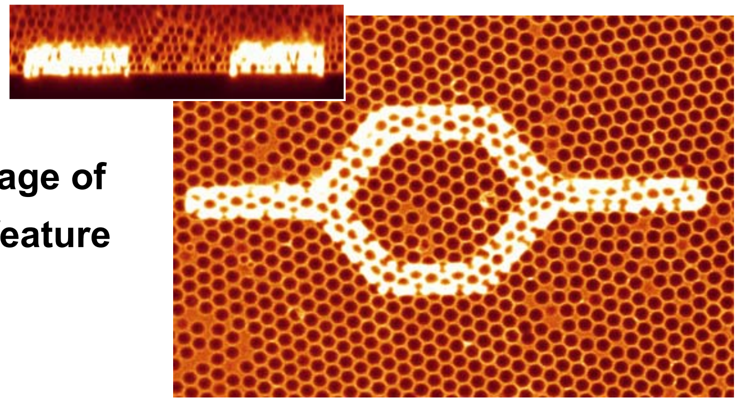


001 face

P. V. Braun, *et al. Adv. Mater.* **13,** 721-724 (2001)

Dielectric contrast enhancement: Melt Imbibing of Selenium

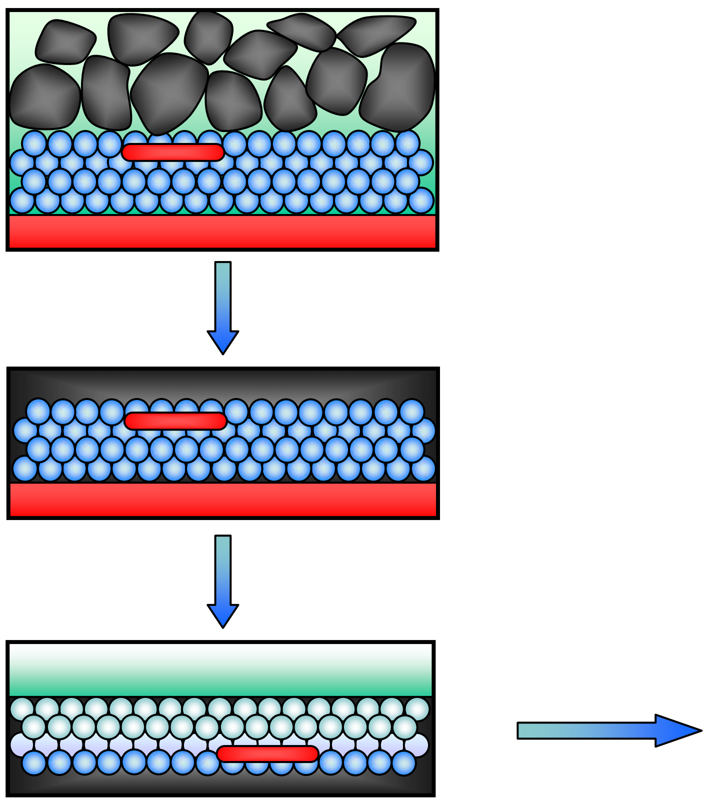
LSCM image of polymer feature

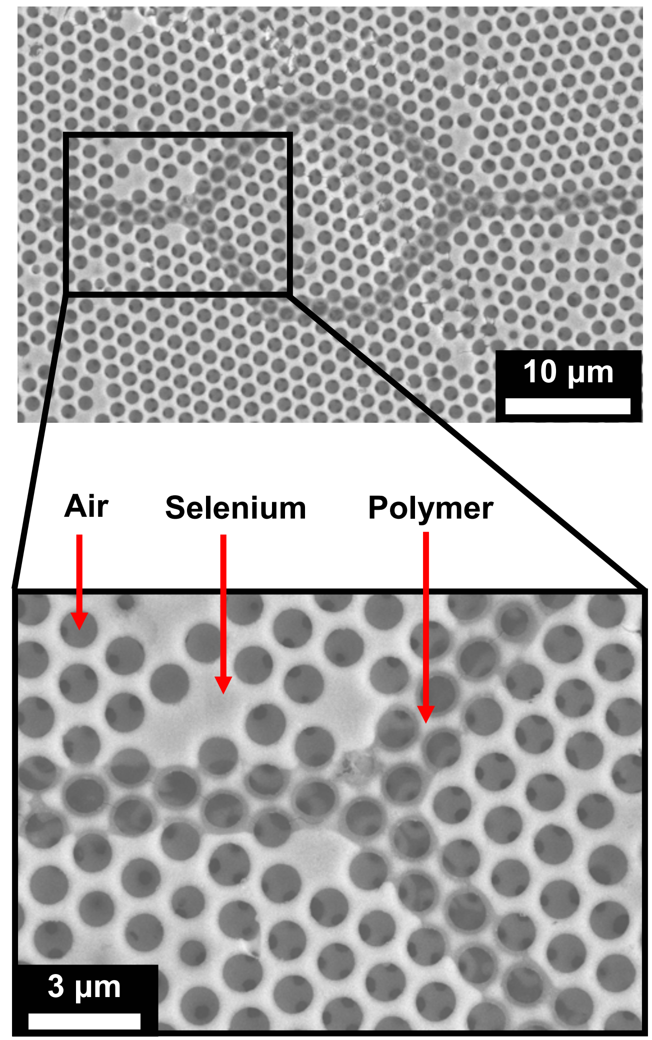


Melt selenium (~250 C)

Pressurize

Etch silica (HF)

