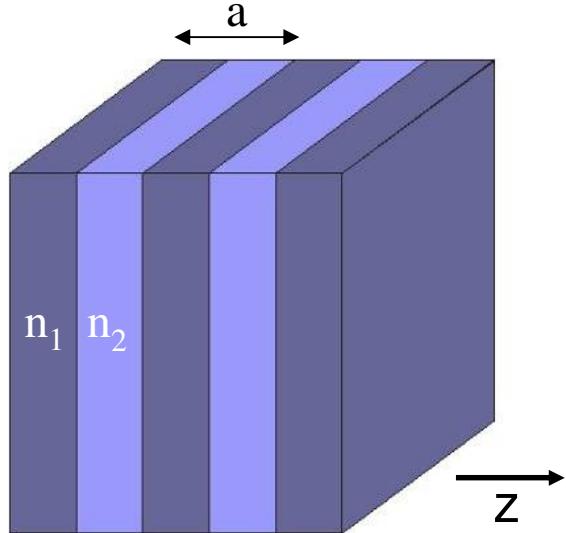


Metodi di fabbricazione PhC

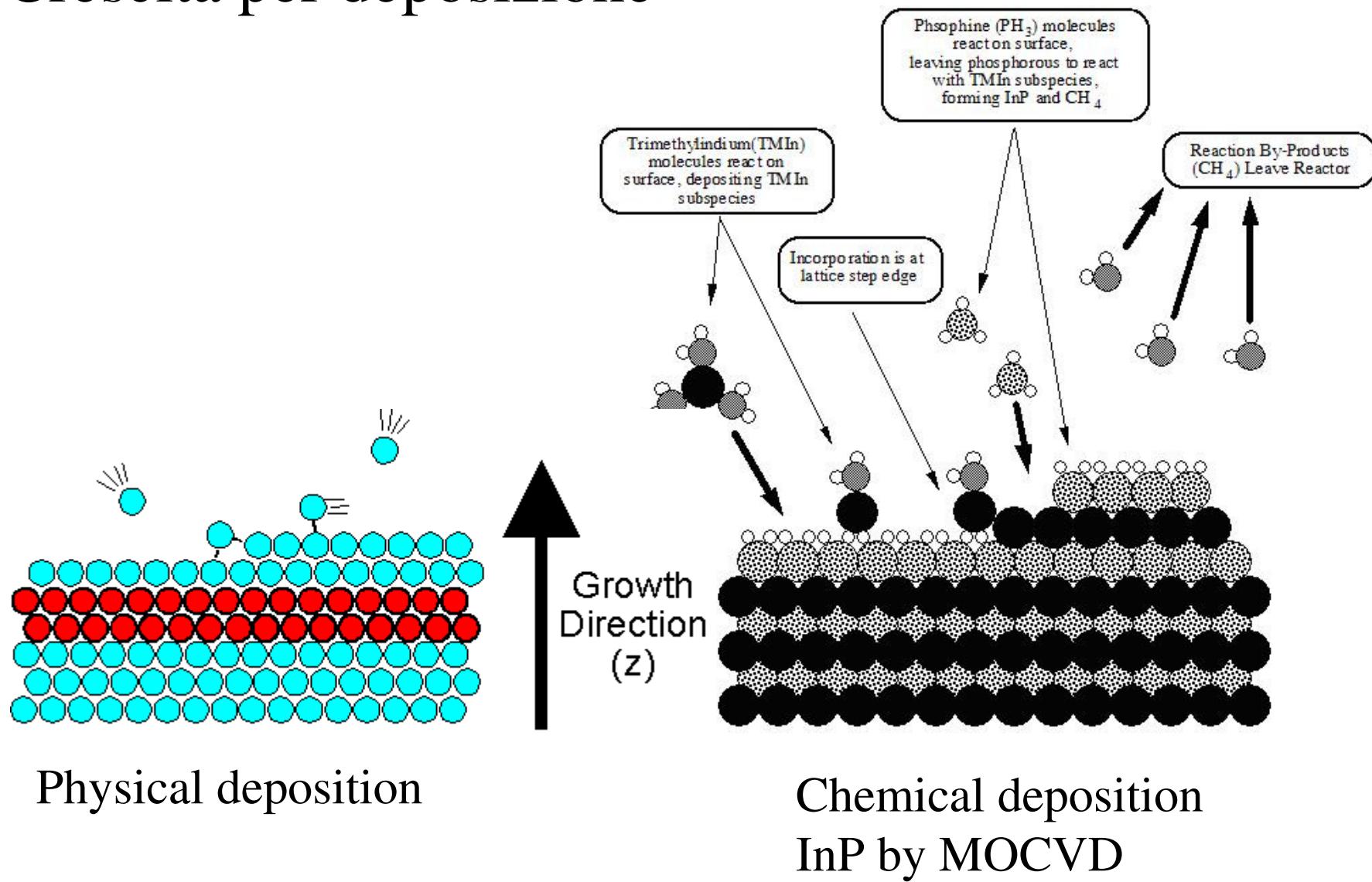
PhC in 1D

1D



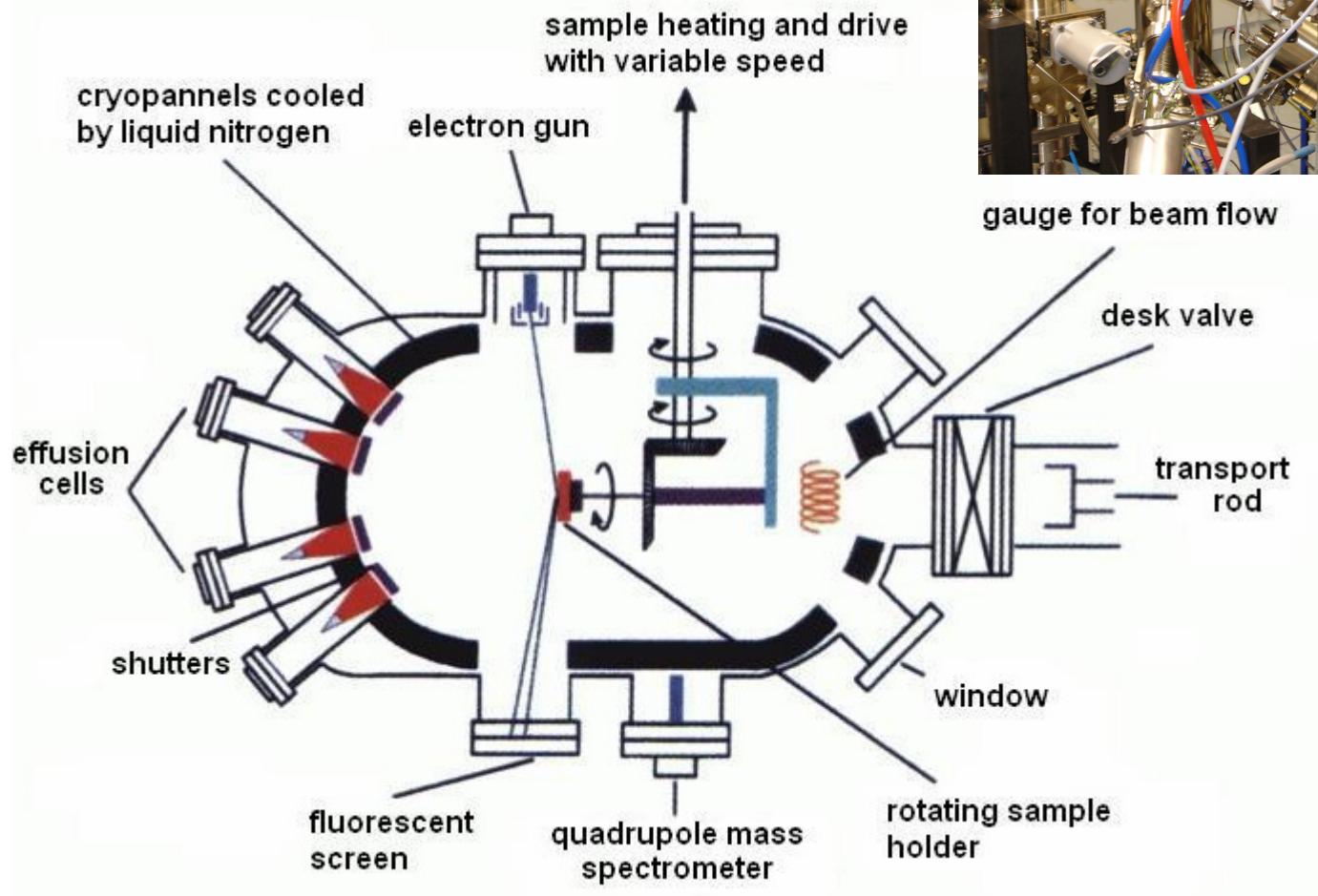
Deposizione multilayer
(MBE,MOCVD,PVD,CVD)
Silicio poroso
Litografia

Crescita per deposizione

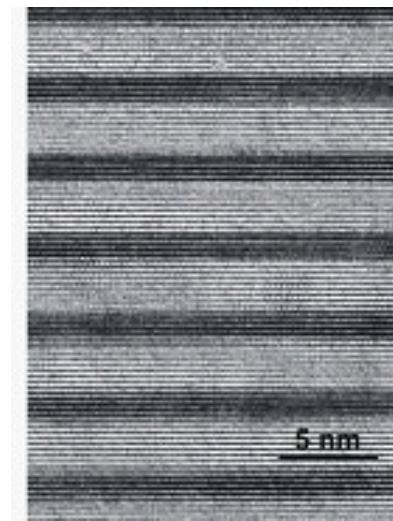
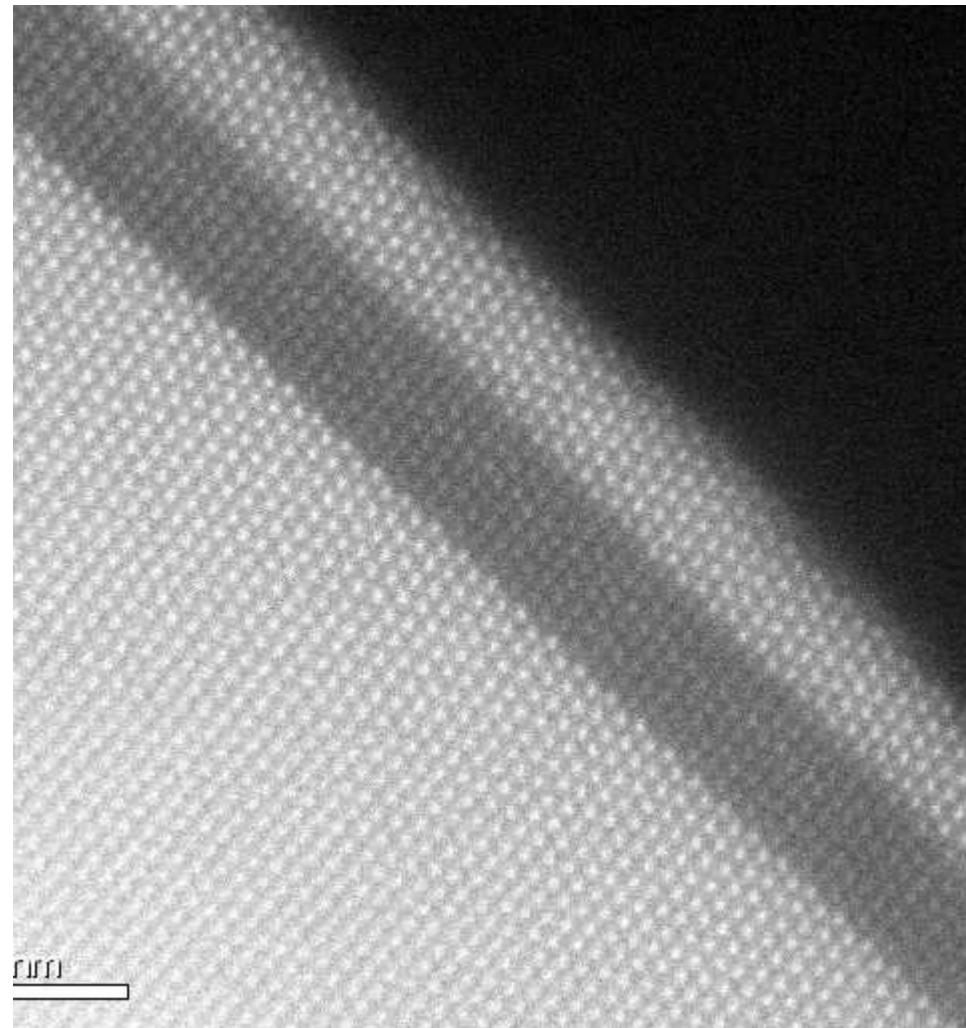


Deposizione controllata

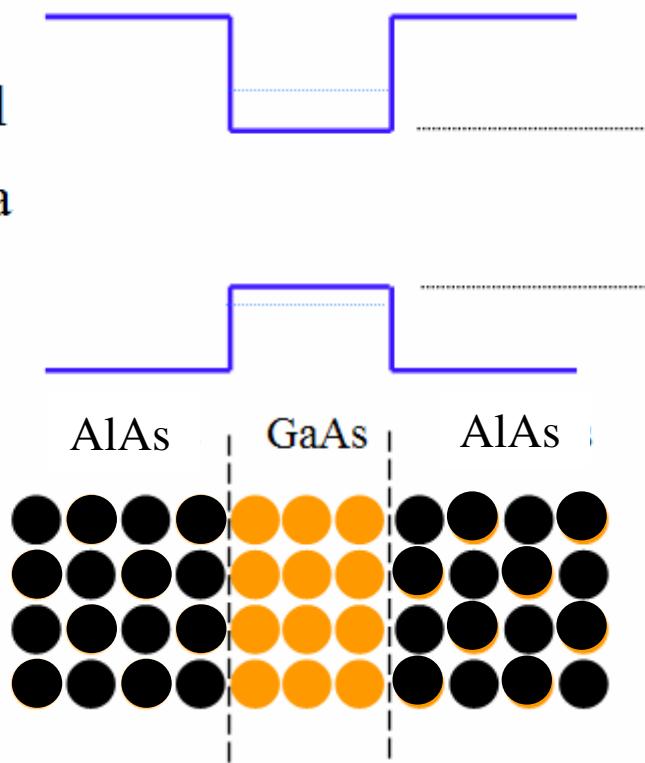
MBE



Heterointerfaces

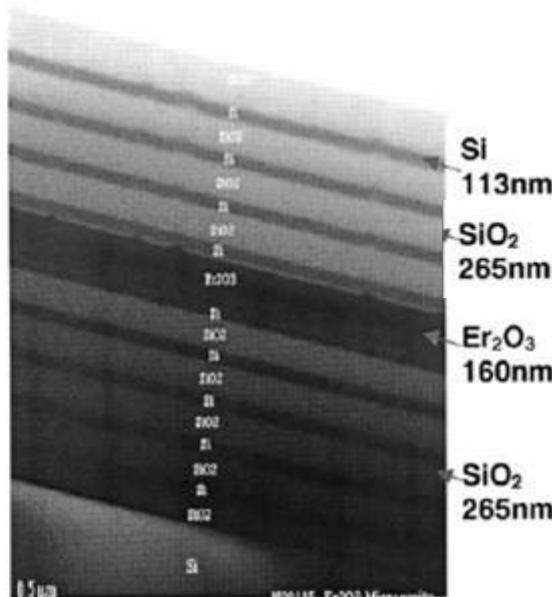
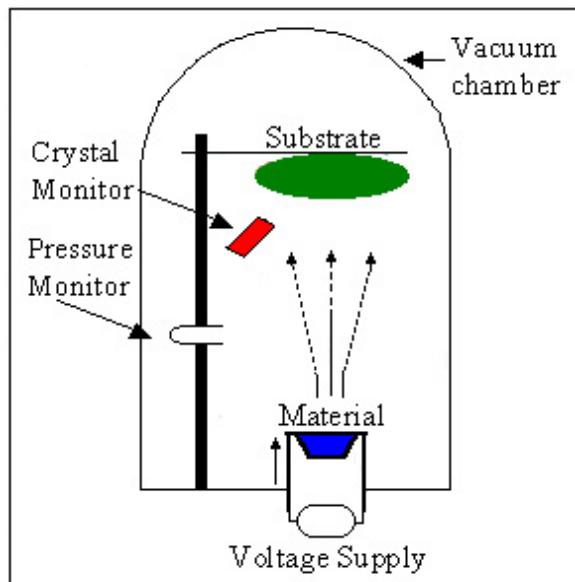


