

Colloidal Crystal-Based Photonic Band Gap Waveguides

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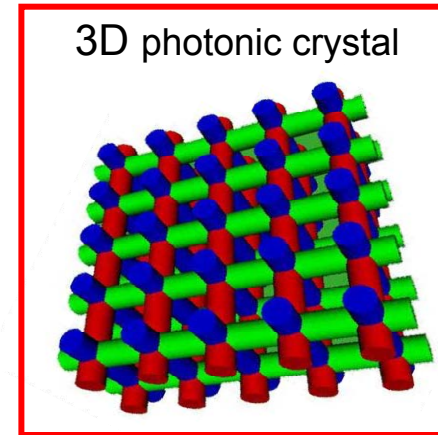
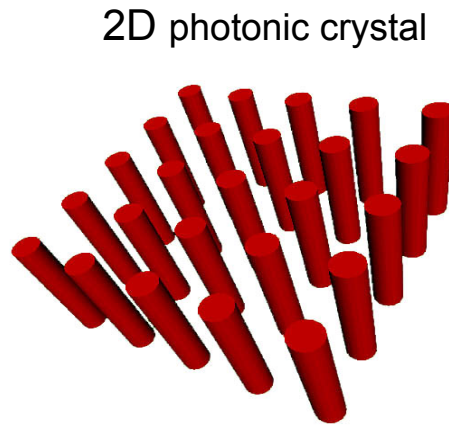
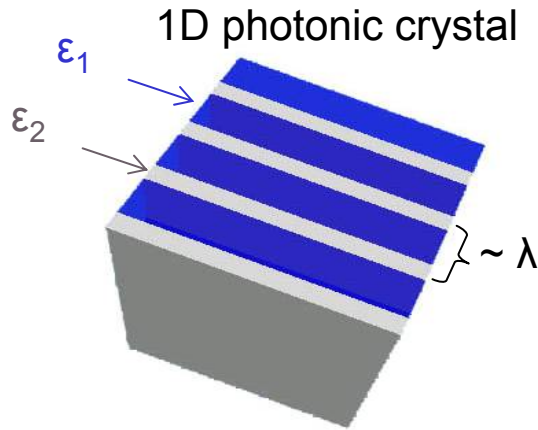
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Frederick Seitz Materials Research Laboratory, and Beckman Institute

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August 2007

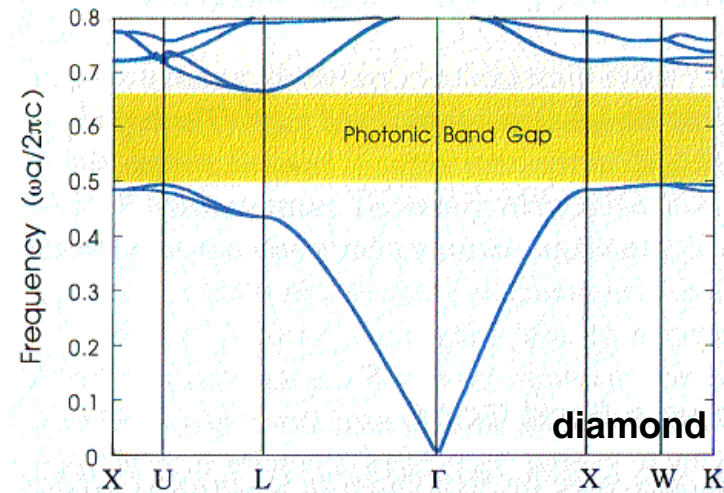
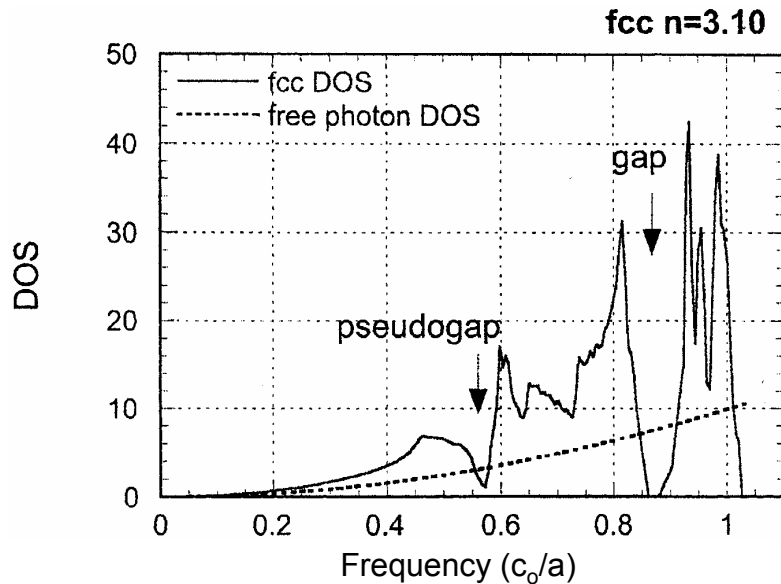
Photonic Crystals

Requirements for a Photonic Crystal: 1) Periodicity in the dielectric constant; 2) Domain sizes $\sim \lambda$



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

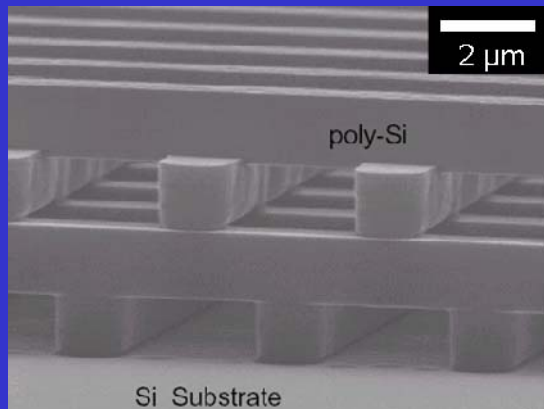
High Dielectric Contrast Photonic Band Gap



Routes to 3D Photonic Crystals

Limited Volume

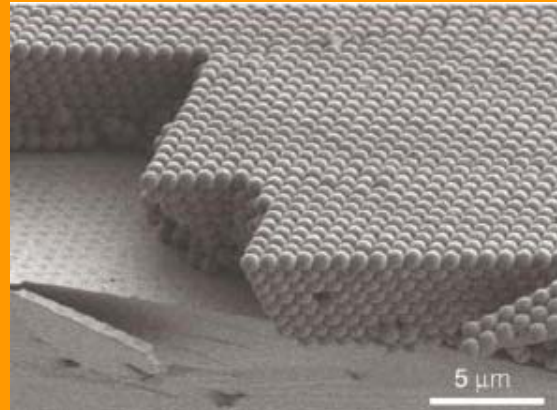
Conventional Lithography



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

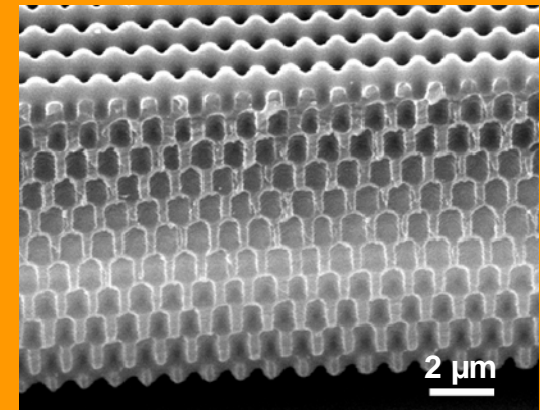
Low Cost & "Large" Volume

Self-Assembly



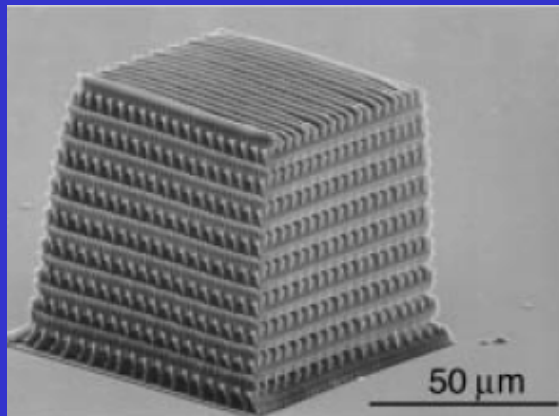
e.g. Y. Vlasov, et al. *Nature* **2001**, 414, 289.

Multi-Beam Holography



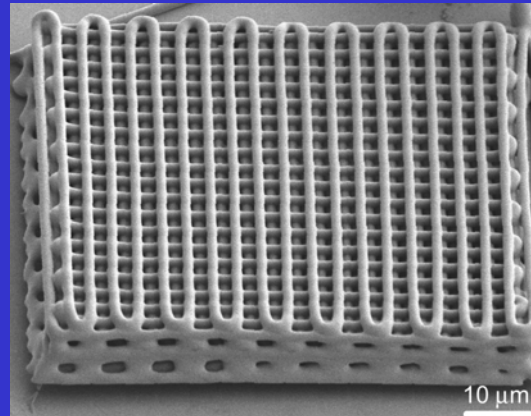
M. Campbell, et al. *Nature* **2000**, 404, 53.

Two-Photon Polymerization



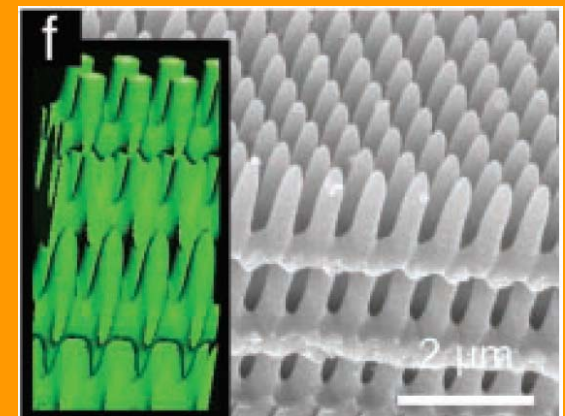
B. H. Cumpston, et al. *Nature* **1999**, 398, 51.

Direct-Write Assembly



G. M. Gratson, et al. *Nature* **2004**, 428, 386.

Phase Mask Lithography



S. Jeon, et al. *PNAS* **2004**, 101, 12428.

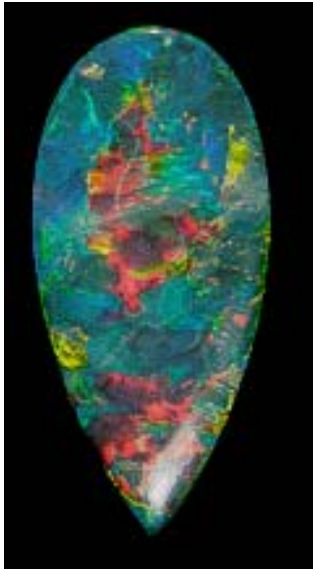
Defined Defects Straightforward

Defined Defects?