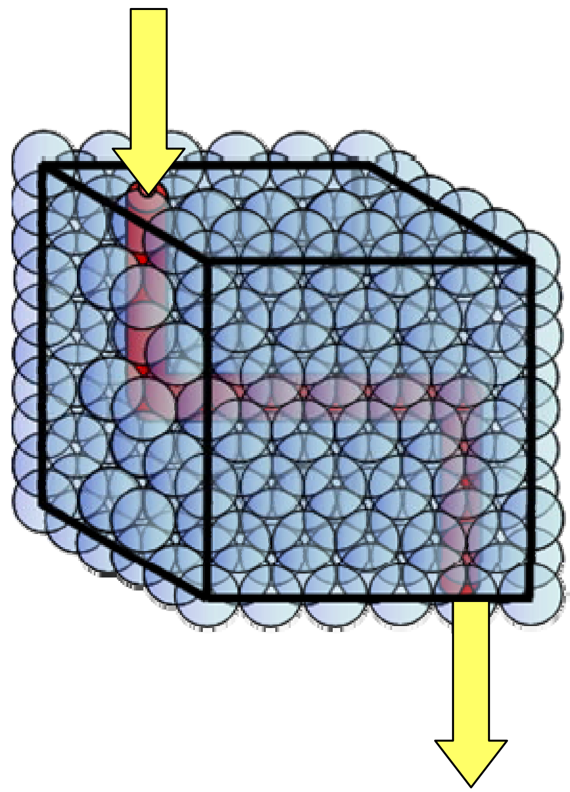




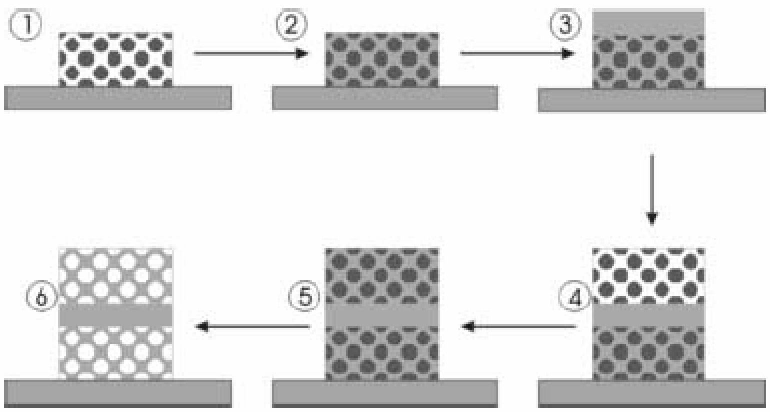
Next Step

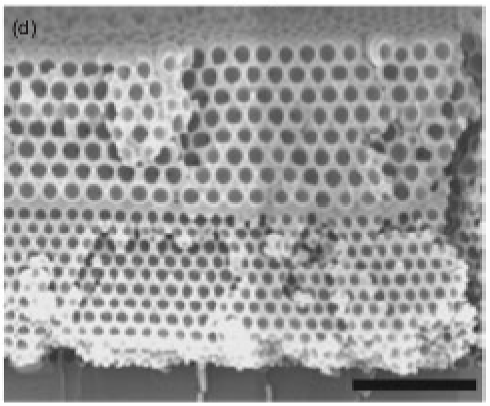
Characterization of transmission

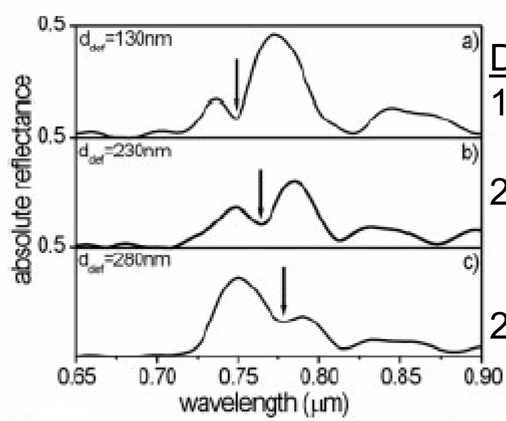
through embedded waveguides



Inserted Planar Defects in Colloidal Crystals







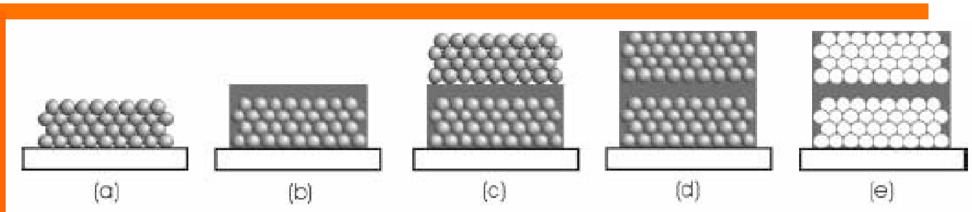
Defect thickness

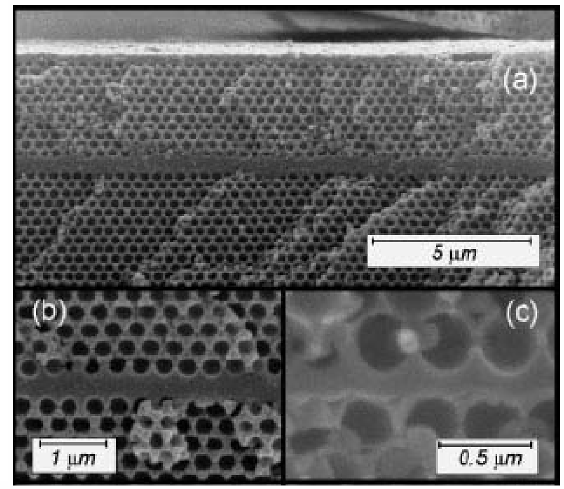
130 nm

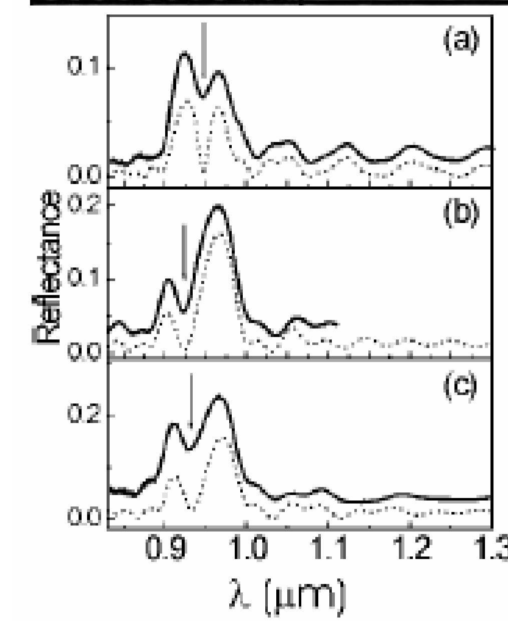
230 nm

280 nm

C. López, *et al.*, *Adv. Mater.* **2004**

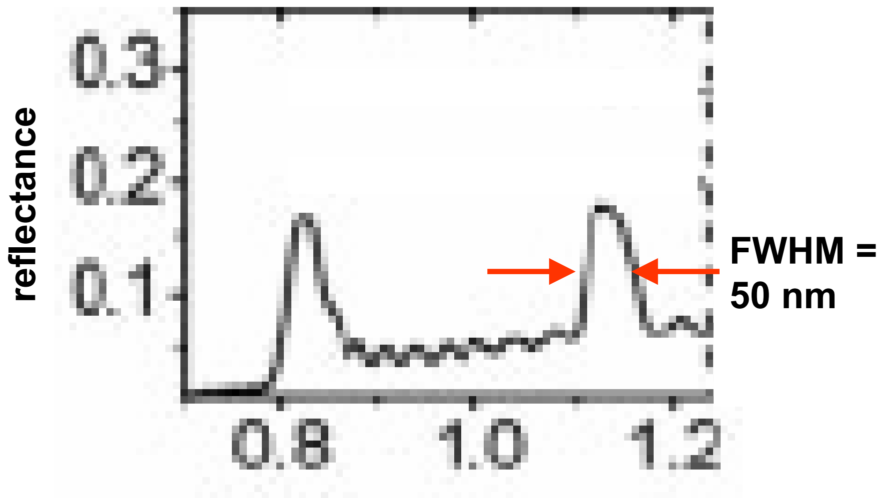


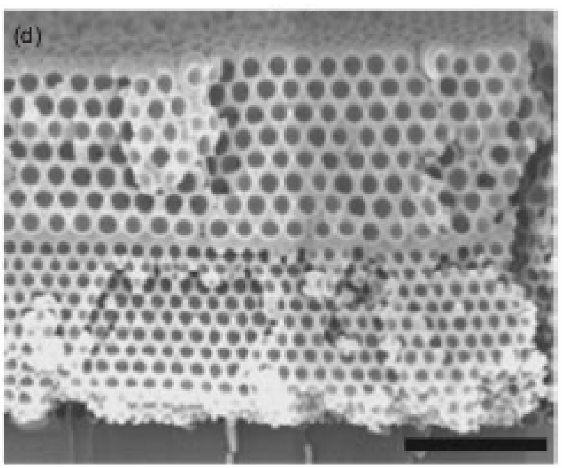


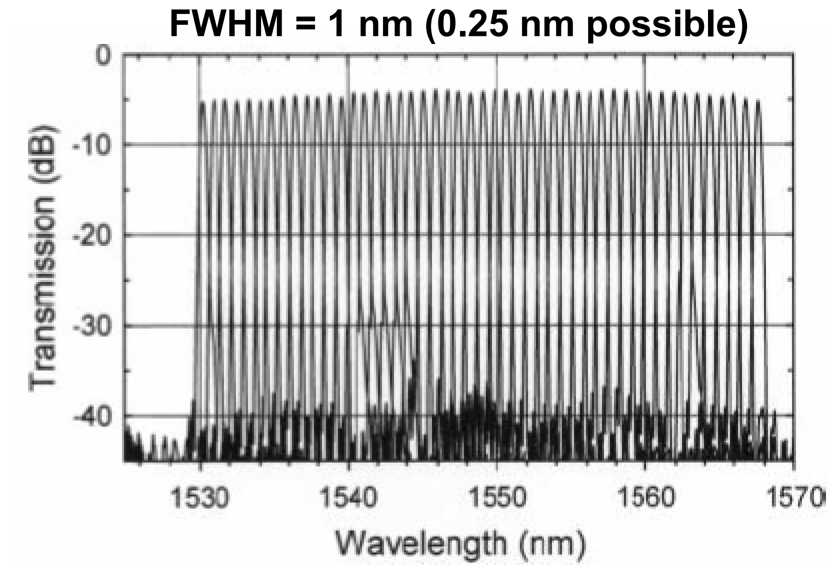


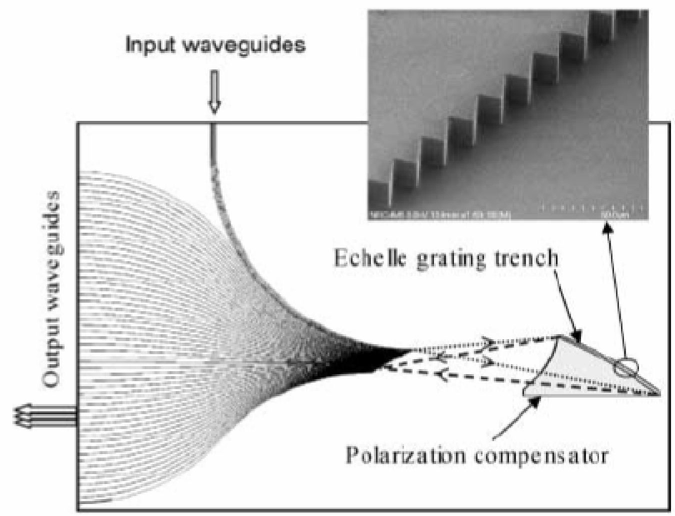
N. Tétreault, *et al.*, *Adv. Mater.* **2004**

Integrated Photonics?









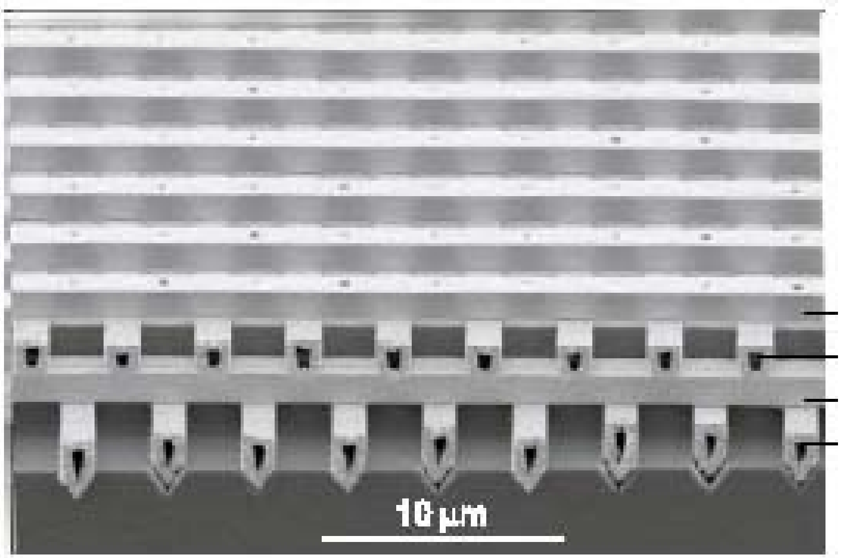
48-channel echelle grating demultiplexer chip.

