Photonic Crystals:
Periodic Surprises in Electromagnetism

Steven G. Johnson
MIT

Those Clever Experimentalists

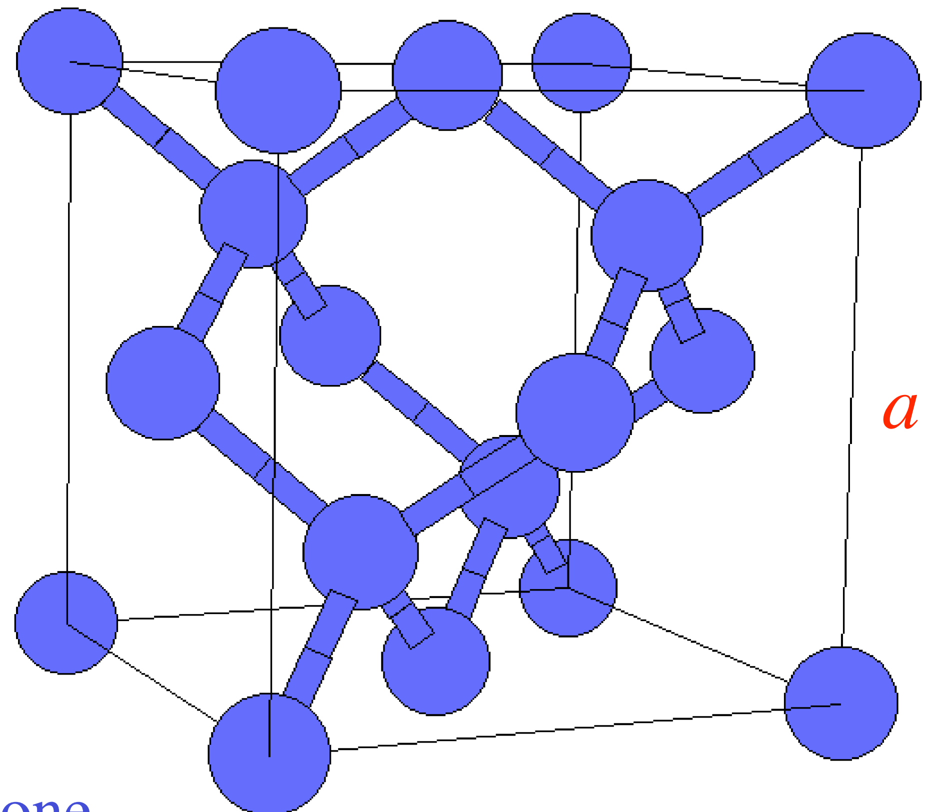
Fabrication of Three-Dimensional Crystals

The Mother of (almost) All Bandgaps

The diamond lattice:

fcc (face-centered-cubic)
with two "atoms" per unit cell

(primitive)



Recipe for a complete gap:

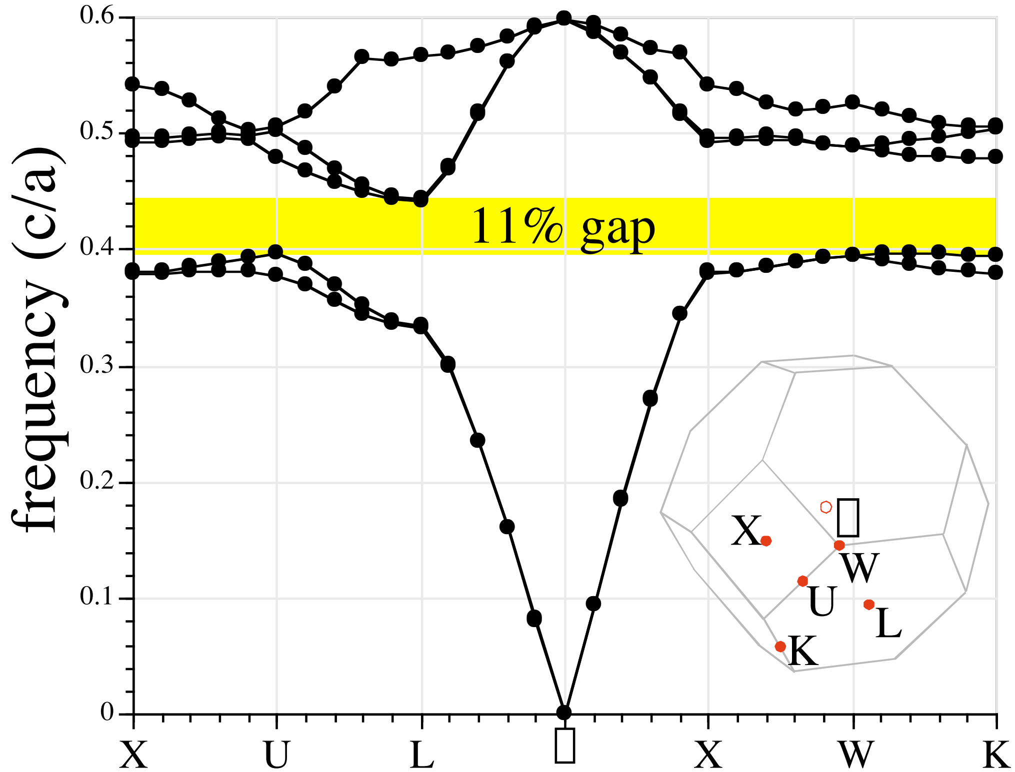
fcc = most-spherical Brillouin zone

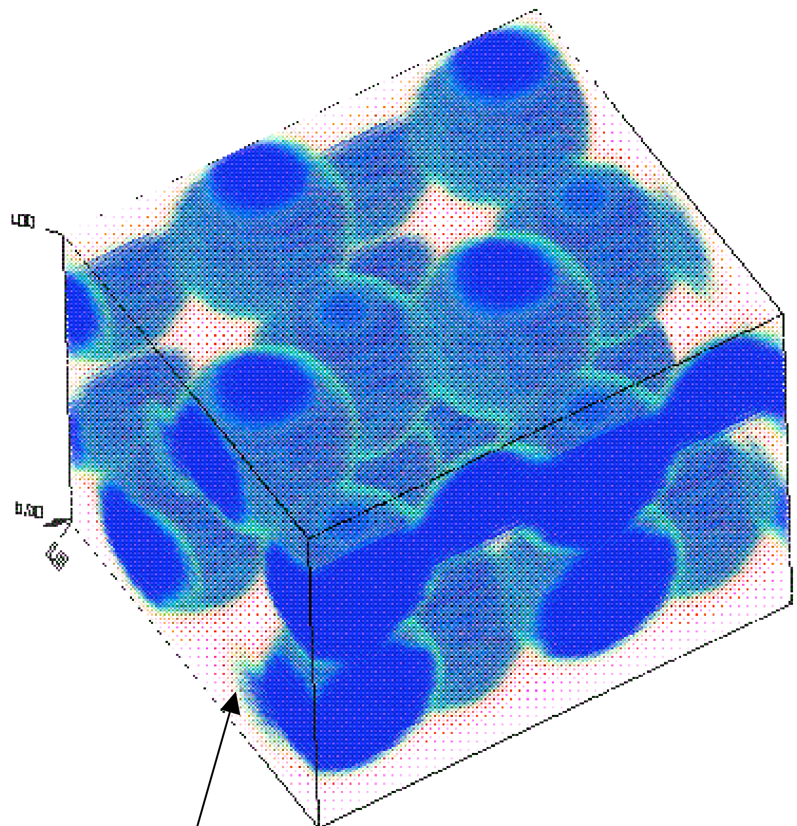
+ diamond "bonds" = lowest (two) bands can concentrate in lines

Image: **http://cst-www.nrl.navy.mil/lattice/struk/a4.html**

The First 3d Bandgap Structure

K. M. Ho, C. T. Chan, and C. M. Soukoulis, *Phys. Rev. Lett.* **65**, 3152 (1990).





for gap at $\lambda = 1.55\mu m$,
sphere diameter ~ 330nm

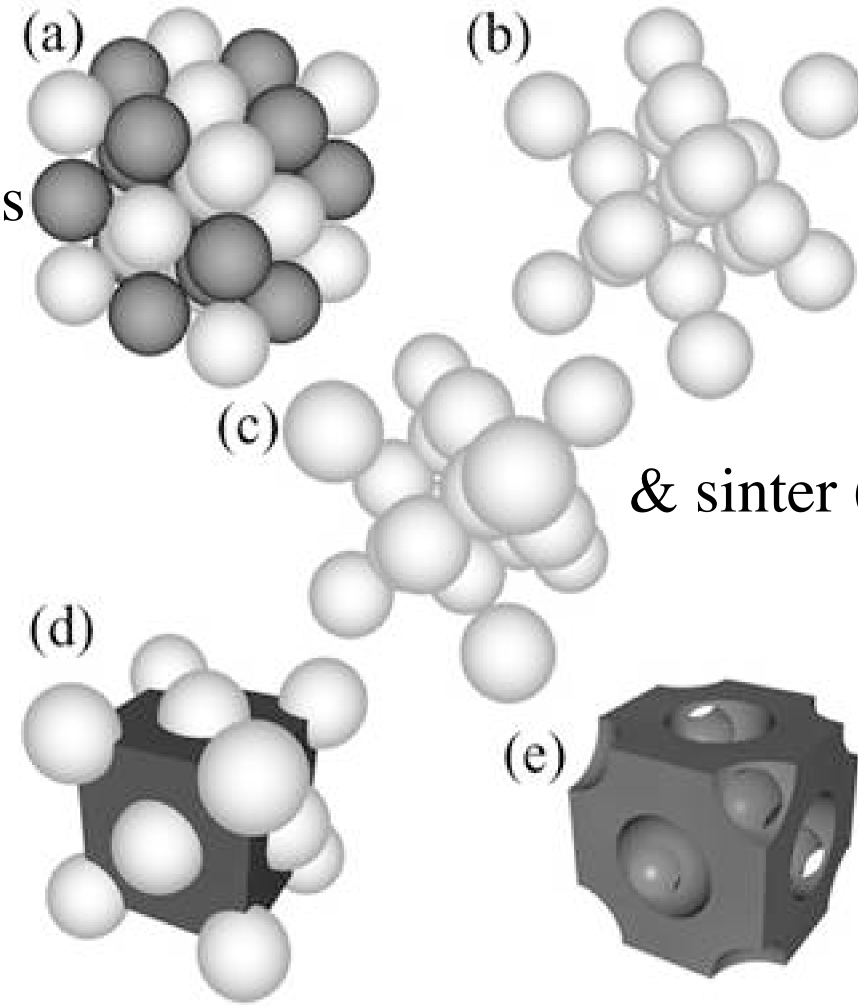
overlapping Si spheres

MPB tutorial, `http://ab-initio.mit.edu/mpb`

Make *that*? Are you crazy? …maybe!

fabrication schematic

carefully stack bcc
silica & latex spheres
via micromanipulation



…dissolve latex

& sinter (heat and fuse)
silica

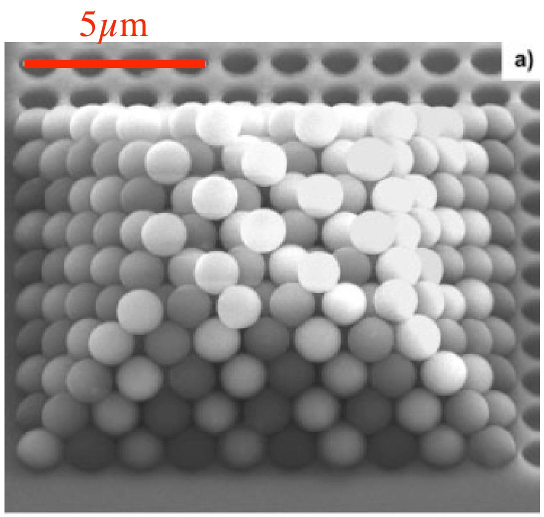
make Si inverse
(12% gap)

[F. Garcia-Santamaria *et al.*, *APL* **79**, 2309 (2001)]

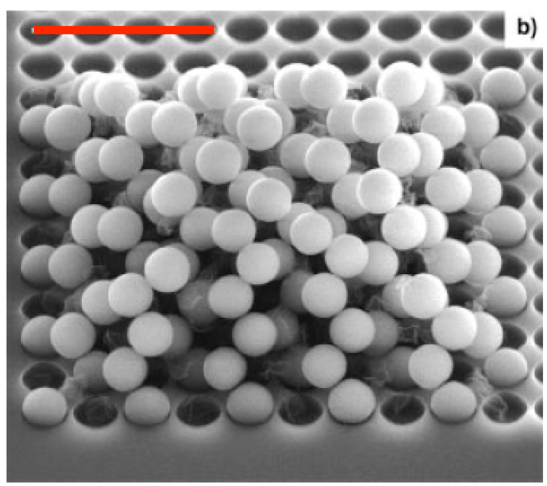
`http://www.icmm.csic.es/cefe/Fab/Robot/robot_strategy.htm`

Make *that*? Are you crazy? …maybe!

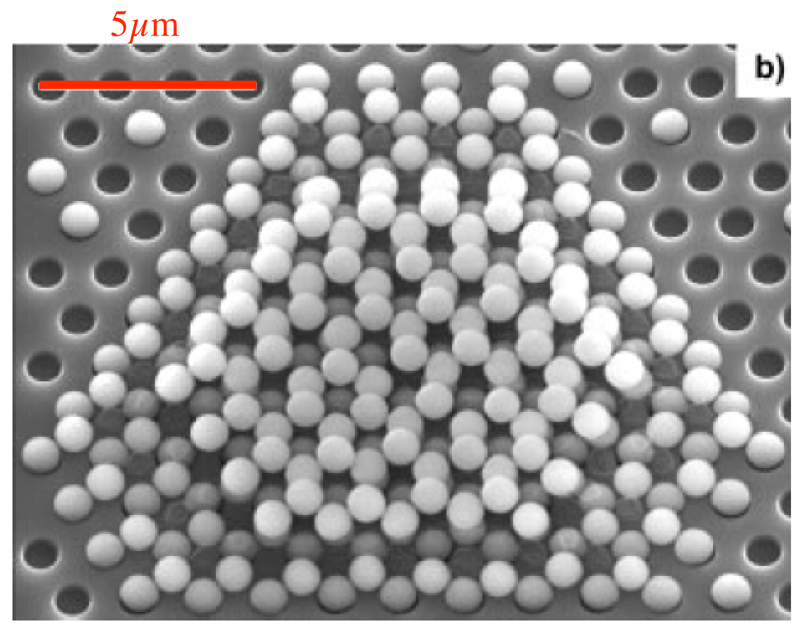
[F. Garcia-Santamaria *et al*., *Adv*. *Mater*. **14** (16), 1144 (2002).]



dissolve
latex spheres



6-layer [001] silica diamond lattice



4-layer [111] silica diamond lattice

Fortunately,
there are easier ways.

Layer-by-Layer Lithography

• Fabrication of 2d patterns in Si or GaAs is very advanced
(think: Pentium IV, 50 million transistors)

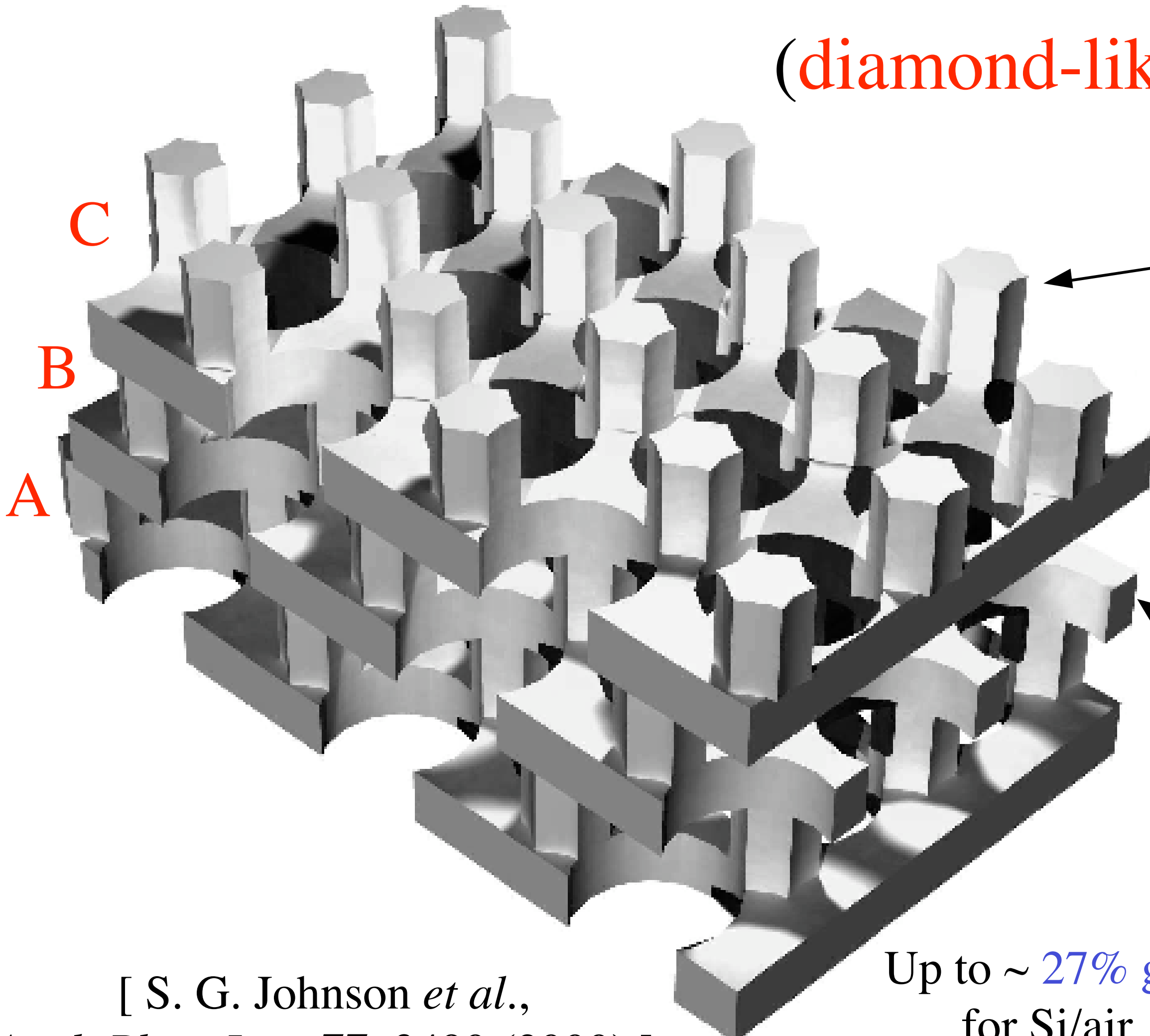
…inter-layer alignment techniques are only slightly more exotic

So, make 3d structure one layer at a time

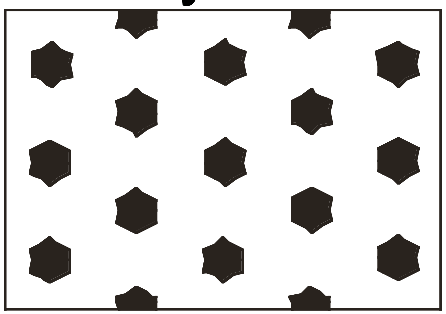
Need a 3d crystal with constant cross-section layers

A Layered Structure We've Seen Already

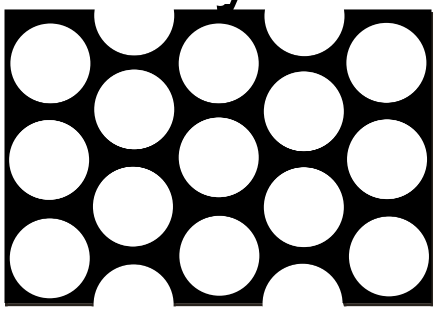
(diamond-like: rods ~ "bonds")



rod layer



hole layer



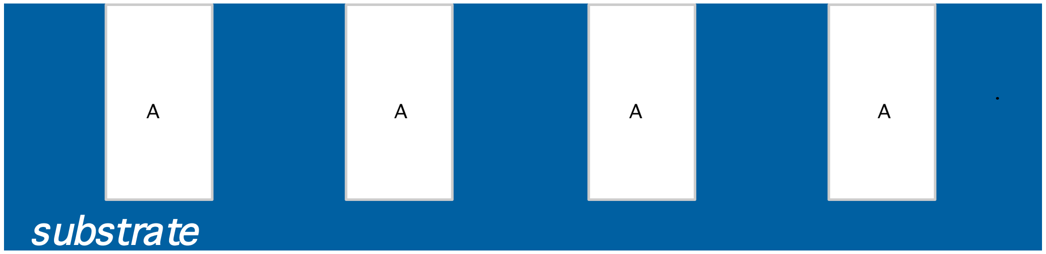
[S. G. Johnson *et al.*,
Appl. Phys. Lett. **77**, 3490 (2000)]