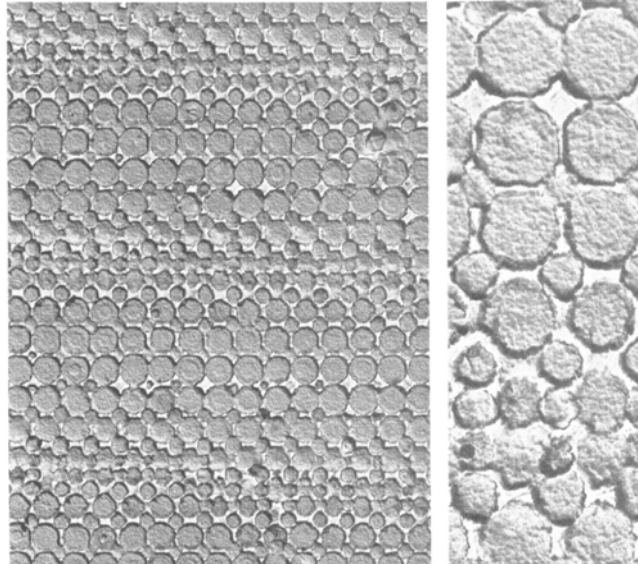
Colloidal Crystals

Natural Photonic Crystal

Opal



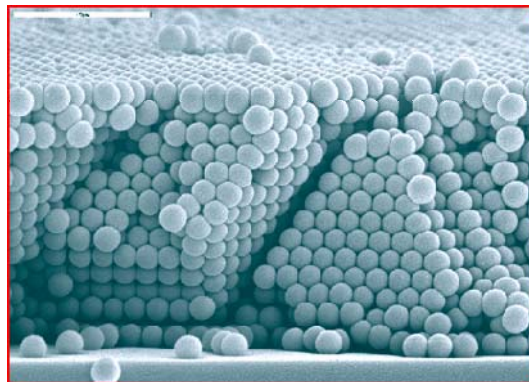
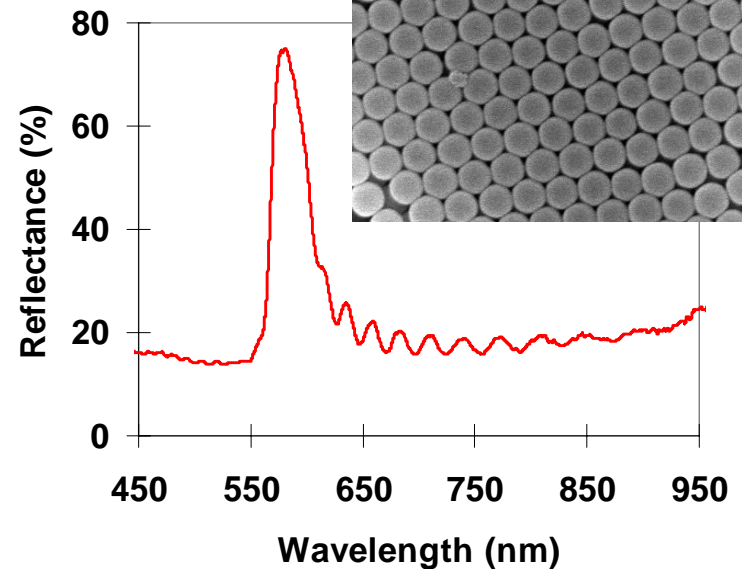
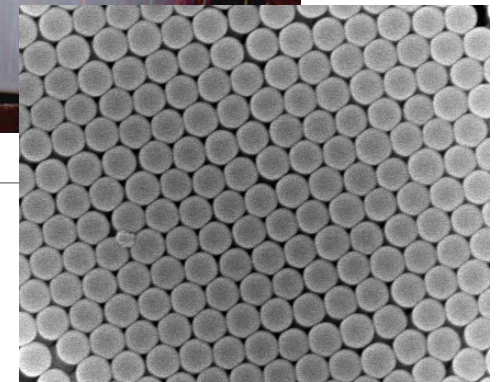
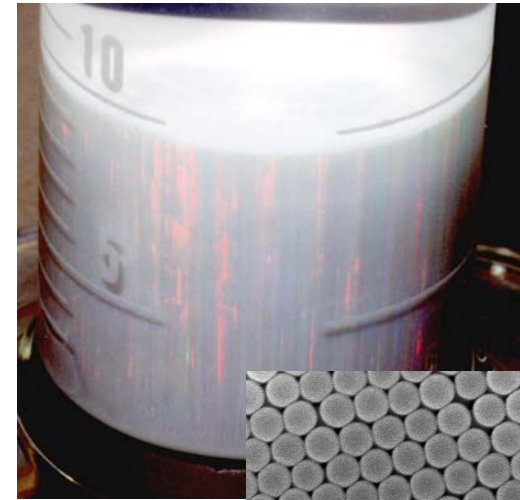
SEM of opal cross-section



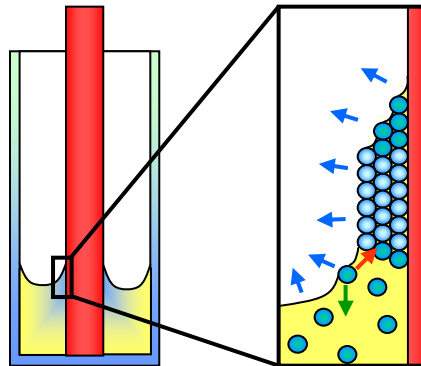
J.V. Sanders, *Phil. Mag. A.* 1980

synthetic "opal"

formed from ~500 nm silica spheres



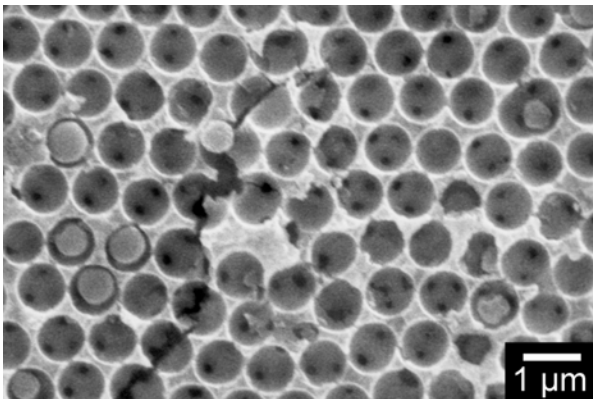
660 nm silica spheres, 0.8% vol, 36°C



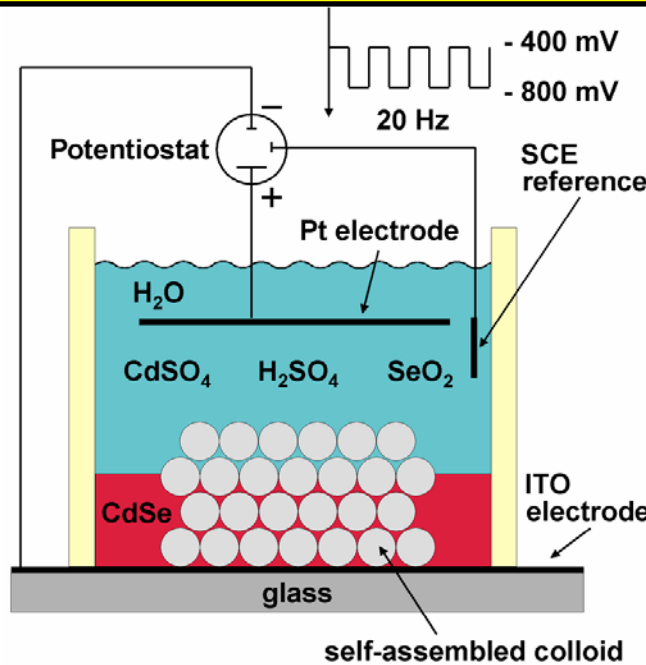
Colloidal Crystal Templating: 3-D Structuring of Materials

New Materials = New Functions

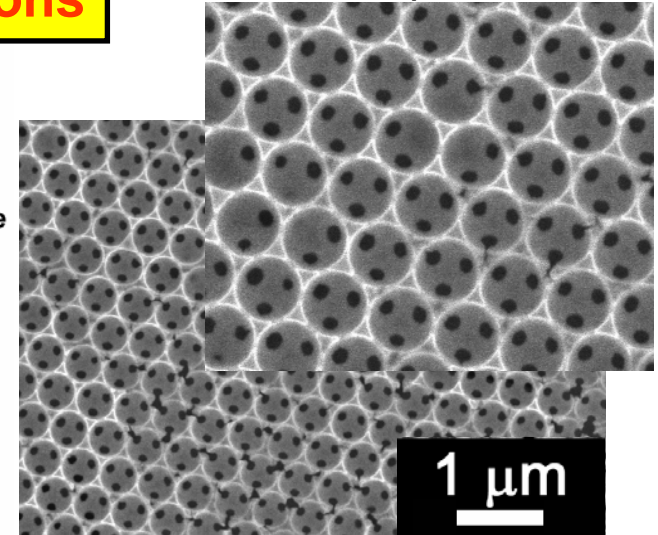
Electrodeposited CdS



PVB, P. Wiltzius, *Nature* 1999

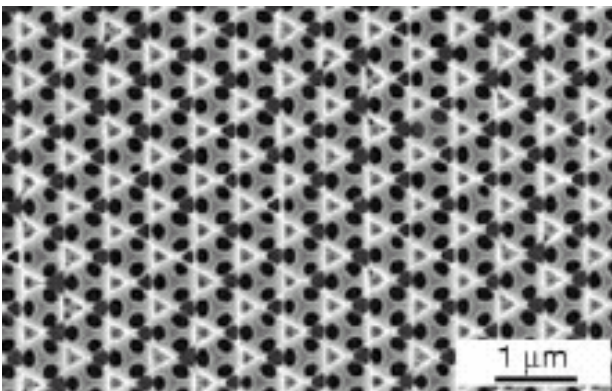


Electrodeposited Ni

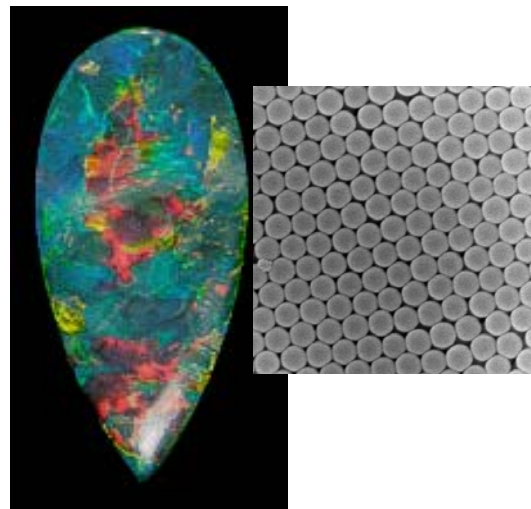


X. Yu, Y.-J. Lee, PVB et al., *Adv. Mater.*, 2007

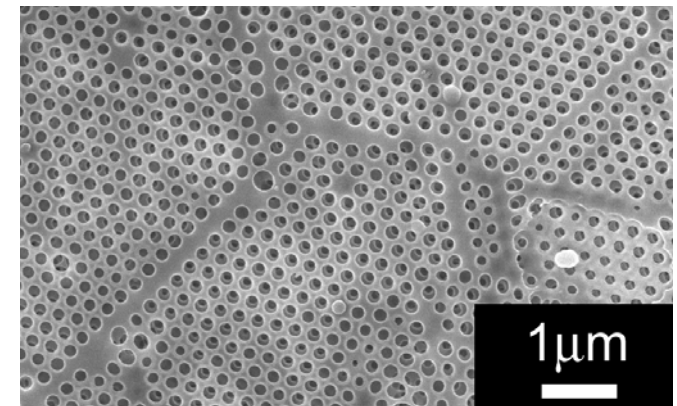
Silicon (CVD)



A. Blanco et al. *Nature* 2000
Y.A. Vlasov et al., *Nature* 2001



Hydrogel, UV polymerized

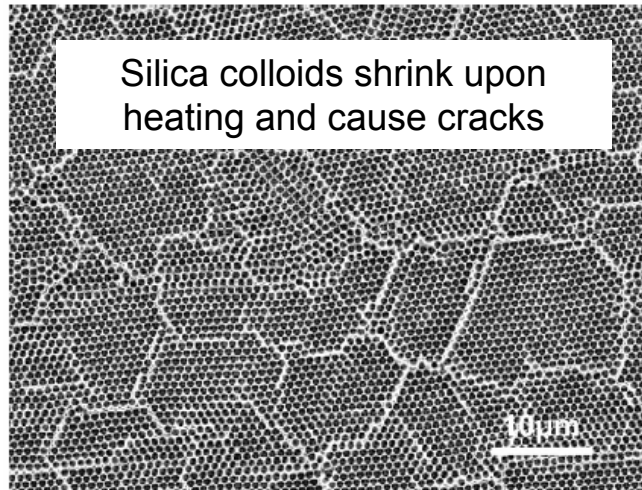


Y.-J. Lee, PVB, *Adv. Mater.* 2003

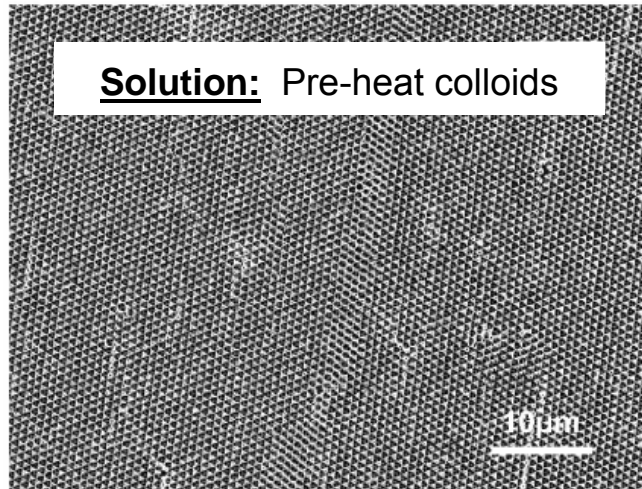
Removing Undesired Defects in Colloidal Crystals