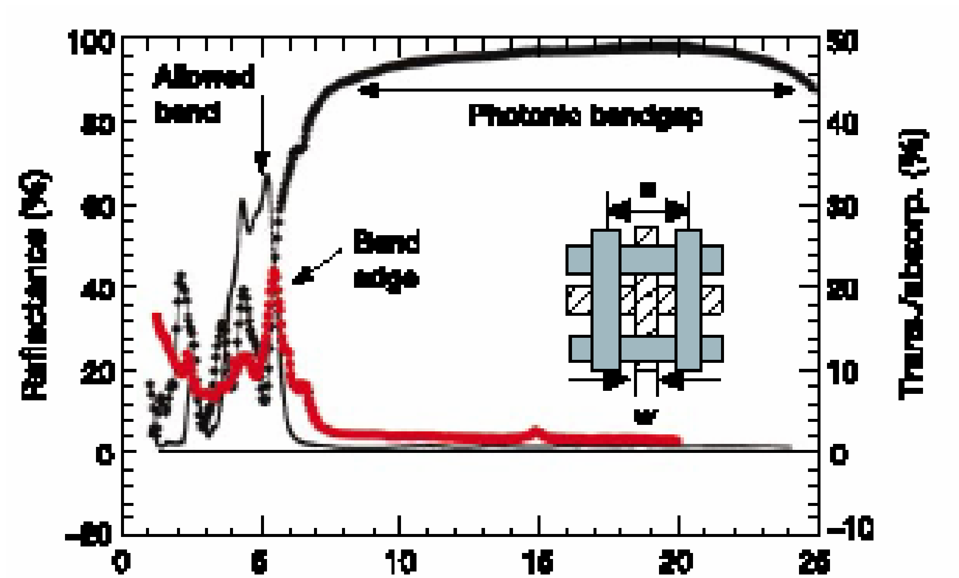
C. López, *et al.*, *Adv. Mater.* **2004**

Siegfried Janz, *Topics Appl. Phys.* **94**, 323 (2004)

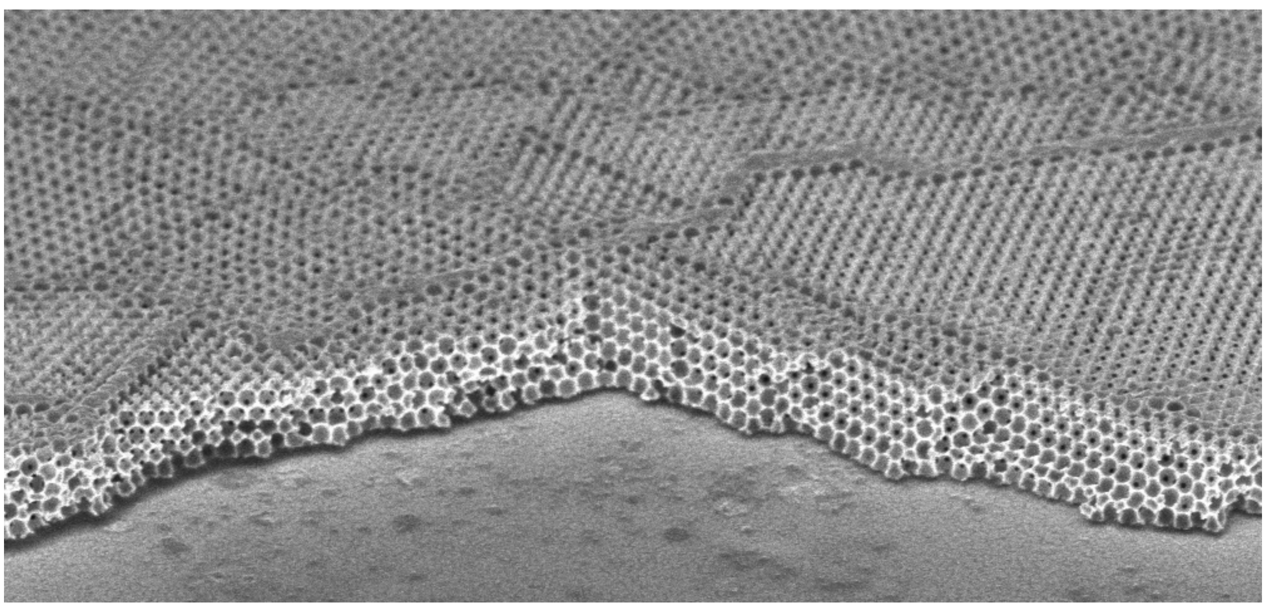
Metallic Photonic Crystals

Enhance blackbody emission?



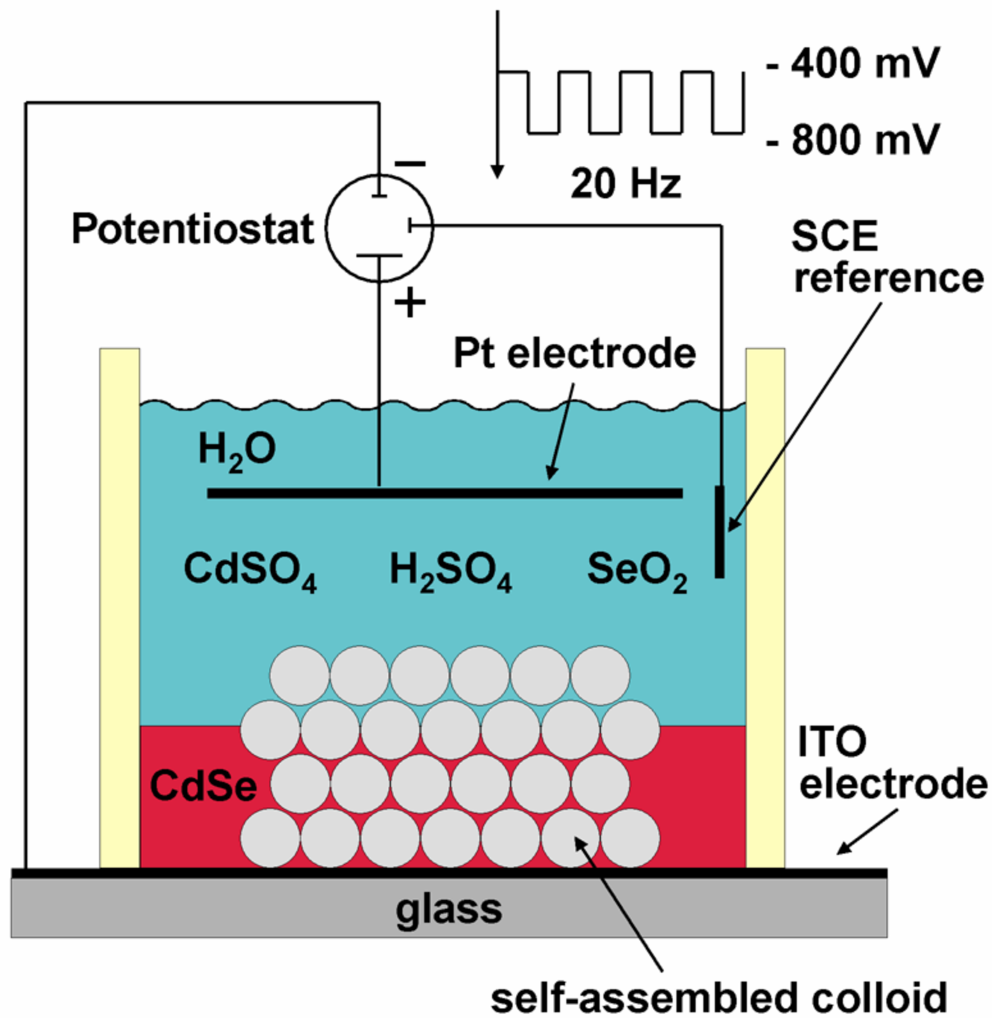


S. Y. Lin, Nature 2002

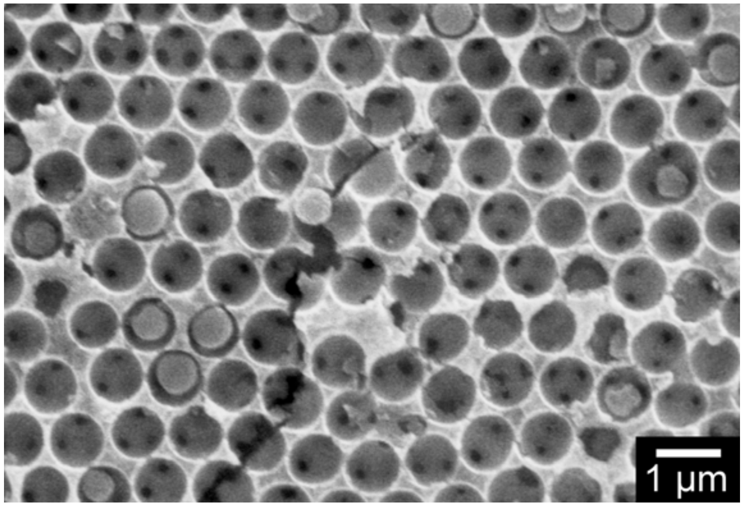


Electrodeposited Ni inverse Opal
Templated by 466 nm PS spheres
Yun-Ju Lee, P. V. Braun unpublished

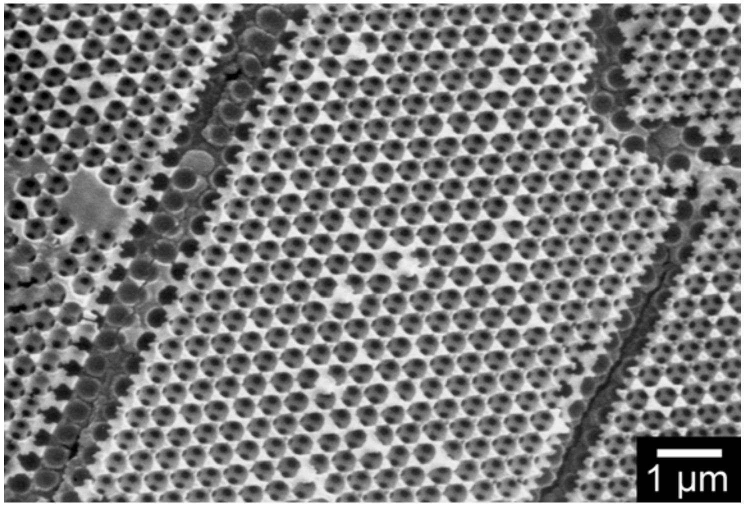
Electrodeposition of Photonic Crystals



After semiconductor electrodeposition, the colloidal particles are removed via solvent



