SAND2018-10131C

Tutorial: Micro and Nanofabrication of Photonic Structures

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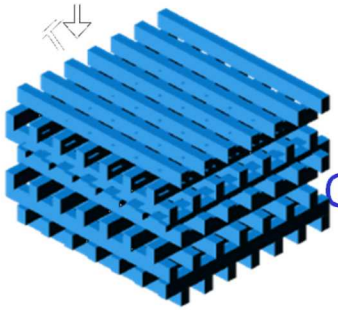
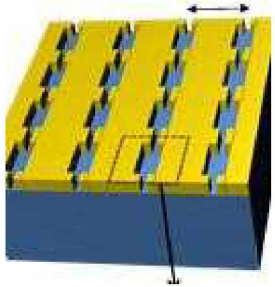
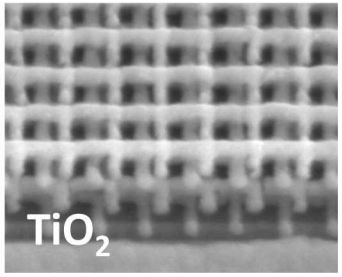
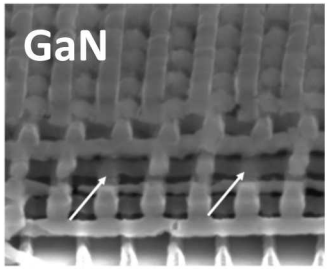
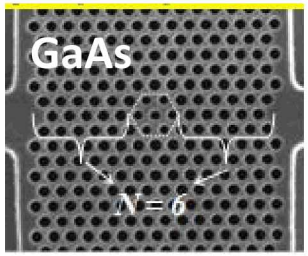


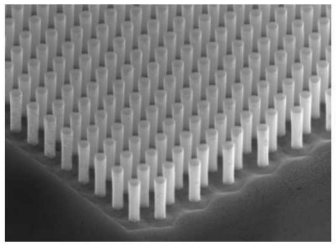


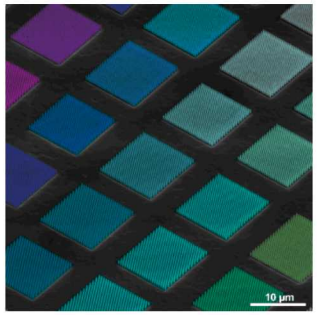
OSI - International Symposium on Optics (OSI-ISO 2018)
19 - 22 September 2018
IIT, Kanpur, India