Colloidal Crystals

SEM of Si Inverse Opals

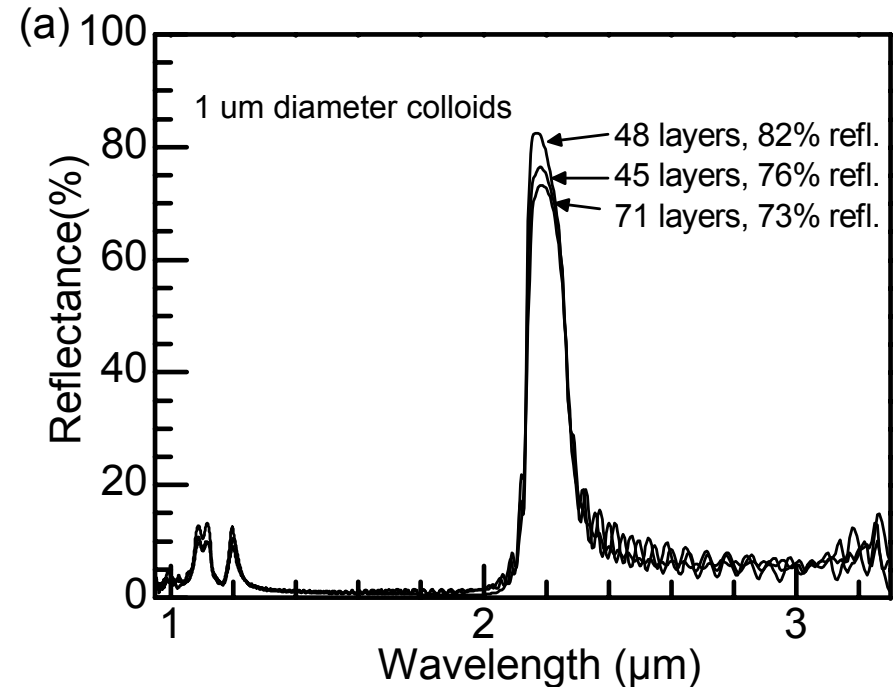


Solution: Pre-heat colloids



A. Chabanov, et al., *Appl. Phys. Lett.* **2004**, *84*, 3573.

>80% reflectance possible

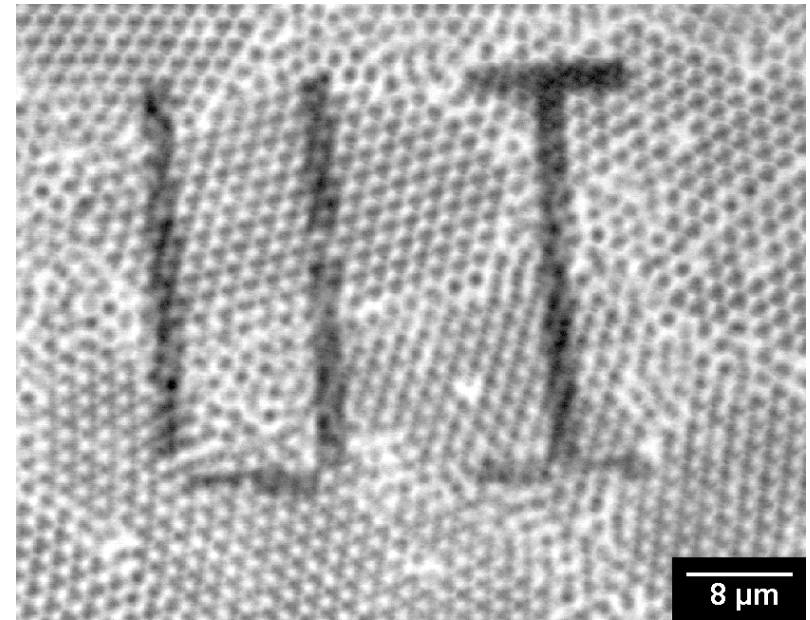
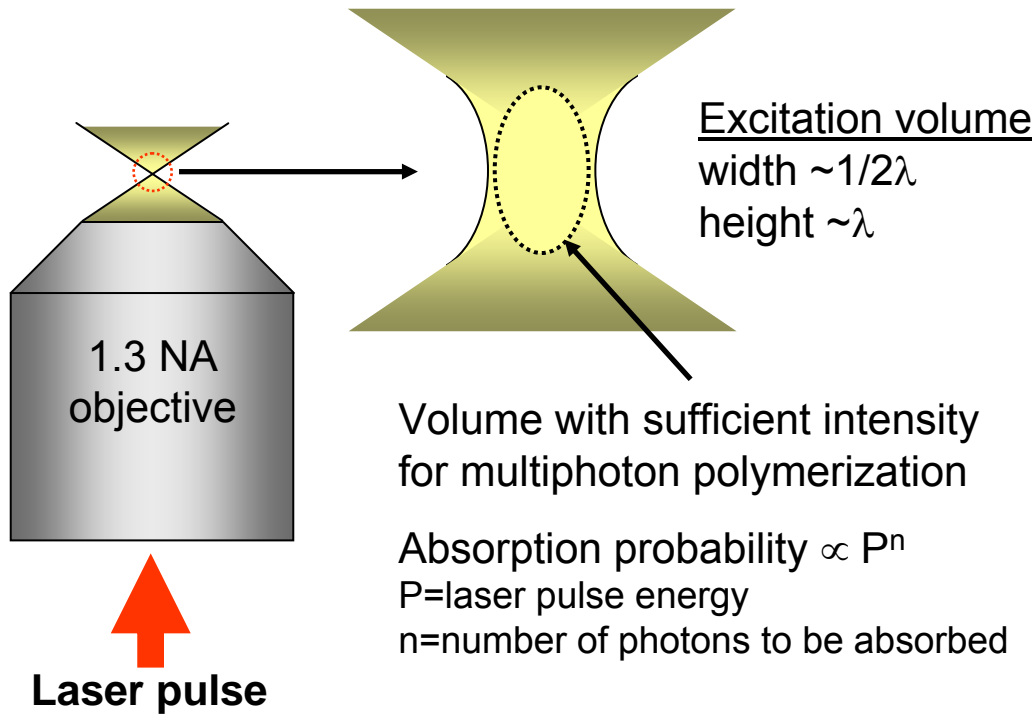


R. G. Shimmin, PVB, *Langmuir* **2006**

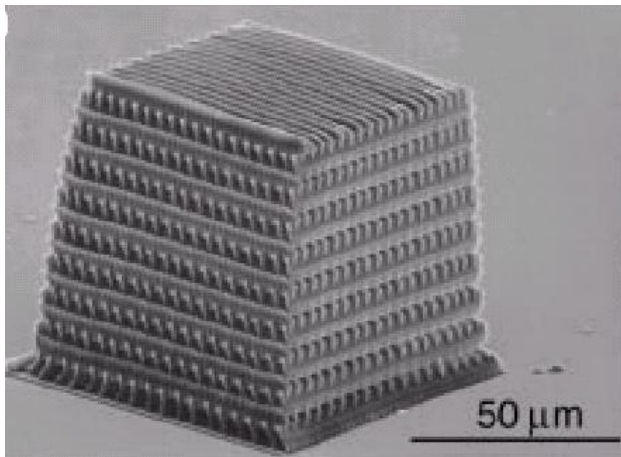
“Tricks” include:

- 1) Low polydispersity (<1.03)
- 2) Controlled deposition conditions
- 3) Pre-heat colloids (for SiO₂, not for PS)
- 4) Coat via ALD or CVD after assembly to eliminate cracking in subsequent processing steps

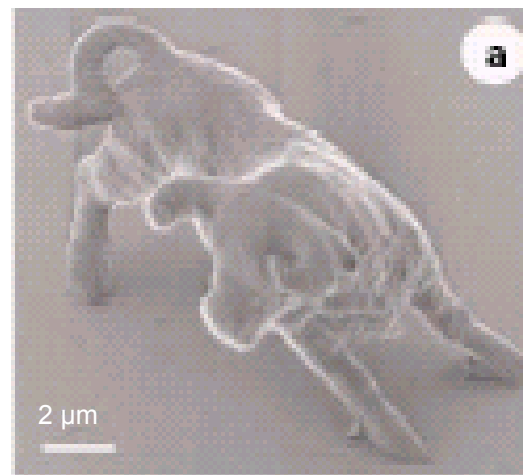
3D Structures through Multiphoton Polymerization



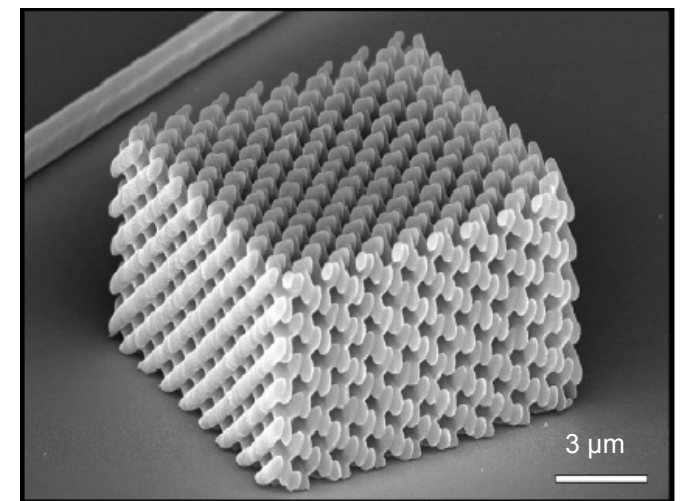
W. Lee, S. A. Pruzinsky, P. V. Braun, *Adv. Mater.* (2002)
S. A. Pruzinsky, P. V. Braun *Adv. Func. Mater.* (2005)



Cumpston et al. *Nature* (1999)



S. Kawata, et al, *Nature* (2001)

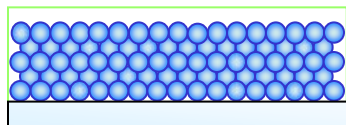


M. Deubel, et al, *APL* (2004)

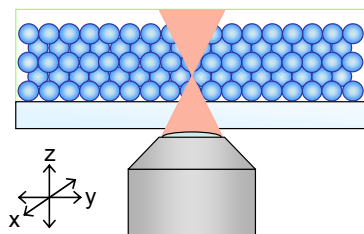
Two-Photon Polymerization

TPP Procedure

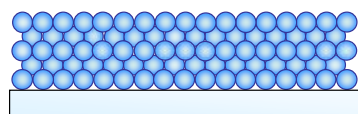
1. Fill colloidal crystal with monomer solution



2. Write TPP features



3. Rinse away excess monomer solution



Beam Parameters:

Ti:Sapphire

$\lambda = 780 \text{ nm}$

$\tau \sim 100 \text{ fs}$

$F = 82 \text{ MHz}$

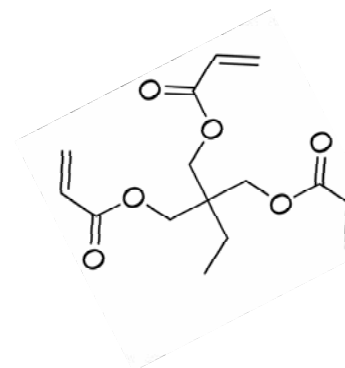
$P \sim 20\text{-}200 \text{ mW}$

$N.A. \sim 1.32$

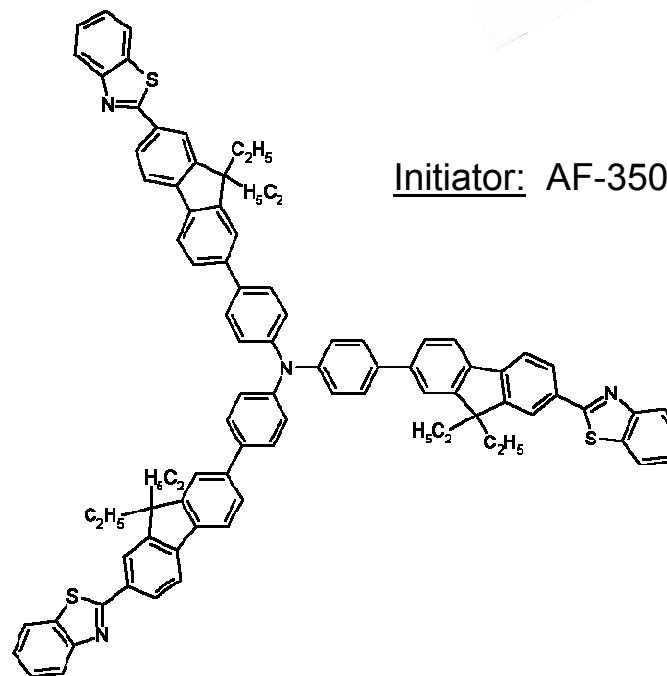
Solution Chemistry

Monomer:

Trimethylolpropane
triacrylate (TMPTA)