CdS

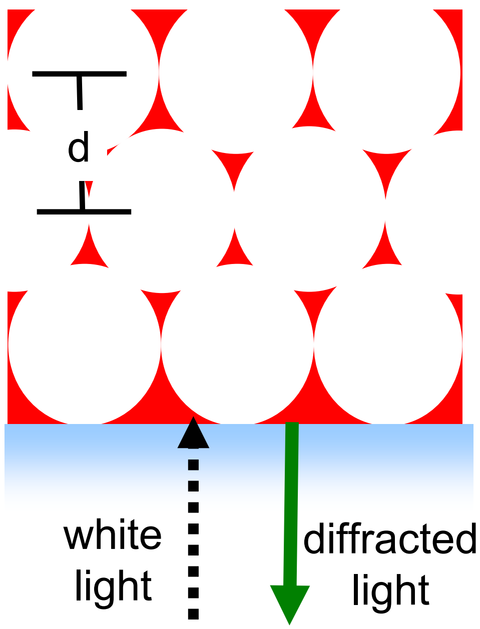


CdSe

Braun and Wiltzius, *Nature* 1999

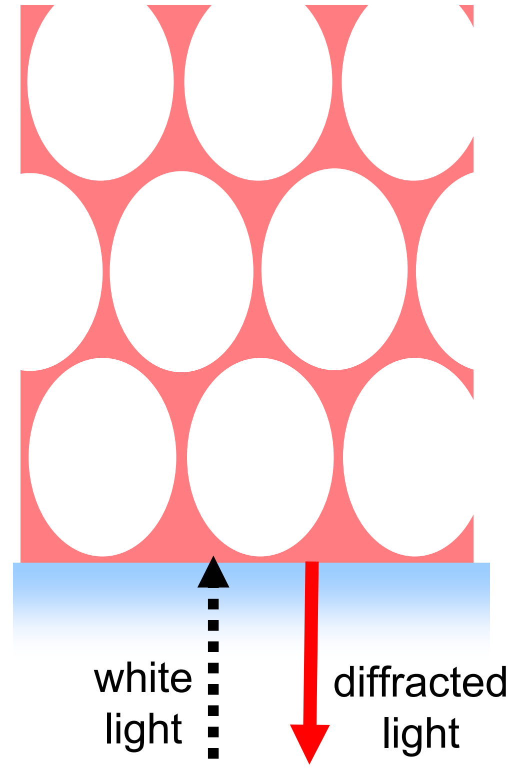
Self-Assembled Chemical Sensors: Polymeric Photonic Crystals

Note: See lectures by Prof. Sandy Asher
Pioneered the field



<u>Possible Stimulus</u>
pH
Ionic strength
Solvent
Binding

$\Delta\lambda$ a function of
Δd
Δn
ΔV



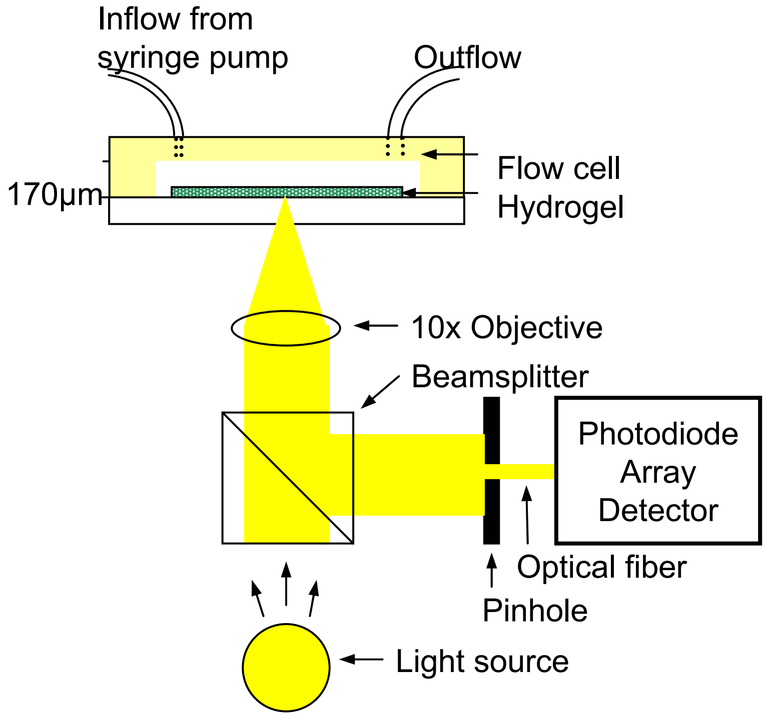
Because $\Delta\lambda \sim \Delta d$, swelling enables sensing

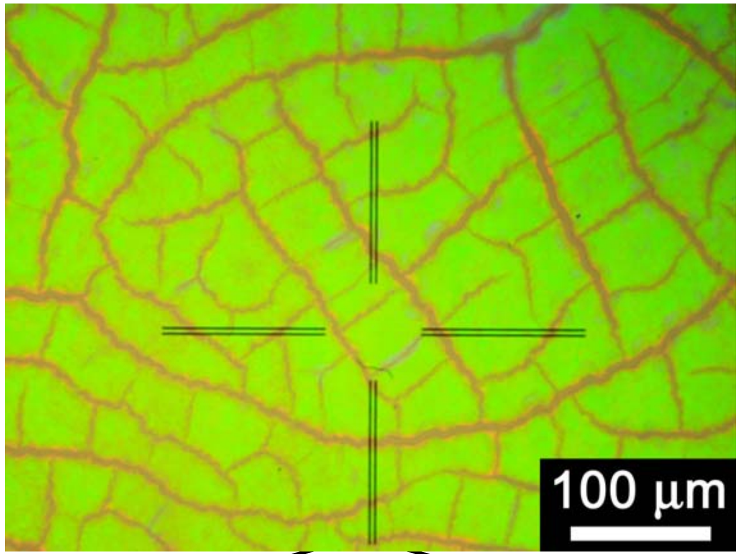
$$\lambda = 2dn_{eff} \cong 2d\left(\sum_i n_i^2 V_i - \sin^2\phi\right)^{1/2}$$

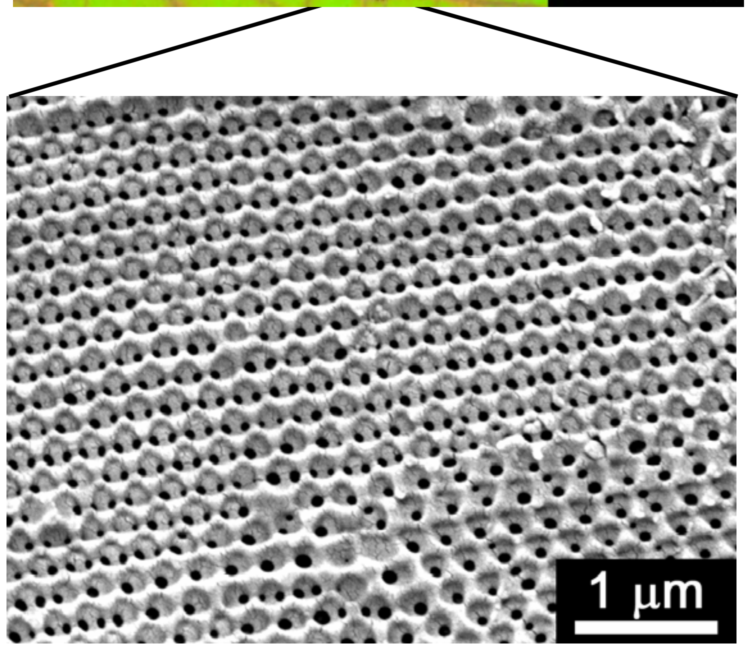
d = interlayer distance
n_i = refractive index of component i
V_i = volume fraction of component i
ϕ = angle between incident beam and sample normal

Polymerization of Templated Hydrogels

1. Assemble colloidal crystal in flow cell
2. Infiltrate with monomer mixture
3. UV irradiate (356 nm, 50 min)
4. $CHCl_3$ etch (24 hours)
5. Solvent exchange
6. Structural and optical characterization



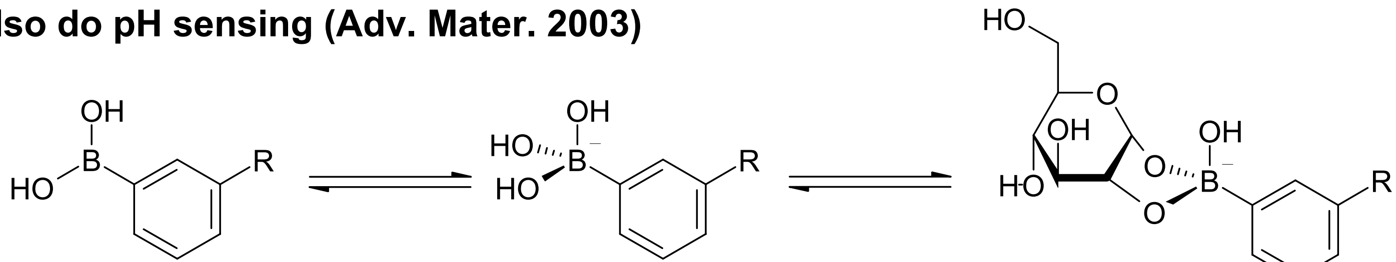




Y.-J. Lee and P.V. Braun, *Adv. Mater.* **2003**, 15, 563
Y.-J. Lee , S. A. Pruzinsky, P.V. Braun, *Langmuir*, in press

