Photonic crystals, PHYS-605

Ecole doctorale photonique

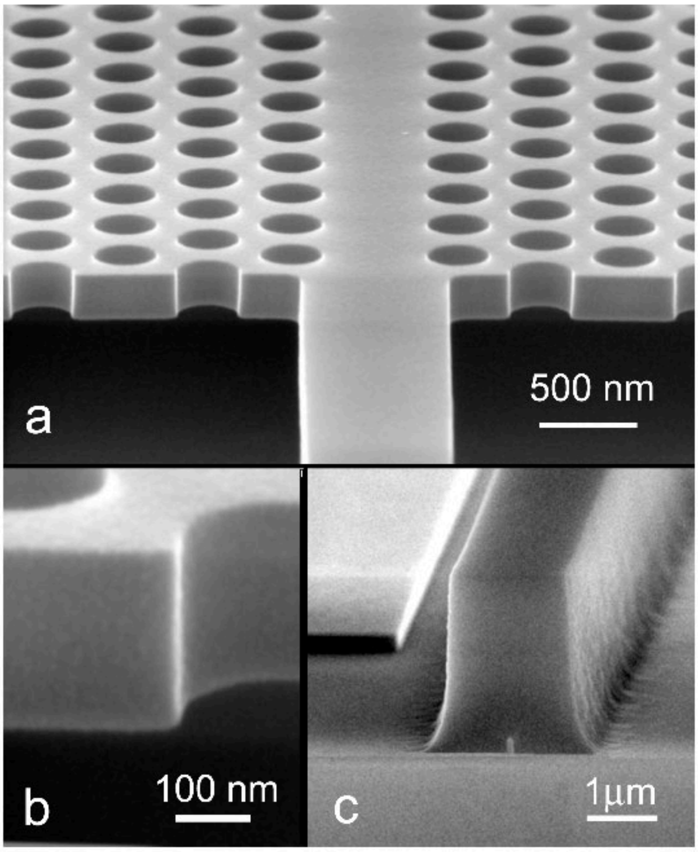
Romuald Houdré

Summer semester 2017

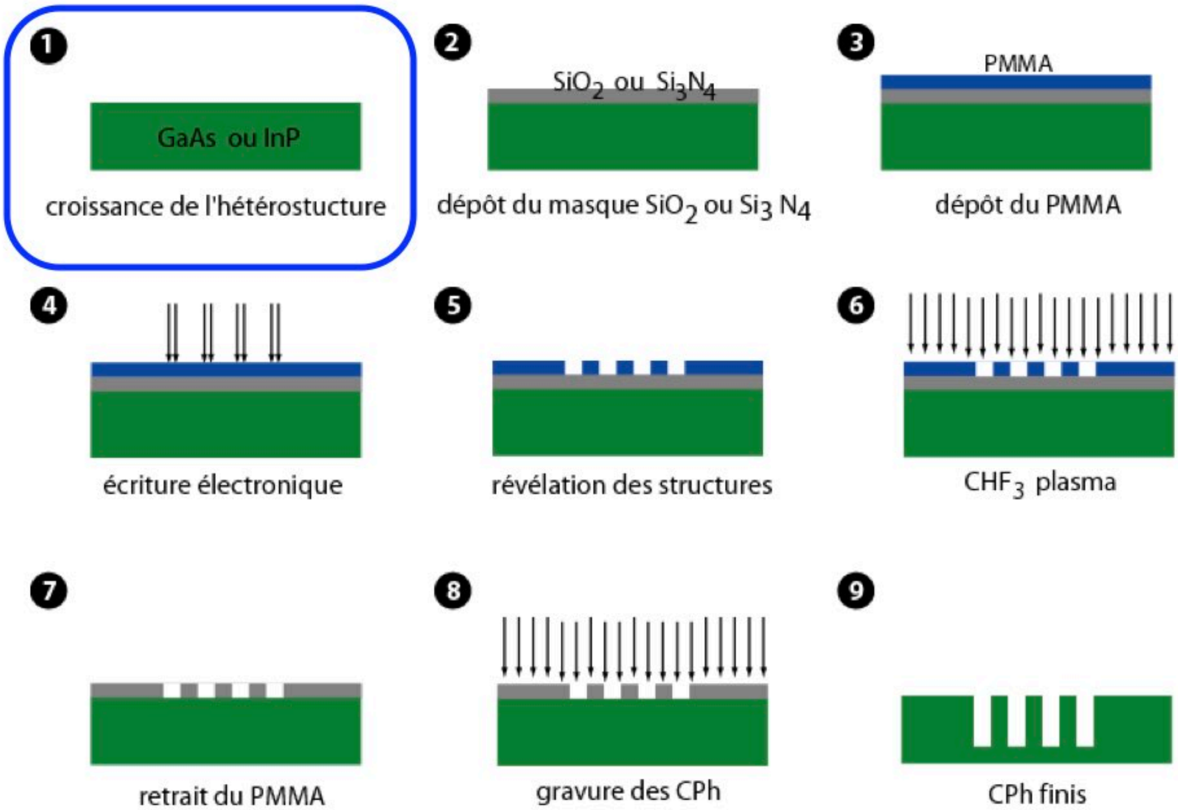
IV Fabrication

Contents

Fabrication 2D structures

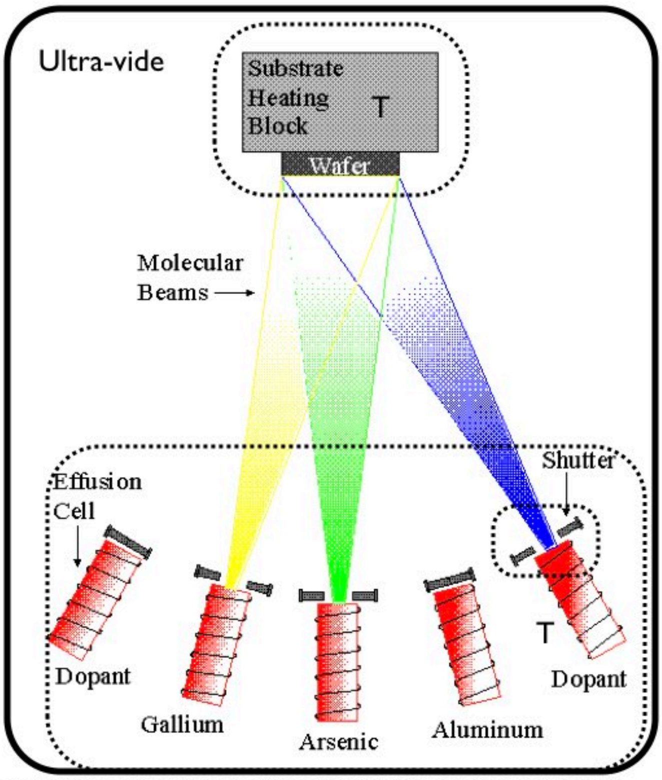


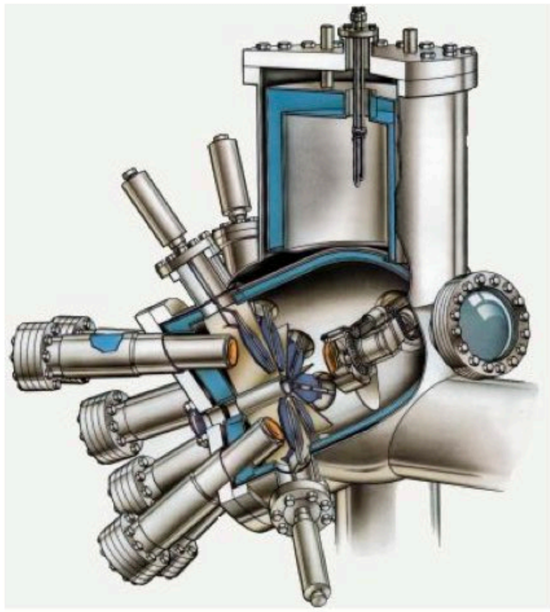
Fabrication 2D structures



Growth or deposition of the planar waveguide

Molecular beam epitaxy (EJM / MBE)

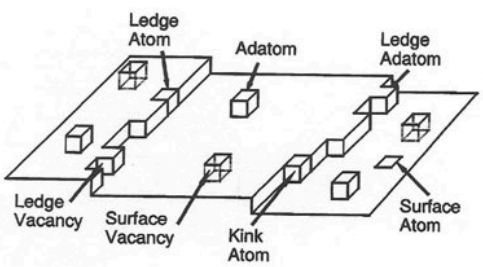


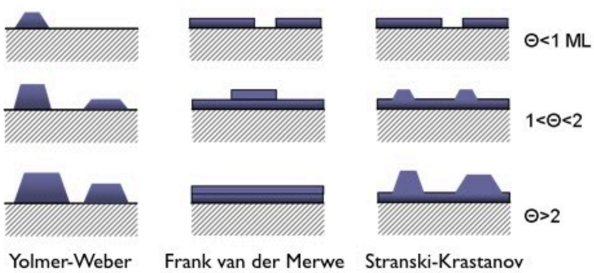


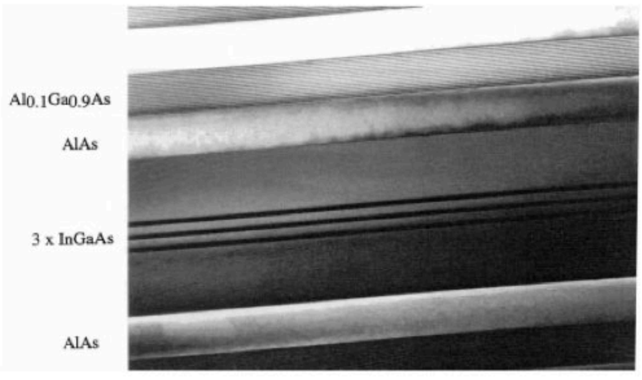
MBE VG

Growth or deposition of the planar waveguide

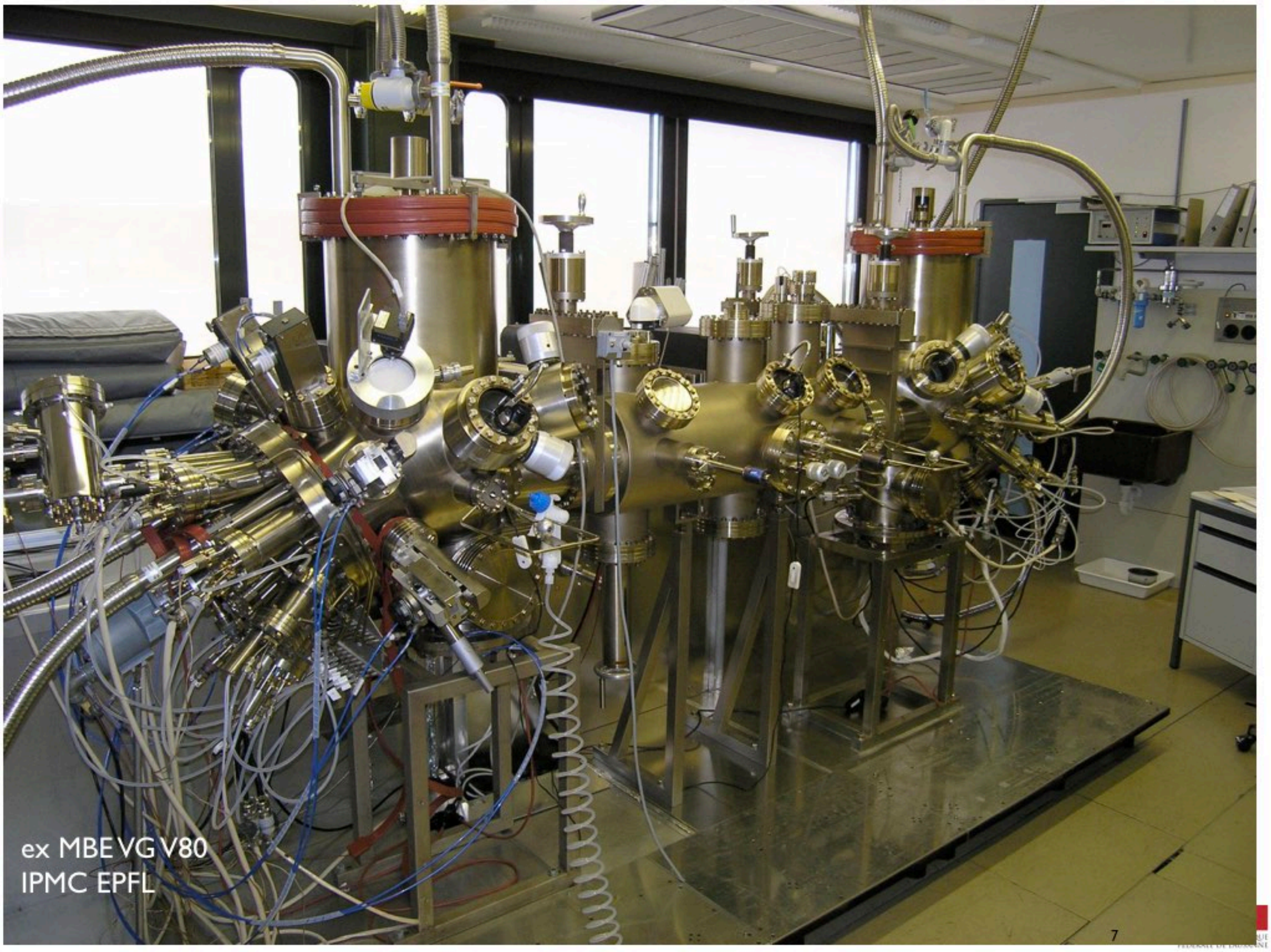
Molecular beam epitaxy (EJM / MBE)



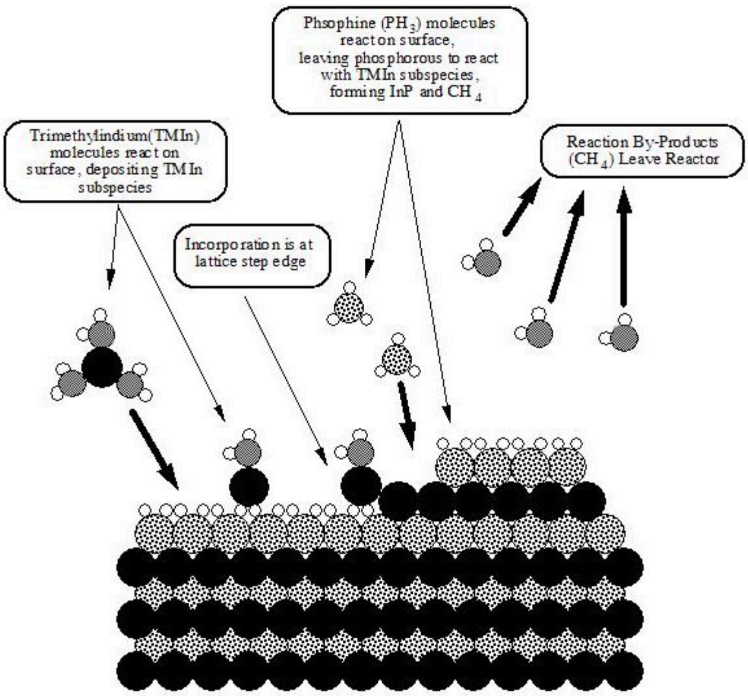




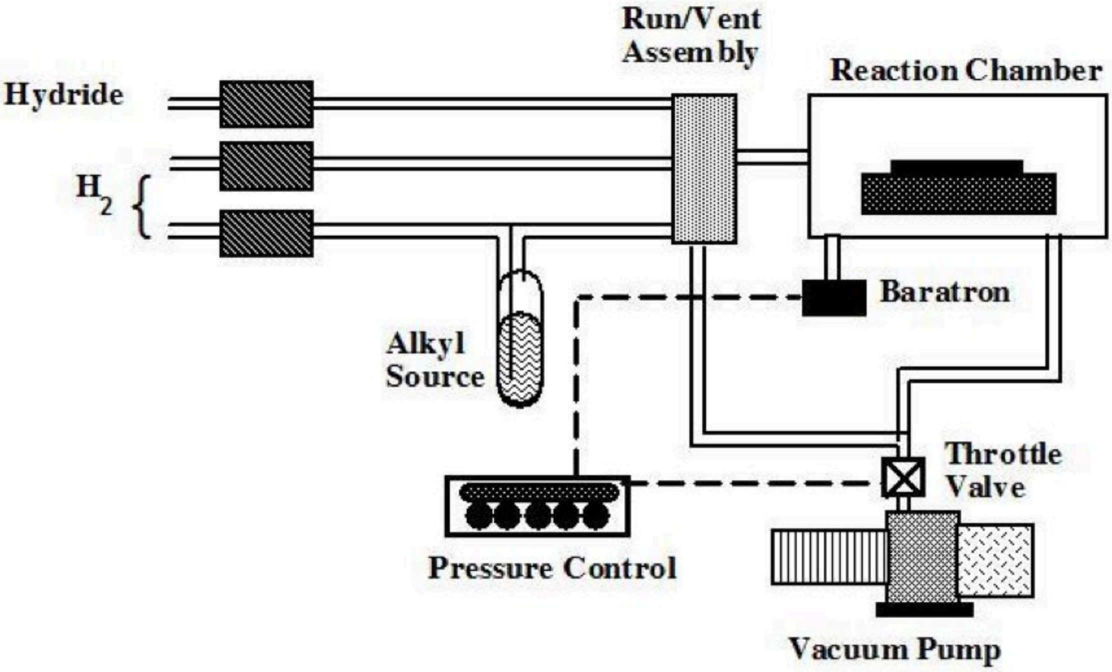
80 Å thick quantum wells

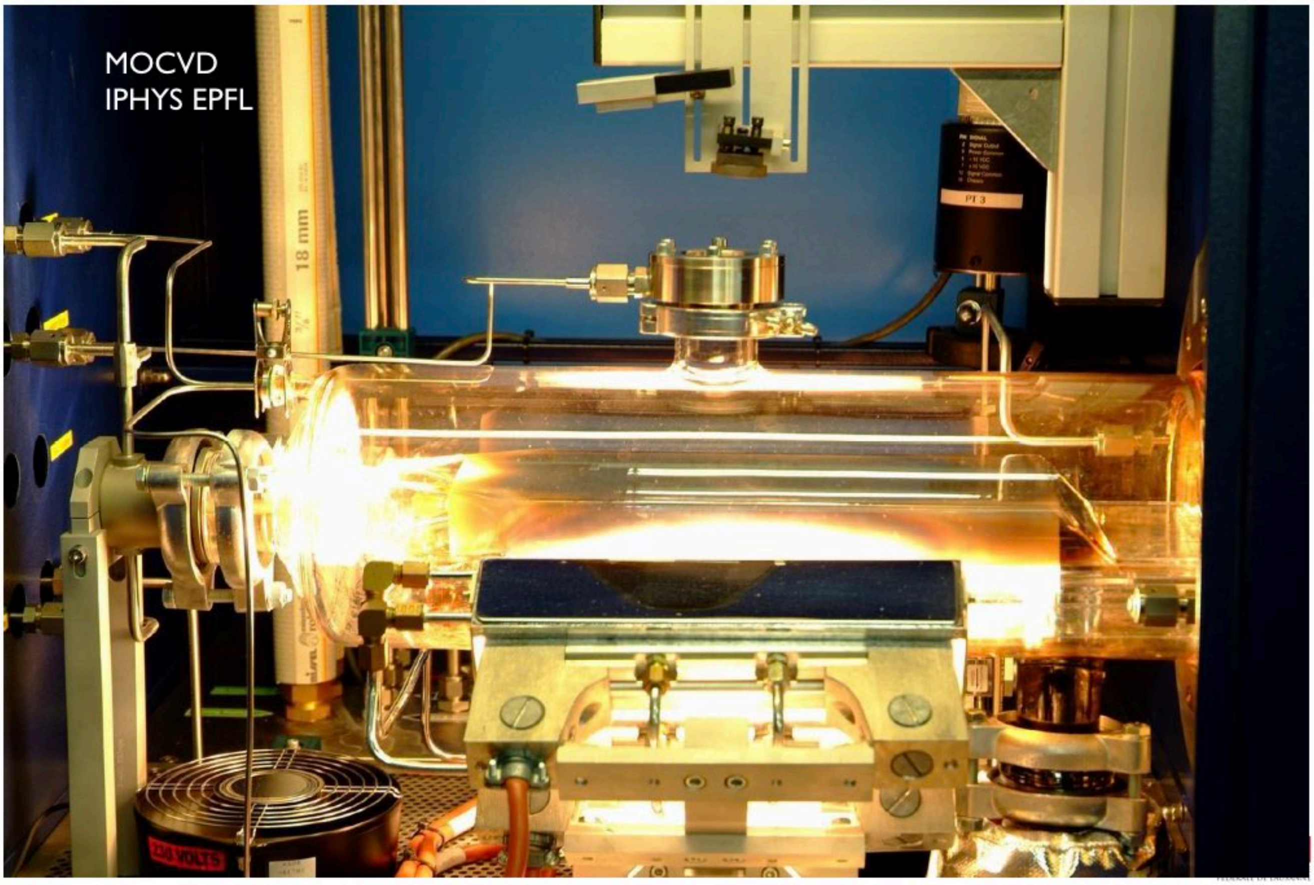


Organometallic based epitaxy

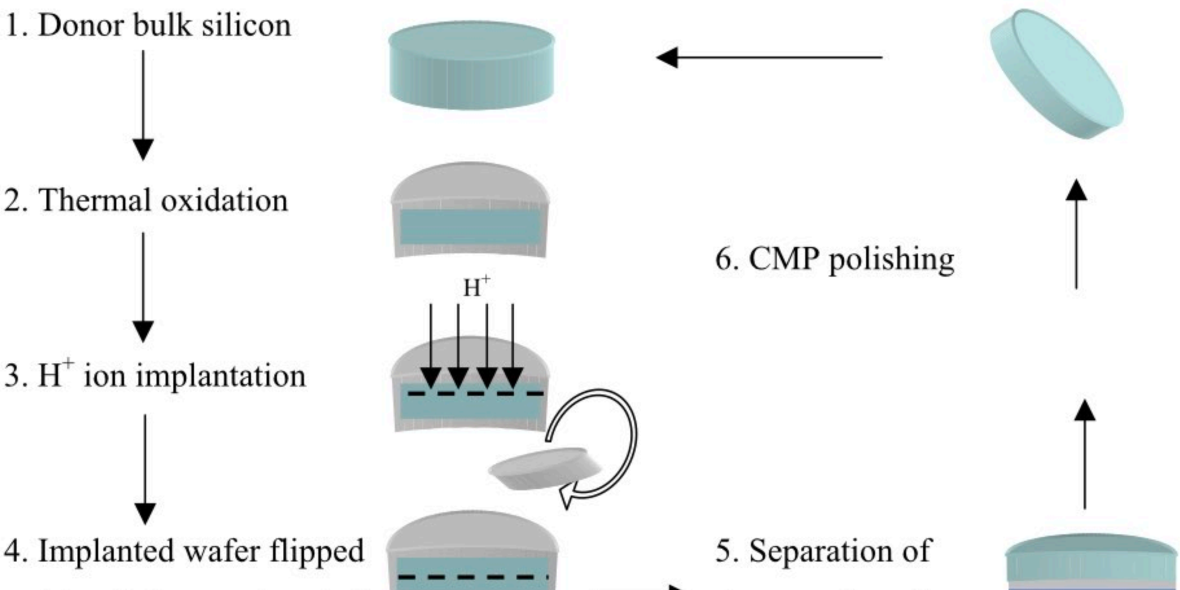


Organometallic based epitaxy



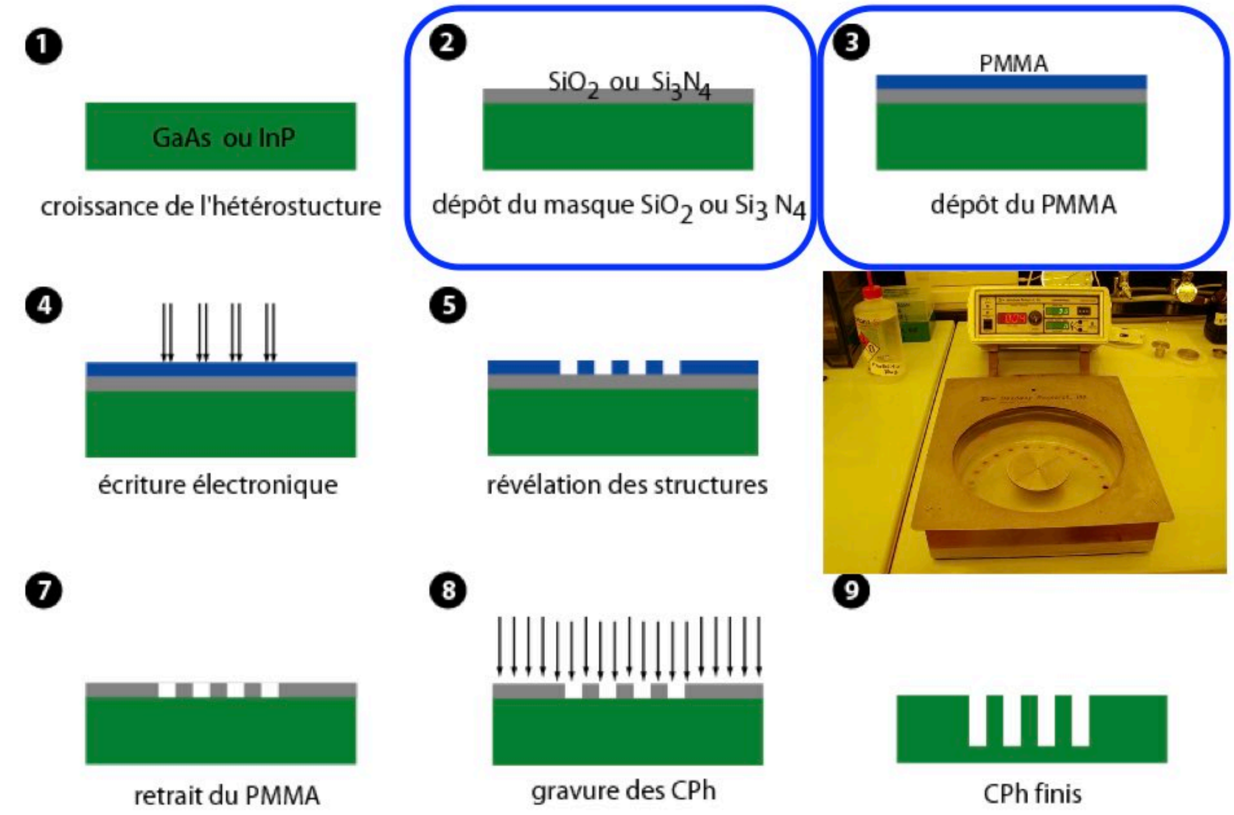


Silicon on insulator structures (SOI)