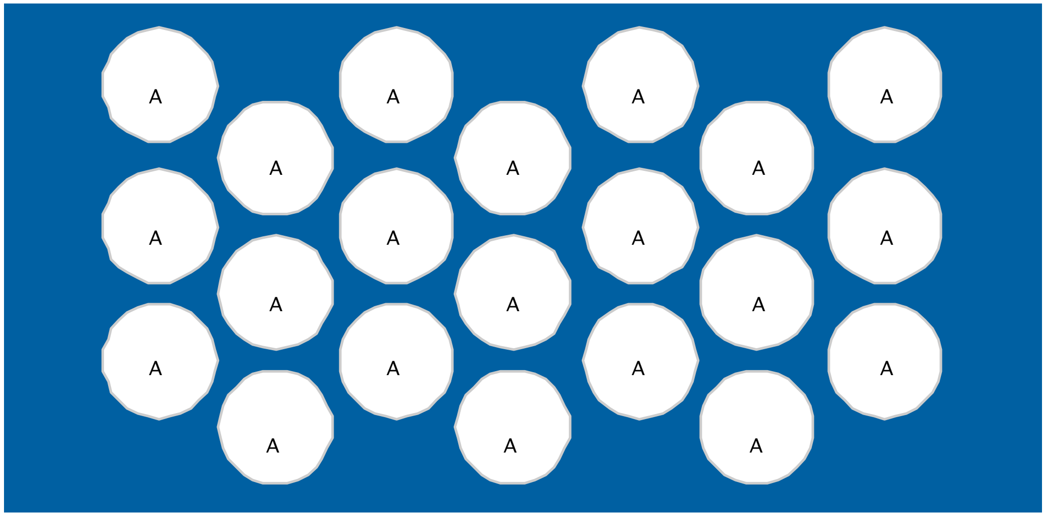
Up to ~ 27% gap
for Si/air

Making Rods & Holes Simultaneously

Making Rods & Holes Simultaneously

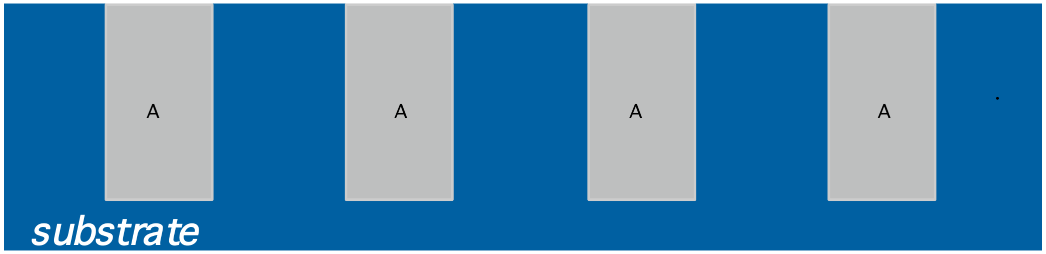
expose/etch
holes

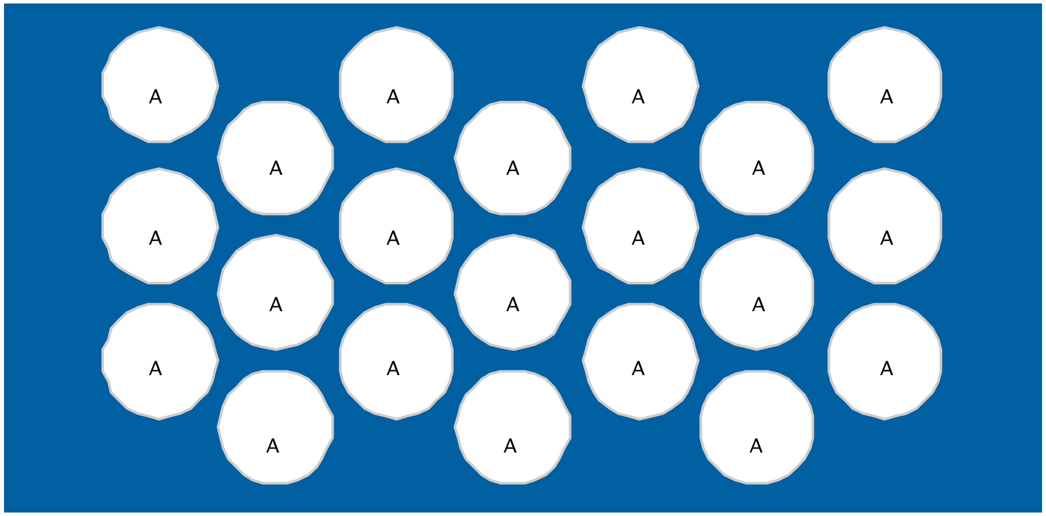




Making Rods & Holes Simultaneously

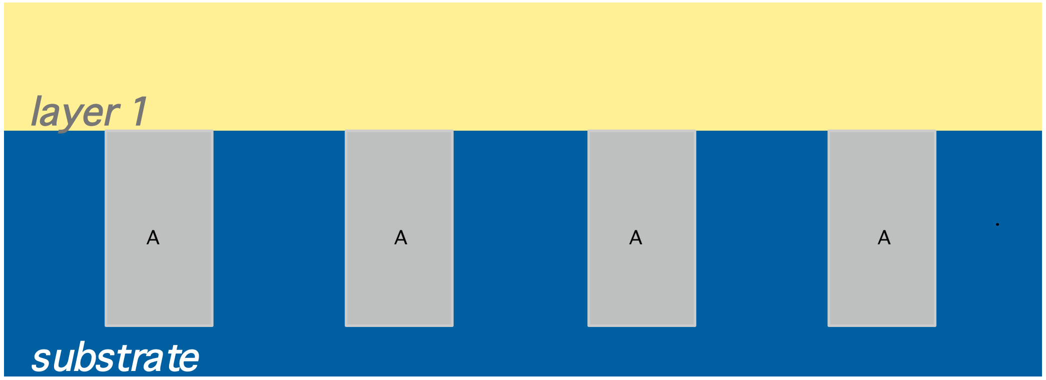
backfill with silica (SiO_2) & polish

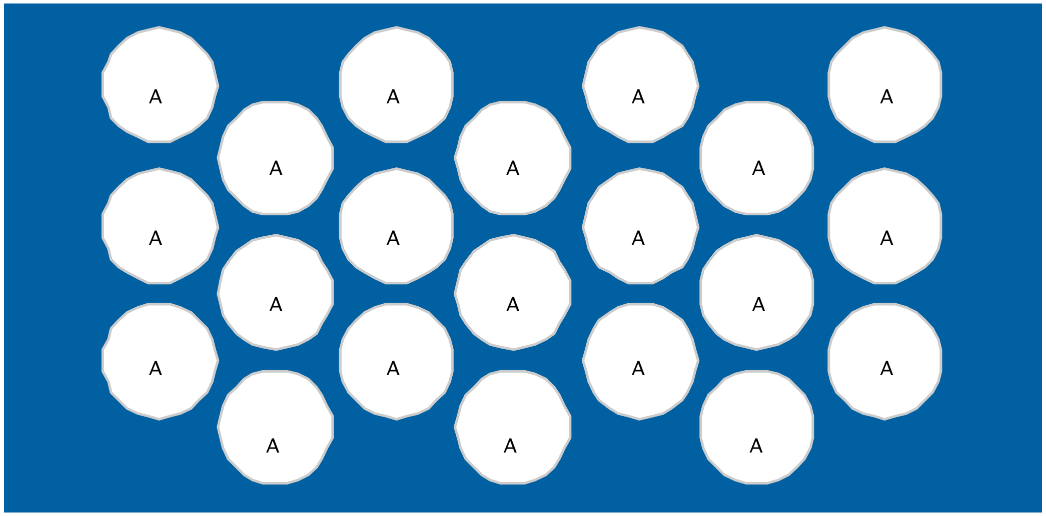




Making Rods & Holes Simultaneously

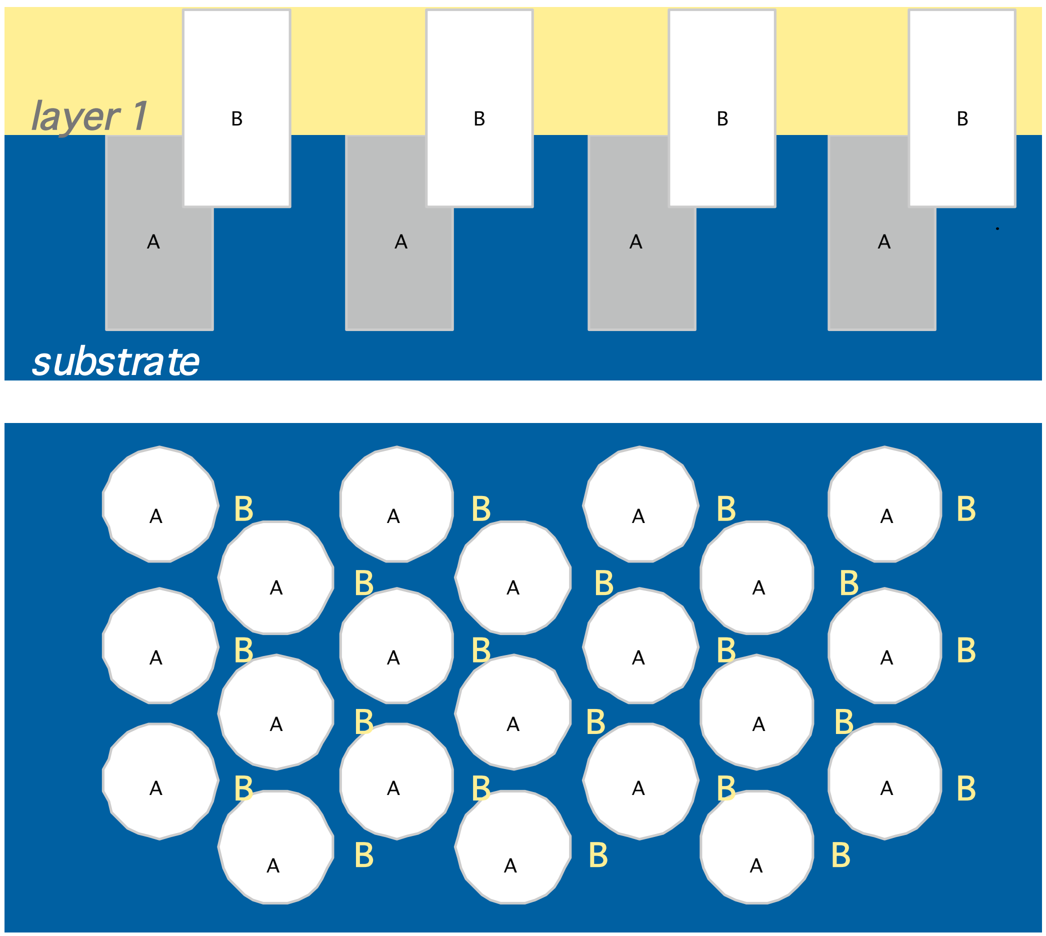
deposit another
Si layer





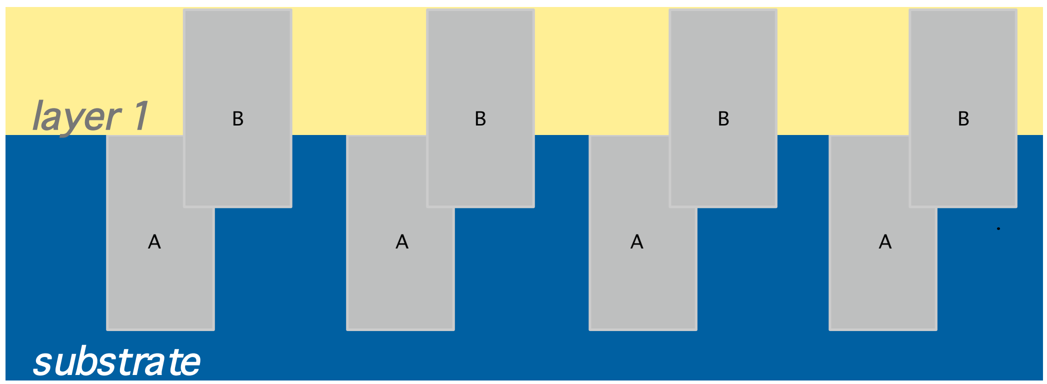
Making Rods & Holes Simultaneously

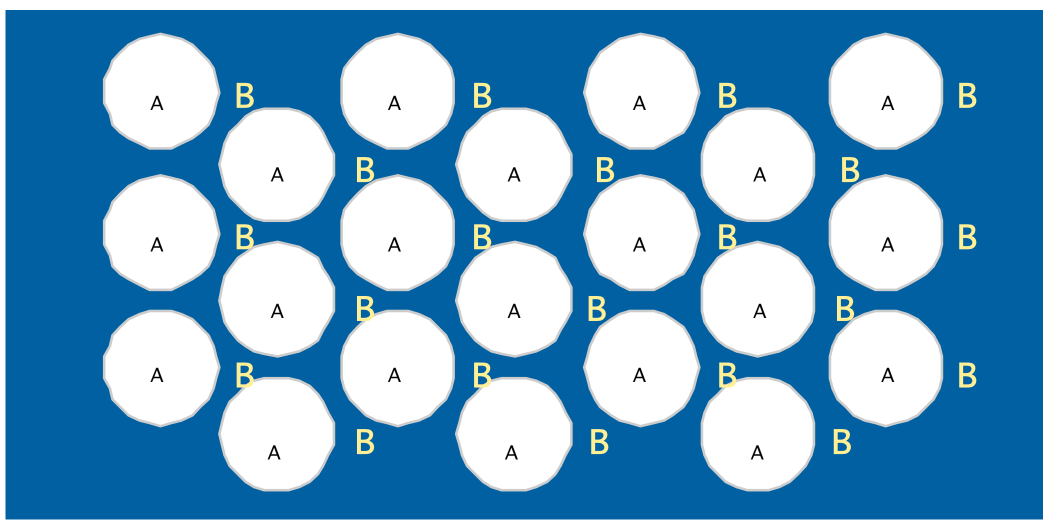
dig more holes
offset
& overlapping



Making Rods & Holes Simultaneously

backfill

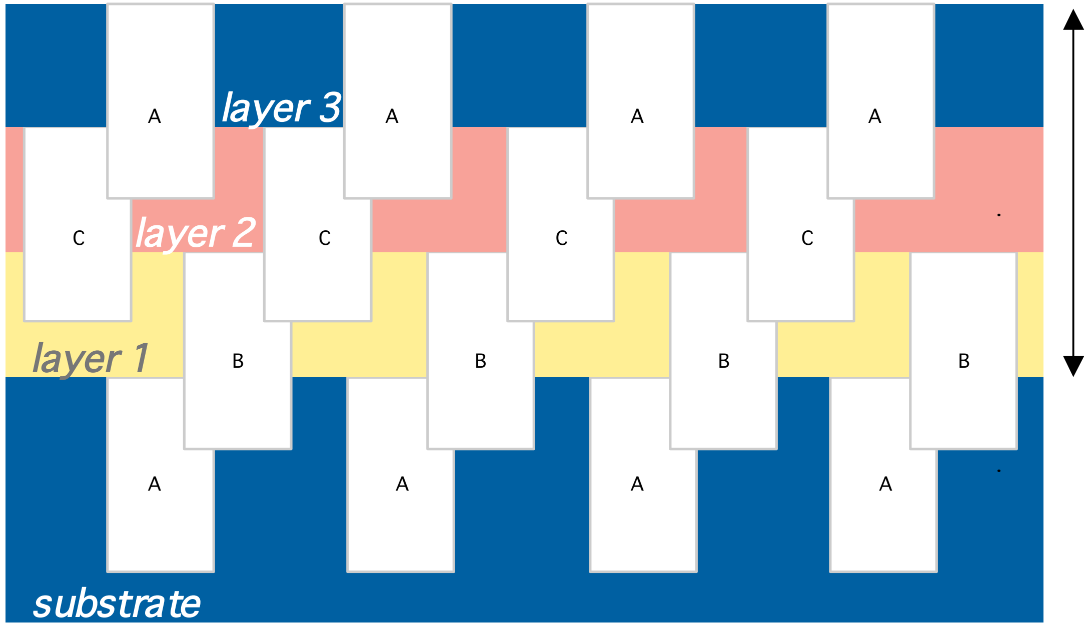




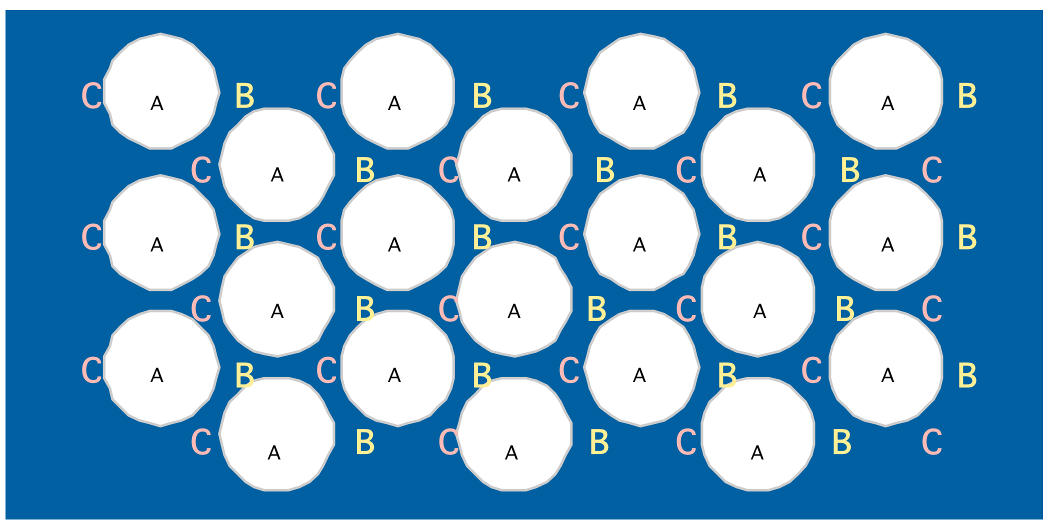
Making Rods & Holes Simultaneously

etcetera

(dissolve silica when done)

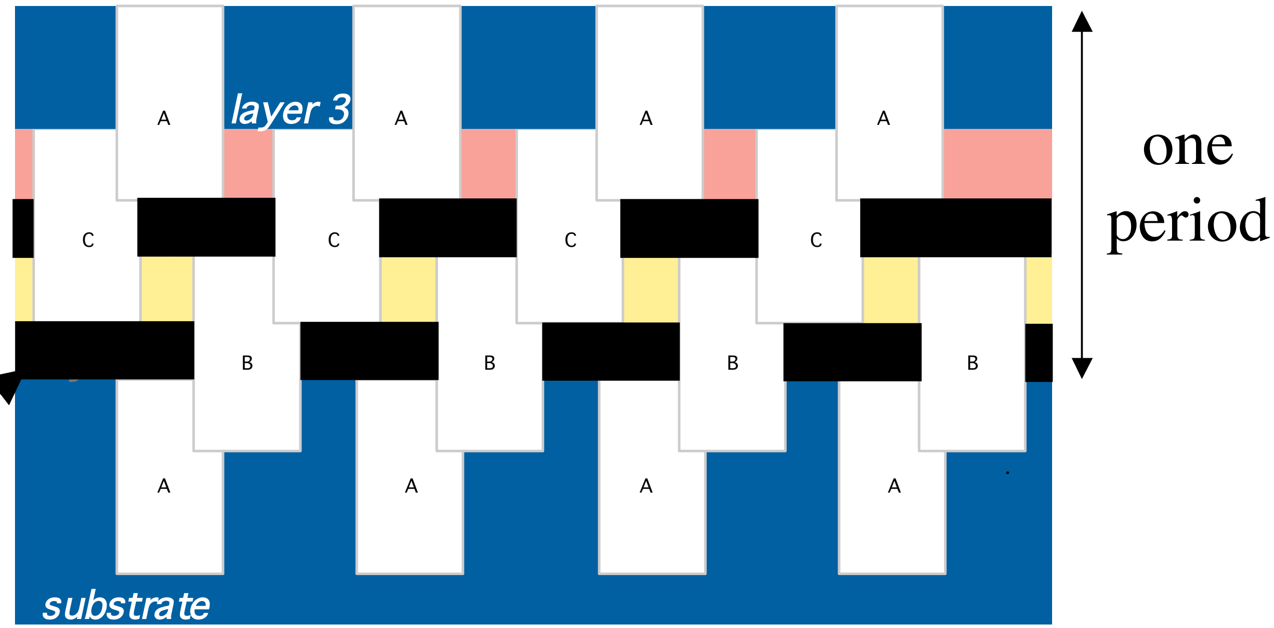


one period

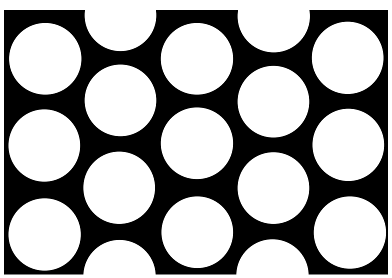


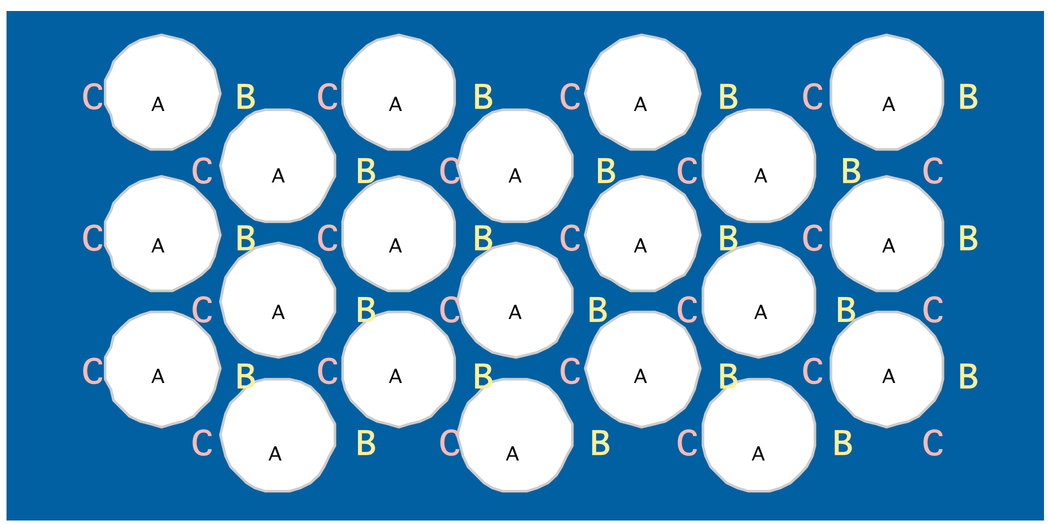
Making Rods & Holes Simultaneously

etcetera



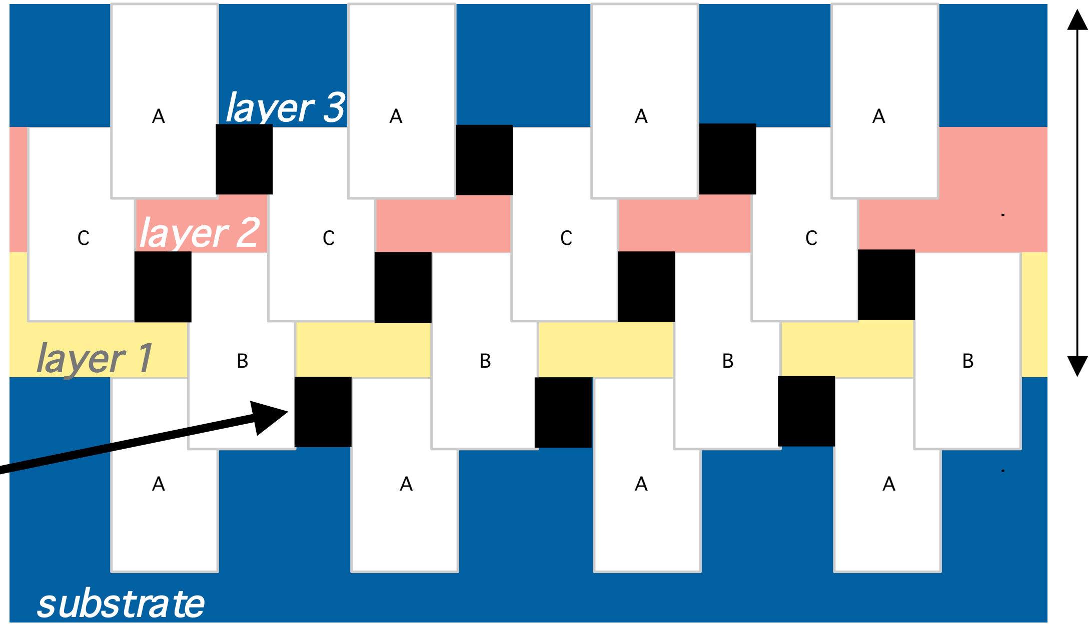
hole layers





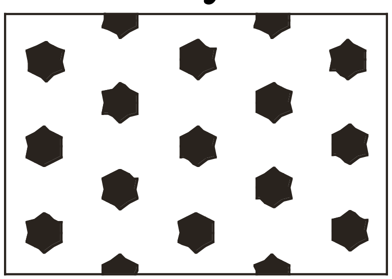
Making Rods & Holes Simultaneously

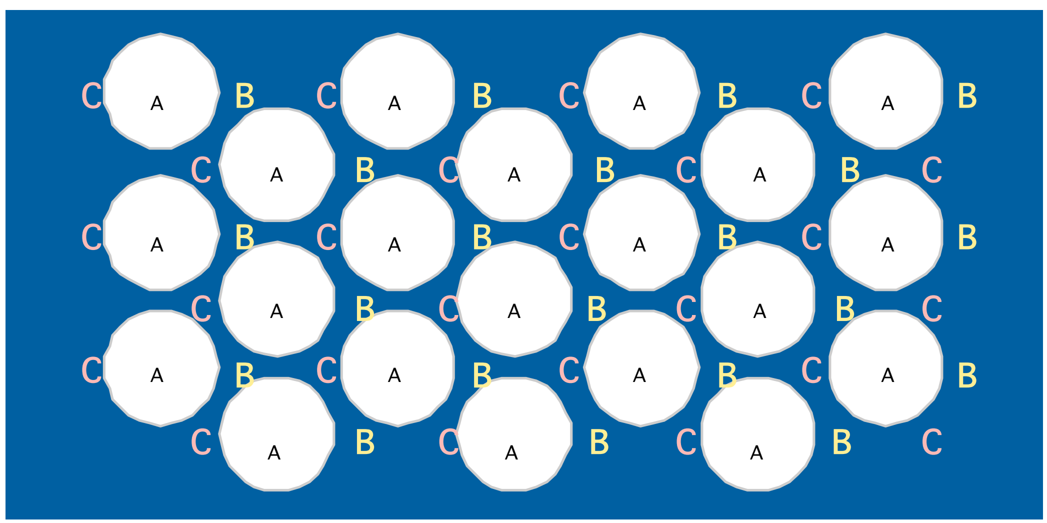
etcetera



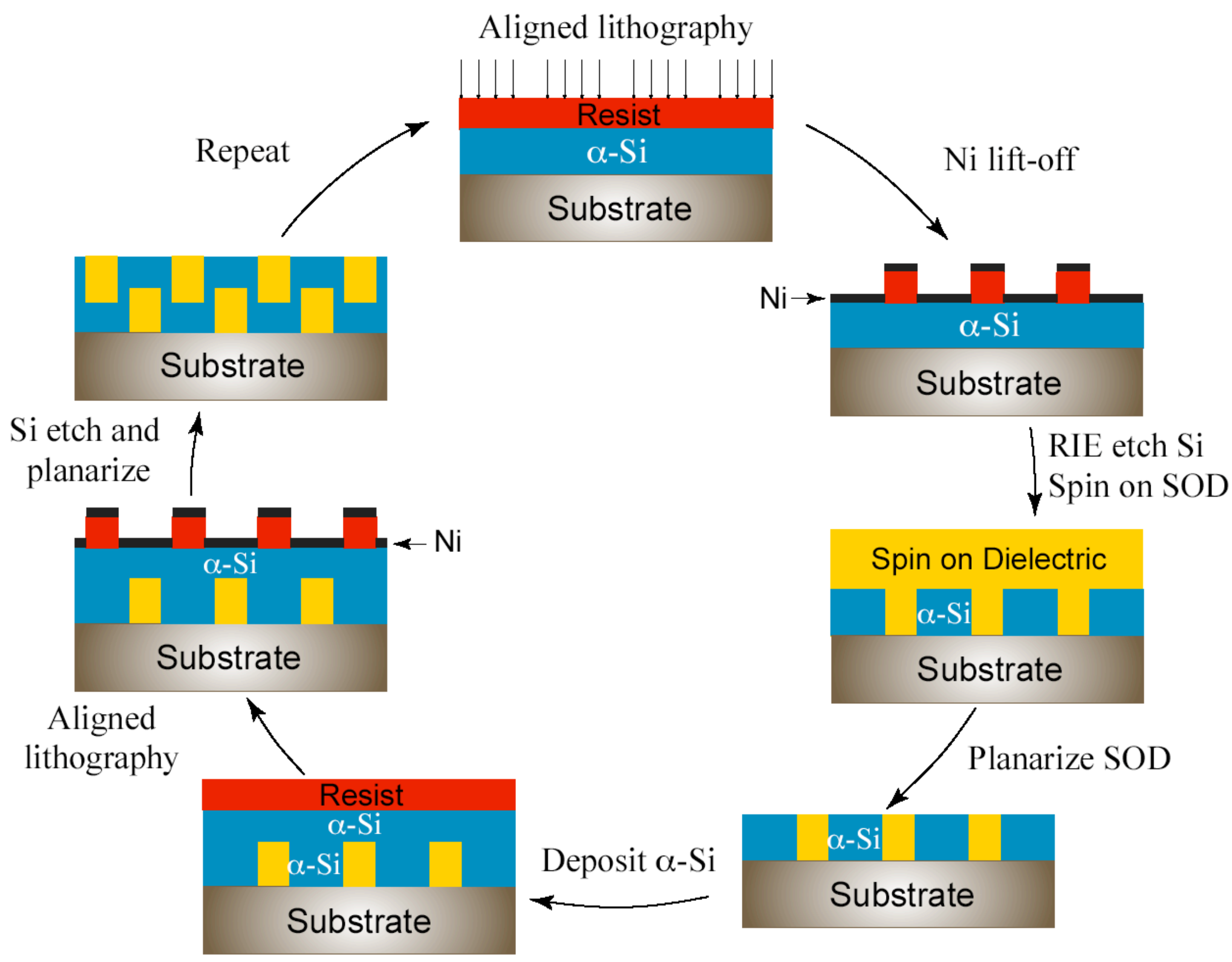
one period

rod layers



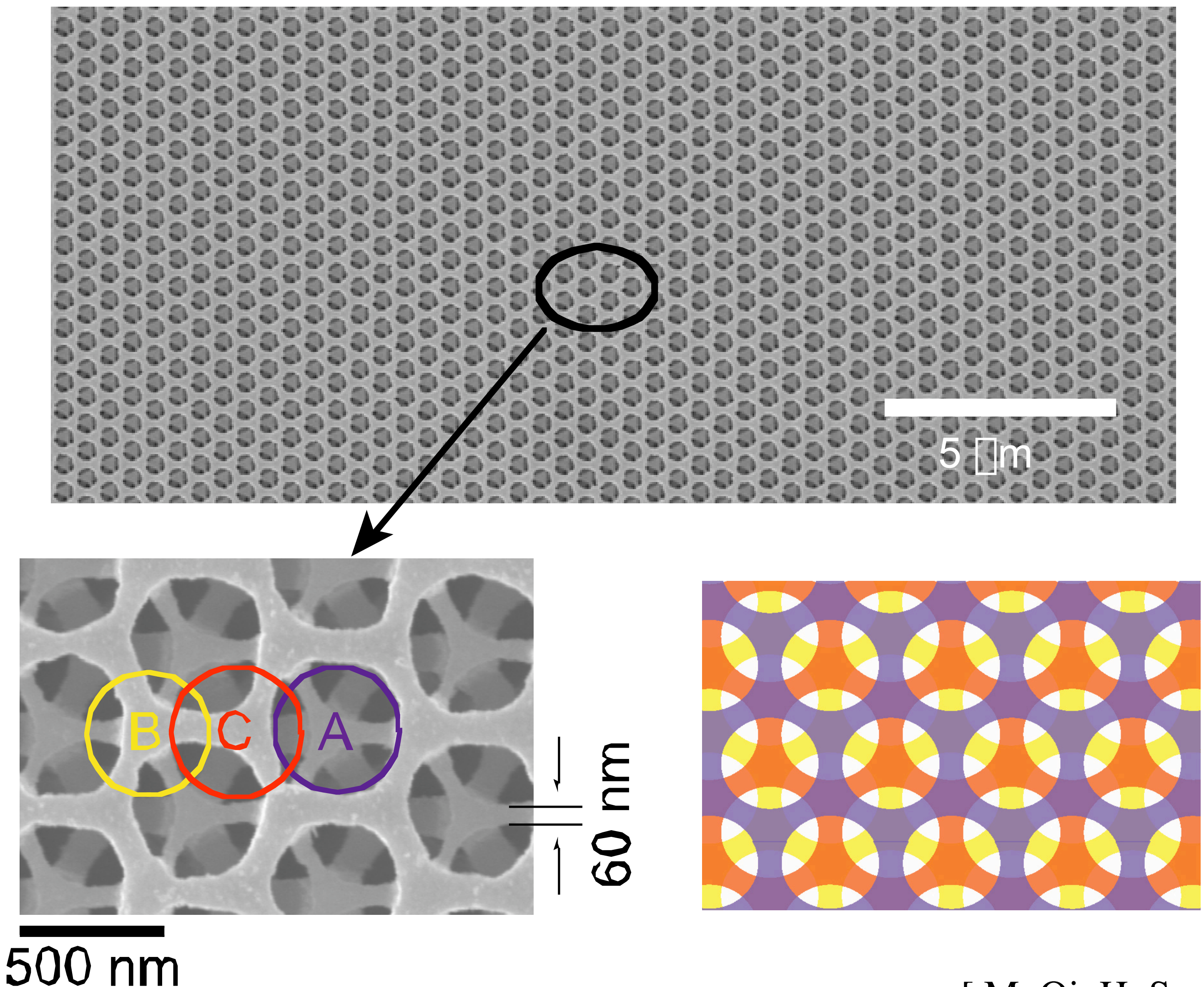


A More Realistic Schematic



[M. Qi, H. Smith, MIT]

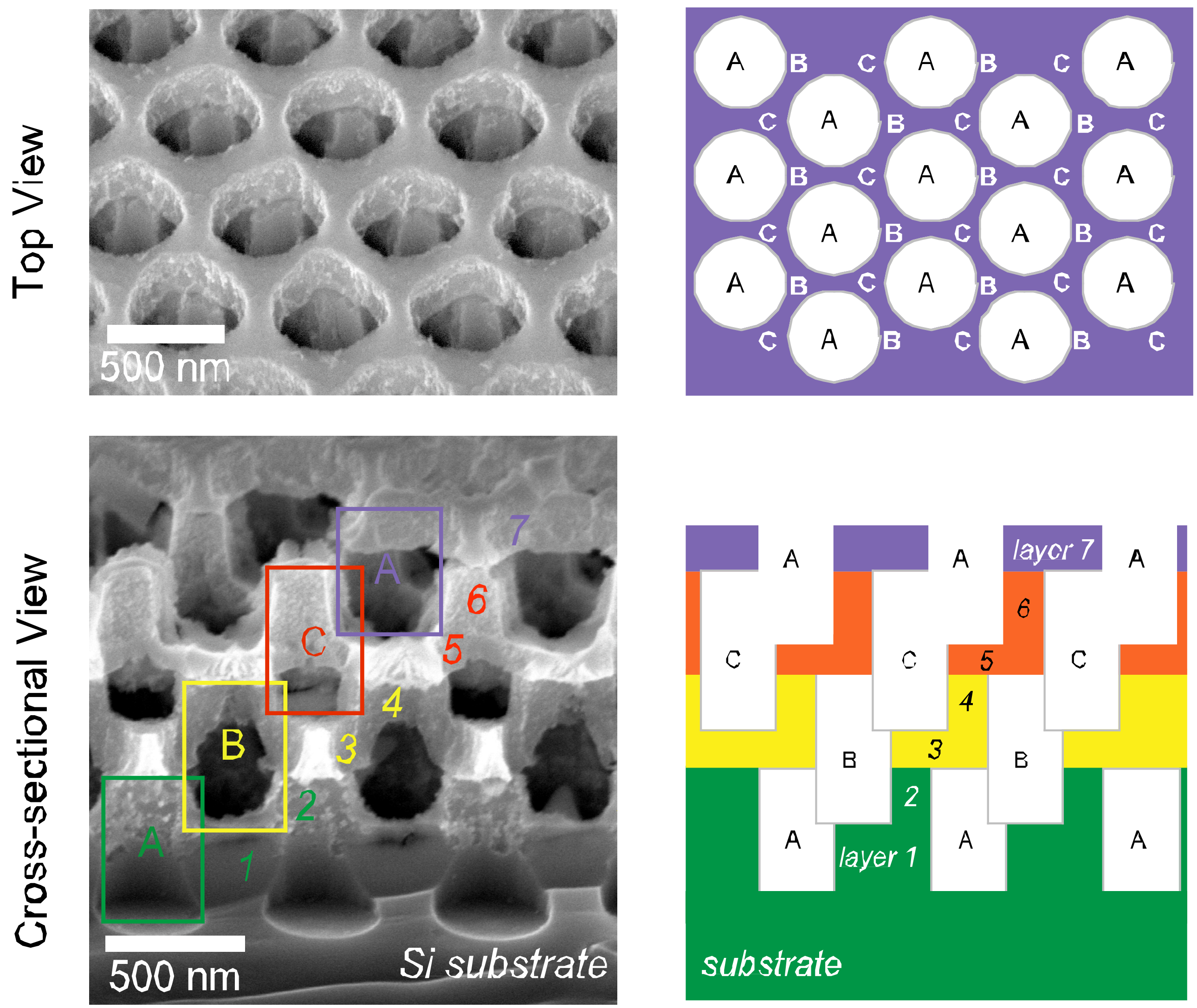
e-beam Fabrication: Top View



[M. Qi, H. Smith, MIT]

e-beam Fabrication: Side Views

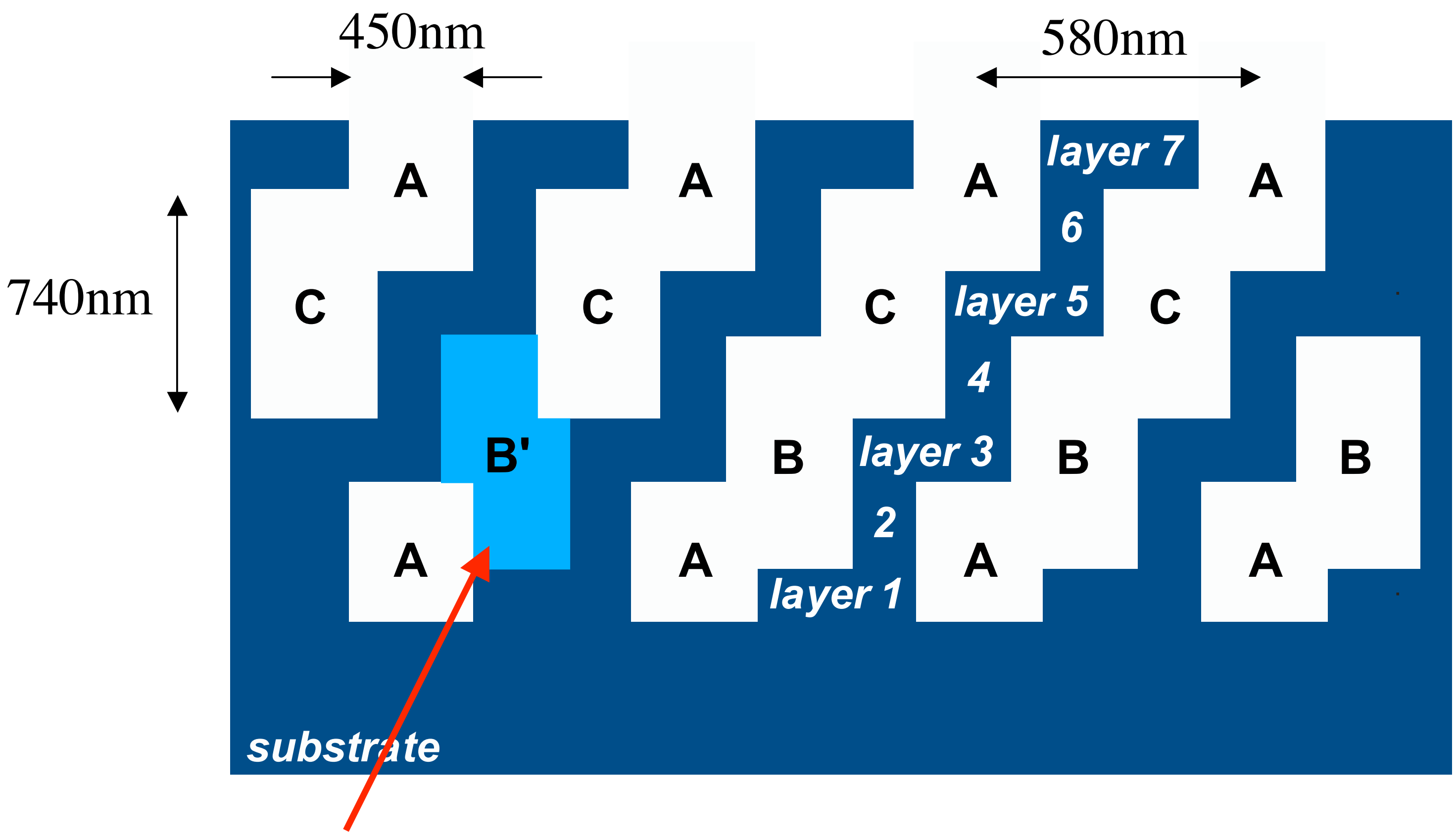
(cleaving worst sample)



(a) SEM micrograph (b) Schematic

[M. Qi, H. Smith, MIT]

