Photonic crystals, PHYS-605

Ecole doctorale photonique

Romuald Houdré

Summer semester 2017

IV Fabrication

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  Introduction
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Fabrication 2D structures

1. GaAs ou InP
   croissance de l'hétérostucture

2. SiO₂ ou Si₃N₄
   dépôt du masque SiO₂ ou Si₃N₄

3. PMMA
   dépôt du PMMA

4. écrture électronique

5. révélaison des structures

6. CHF₃ plasma

7. retrait du PMMA

8. gravure des CPh

9. CPh finis
Growth or deposition of the planar waveguide
Molecular beam epitaxy (EJM / MBE)

Growth or deposition of the planar waveguide
Molecular beam epitaxy (EJM / MBE)

80 Å thick quantum wells
Organometallic based epitaxy

Phosphine (PH₃) molecules react on surface, leaving phosphorus to react with TMLn substrates, forming InP and CH₃.

Trimethylindium (TMLn) molecules react on surface, depositing TMLn substrates.

Integrate react at lattice step edge.

Reactant B) Product (CH₃) Leave Reactor.

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Organometallic based epitaxy

[Diagram of a reaction chamber with labeled parts: Hydride, H₂, Run/Vent Assembly, Reaction Chamber, Alkyl Source, Baratron, Throttle Valve, Pressure Control, Vacuum Pump]
Silicon on insulator structures (SOI)

1. Donor bulk silicon
2. Thermal oxidation
3. H⁺ ion implantation
4. Implanted wafer flipped and bonded to receiver bulk wafer
5. Separation of donor and receiver wafer
6. CMP polishing

SOITEC, and also UNIBOND etc...
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Patterning

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

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

Decrease the wavelength:
- deep UV
- electrons
- ions

Patterning

E-beam lithography

- 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

Scanning electron microscope
E-beam patterning

Patterning

E-beam lithography

Limits:
- Non parallel process, slow
- Limited writing field (a few 100X100μm²), field stitching issues

Courtesy, M. Först, Aachen
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
Fabrication 2D structures

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Patterning

Deep UV and X-ray lithography

1. SOI wafer
2. Bottom Antireflective coating (BARC) and bake
3. Resist coating and bake
4. Exposure (193nm stepper)
5. Post exposure bake
6. Development
7. BARC and Silicon etch
8. Final Photonic wire
Simultaneous patterning and etching
Focused ion beam (FIB)

Mechanical erosion with a focused beam of ions


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**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

---

**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

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**Generic, capacity coupled plasma (CCP)**
Plasma etching

Electro-cyclotron resonance (ECR)

(a) 

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

Plasma etching

Inductively coupled plasma (ICP)

(b) 

- 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

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

CF$_4$, CHF$_3$, H$_2$, SiCl$_4$, CI$_2$, 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$_3$N$_4$, metal, ...)
- ...
Plasma etching
Low index contrast structures

(a)

Flancs verticaux et lisses

Gaine Supérieure (330 nm)
Cœur (241 nm)
Gaine Inférieure (400 nm)

GaAs
Al$_{0.3}$Ga$_{0.7}$As
Al$_{0.3}$Ga$_{0.7}$As
GaAs
GaAs + émetteurs
GaAs
Al$_{0.3}$Ga$_{0.7}$As
GaAs

a$_{min}$ = 180 nm
a$_{max}$ = 400 nm

b$_{max}$ = 85 nm
d$_{max}$ = 297 nm

Profondeur > 1 µm

(b)

Profilometer (nm)

Diamètre (nm)

Low index contrast structures

<table>
<thead>
<tr>
<th>Hole shape</th>
<th>Etch depth (µm)</th>
<th>Aspect ratio</th>
<th>Limiting factors</th>
</tr>
</thead>
<tbody>
<tr>
<td>ECR (InP)</td>
<td>tapered</td>
<td>3-4</td>
<td>16 mask selectivity</td>
</tr>
<tr>
<td>ICP (InP)</td>
<td>cylindrical</td>
<td>4.5</td>
<td>14 mask selectivity</td>
</tr>
<tr>
<td>CAIBE (InP)</td>
<td>tapered</td>
<td>2.5-4.5</td>
<td>10-20 mask thickness/removal of etch products</td>
</tr>
<tr>
<td>ECR (GaAs)</td>
<td>cylindrical</td>
<td>1.1</td>
<td>6 mask thickness</td>
</tr>
</tbody>
</table>
Low index contrast structures

State of the art in InP based structures

Two-step process


Membrane structures

1 Waveguide

Membrane
Sacrificial layer
Substrate

2 Etching

Photonic crystal

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

Suspended membrane
Air
Membrane structures

GaAs

Air

GaAs

Deep etching by anodisation

Electrochemical process

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

Example InP


Example Si

Limited to the medium IR technique \( (\lambda \approx 10 \mu m) \)
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

Less desperate:

**Up to ~ 27% gap for Si/air**

diamond-like: rods ~ “bonds”

rod layer

hole layer

Making Rods & Holes Simultaneously

expose/etch holes

Making Rods & Holes Simultaneously

backfill with silica (SiO₂) & 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

etc...

hole layers

one period

Making Rods & Holes Simultaneously

etc...

rod layers

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


Woodpile structure

Up to ~ 17% gap for Si/air

diamond-like bonds

Woodpile structure

(4 “log” layers = 1 period)

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

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Woodpile structure

Fabricated by succession of etching and planarization


fuse wafers together...

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...dissolve upper substrate

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Woodpile by Wafer Fusion

A

1st 3rd 2nd 4th

B  C

1st 2nd 1st 2nd

D

<001> <110> <010> <100>

0.7μm

10μm

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Woodpile structure

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Stacking by Micromanipulation

(a) microsphere into hole
(b) break off suspended layer

(c) lift up and move to substrate
(d) tap down holes onto spheres

(e) spheres enforce alignment

(f) goto a;

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Stacking by Micromanipulation

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Stacking by Micromanipulation

- 20 layers
- 16 layers
- 12 layers
- 8 layers
- 4 layers

50nm accuracy:

(gap effects are limited by finite lateral size)

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**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…

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**Holographic Lithography**

Four beams make 3d-periodic interference pattern

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absorptive material

$\lambda \approx \lambda_{\text{PhC}}$

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

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beam polarizations + amplitudes (8 parameters) give unit cell


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Holographic Lithography

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


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Holographic Lithography

[111] cleavages

simulated structure

[111] closeup

titania inverse structure


Colloids (opals)

(evaporate)

silica (SiO$_2$) microspheres (diameter < 1 μm)

sediment by gravity into close-packed fcc lattice!

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

fcc solid spheres do not have a gap…

…but fcc spherical holes in Si do have a gap

sub-micron colloidal spheres

Template (synthetic opal)

3D

Infiltration

Remove Template

“Inverted Opal”

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

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

Heat Source

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

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A More Perfect Crystal…

Inverted opals

Inverted opals


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Controlled defect in opals

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


“GLAD” = “GLancing Angle Deposition”

15% gap for Si/air

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

“GLAD” = “GLancing Angle Deposition”

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Auto-cloning

start with an old layer-by-layer

modify layering slightly…

(don’t forget the holes)

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


Auto-cloning

thermal oxide on Si sub.

Back to the first proposed structure

diamond-like fcc crystal
earliest “fabrication-amenable”
alternative to diamond spheres

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


(deep vertical holes)


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