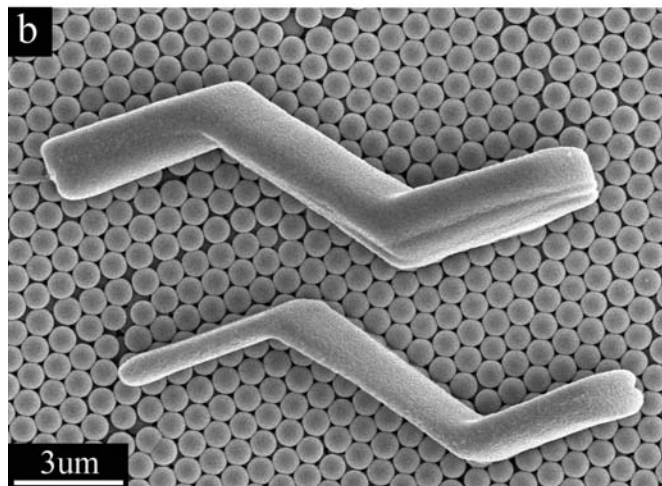
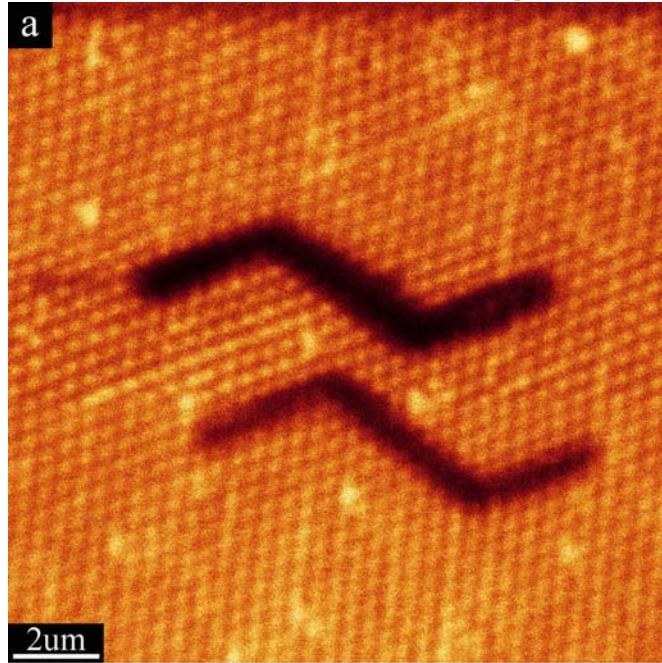
Initiator: AF-350*



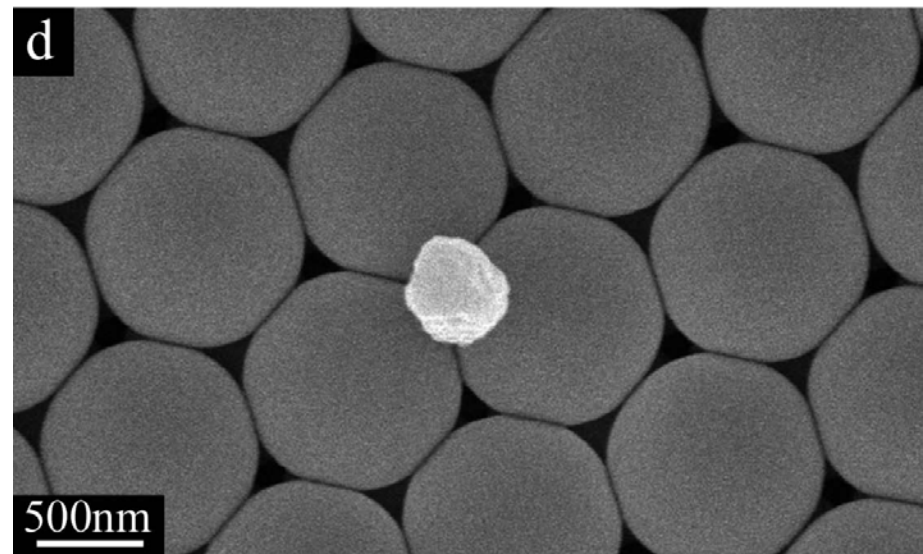
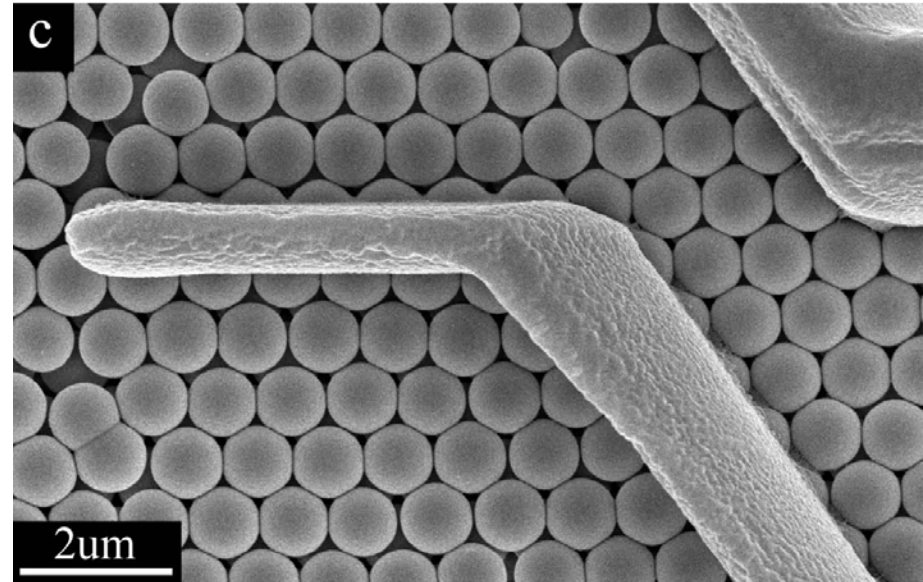
*Courtesy of Air Force Research Laboratory (e.g.
R. Kannan et al. *Chem. Mater.* 2001

Registration with Colloidal Crystal Lattice

Fluorescence Image



SEM

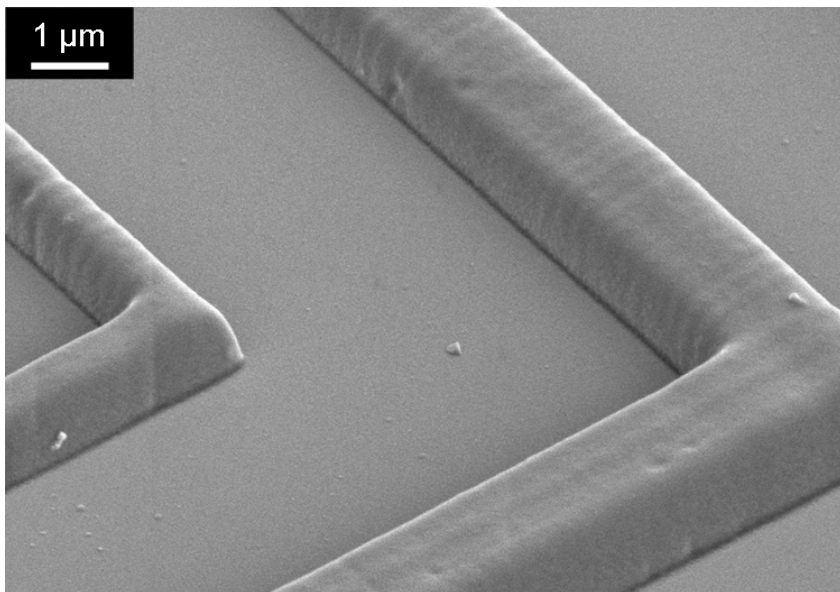
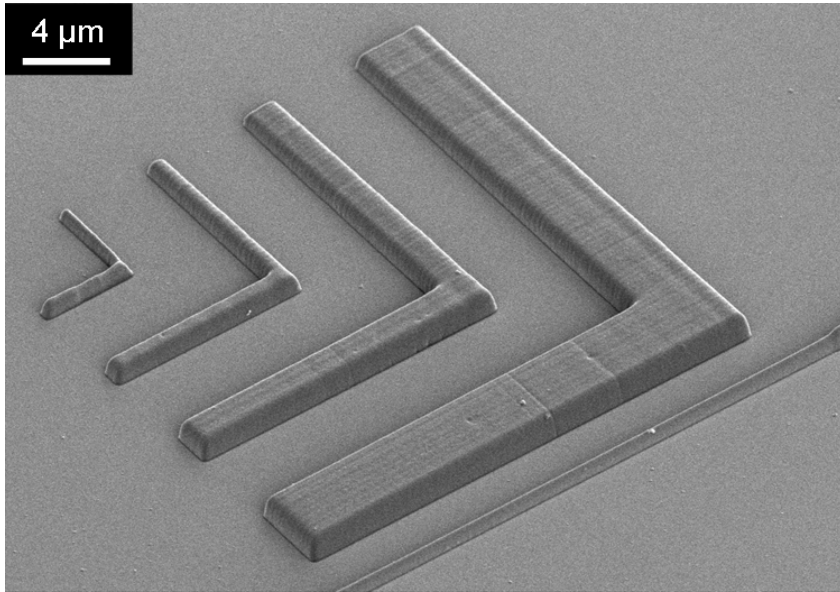


E.C. Nelson and P.V. Braun, *in preparation*

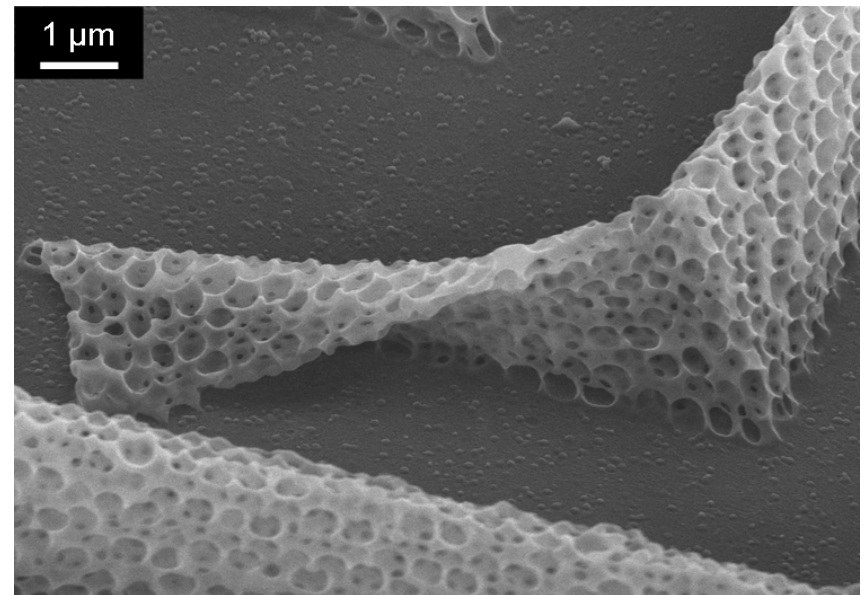
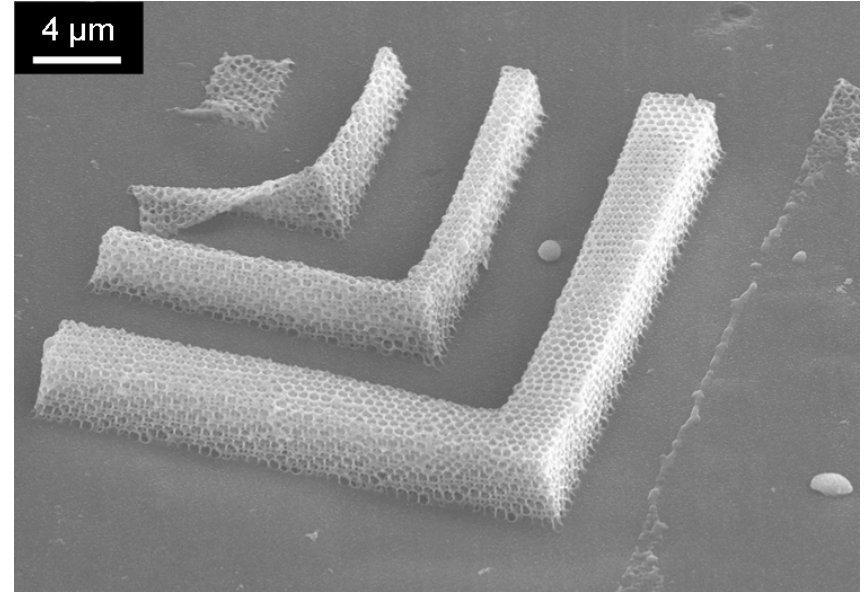
~300 nm Diameter Polymer Dot