Adding "Defect" Microcavities



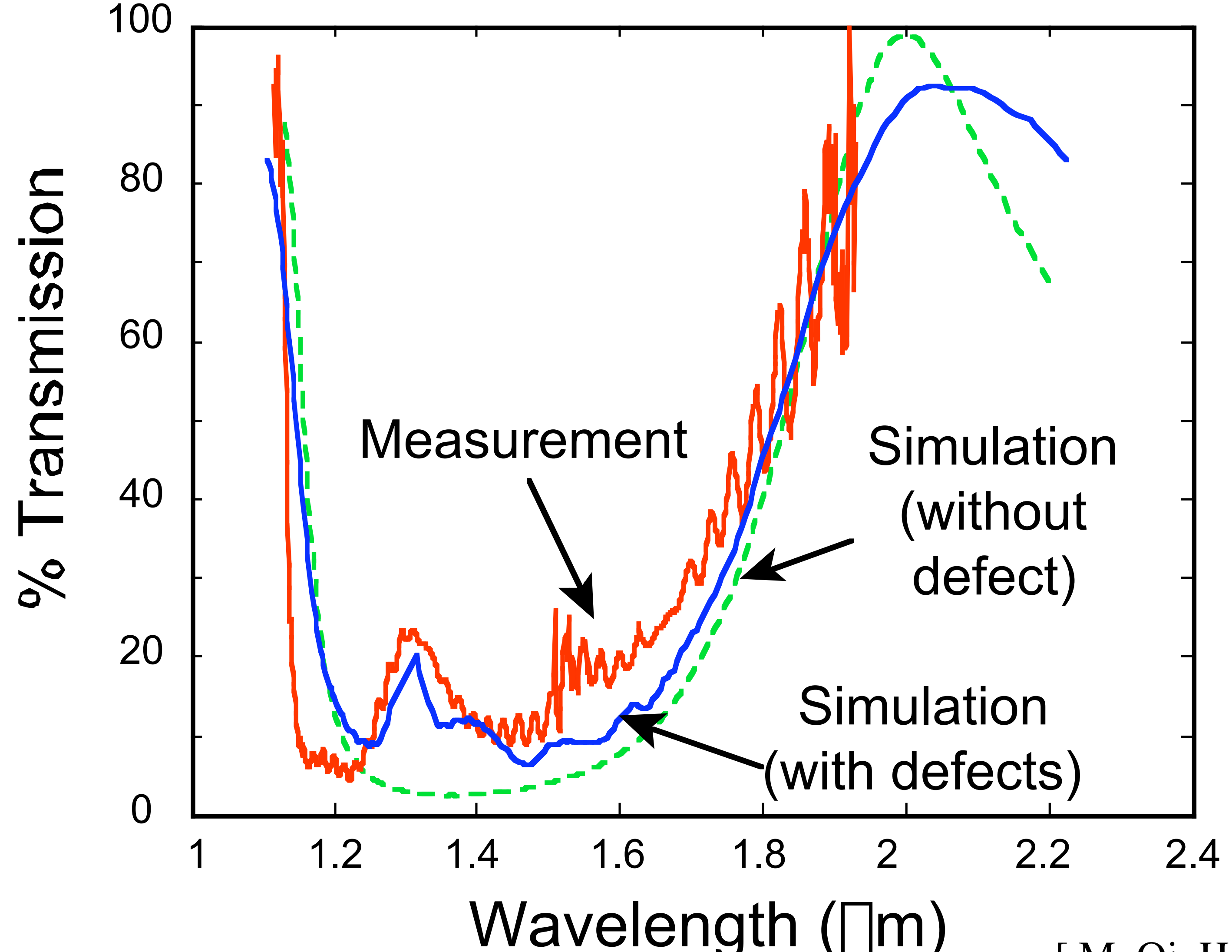
Easiest defect: don't etch some **B** holes

— non-periodically distributed: suppresses sub-band structure

— low Q = easier to detect from planewave

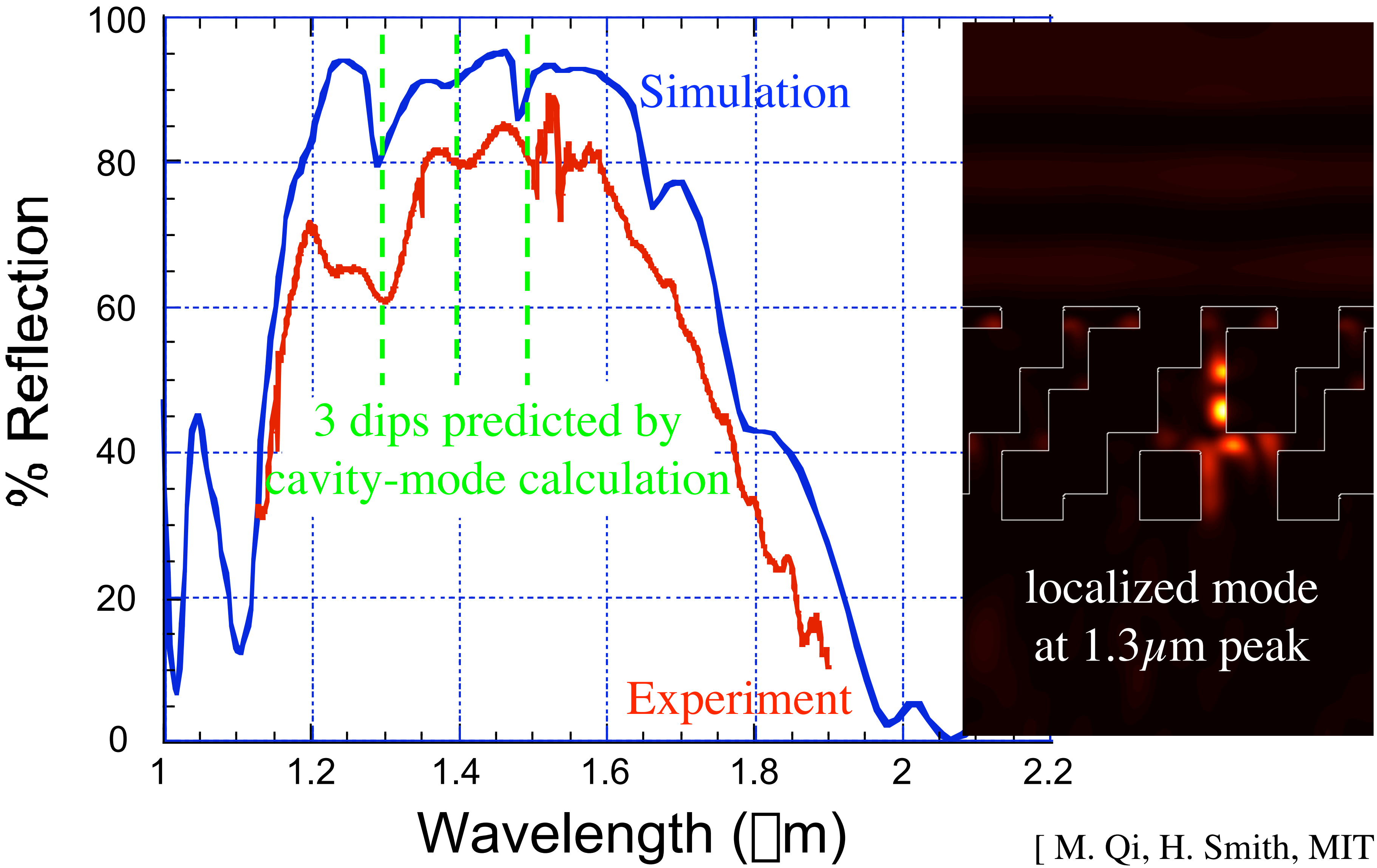
[M. Qi, H. Smith, MIT]

Supercontinuum-Source vs. Theoretical Transmission Spectra



[M. Qi, H. Smith, MIT]

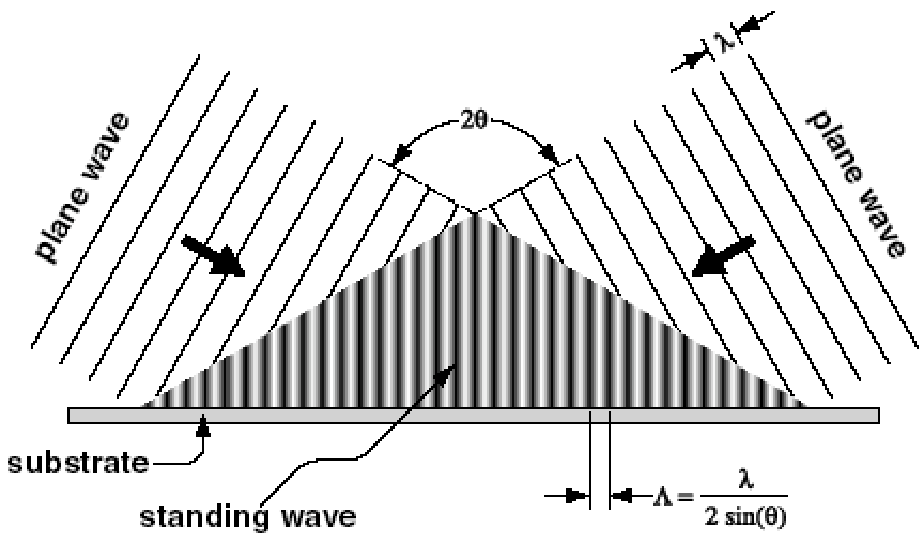
Supercontiuum vs. Theory: Reflection

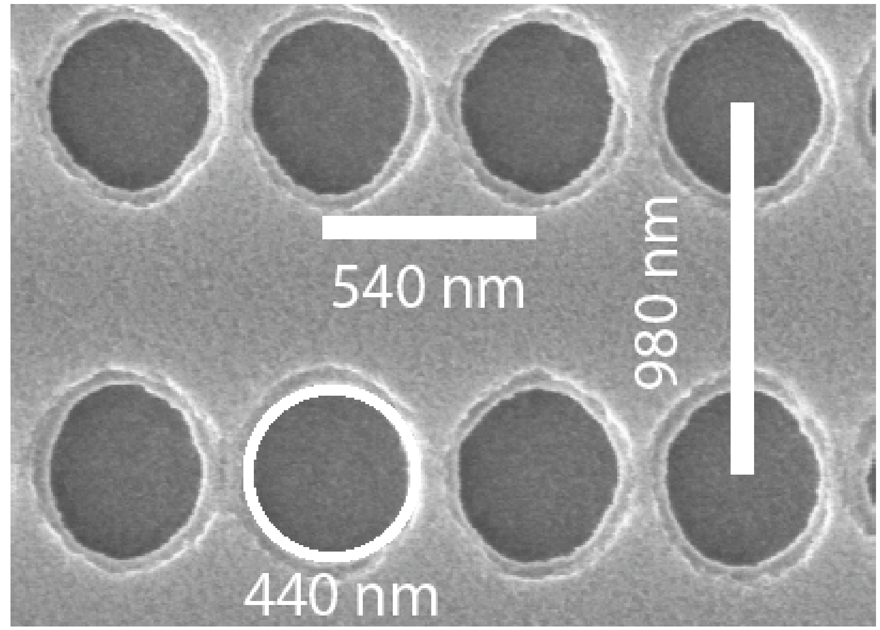


[M. Qi, H. Smith, MIT]

Future Work: X-ray Interference Lithography

[M. Qi, H. Smith, MIT]





The Good

Large area: up to 10x10cm!

Cheap ($50k vs. $500k for e-beam)

Nearly perfect periodicity

High resolution

The Ugly

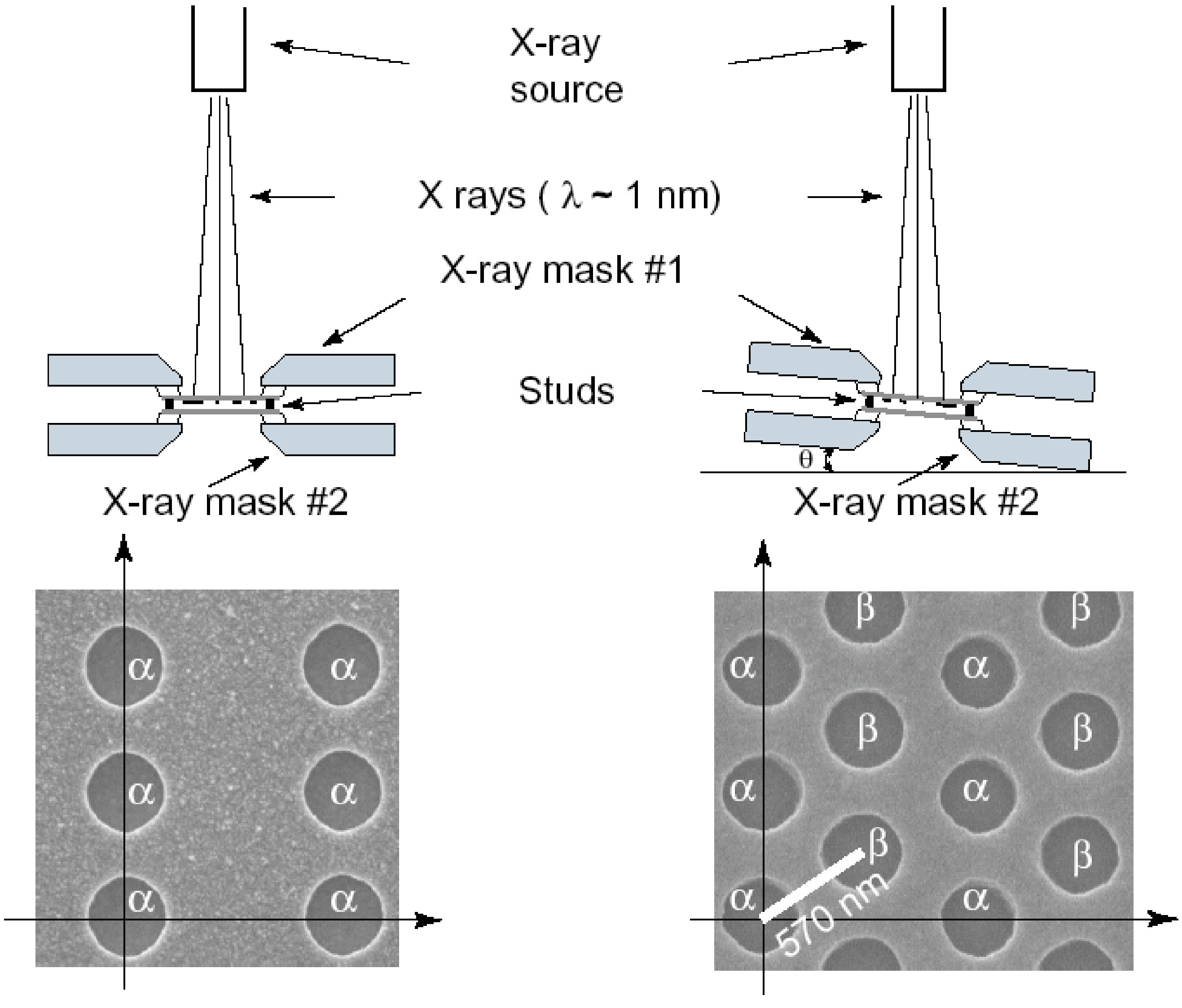
Layer alignment still tricky

no defects: use e-beam locally

non-rectangular more tricky…

From Rectangular to Hexagonal

[M. Qi, H. Smith, MIT]

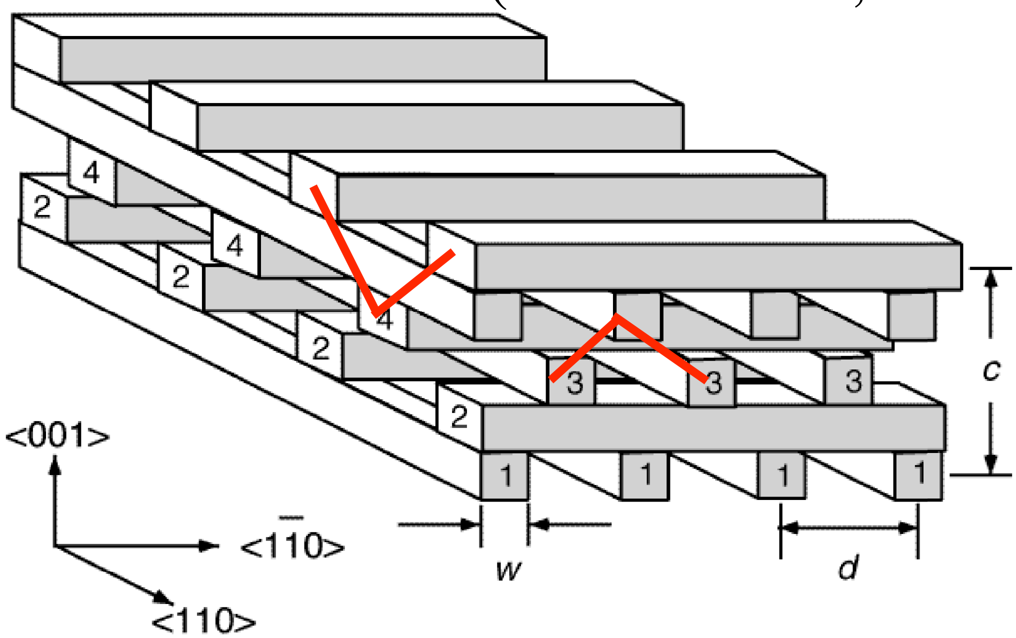


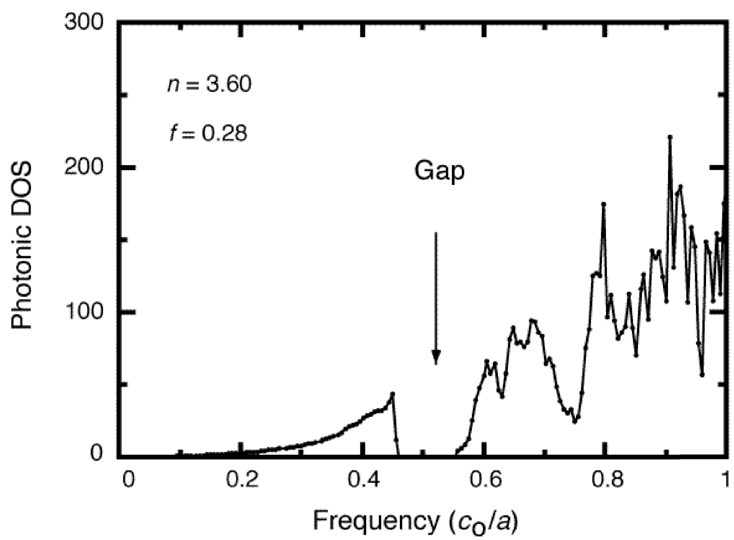
an earlier design:
(& currently more popular)

The Woodpile Crystal

[K. Ho *et al.*, *Solid State Comm.* **89**, 413 (1994)]   [H. S. Sözüer *et al.*, *J. Mod. Opt.* **41**, 231 (1994)]

(diamond-like, "bonds")





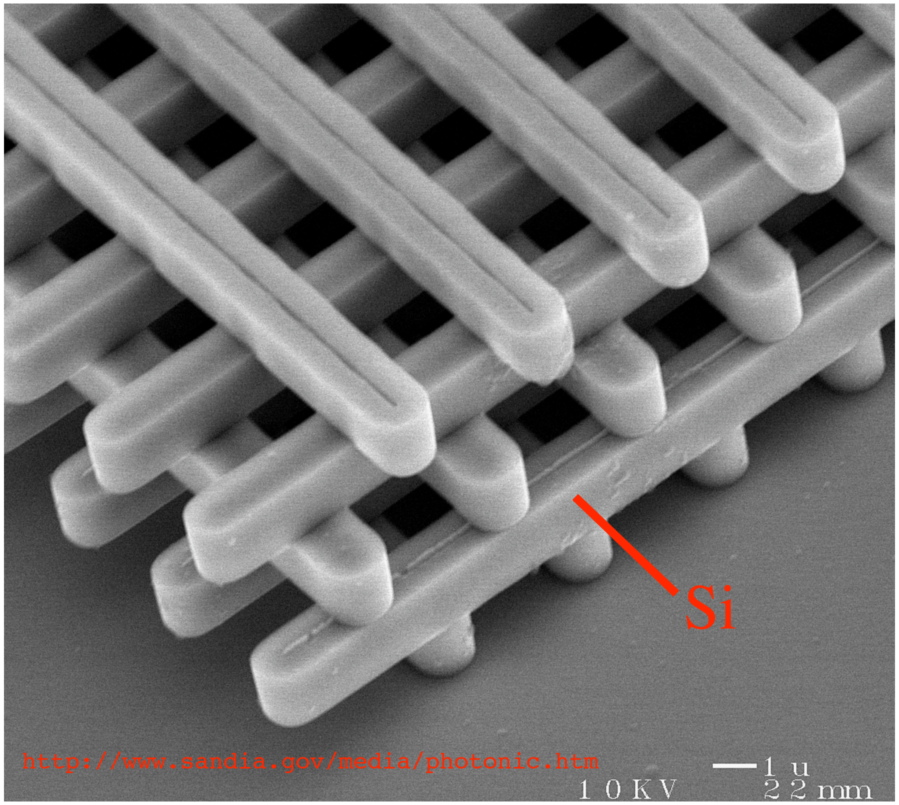
Up to ~ 17% gap for Si/air

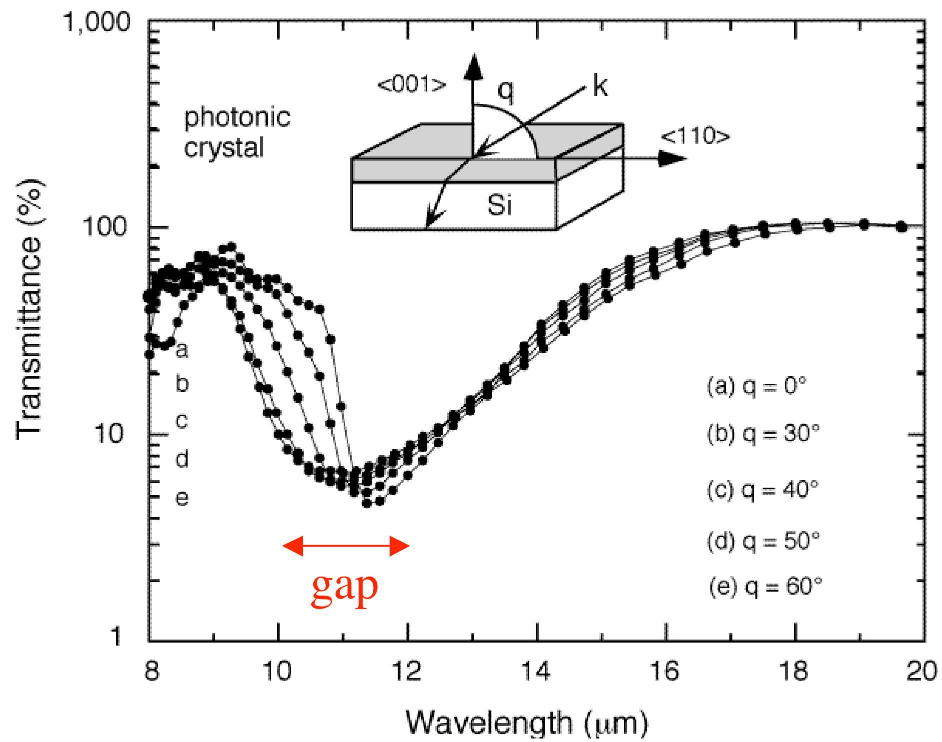
[Figures from S. Y. Lin *et al.*, *Nature* **394**, 251 (1998)]

1.25 Periods of Woodpile

(4 "log" layers = 1 period)

[S. Y. Lin *et al.*, *Nature* **394**, 251 (1998)]





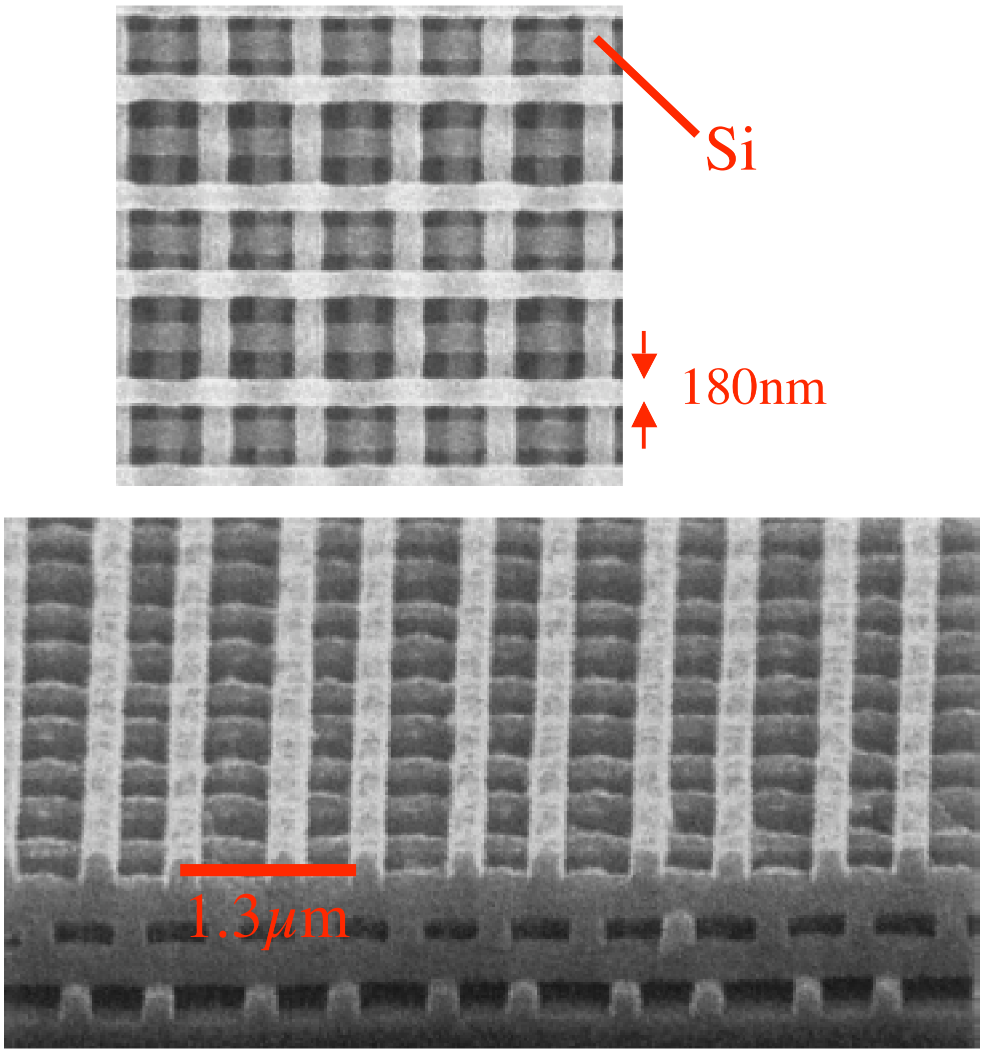
"UV Stepper:" e-beam mask at ~4x size
+ UV through mask, focused on substrate

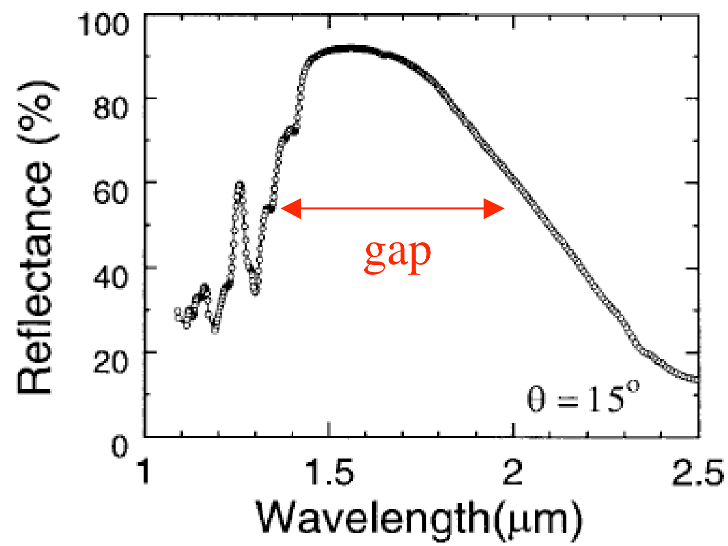
Good: high resolution, mass production   Bad: expensive ($20 million)

1.25 Periods of Woodpile @ 1.55μm

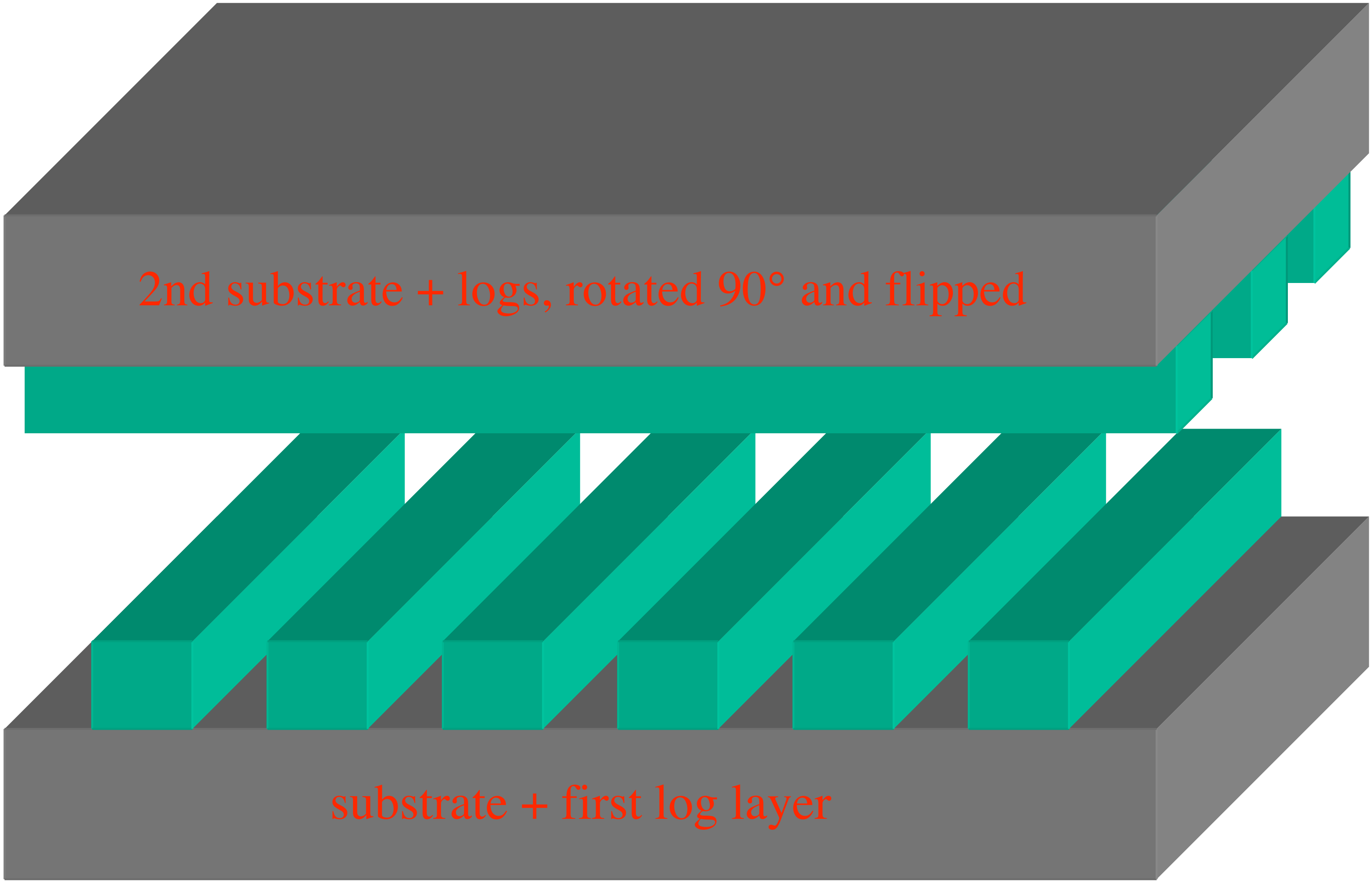
(4 "log" layers = 1 period)

[S. Y. Lin *et al.*, *Nature* **394**, 251 (1998)]