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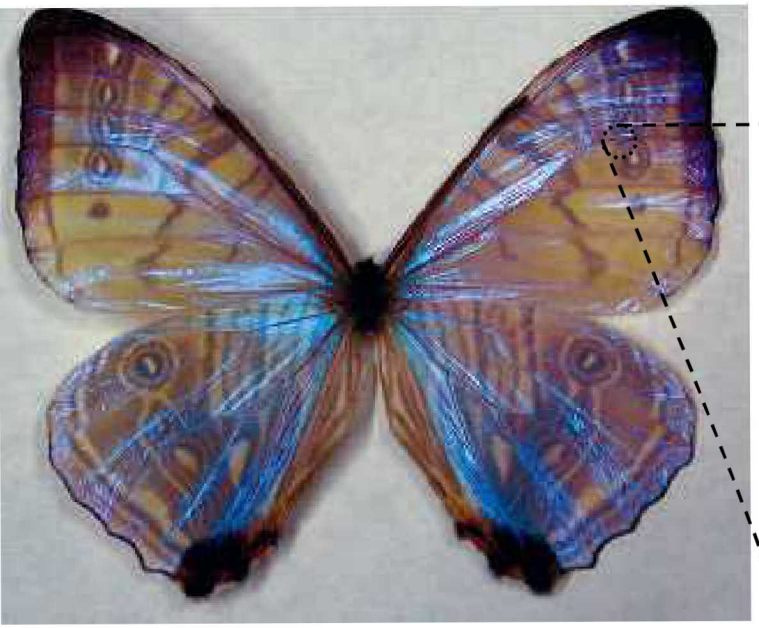
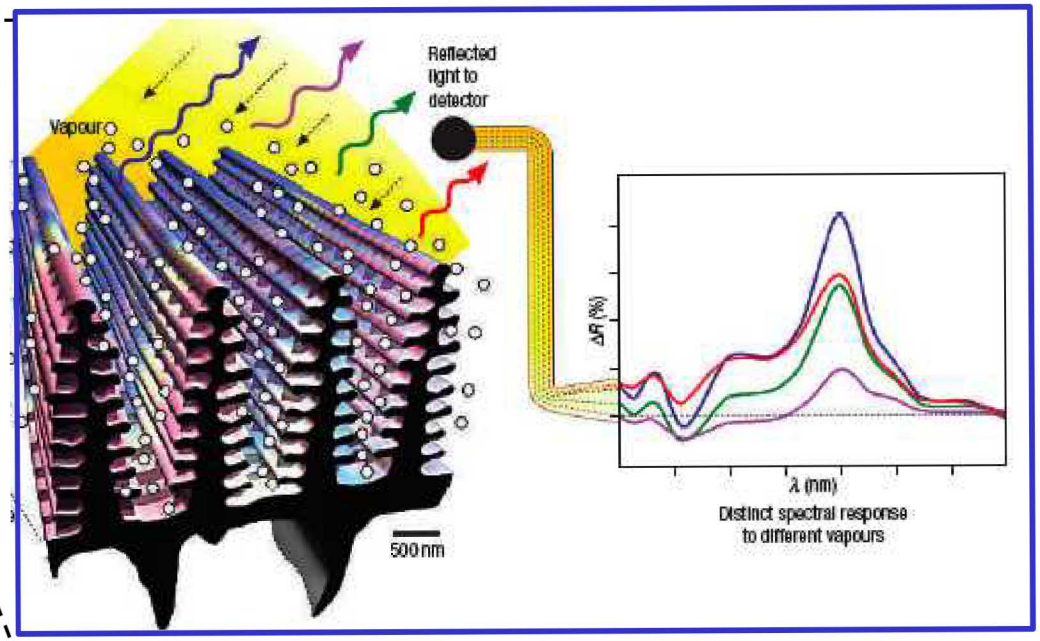
Light Control in Nature Via Nanostructuring

- **Color response highly sensitive to different vapors**



Morpho Butterfly

(M. Sulkowskyi)



* R.A. Potyrailo et. al. , Nature Photonics , **1**, 123(2007).

Nanophotonics Activity

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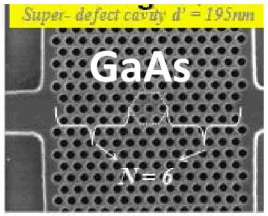
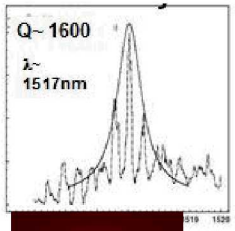
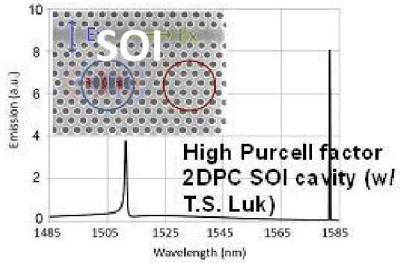
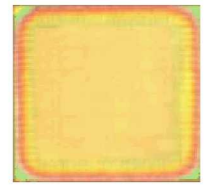
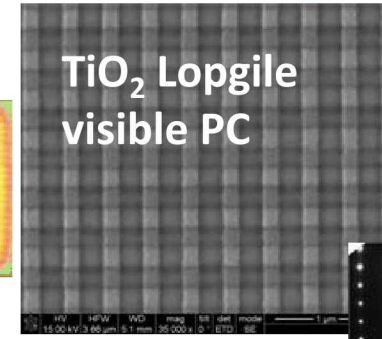
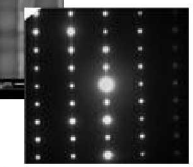