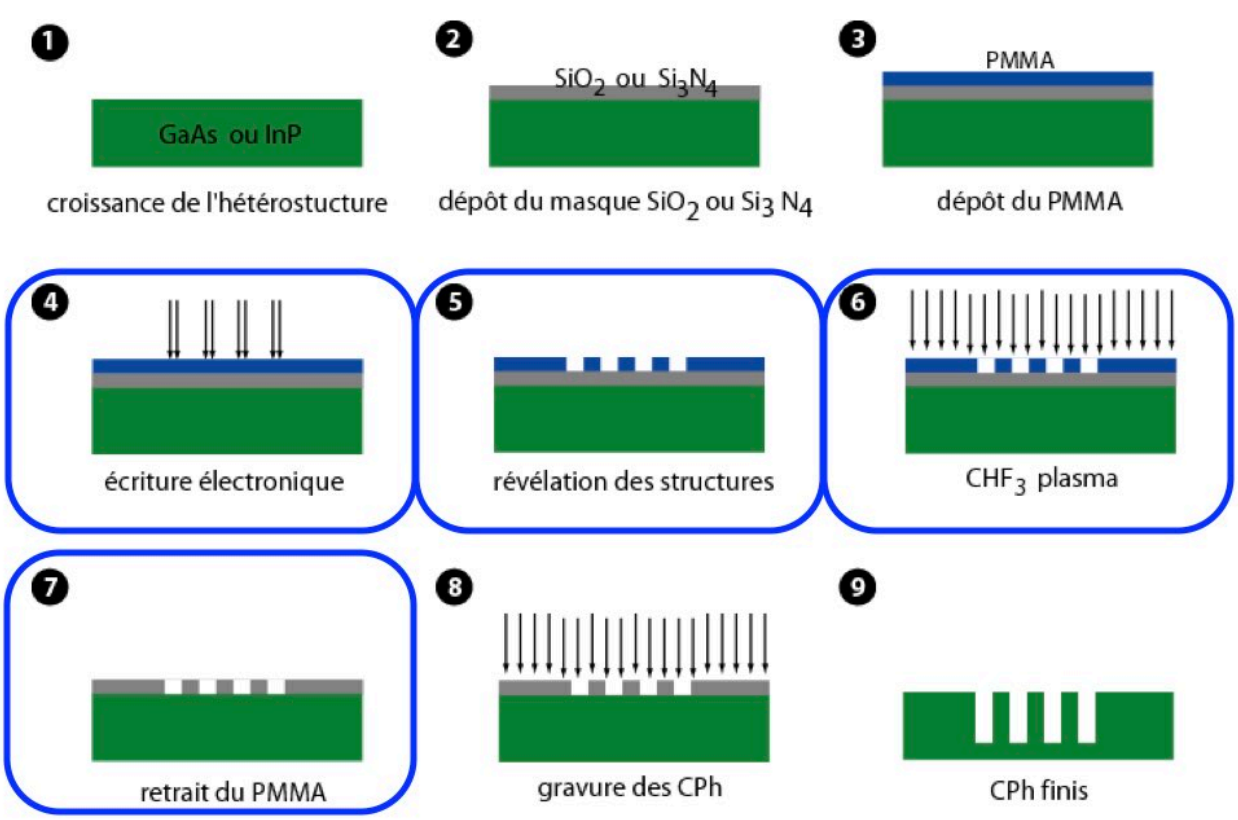


SOITEC, and also UNIBOND etc...

Fabrication 2D structures

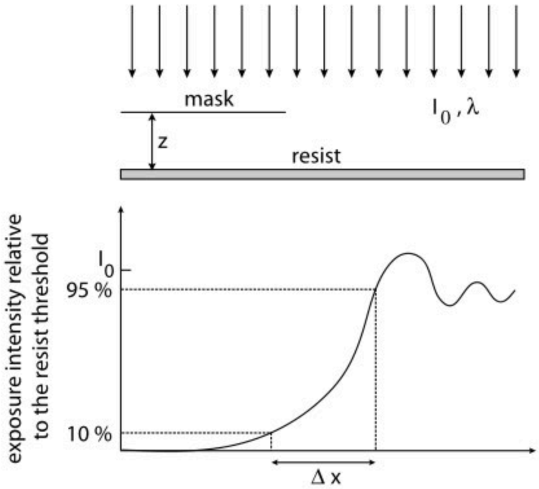


Fabrication 2D structures



Patterning

Standard optical lithography techniques used in microelectronics do not have enough spatial resolution



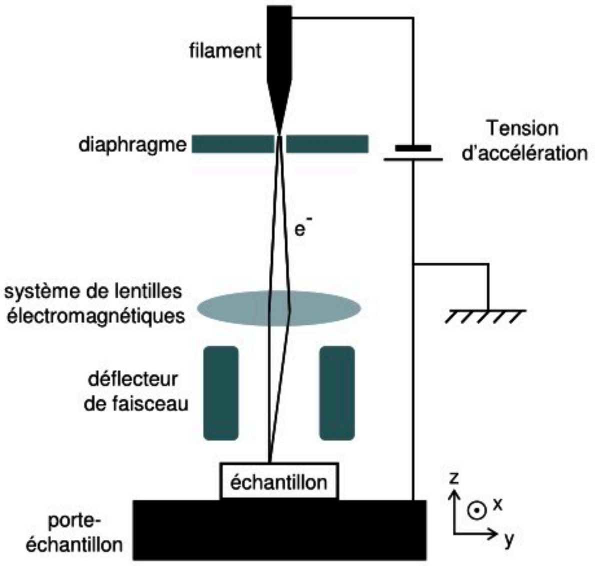
$$\Delta x = \frac{3}{2}\sqrt{\lambda(z + \frac{d}{2})}$$

Decrease the wavelength:

- deep UV
- electrons
- ions

Patterning

E-beam lithography



Scanning electron microscope

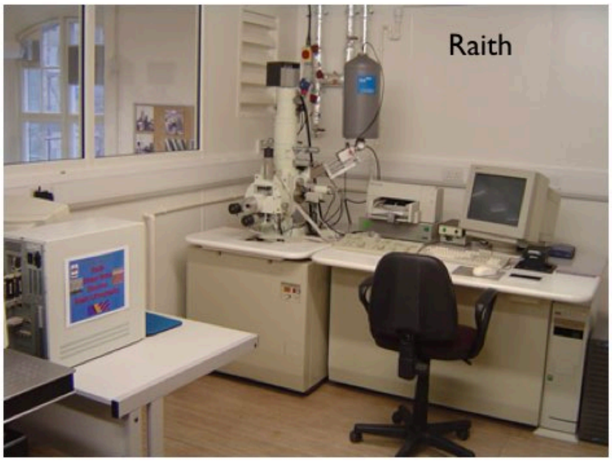
•Patterning in resist sensitive to e-beam irradiation

•Polymer resists (PMMA, ZEP, HSQ etc...)

•Electrons (20-100 keV) break the long polymer chains in shorter one

•Selective dissolution between exposed and non-exposed resist

E-beam patterning

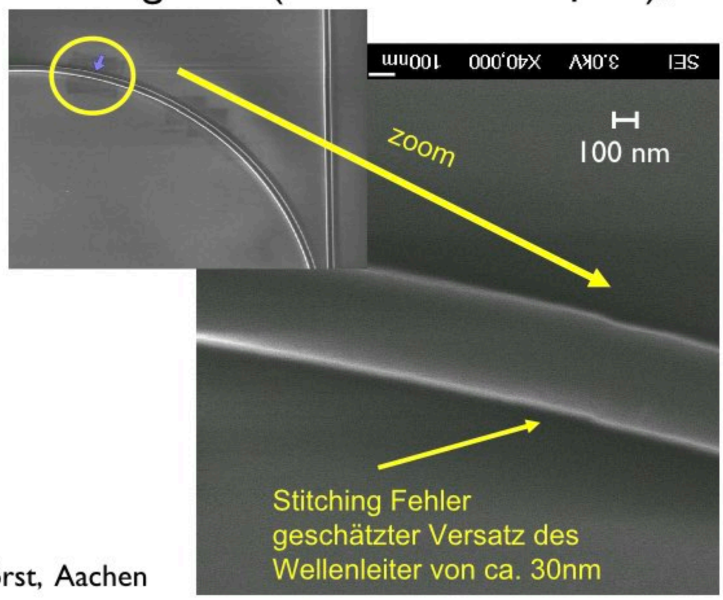


Patterning

E-beam lithography

Limits :

- Non parallel process, slow
- Limited writting field (a few 100X100µm^2), field stitching issues



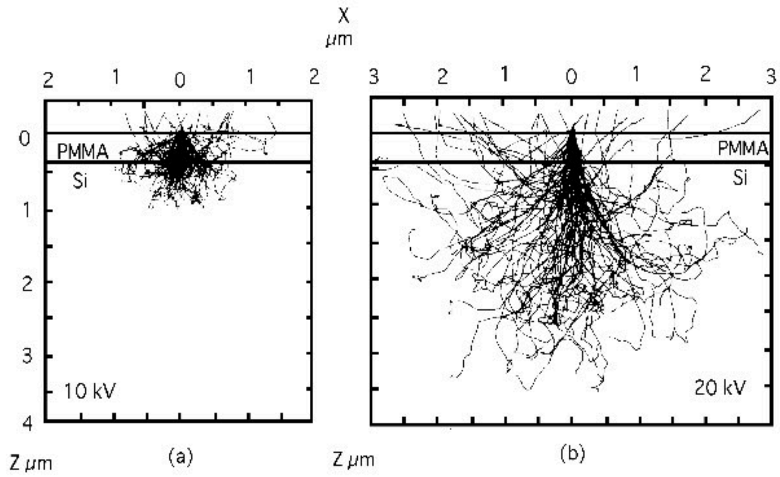
Courtesy, M. Först, Aachen

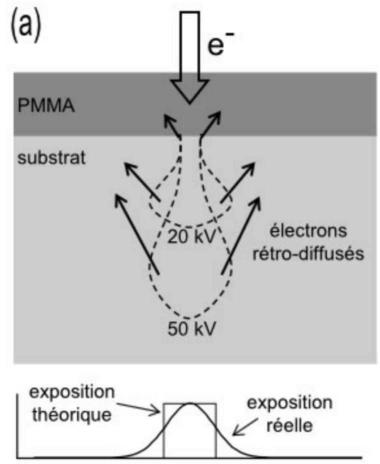
Patterning

E-beam lithography

Limits :

- Proximity effects



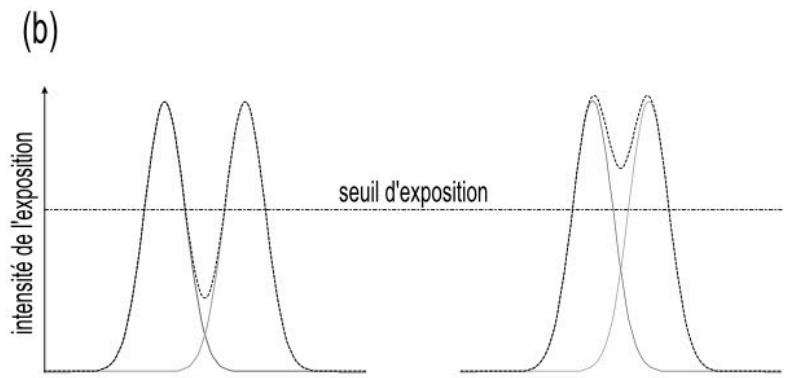


Patterning

E-beam lithography

Limits :

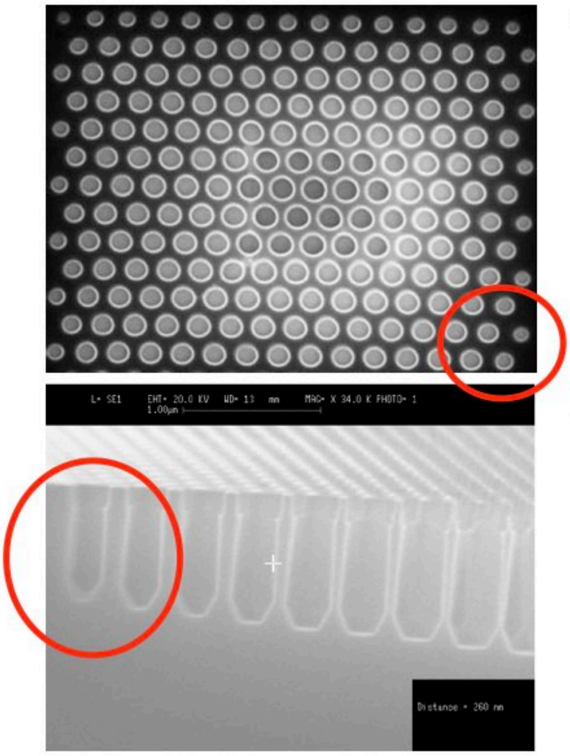
- Proximity effects

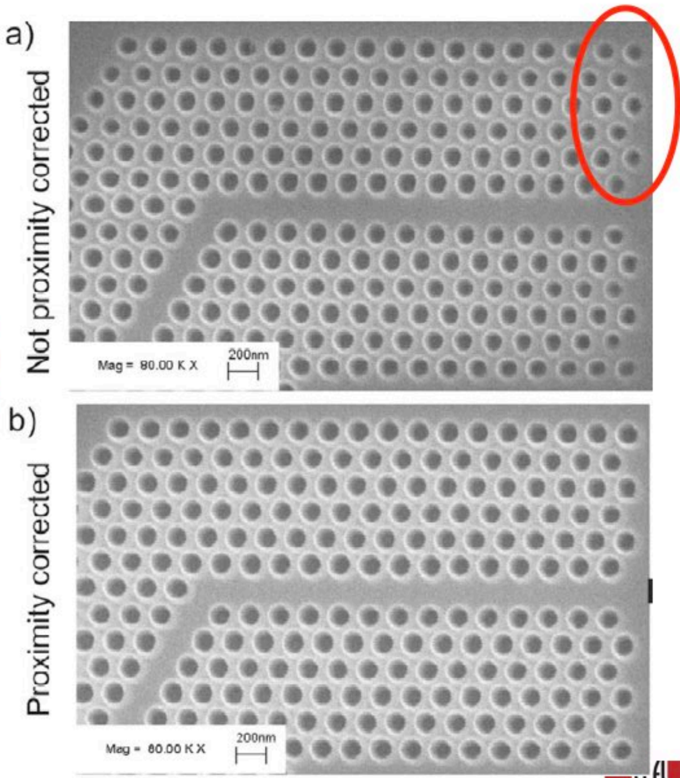


Correction by modulation of the electron doses (require large amount of CPU time)

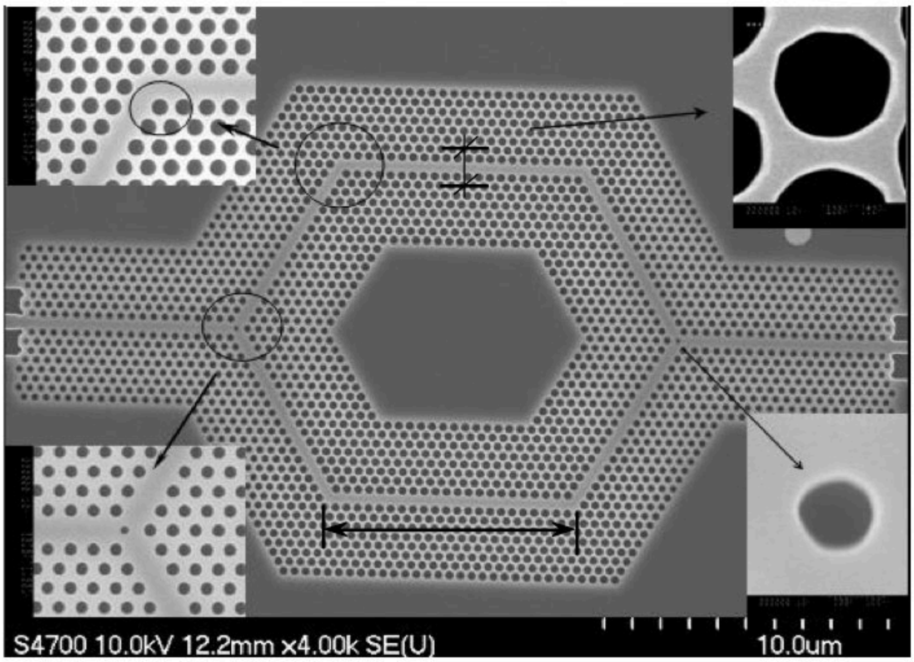
Proximity effects are maximum around 50 keV

E-beam lithography
Limits :
- Proximity effects



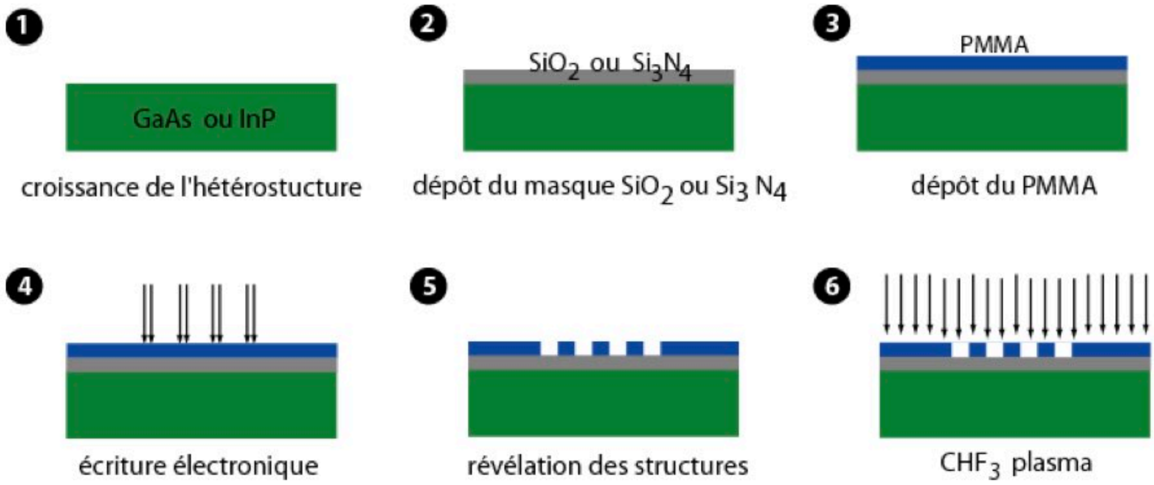


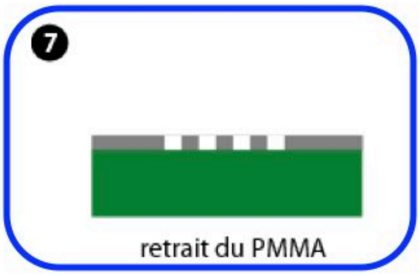
Patterning

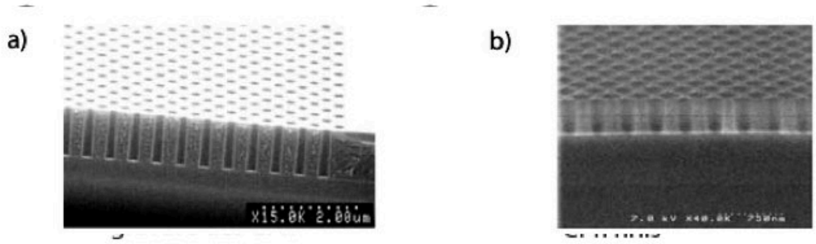


Thesis A.C. Edilson, Glasgow

Fabrication 2D structures

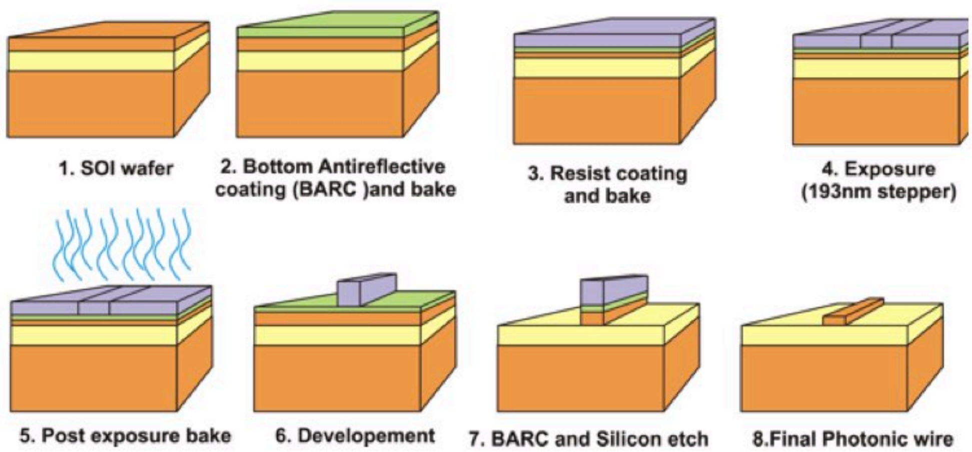


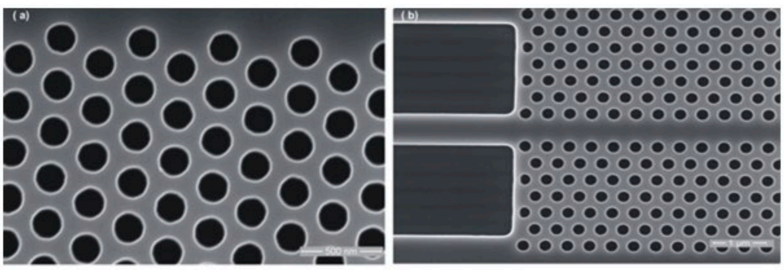




Patterning

Deep UV and X-ray lithography



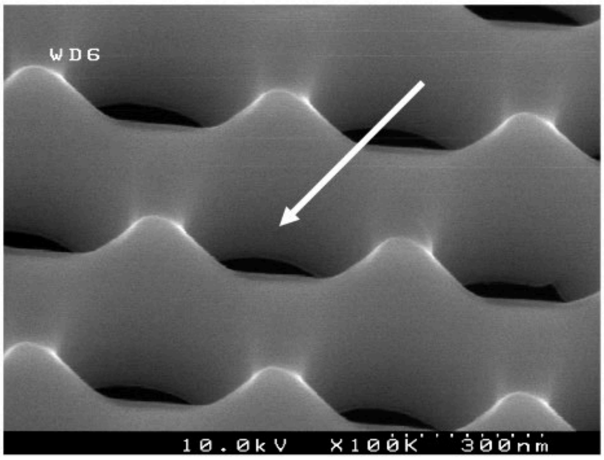


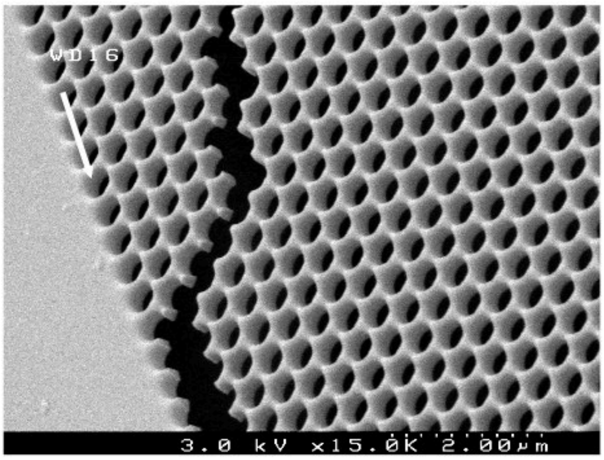
IPEQ

Simultaneous patterning and etching

Focused ion beam (FIB)