● Al
● Ga

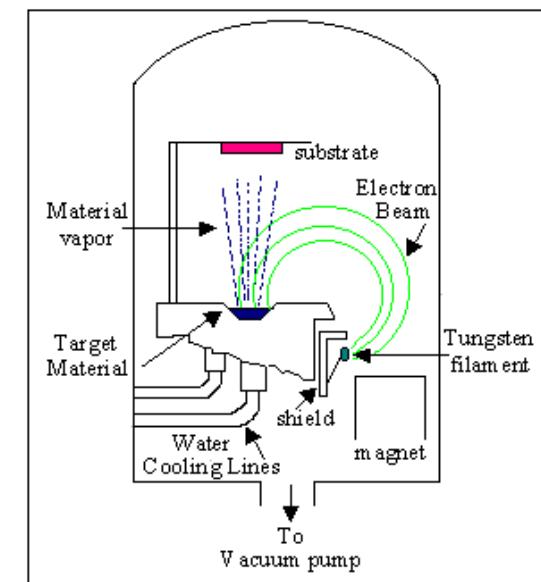


Per la fotonica bastano precisioni inferiori

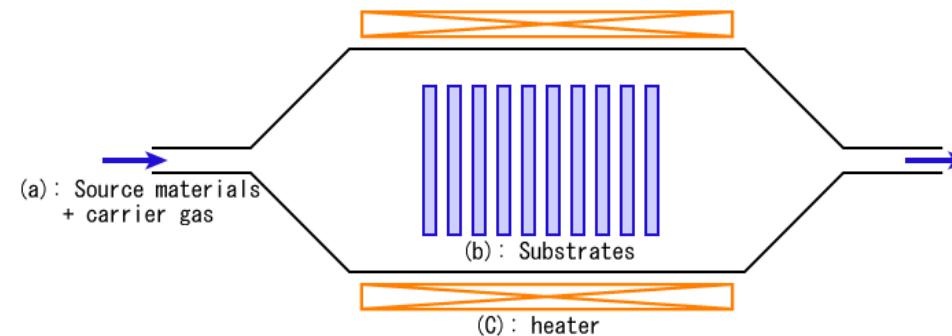
Thermal evaporation



Sputtering, PVD



CVD



Silicio poroso

Etching elettrochimico controllato

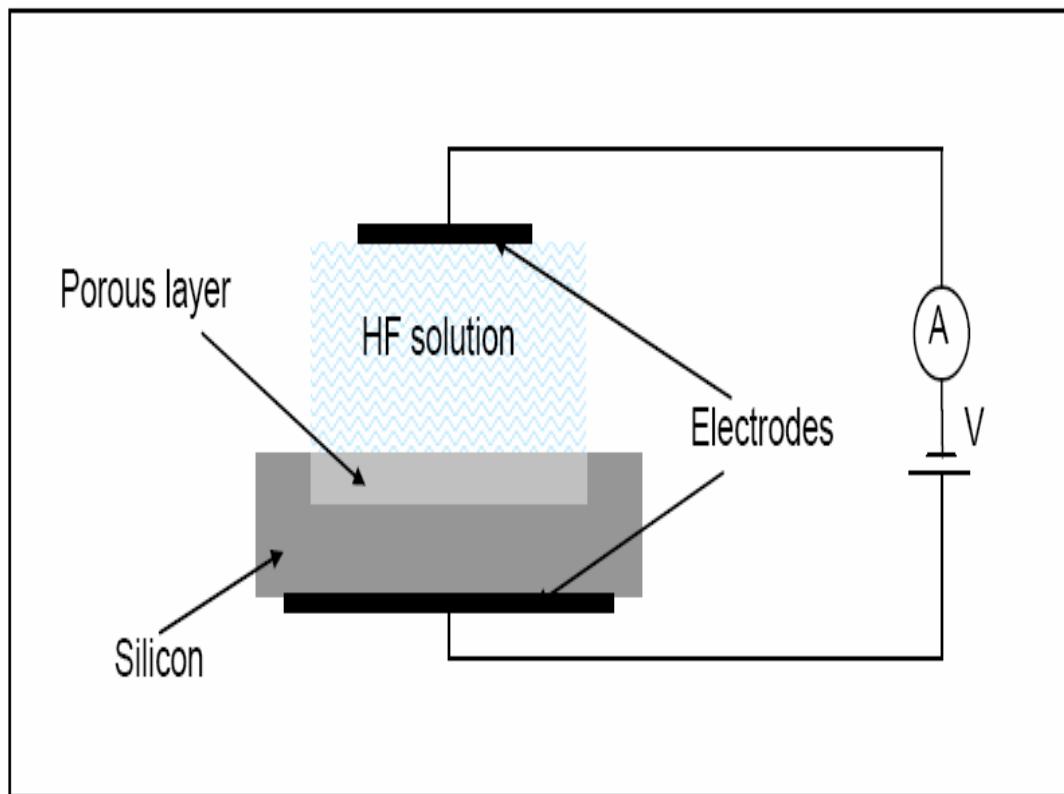
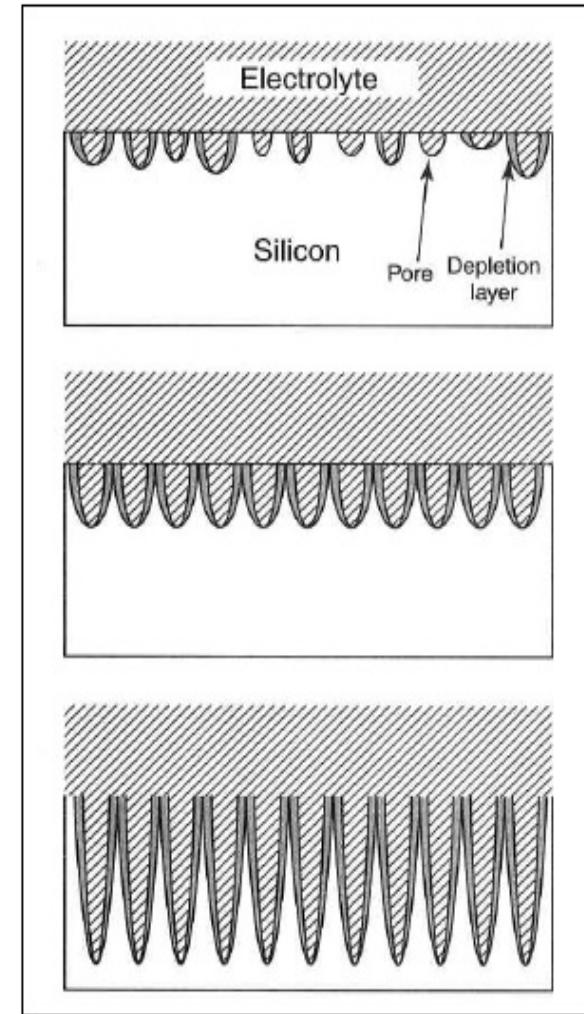
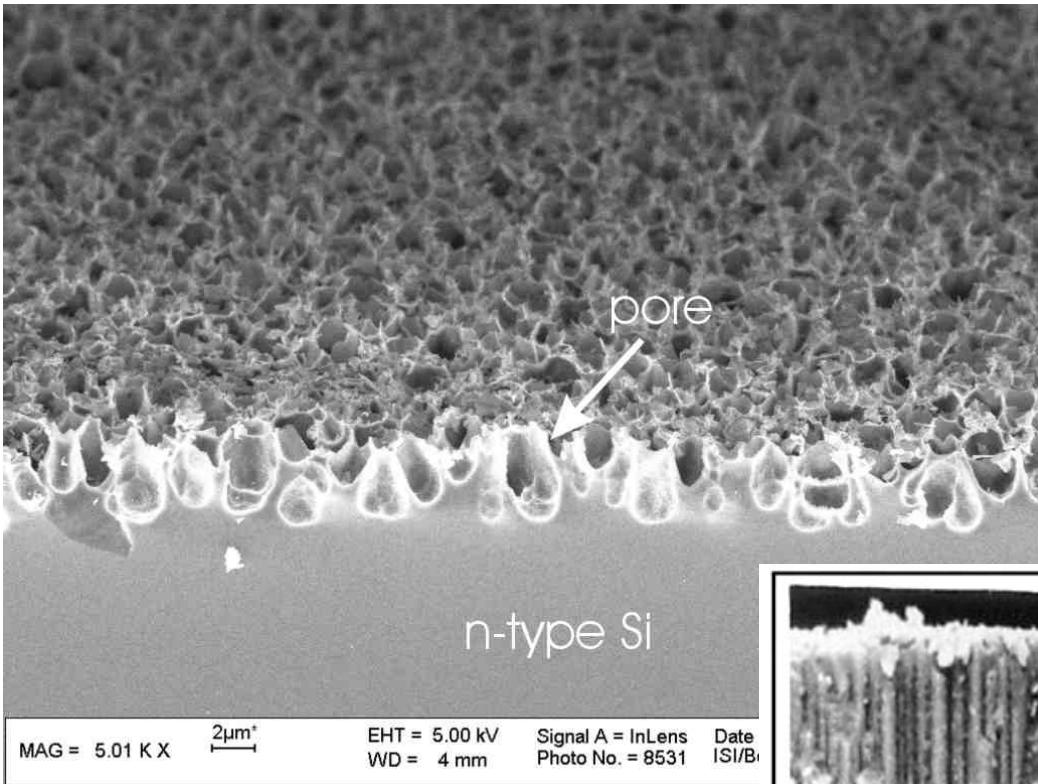


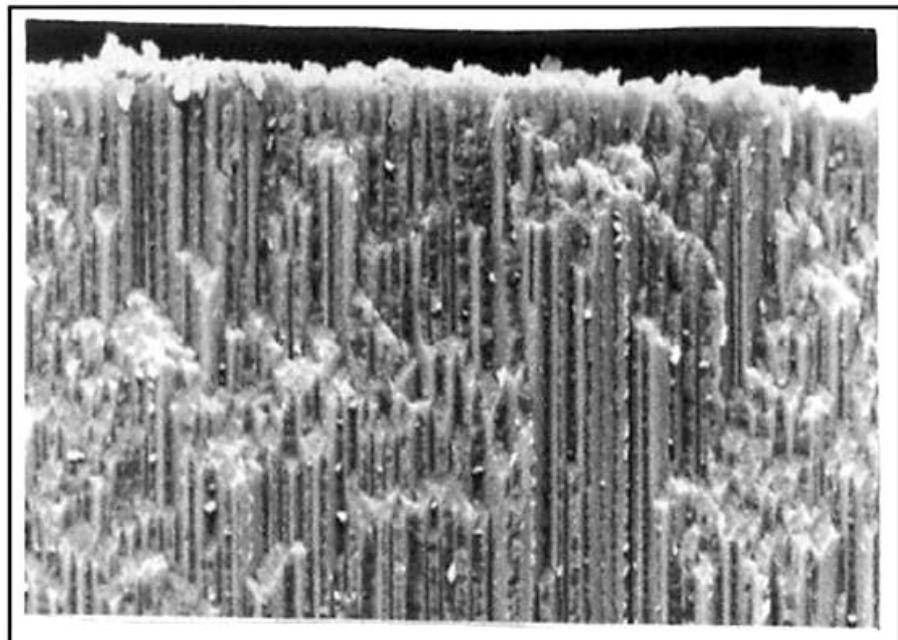
Fig. 2.1. Schematic diagram of the porous silicon anodization circuit.



Disordered porous silicon

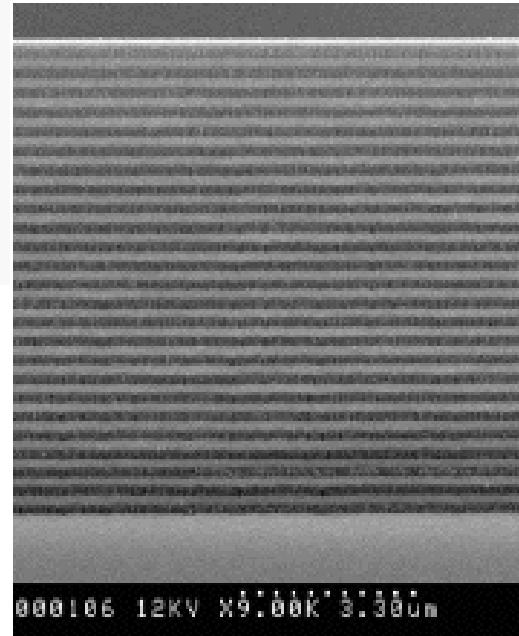
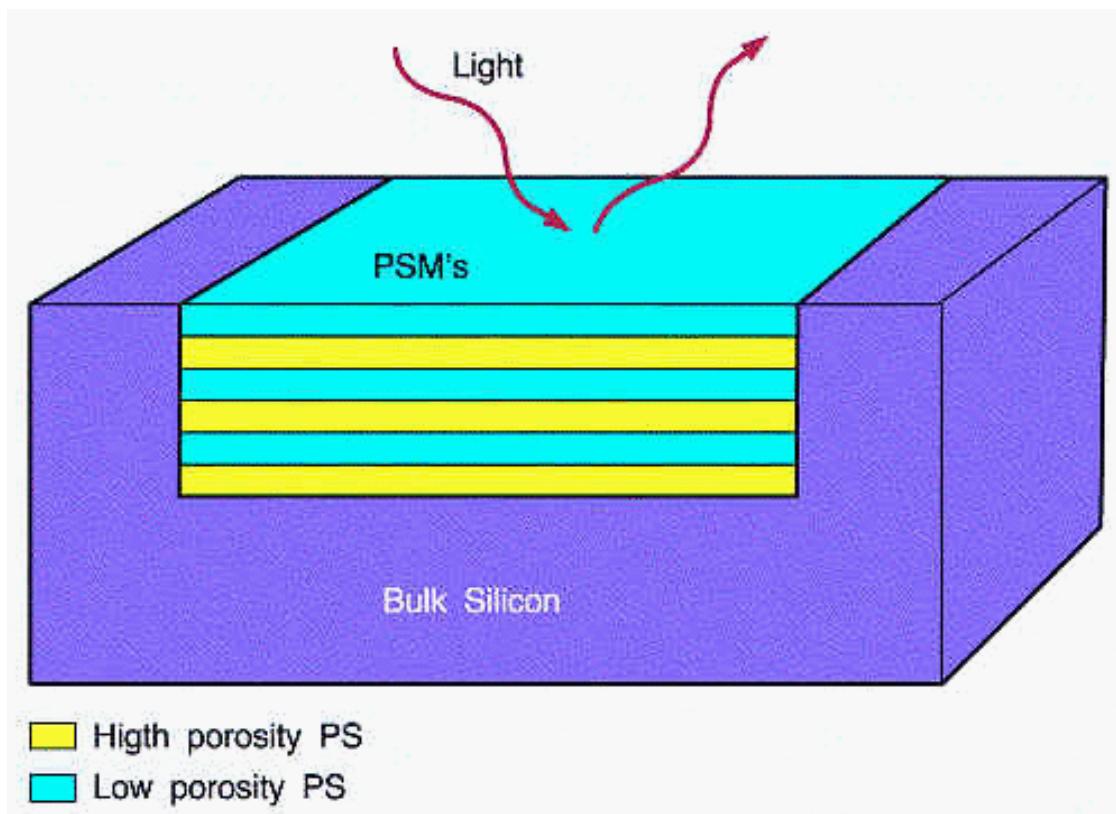


$$n_{eff} = \frac{n_{Si} V_{Si} + n_{Air} V_{Air}}{V_{Si} + V_{Air}}$$

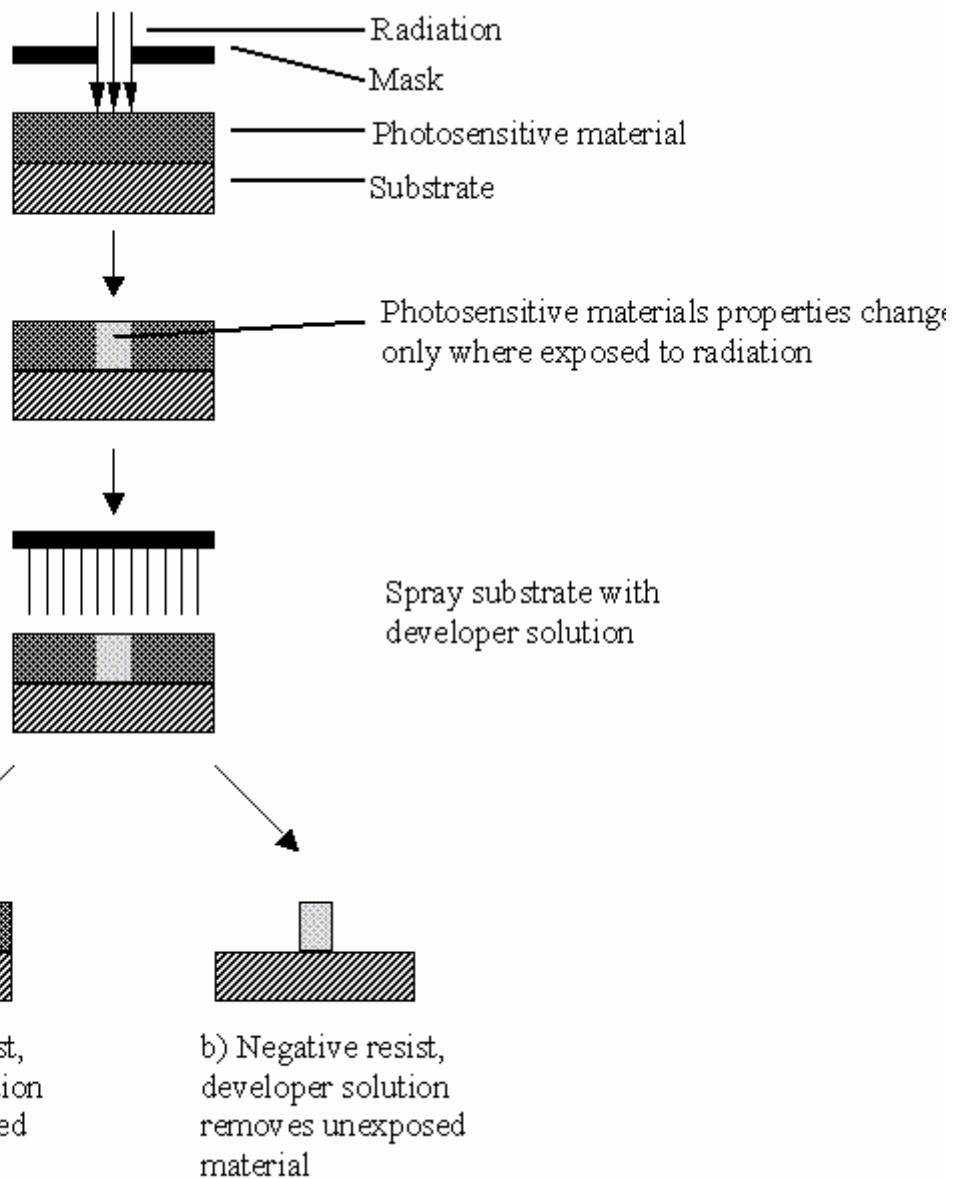


Micrograph of electro-etched porous silicon surface (from Sailor)

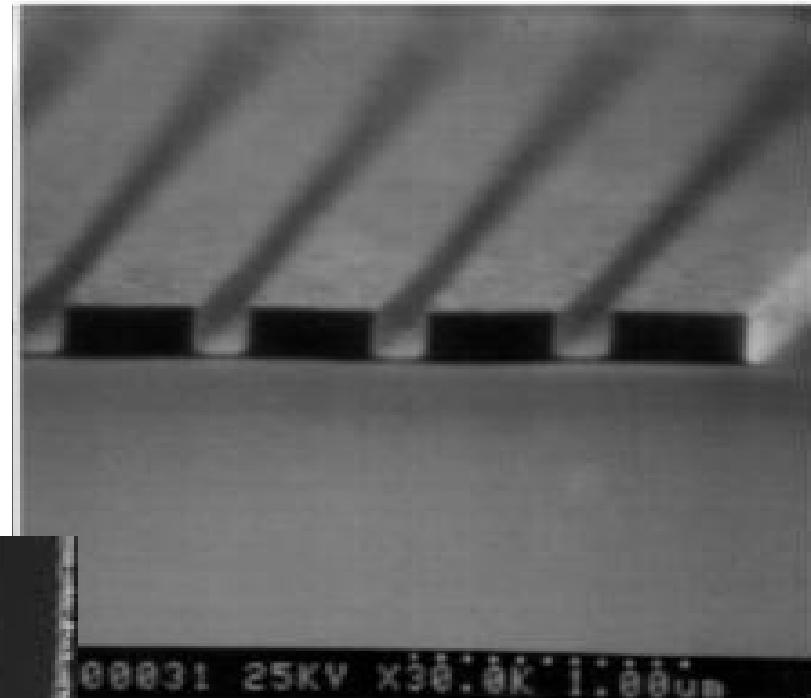
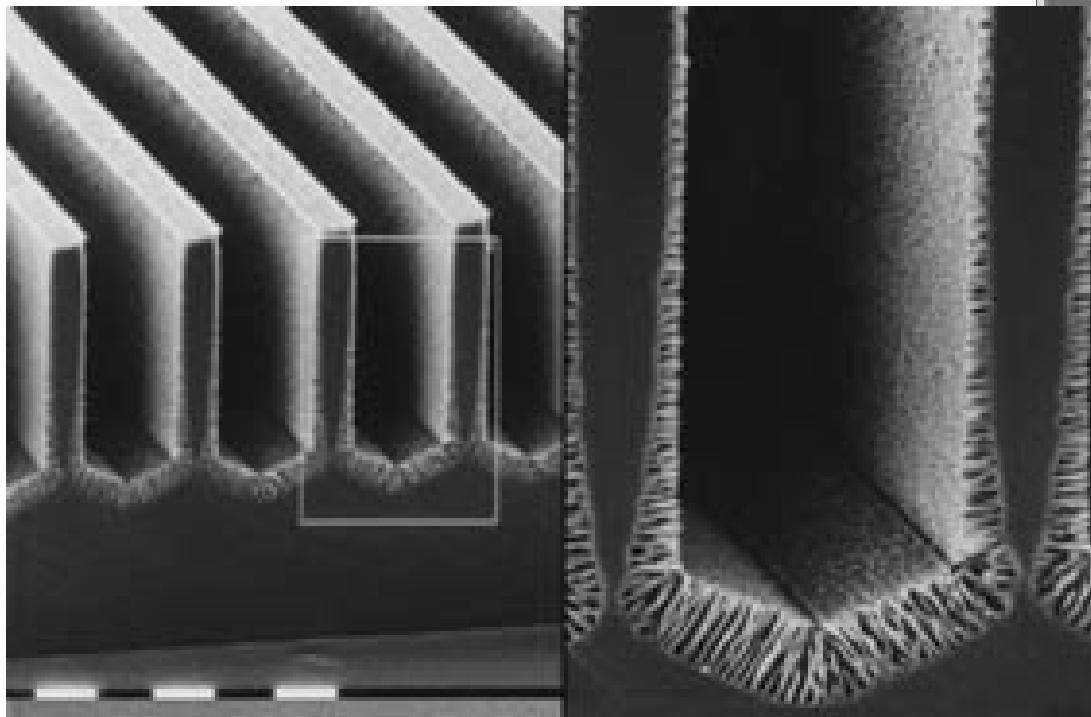
Multilayers



Litografia

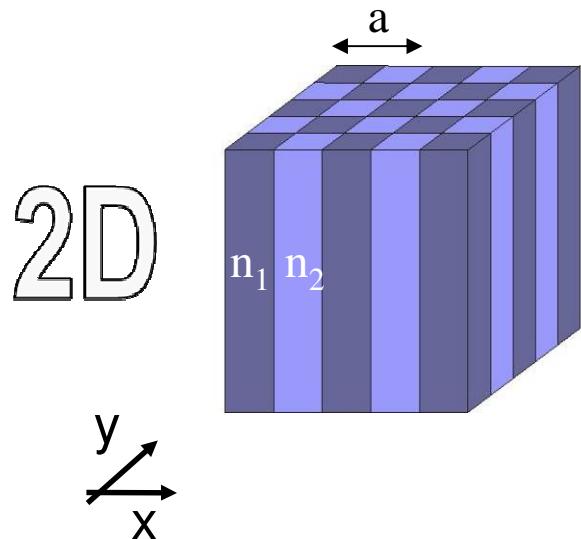


Litografia



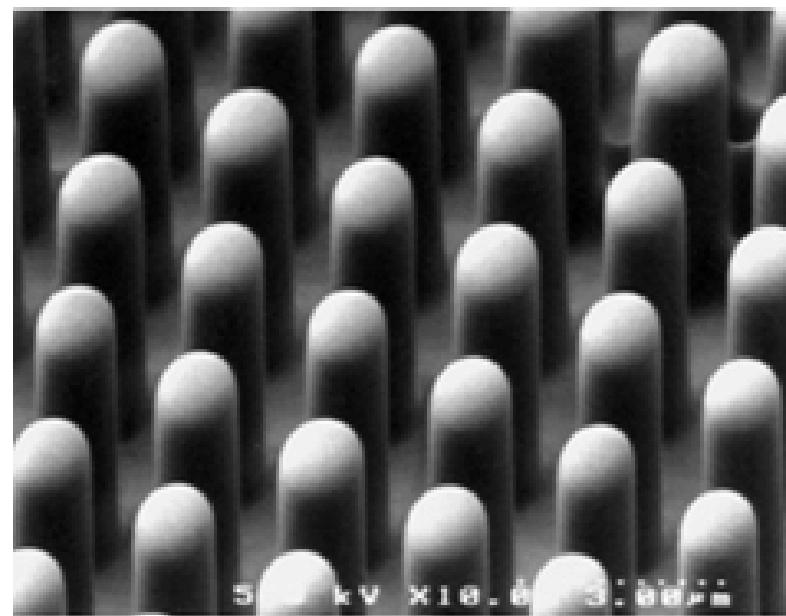
La geometria delle strutture può essere disegnata a piacere