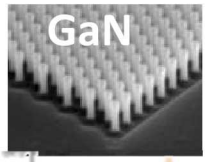


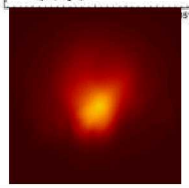








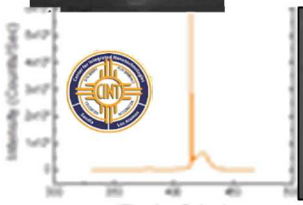


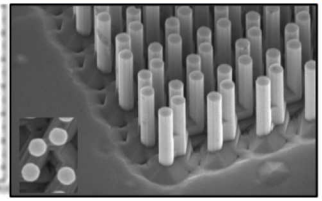


1,2D PC

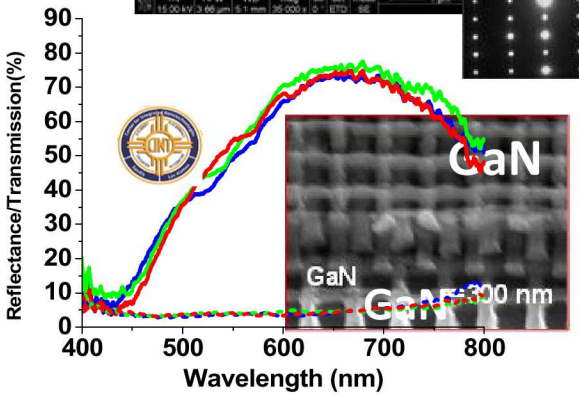
3D PC

Photonic Nanostructures



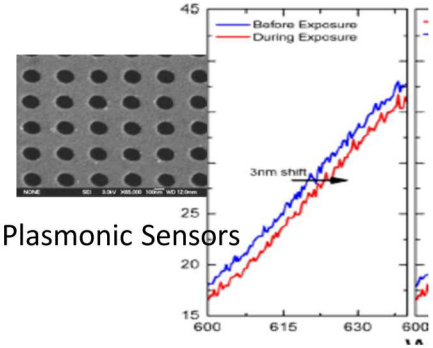


GaN 2DPC laser w/ G. Wang, I. Brener

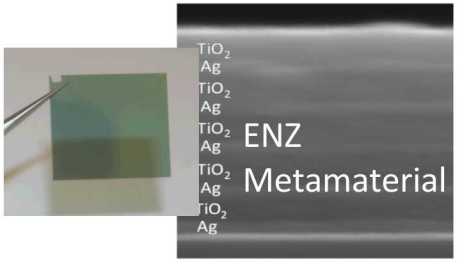


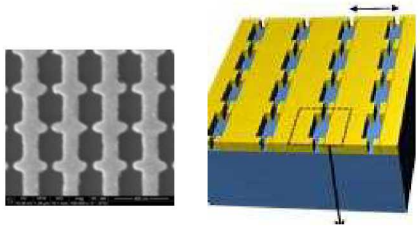
(w/ G.Wang, A. Fischer, D. Koleske)

Metal optics and Metamaterials



Plasmonic Sensors





Double groove Metal Nanostructure

Integrated Photonics, Nanoscale lasing, Emission control, Solid State lighting, Energy conversion, Non-classical light sources, Subwavelength light control, Detection, Sensing , Nanocircuitry

3DPCs: Wavelength, Materials

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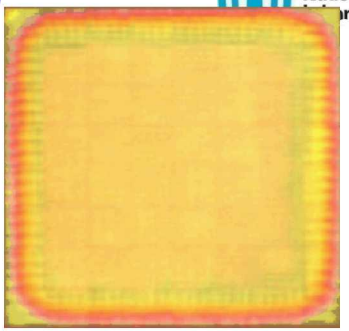
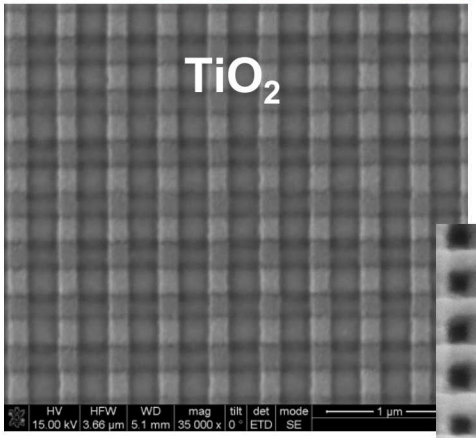
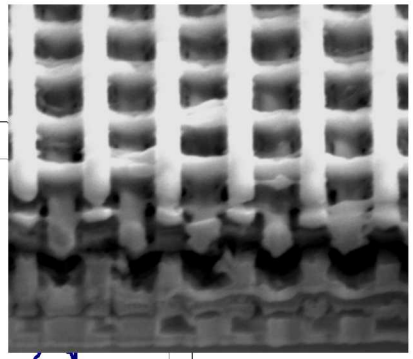
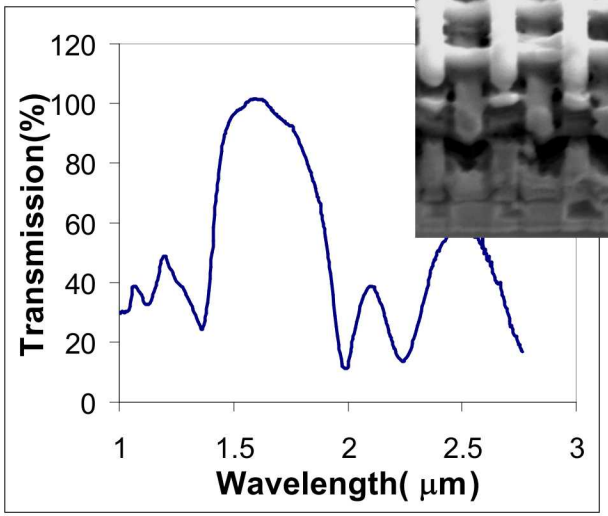
Visible