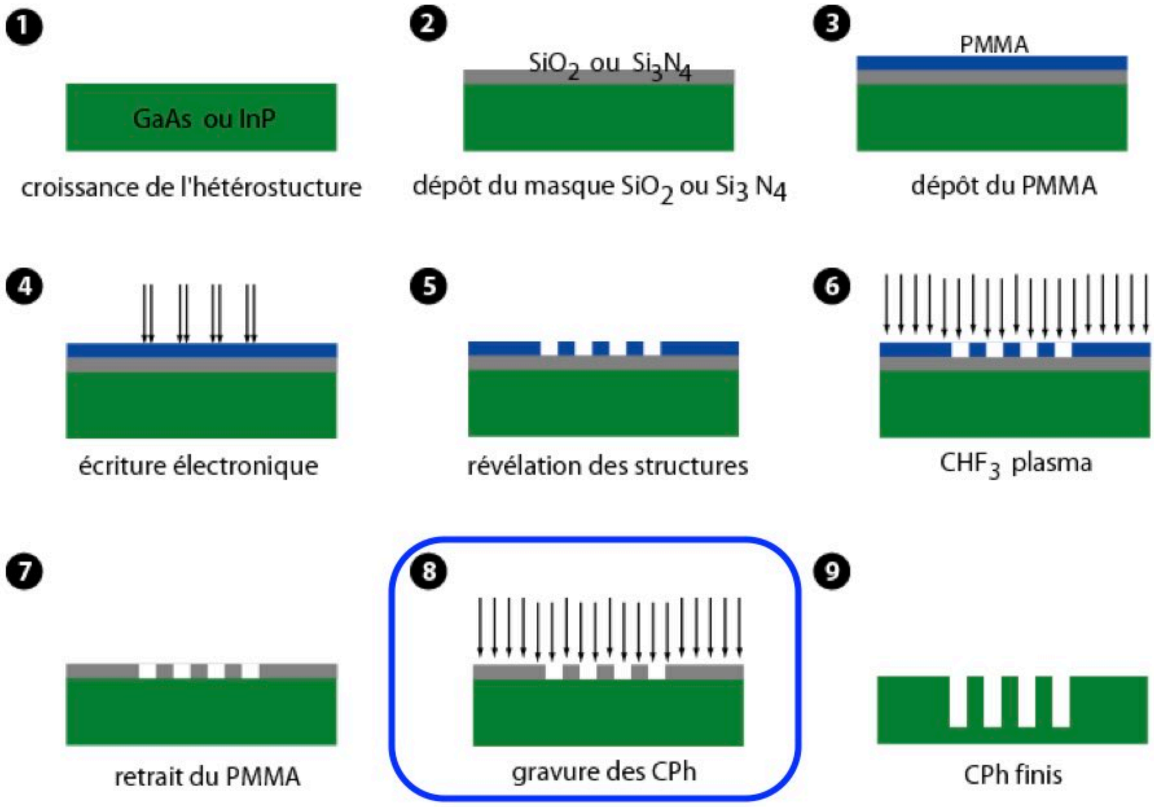
Mechanical erosion with a focused beam of ions





D. Freeman et al., Opt. Exp., 13, 3079 (2005)

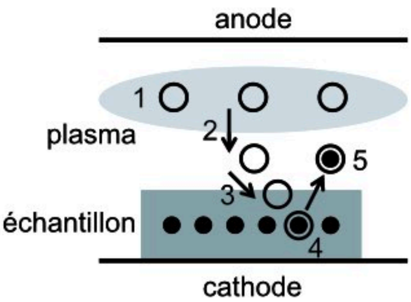
Fabrication 2D structures



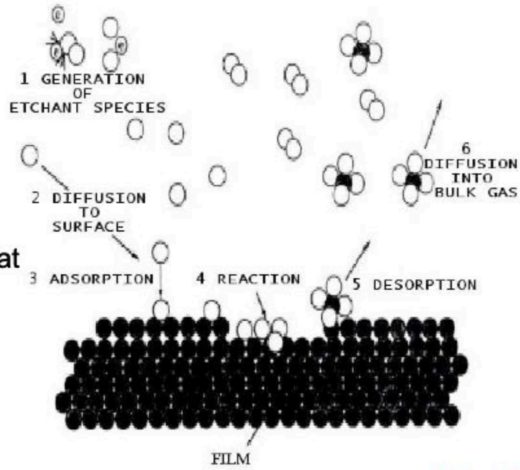
Etching

Dry plasma etching

- Physical etching by mechanical erosion
  - isotropic
  - may generates defects
  - low selectivity
- Chemical etching by chemical reaction with the plasma ions
  - anisotropic
  - selectivity
  - fast



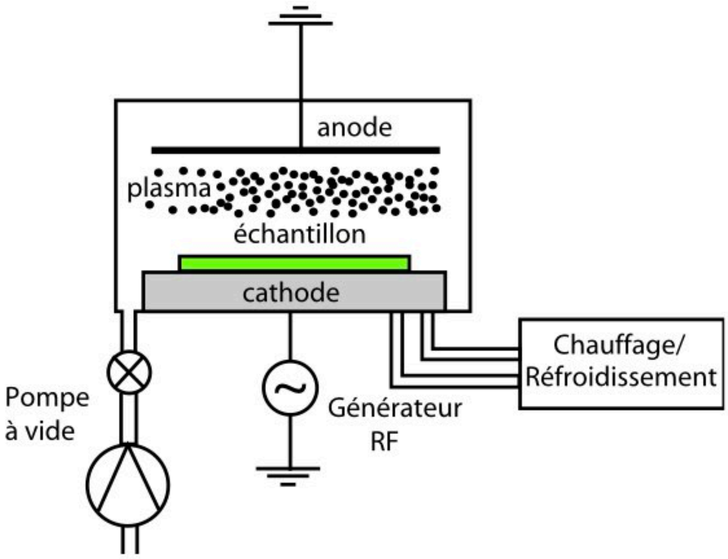
1) Création des réactants
2) Migration vers le substrat
3) Adsorption
4) Réaction chimique
5) Désorption



Plasma etching

Different plasma etching systems

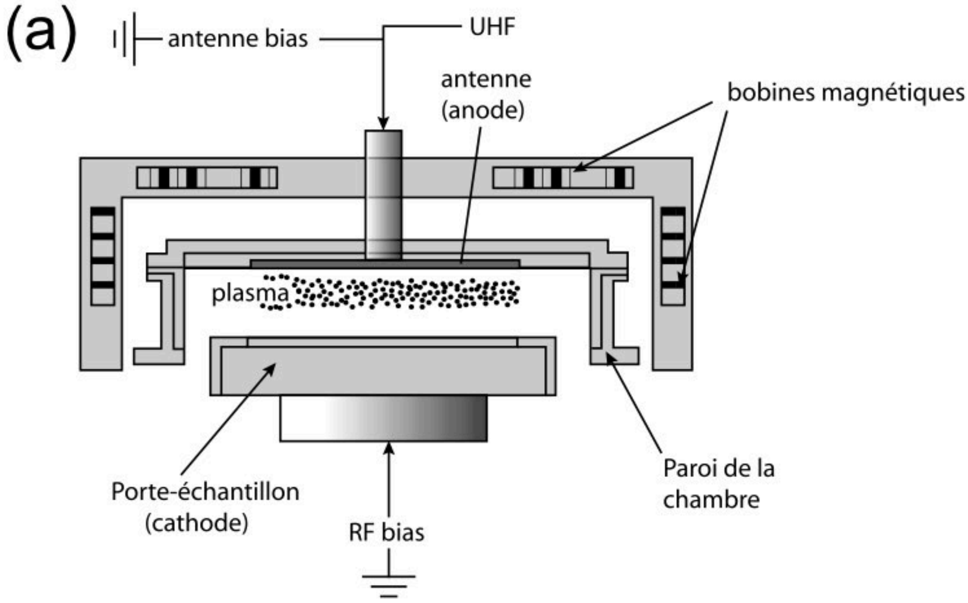
- RF generator
- Directivity increases with the mean free path when plasma pressure decreases
- Low pressure requires increased power to initiate the plasma
- Difficult to control the balance between chemical and physical etching



Generic, capacity coupled plasma (CCP)

Plasma etching

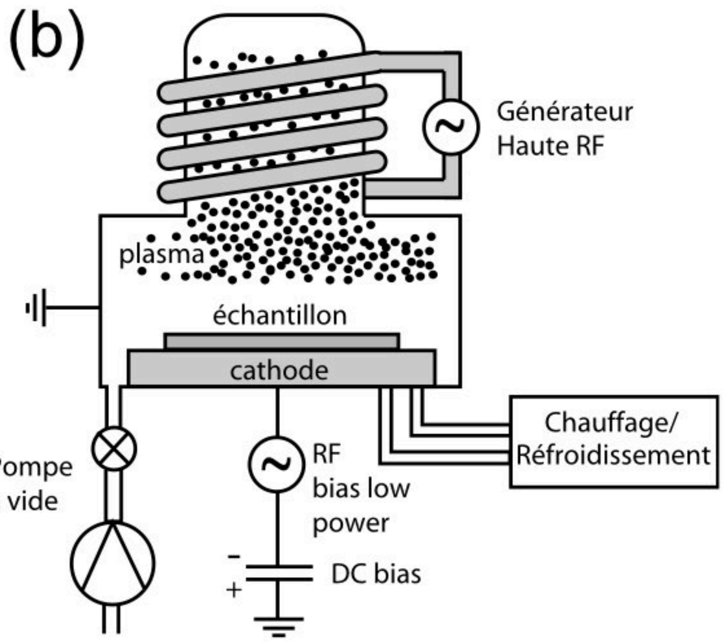
Electro-cyclotron resonance (ECR)



- UHF wave + magnetic field
- Independent control of the ions energy and plasma density

Plasma etching

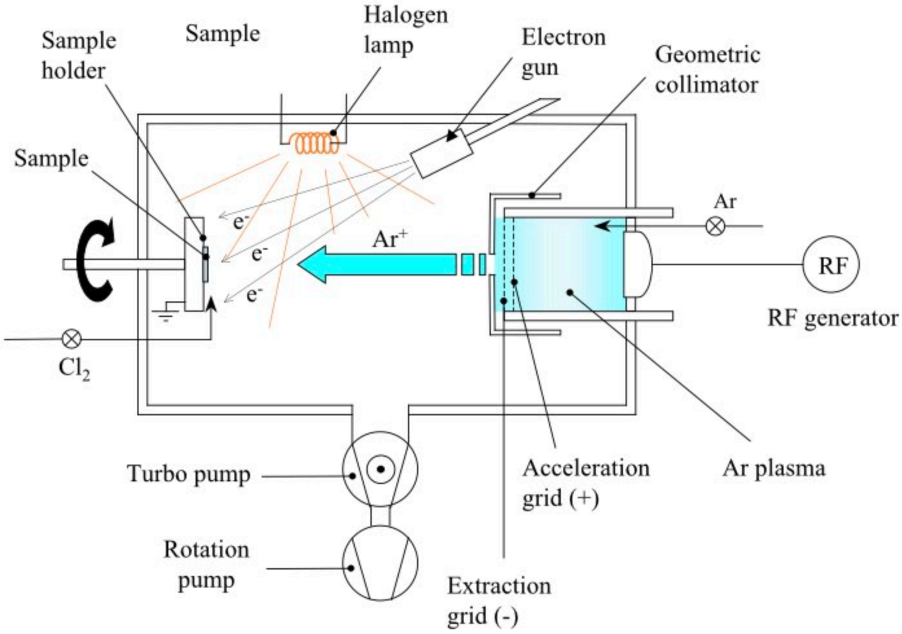
Inductively coupled plasma (ICP)



- Magnetic field
- Control of the ions energy and plasma density independently of electrodes potentials

Plasma etching

Chemical assisted ion beam etching (CAIBE)



- Two separate chambers
- 1 Generation of the plasma (for physical etching)
- 2 Ions for chemical etching are introduced separately

Plasma etching

Selection of the ions to be used is function of a large number of parameters

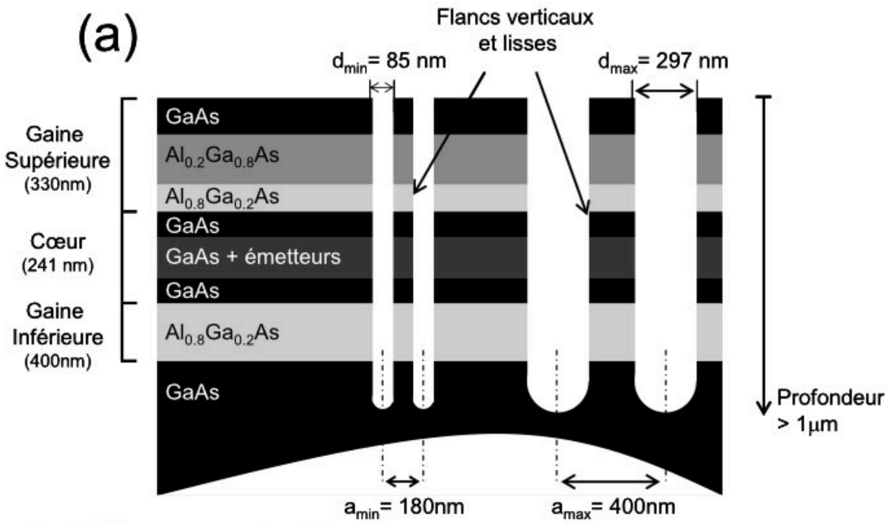
CF_4, CHF_3, H_2, $SiCl_4$, Cl_2, Ar, O_2

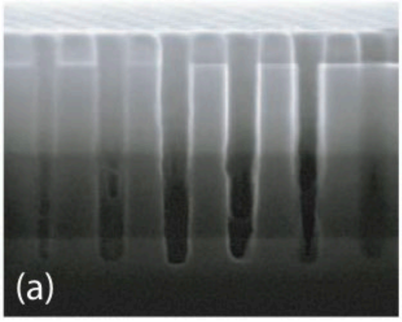
- Balance between physical and chemical etching
- Material to be etched (GaAs, InP, Si, etc...)
- Type of plasma (ECR, ICP, CAIBE, ...)
- Type sample (deep holes or not ...)
- Nature of the mask (SiO_2, Si_3N_4, metal, ...)
- ...

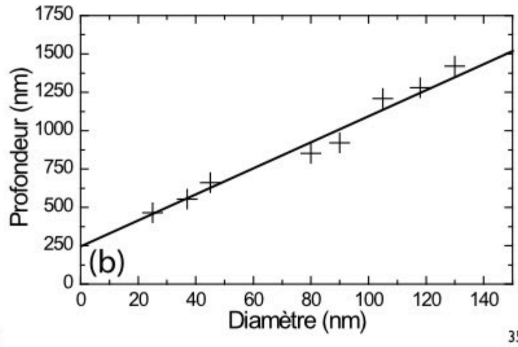
Plasma etching

Plasma etching

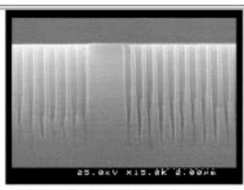
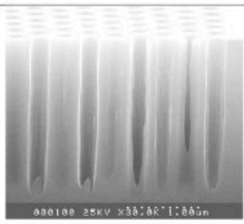
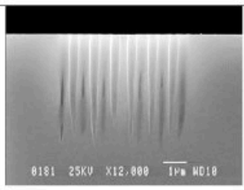
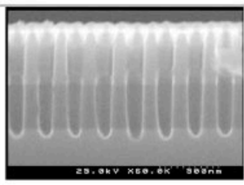
Low index contrast structures





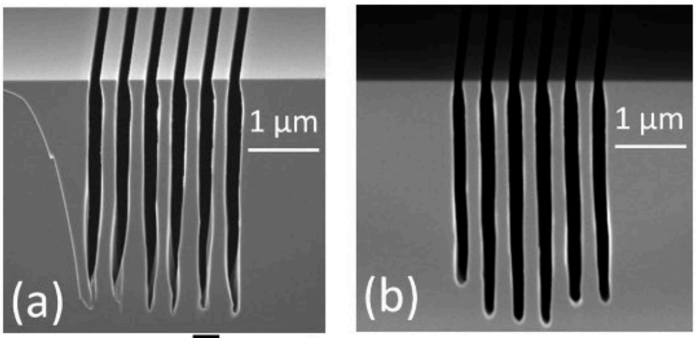


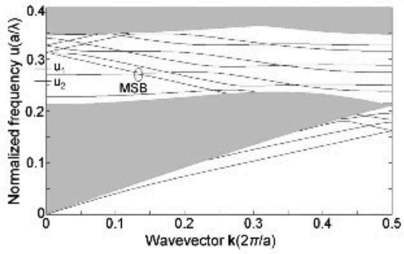
Low index contrast structures

		Hole shape	Etch depth (μm)	Aspect ratio	Limiting factors
ECR (InP)		tapered	3-4	16	mask selectivity
ICP (InP)		cylindro-conical	4.5	14	mask selectivity
CAIBE (InP)		tapered	2.5-4.5	10-20	mask thickness/ removal of etch products
ECR (GaAs)		cylindrical	1.1	6	mask thickness

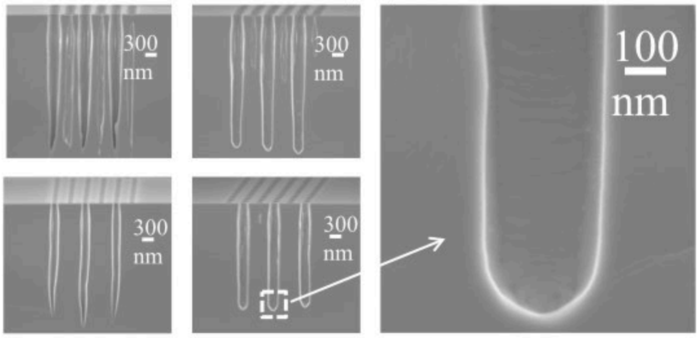
Low index contrast structures

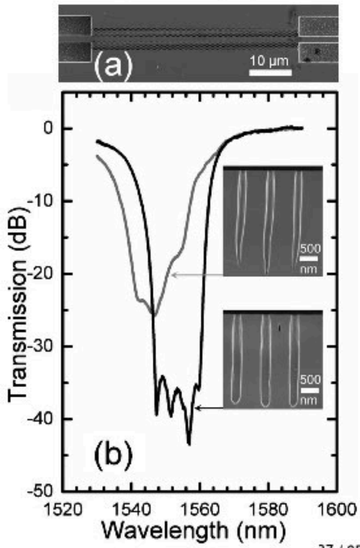
State of the art in InP based structures





Two-step process





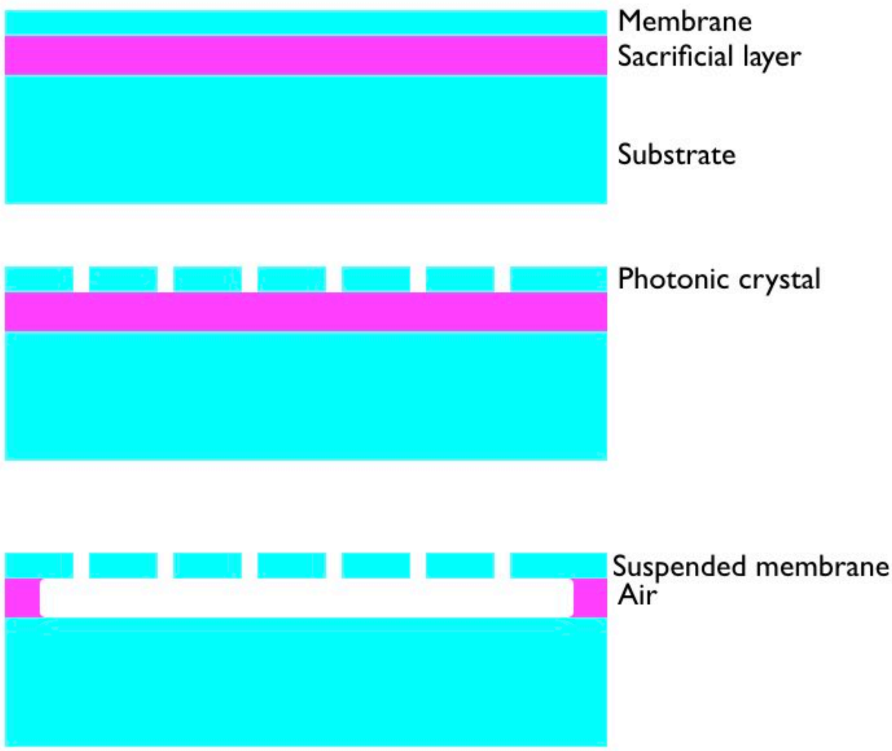
N. Shadid et al., J. Vac. Sci. Technol. B, 29, 031202 (2011)
N. Shadid et al., App. Phys. Lett., 98, 081112 (2011)