PhC in 2D



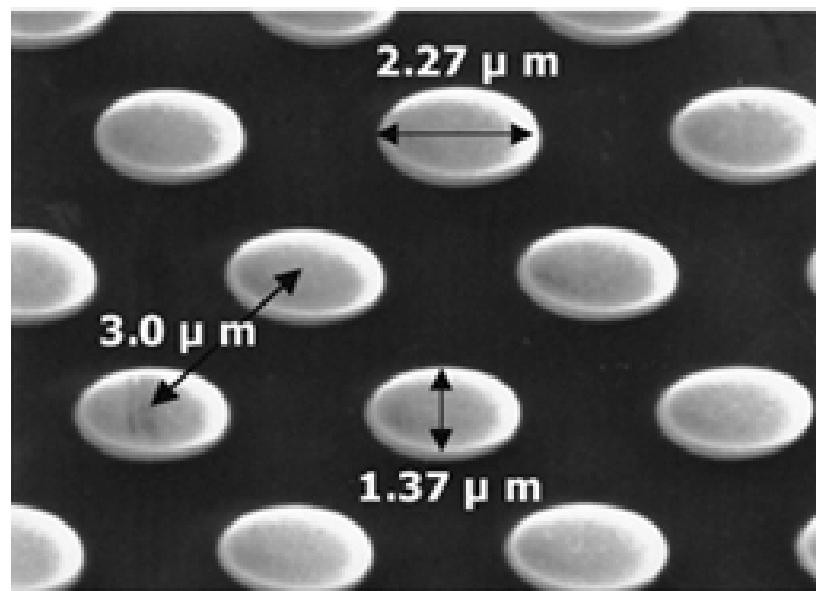
Silicio poroso
Litografia

2 configurazioni

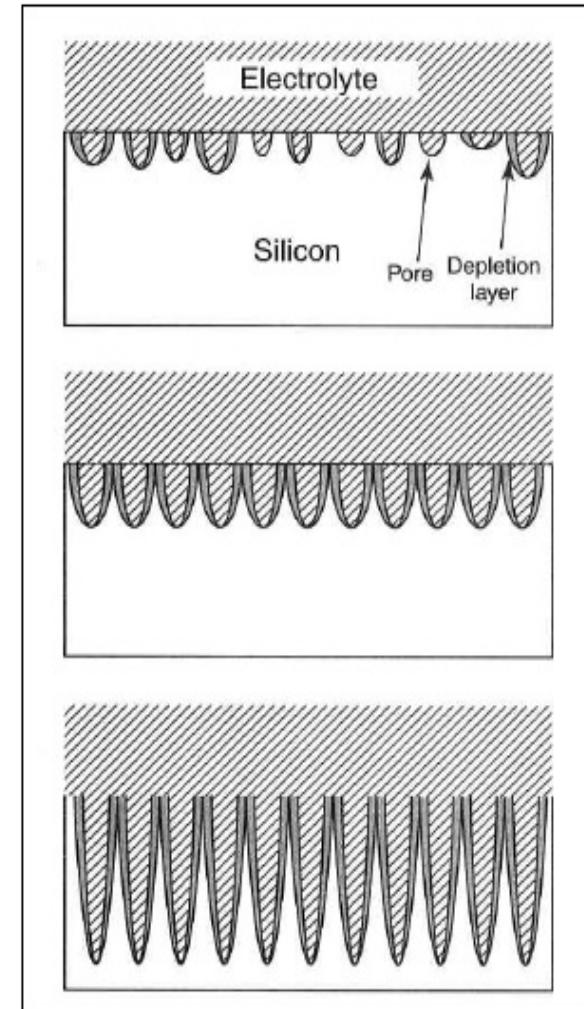
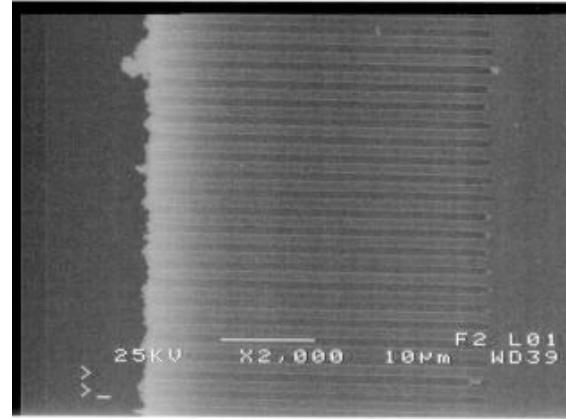
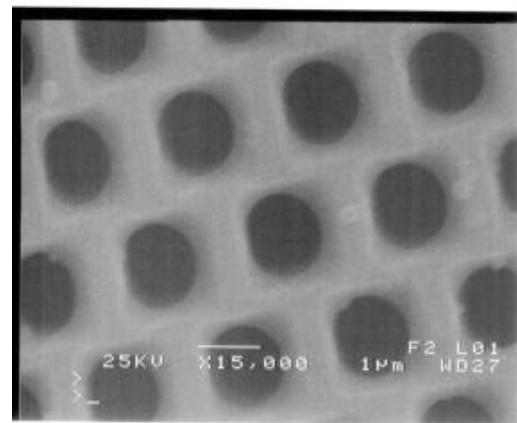
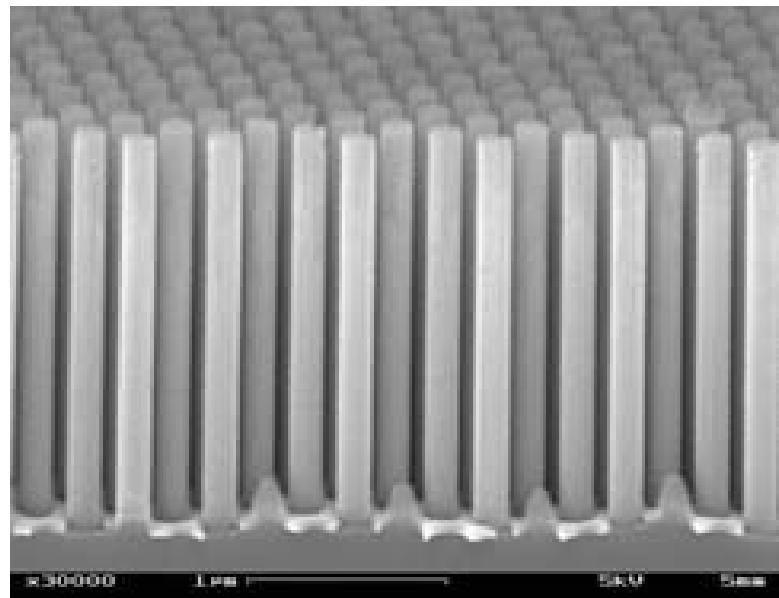


colonne

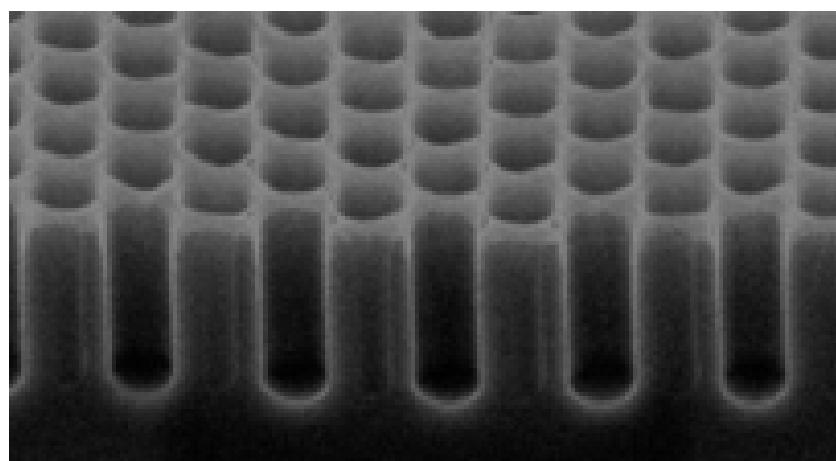
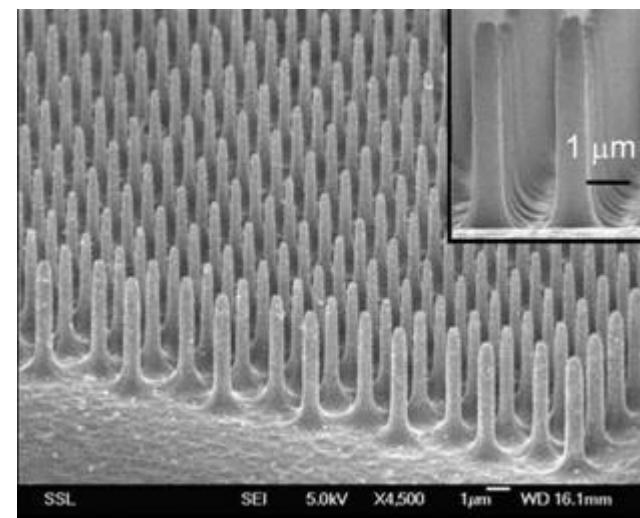
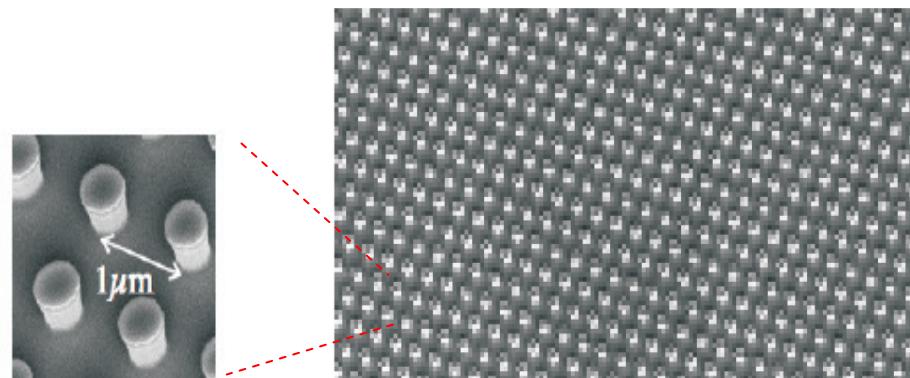
fori



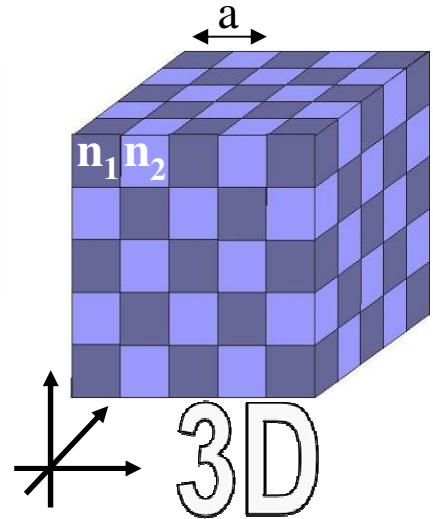
Silicio macroporoso ordinato



Litografia

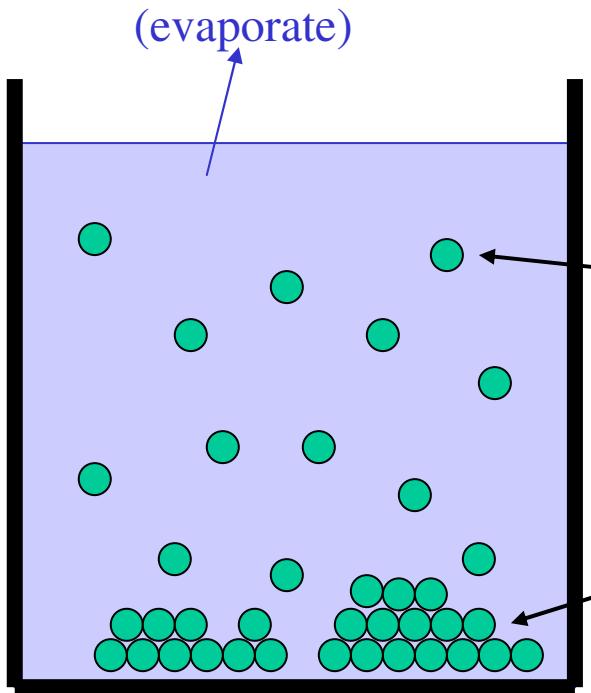


PhC in 3D



Self assembly
Litography
Direct laser writing
Micromanipulation
Olographic lithography

Self assembly of Colloids



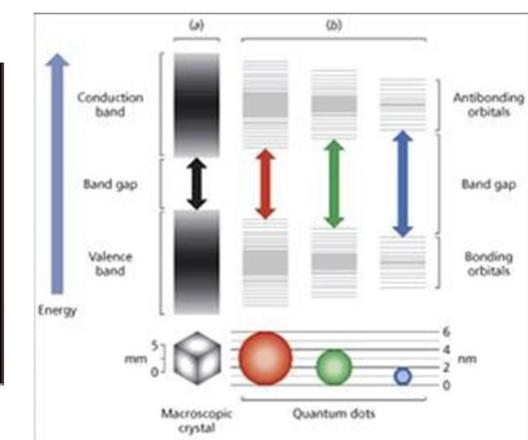
sediment by gravity into close-packed fcc lattice!



silica (SiO_2)

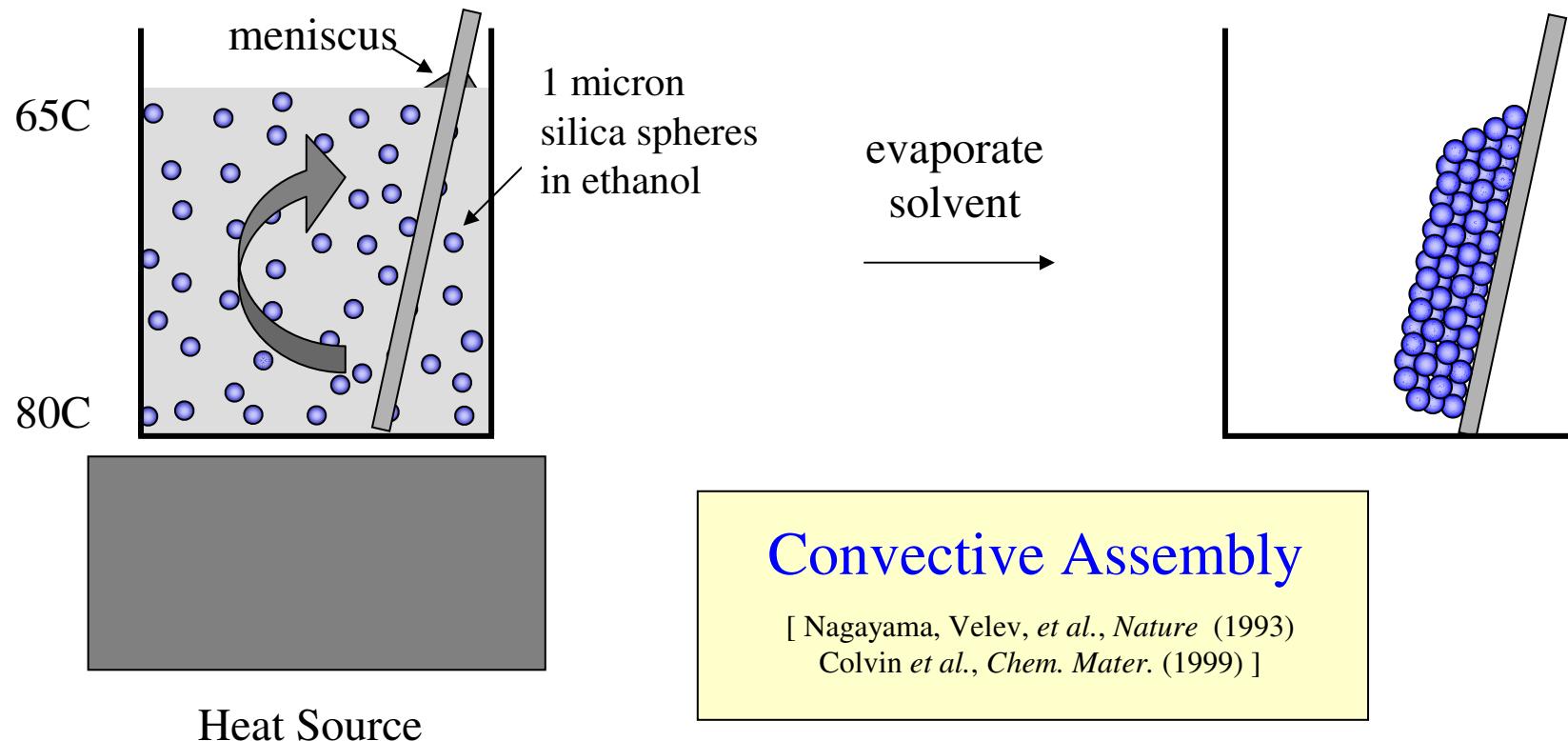


CdS/ZnO



In Order To Form a More Perfect Crystal...

[figs courtesy
D. Norris, UMN]

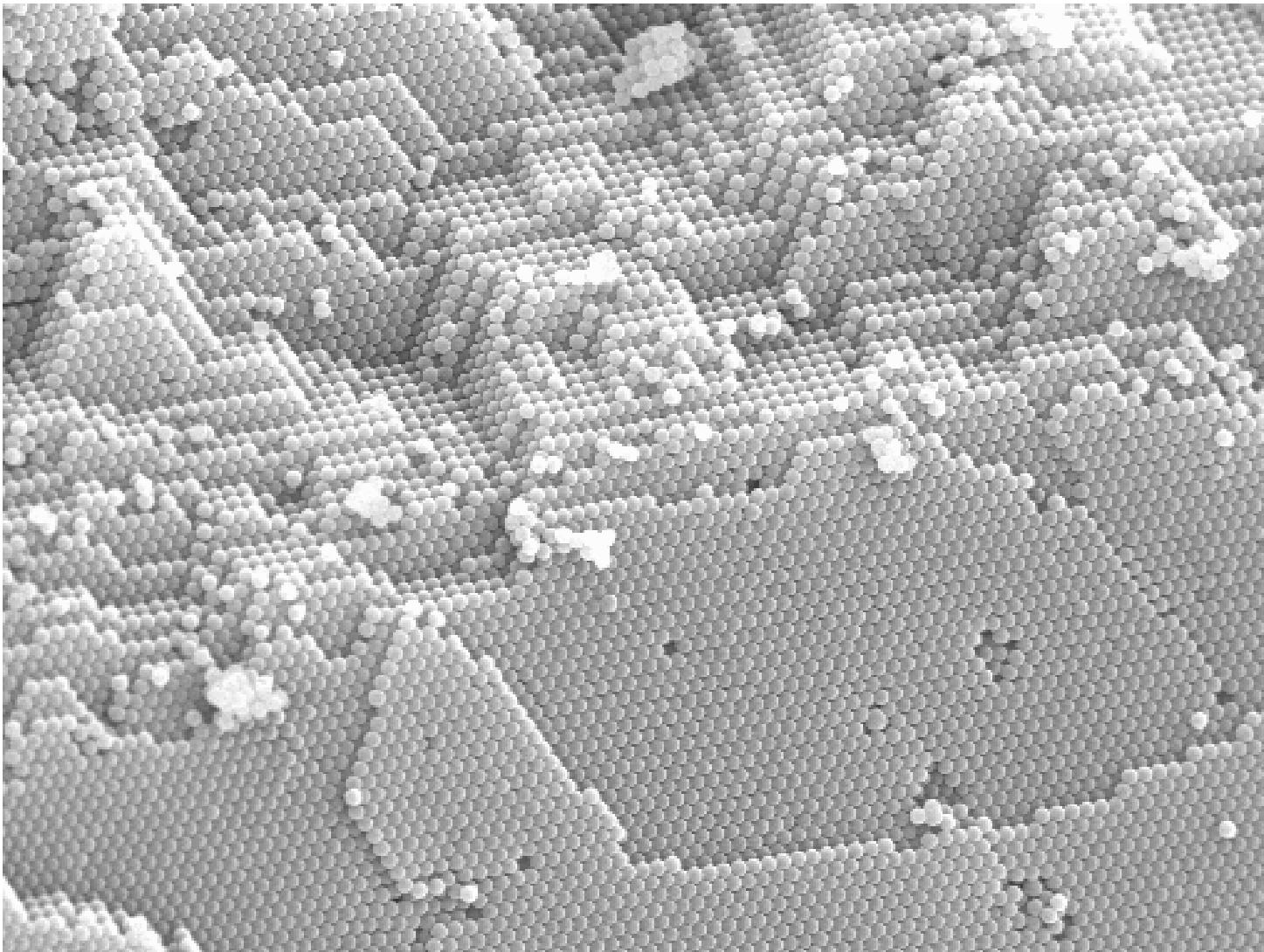


Convective Assembly

[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

Massive PhC



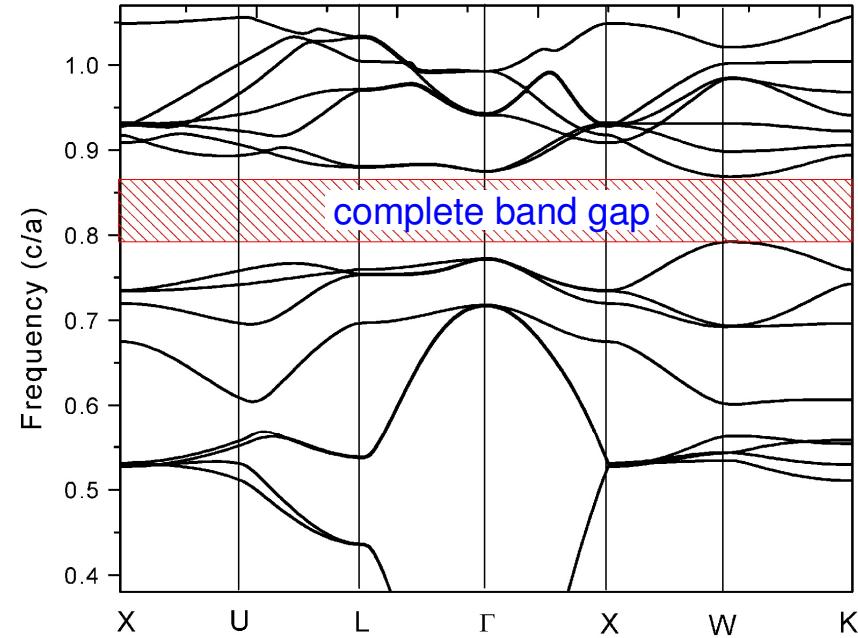
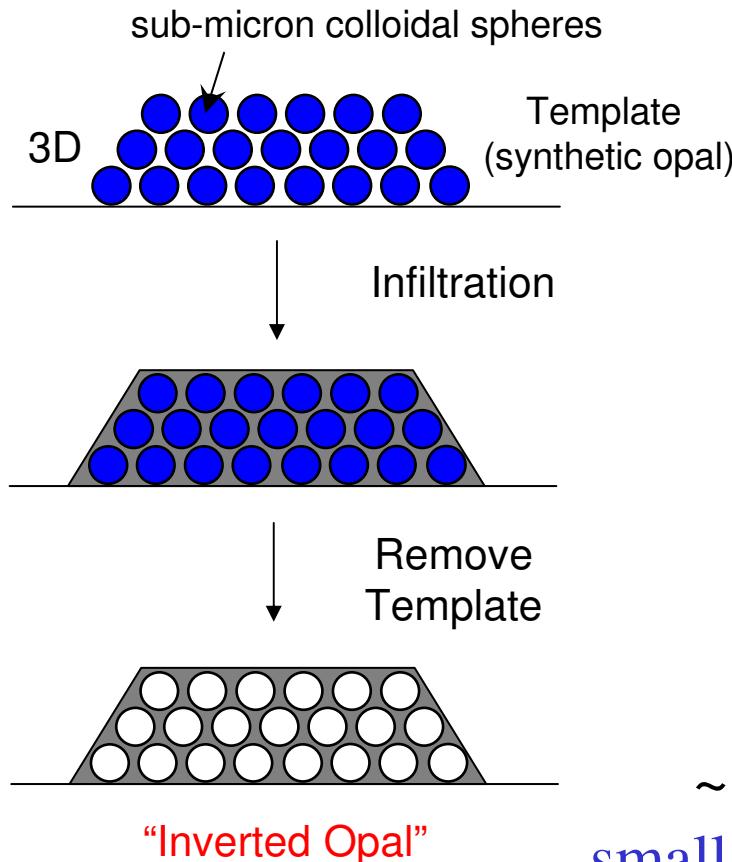
<http://www.icmm.csic.es/cefe/>

[figs courtesy
D. Norris, UMN]

Inverse Opals

fcc solid spheres do not have a gap...