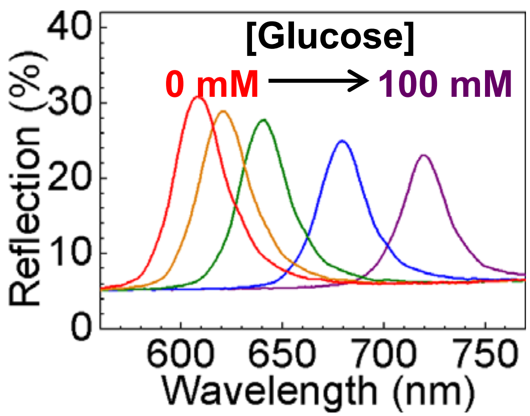
Glucose Sensing with Mesoscale Photonic Crystals

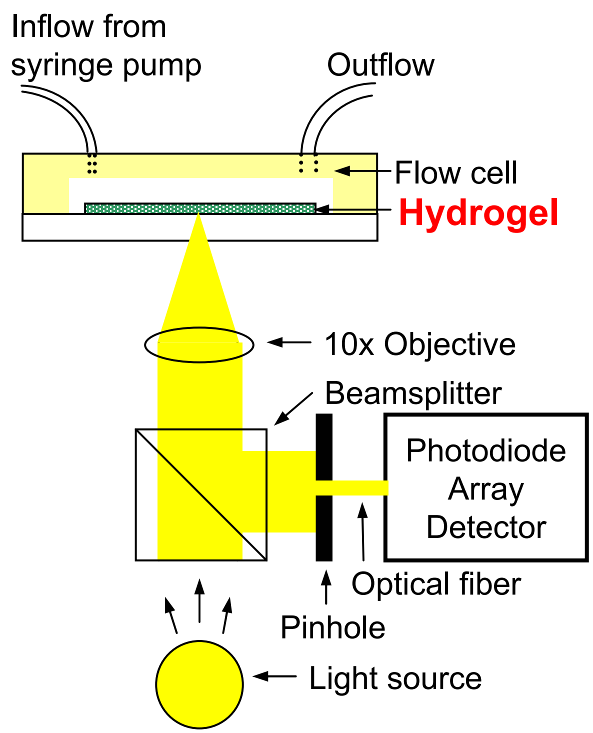
Can also do pH sensing (Adv. Mater. 2003)

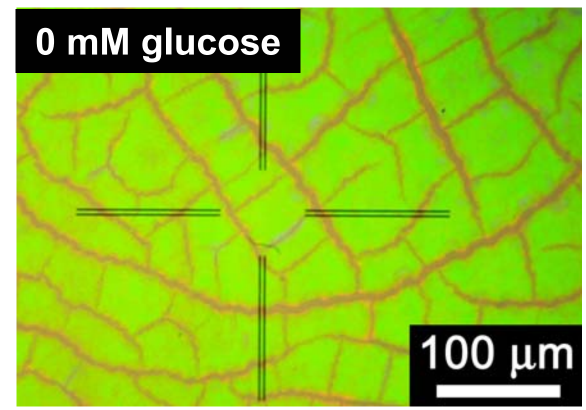


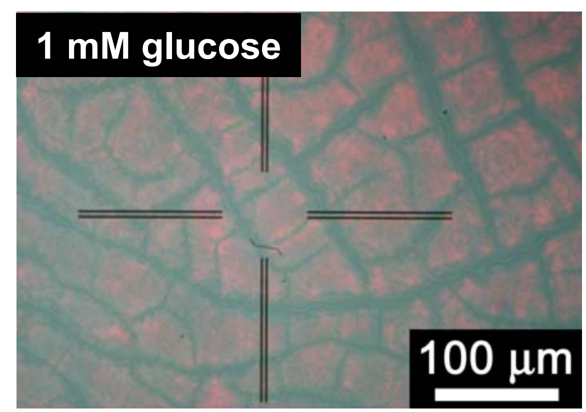
PBA (phenylboronic acid)