Membrane structures

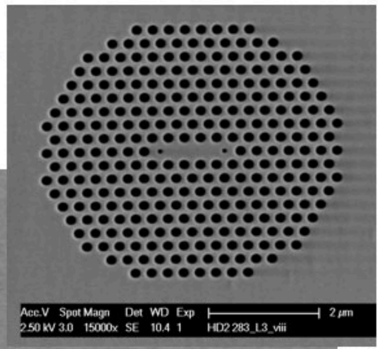
1 Waveguide

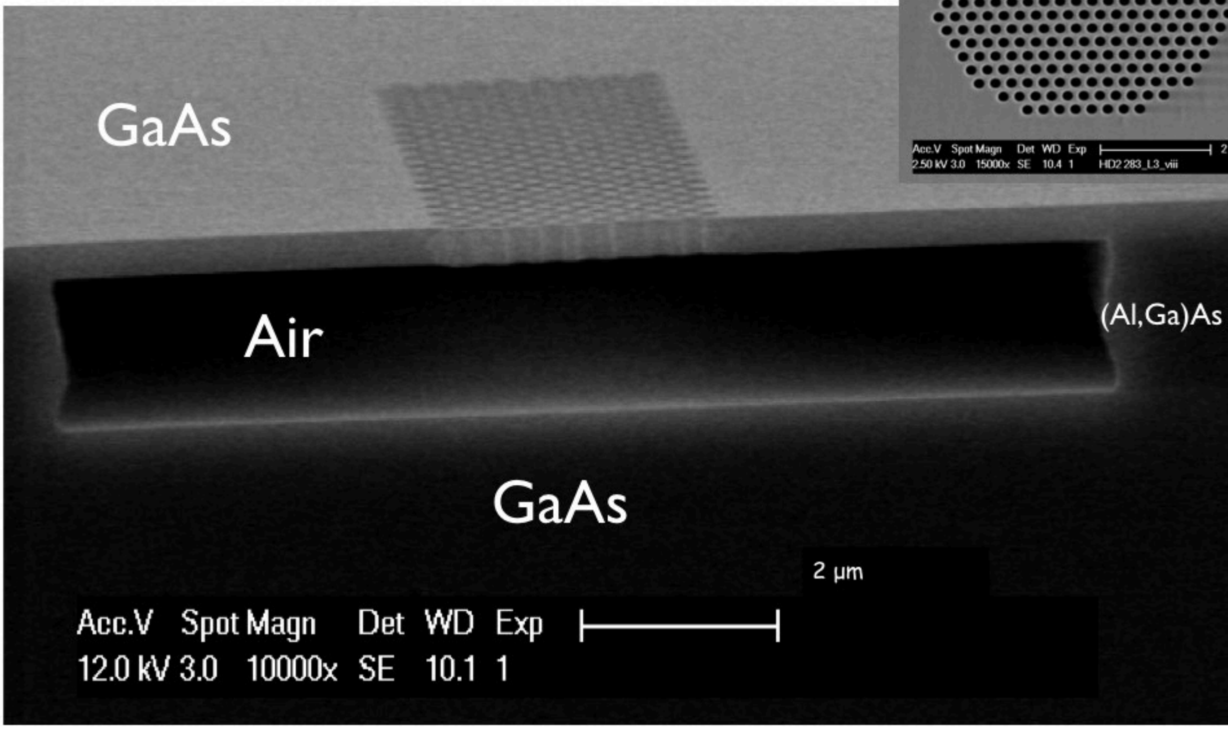
2 Etching

3 Wet or dry selective etching of the sacrificial layer + drying (tricky)



Membrane structures

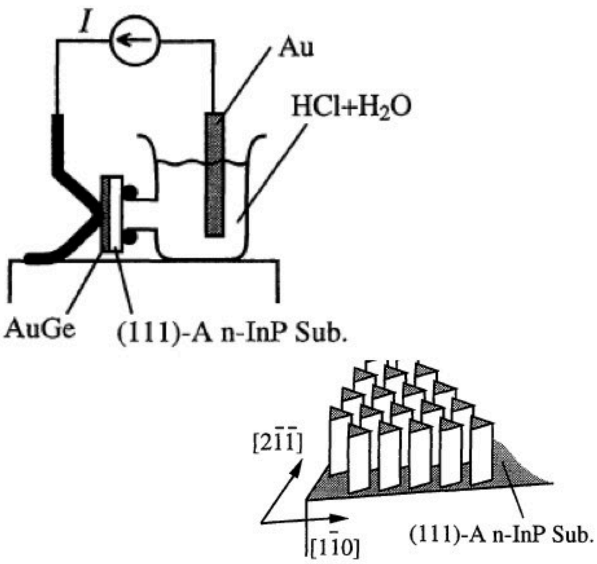


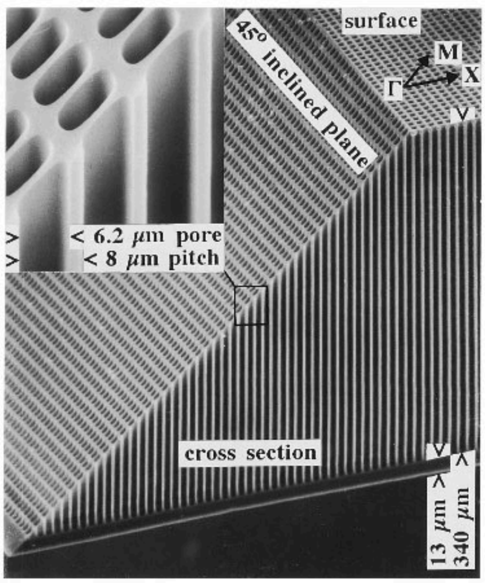


Courtesy, A. Fiore, EPFL and Eindhoven

Deep etching by anodisation

Electrochemical process





T. Baba et al., JJAP 34, 1405 (1995)

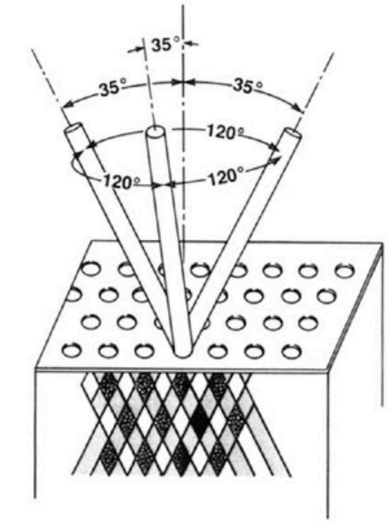
U. Grüning et al. App. Phys. Lett. 66 3254, (1995)

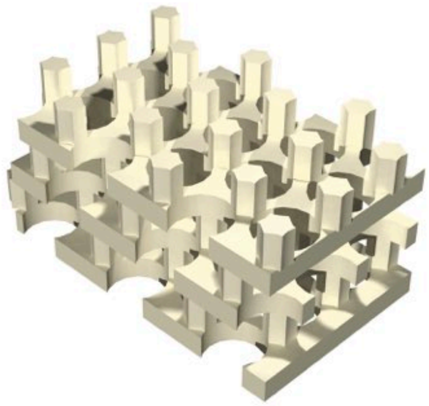
Example InP

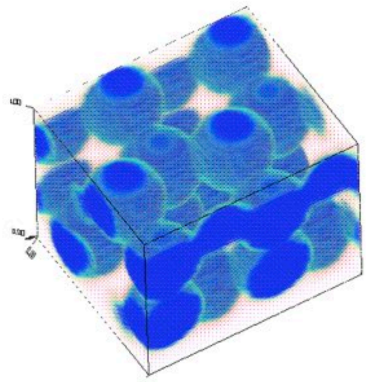
Example Si

Limited to the medium IR technique (λ >≈ 10 µm)

3D structures

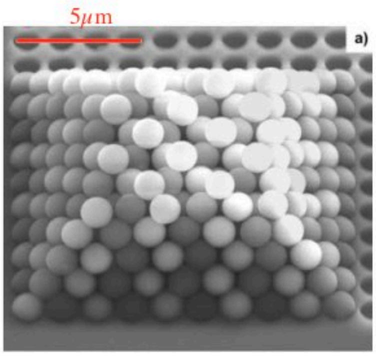




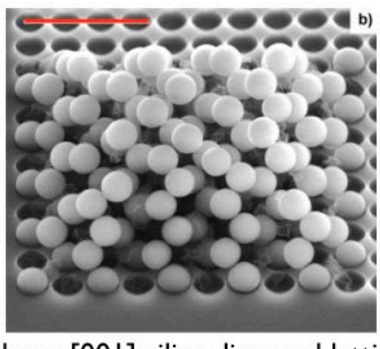


How to fabricate such object at optical wavelengths ?

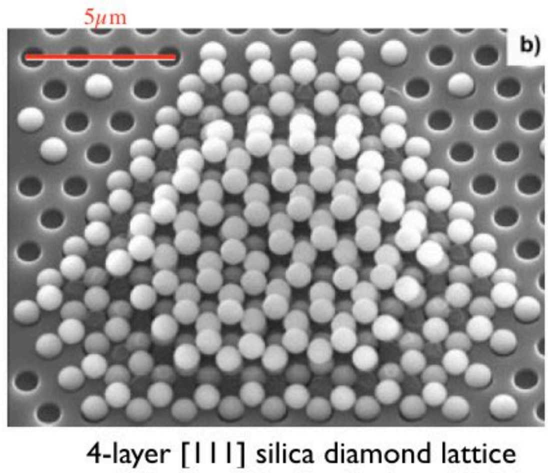
By hand, position each sphere, one by one ...



dissolve
latex spheres



6-layer [001] silica diamond lattice

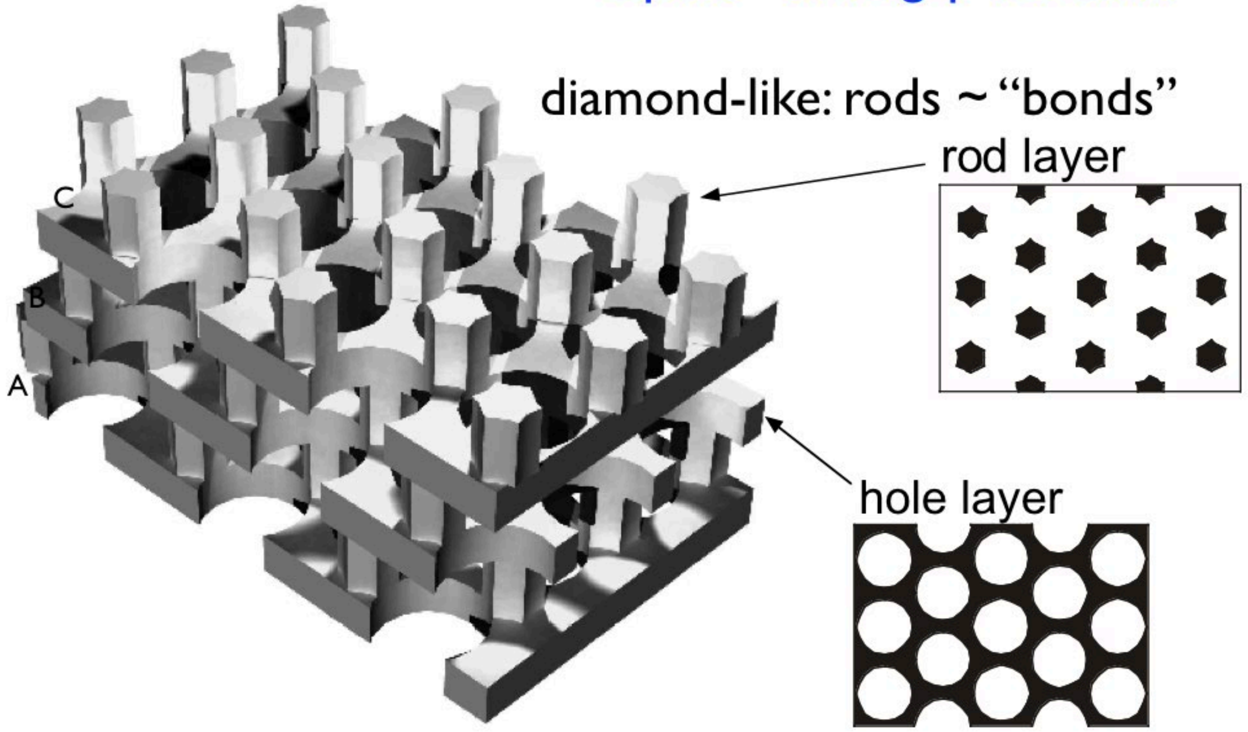


4-layer [111] silica diamond lattice

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

Less desperate :

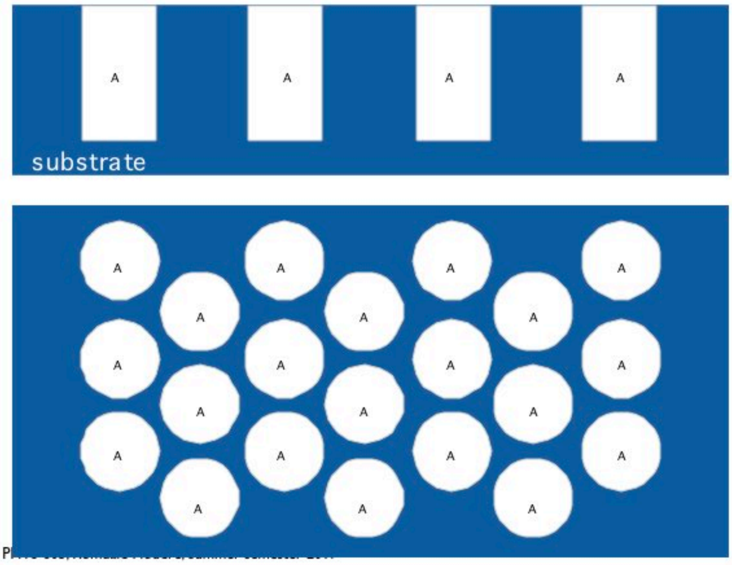
Up to ~ 27% gap for Si/air



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

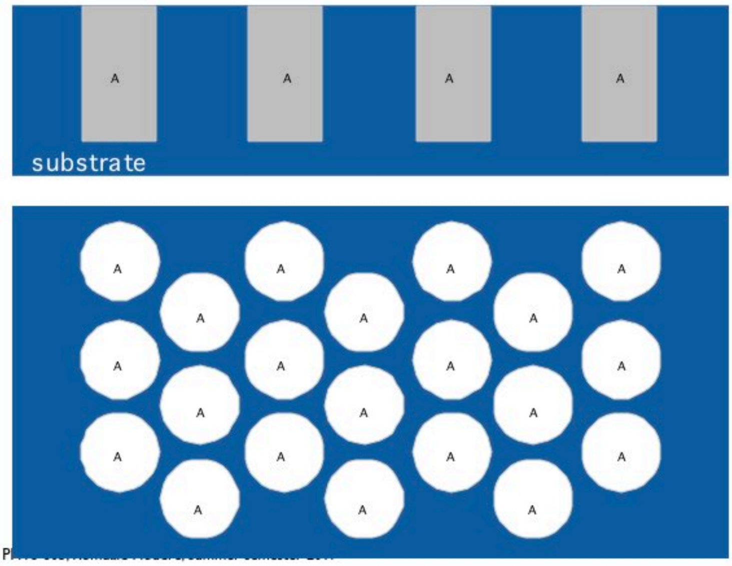
Making Rods & Holes Simultaneously

expose/etch holes



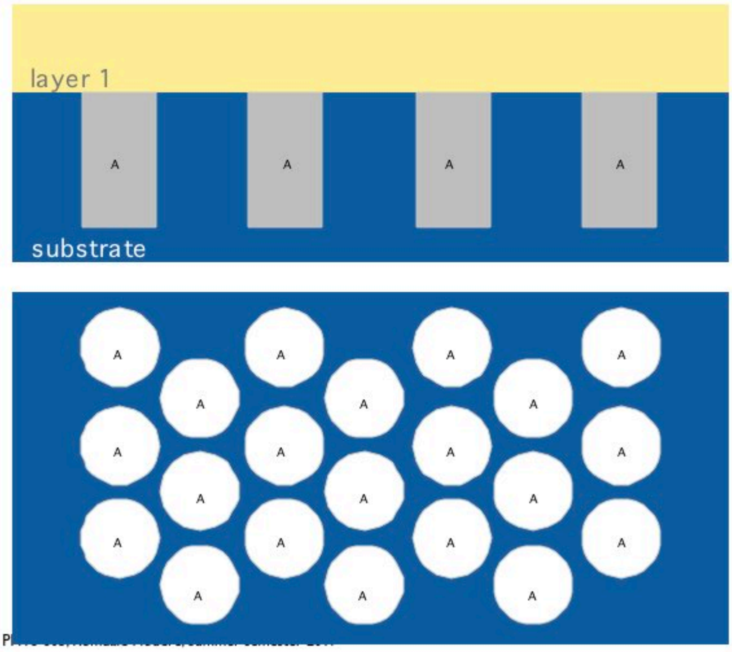
Making Rods & Holes Simultaneously

backfill with silica (SiO_2) & polish



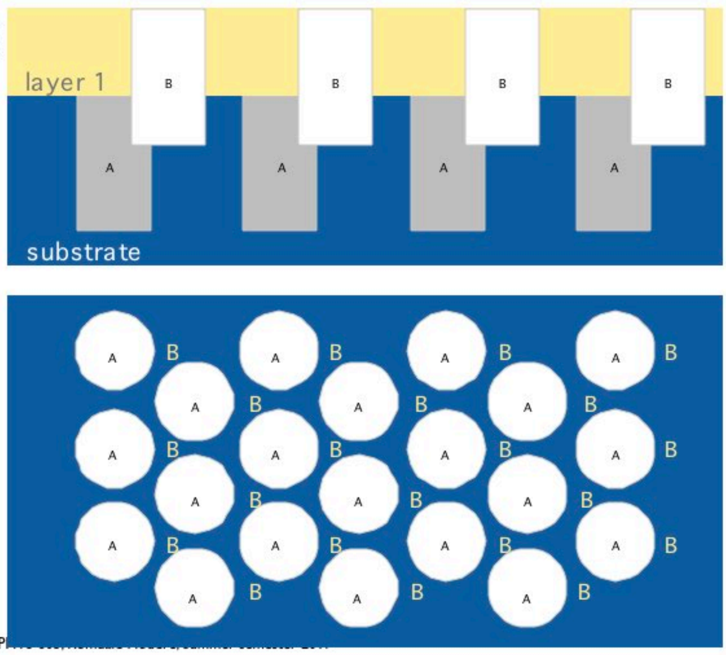
Making Rods & Holes Simultaneously

deposit another
Si layer

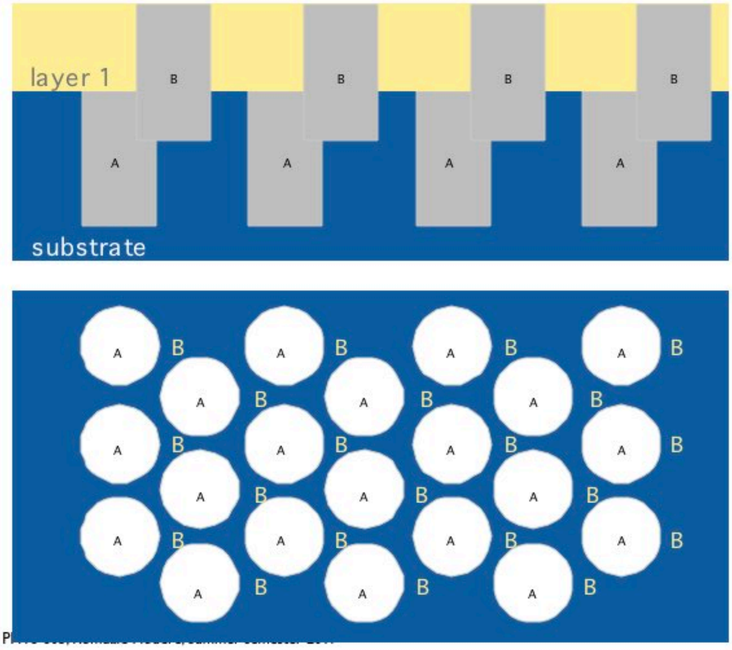


Making Rods & Holes Simultaneously

dig more holes
offset &
overlapping



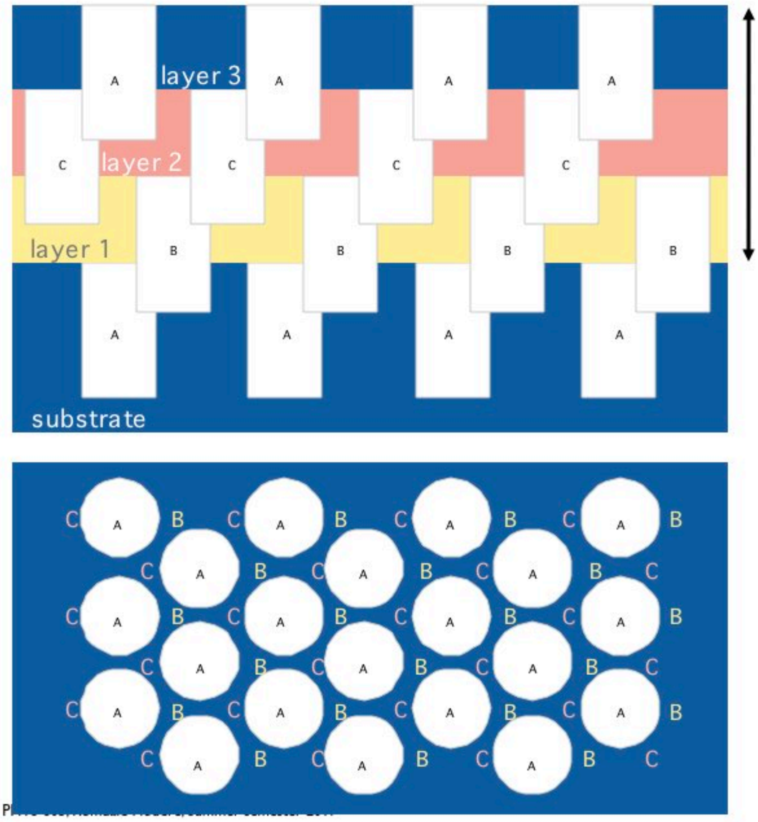
backfill



Making Rods & Holes Simultaneously

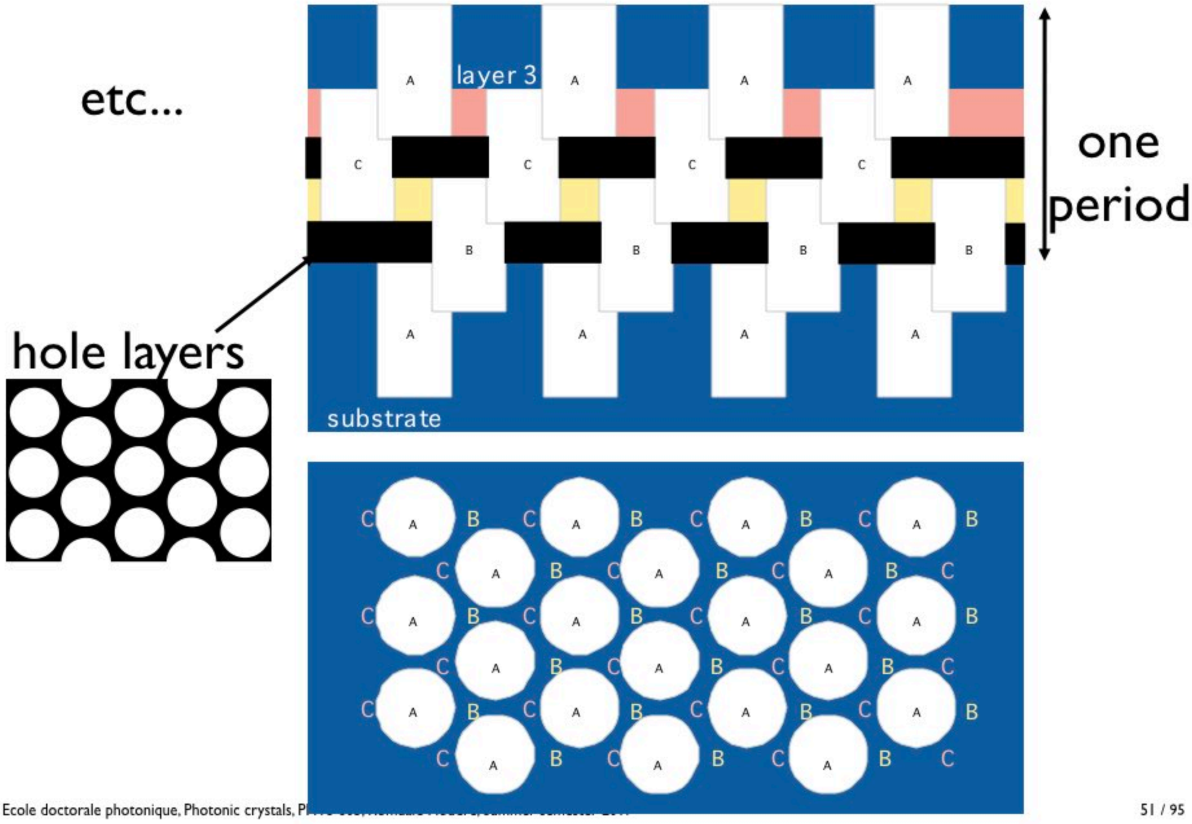
etc...