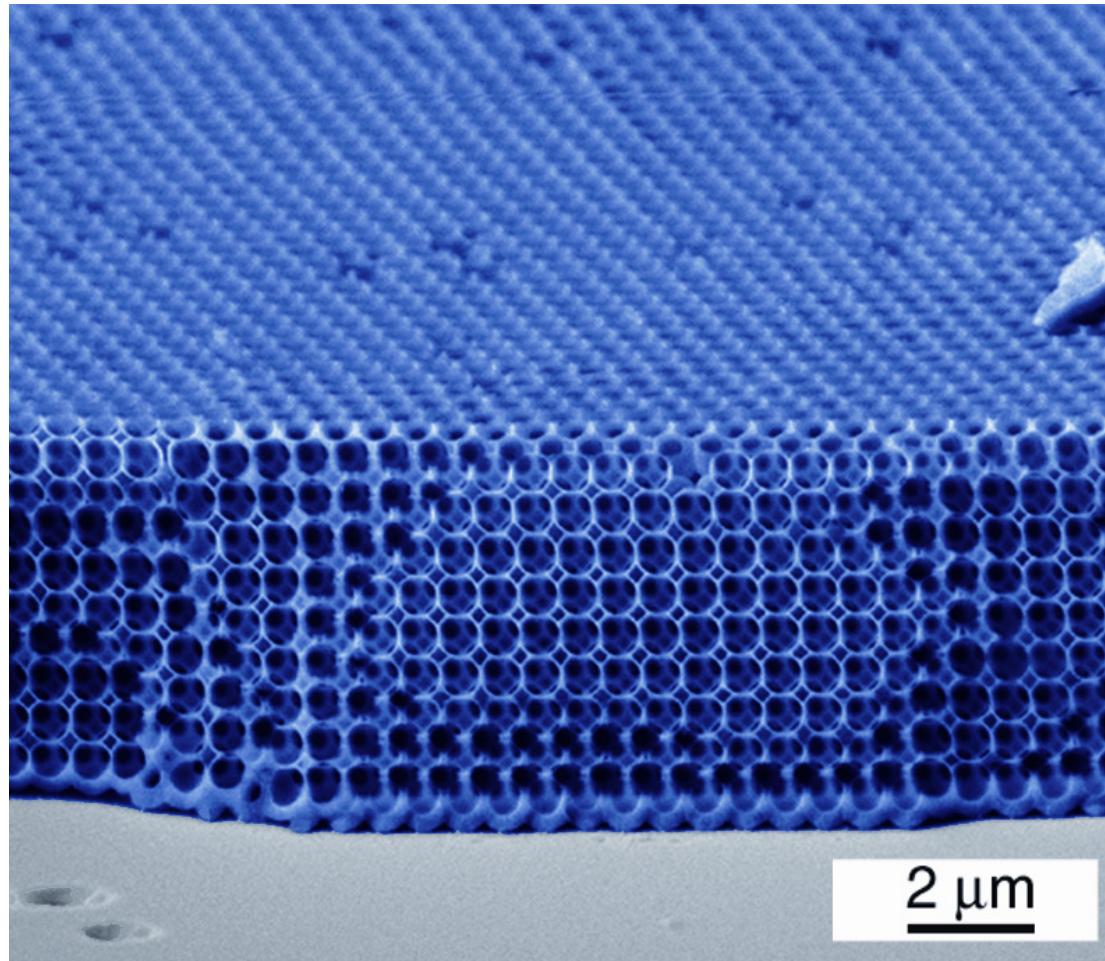
...but fcc spherical holes in Si *do* have a gap



~ 10% gap between 8th & 9th bands
small gap, upper bands: sensitive to disorder

Inverse-Opal Photonic Crystal

[fig courtesy
D. Norris, UMN]



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

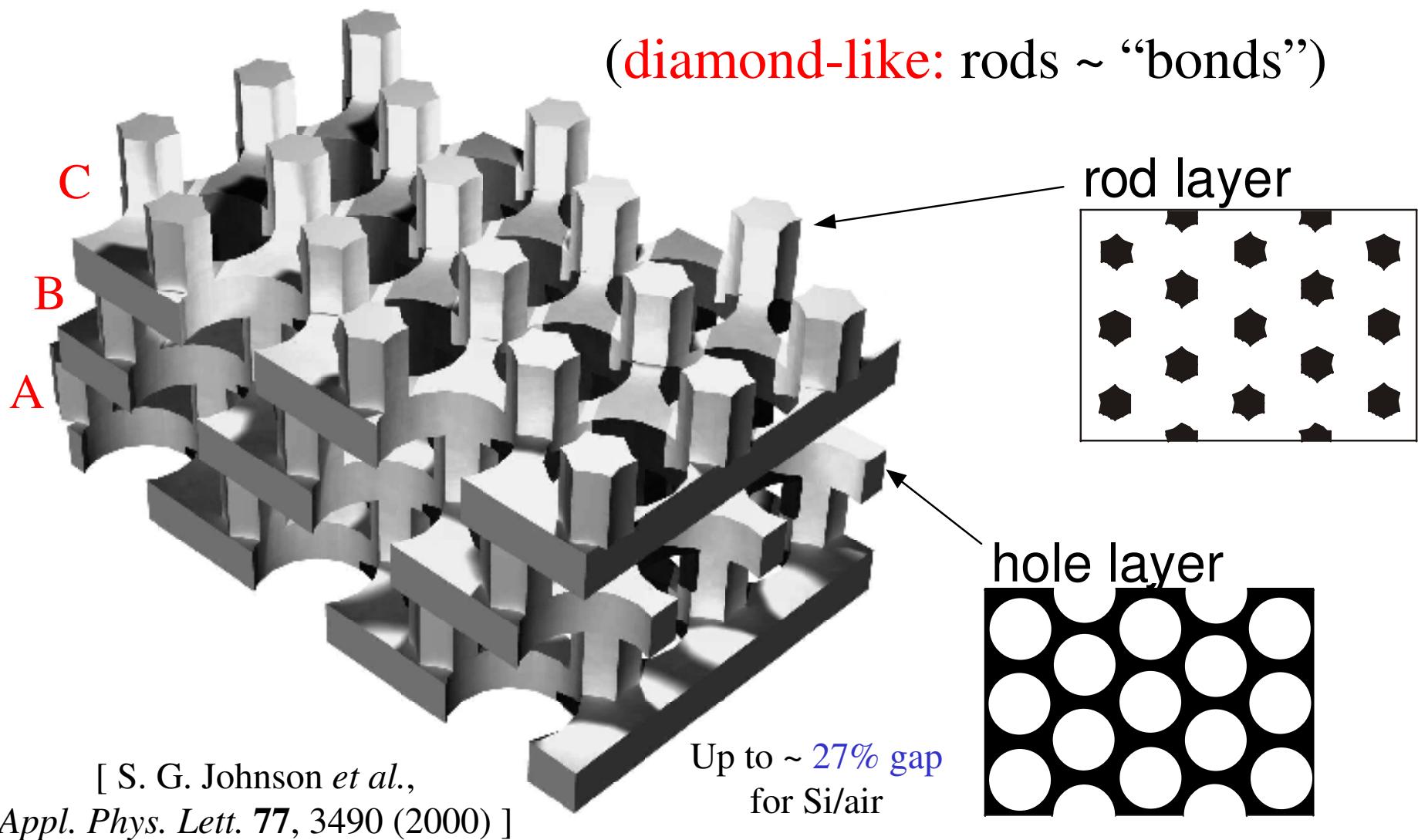
Layer-by-Layer Lithography

- 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



Making Rods & Holes Simultaneously

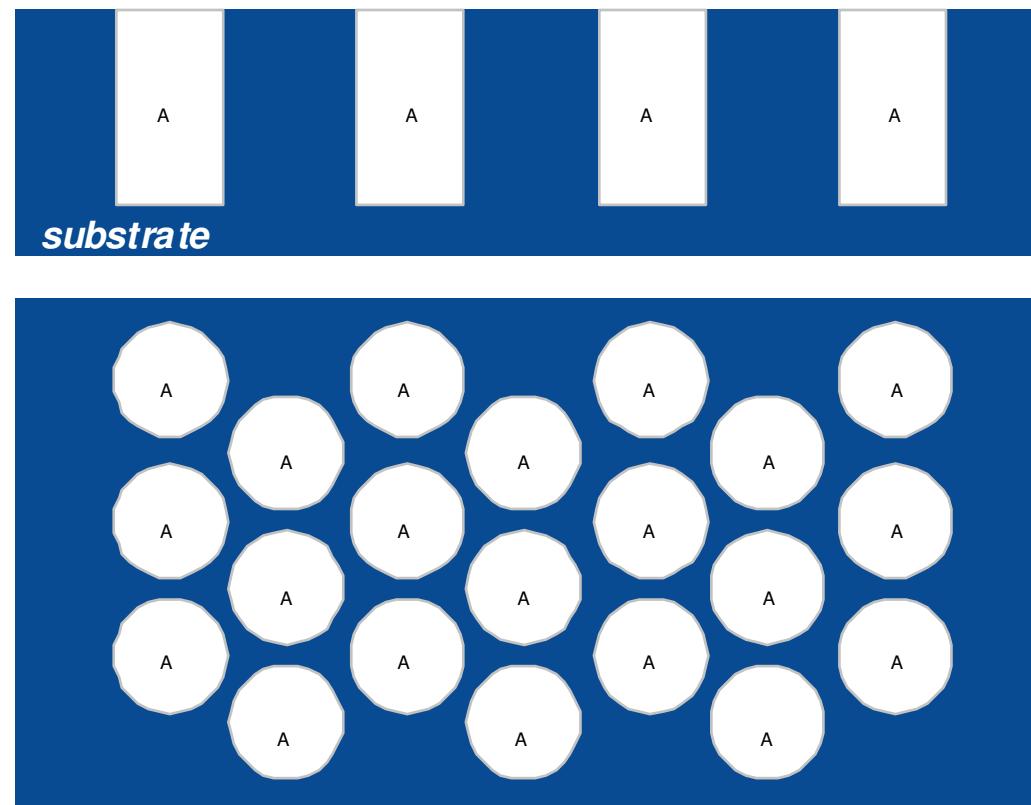
side view



top view

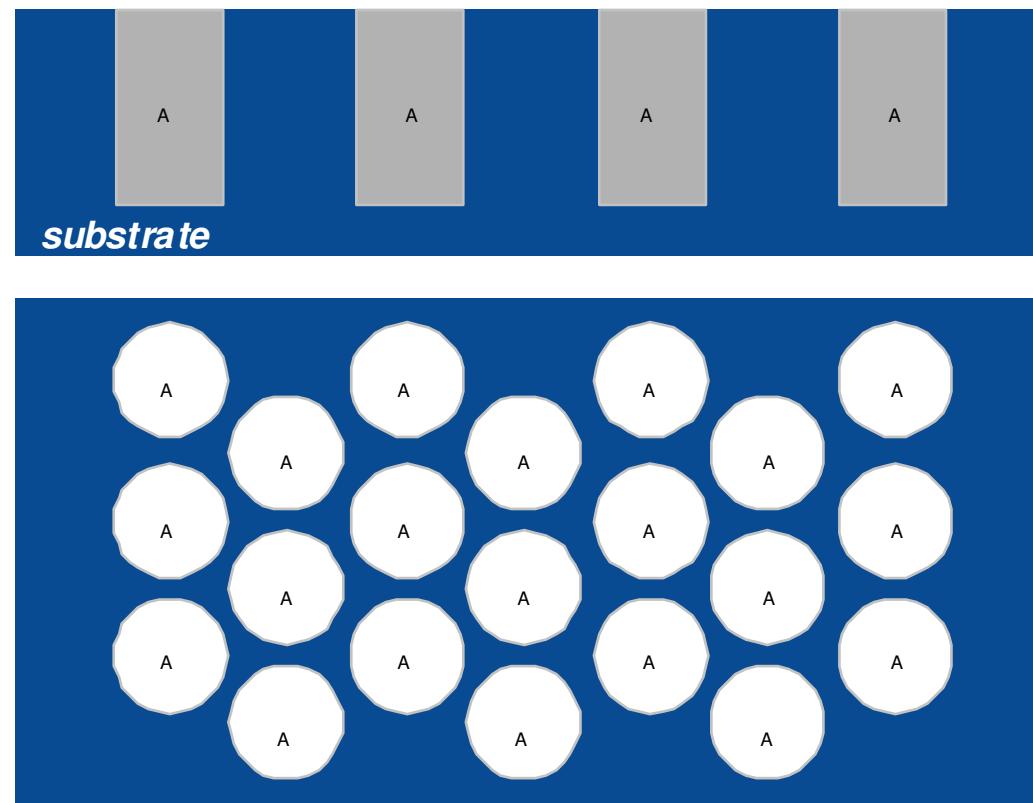
Making Rods & Holes Simultaneously

expose/etch
holes



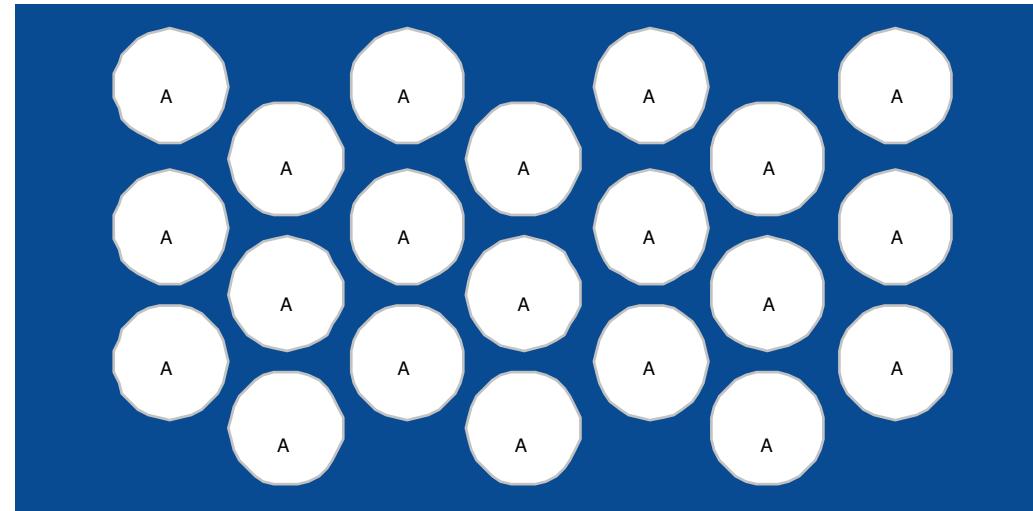
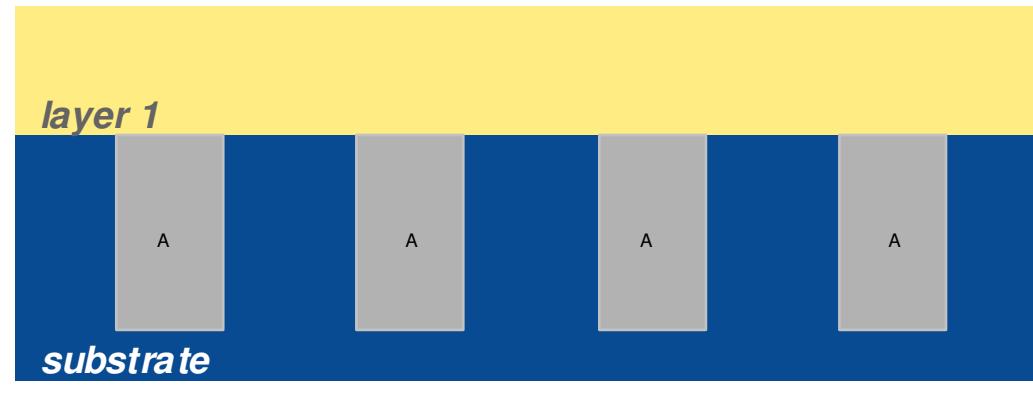
Making Rods & Holes Simultaneously

backfill with
silica (SiO_2)
& polish



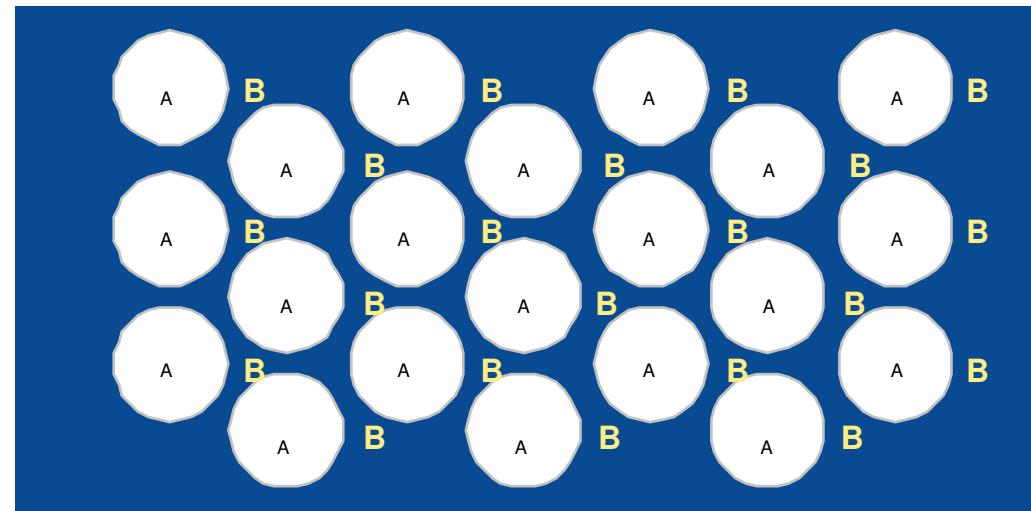
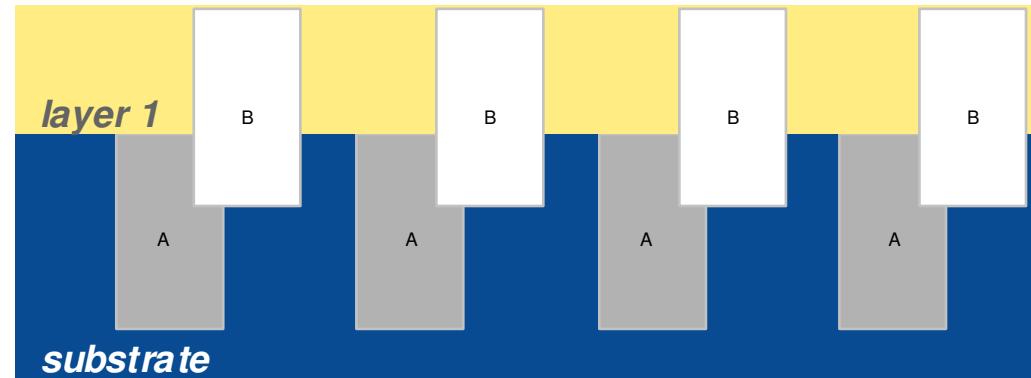
Making Rods & Holes Simultaneously

deposit another
Si layer



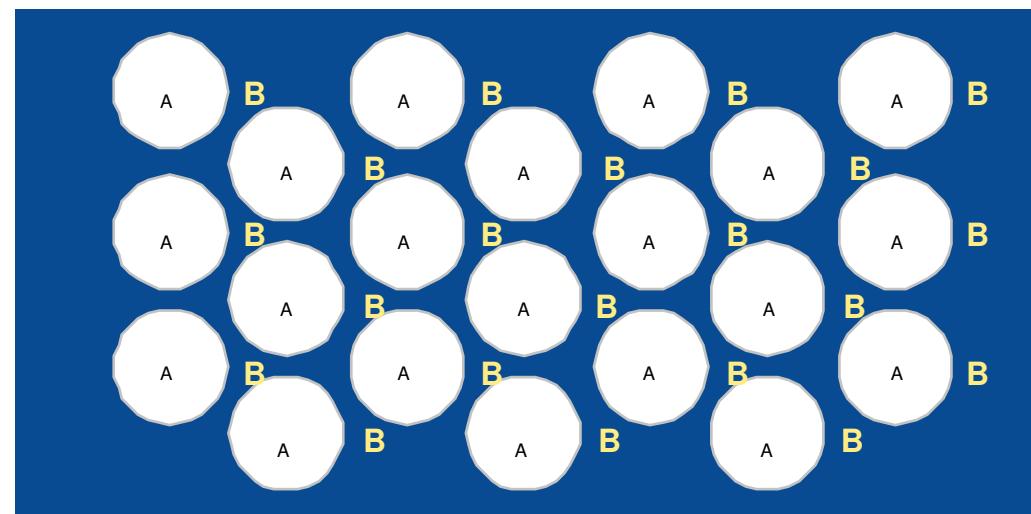
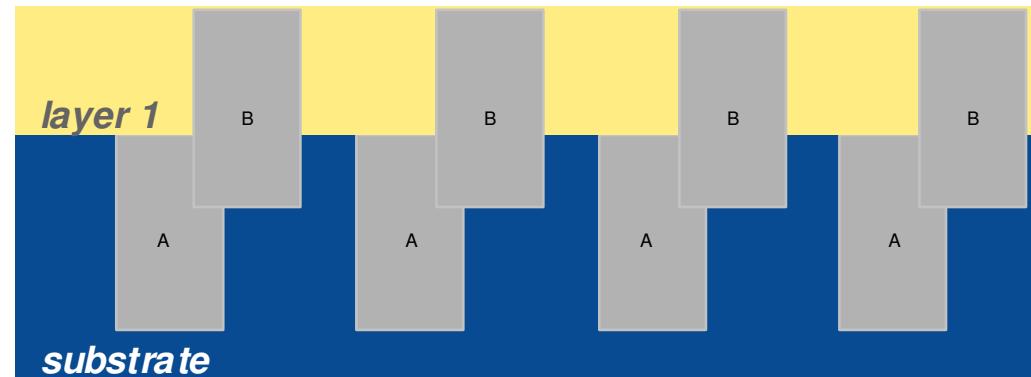
Making Rods & Holes Simultaneously