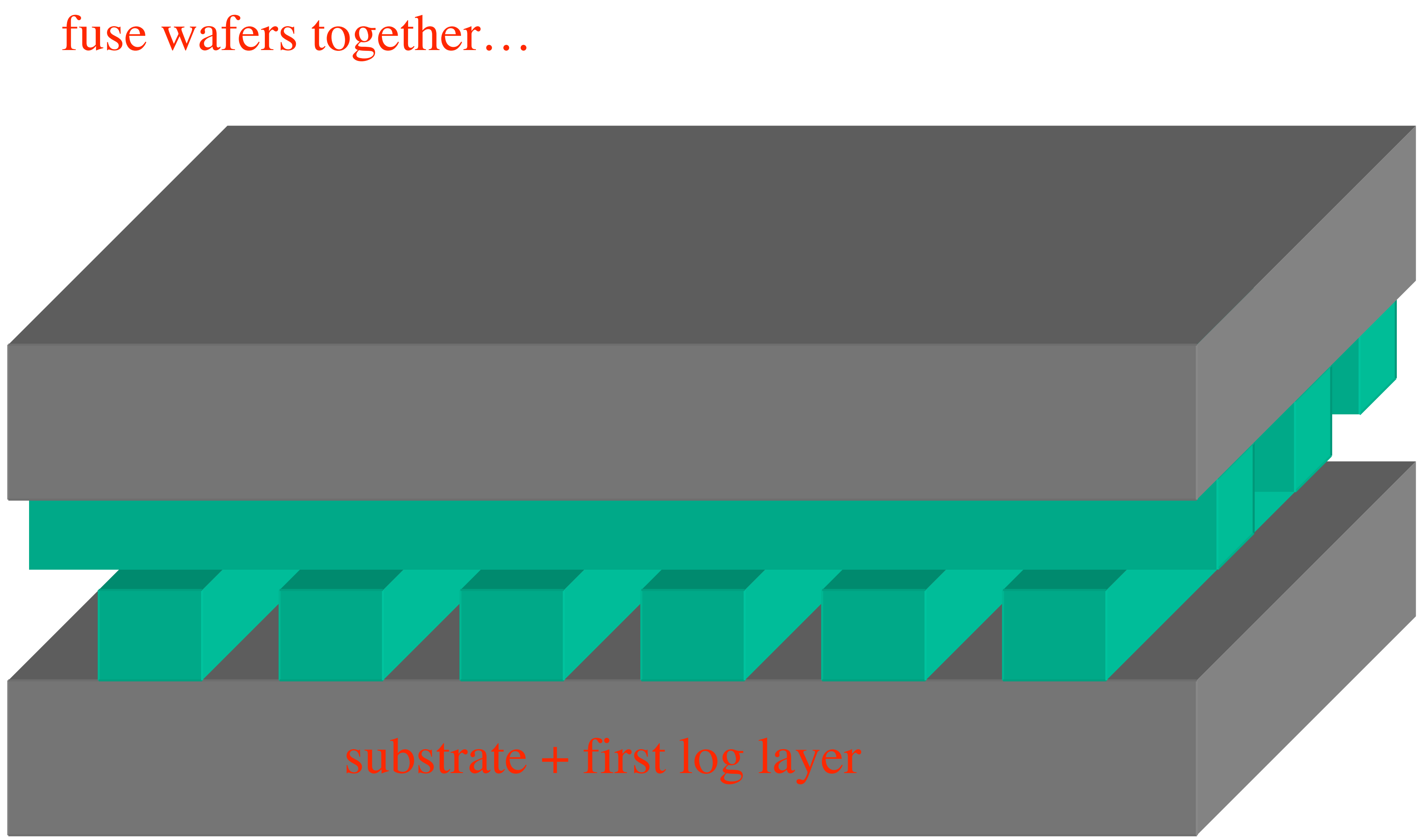


Woodpile by Wafer Fusion



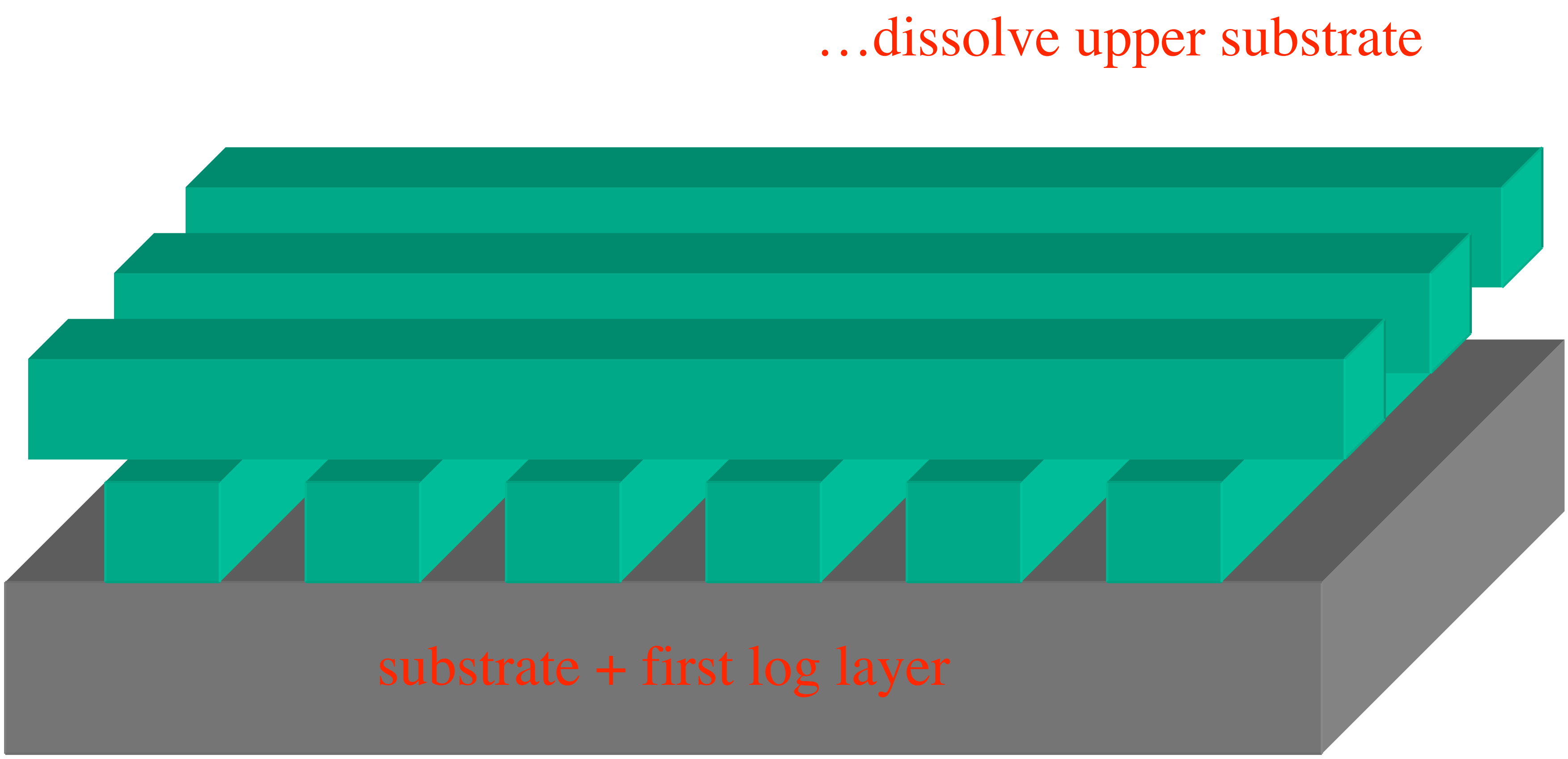
[S. Noda *et al.*, *Science* **289**, 604 (2000)]

Woodpile by Wafer Fusion



[S. Noda *et al.*, *Science* **289**, 604 (2000)]

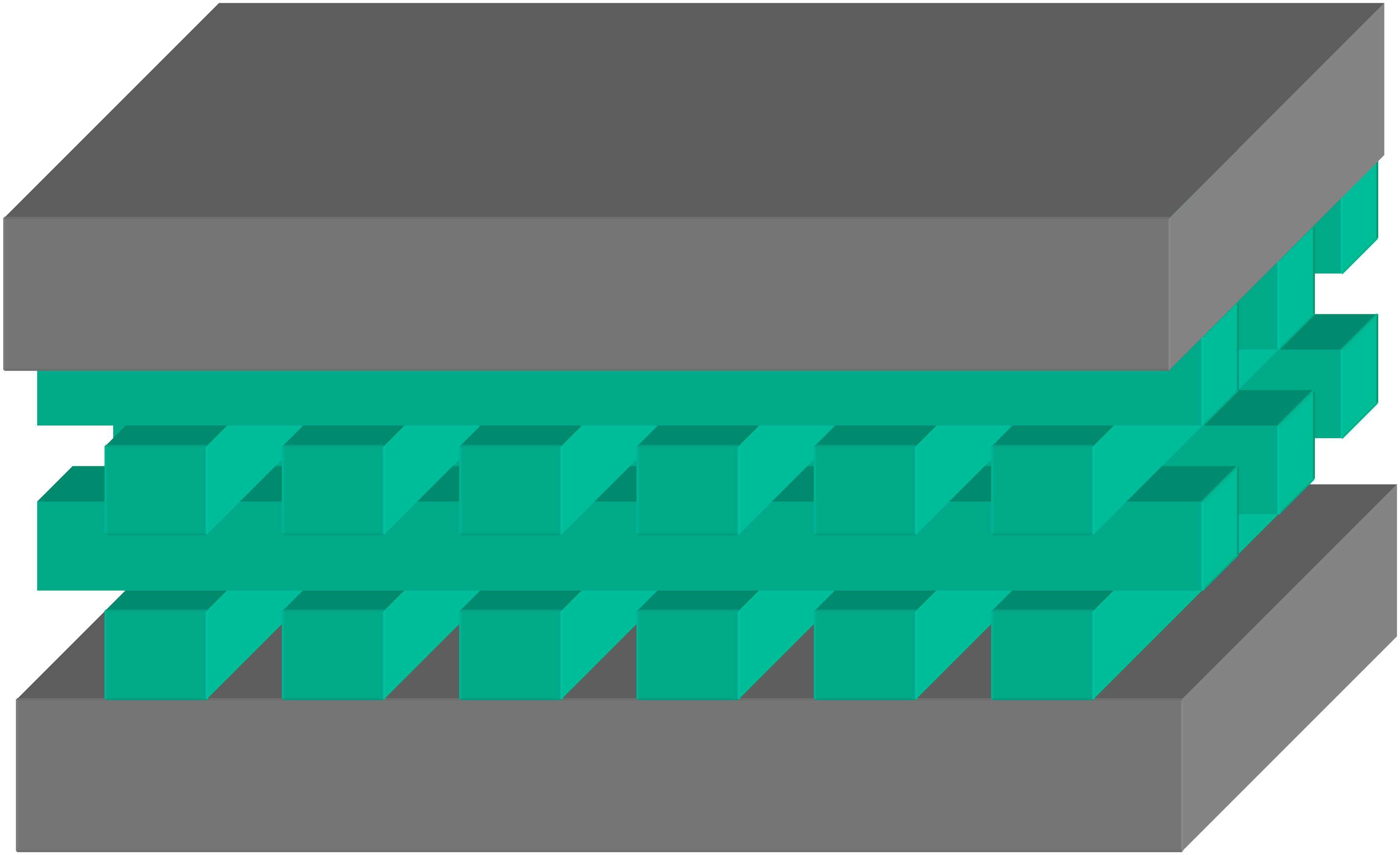
Woodpile by Wafer Fusion



[S. Noda *et al.*, *Science* **289**, 604 (2000)]

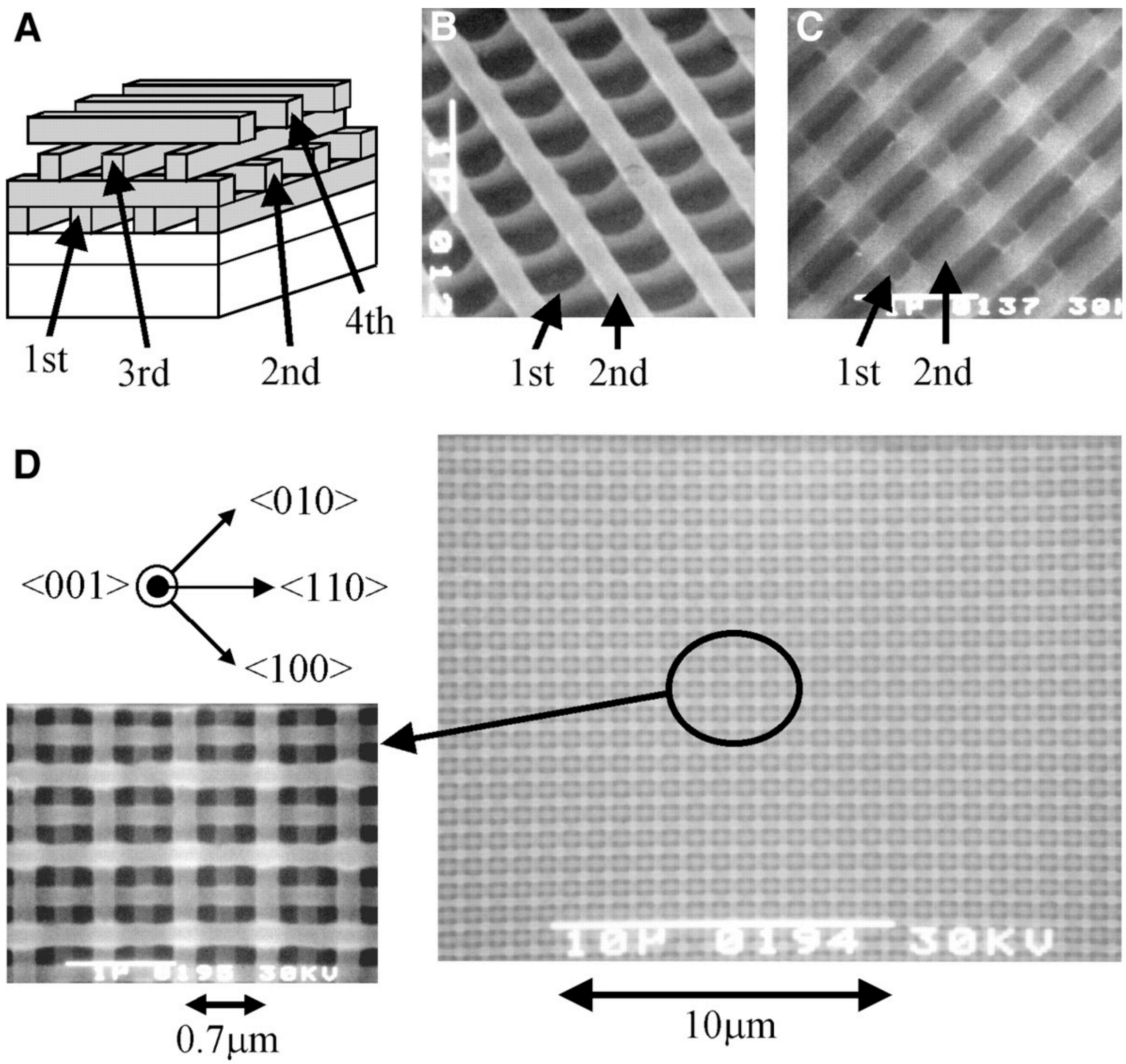
Woodpile by Wafer Fusion

double, double, toil and trouble…



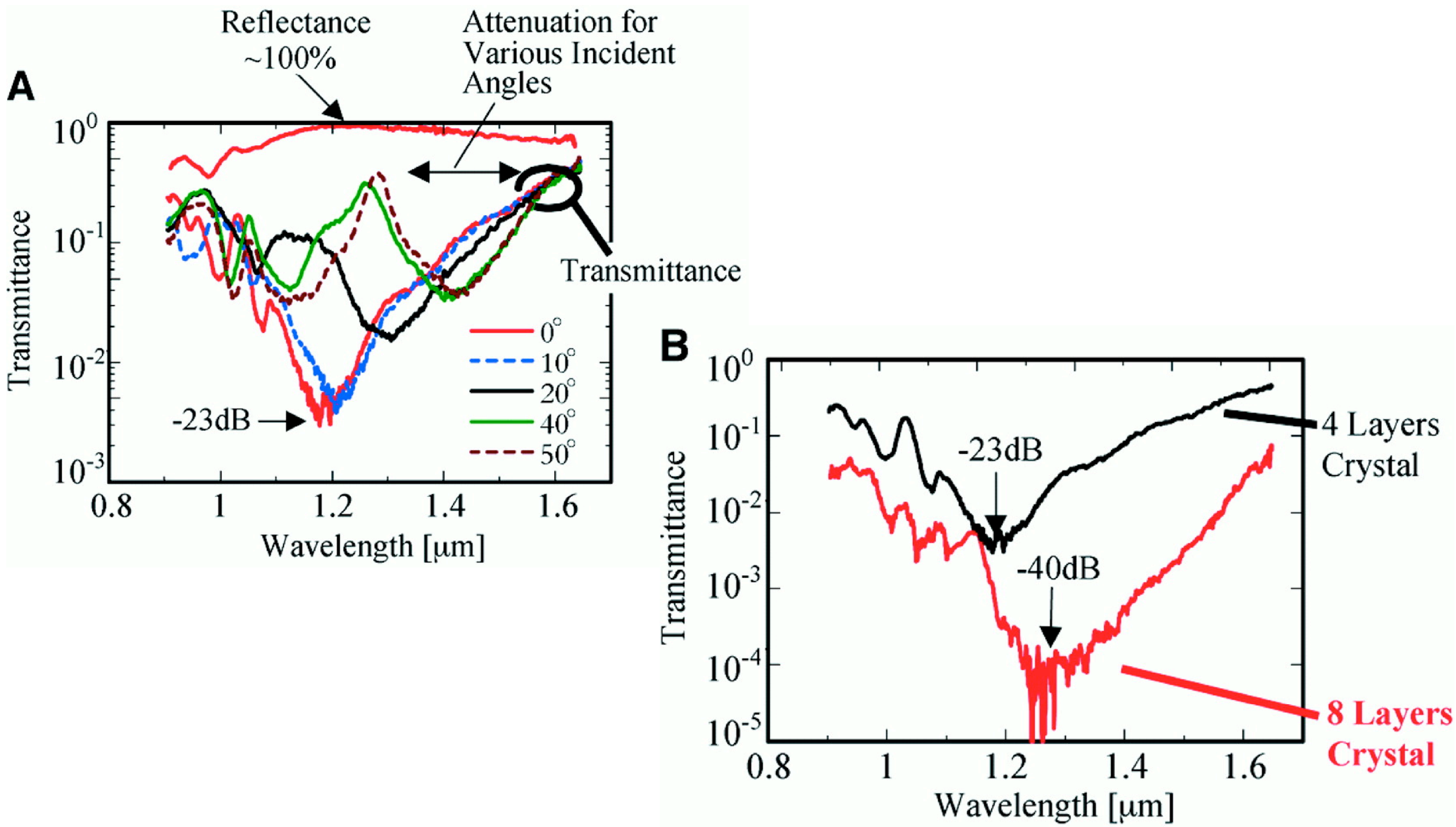
[S. Noda *et al.*, *Science* **289**, 604 (2000)]

“It’s only wafer-thin.” [M. Python]



[S. Noda *et al*., *Science* **289**, 604 (2000)]

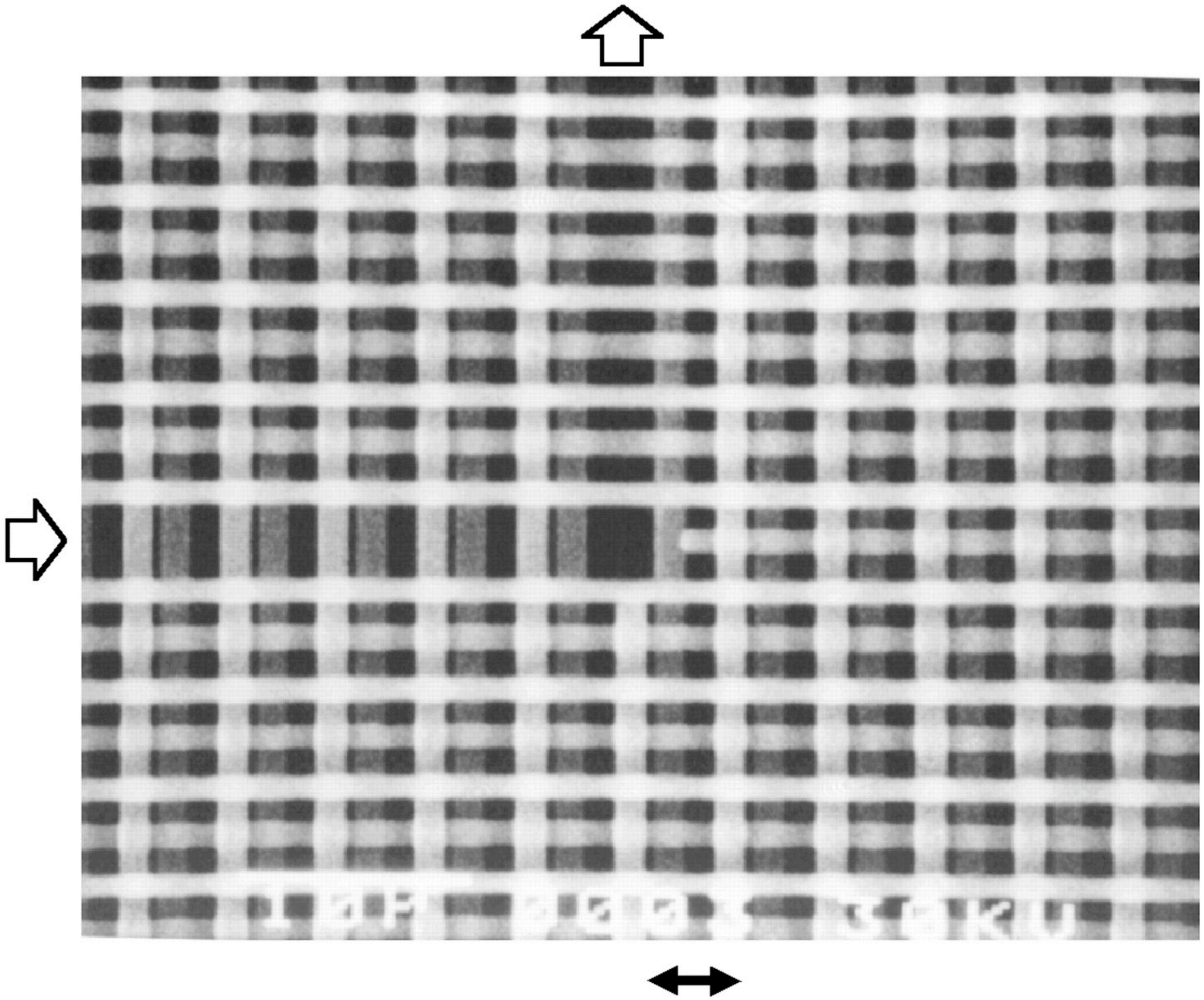
Woodpile Gap from 1.3–1.55μm



[S. Noda *et al.*, *Science* **289**, 604 (2000)]

Finally, a Defect!

WAVEGUIDE

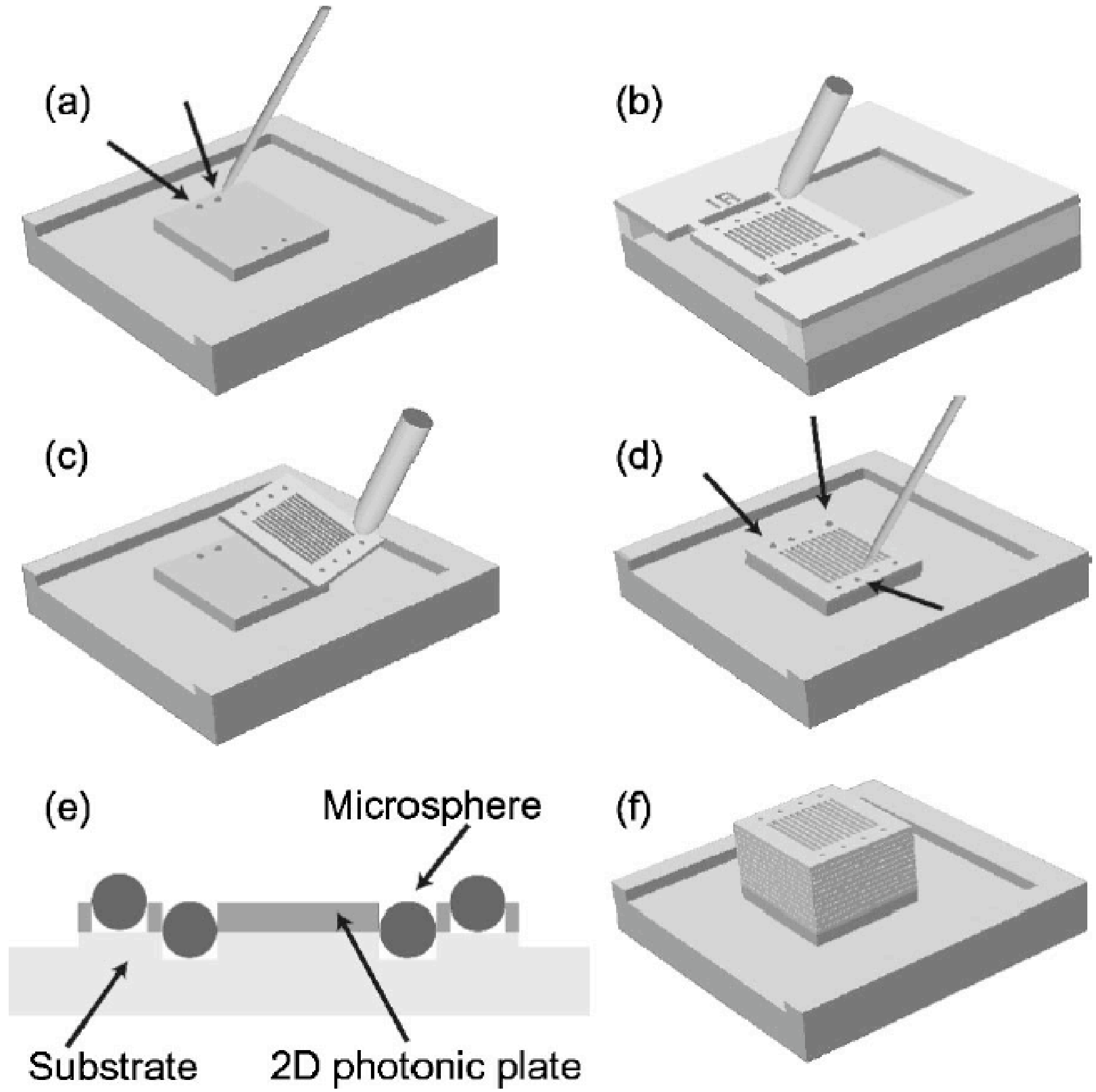


4μm

[S. Noda *et al.*, *Science* **289**, 604 (2000)]

Stacking by Micromanipulation

[K. Aoki *et al*., Appl. Phys. Lett. 81 (17), 3122 (2002)]



microsphere into hole

break off suspended layer

lift up and move to substrate

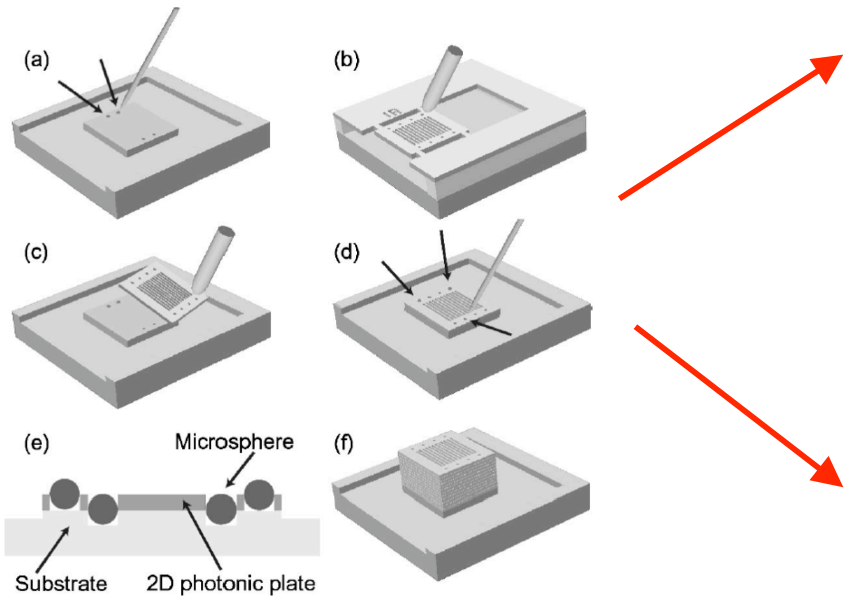
tap down holes onto spheres

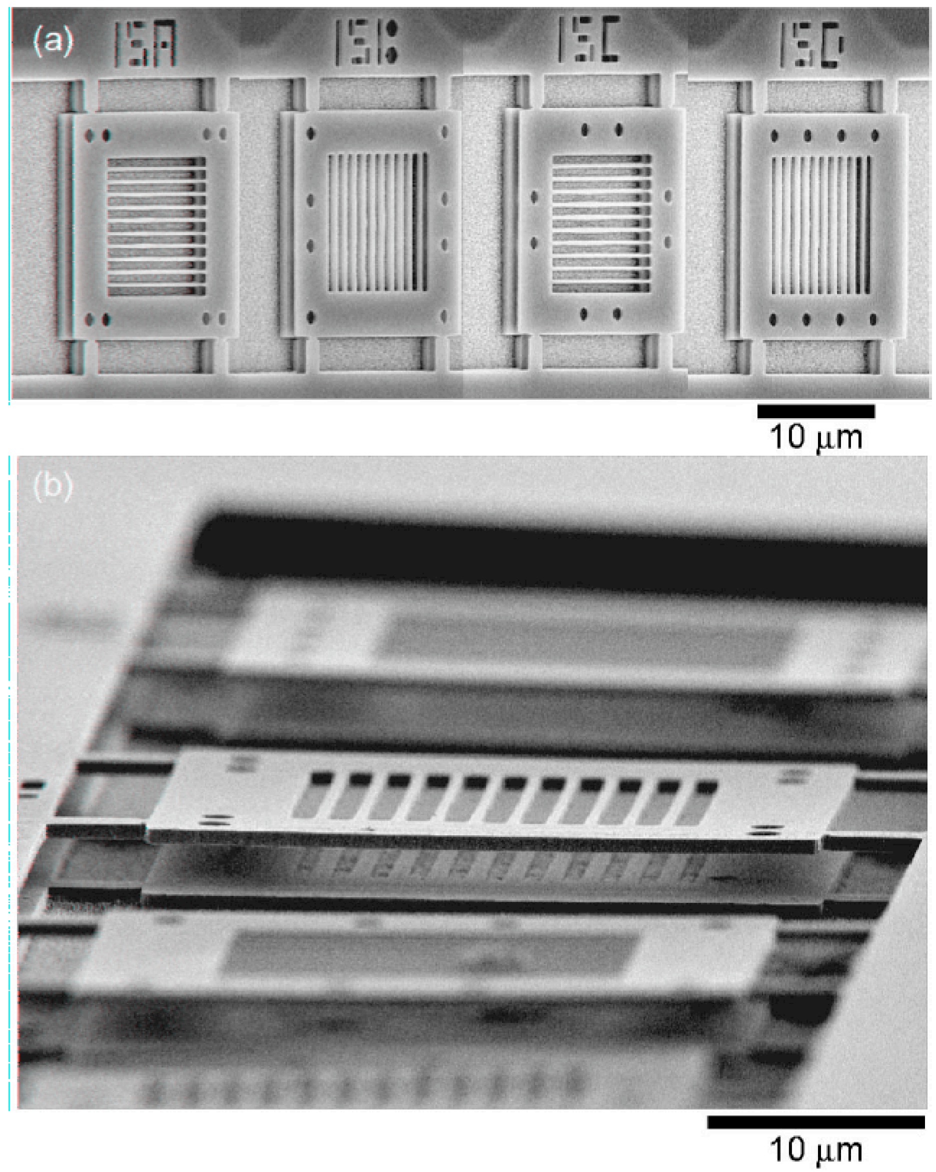
spheres enforce alignment

`goto a;`

Stacking by Micromanipulation

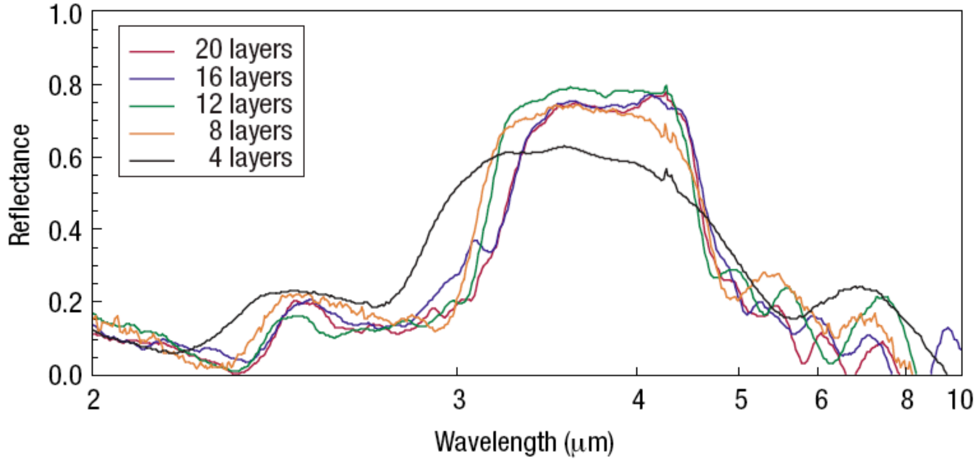
[K. Aoki *et al*., Appl. Phys. Lett. 81 (17), 3122 (2002)]