Multiphoton Writing

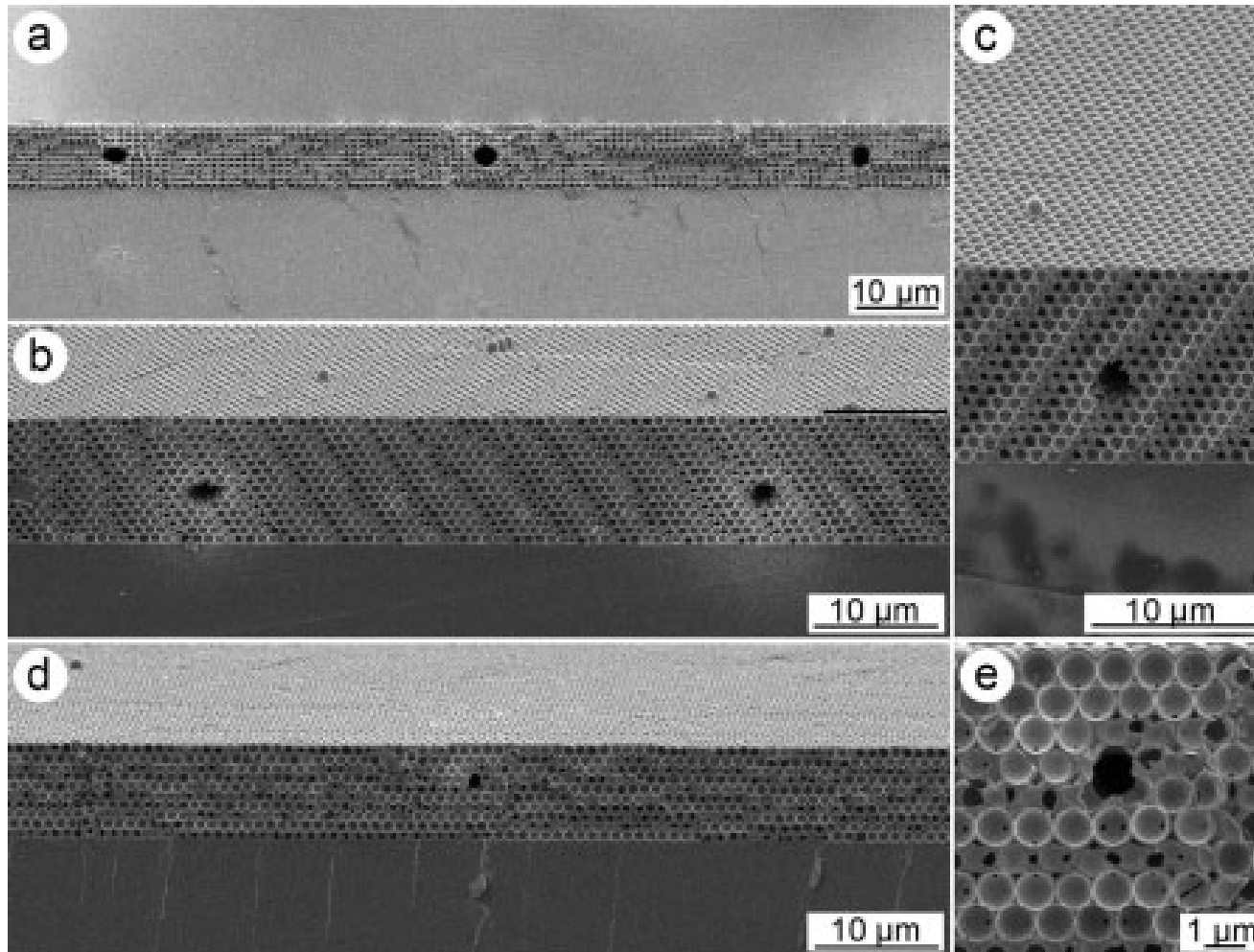
In Monomer Only



In Colloidal Crystals (Etched with HF)



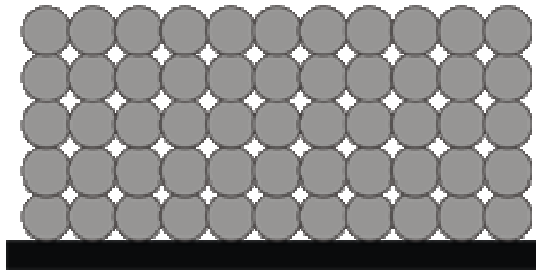
Silicon Inverse Opals with Defects



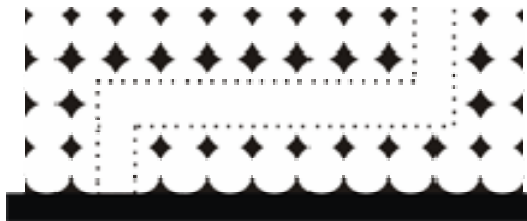
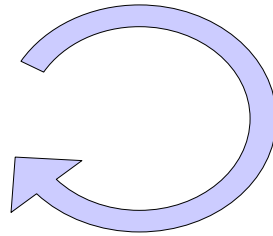
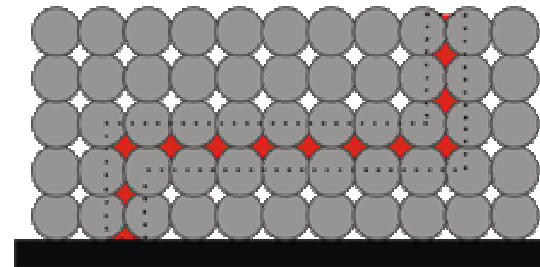
Y. Jun, D. Norris *et al.* *Adv. Mater.*17, 1908 (2005).

Target: Silicon Inverse Opals with Defects

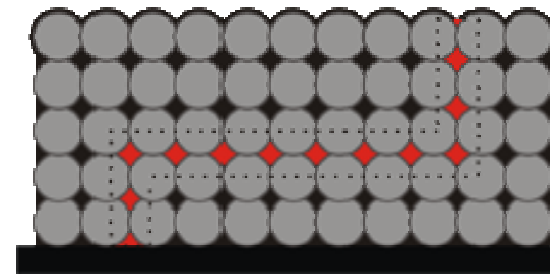
Artificial opal + oxide layer



Embedding polymer features



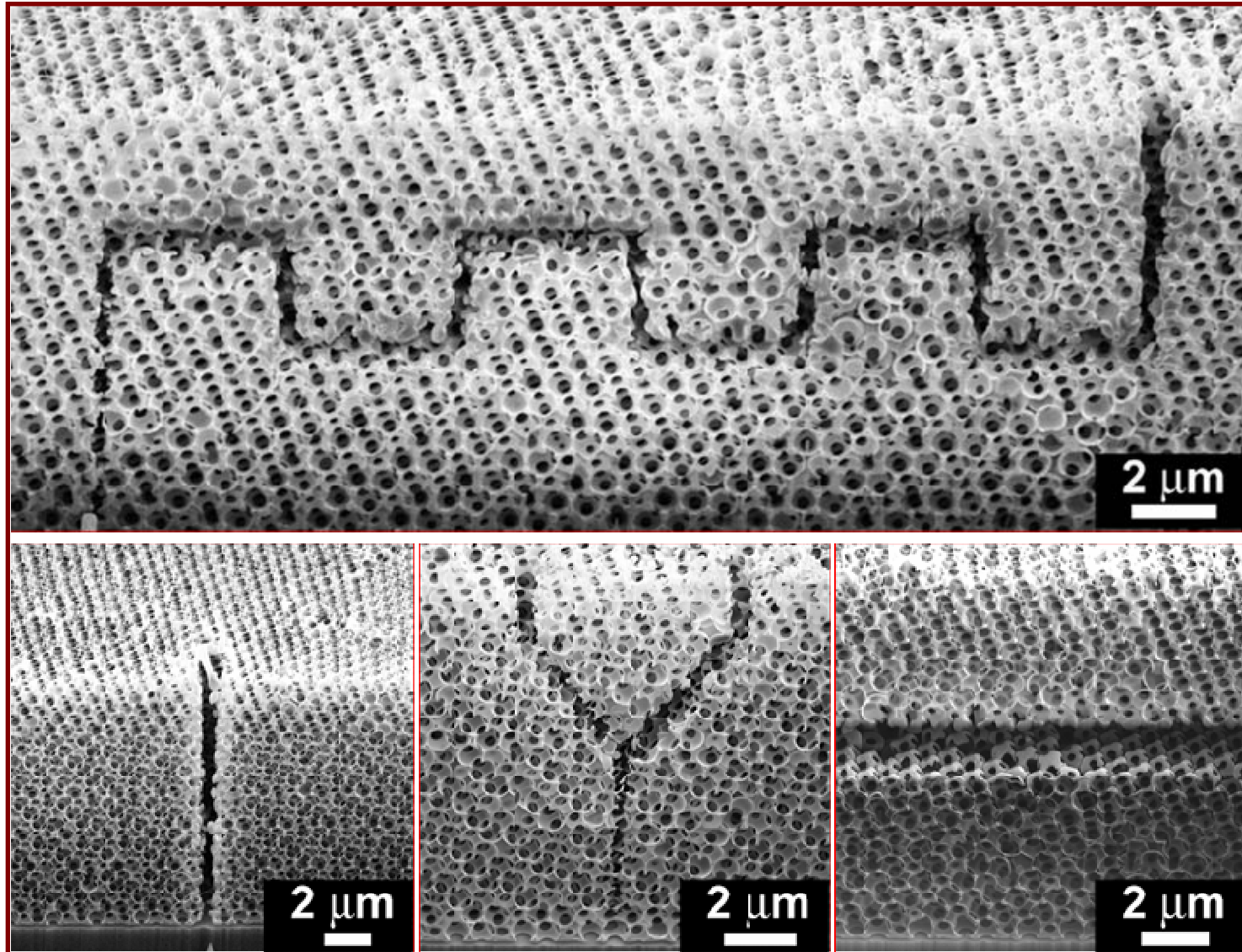
Oxide and polymer etching



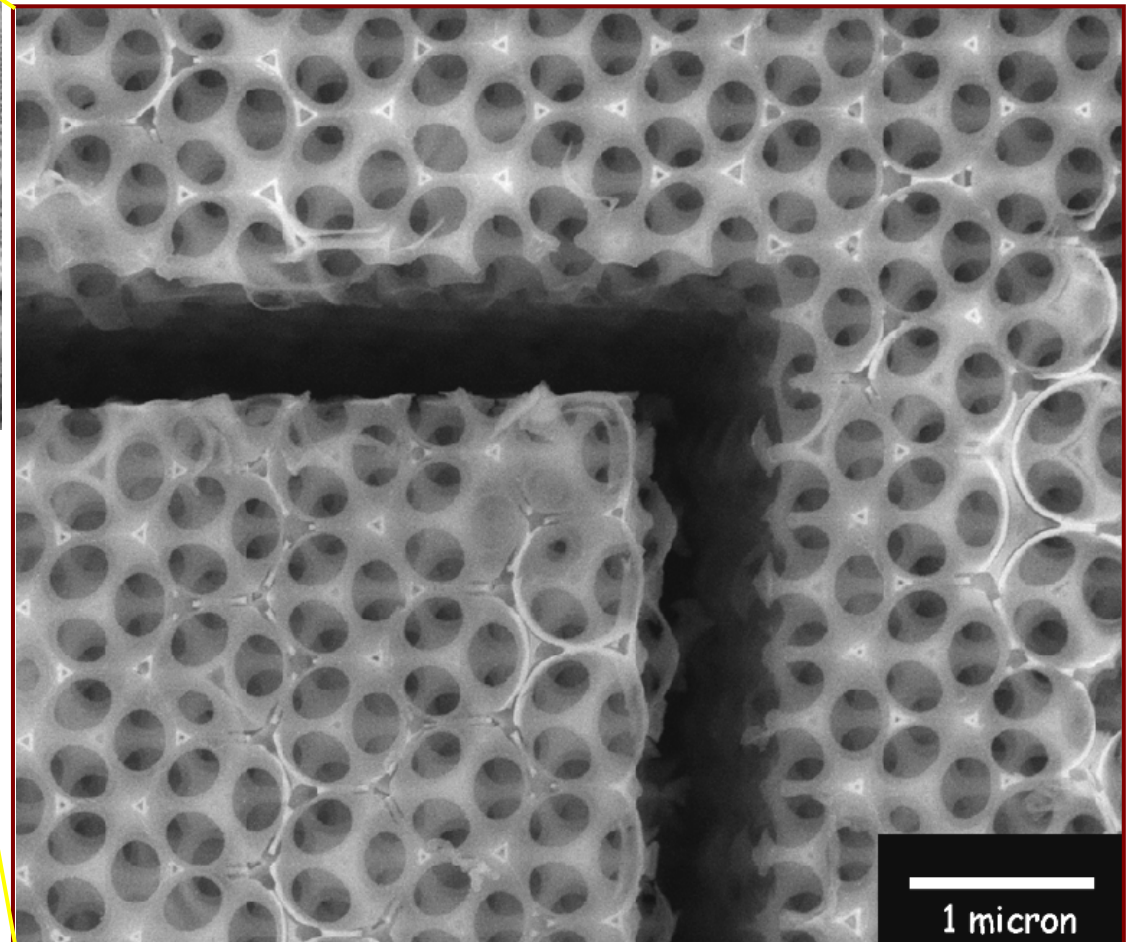
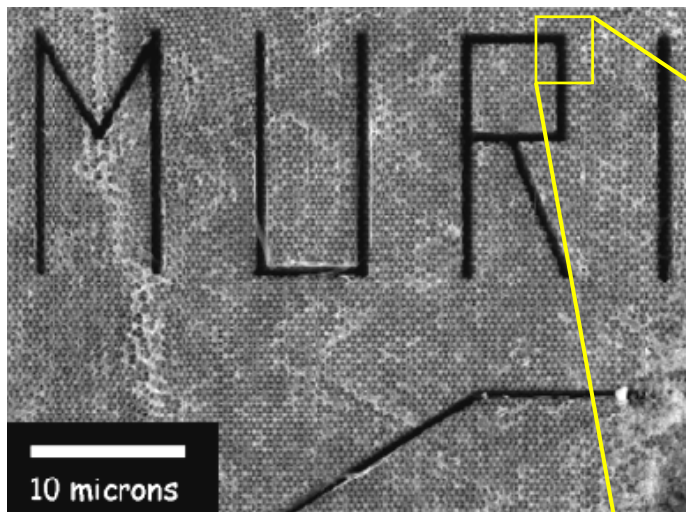
Silicon CVD