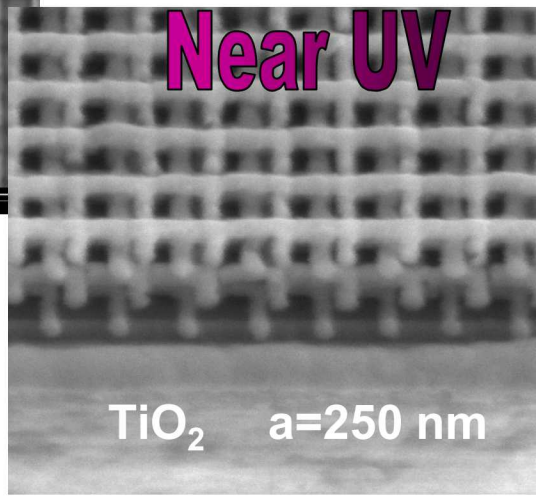


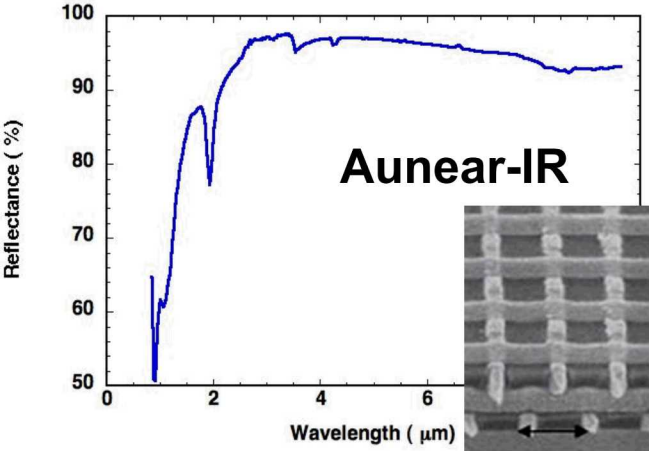
Si near-IR

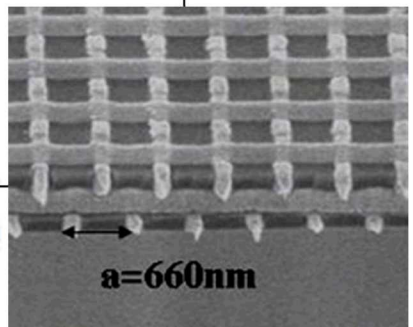