and dissolve silica when done

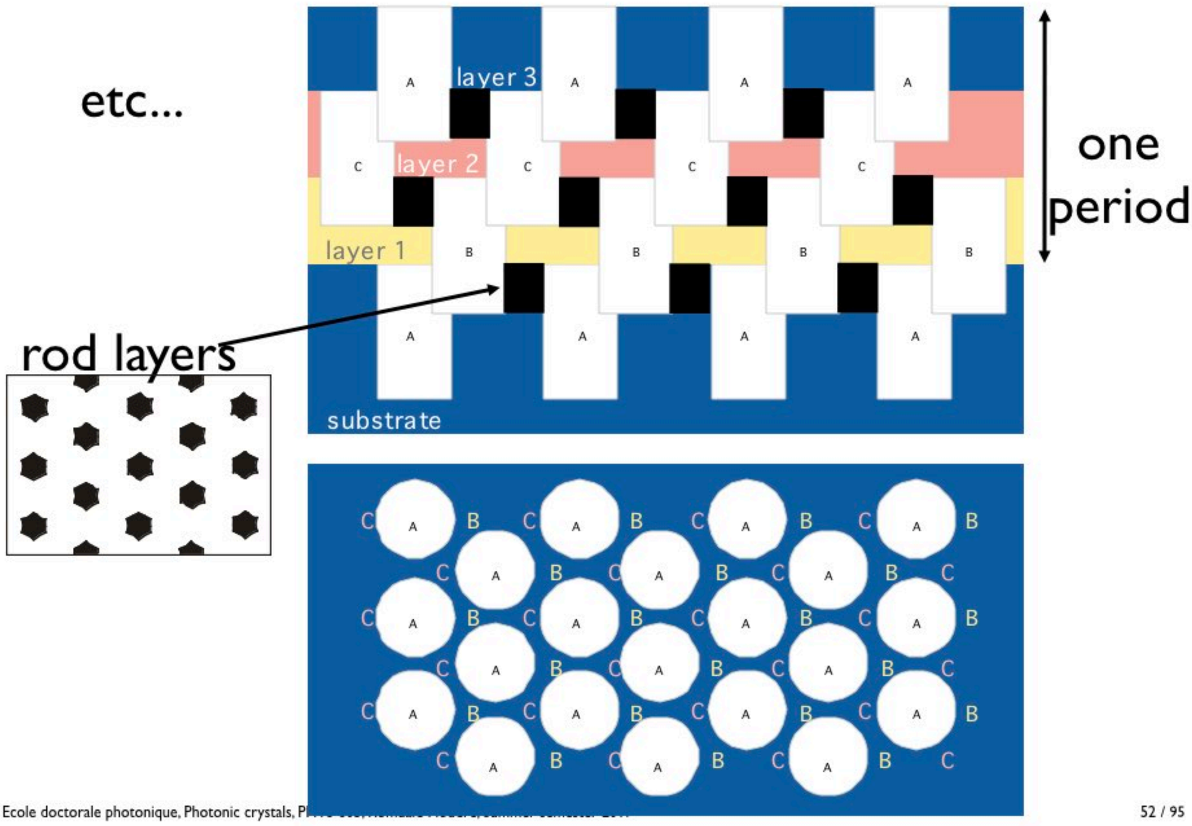


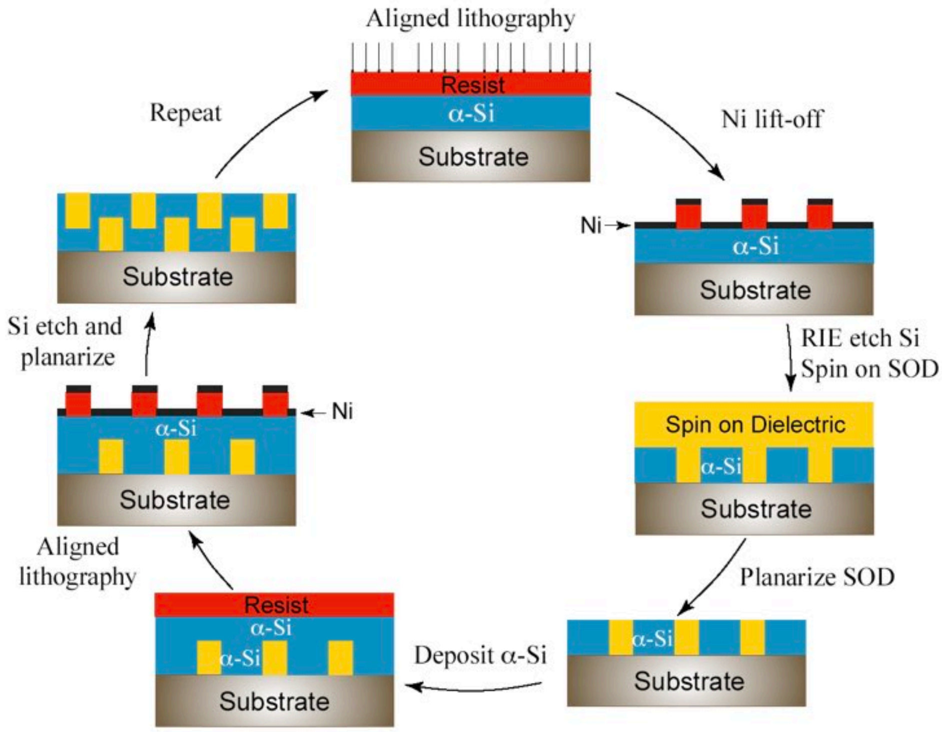
one period

Making Rods & Holes Simultaneously

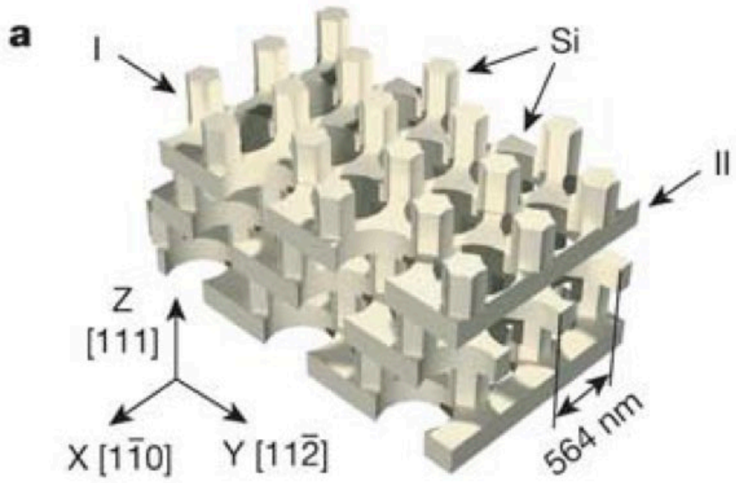


Making Rods & Holes Simultaneously

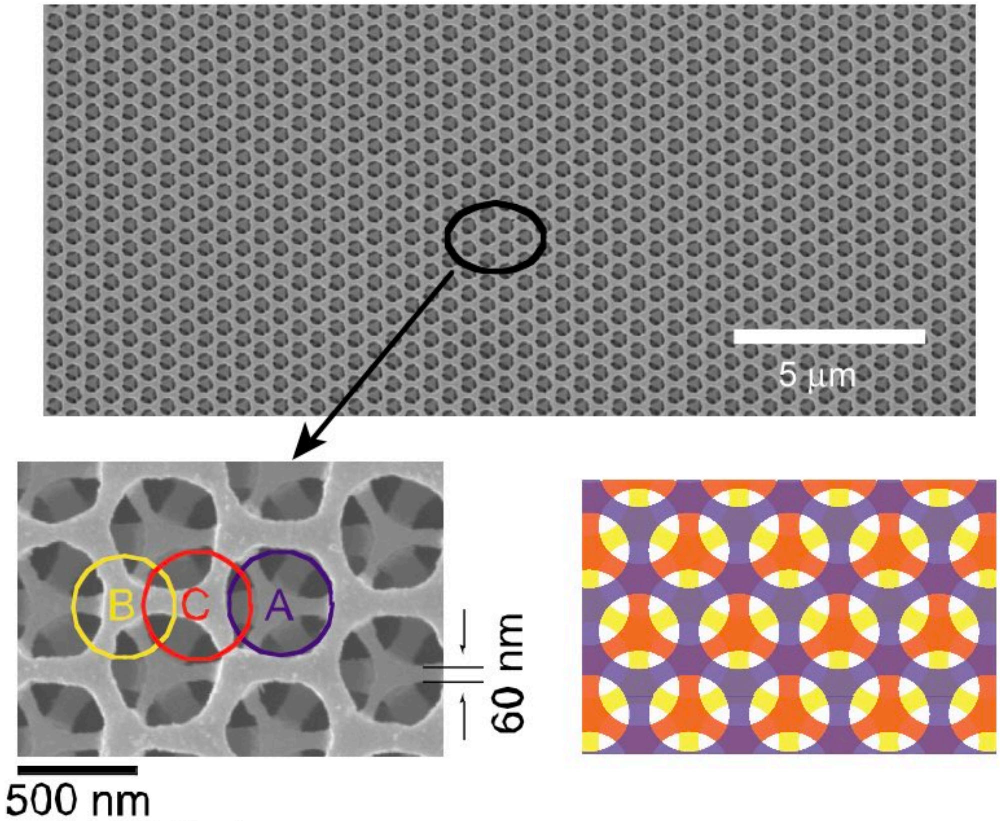




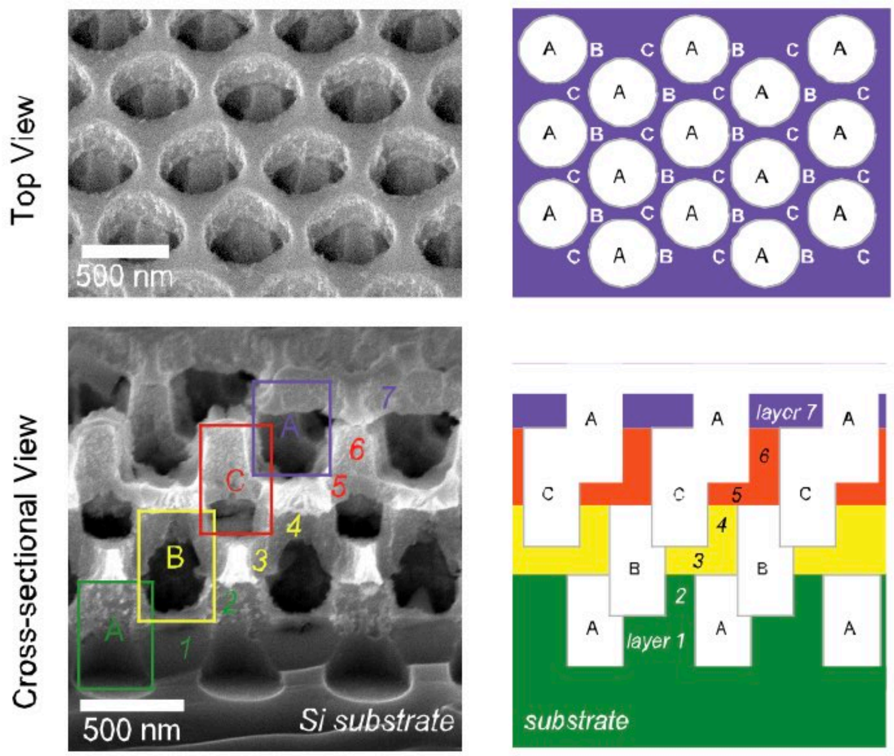
M. Qi, Nature, 429, 538 (2004)



M. Qi, Nature, 429, 538 (2004)

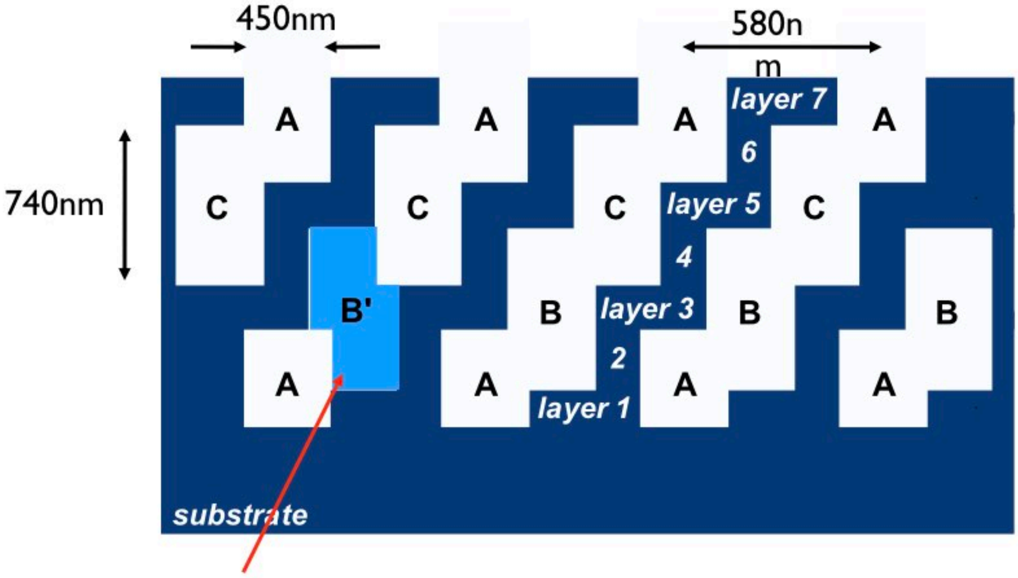


M. Qi, Nature, 429, 538 (2004)



(a) SEM micrograph (b) Schematic

M. Qi, Nature, 429, 538 (2004)



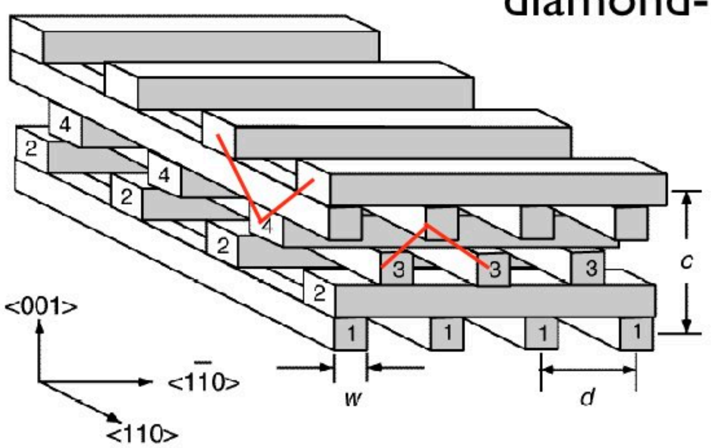
Easiest defect: don't etch some B holes
— non-periodically distributed: suppresses sub-band structure
— low Q = easier to detect from planewave

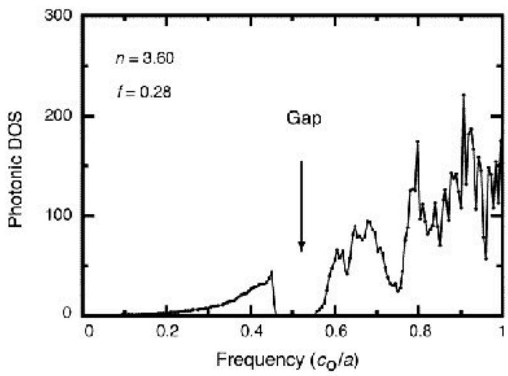
M. Qi, Nature, 429, 538 (2004)

Woodpile structure

Up to ~ 17% gap for Si/air

diamond-like bonds

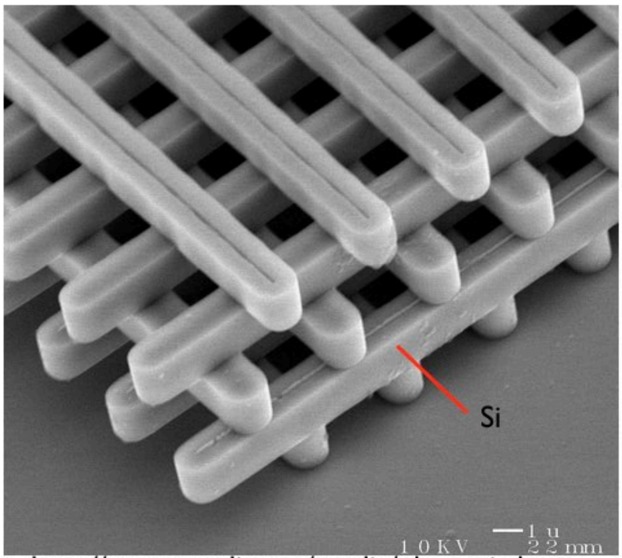




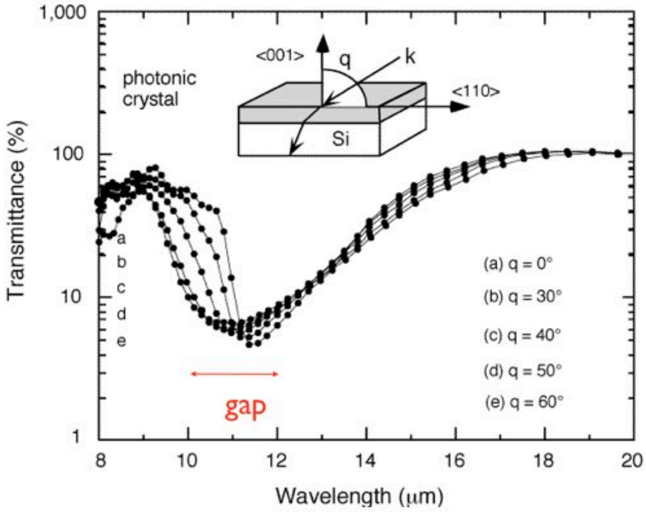
K. Ho et al., Solid State Comm. 89, 413 (1994) H. S. Sözüer et al., J. Mod. Opt. 41, 231 (1994)

Woodpile structure

(4 "log" layers = 1 period)



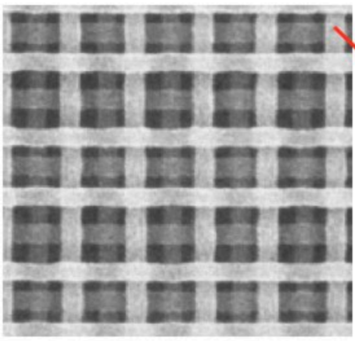
http://www.sandia.gov/media/photonic.htm

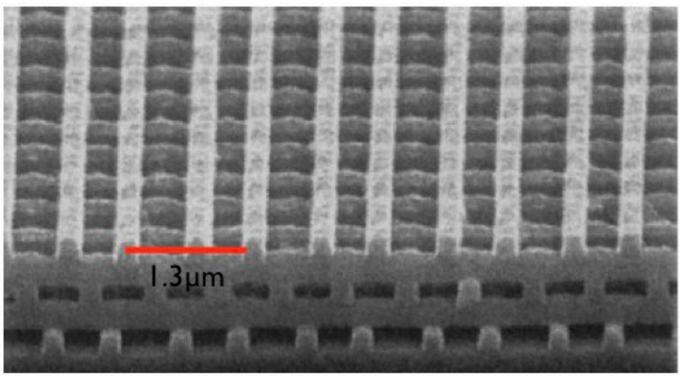


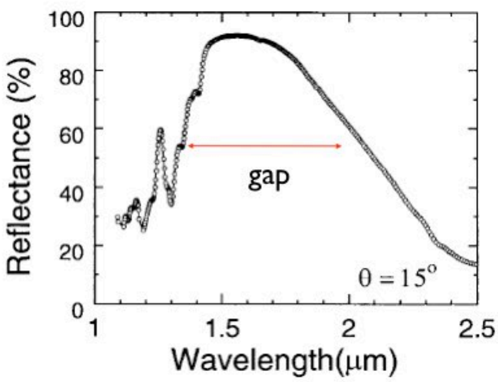
S.Y. Lin et al., Nature 394, 251 (1998)

Woodpile structure

(4 "log" layers = 1 period)





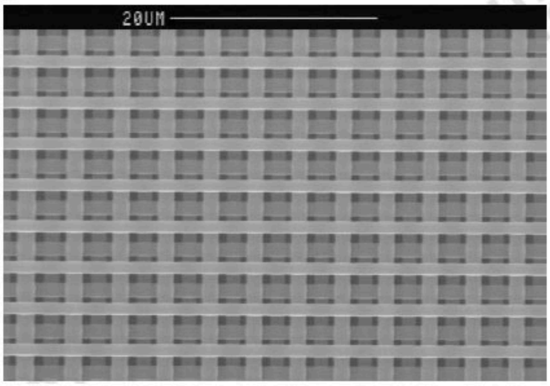


S.Y. Lin et al., Nature 394, 251 (1998)

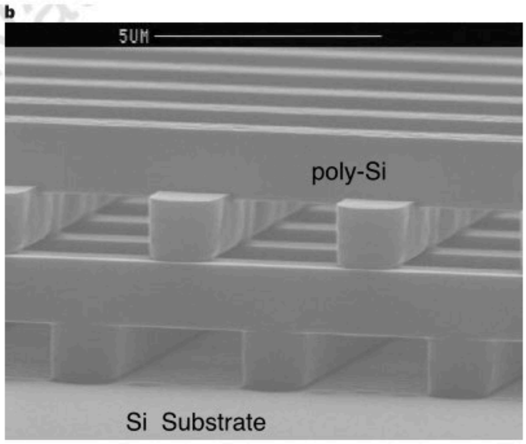
Woodpile structure

Fabricated by succession of etching and planarization

a

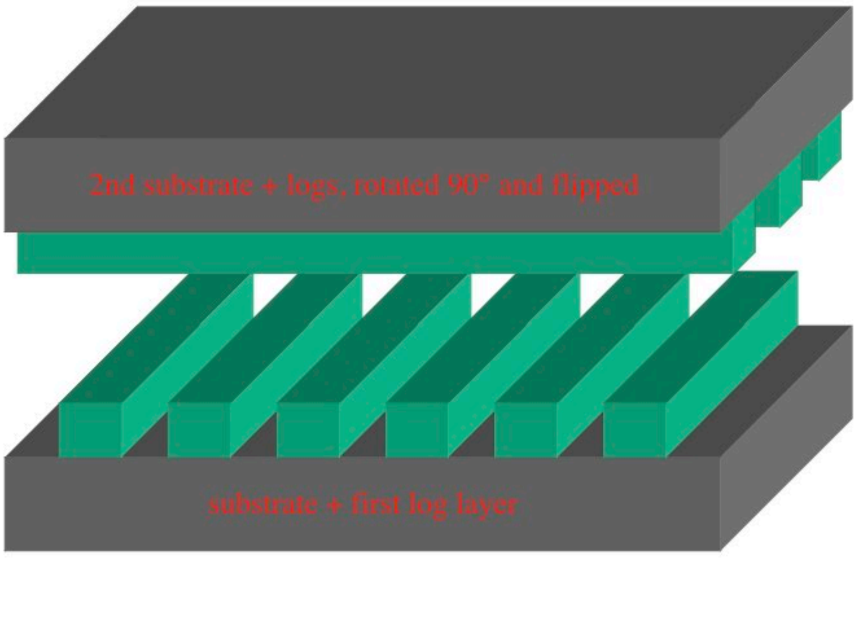


b

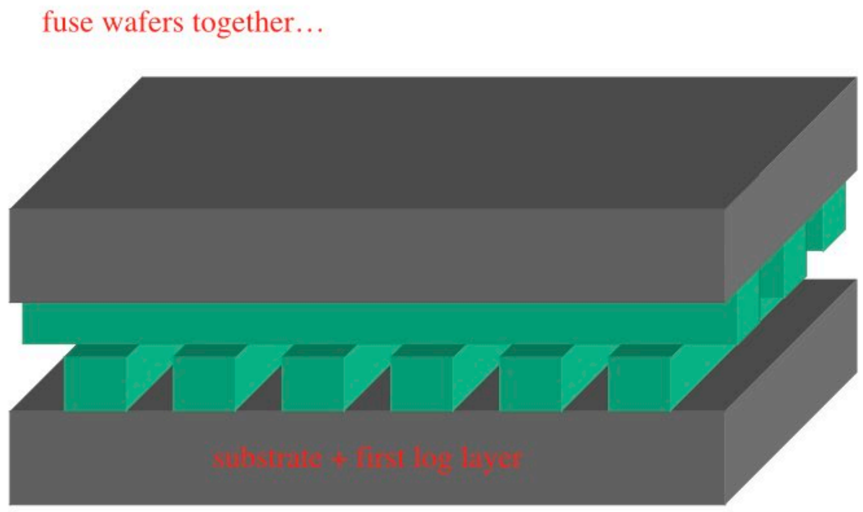


S.Y. Lin et al., Nature 394, 251 (1998)