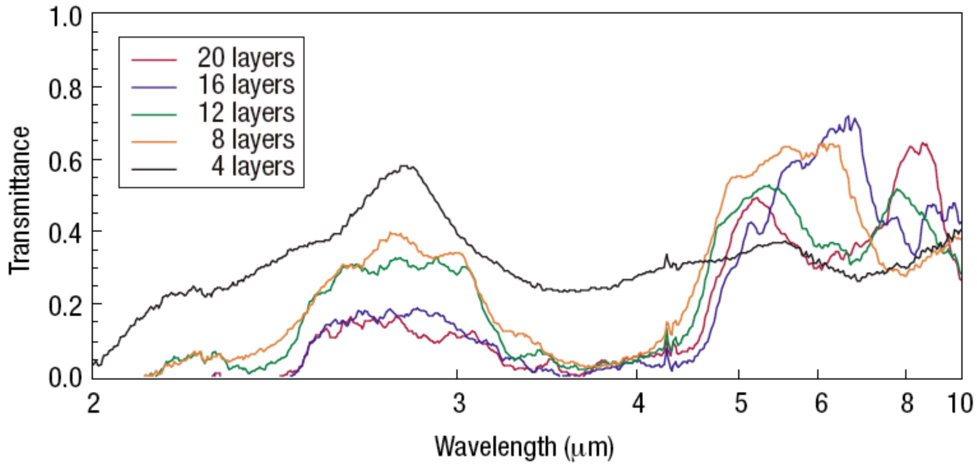




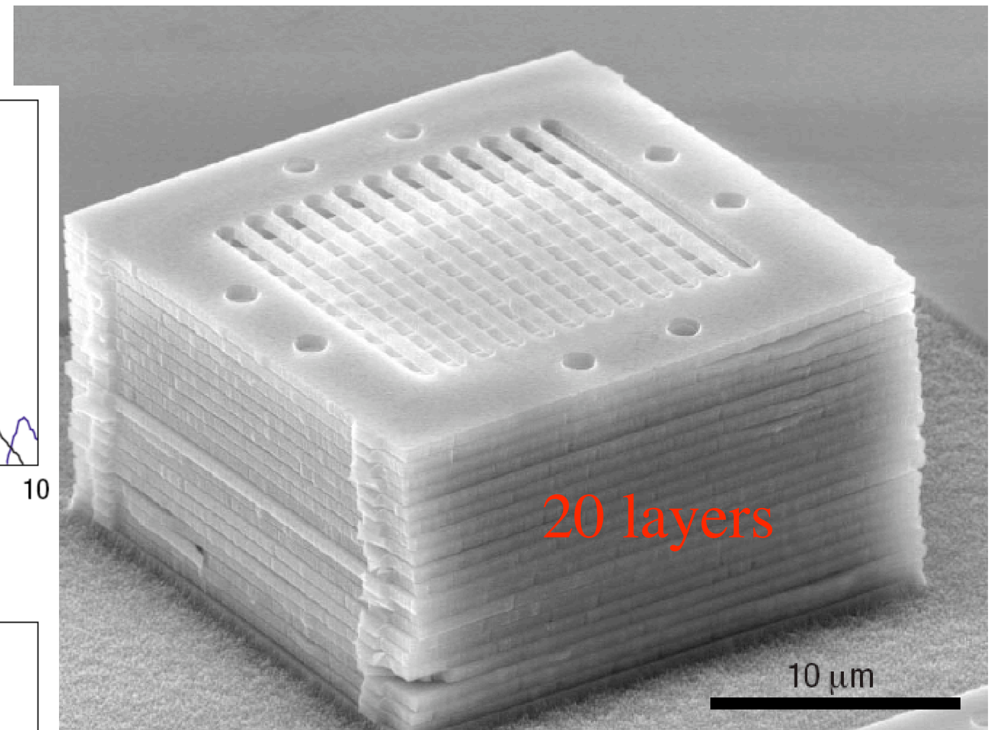
Yes, it works: Gap at ~4μm

[K. Aoki *et al.*, *Nature Materials* **2** (2), 117 (2003)]

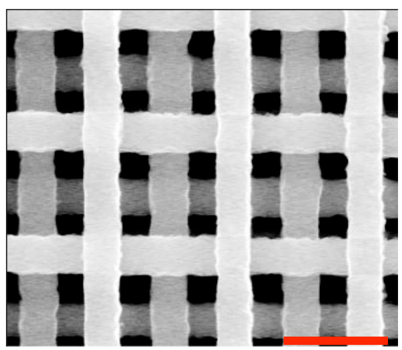




(gap effects are limited by finite lateral size)



50nm accuracy:

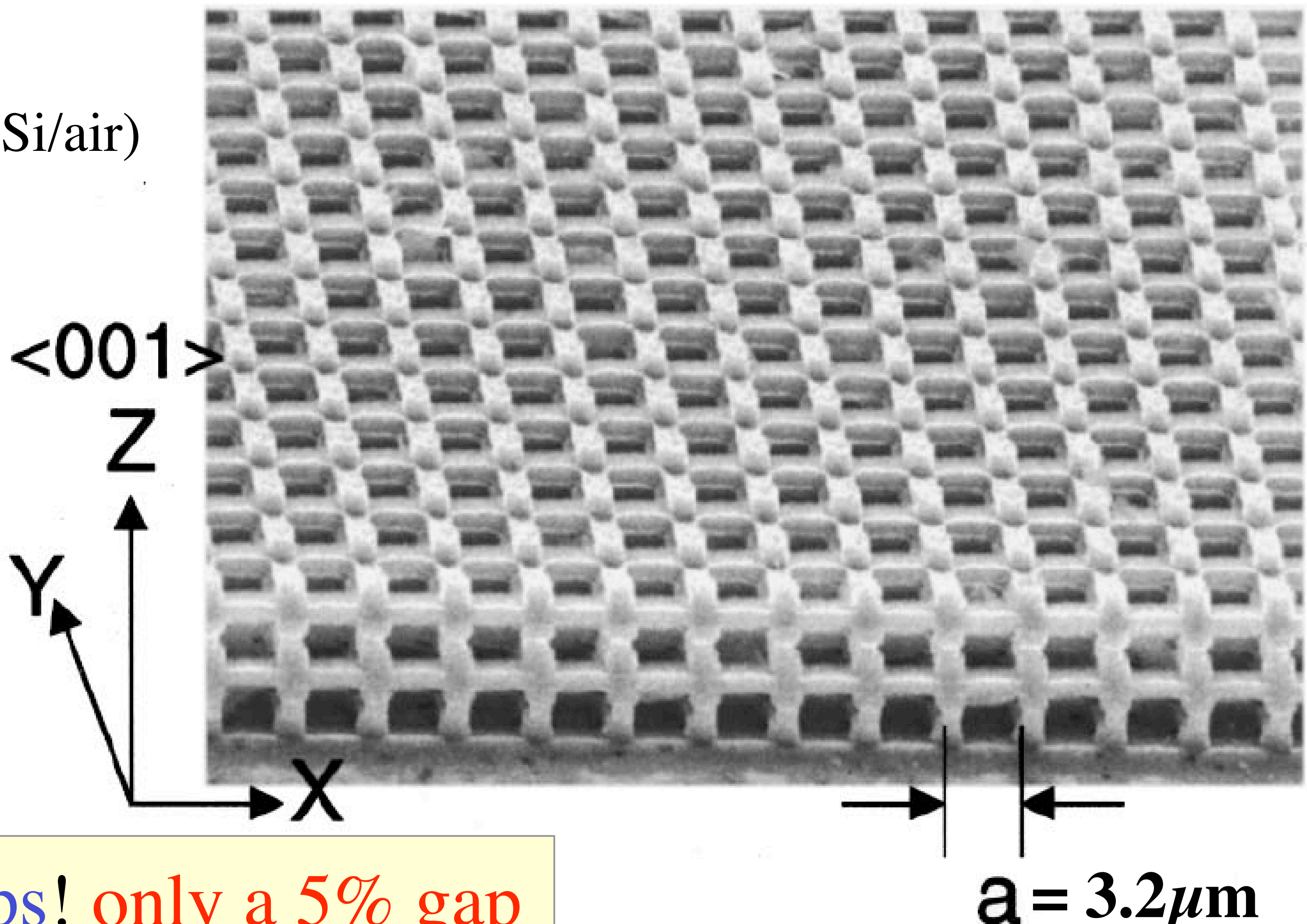


1μm

Hey, forget these FCC crystals!

simple-cubic lattice [S.-Y. Lin *et al.*, *JOSA B* **18**, 32 (2001).]

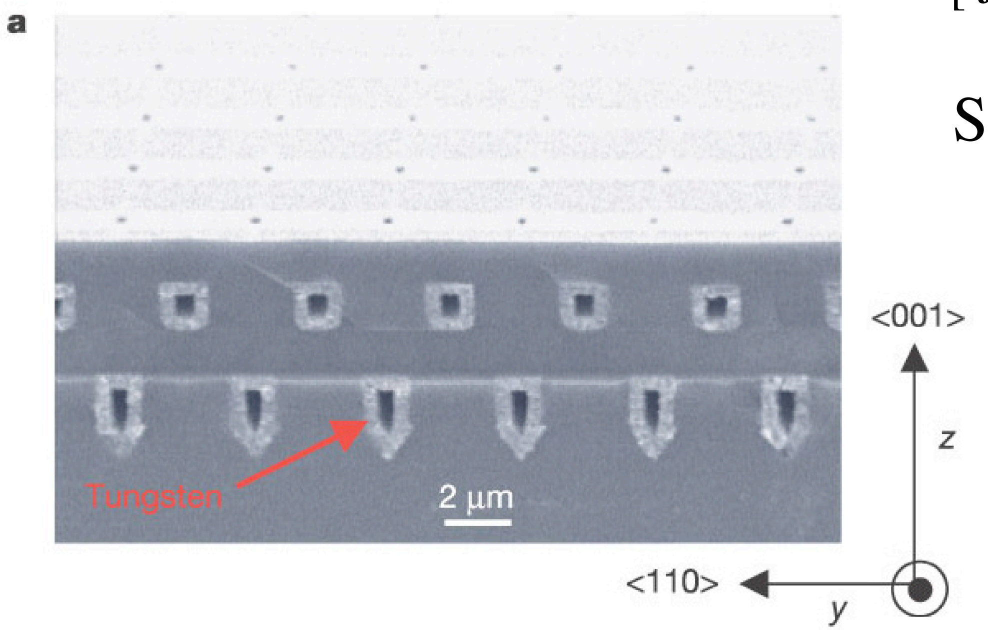
(UV stepper, Si/air)



Whoops! only a 5% gap

A *Metal* Photonic Crystal

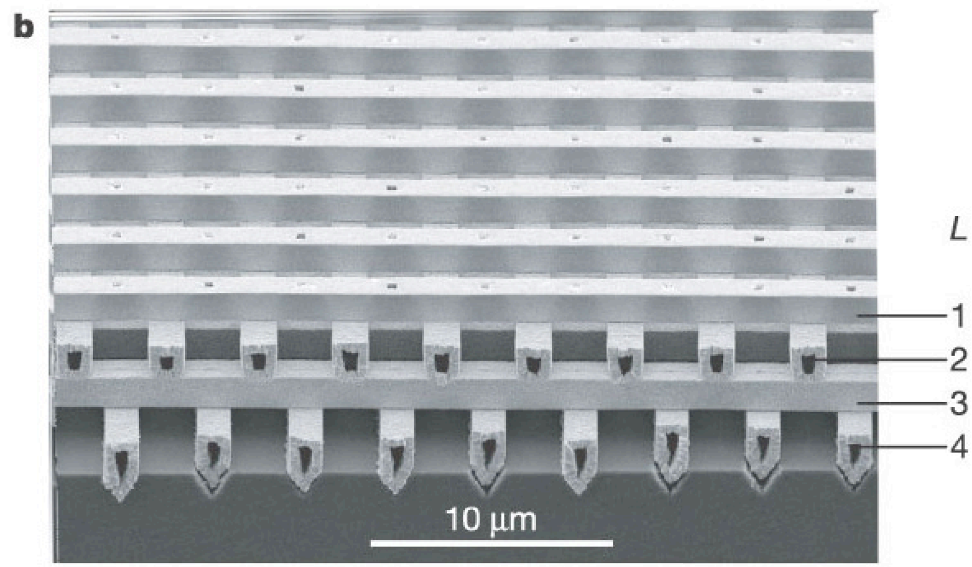
[J. G. Fleming *et al.*, *Nature* **417**, 52 (2002)]



Start with Si woodpile in SiO_2…

dissolve Si with KOH…

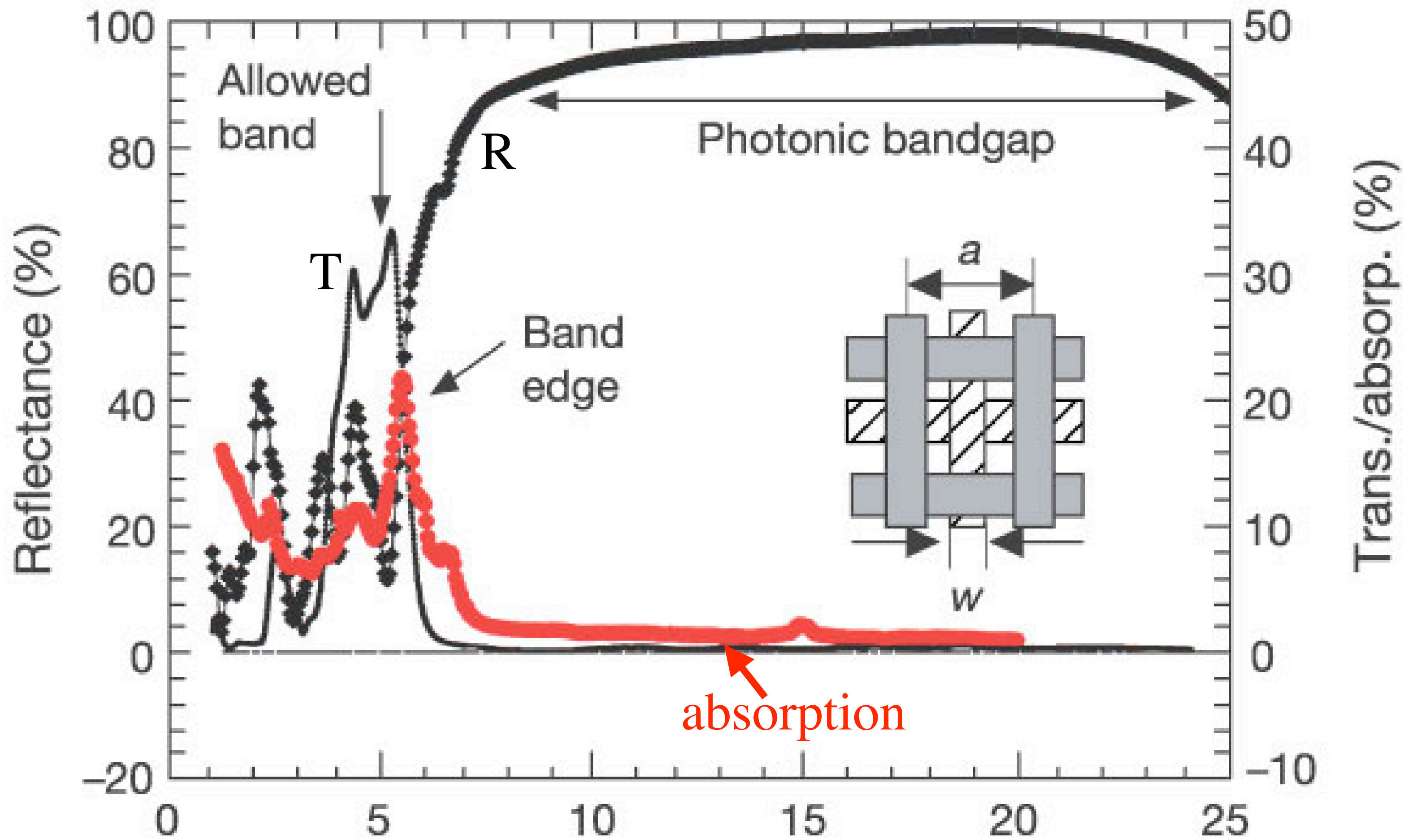
fill with Tungsten
via chemical vapor deposition (CVD)
(on thin TiN layer)



dissolve SiO_2 with HF…

Thermal properties of metal crystal

[J. G. Fleming *et al.*, *Nature* **417**, 52 (2002)]



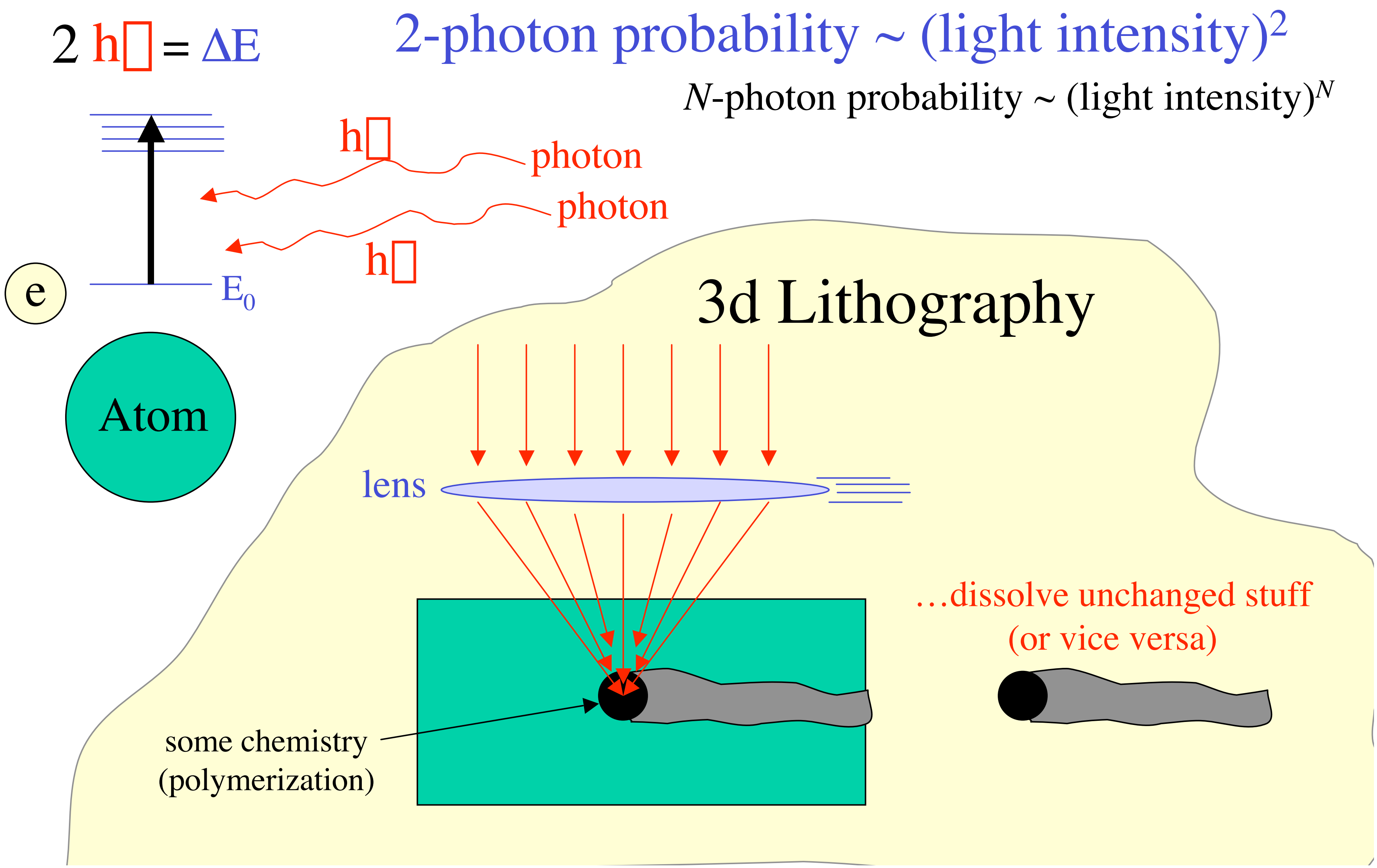
Kirchoff's Law: a good absorber is a good emitter …modify thermal emission!

solar cells…

light bulbs…

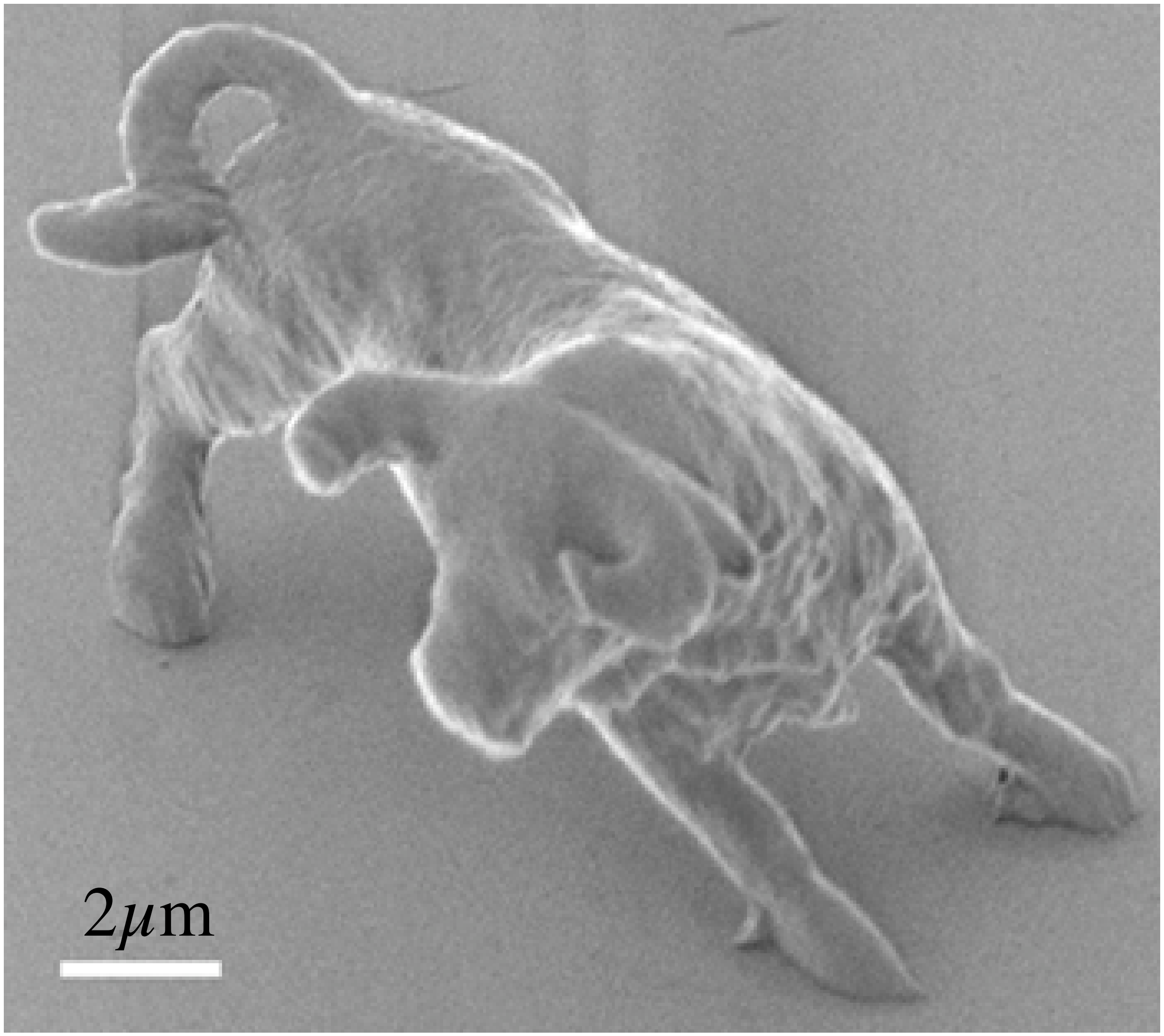
enough layer-by-layer already!

Two-Photon Lithography



Lithography is a Beast

[S. Kawata *et al.*, *Nature* **412**, 697 (2001)]



□ = 780nm

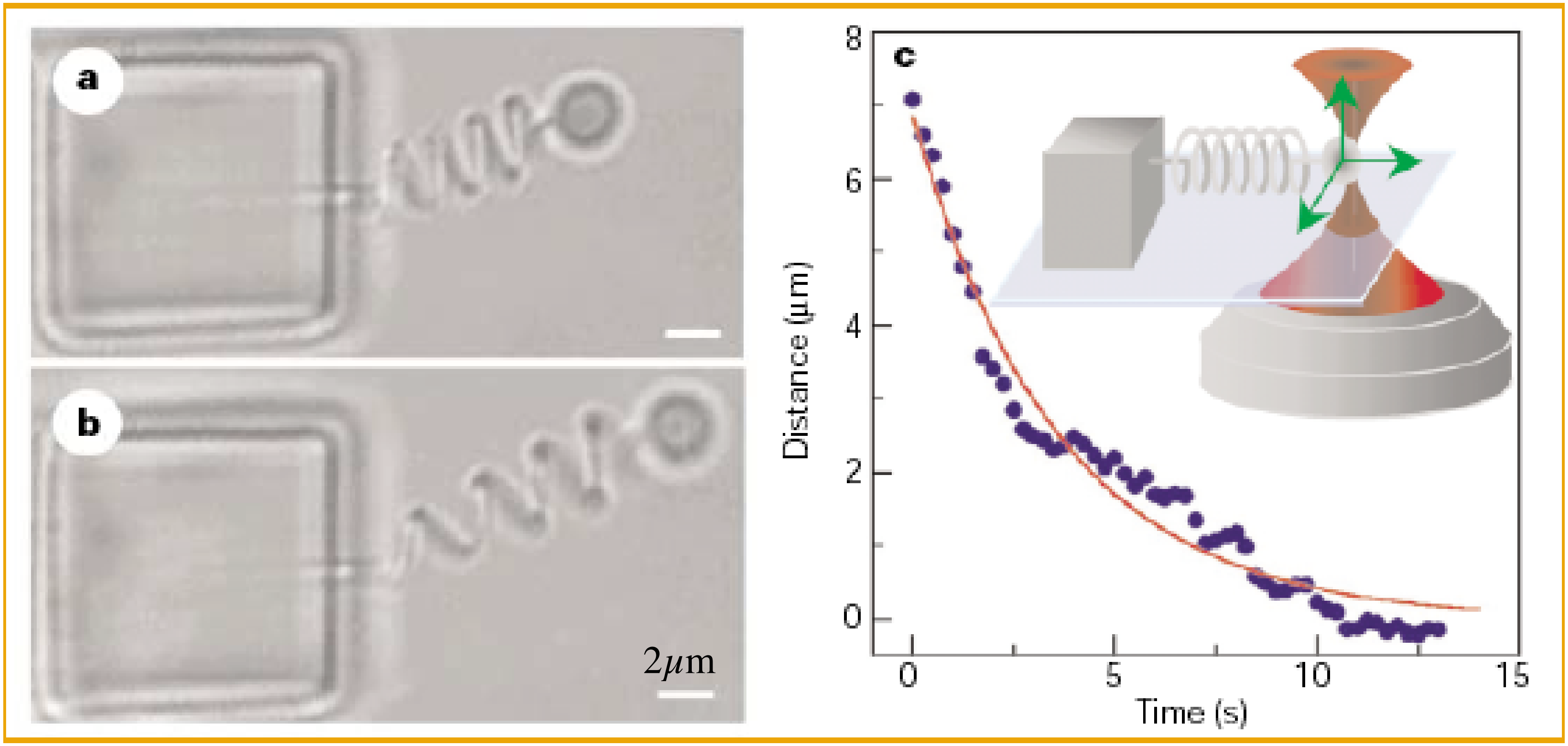
resolution = 150nm

7μm

(3 hours to make)

For a physicist, this is cooler…

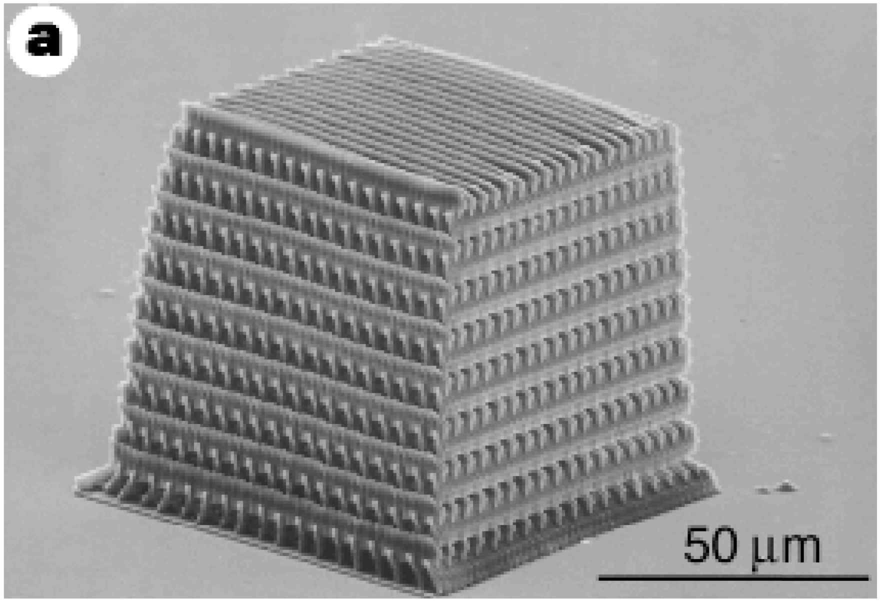
[S. Kawata *et al.*, *Nature* **412**, 697 (2001)]



(300nm diameter coils, suspended in ethanol, viscosity-damped)

A Two-Photon Woodpile Crystal

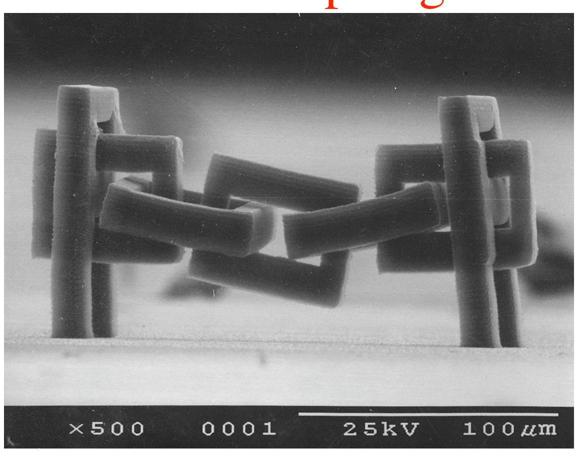
[B. H. Cumpston *et al.*, *Nature* **398**, 51 (1999)]



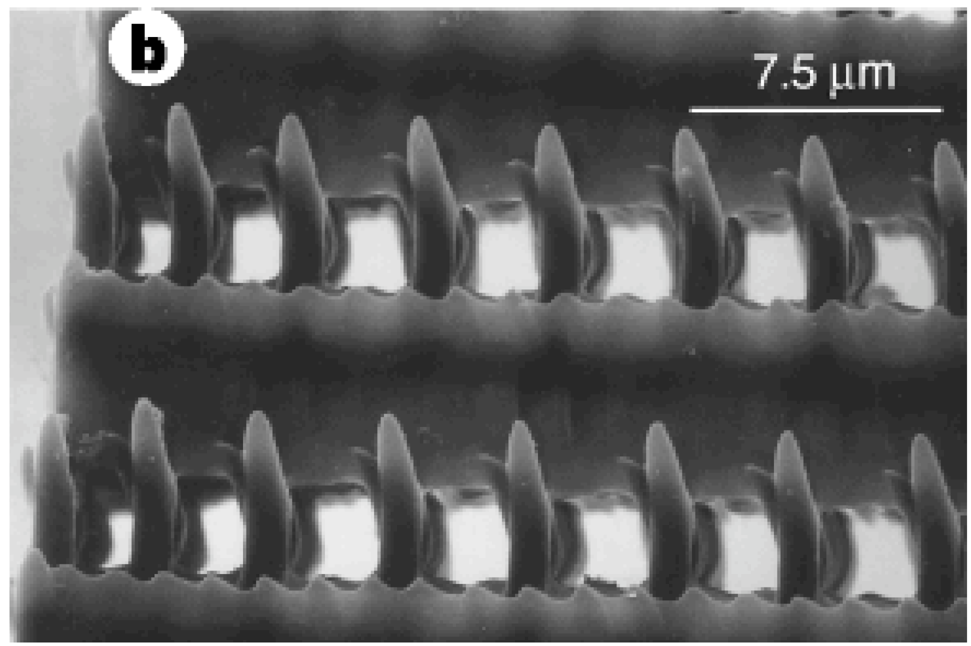
(much work on materials
with lower power 2-photon process)

- Arbitrary lattice
- No "mask"
- Fast/cheap prototyping

Difficult topologies



[fig. courtesy J. W. Perry, U. Arizona]



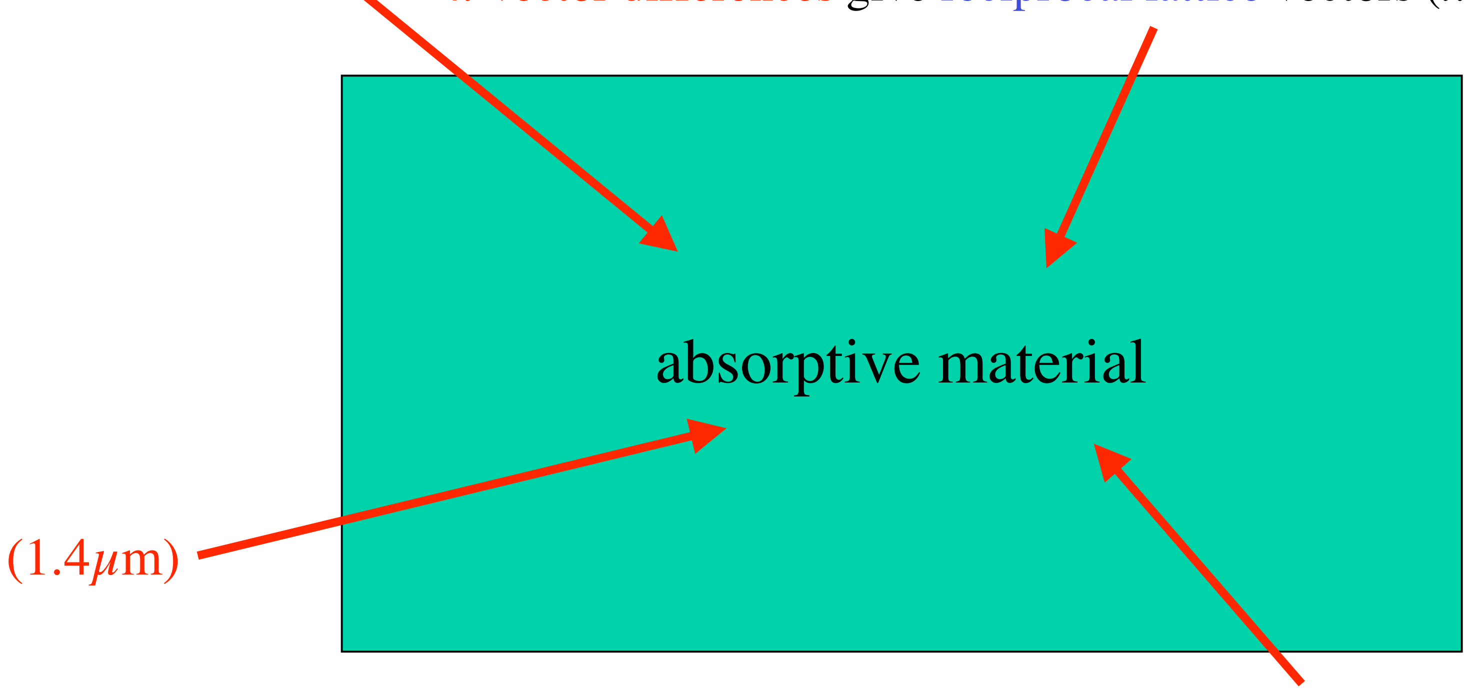
Mass-production, pretty please?