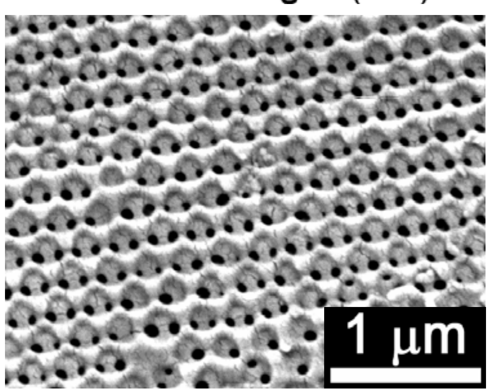
Glucose-PBA complex









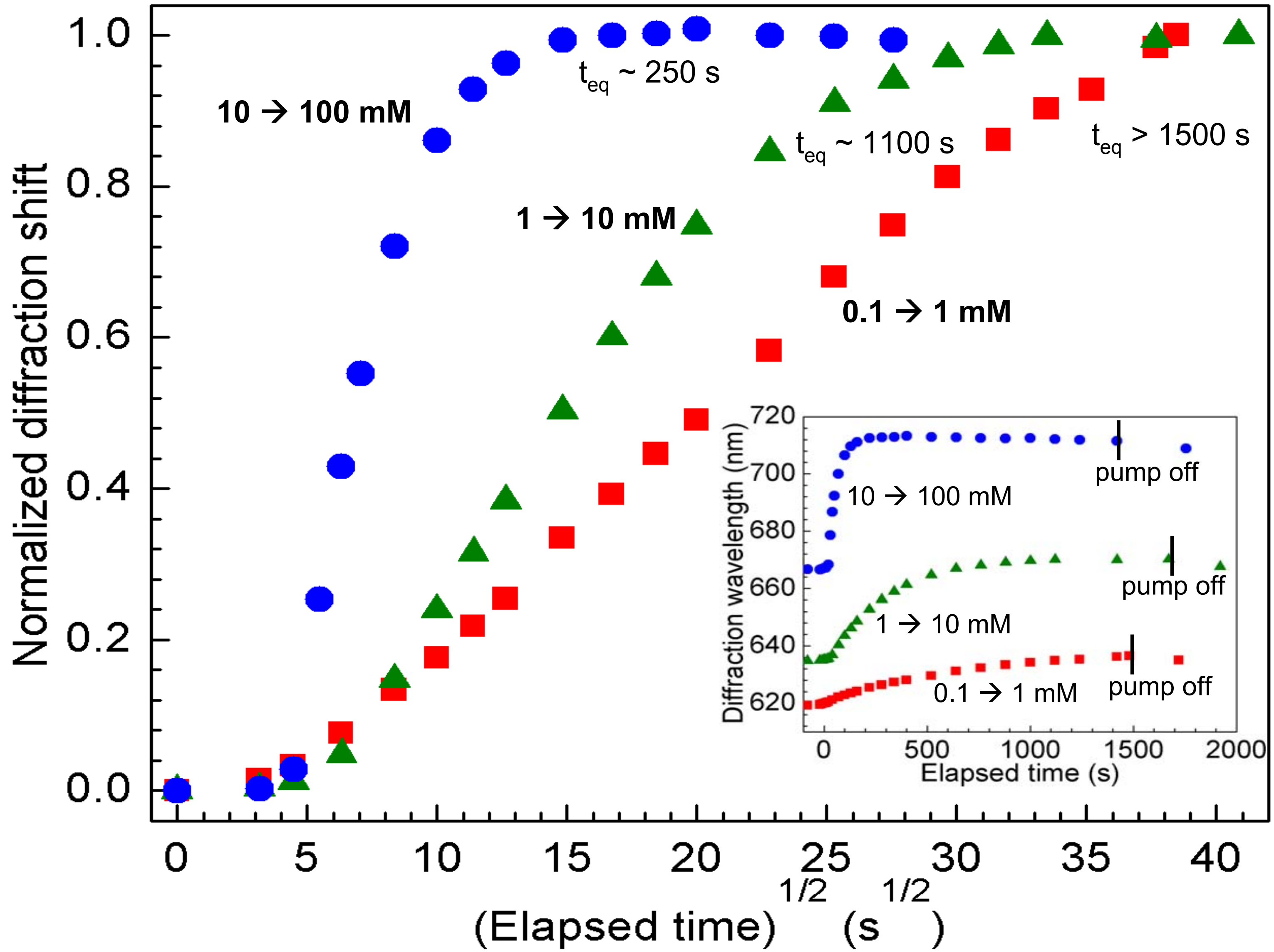


SEM of templated hydrogel

Y.-J. Lee *et al. Langmuir*, 2004

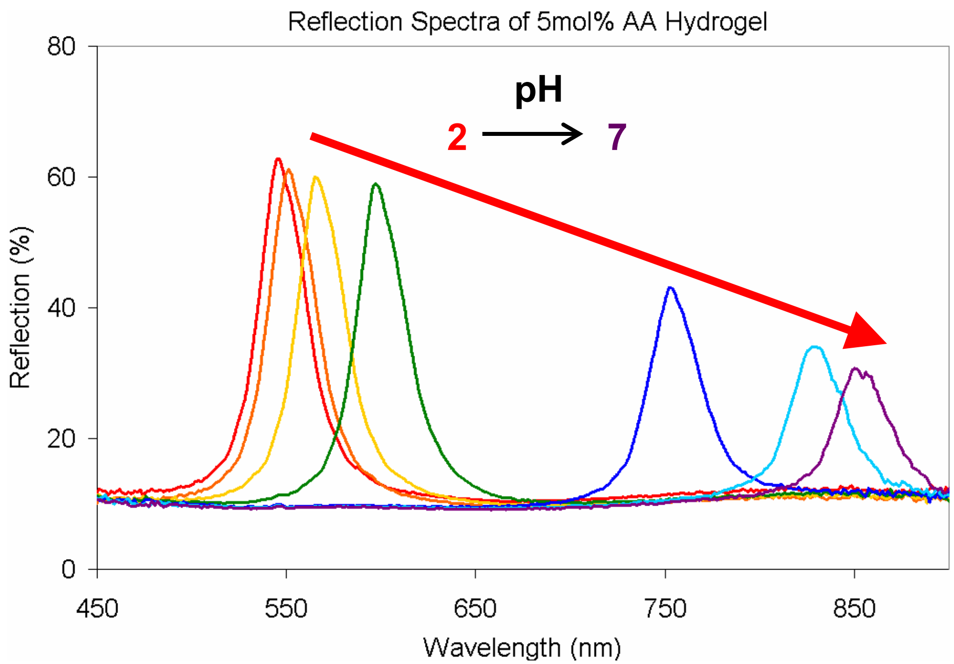
Kinetics of Glucose Sensing

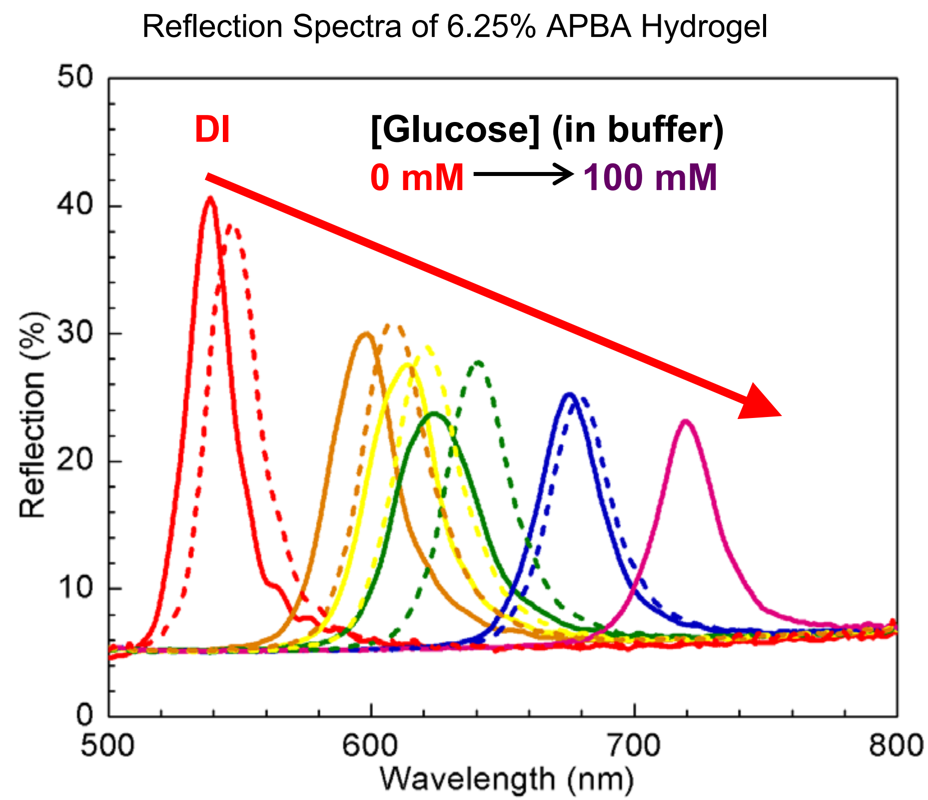
Increasing [Glu] Diffraction Shift Kinetics



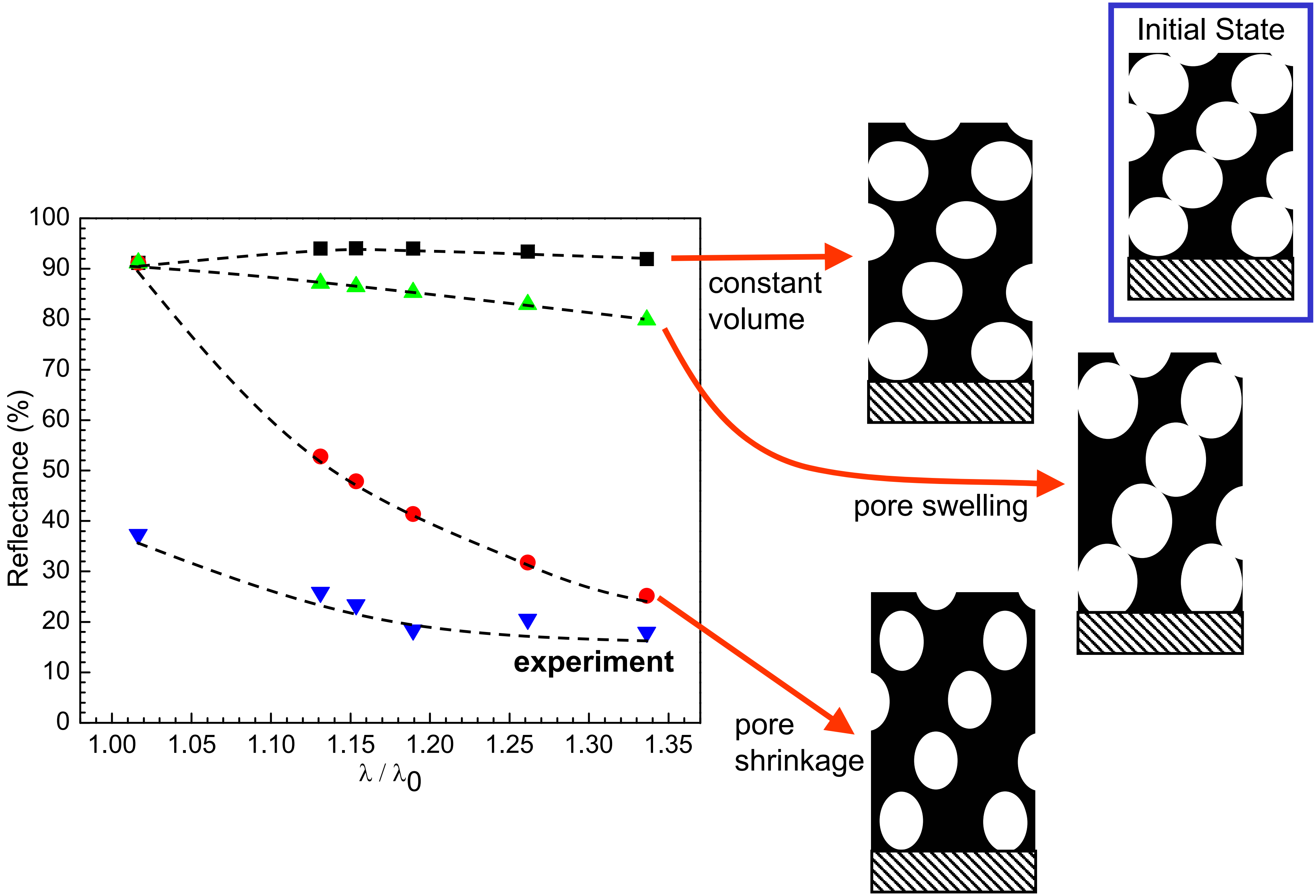
Dramatic Decrease in Diffraction Efficiency with Swelling

WHY?



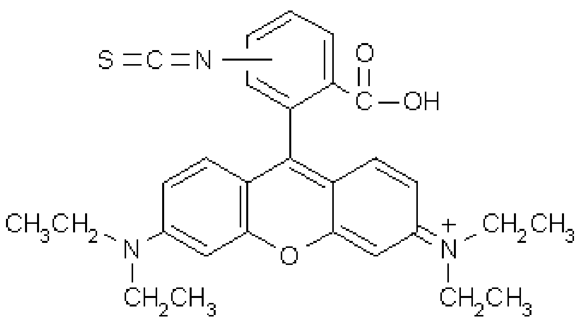


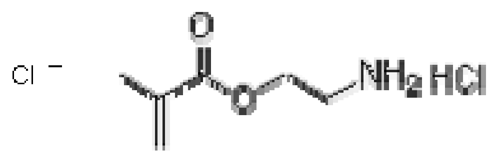
Simple Models for Hydrogel Swelling → Diffraction Response



Confocal Imaging of Inverse Opal Hydrogels

1. Synthesize Acrylated Rhodamine B
   Rhodamine B-ITC + 2-Aminoethylmethacrylate·HCl

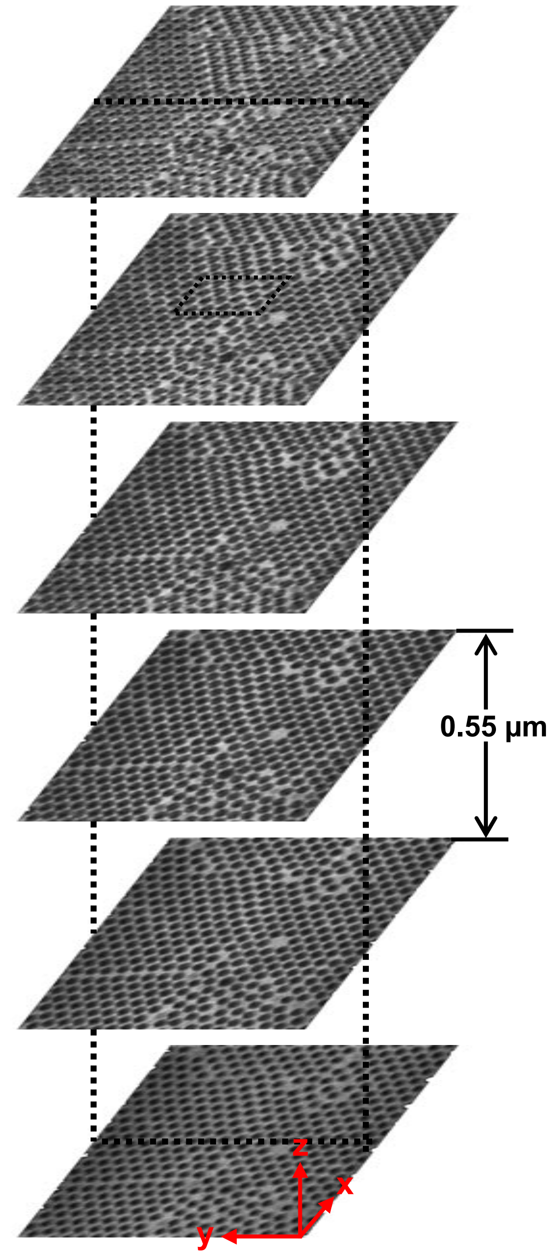




2. Polymerize hydrogel in colloidal crystal (PS, d = 3 µm, t = 25 µm) HEMA + 5% AA + 0.66% EDGM + ~10 µM acrylated Rhodamine B