dig more holes
offset
& overlapping



Making Rods & Holes Simultaneously

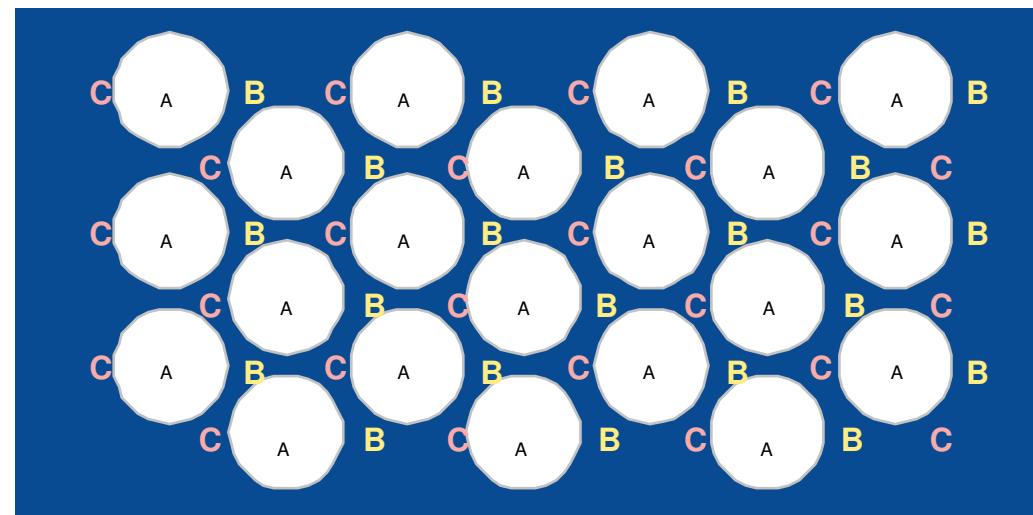
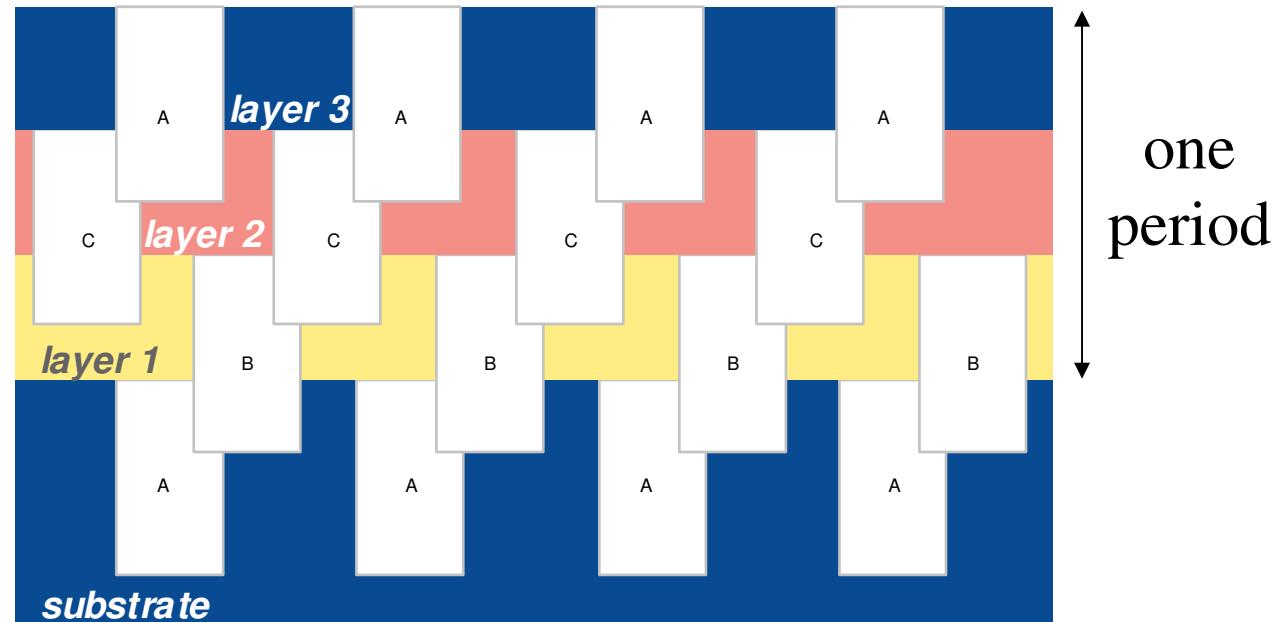
backfill



Making Rods & Holes Simultaneously

etcetera

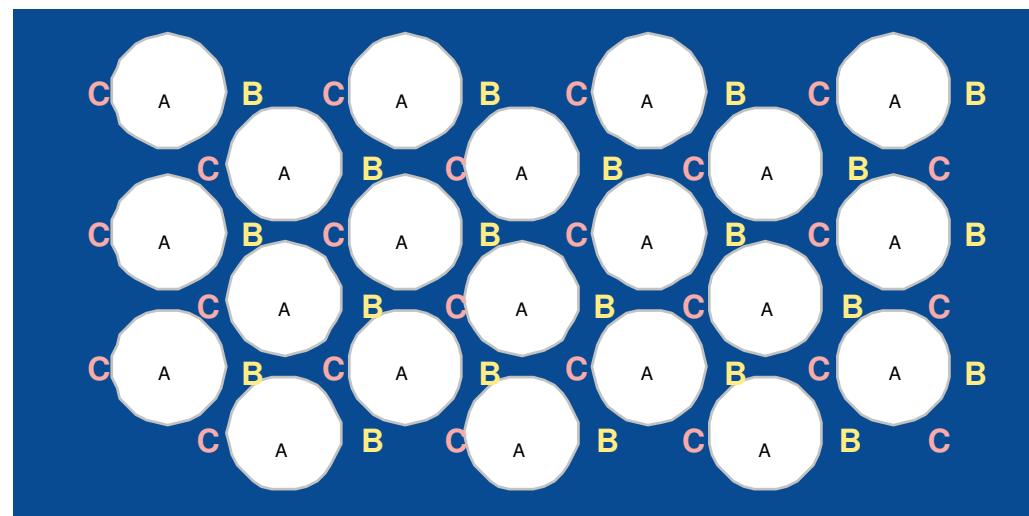
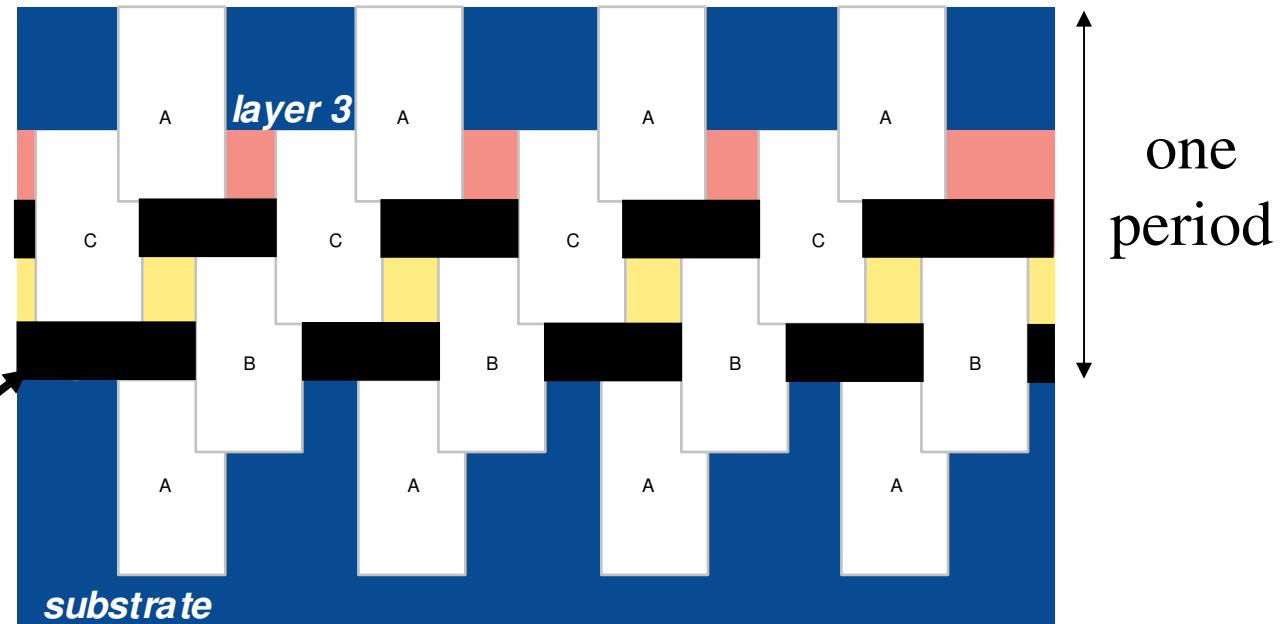
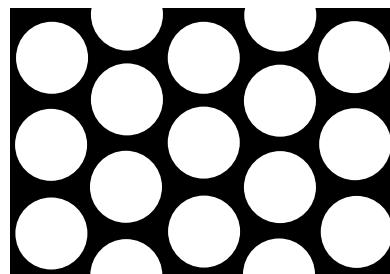
*(dissolve
silica
when
done)*



Making Rods & Holes Simultaneously

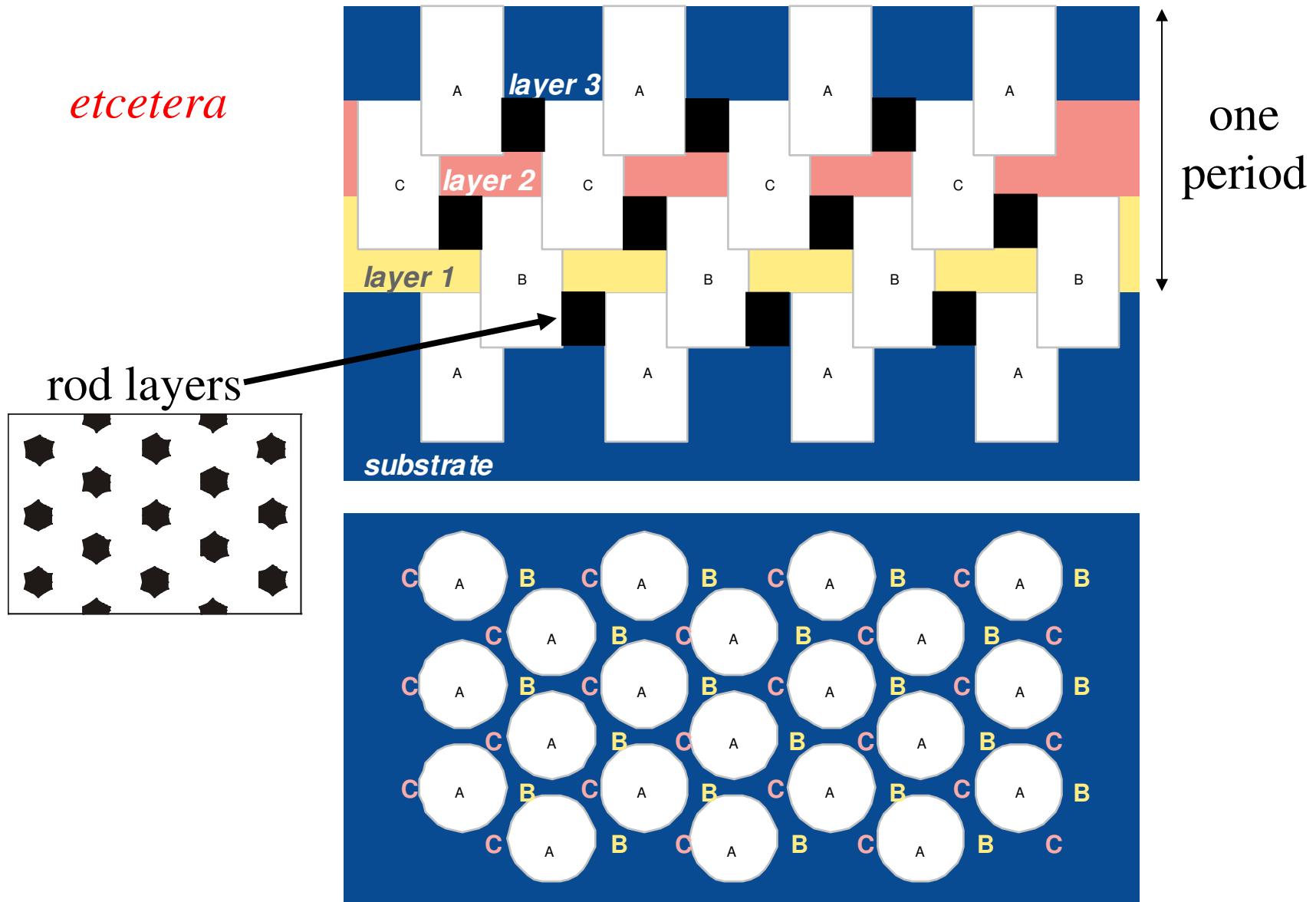
etcetera

hole layers

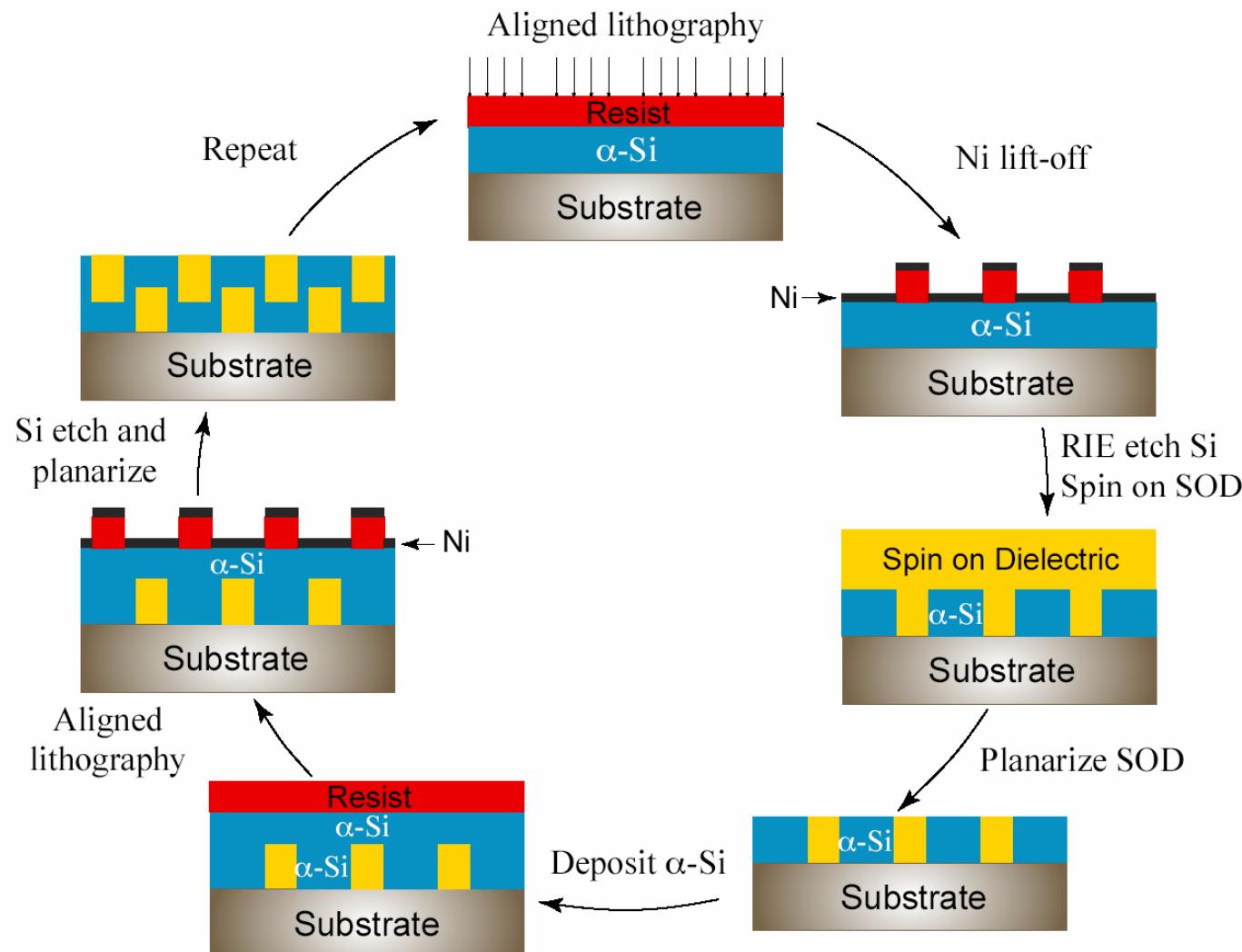


Making Rods & Holes Simultaneously

etcetera

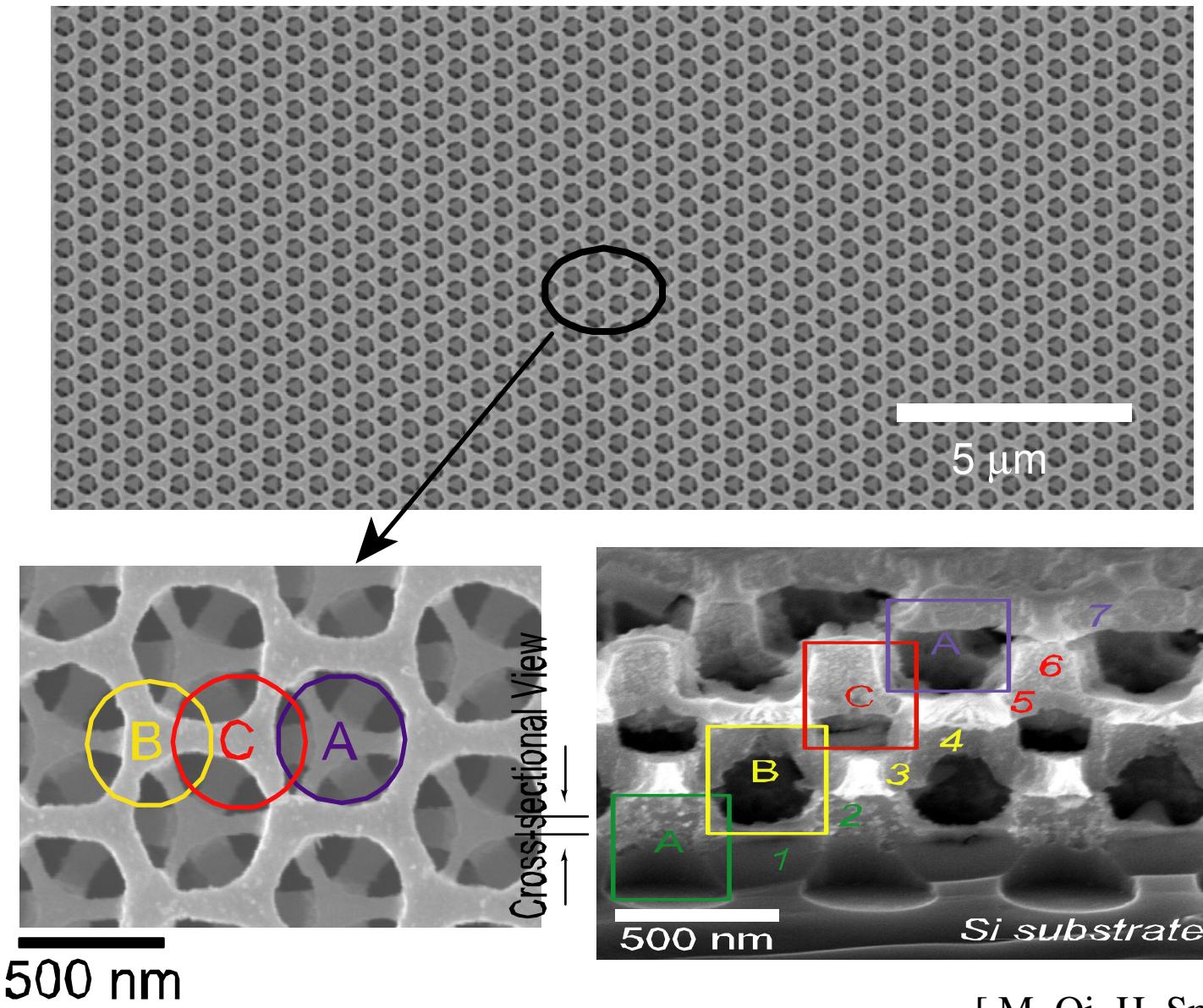


A More Realistic Schematic



[M. Qi, H. Smith, MIT]

e-beam Fabrication: Top View

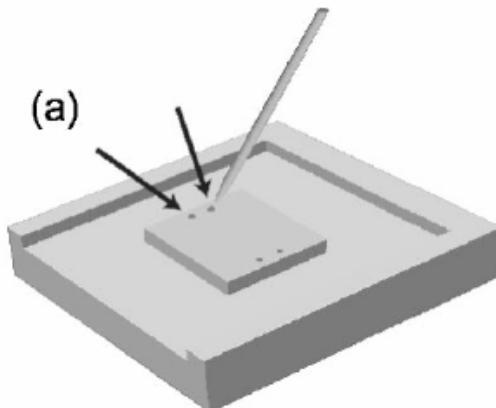


[M. Qi, H. Smith, MIT]

