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
The First 3d Bandgap Structure


for gap at $\square = 1.55\,\mu m$, sphere diameter $\sim 330nm$

MPB tutorial, http://ab-initio.mit.edu/mpb
Make *that*? Are you crazy? ...maybe!

carefully stack bcc silica & latex spheres via micromanipulation

fabrication schematic

...dissolve latex & sinter (heat and fuse) silica

make Si inverse (12% gap)


http://www.icmm.csic.es/cefe/Fab/Robot/robot_strategy.htm
Make *that*? Are you crazy? ...maybe!

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”)


Up to ~ 27% gap for Si/air
Making Rods & Holes Simultaneously

side view

*substrate*

Si

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)

one period
Making Rods & Holes Simultaneously

etcetera

hole layers

one period
Making Rods & Holes Simultaneously

etcetera

rod layers

one period

substrate
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)
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

Simulation (with defects)
Simulation (without defect)
Measurement

[ M. Qi, H. Smith, MIT ]
Supercontinuum vs. Theory: Reflection

Localization mode at 1.3µm peak

3 dips predicted by cavity-mode calculation

[ 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…

\[
\Lambda = \frac{\lambda}{2 \sin(\theta)}
\]
From Rectangular to Hexagonal

[ M. Qi, H. Smith, MIT ]

X-ray source

X rays (\( \lambda \sim 1 \text{ nm} \))

X-ray mask #1

Studs

X-ray mask #2

\( \alpha \)

\( \beta \)

570 nm
an earlier design: **The Woodpile Crystal**

(\& currently more popular)


(diamond-like, “bonds”)

Up to ~ 17% gap for Si/air

1.25 Periods of Woodpile

(4 “log” layers = 1 period)


“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)


![Diagram of Woodpile structure with images and graph showing reflectance over wavelength.](image-url)
Woodpile by Wafer Fusion

Woodpile by Wafer Fusion

fuse wafers together…

Woodpile by Wafer Fusion

...dissolve upper substrate

Woodpile by Wafer Fusion

double, double, toil and trouble…

“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!

Stacking by Micromanipulation


- 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

Yes, it works: Gap at \( \sim 4\mu m \)


(gap effects are limited by finite lateral size)
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

$\alpha = 3.2 \mu m$
A *Metal* Photonic Crystal


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


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

\[ 2 \hbar = \Delta E \]

2-photon probability \( \sim (\text{light intensity})^2 \)

\[ N \text{-photon probability} \sim (\text{light intensity})^N \]

Atom

3d Lithography

\[ \text{some chemistry (polymerization)} \]

\[ \text{...dissolve unchanged stuff (or vice versa)} \]
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


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

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

Difficult topologies

[ img. courtesy J. W. Perry, U. Arizona ]
Mass-production, pretty please?
One-Photon Holographic Lithography


Four beams make 3d-periodic interference pattern

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

absorptive material

(1.4µm)

beam polarizations + amplitudes (8 parameters) give unit cell
One-Photon Holographic Lithography


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
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

fcc solid spheres do not have a gap…

…but fcc spherical holes in Si do have a gap

Infiltration sub-micron colloidal spheres

3D Template (synthetic opal)

Infiltration

Remove Template

“Inverted Opal”

~ 10% gap between 8th & 9th bands

small gap, upper bands: sensitive to disorder

[ figs courtesy D. Norris, UMN ]
In Order To Form a More Perfect Crystal...

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

[ figs courtesy D. Norris, UMN ]

Convective Assembly

A Better Opal

[ fig courtesy D. Norris, UMN ]
Inverse-Opal Photonic Crystal

Inverse-Opal Band Gap

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

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

\textit{e.g., Waveguides}

\textit{Three}-photon lithography with laser scanning confocal microscope (LSCM)

Mass-Production III: **Block** (not Bloch) **Copolymers**

two polymers can segregate, ordering into periodic arrays

periodicity $\sim$ polymer block size $\sim$ 50nm (possibly bigger)

Block-Copolymer 1d Crystal

CdSe nanocrystals for higher index
(with surfactant to attract particles to one phase)

(UV bandgap)

Block-Copolymer 1d **Visible Bandgap** / homopolymer

**Flexible material:** bandgap can be shifted by stretching it!

dark/light: polystyrene/polyisoprene

n = 1.59/1.51

Block-Copolymer 2d Crystal

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

GLAD it works?

GLAD it works!

A new twist on layer-by-layer...

start with an old layer-by-layer

modify layering slightly...

(14% gap for Si/SiO$_2$/air)

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

Auto-cloning

Competition between 3 processes “clones” shape of substrate

(a) Grid patterning

(b) Auto-cloning

(c) Drilling (Etching)

diffuse deposition leaves trenches (shadows)

bias sputtering cuts corners (prefers 60°)

re-deposition fills trenches

neutral atoms

ions

... so, only planar patterning is in substrate

... only drilling needs alignment

... minimize etch roughness

Auto-cloned Photonic Crystal

“Yablonovite”


diamond-like fcc crystal

earliest “fabrication-amenable” alternative to diamond spheres

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

[ image: http://www.ee.ucla.edu/labs/photon/ ]
Making Yablonovite
e-beam mask + chemically-assisted ion-beam etching

Making ~Yablonovite (II)
electrochemical + focused-ion-beam (FIB) etching

(deep vertical holes)

in short:

Those experimentalists are damned clever*

* either that, or they are out of their minds