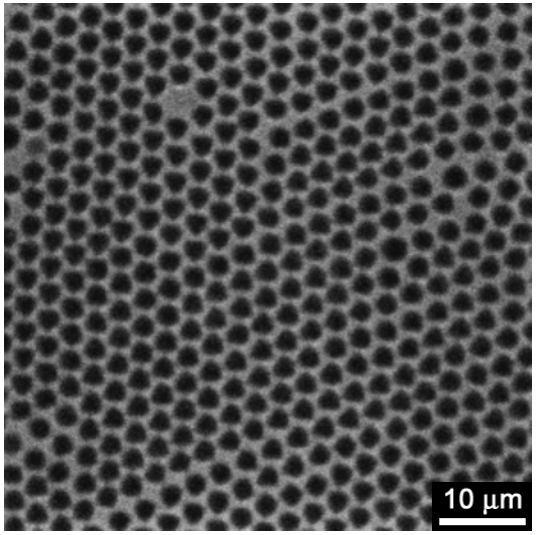
3. Etch colloids

4. Image with 2-photon confocal microscopy

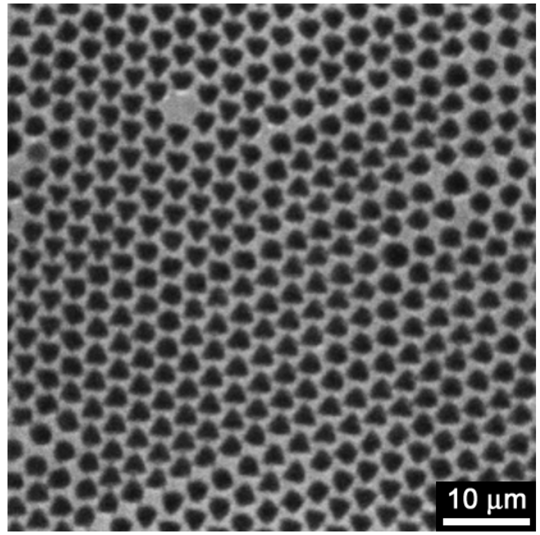


Two-photon Imaging – Bottom Layer

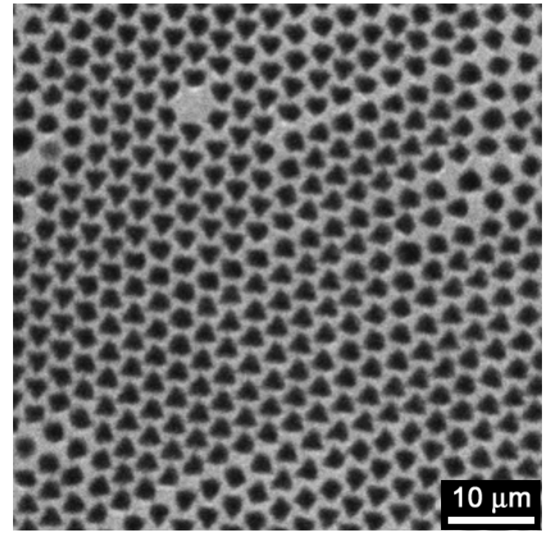
fcc (111), bottom layer



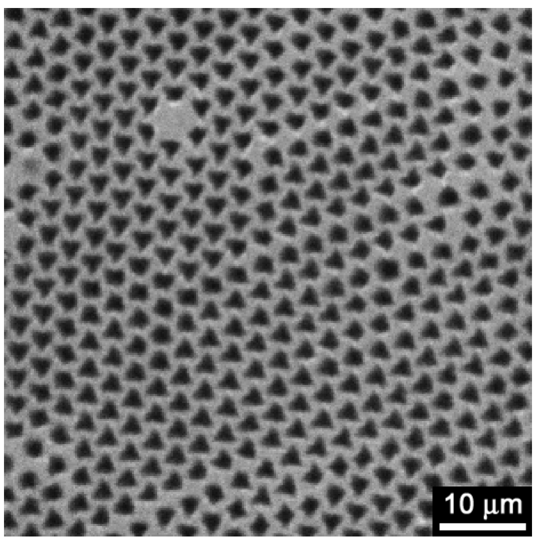
pH 3.4



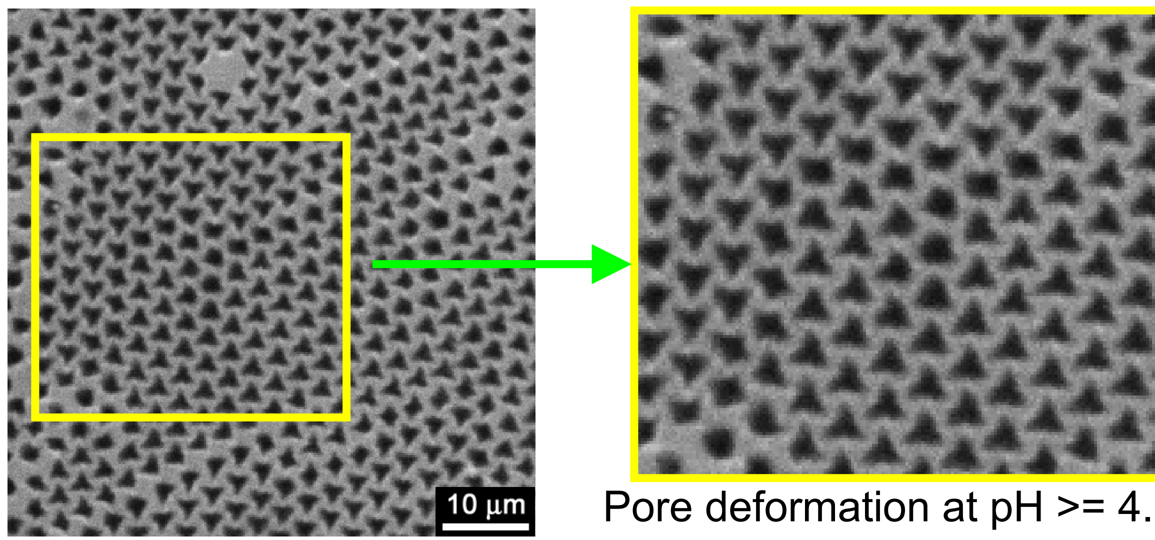
pH 4.5 (~ pK_a)