One-Photon
Holographic Lithography

[D. N. Sharp *et al.*, *Opt. Quant. Elec.* **34**, 3 (2002)]

Four beams make 3d-periodic interference pattern

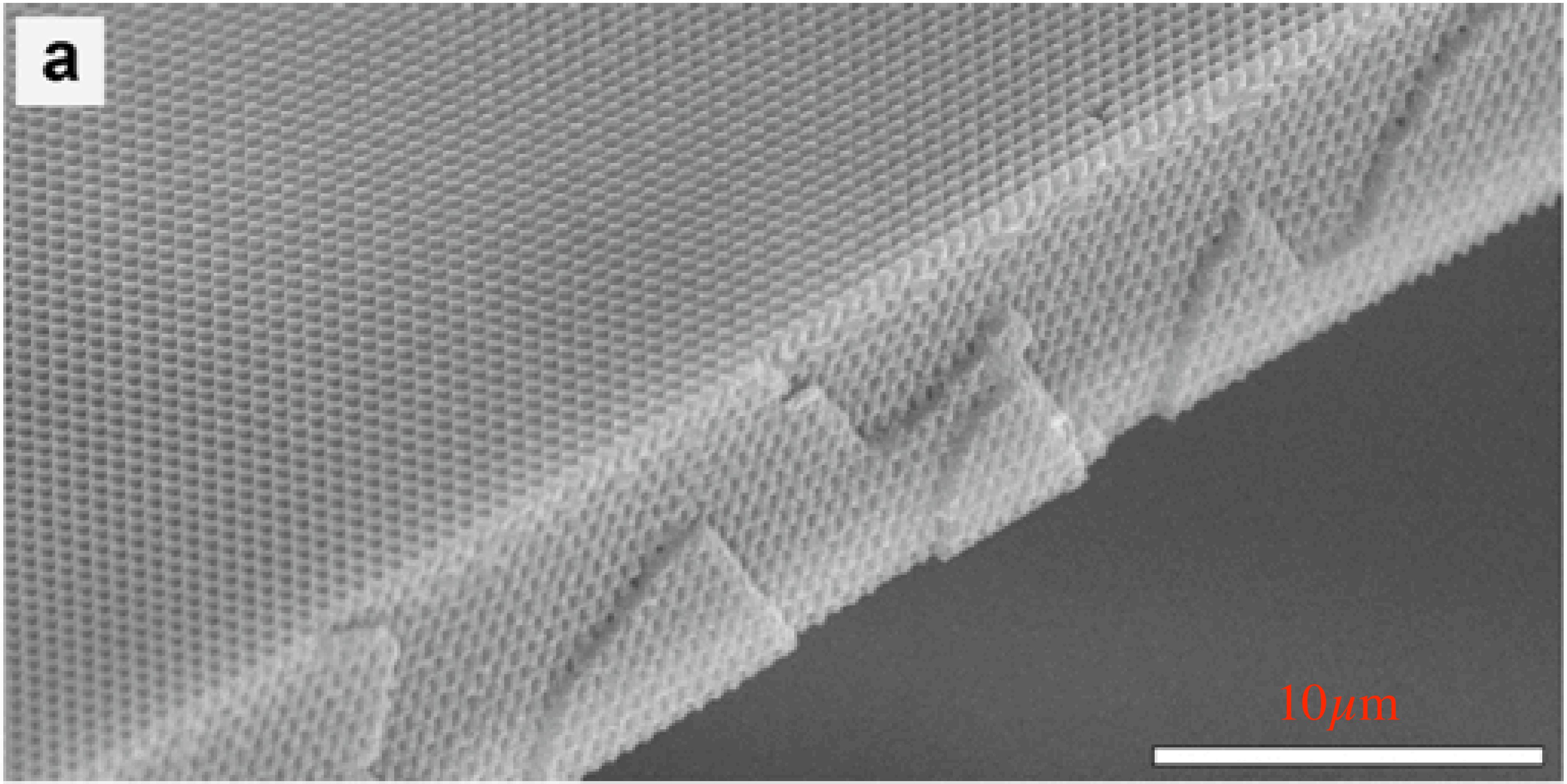
k-vector differences give reciprocal lattice vectors (*i.e.* periodicity)



beam polarizations + amplitudes (8 parameters) give unit cell

One-Photon
Holographic Lithography

[D. N. Sharp *et al.*, *Opt. Quant. Elec.* **34**, 3 (2002)]



huge volumes, long-range periodic, fcc lattice…backfill for high contrast

One-Photon
Holographic Lithography

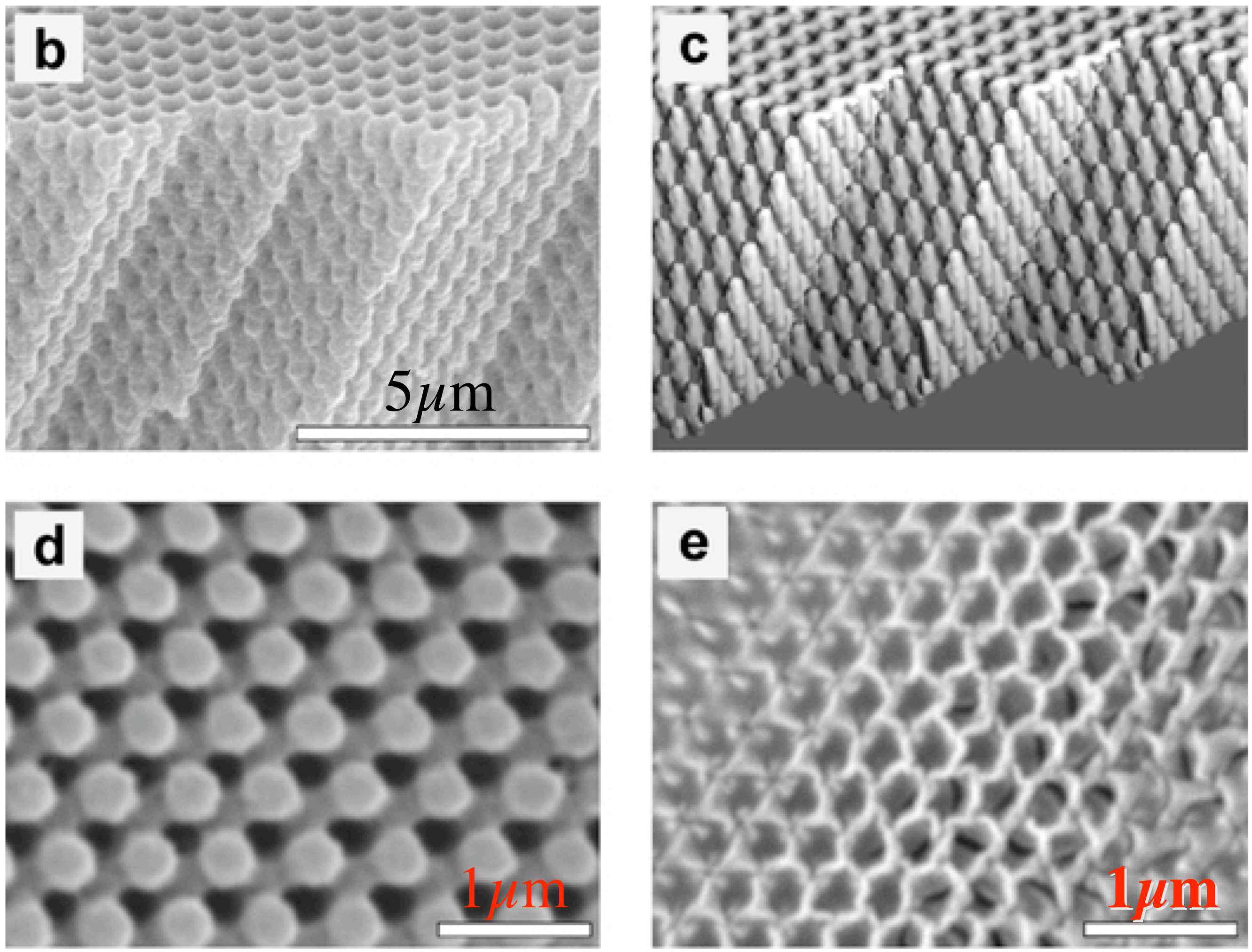
[D. N. Sharp *et al.*, *Opt. Quant. Elec.* **34**, 3 (2002)]

[111]
cleavages

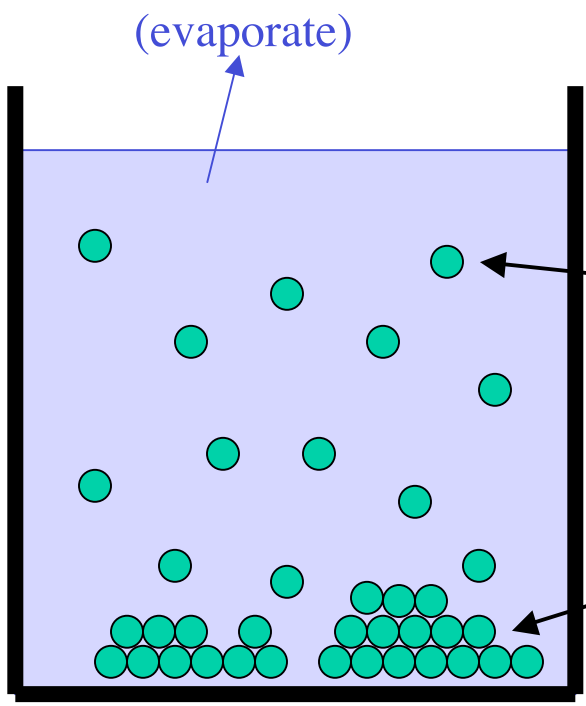
simulated
structure

[111]
closeup

titania
inverse
structure



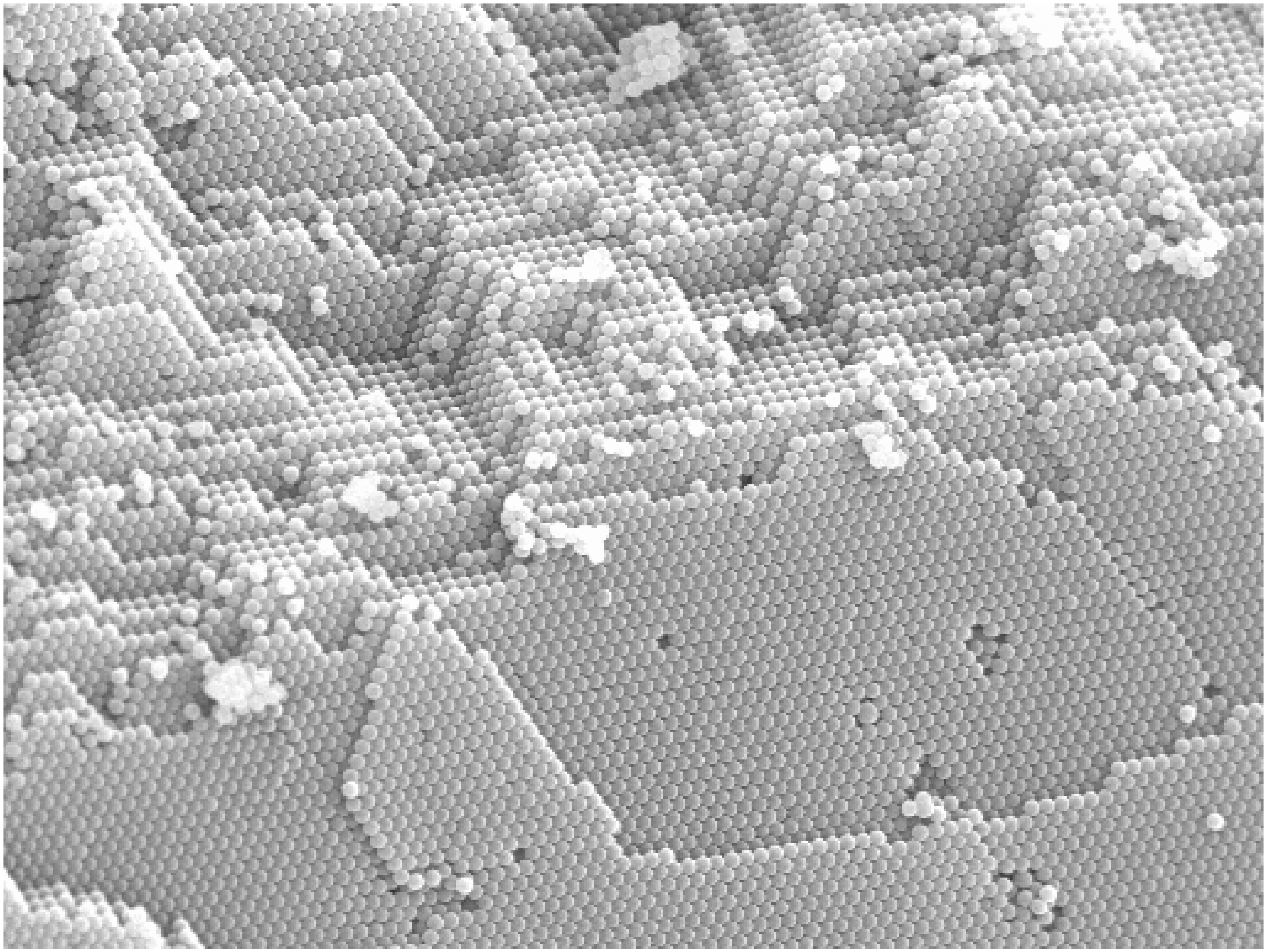
Mass-production II: Colloids



silica (SiO_2) microspheres (diameter < 1μm)

sediment by gravity into close-packed fcc lattice!

Mass-production II: Colloids



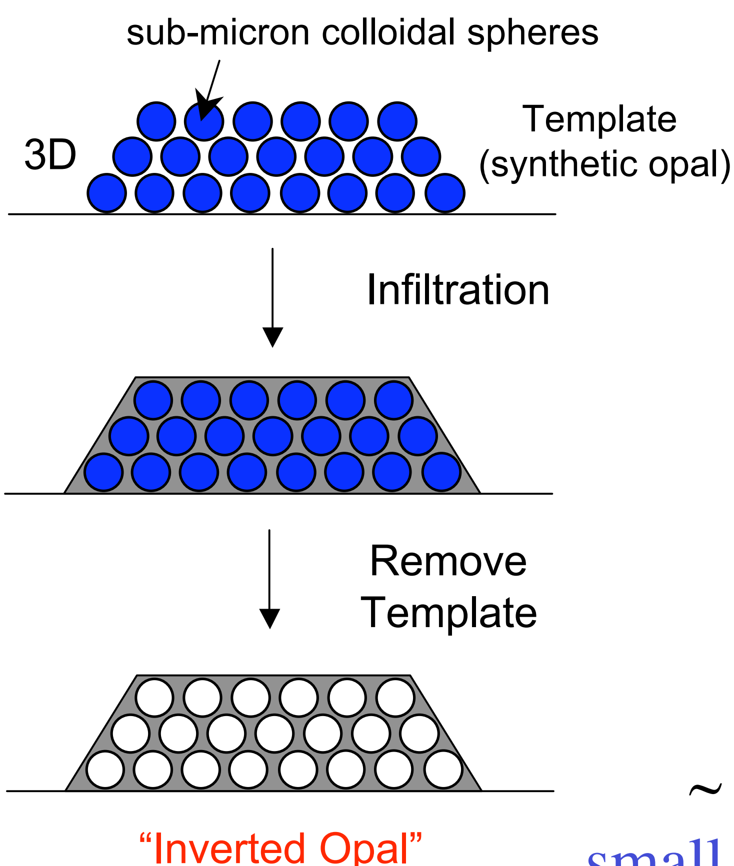
http://www.icmm.csic.es/cefe/

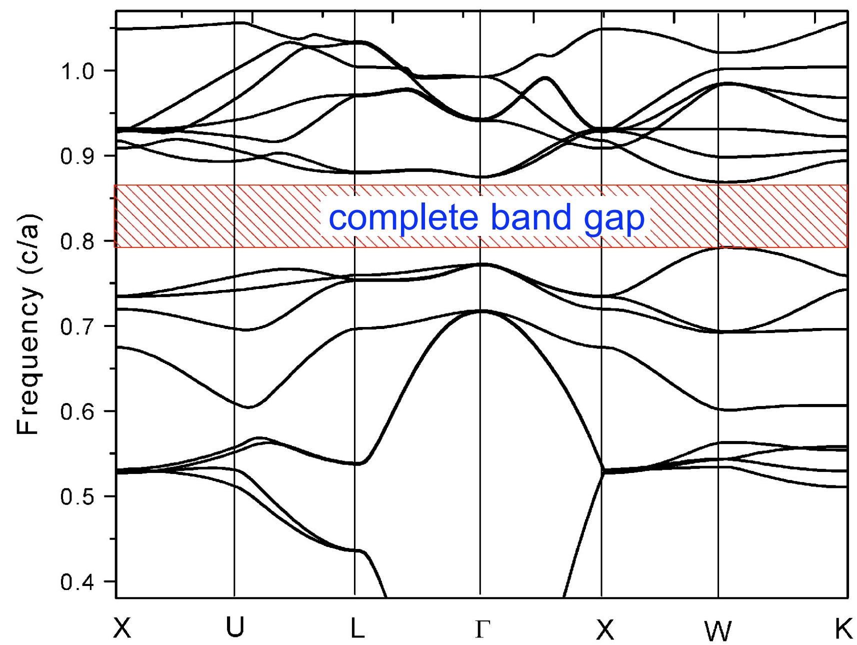
Inverse Opals

[figs courtesy
D. Norris, UMN]

fcc solid spheres do not have a gap…

…but fcc spherical holes in Si *do* have a gap



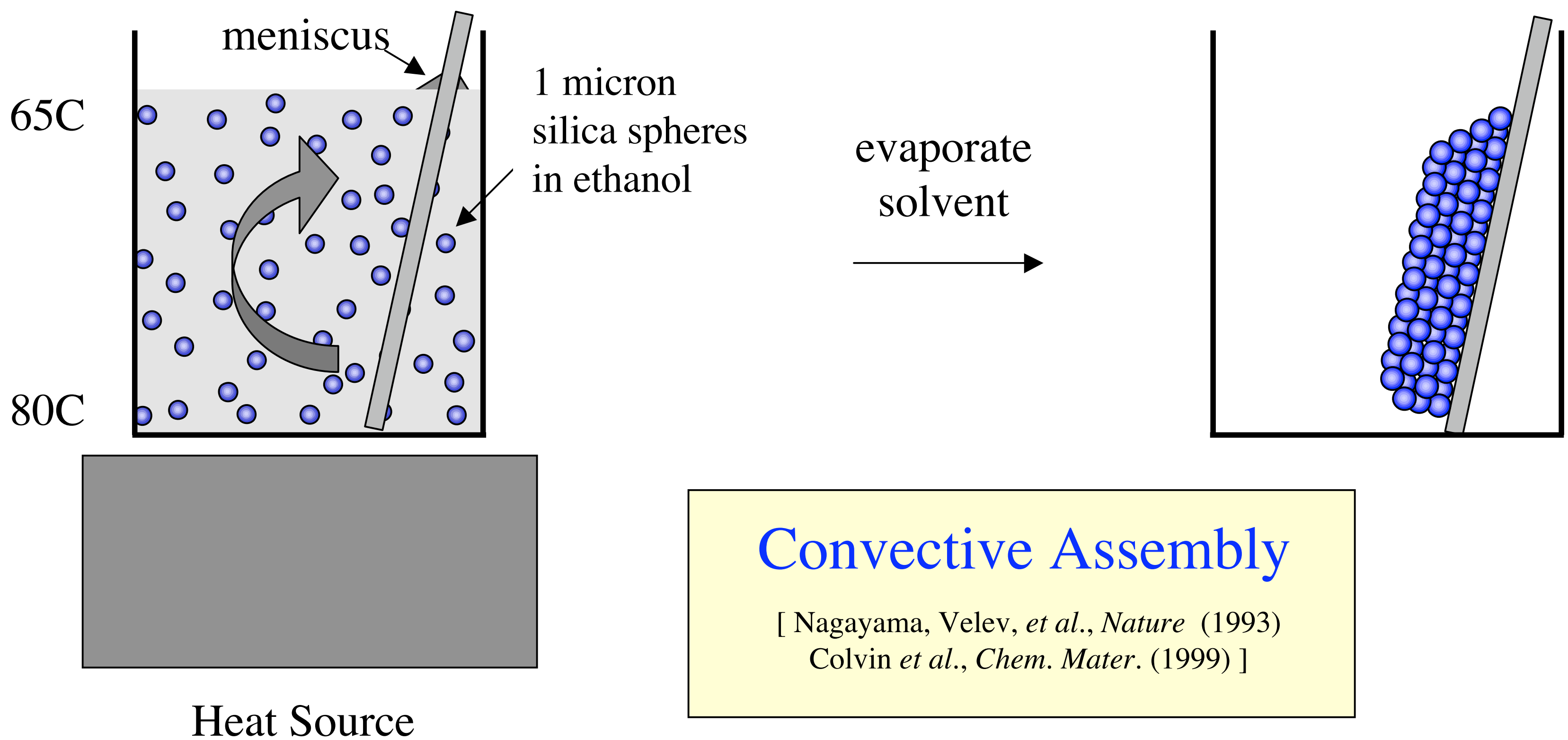


~ 10% gap between 8th & 9th bands

small gap, upper bands: sensitive to disorder

In Order To Form a More Perfect Crystal…

[figs courtesy D. Norris, UMN]



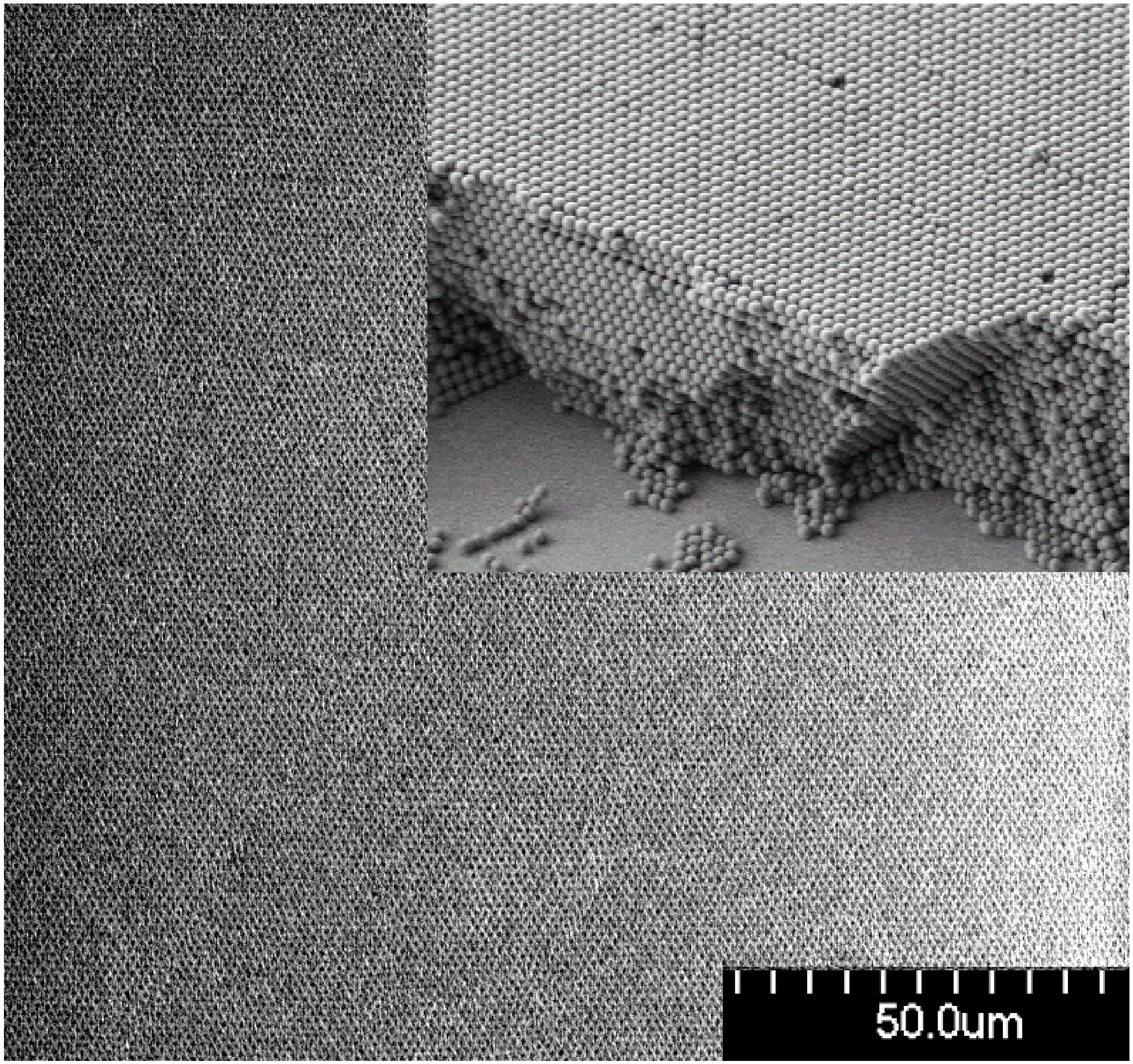
Convective Assembly

[Nagayama, Velev, *et al.*, *Nature* (1993)
Colvin *et al.*, *Chem. Mater*. (1999)]

- Capillary forces during drying cause assembly in the meniscus
- Extremely flat, large-area opals of controllable thickness

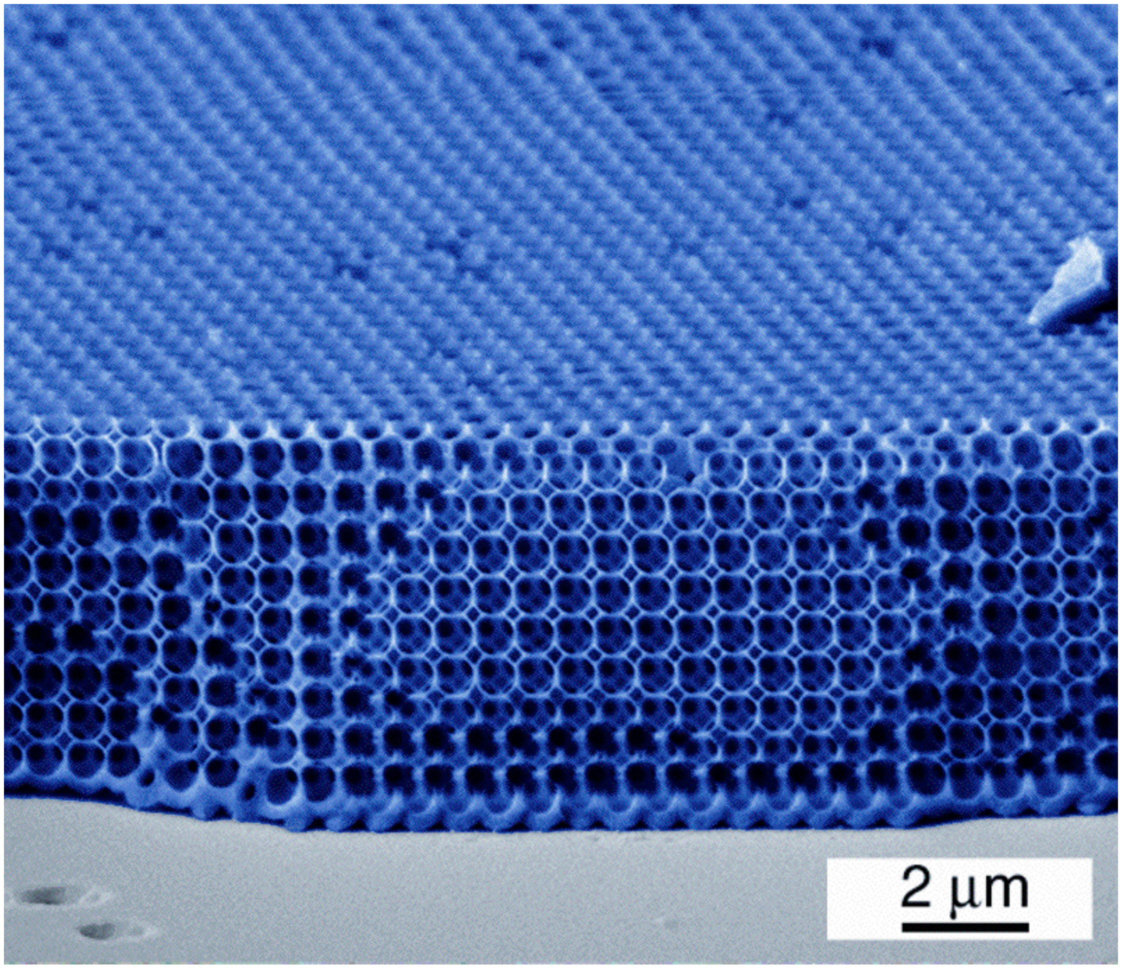
A Better Opal

[fig courtesy
D. Norris, UMN]