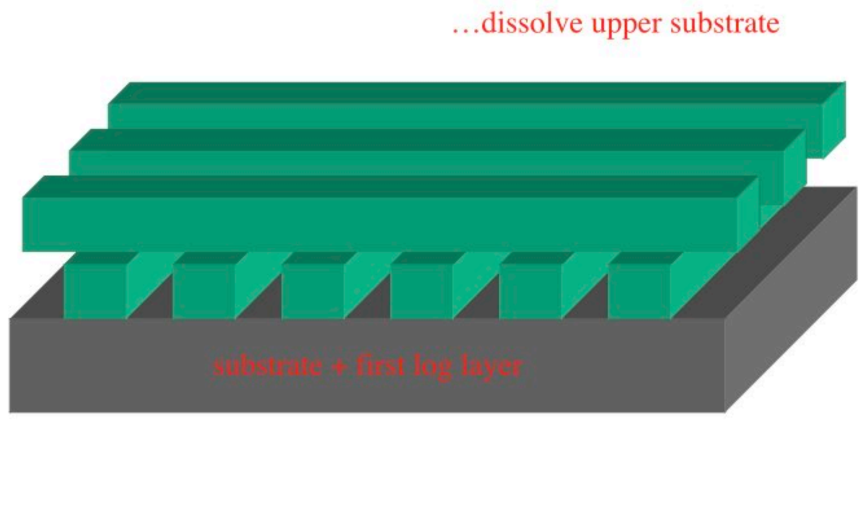
Woodpile structure



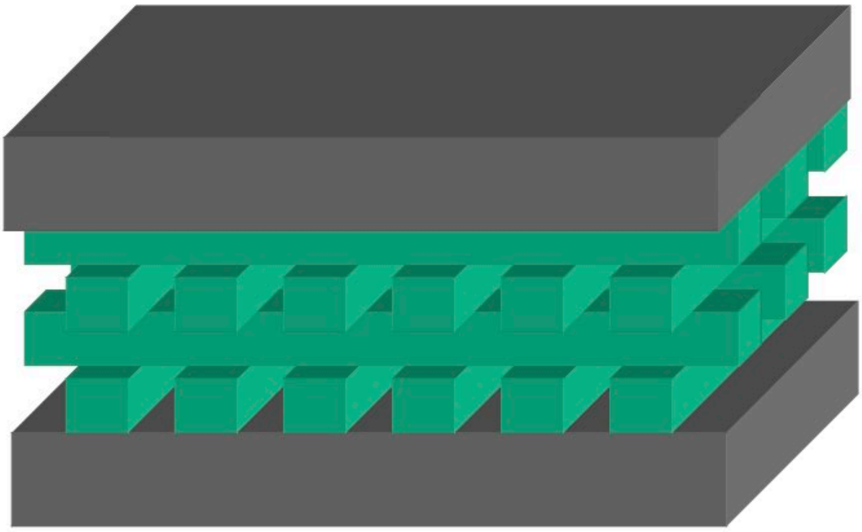
S. Noda et al., Science 289, 604 (2000)



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

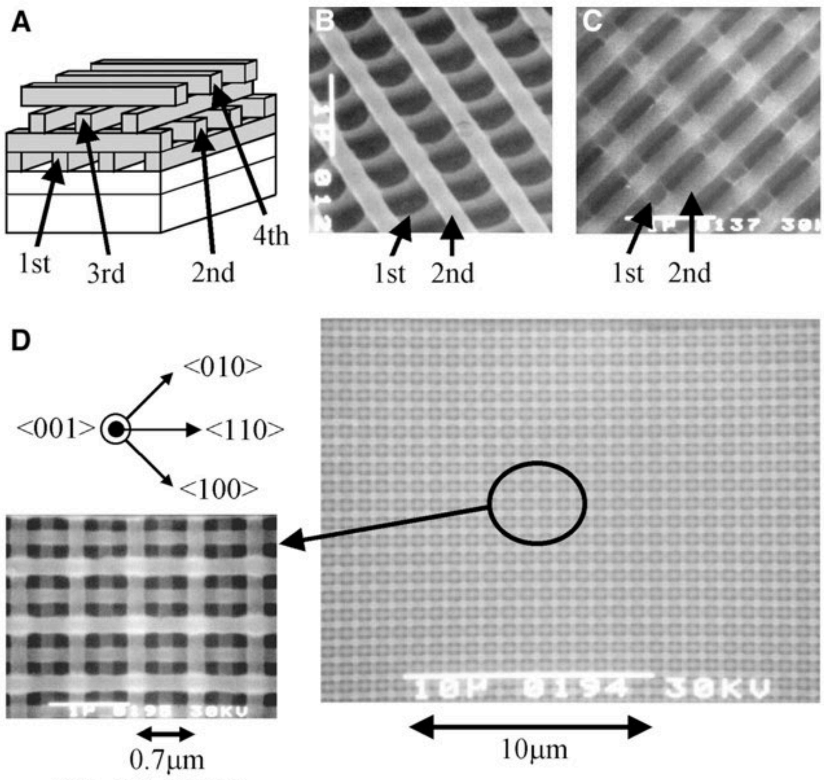


S. Noda et al., Science 289, 604 (2000)



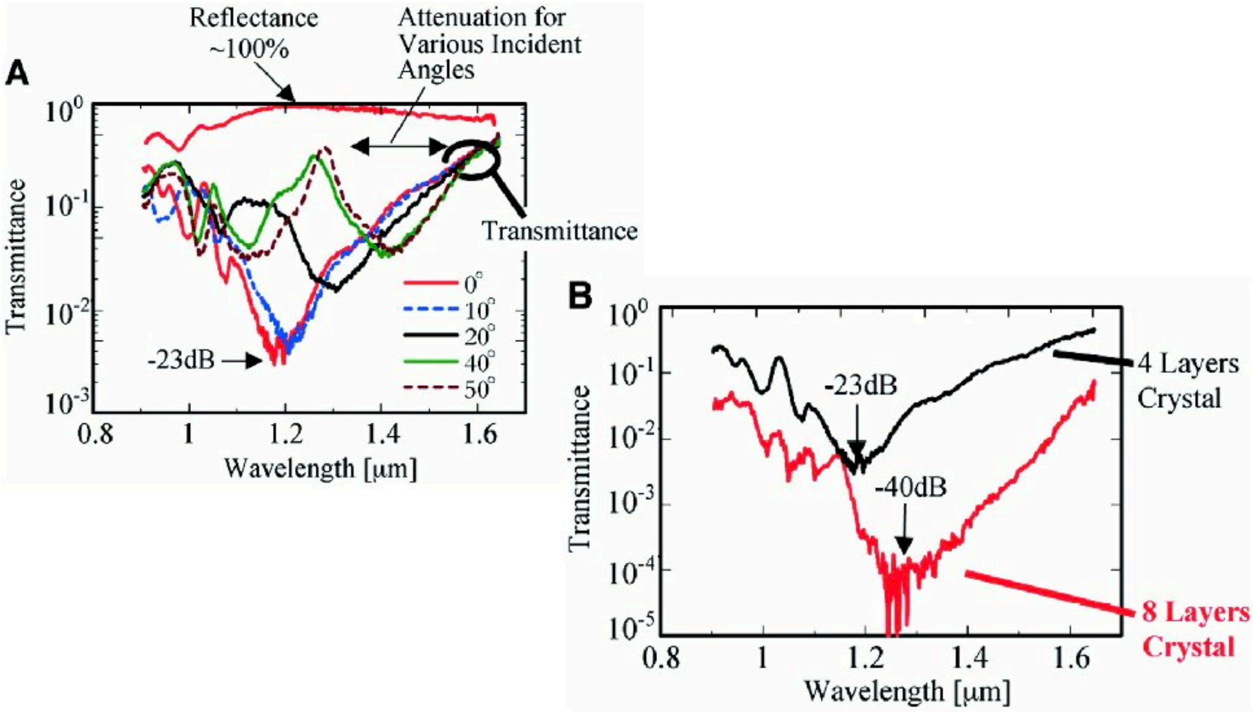
S. Noda et al., Science 289, 604 (2000)

Woodpile by Wafer Fusion



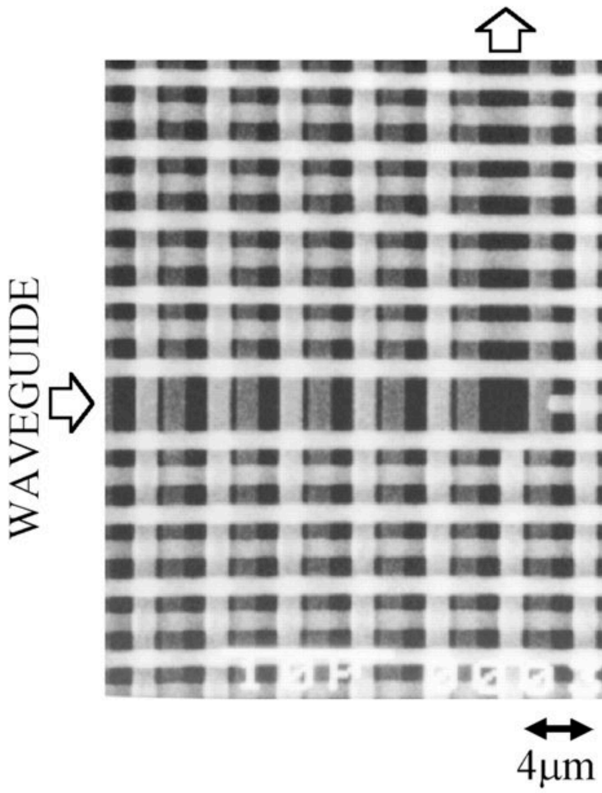
S. Noda et al., Science 289, 604 (2000)

Woodpile structure



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

Woodpile structure

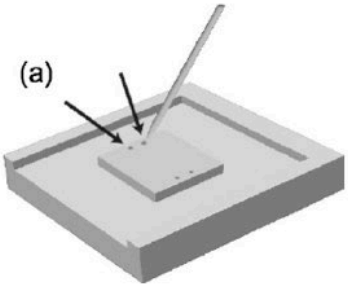


but no measurements on the bend

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

Stacking by Micromanipulation

microsphere into hole



break off suspended layer

lift up and move to substrate

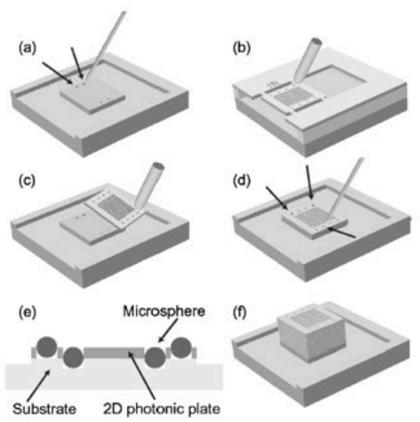
tap down holes onto spheres

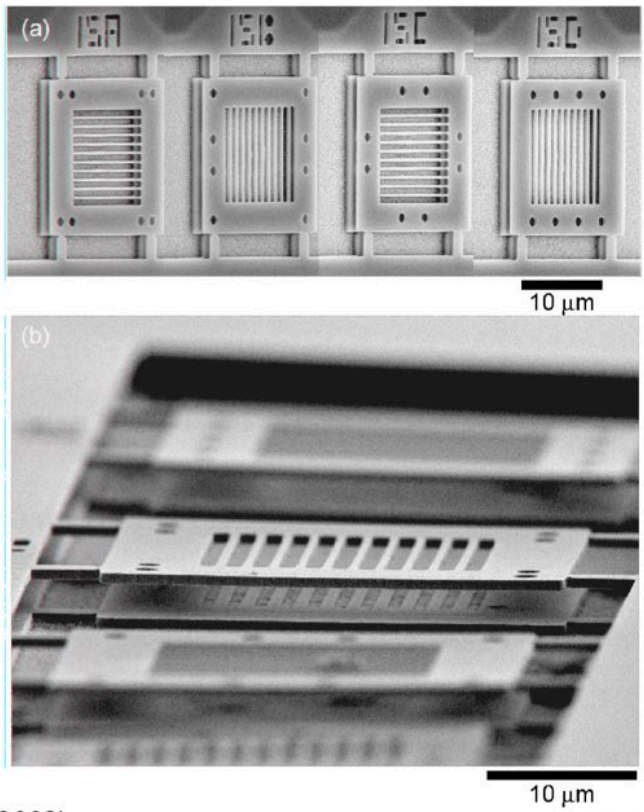
spheres enforce alignment

goto a;

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

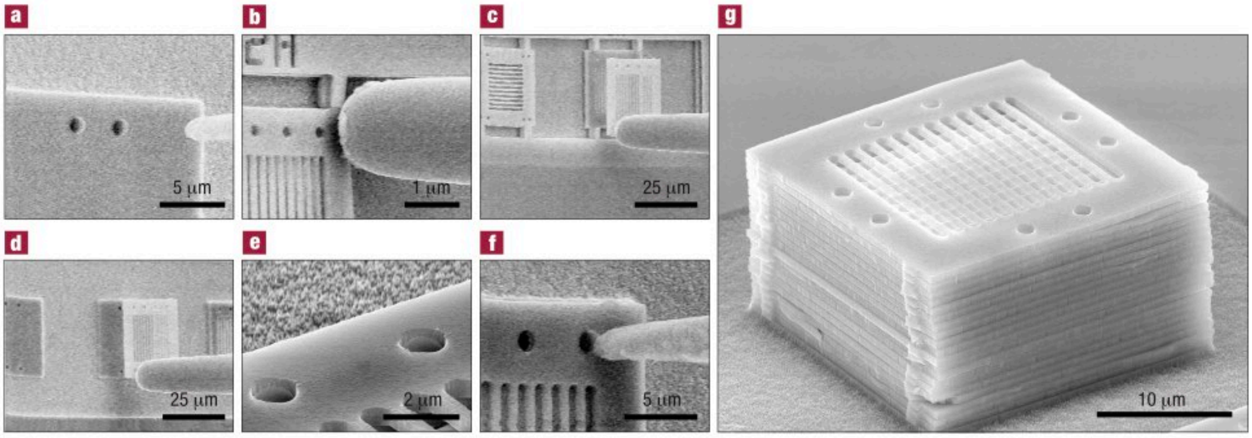
Stacking by Micromanipulation





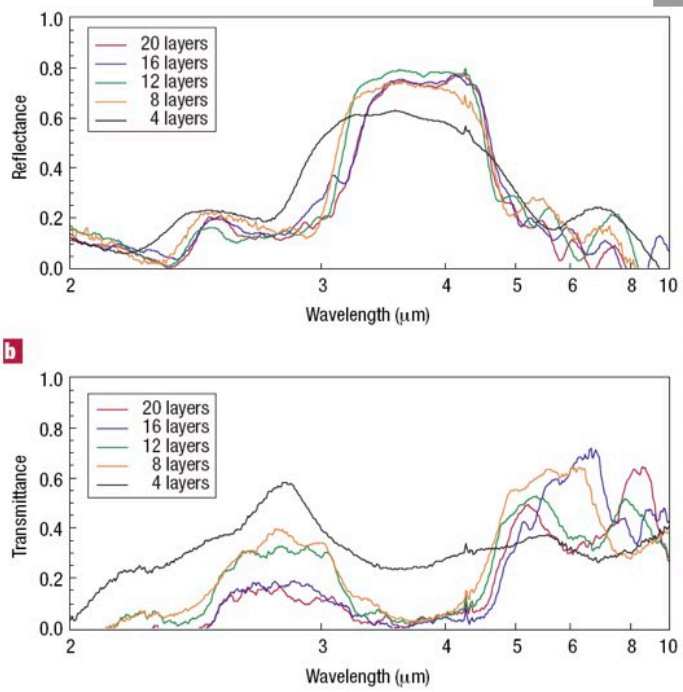
K. Aoki et al., Appl. Phys. Lett. 81 (17), 3122 (2002)

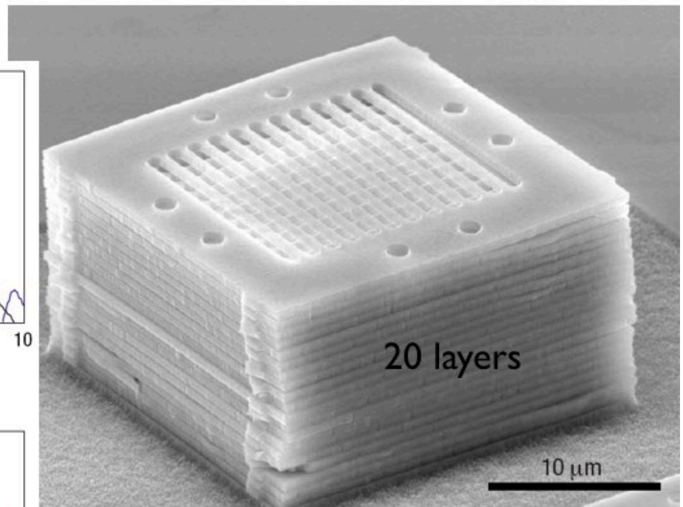
Stacking by Micromanipulation



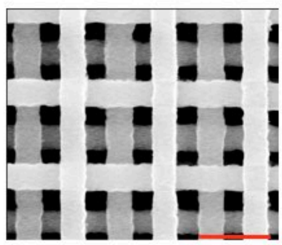
K. Aoki et al., Appl. Phys. Lett. 81 (17), 3122 (2002)

Stacking by Micromanipulation





50nm accuracy:

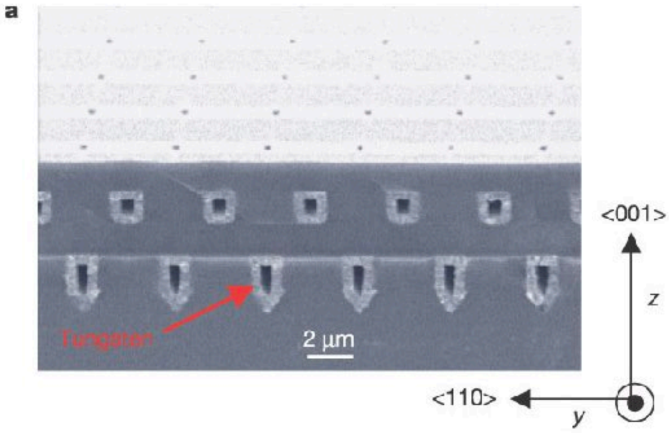


1 µm

(gap effects are limited by finite lateral size)

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

Metallic coating

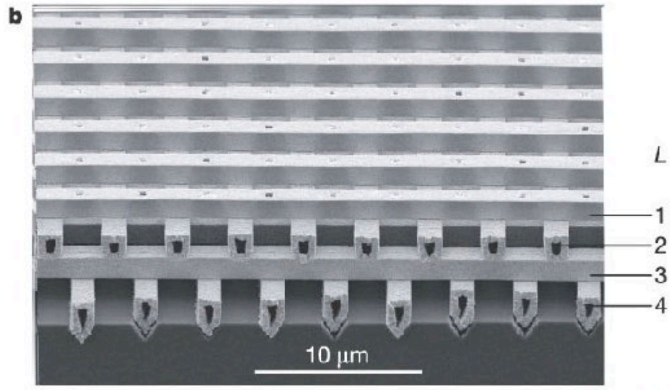


Start with Si woodpile in SiO_2…

dissolve Si with KOH…

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

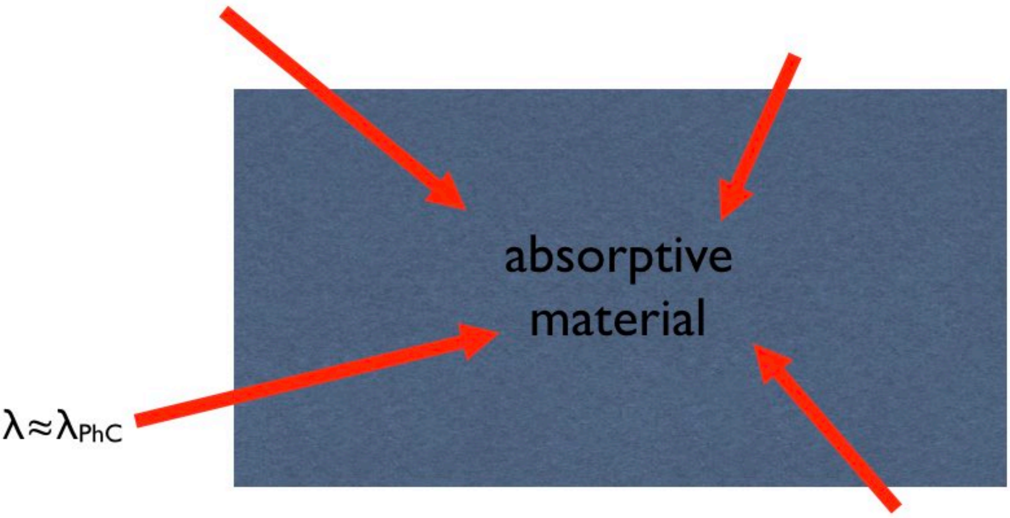
dissolve SiO_2 with HF…



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

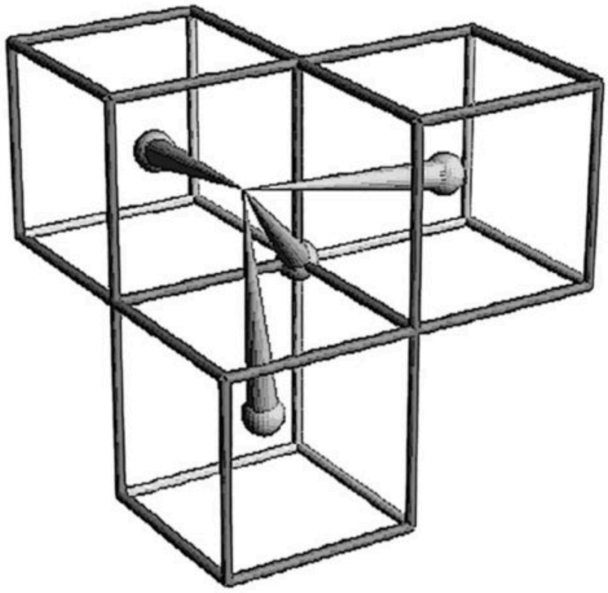
Holographic Lithography

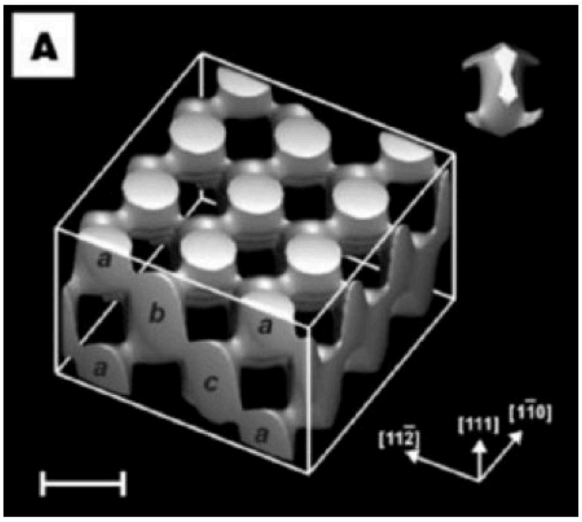
Four beams make 3d-periodic interference pattern