pH 5.0



pH 5.7



pH 6.6

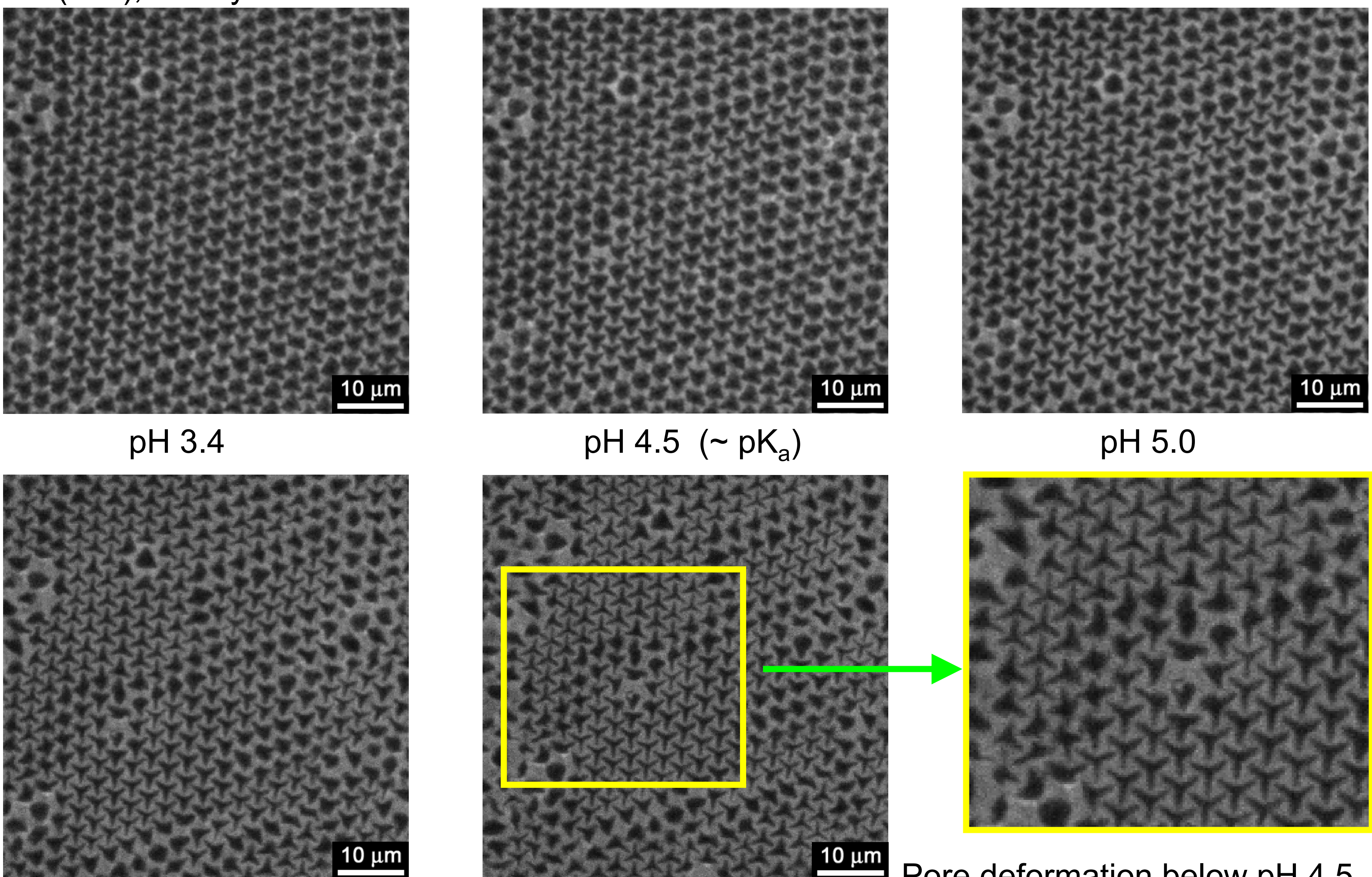
Pore deformation at pH >= 4.5

Partial pore closure at high pH

- Substrate pinning

Two-photon Imaging Results – Layer 2

fcc (111), 2nd layer



pH 5.7

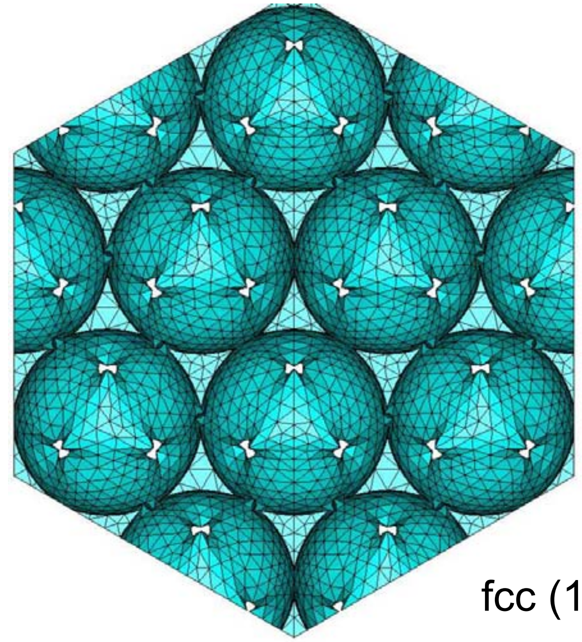
pH 6.6

Pore deformation below pH 4.5
Nearly complete collapse at pH 6.6

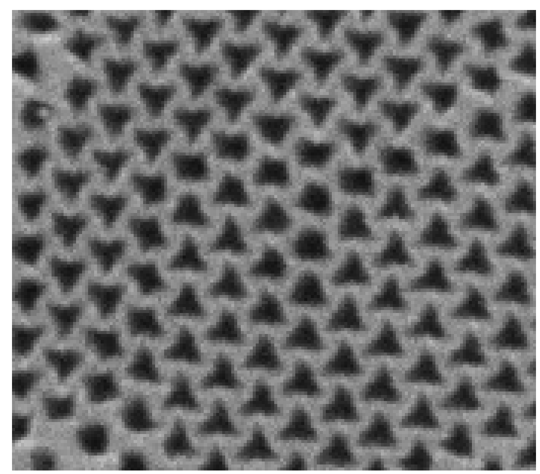
Finite Element Analysis

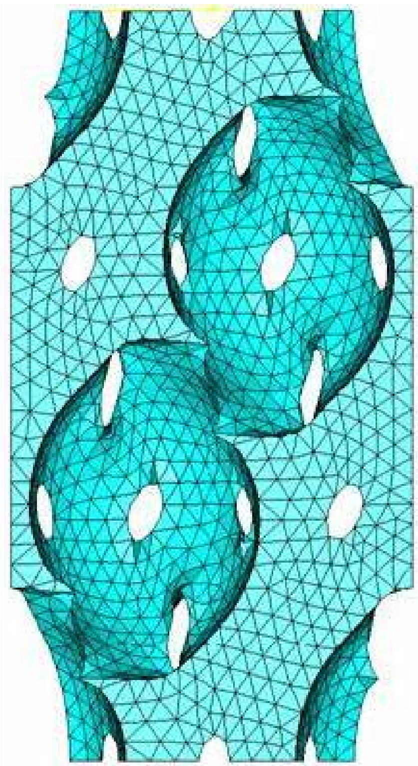
<u>Parameters</u>

- ¼ of an inverse fcc unit cell modeled
- Periodic boundary conditions
- Bottom surface does not move vertically
- Thermal strain applied → 59% volume change
- $E = 10^6\ N/m^2$, $\nu = 0.499$

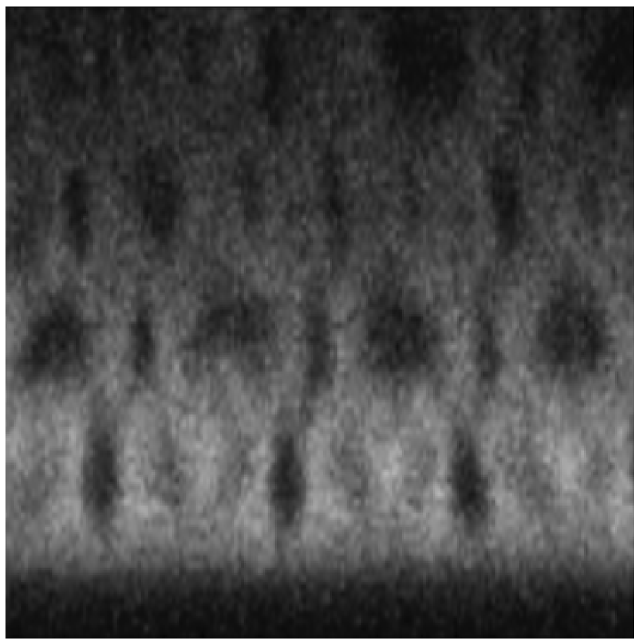


fcc (111)





fcc (110)

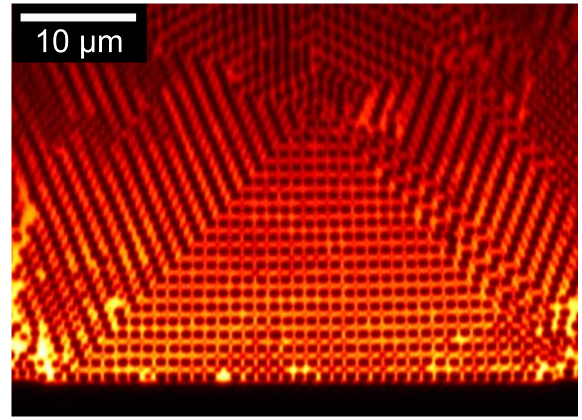


~50% volume change

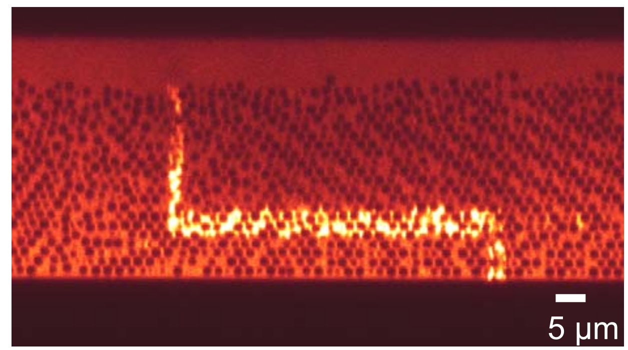
So, how will this impact the optical response?

Conclusions and Acknowledgements

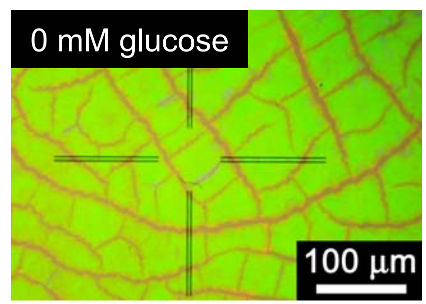
Colloidal Epitaxy
Binary nanoparticle-colloid suspensions enable the formation of crack-free, low defect density dry colloidal crystals
Dr. Wonmok Lee, Dr. Michael Bevan, Prof. Jennifer Lewis

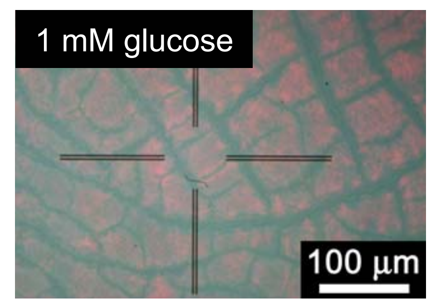


Waveguides
Direct writing of 3-D structures in colloidal crystals through multiphoton polymerization
Stephanie Pruzinsky, Dr. Wonmok Lee



Chemical Sensors
Optically active structures formed from chemically responsive inverse opal hydrogels
Yun-Ju (Alex) Lee, Stephanie Pruzinsky, Carla Heitzman, Walter Frey, Prof. Harley Johnson





Funding: NSF, DOE, ARO – MURI, Beckman Foundation, 3M

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