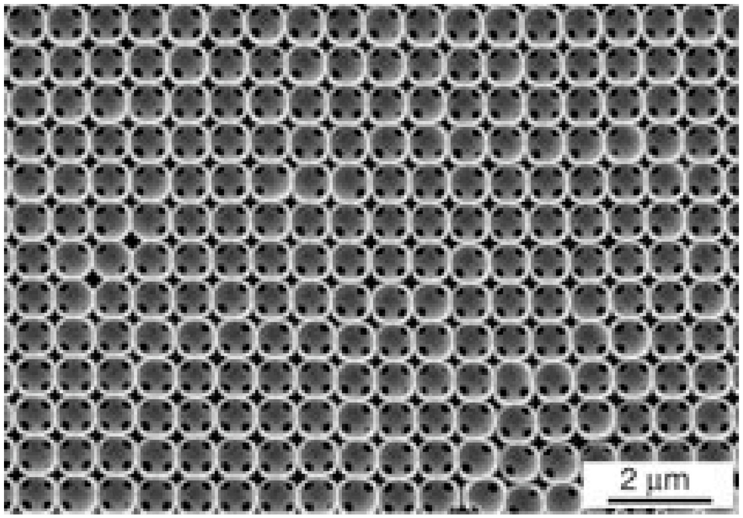
Inverse-Opal Photonic Crystal

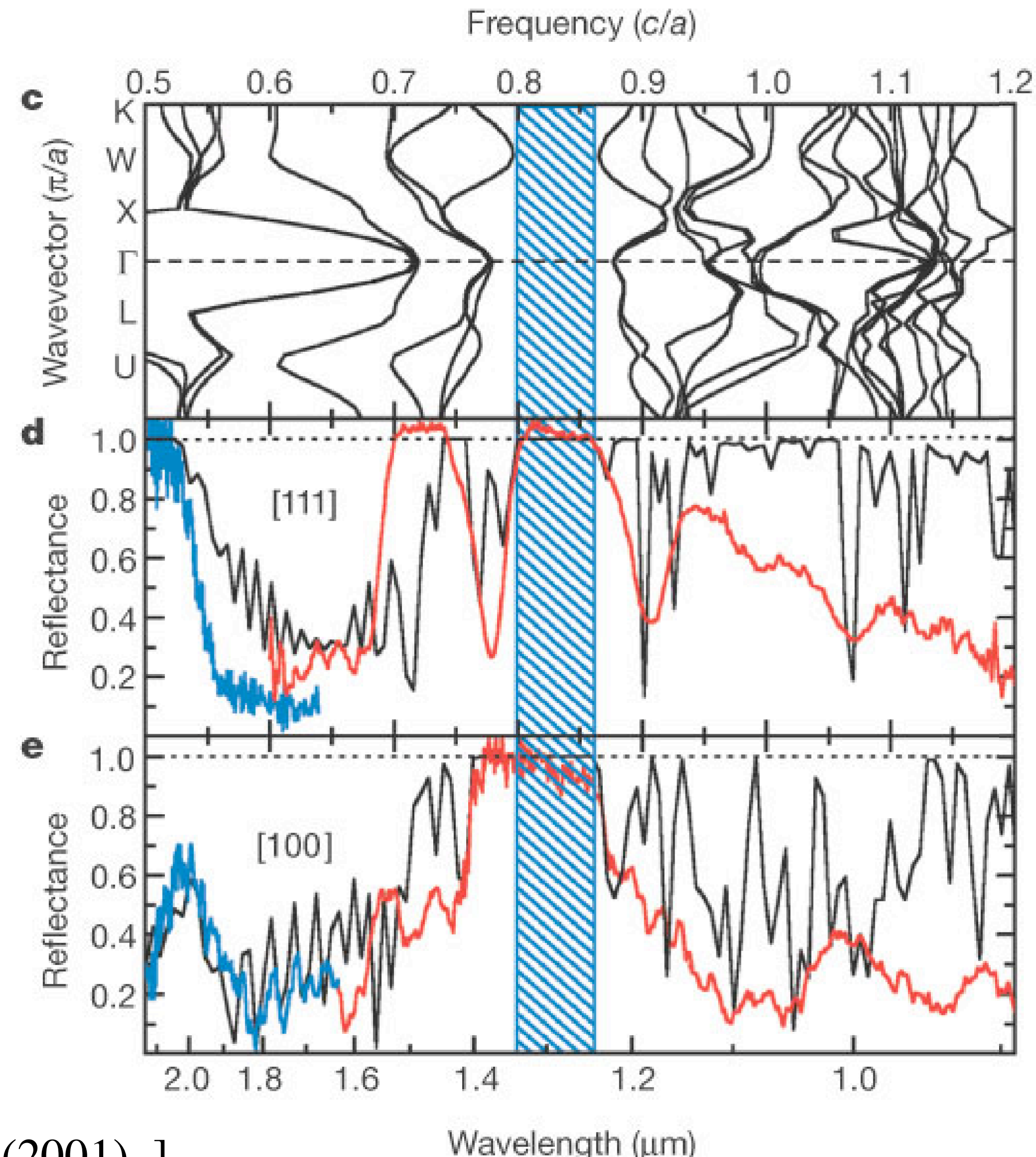
[fig courtesy
D. Norris, UMN]



[Y. A. Vlasov *et al.*, *Nature* **414**, 289 (2001).]

Inverse-Opal Band Gap





good agreement
between **theory** (black)
& experiment (red/blue)

[Y. A. Vlasov *et al.*, *Nature* **414**, 289 (2001).]

Mass-Production?

What about defects?

(Remember cavities, waveguides…?)

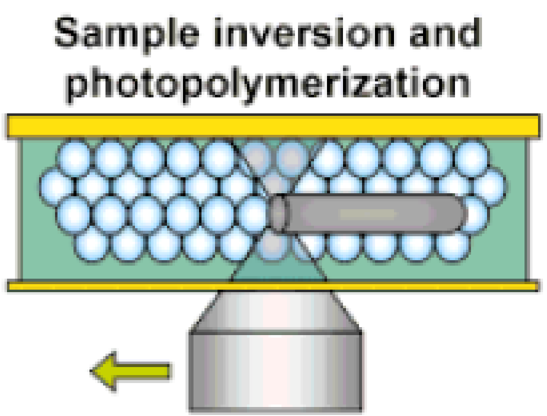
Answer: fabricate bulk crystal via mass production

+ *N*-photon lithography for defects

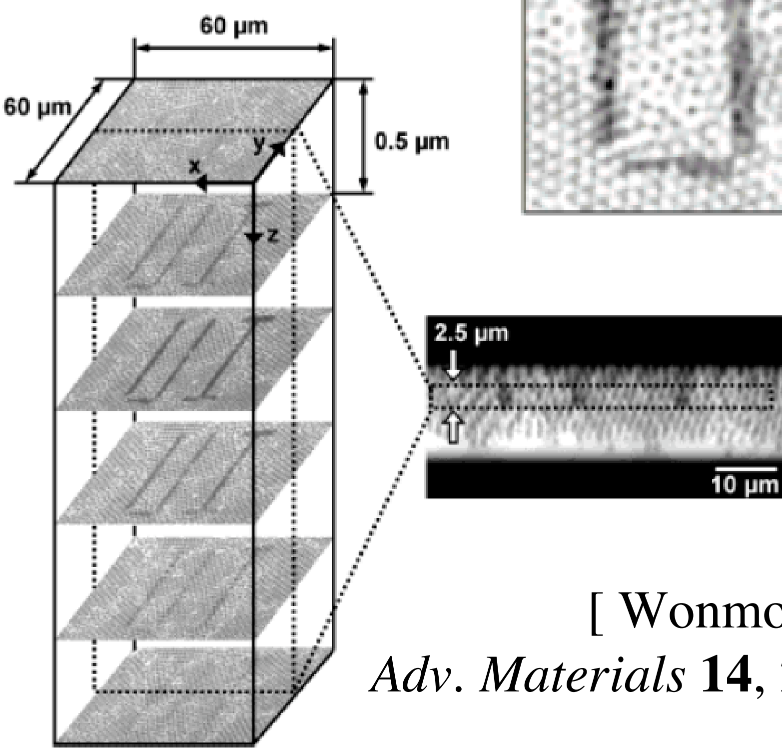
(Use confocal microscopy to see what you are doing, *i.e.* alignment)

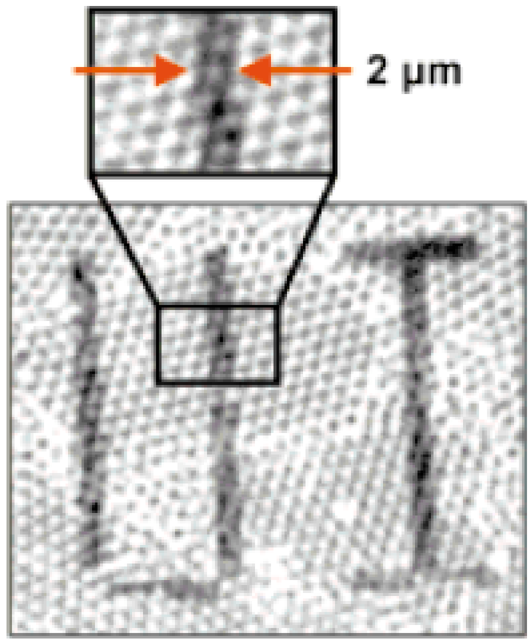
Inserting Defects in Inverse Opals

e.g., Waveguides



Three-photon lithography
with
laser scanning
confocal microscope
(LSCM)



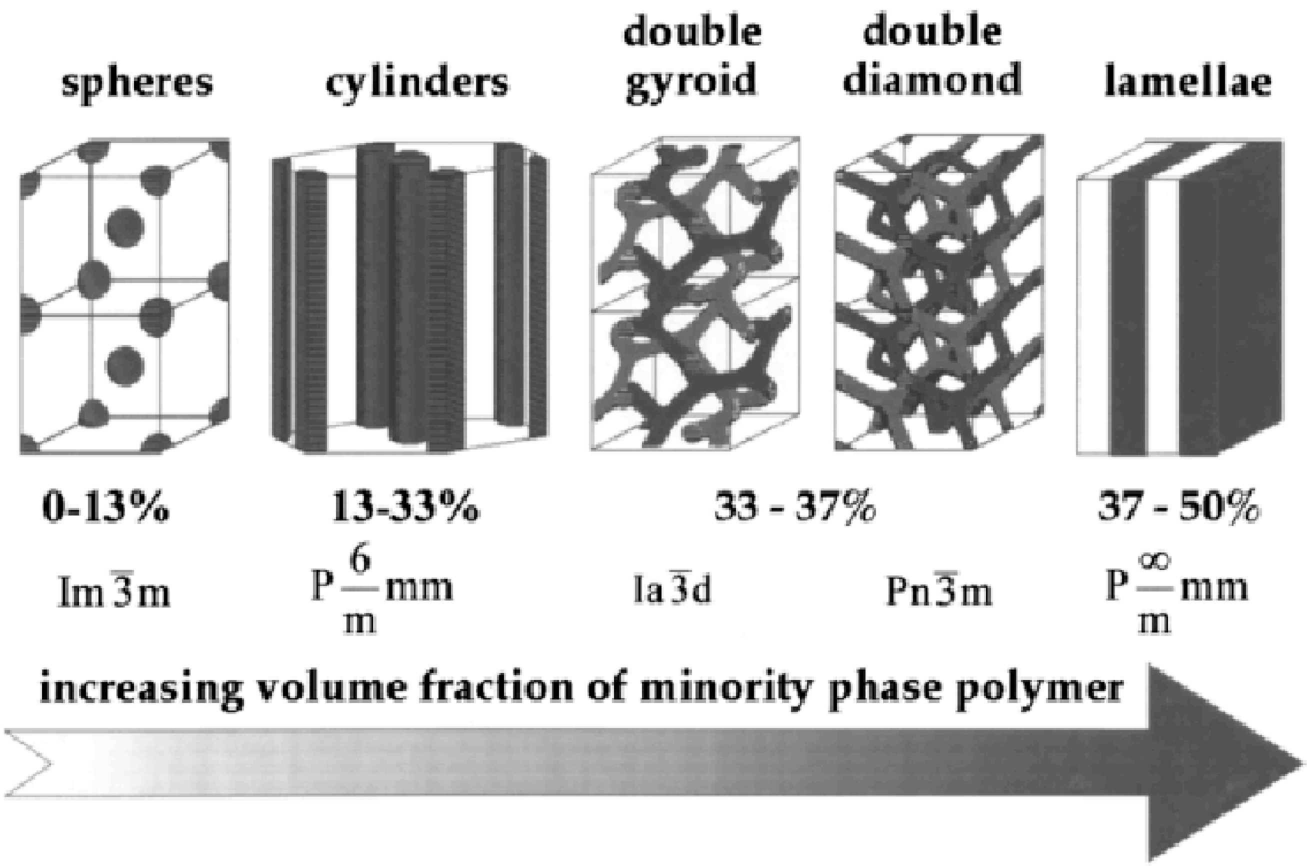


[Wonmok,
Adv. Materials **14**, 271 (2002)]

Mass-Production III:
Block (not Bloch) Copolymers

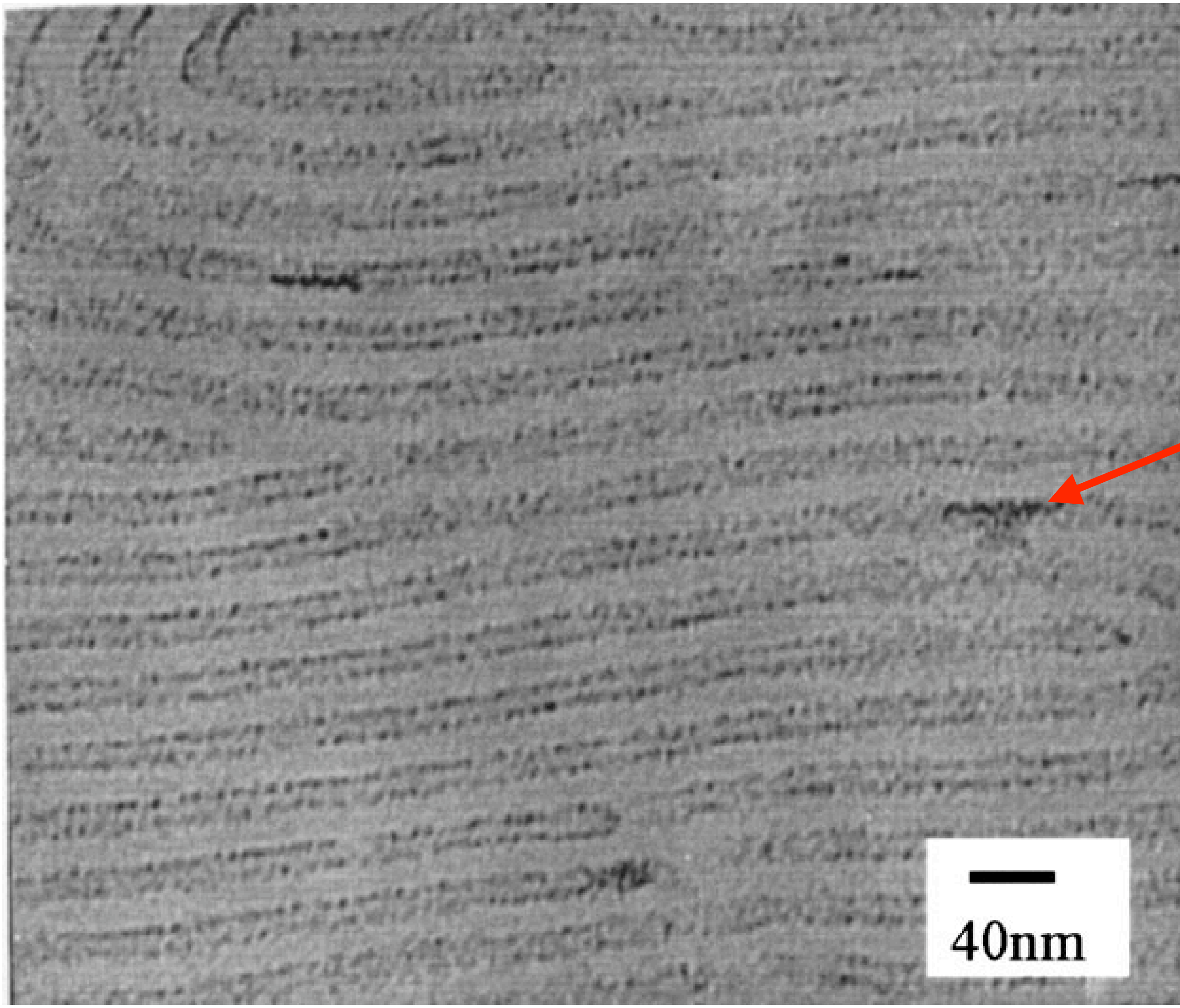
two polymers
can segregate,
ordering into
periodic arrays

periodicity ~
polymer block size
~ 50nm
(possibly bigger)



[Y. Fink, A. M. Urbas, M. G. Bawendi, J. D. Joannopoulos, E. L. Thomas, *J. Lightwave Tech.* **17**, 1963 (1999)]

Block-Copolymer 1d Crystal



CdSe nanocrystals for higher index

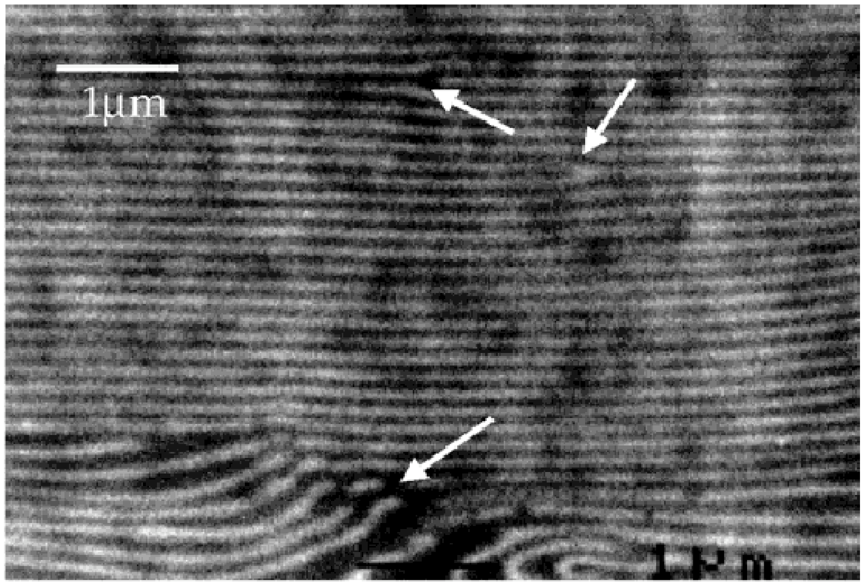
(with surfactant to attract particles to one phase)

(UV bandgap)

[Y. Fink, A. M. Urbas, M. G. Bawendi, J. D. Joannopoulos, E. L. Thomas, *J. Lightwave Tech*. **17**, 1963 (1999)]

Block-Copolymer 1d Visible Bandgap

/ homopolymer

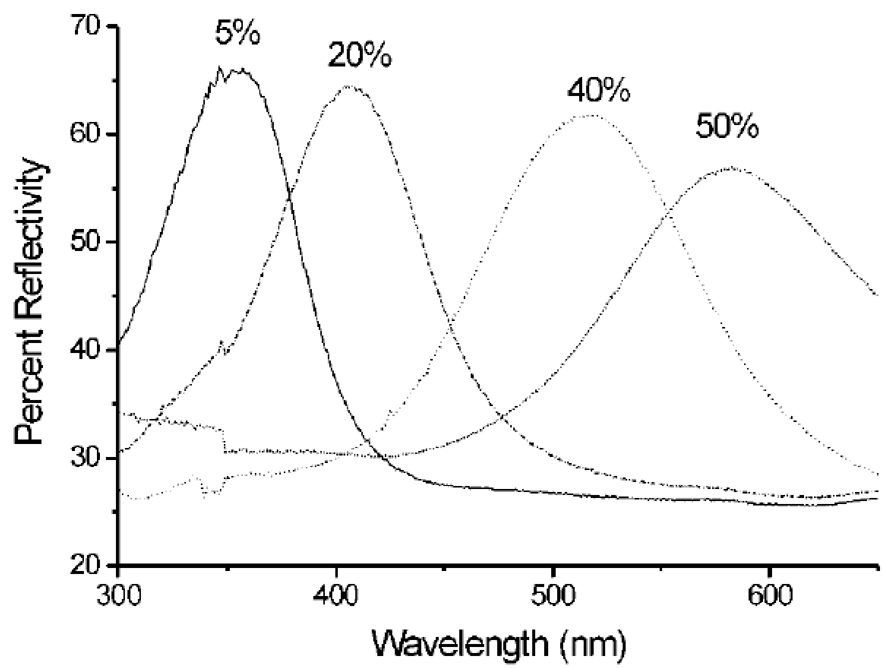


dark/light:
polystyrene/polyisoprene

n = 1.59/1.51

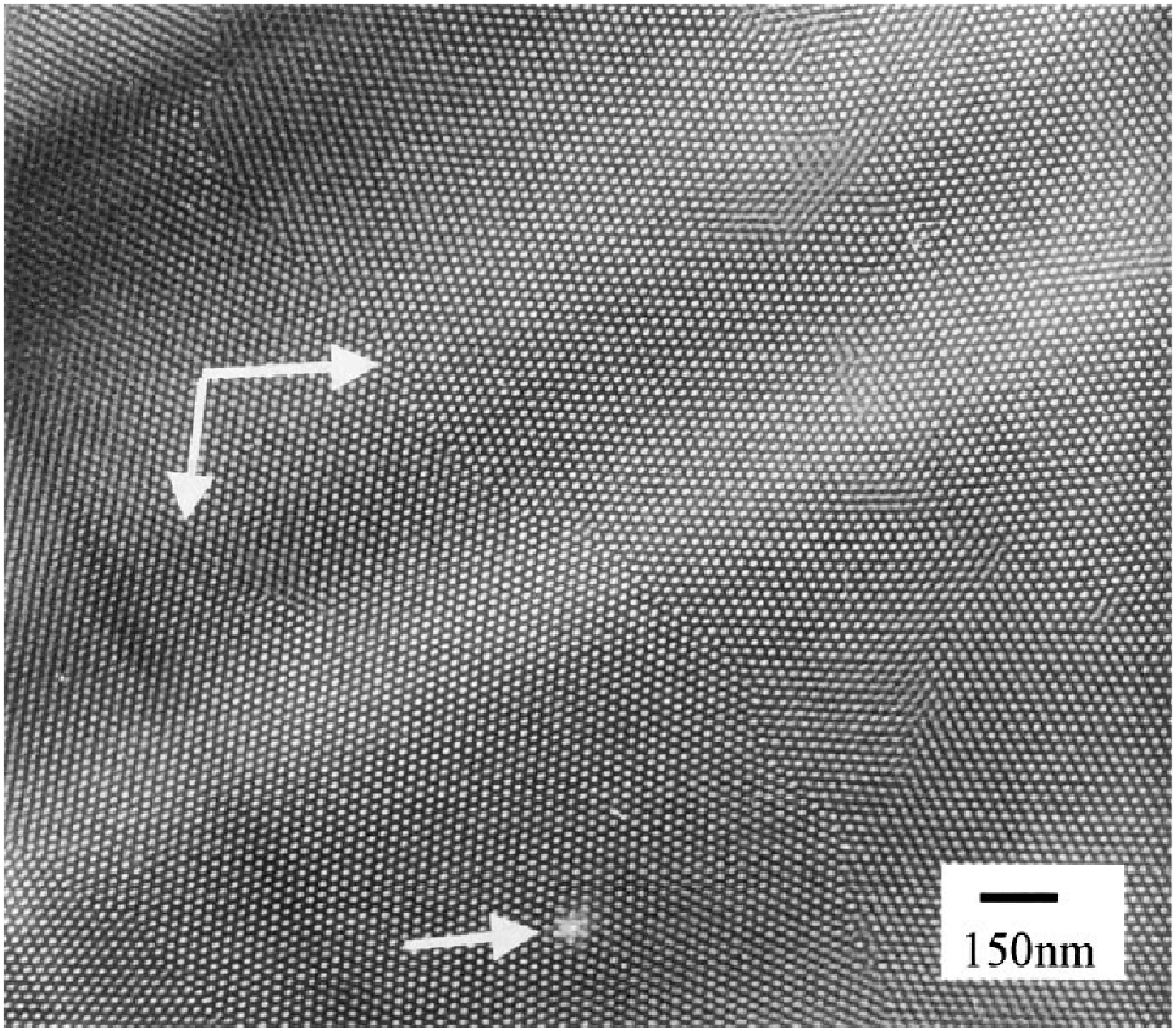
Flexible material:
bandgap can be
shifted by stretching it!

reflection for differing homopolymer %



[A. Urbas *et al.*, *Advanced Materials* **12**, 812 (2000)]

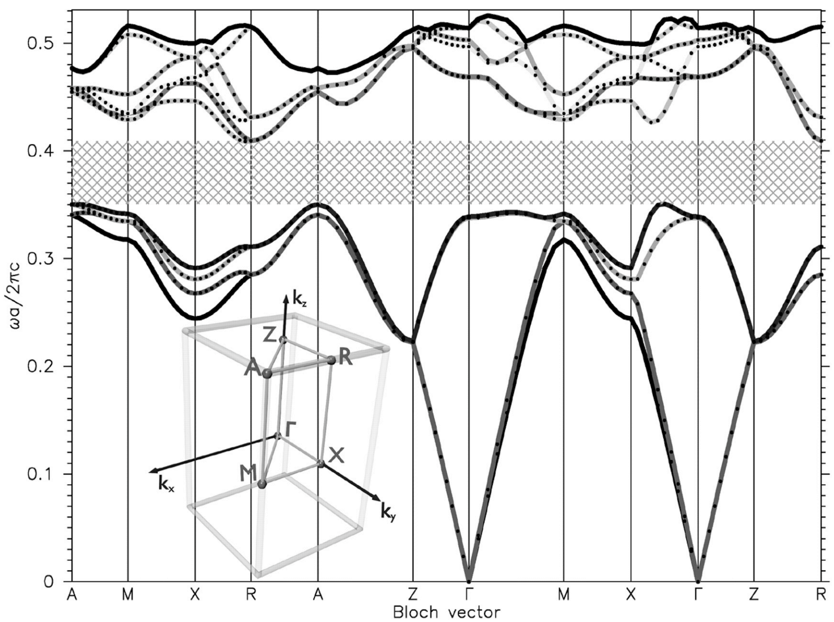
Block-Copolymer 2d Crystal

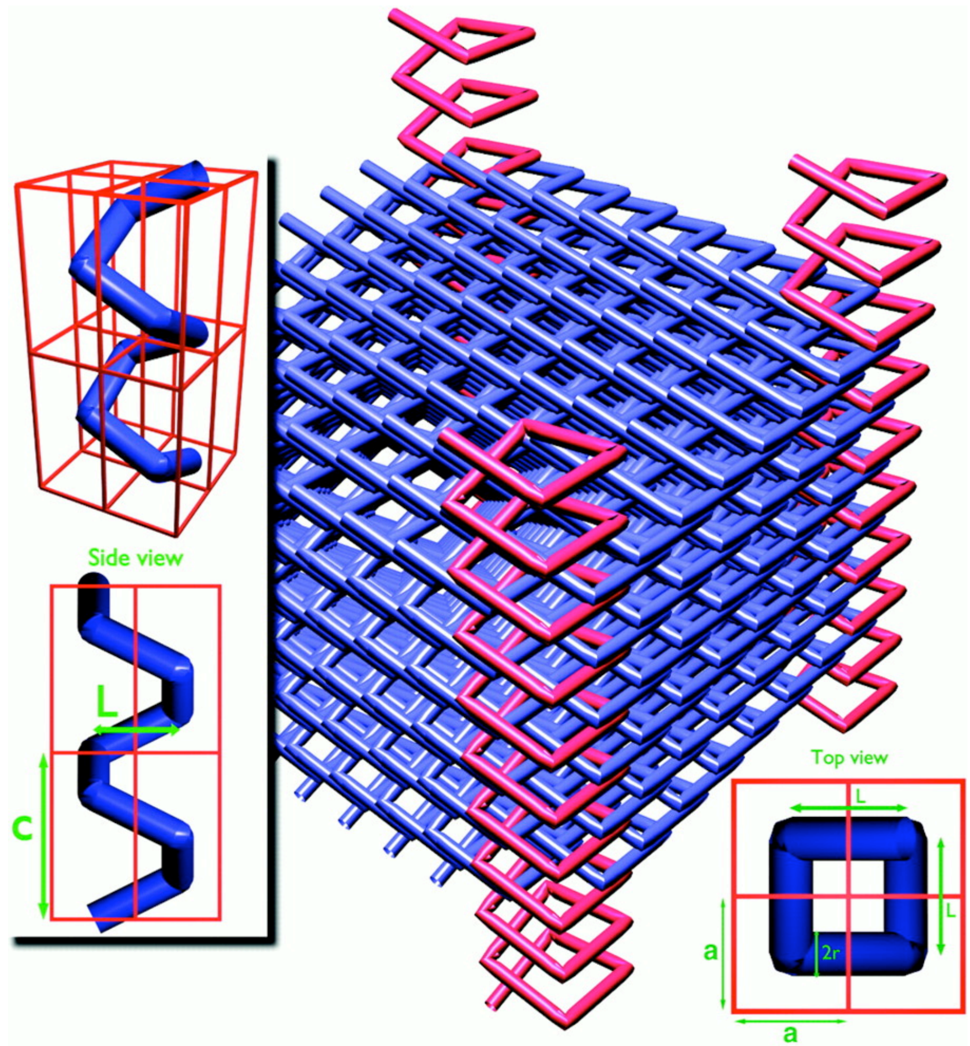


[Y. Fink, A. M. Urbas, M. G. Bawendi, J. D. Joannopoulos, E. L. Thomas, *J. Lightwave Tech*. **17**, 1963 (1999)]

Be GLAD: Even more crystals!