Results: 3D defects

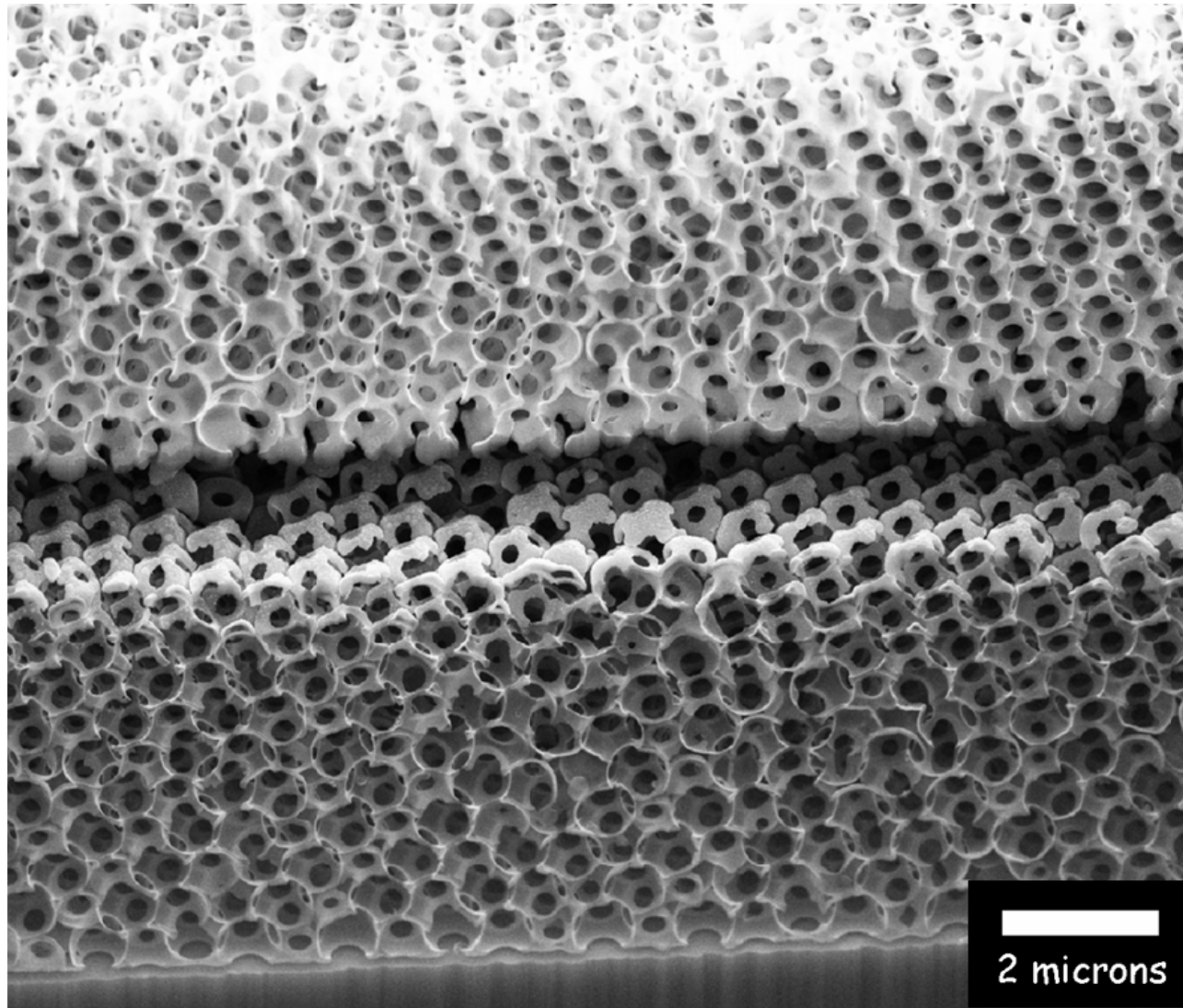
(FIB cross-sections)



Results: low edge roughness



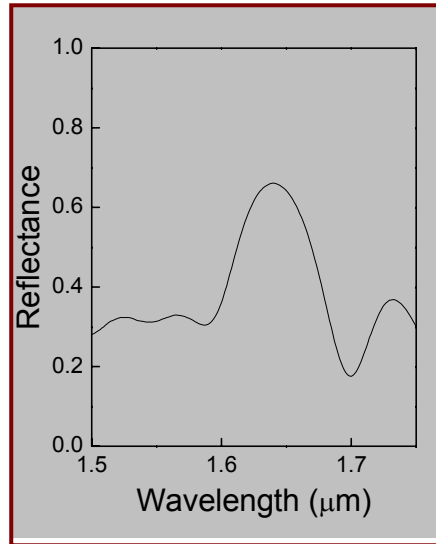
Results: Planar defect



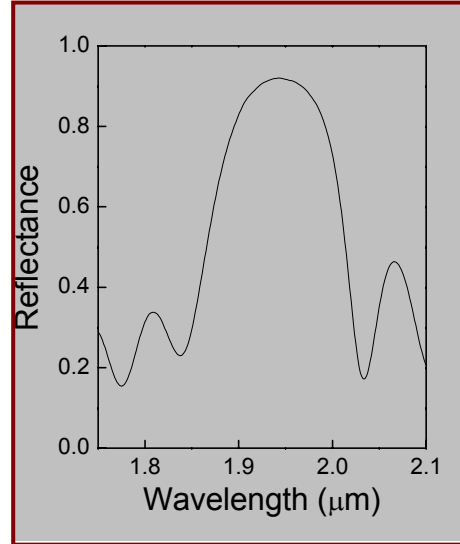
Optics on a planar defect

No defect

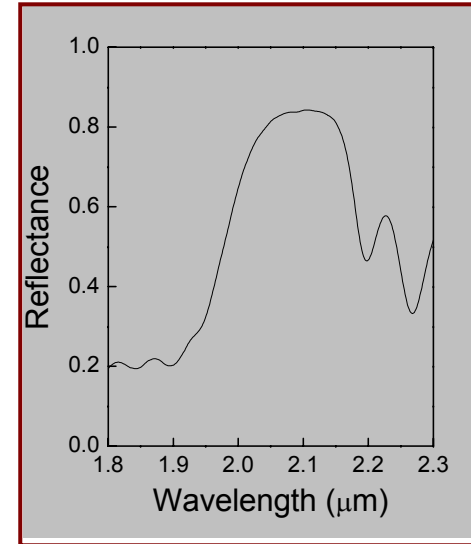
Oxide opal



Silicon (40% pore)

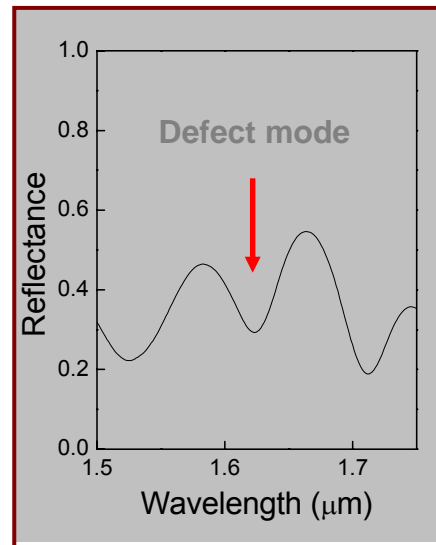


Silicon (80% pore)

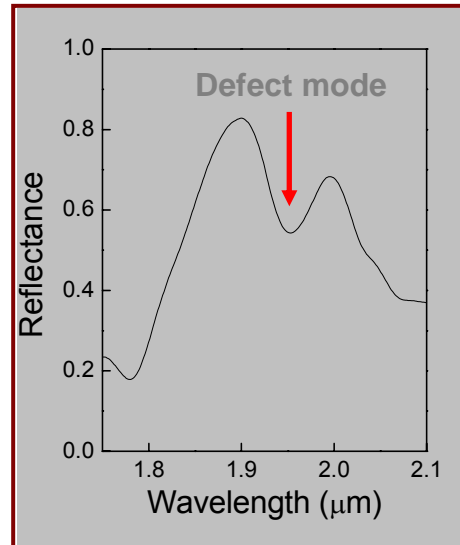


Defect

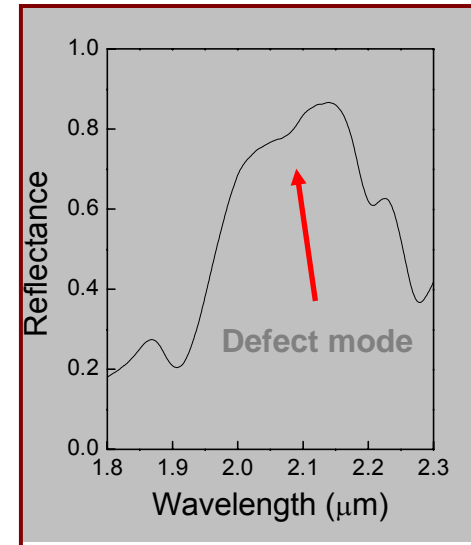
Defect mode



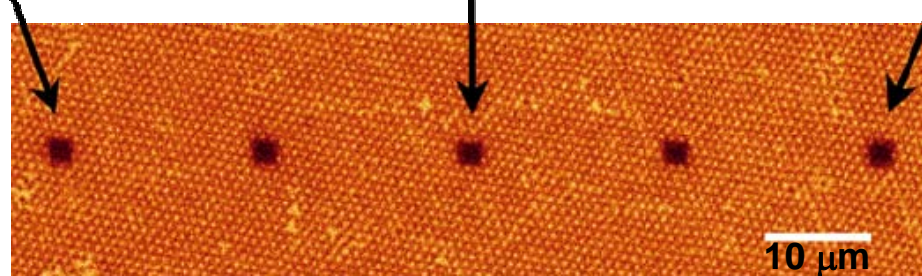
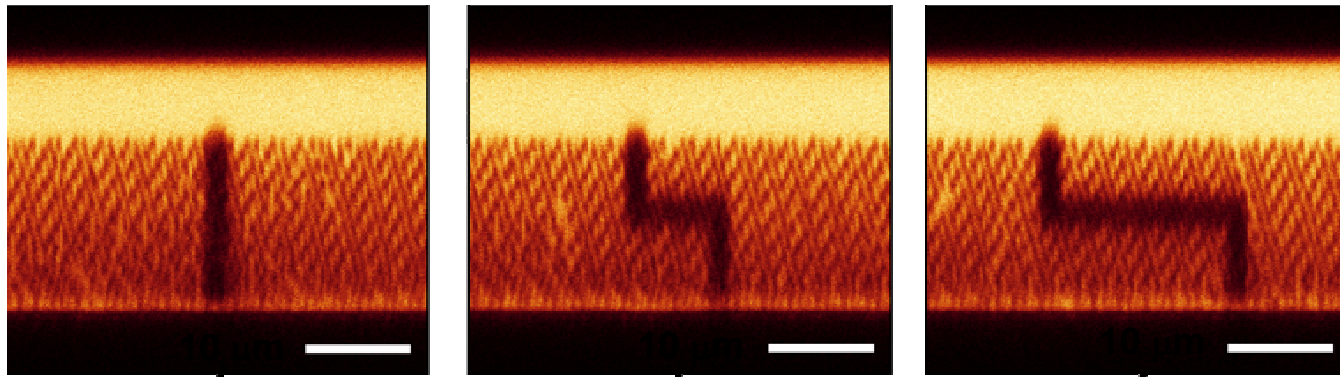
Defect mode