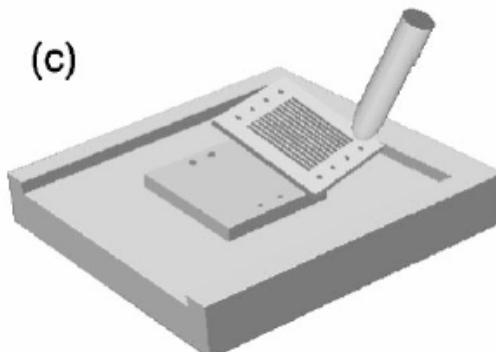
Stacking by Micromanipulation

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

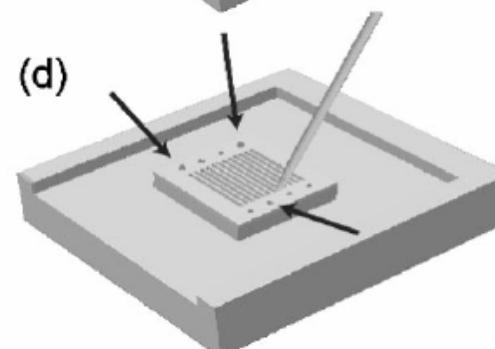
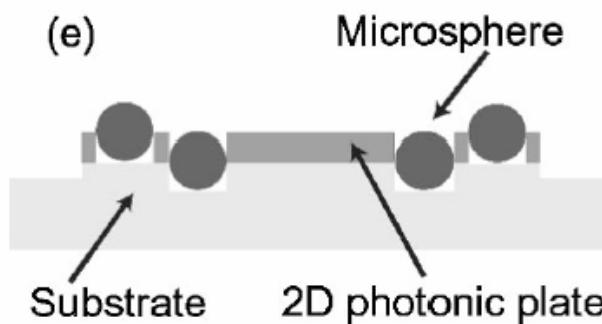
microsphere
into hole



lift up and
move to
substrate

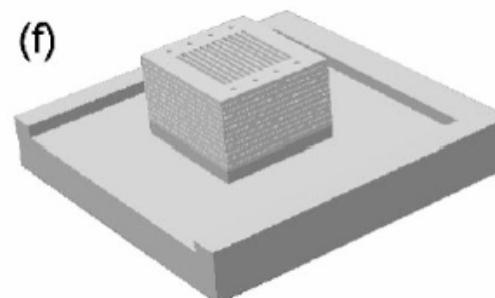


spheres
enforce
alignment



break off
suspended
layer

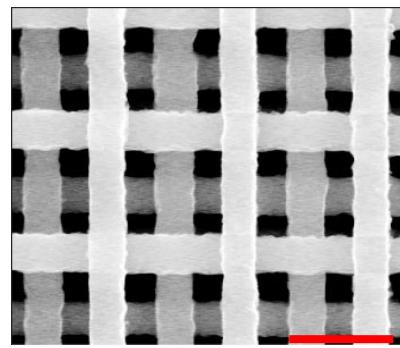
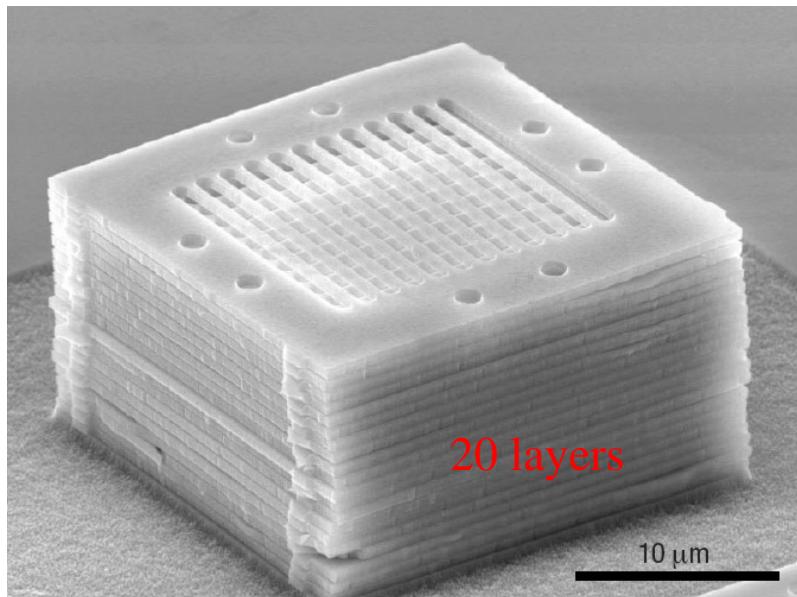
tap down
holes onto
spheres



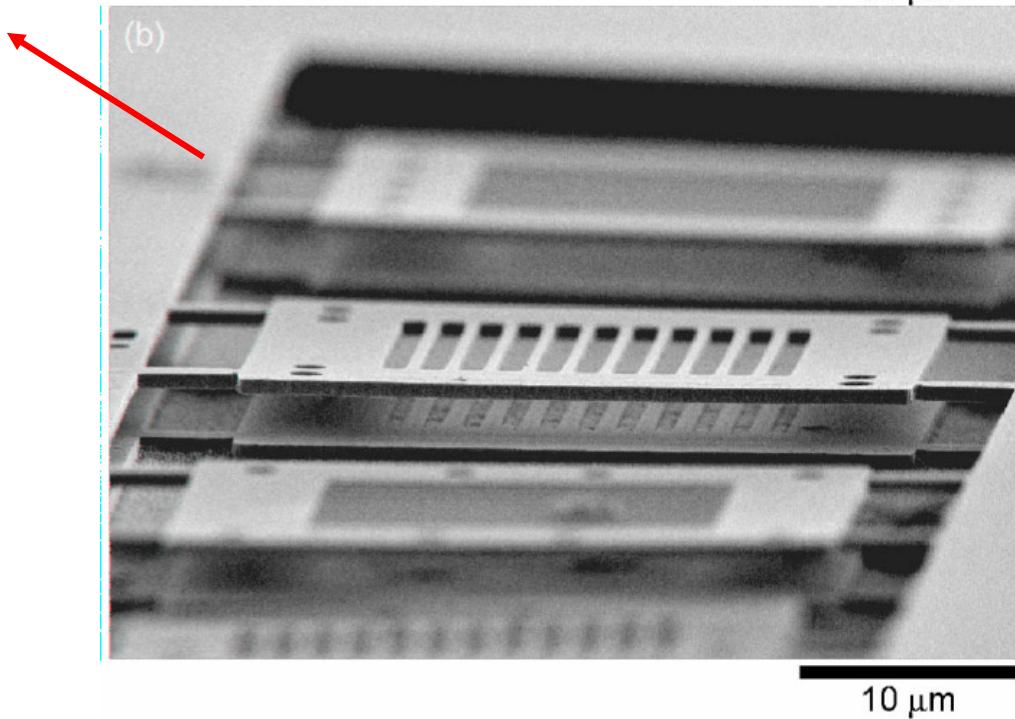
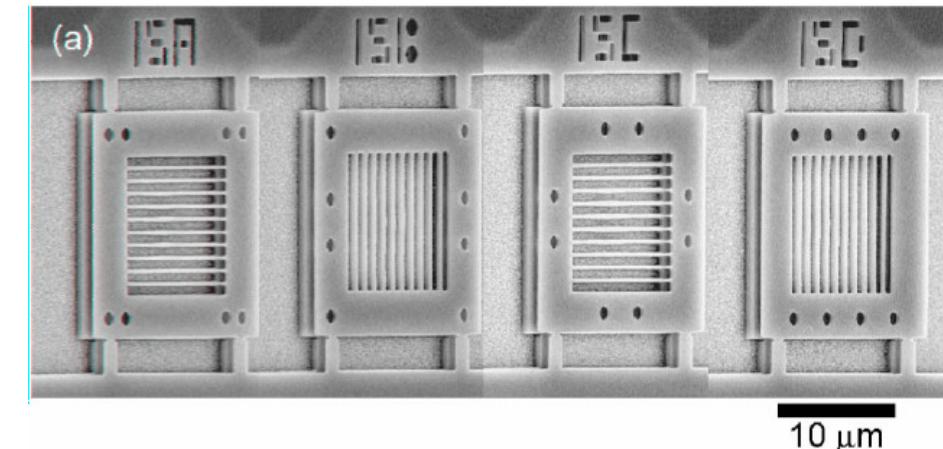
goto a;

Stacking by Micromanipulation

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



50nm accuracy:



Stacking by Micromanipulation

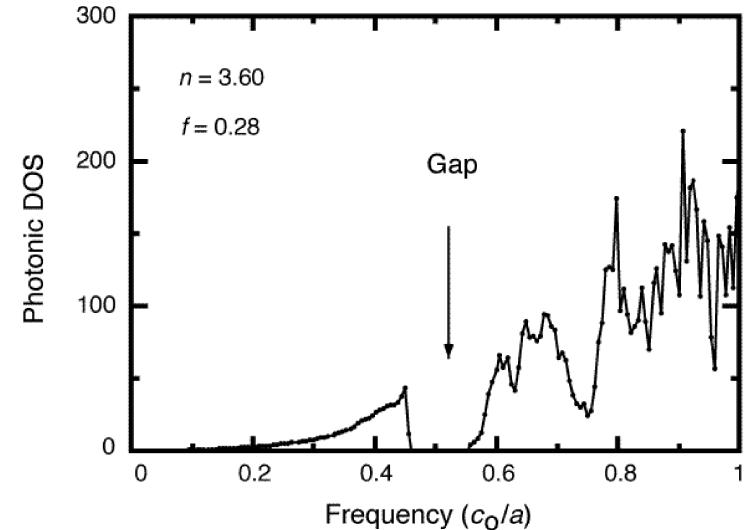
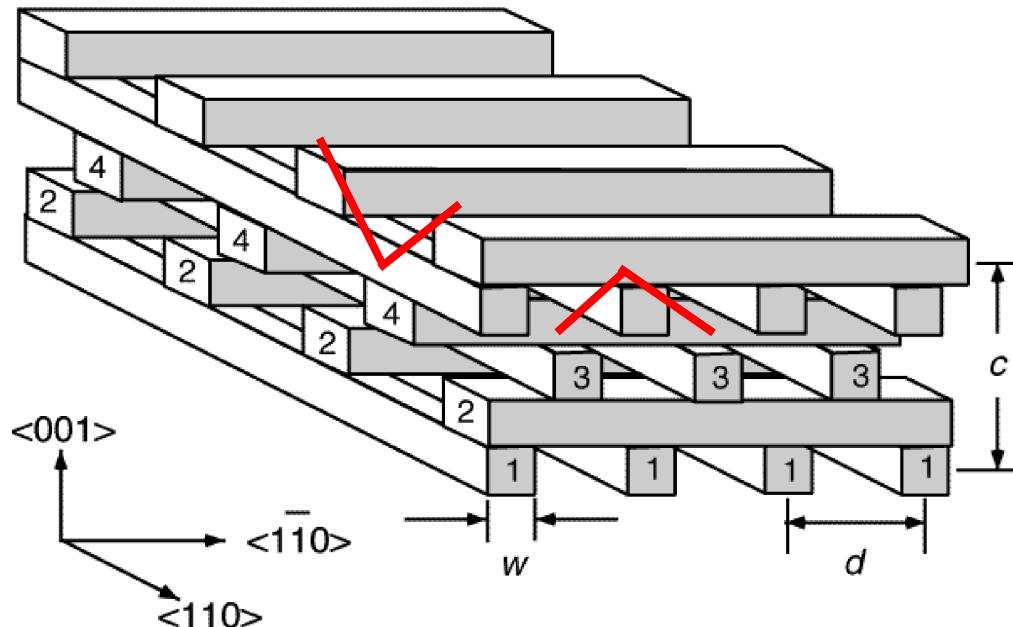
an earlier design:
(& currently more popular)

The Woodpile Crystal

[K. Ho *et al.*, *Solid State Comm.* **89**, 413 (1994)]

[H. S. Sözüer *et al.*, *J. Mod. Opt.* **41**, 231 (1994)]

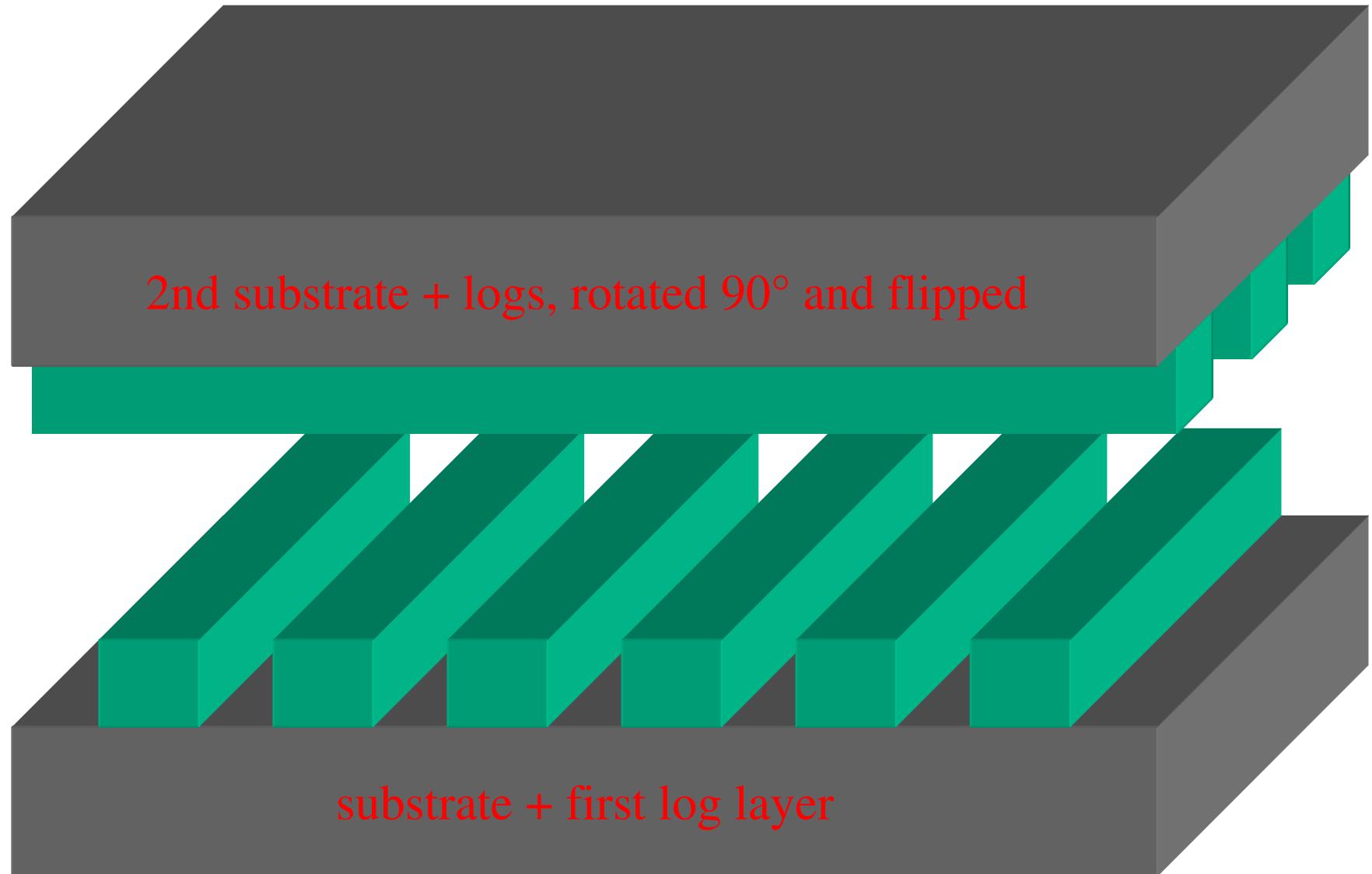
(diamond-like, “bonds”)



Up to ~ 17% gap for Si/air

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

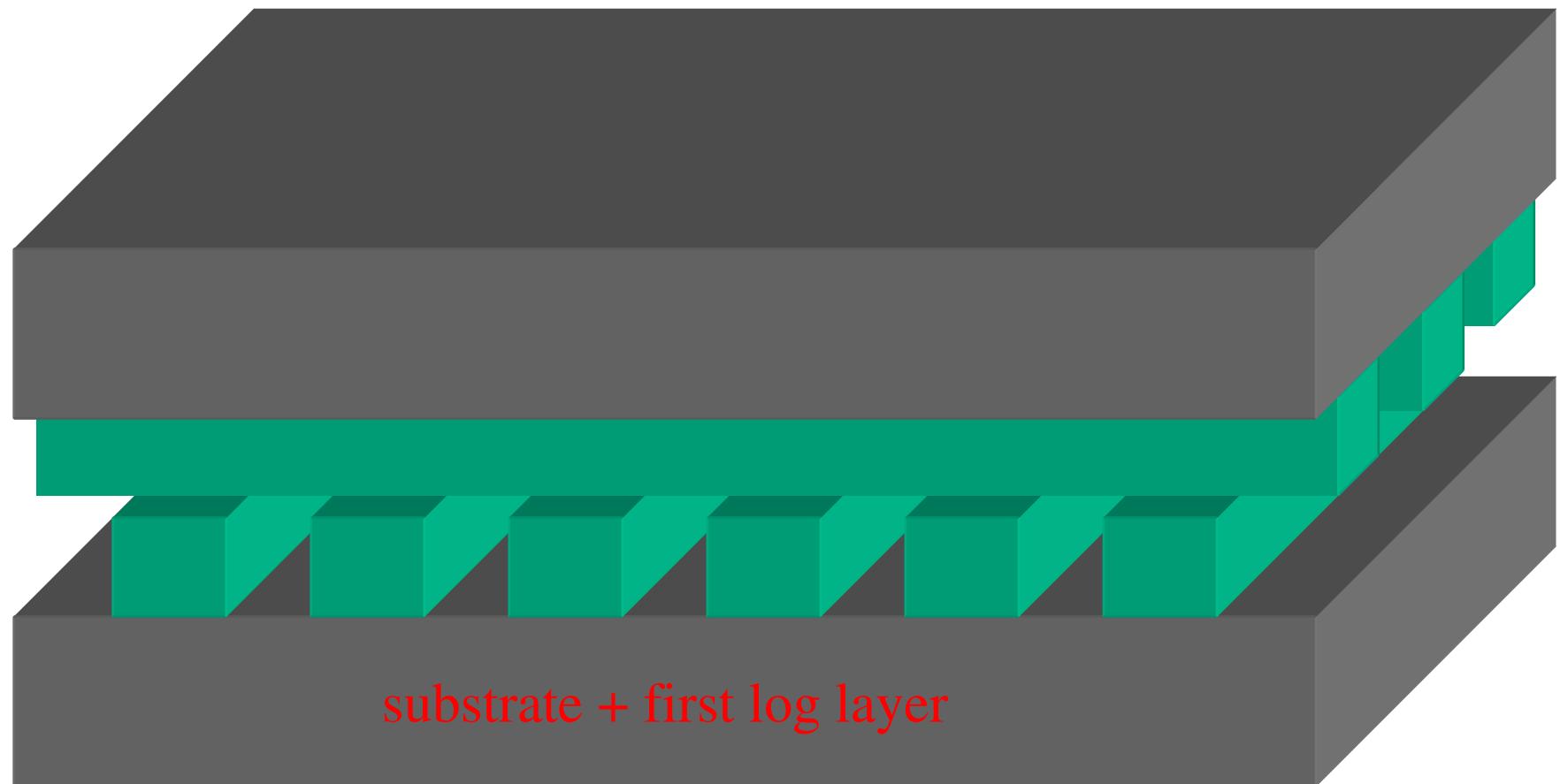
Woodpile by Wafer Fusion



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

Woodpile by Wafer Fusion

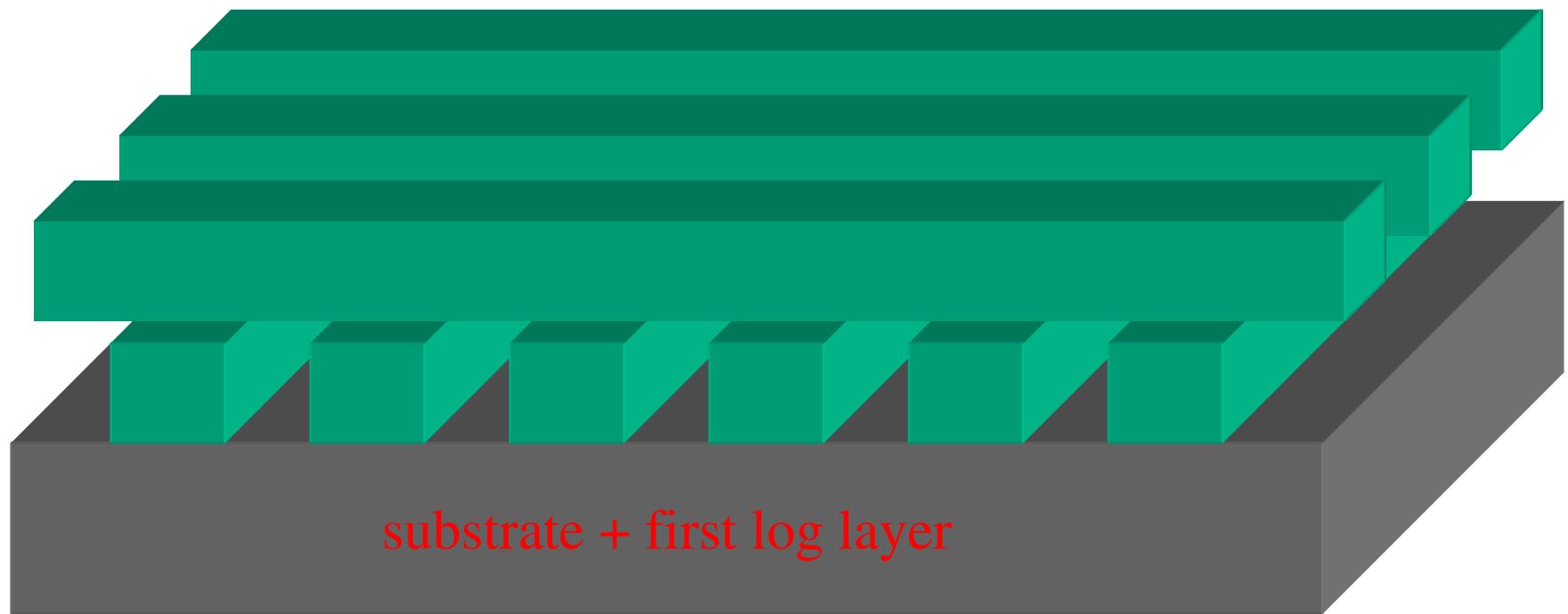
fuse wafers together...