"GLAD" = "GLancing Angle Deposition"





15% gap for Si/air

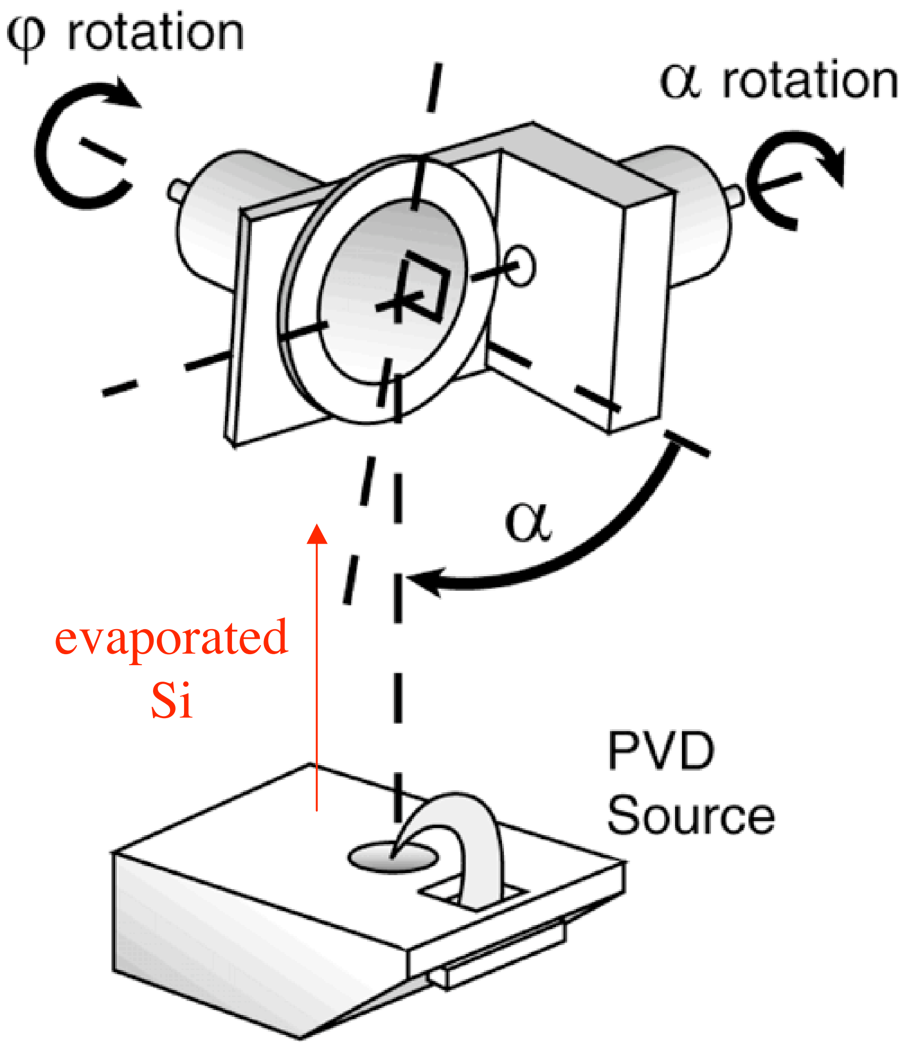
diamond-like

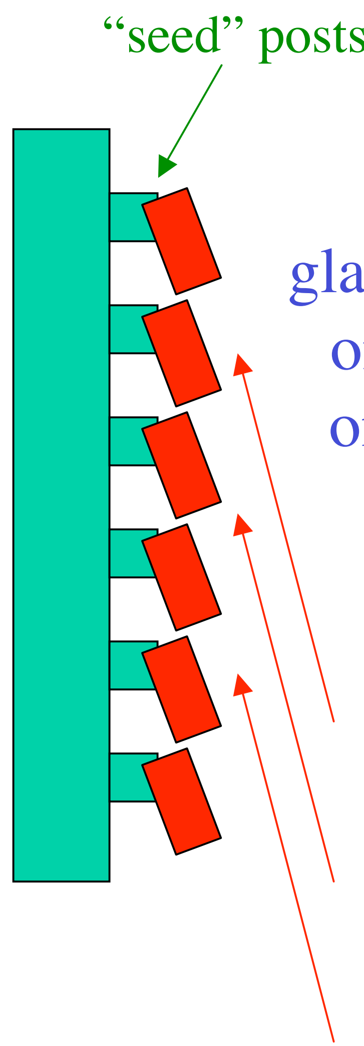
with "broken bonds"

doubled unit cell, so gap between 4th & 5th bands

[O. Toader and S. John, *Science* **292**, 1133 (2001)]

GLAD it works?



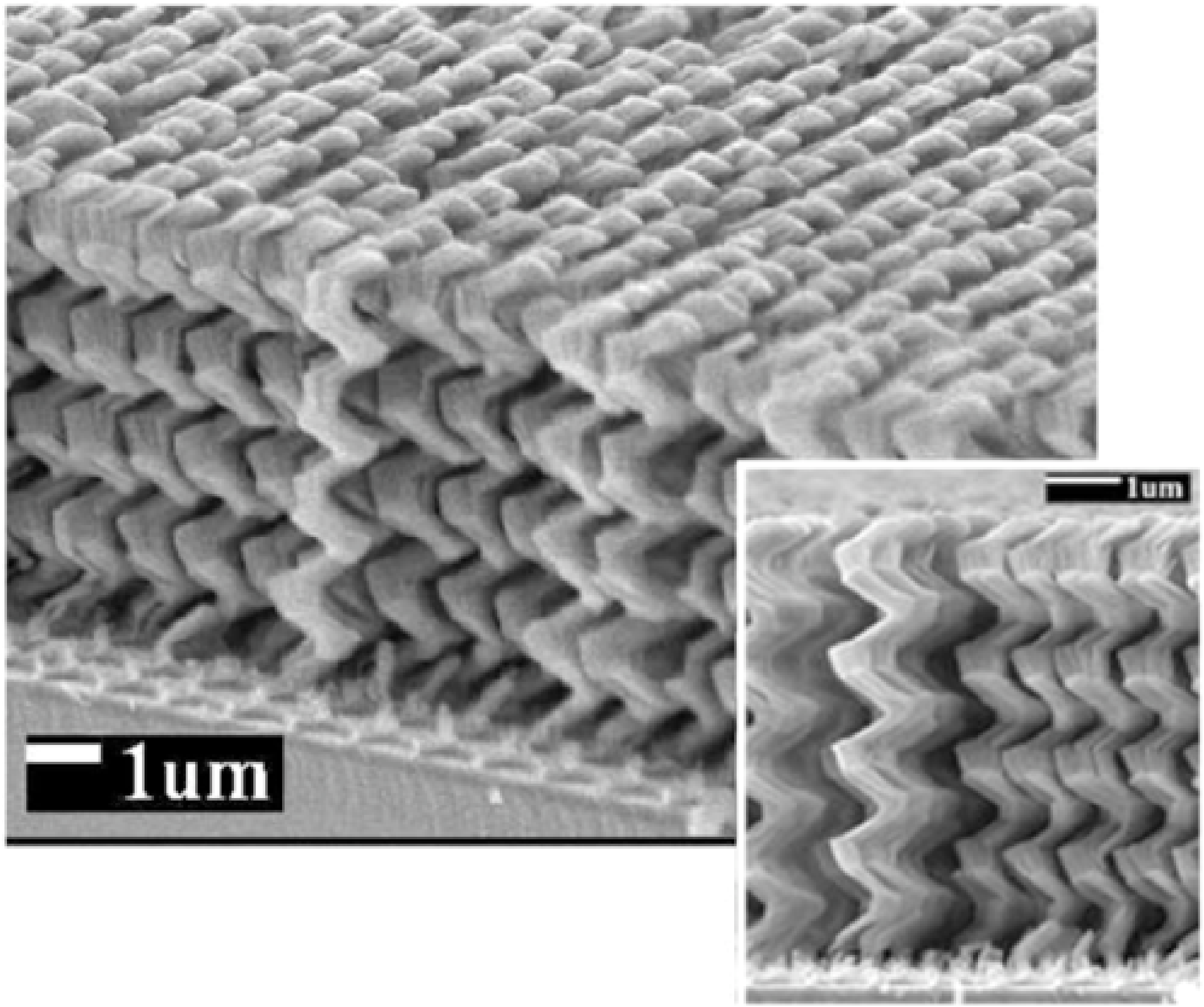


glancing-angle Si only builds up on protrusions

…rotate to spiral

[S. R. Kennedy *et al.*, *Nano Letters* **2**, 59 (2002)]

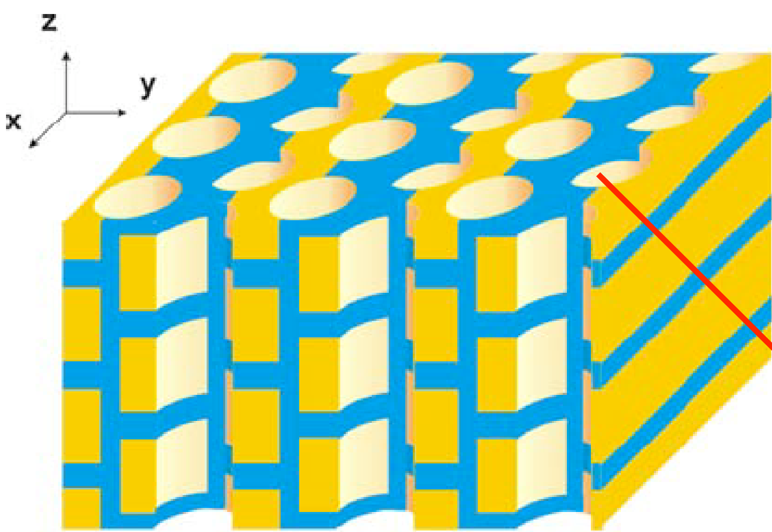
GLAD it works!



[S. R. Kennedy *et al.*, *Nano Letters* **2**, 59 (2002)]

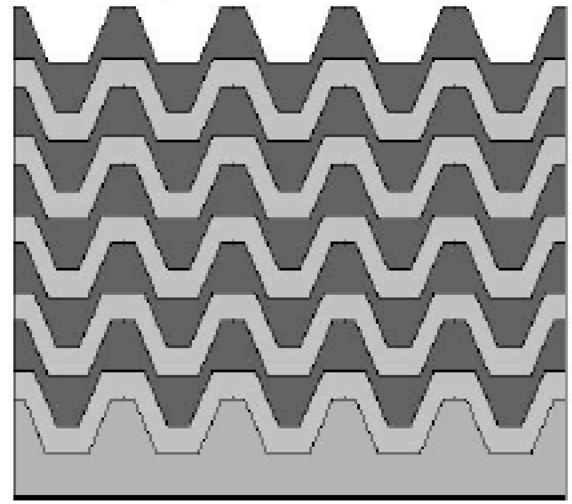
A new twist on layer-by-layer…

start with an old layer-by-layer



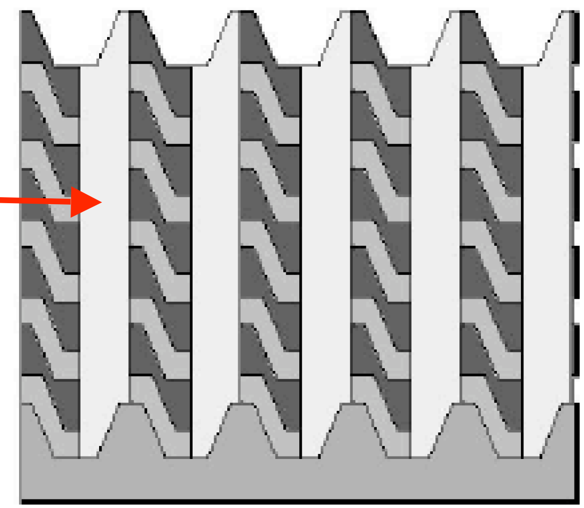
(14% gap for Si/SiO_2/air)

[S. Fan *et al*., *Appl*. *Phys*. *Lett*. **65**, 1466 (1994)]



modify layering slightly…

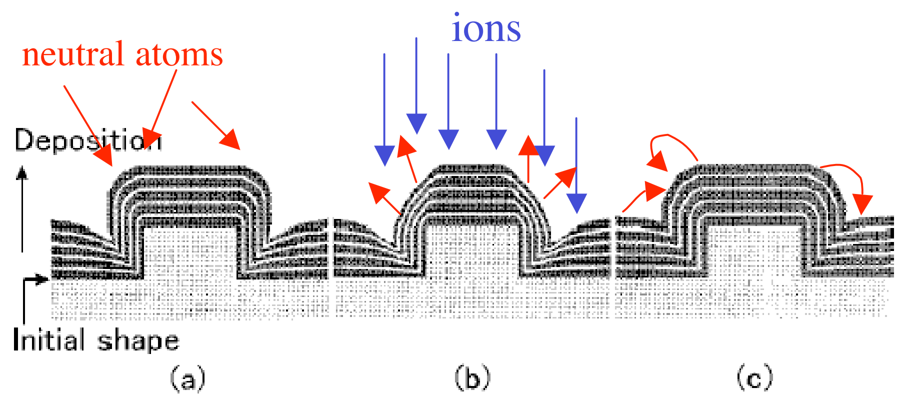
(don't forget the holes)



[S. Kawakami *et al*., *Appl*. *Phys*. *Lett*. **74**, 463 (1999)]

Auto-cloning

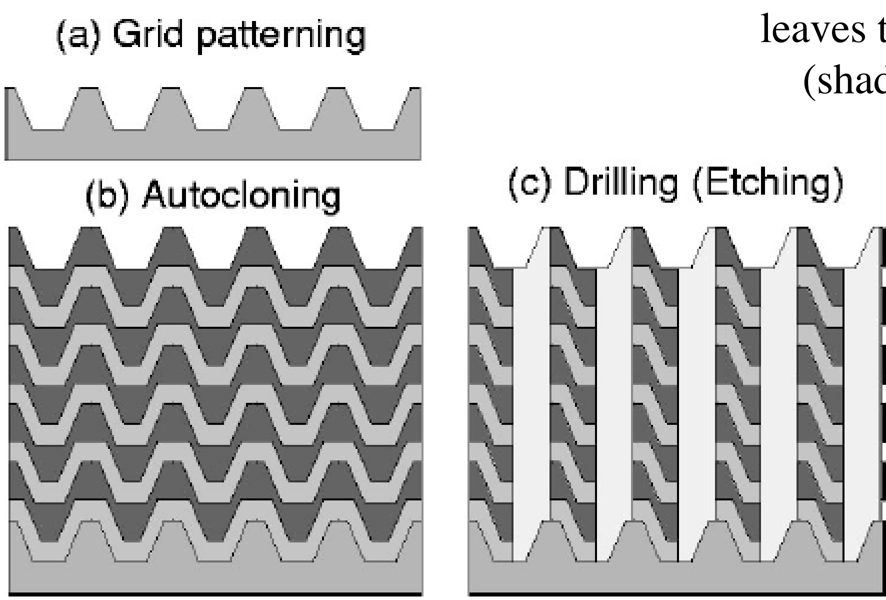
Competition between 3 processes "clones" shape of substrate



diffuse deposition leaves trenches (shadows)

bias sputtering cuts corners (prefers 60°)

re-deposition fills trenches



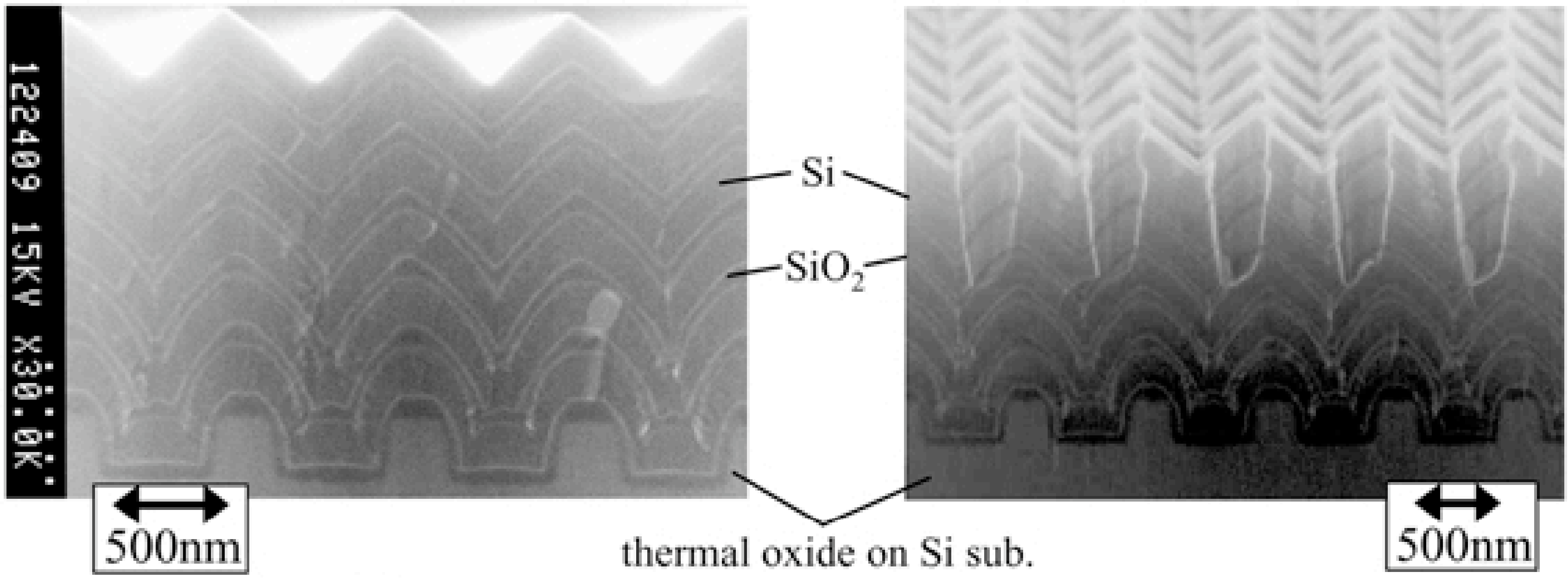
… so, only planar patterning is in substrate

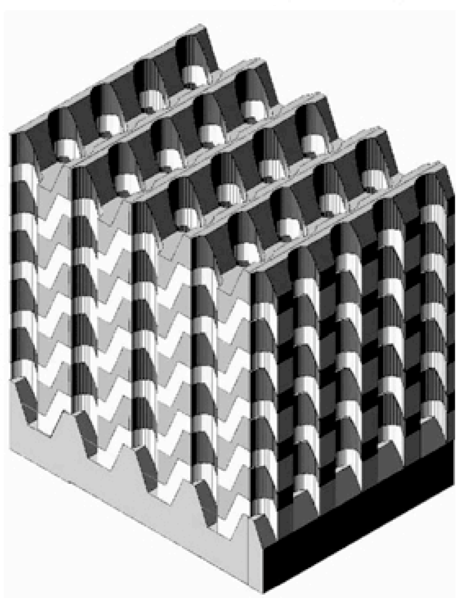
…only drilling needs alignment

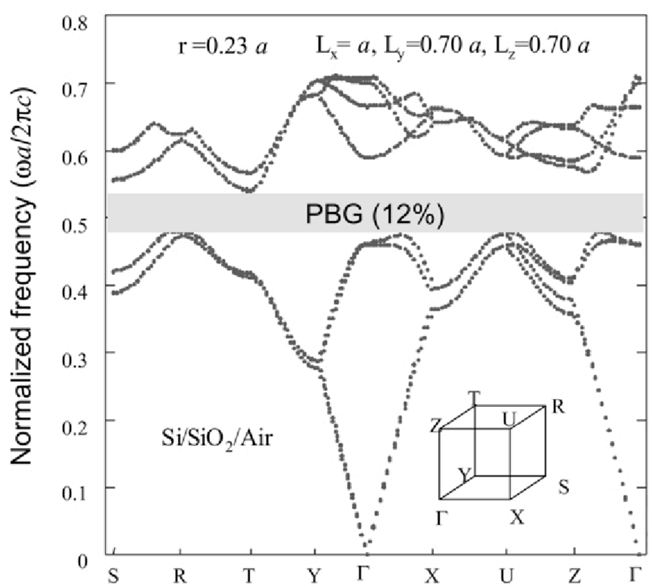
…minimize etch roughness

[S. Kawakami *et al.*, *Appl. Phys. Lett.* **74**, 463 (1999)]

Auto-cloned Photonic Crystal



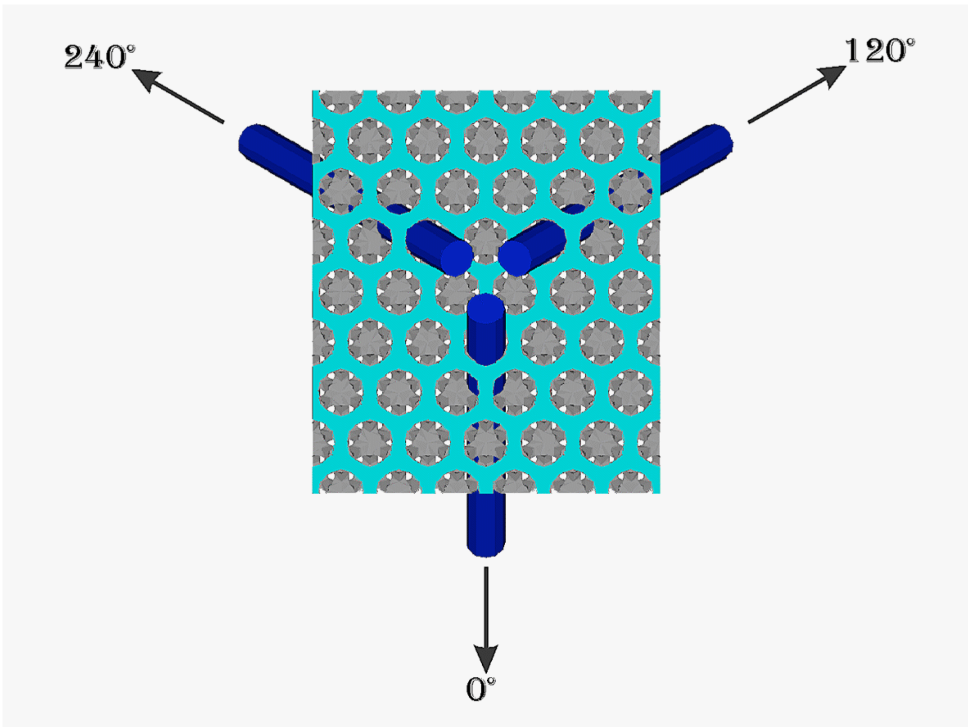




[E. Kuramochi *et al*., *Opt*. *Quantum*. *Elec*. **34**, 53 (2002)]

“Yablonovite”

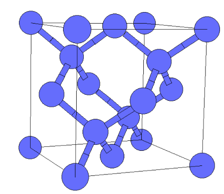
[E. Yablonovitch, T. M. Gmitter, and K. M. Leung, *Phys. Rev. Lett.* **67**, 2295 (1991)]

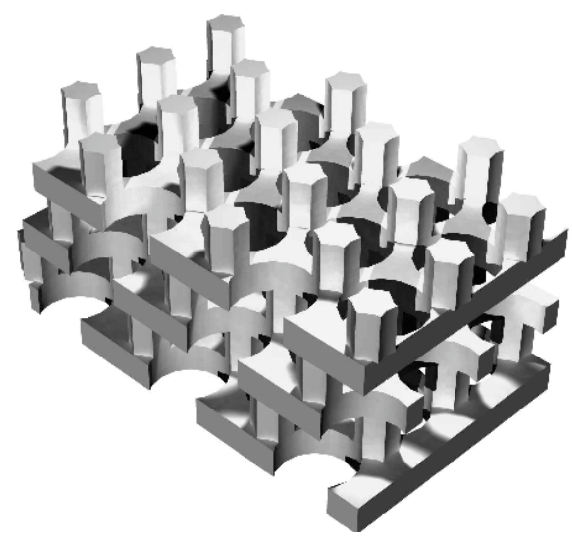


[image: `http://www.ee.ucla.edu/labs/photon/`]

diamond-like fcc crystal

earliest “fabrication-amenable” alternative to diamond spheres

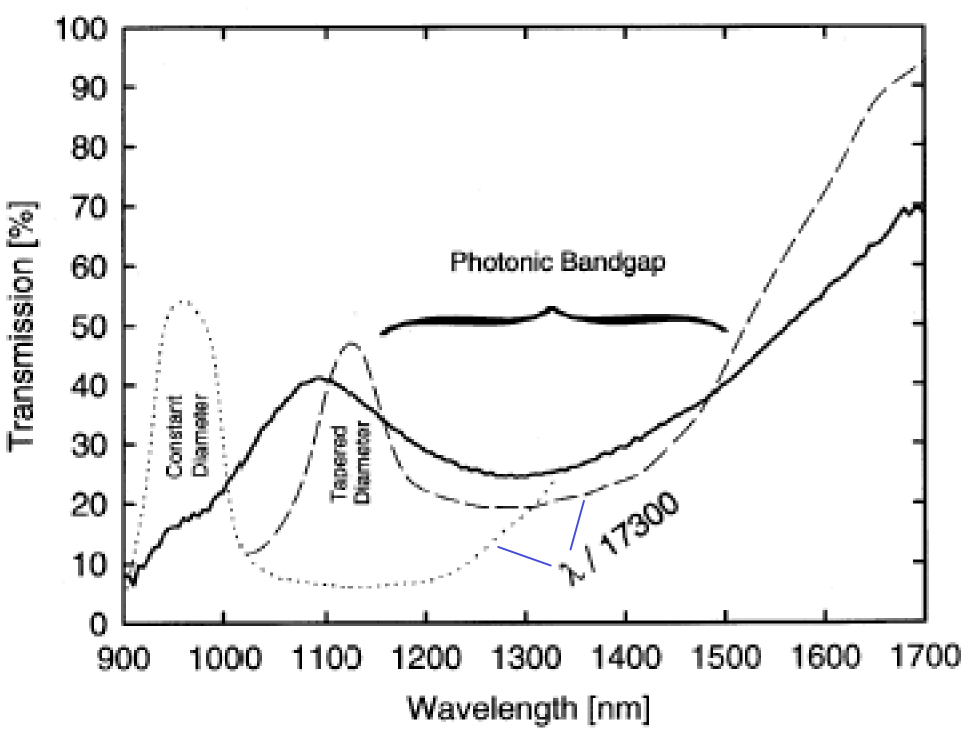


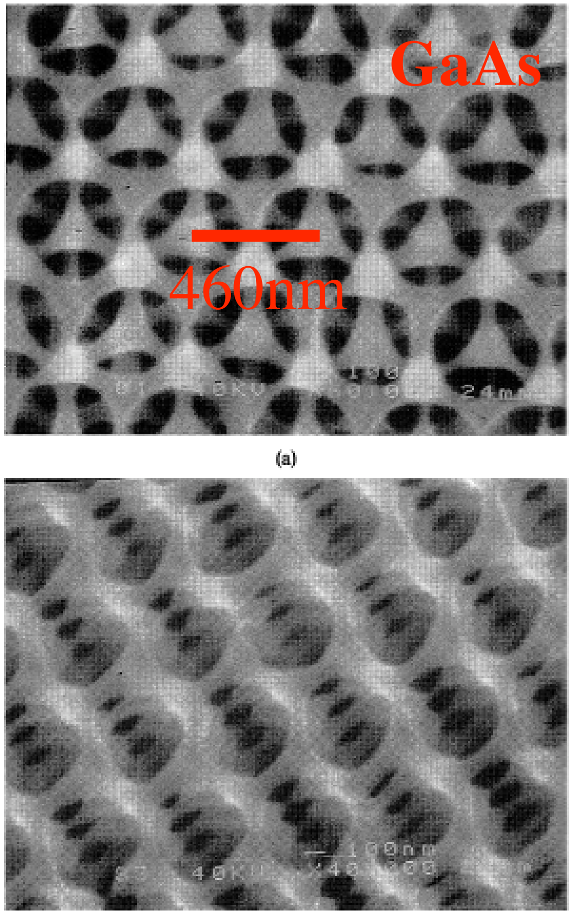


(Topology is very similar to 2000 layer-by-layer crystal)

Making Yablonovite

e-beam mask + chemically-assisted ion-beam etching



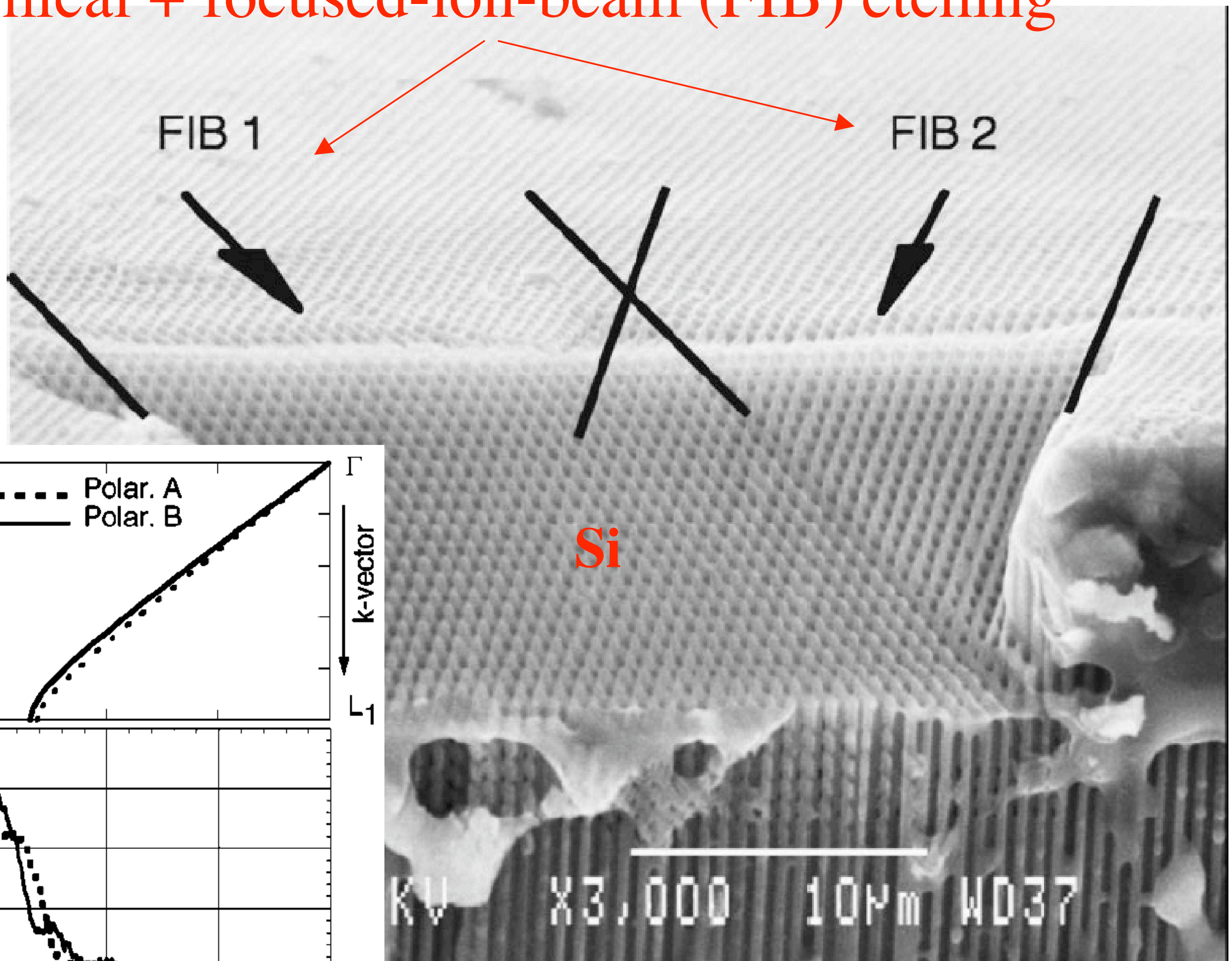


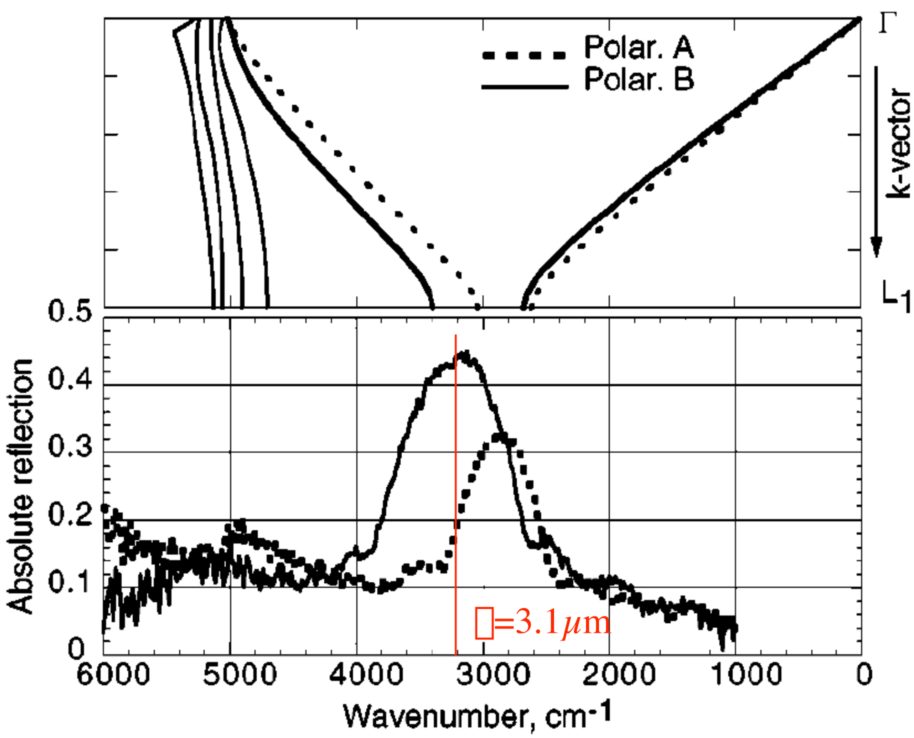
[C. C. Cheng *et al.*, *Physica Scripta*. **T68**, 17 (1996)]

Making ~Yablonovite (II)

electrochemical + focused-ion-beam (FIB) etching

(deep vertical holes)





[A. Chelnokov *et al.*, *Appl. Phys. Lett.* **77**, 2943 (2000)] *in short:*

Those experimentalists
are damned clever*

* either that, or they are out of their minds