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

D. N. Sharp et al., Opt. Quant. Elec. 34, 3 (2002) & M. Campbell, Nature, 404, 53 (2000)

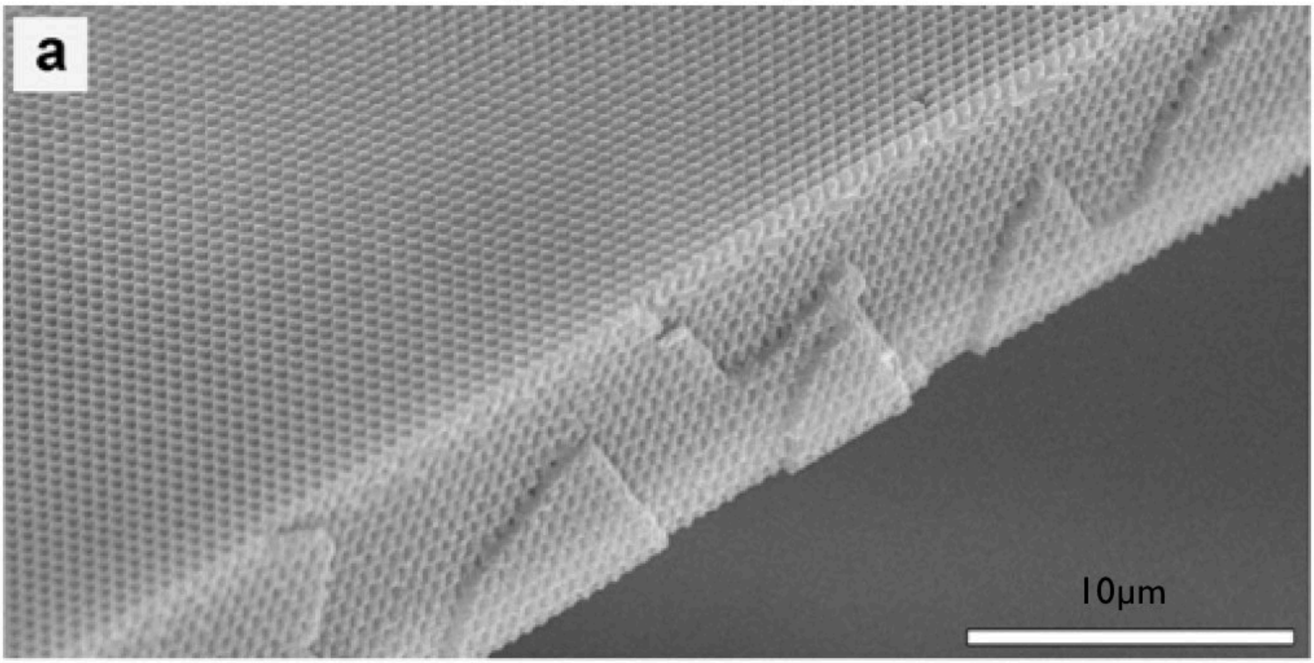




beam polarizations + amplitudes (8 parameters) give unit cell

D. N. Sharp et al., Opt. Quant. Elec. 34, 3 (2002) & M. Campbell, Nature, 404, 53 (2000)

Holographic Lithography

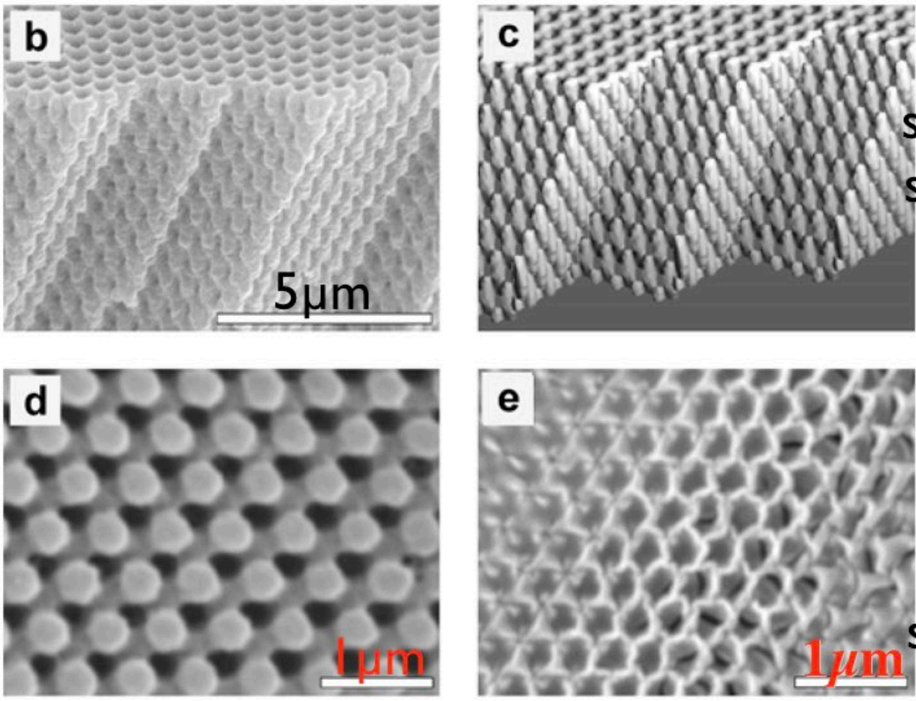


huge volumes, long-range periodic, fcc lattice…backfill for high contrast

D. N. Sharp et al., Opt. Quant. Elec. 34, 3 (2002) & M. Campbell, Nature, 404, 53 (2000)

Holographic Lithography

[111] cleavages



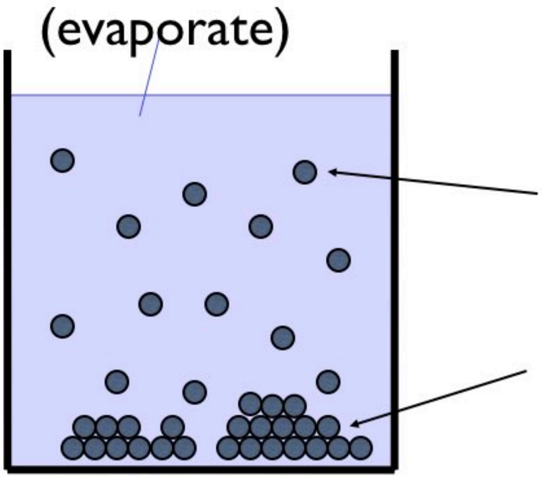
simulated structure

[111] closeup

titania inverse structure

D. N. Sharp et al., Opt. Quant. Elec. 34, 3 (2002) & M. Campbell, Nature, 404, 53 (2000)

Colloids (opals)

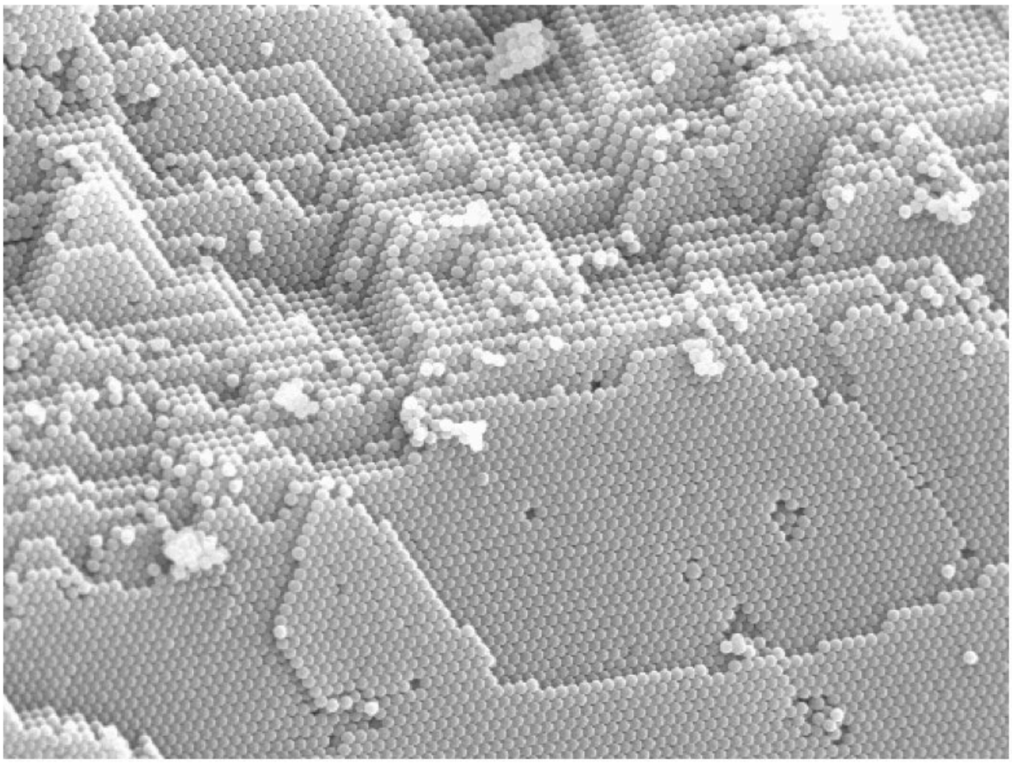


silica (SiO_2) microspheres (diameter < 1μm)

sediment by gravity into close-packed fcc lattice!

Recommended review paper on opals : J. F. Gallisteo-López et al., Ad. Mater. 23, 30 (2011)

Colloids (opals)

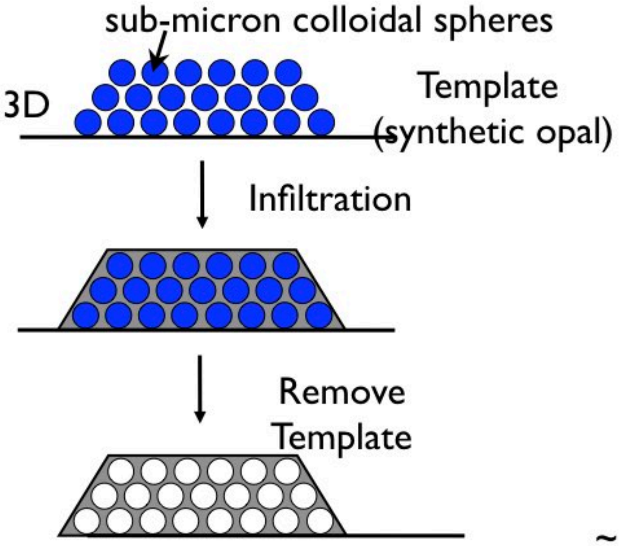


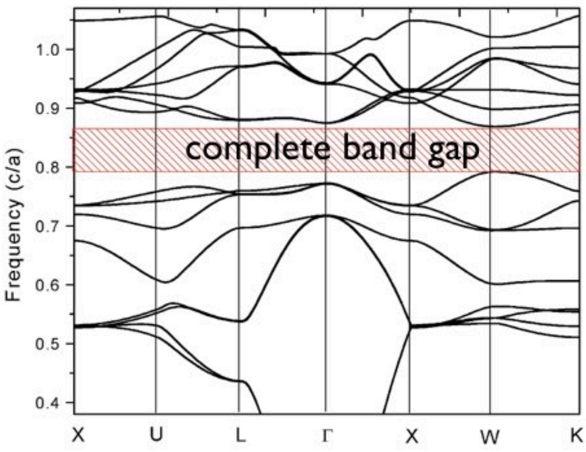
http://www.icmm.csic.es/cefe/

Inverted opals

fcc solid spheres do not have a gap…

…but fcc spherical holes in Si do have a gap

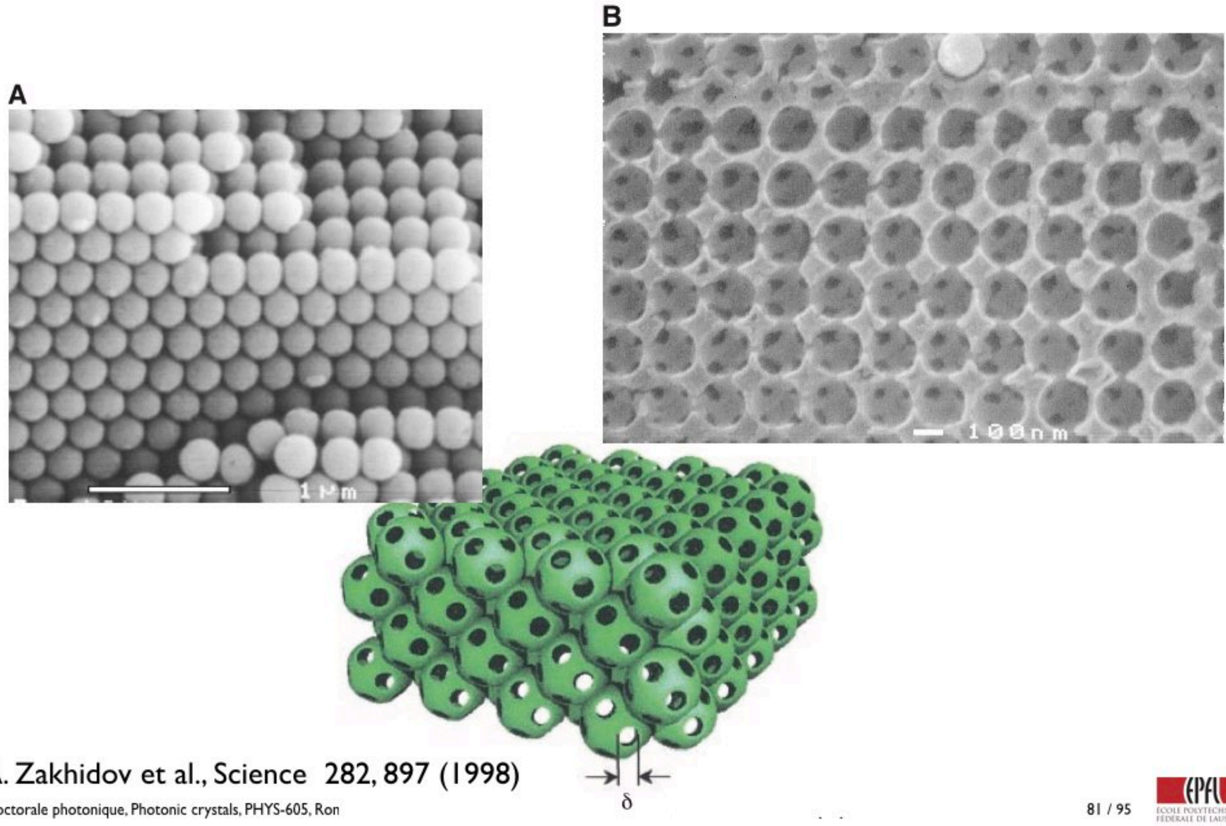




~ 10% gap between 8th & 9th bands

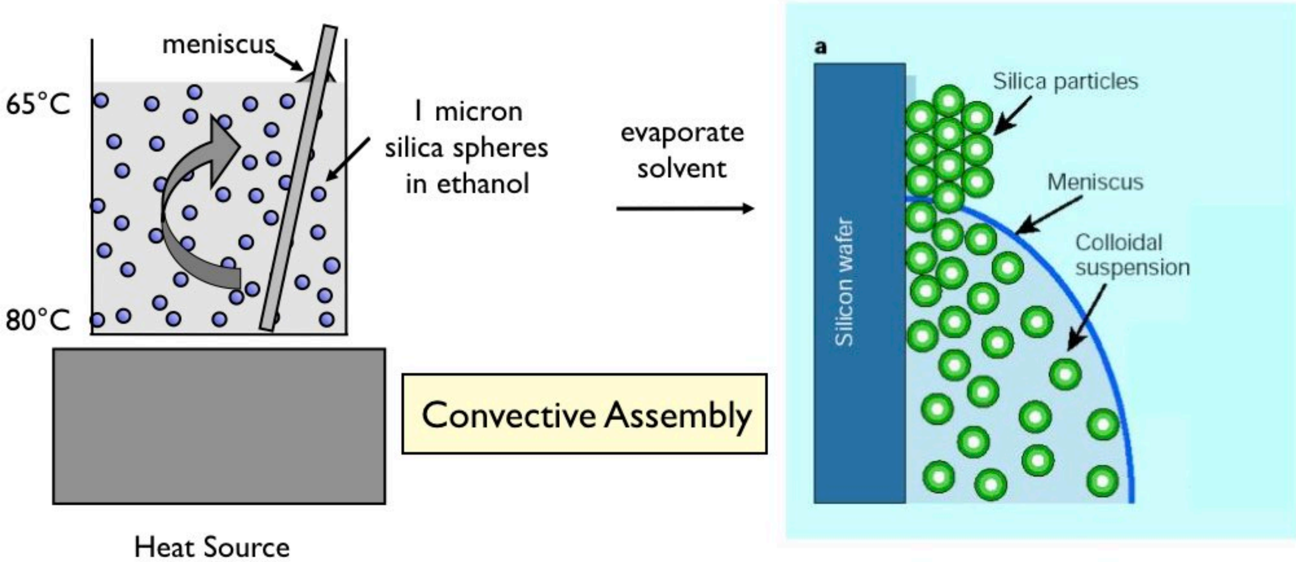
small gap, upper bands: sensitive to disorder

Inverted opals



A.A. Zakhidov et al., Science 282, 897 (1998)

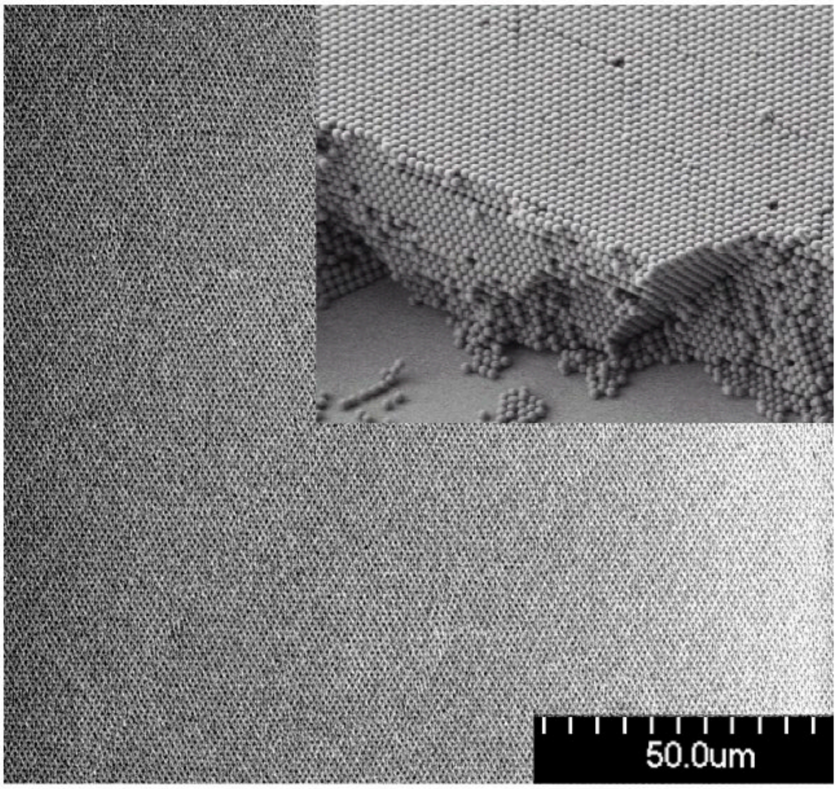
Colloids (opals)



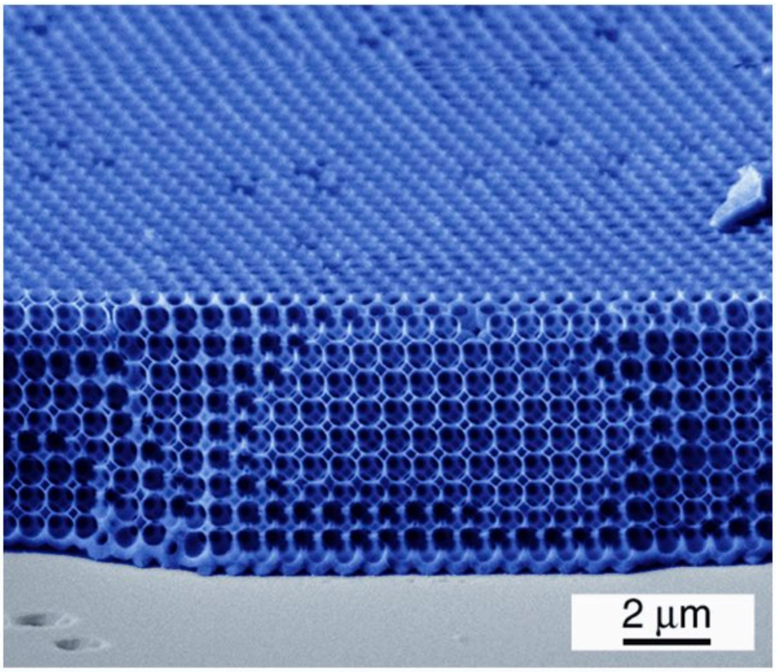
- Capillary forces during drying cause assembly in the meniscus
- Extremely flat, large-area opals of controllable thickness

Nagayama, Velev, et al., Nature (1993) & Colvin et al., Chem. Mater. (1999)

A More Perfect Crystal…

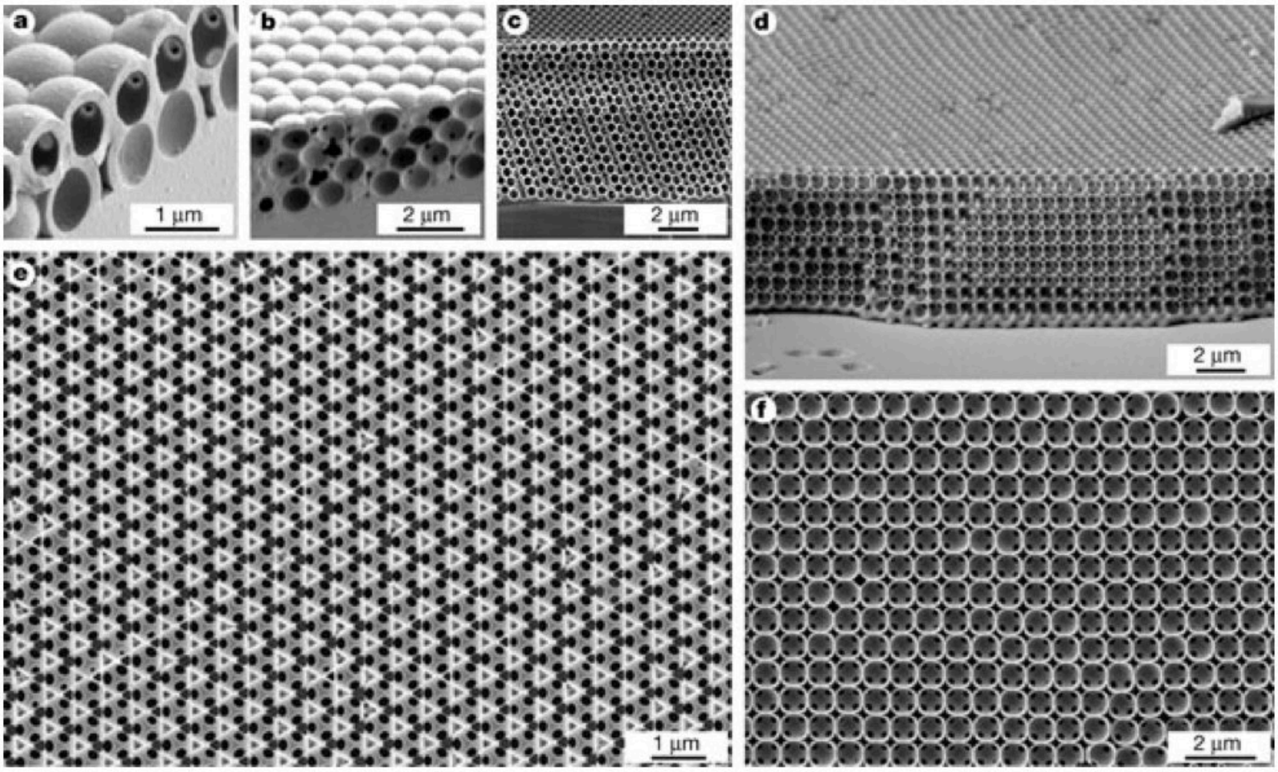


Inverted opals



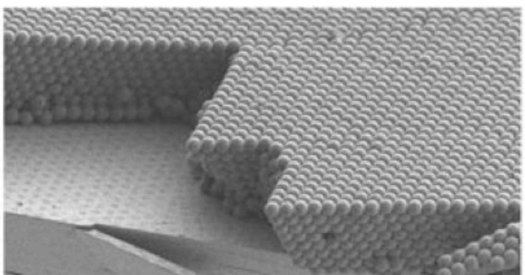
Y. A. Vlasov et al., Nature 414, 289 (2001)