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

Woodpile by Wafer Fusion

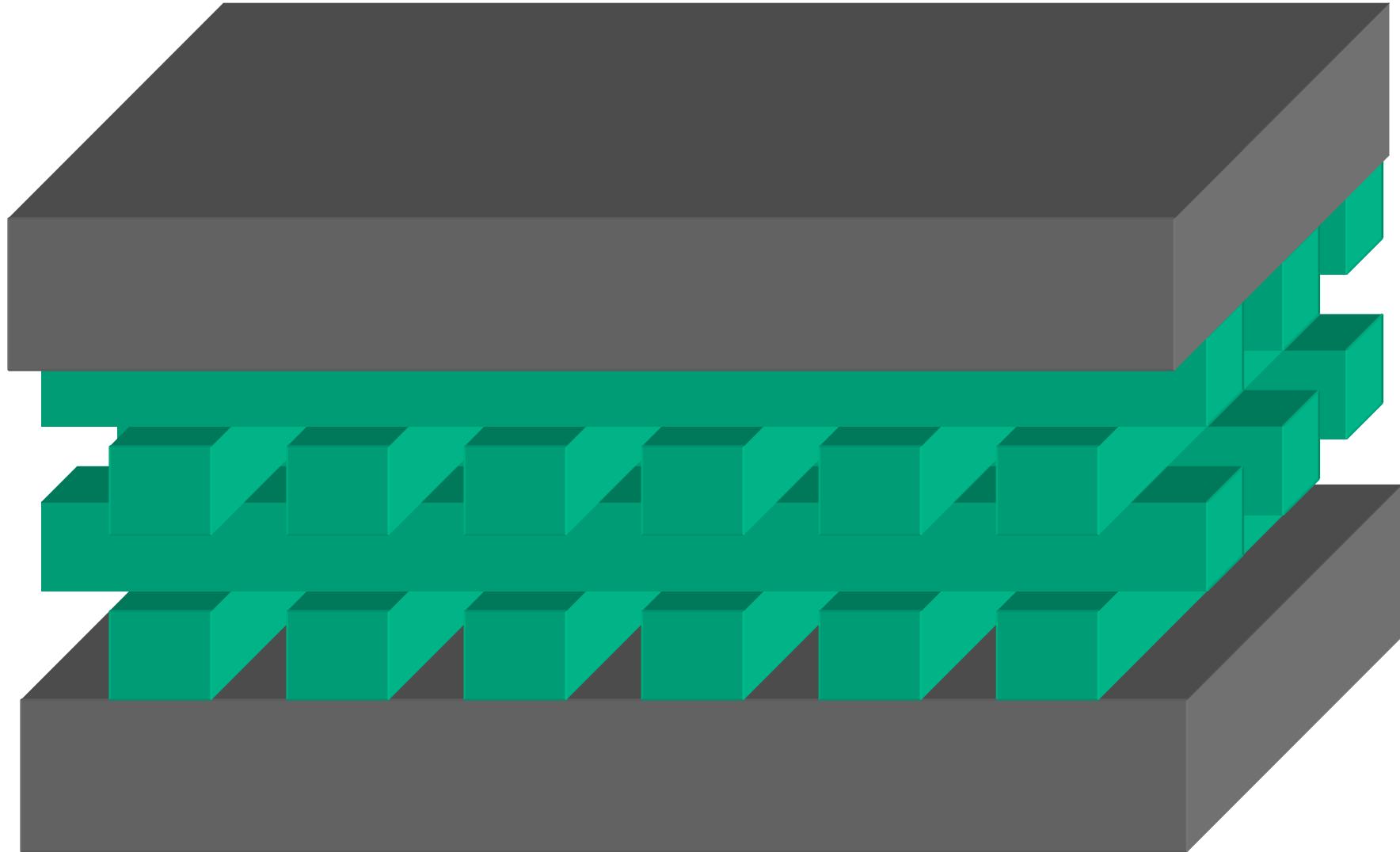
...dissolve upper substrate



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

Woodpile by Wafer Fusion

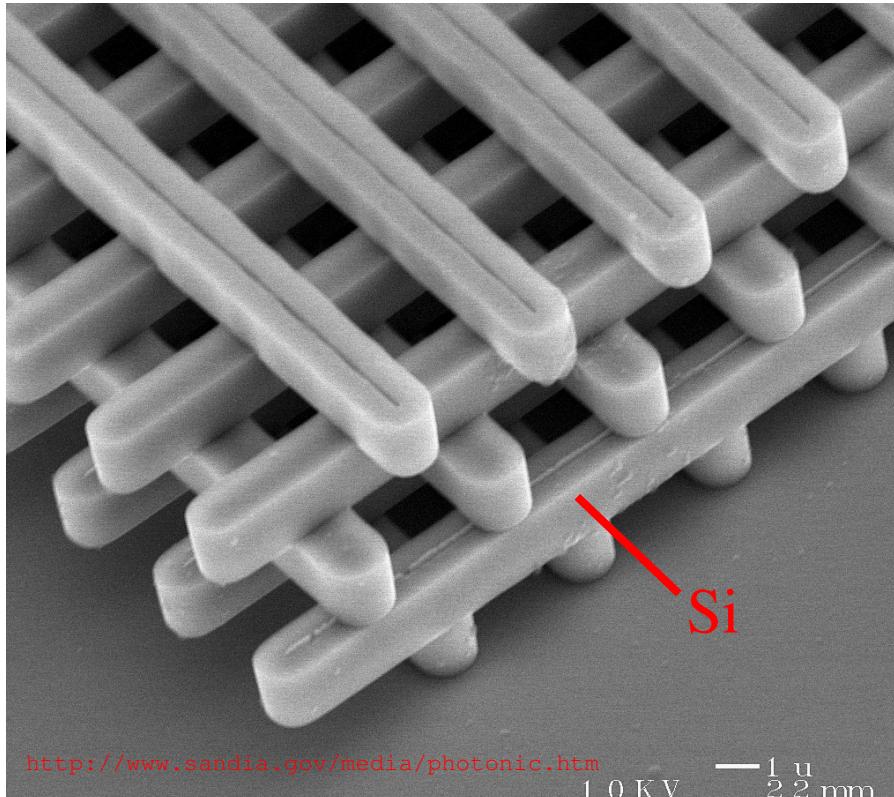
double, double, toil and trouble...



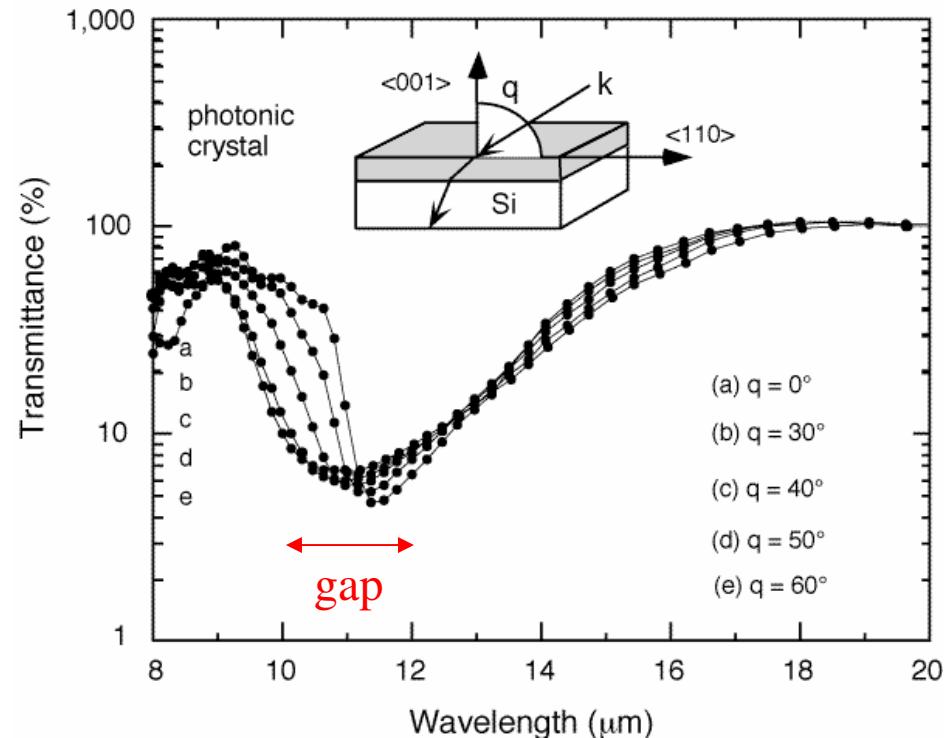
[S. Noda *et al.*, *Science* **289**, 604 (2000)]

1.25 Periods of Woodpile

(4 “log” layers = 1 period)



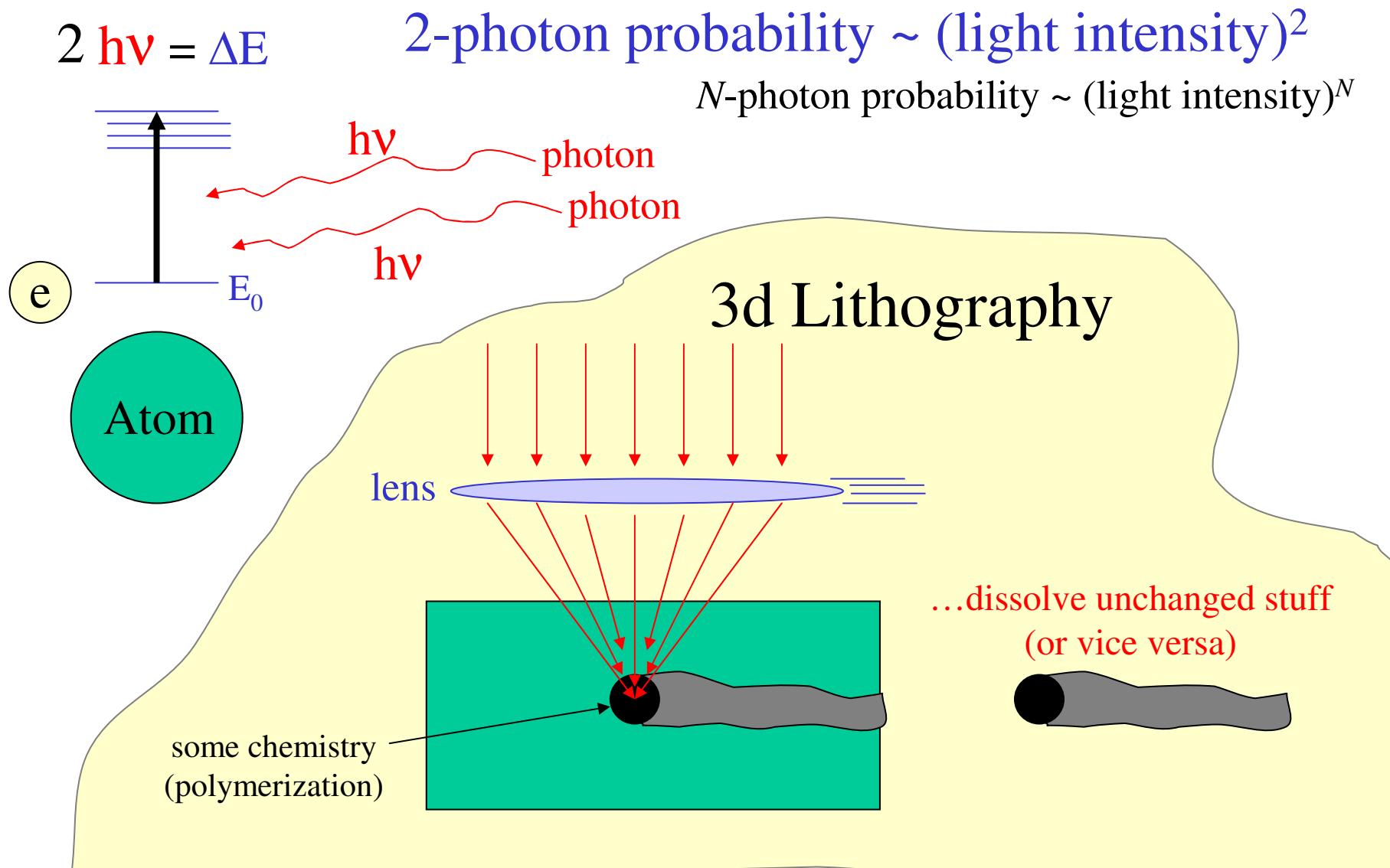
[S. Y. Lin *et al.*, *Nature* **394**, 251 (1998)]

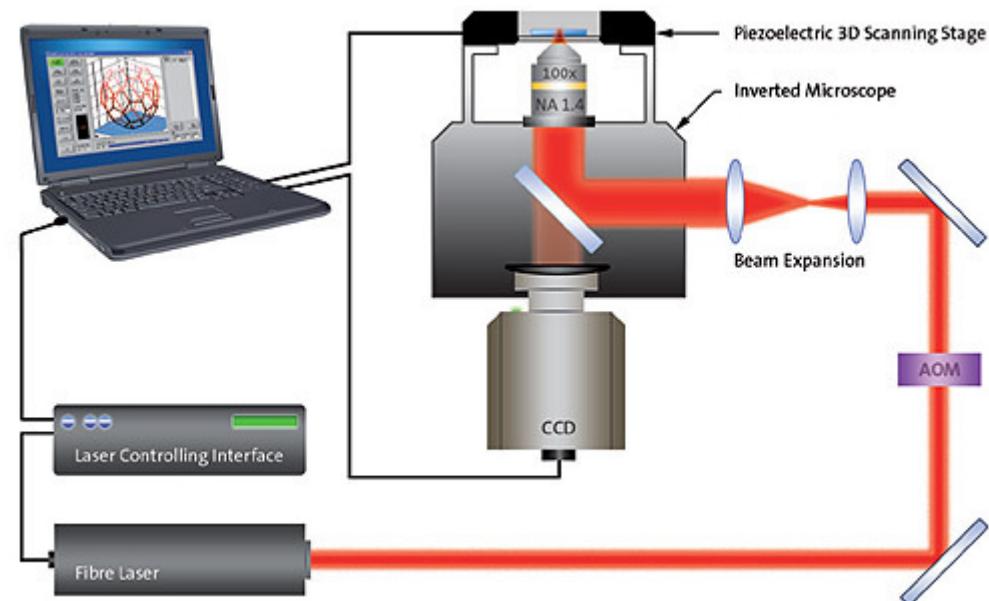
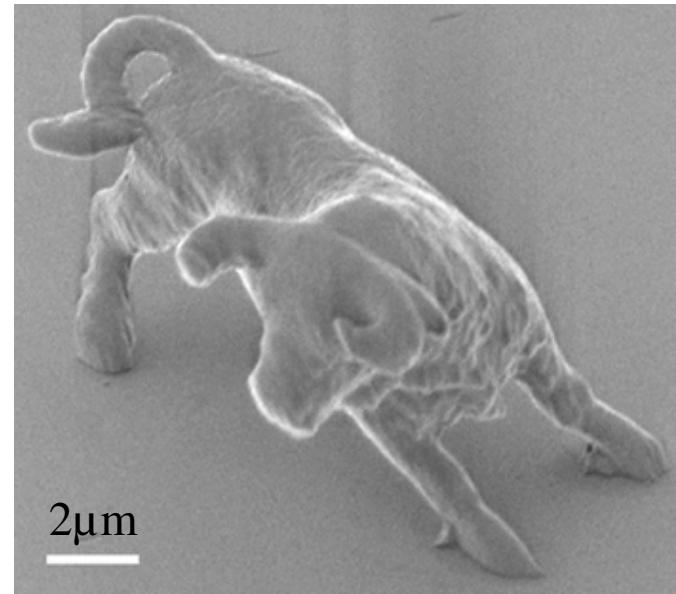
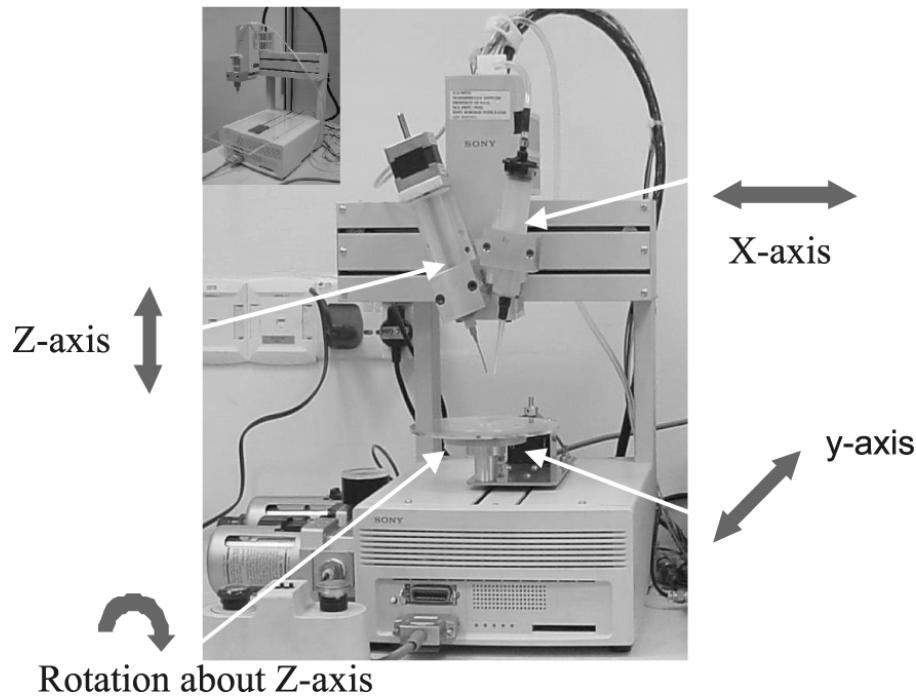


“UV Stepper:” e-beam mask at ~4x size
+ UV through mask, focused on substrate

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

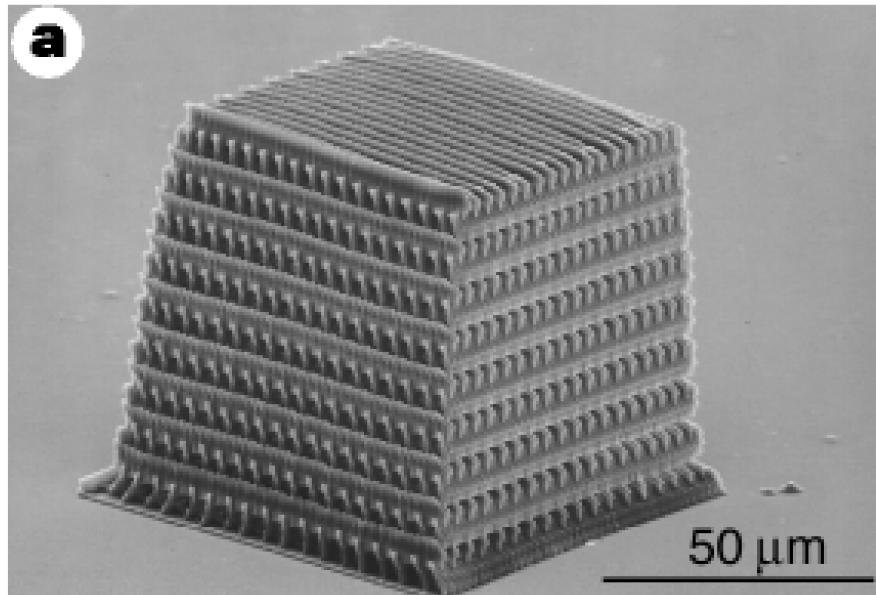
Direct laser writing (two photon) ANCHE AL LENS