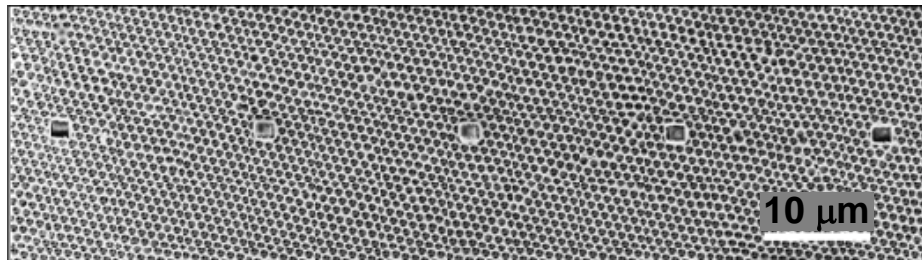
Defect mode



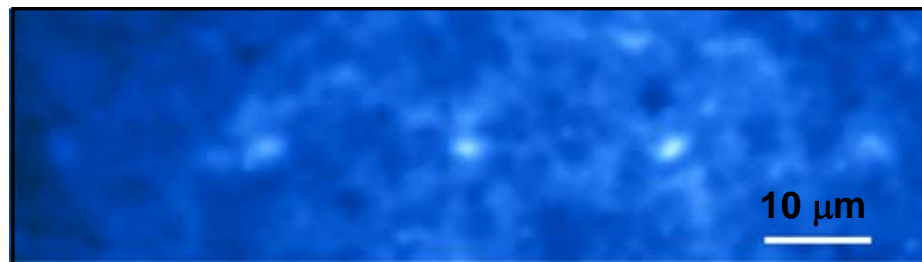
Transmission through a waveguide



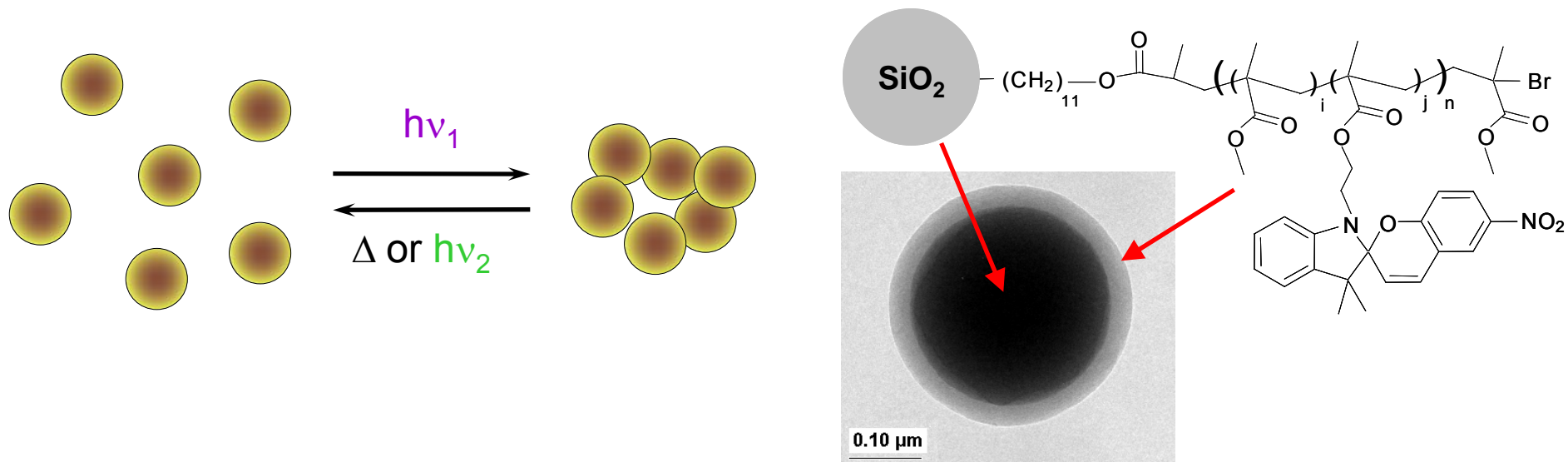
Confocal



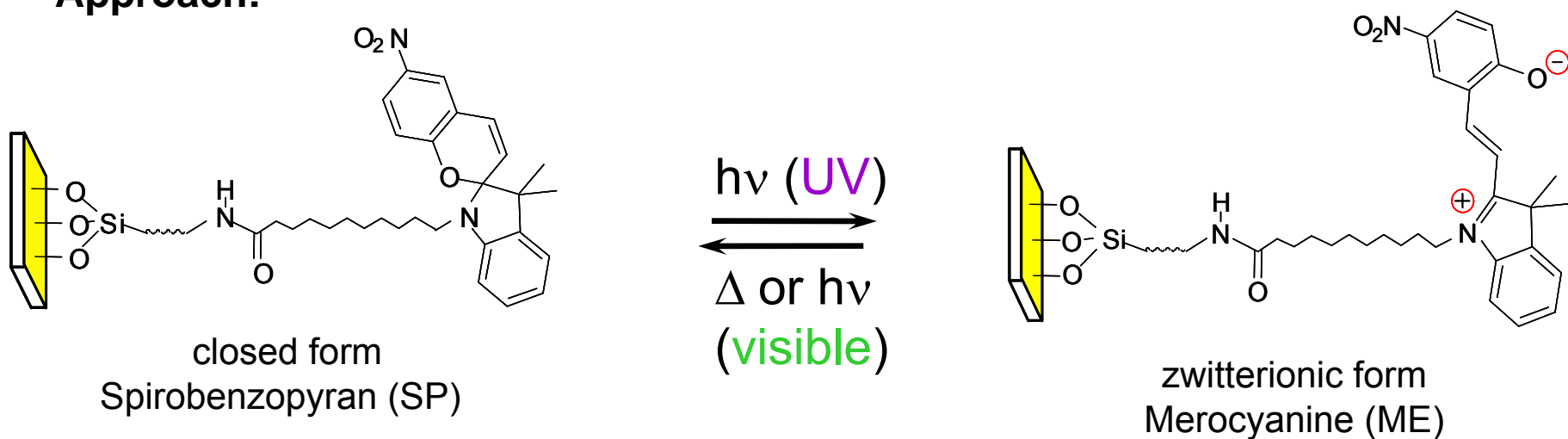
SEM



Infrared
 $\lambda = 1.48 \mu\text{m}$



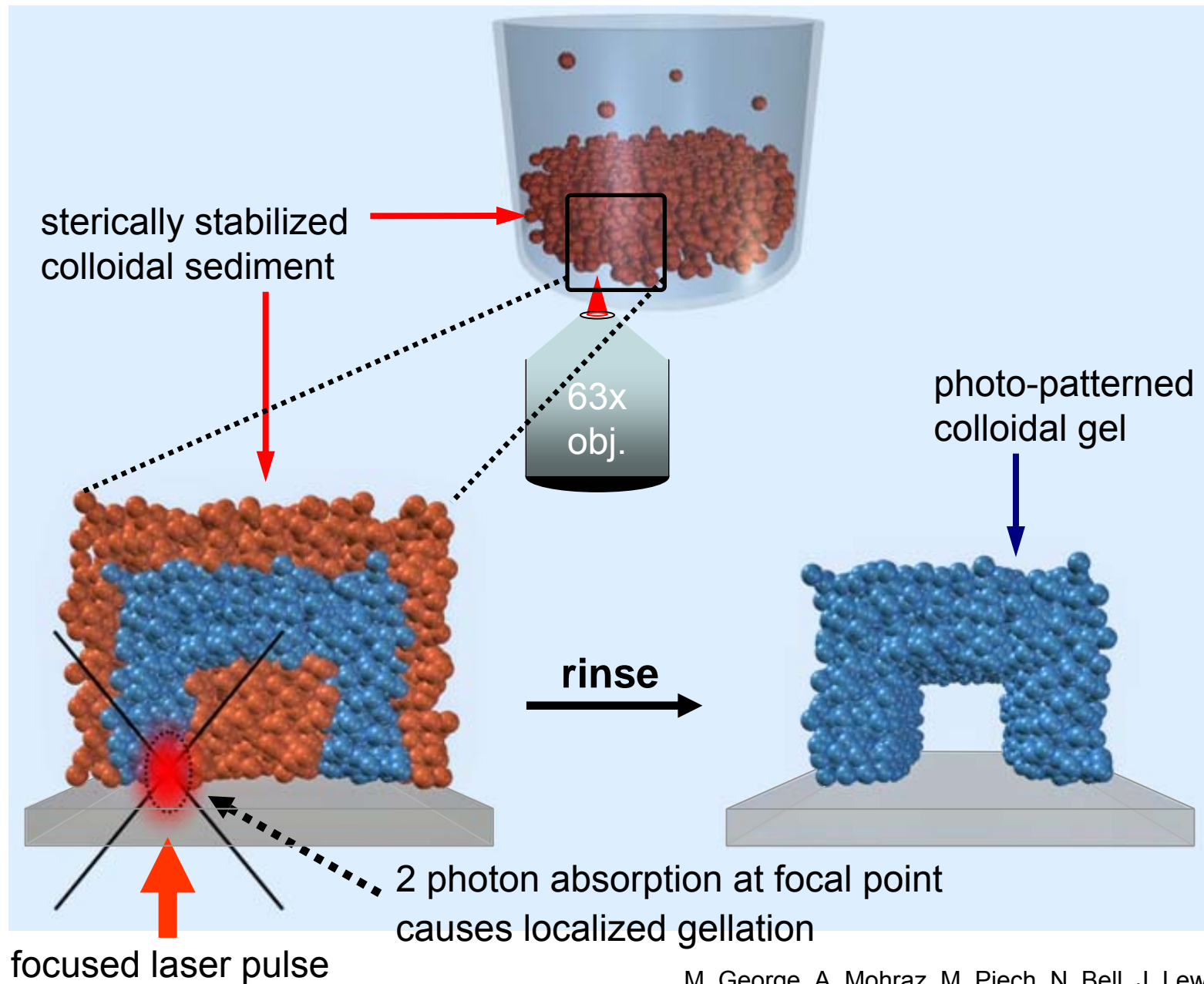
Approach:



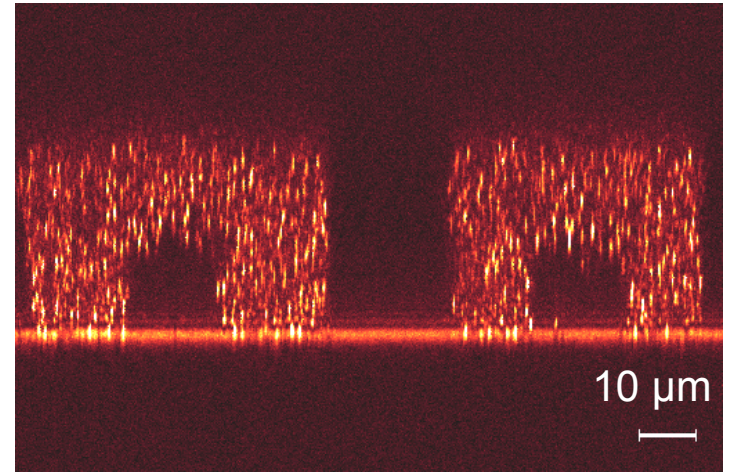
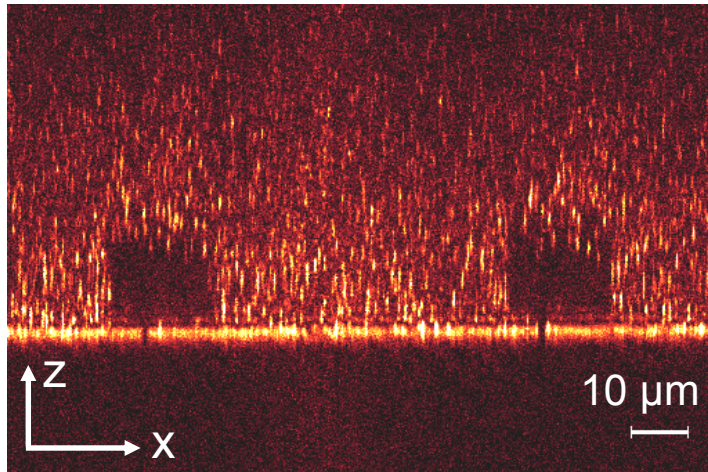
Background:

K. Ichimura, et al. *J. Mat. Chem.* **4**, 883 (1994)

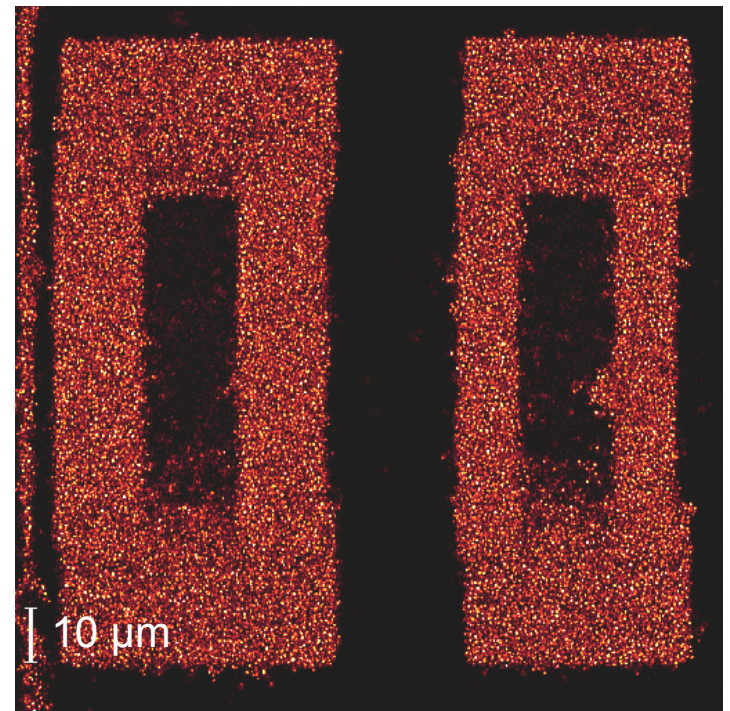
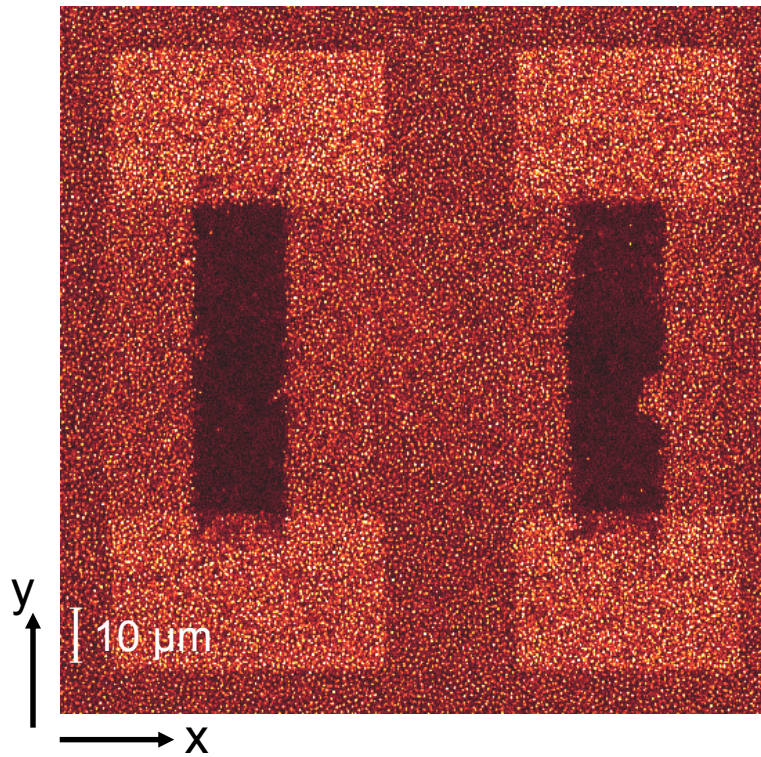
Multiphoton Patterning of Colloidal Gels



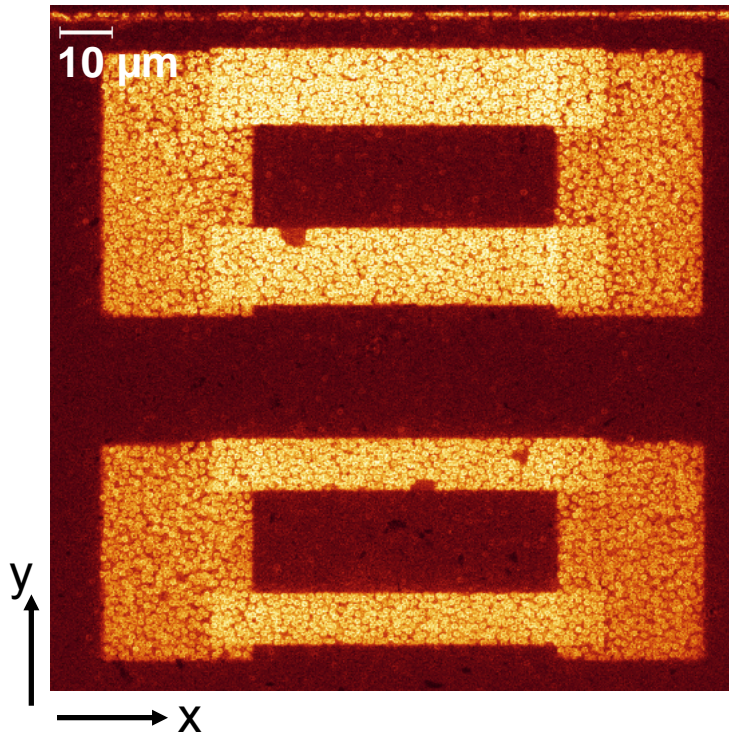
Colloidal Gel Structures: Porous-Walled Microcavity



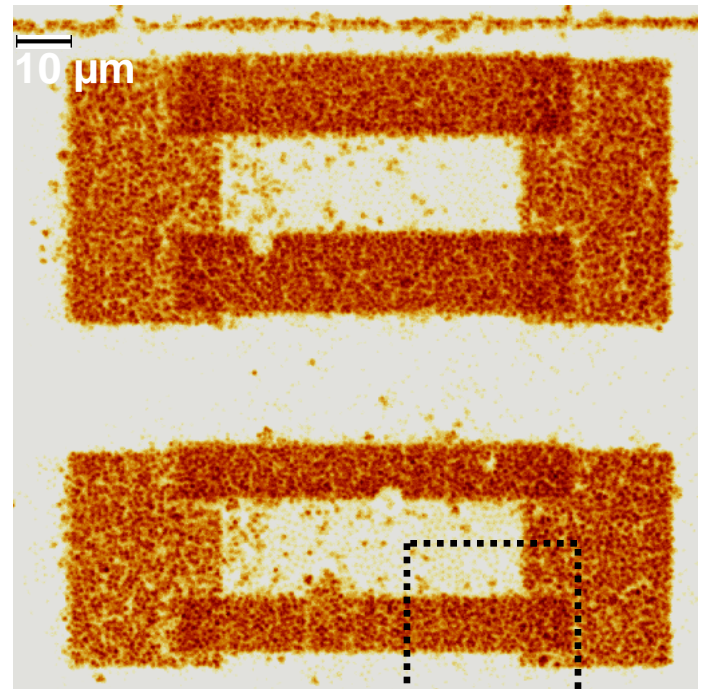
rinse
→



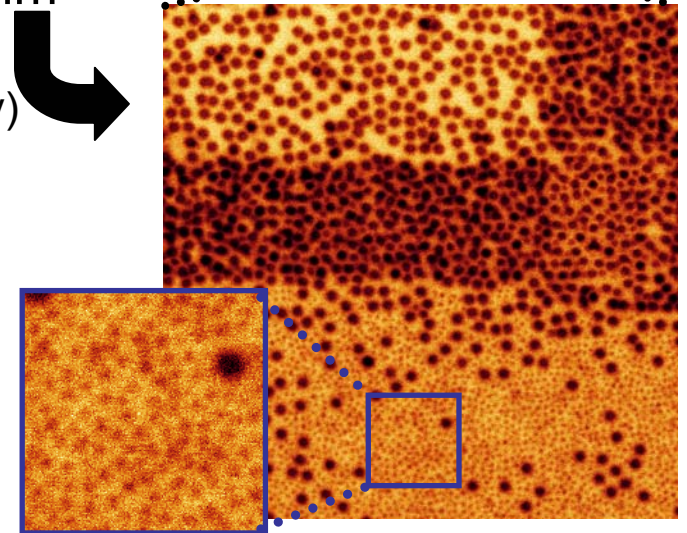
Size selective wall permeability



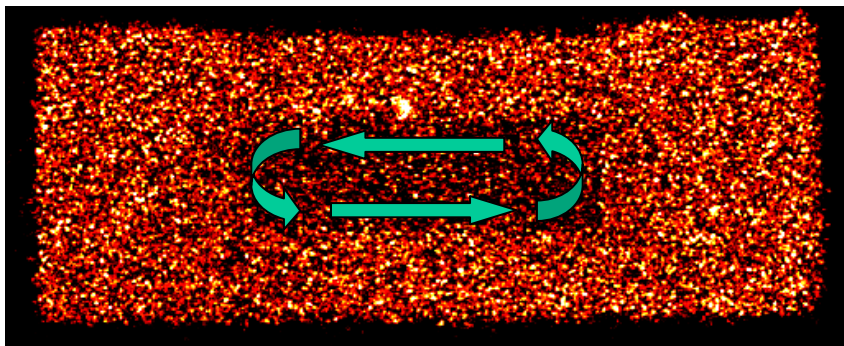
added dye
→
(outside cavity)



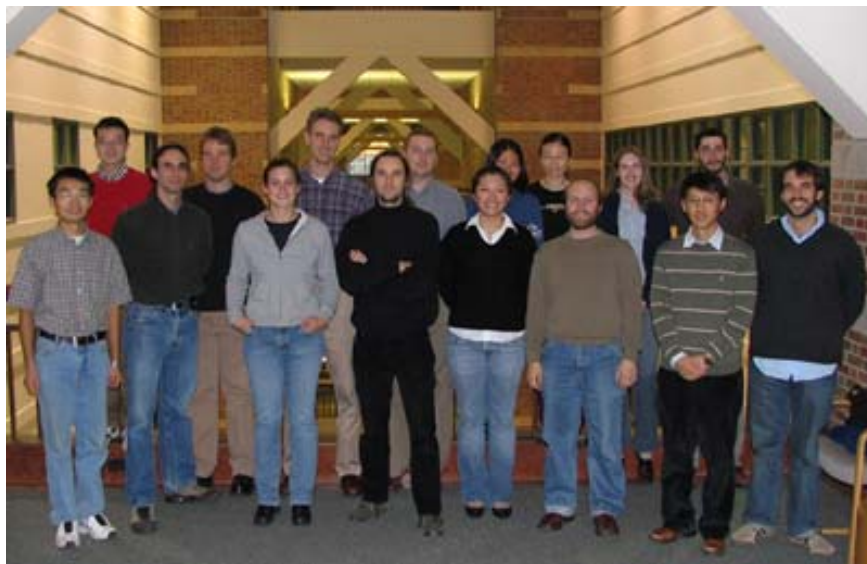
added 500nm
colloids
(outside cavity)



Trapped colloidal fluid



Acknowledgements



Graduate Students

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Erik Nelson
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Vinayak Ramanan
Robert Shimmin
Margaret Shyr
Xindi Yu

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Santamaría
Dr. Wonmok Lee
Dr. Ryan Kershner
Dr. Weon Sik Chae
Dr. J. T. Lee
Dr. Joe Geddes
Dr. Dong-Guk Yu

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(Stanford)
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Greg Gratson
Mingjie Xu
Prof. Pierre Wiltzius
Dr. Martin Piech (SNL)
Dr. Nelson Bell (SNL)



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Foundation, DOE, NSF, 3M

Facilities

Center for Microanalysis of Materials, Frederick Seitz
Materials Research Laboratory

Imaging Technologies Group, Beckman Institute