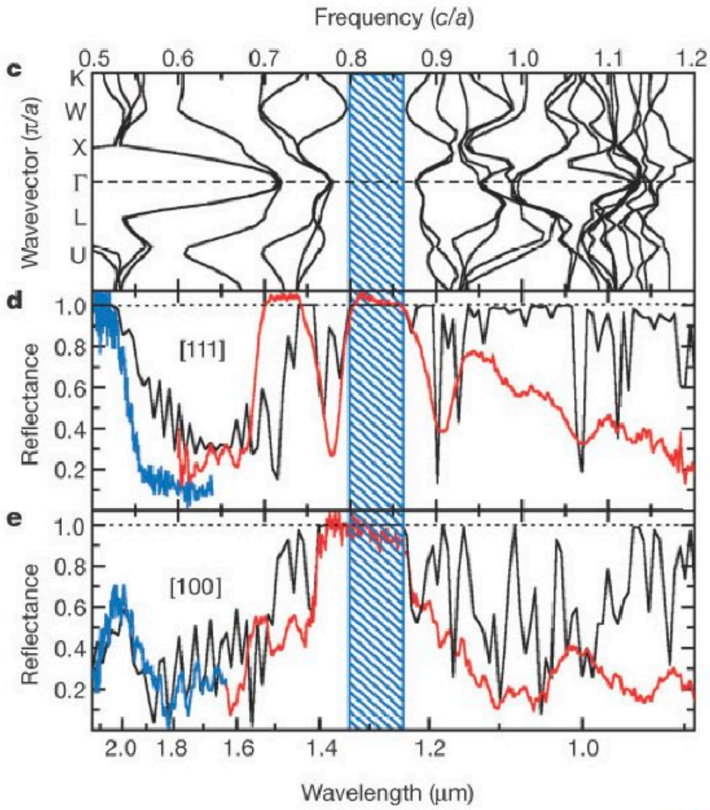
Inverted opals



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

Inverted opals

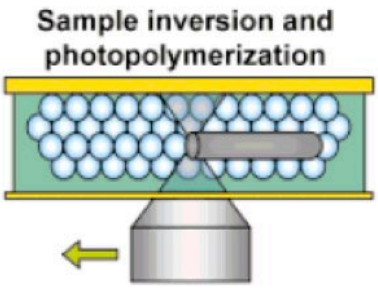




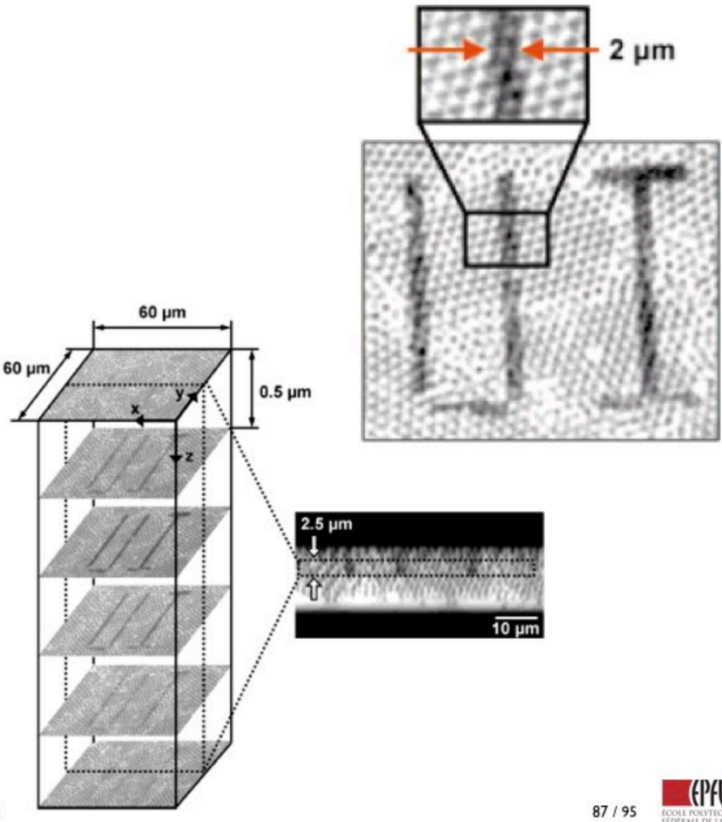
good agreement
between theory (black)
& experiment (red/blue)

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

Controlled defect in opals

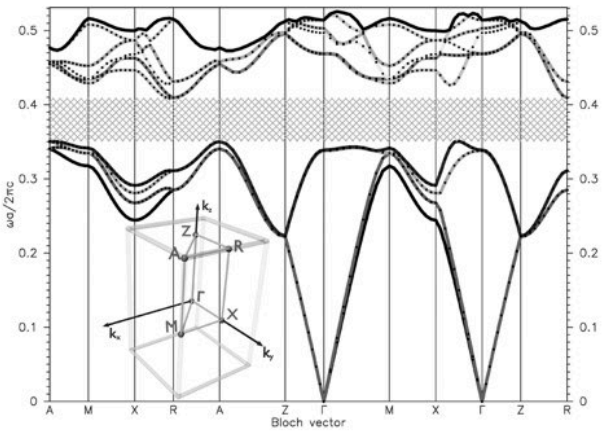


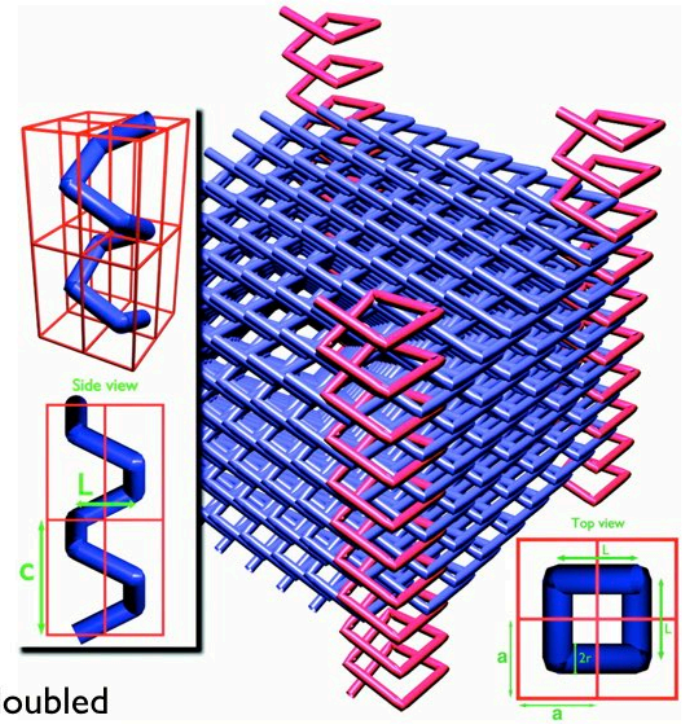
Three-photon lithography
with
laser scanning
confocal microscope
(LSCM)



Wonmok, Adv. Materials 14, 271 (2002)

"GLAD" = "GLancing Angle Deposition"



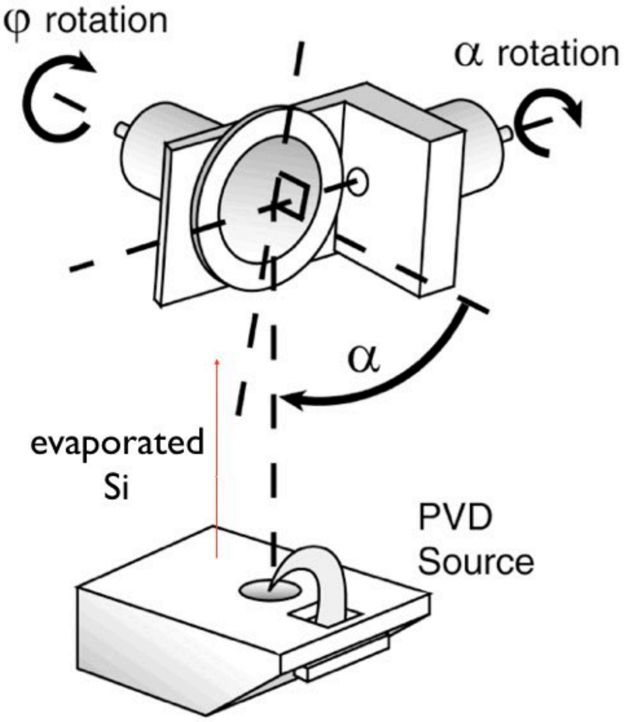


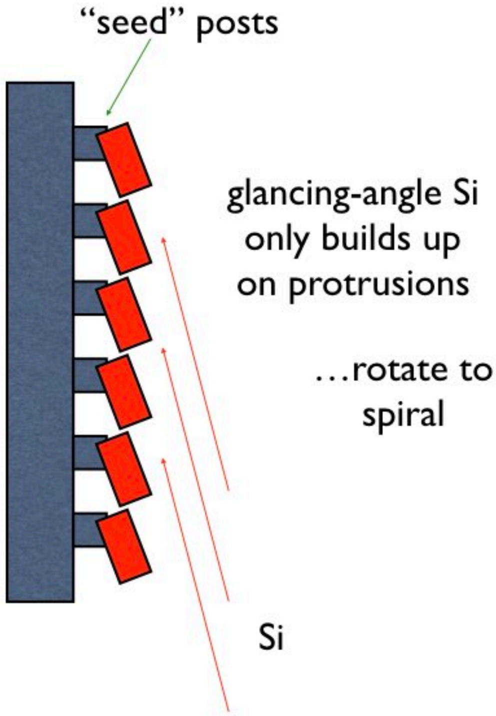
15% gap for Si/air

diamond-like with "broken bonds" doubled unit cell, so gap between 4th & 5th bands

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

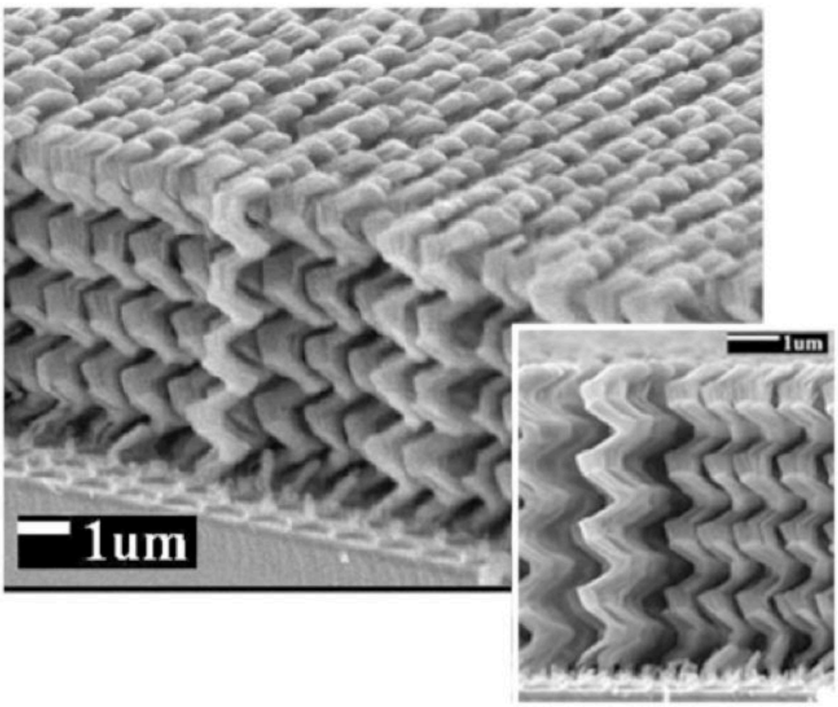
“GLAD” = “GLancing Angle Deposition”





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

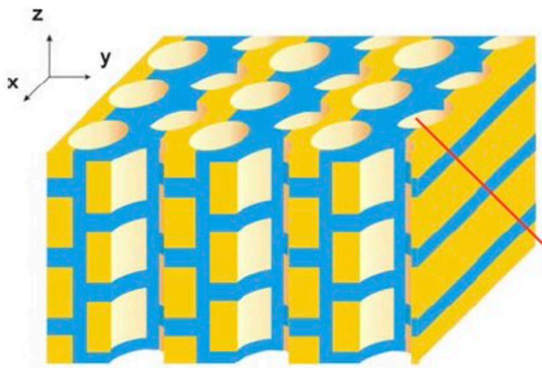
“GLAD” = “GLancing Angle Deposition”



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

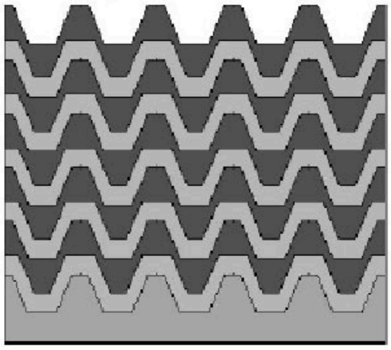
Auto-cloning

start with an old layer-by-layer



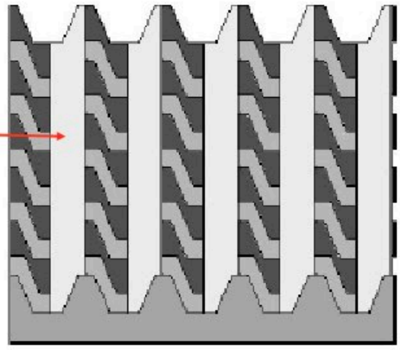
(14% gap for Si/SiO_2/air)

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



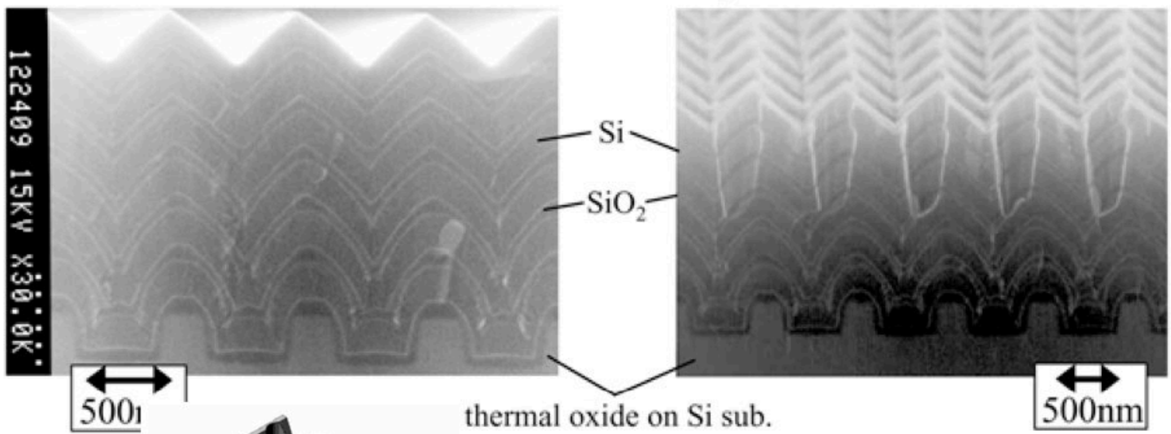
modify layering slightly…

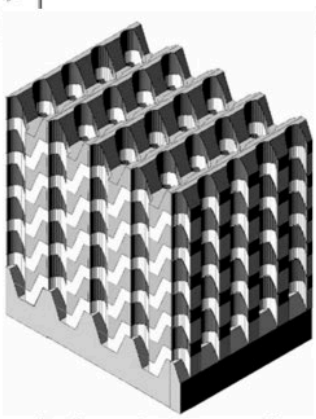
(don't forget the holes)

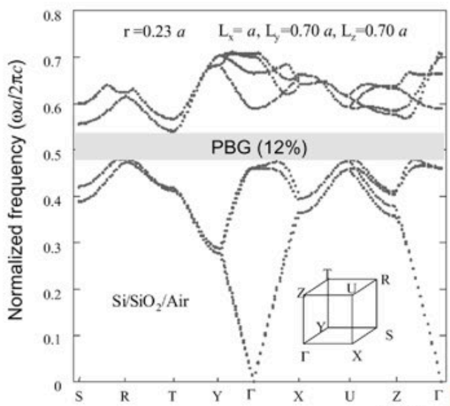


S. Kawakami et al., Appl. Phys. Lett. 74, 463 (1999)

Auto-cloning







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

Back to the first proposed structure

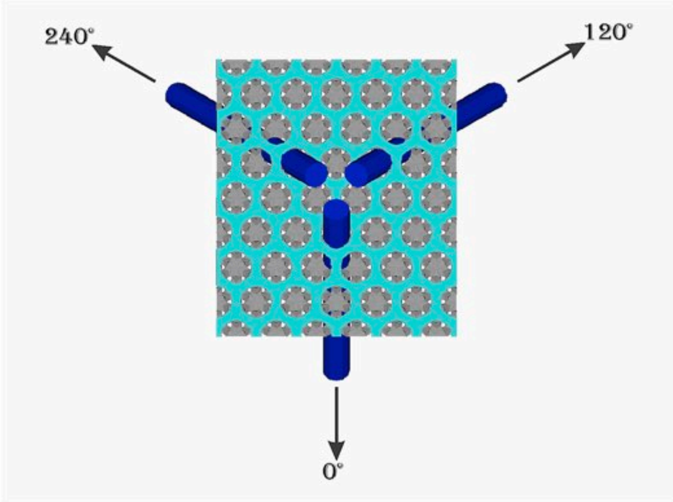
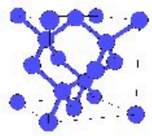


image: http://www.ee.ucla.edu/labs/photon/

diamond-like fcc crystal

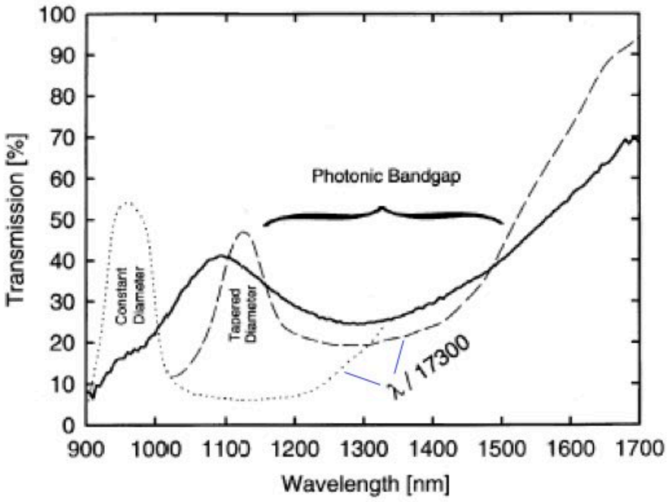
earliest "fabrication-amenable" alternative to diamond spheres

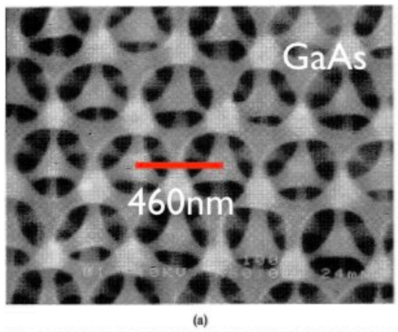


(Topology is very similar to 2000 layer-by-layer crystal)

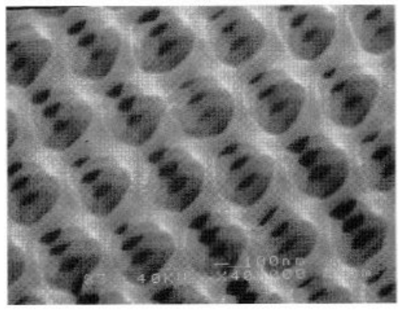
E. Yablonovitch, T. M. Gmitter, and K. M. Leung, Phys. Rev. Lett. 67, 2295 (1991)

Back to the first proposed structure



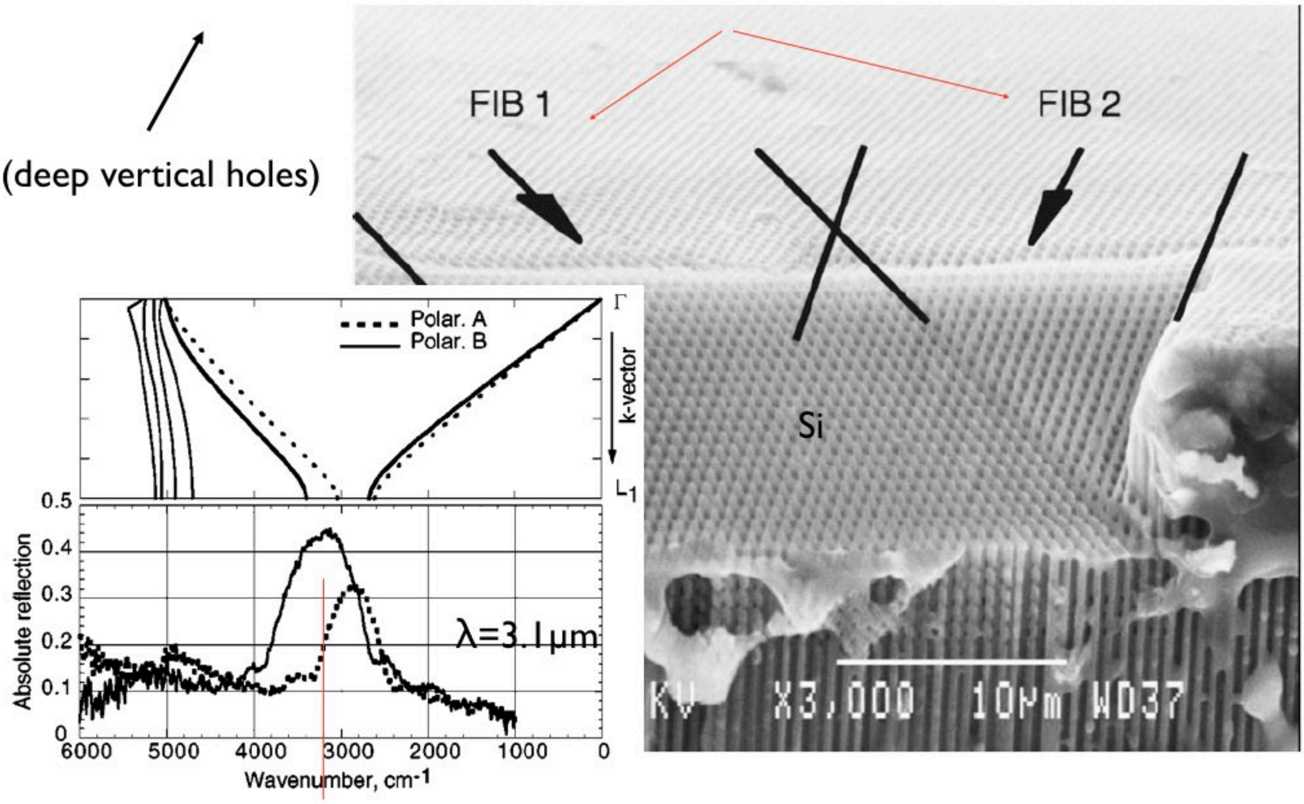


(a)



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

(deep vertical holes)



A. Chelnokov et al., Appl. Phys. Lett. 77, 2943 (2000)