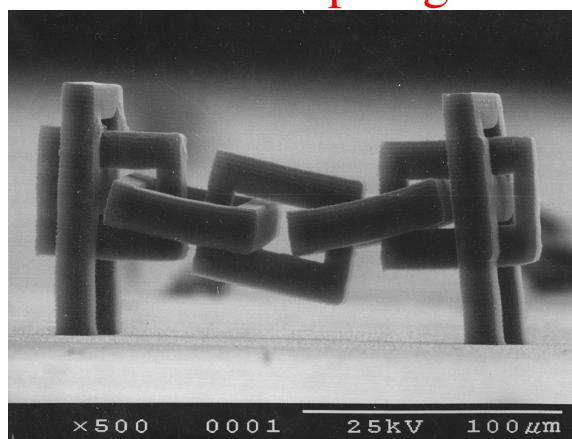


A Two-Photon Woodpile Crystal

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



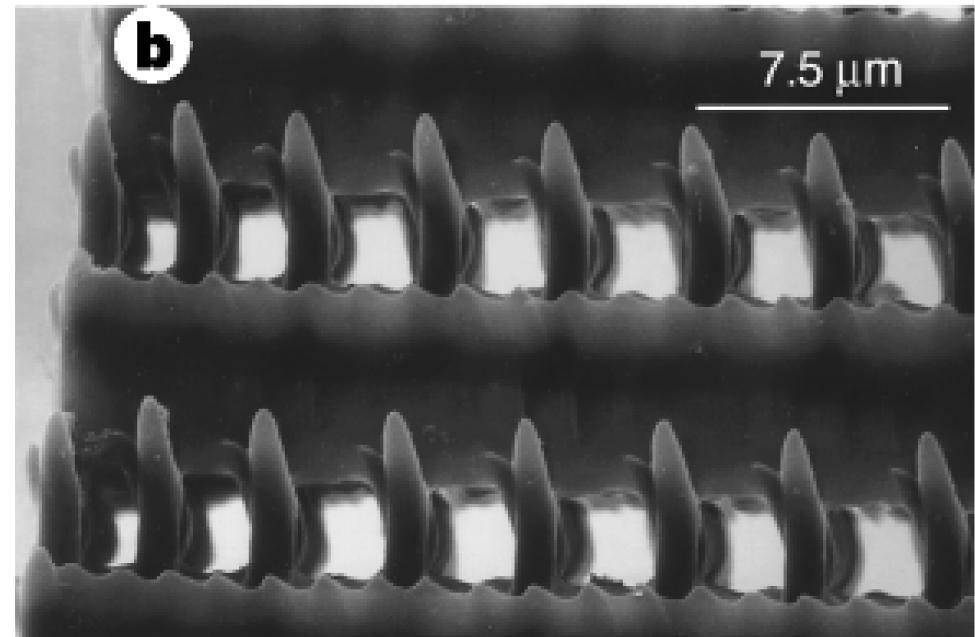
a



Difficult topologies

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

- **Arbitrary lattice**
- No “mask”
- **Fast/cheap prototyping**



b

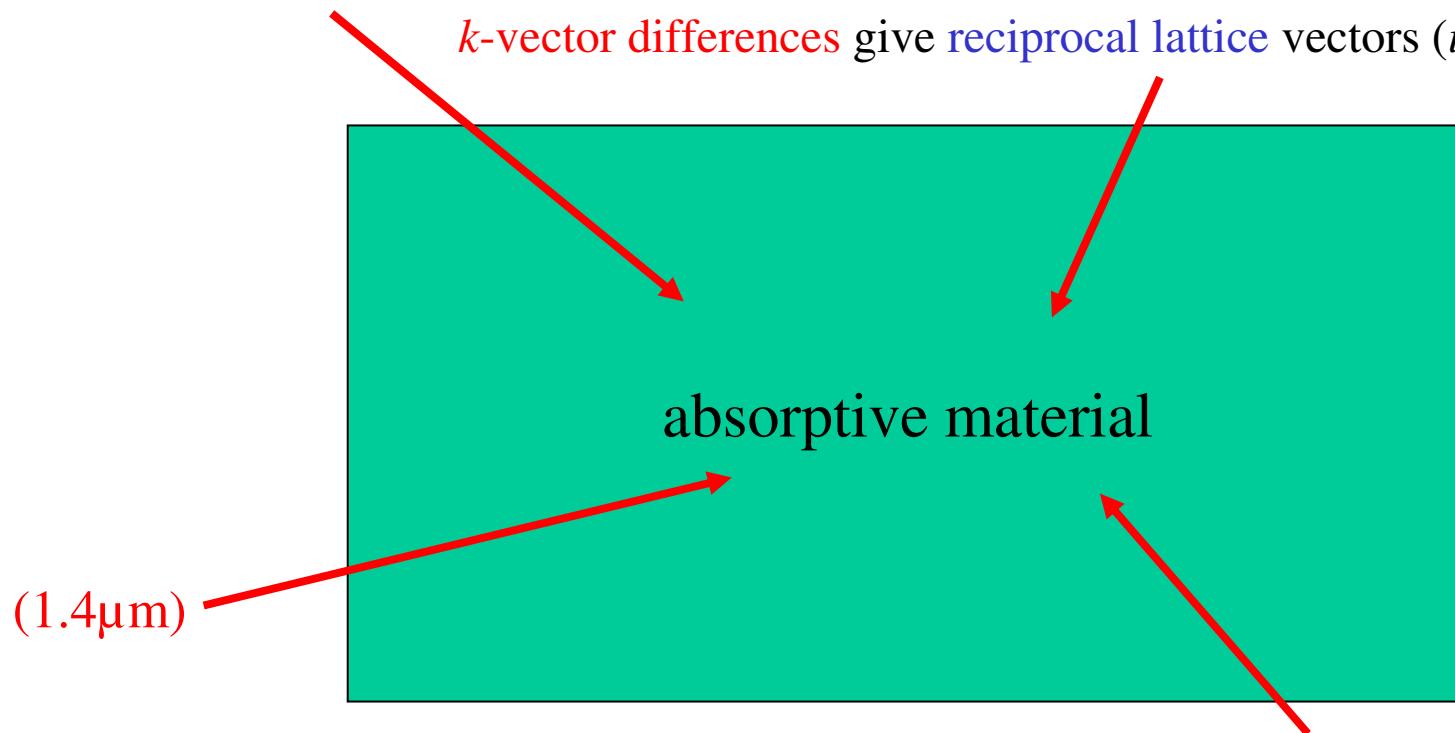
[fig. courtesy J. W. Perry, U. Arizona]

One-Photon Holographic Lithography

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

Four beams make 3d-periodic interference pattern

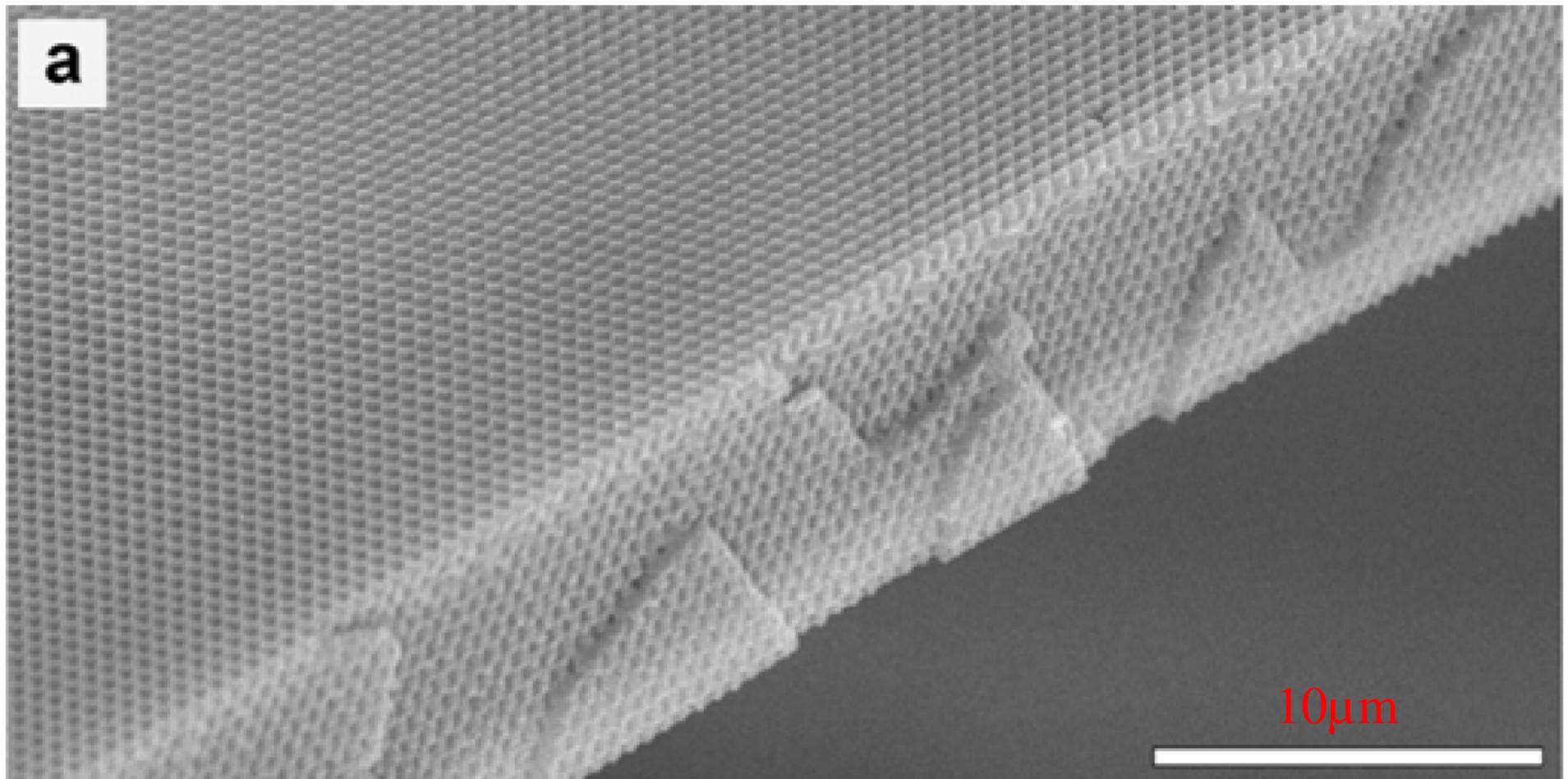
k-vector differences give reciprocal lattice vectors (*i.e.* periodicity)



beam polarizations + amplitudes (8 parameters) give unit cell

One-Photon Holographic Lithography

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

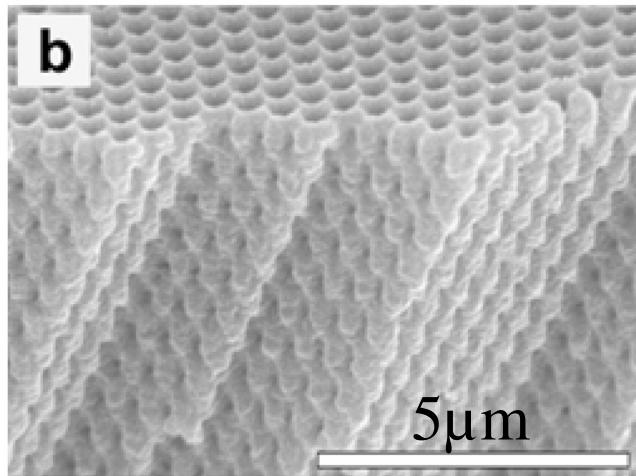


huge volumes, long-range periodic, fcc lattice...backfill for high contrast

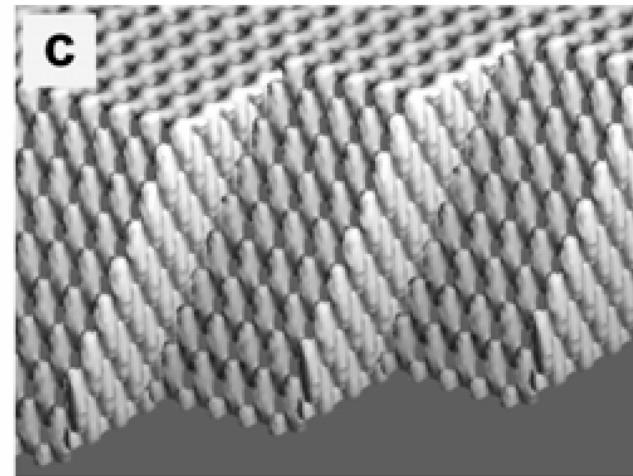
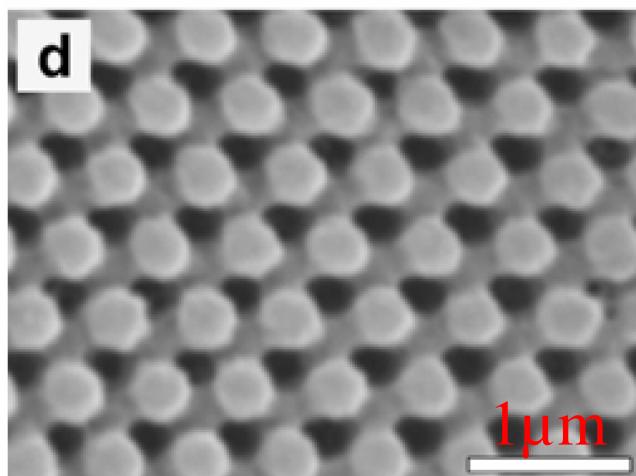
One-Photon Holographic Lithography

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

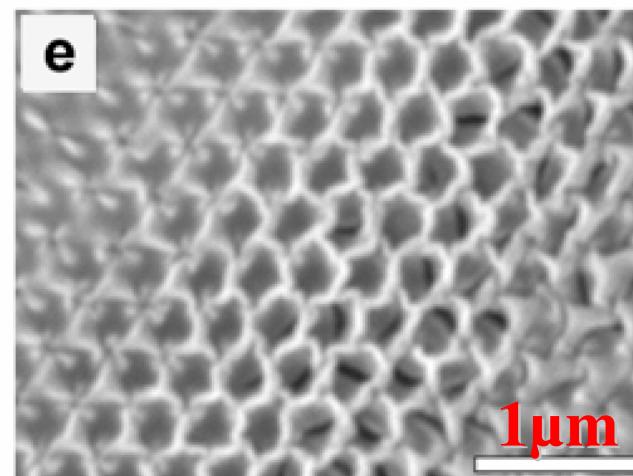
[111]
cleavages



[111]
closeup



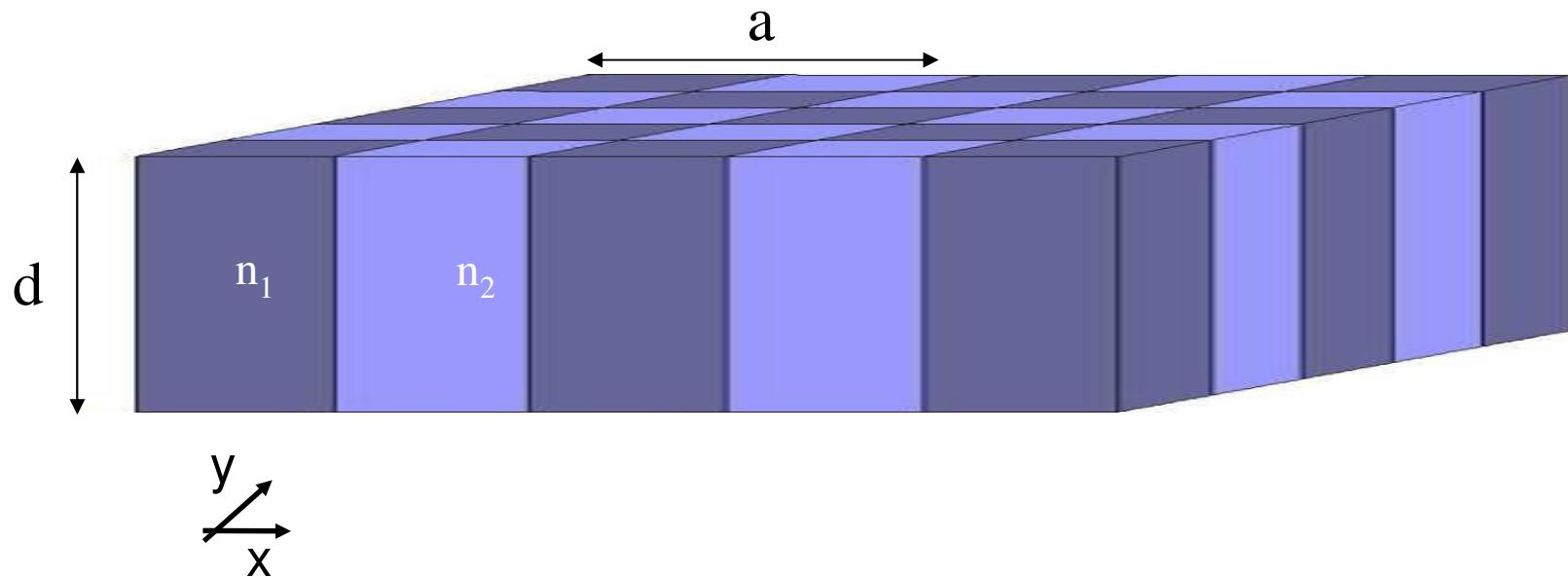
simulated
structure



titania
inverse
structure

PhC in 2.5D

$$a, d \approx \lambda$$

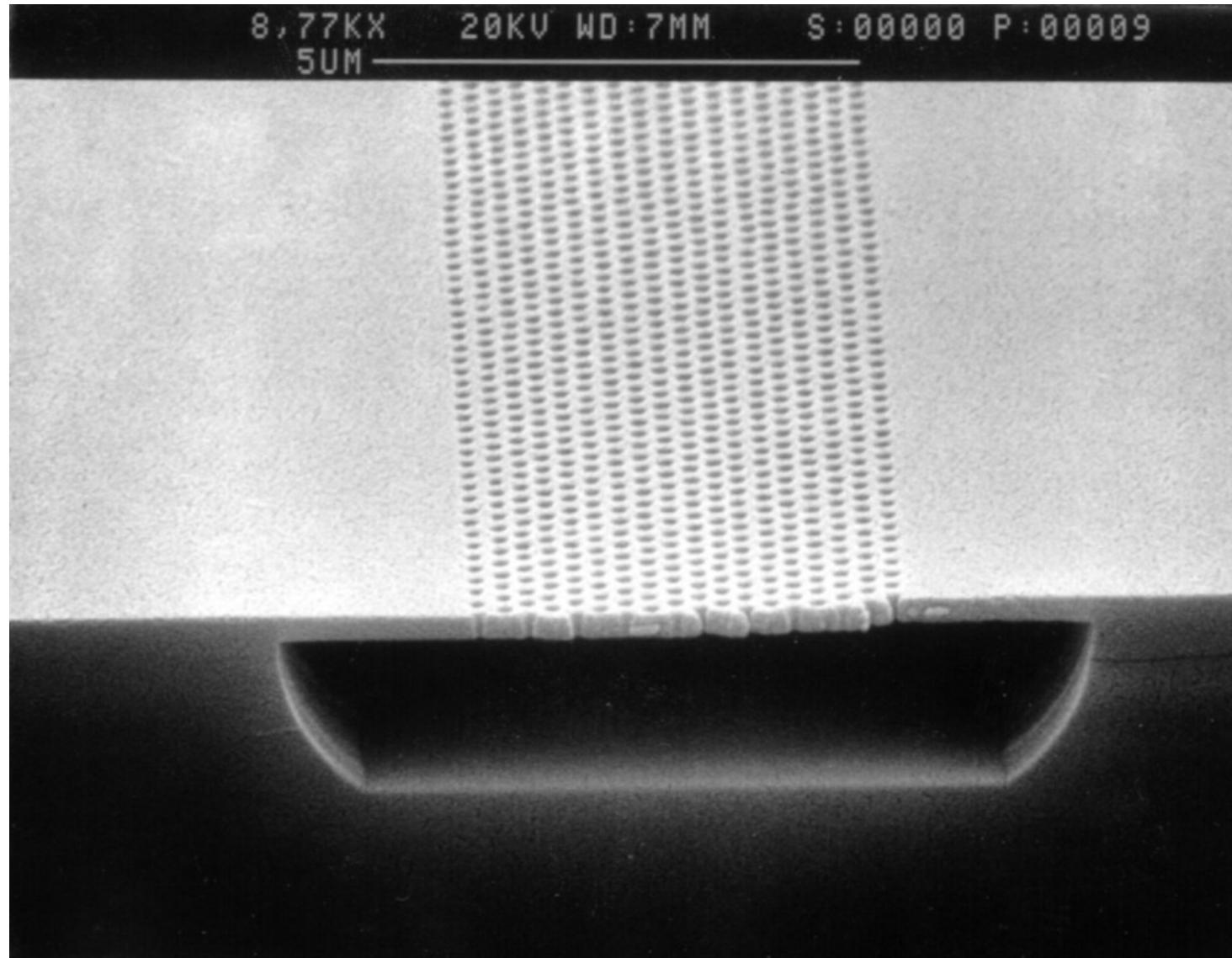


Litografia + selective etching

8,77KX
5UM -

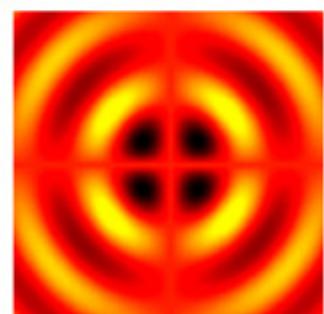
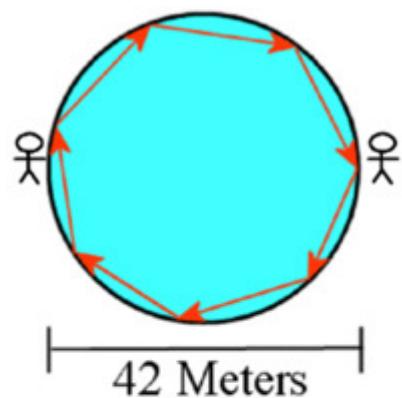
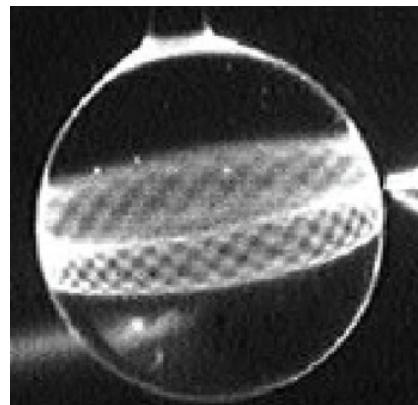
20KV WD:7MM

S:00000 P:00009



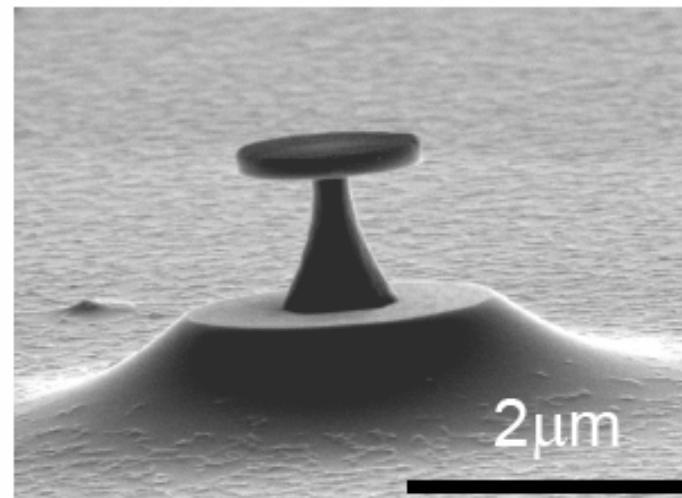
Altri design per
confinamento
quasi 3D

Individual sphere

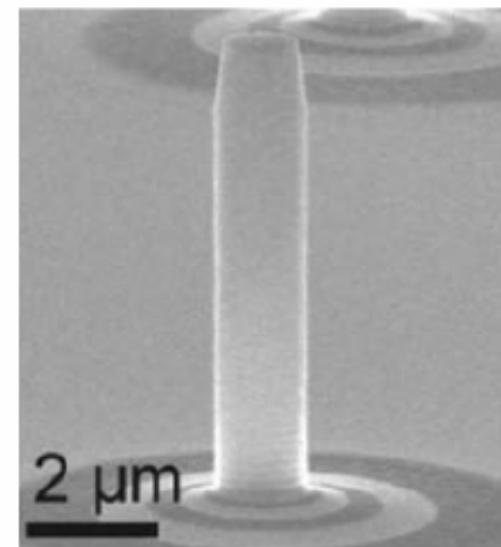


Whispering gallery modes

Microdisk



Micropillar



A. Forchel group, Wuerzburg