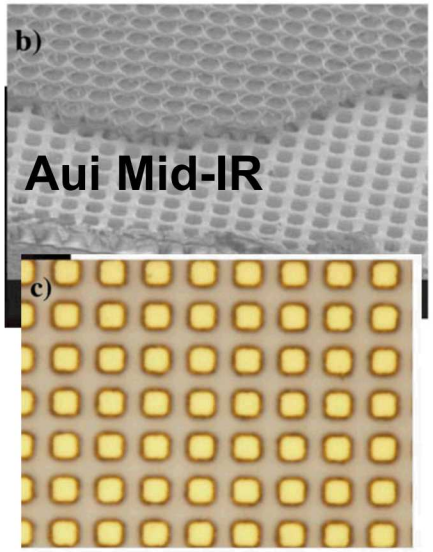


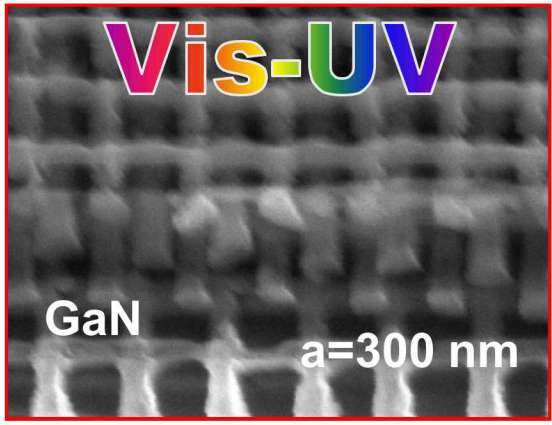
- Mid IR to Near UV
- Si, Au, TiO2 and GaN



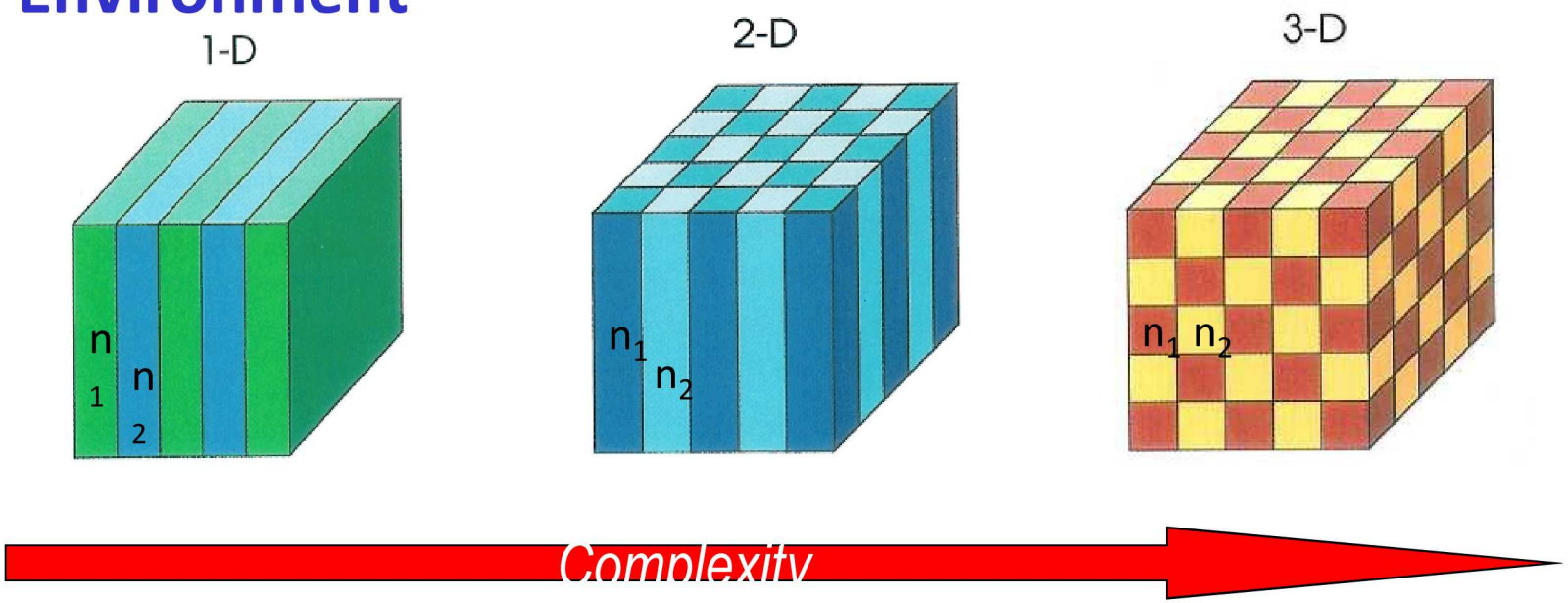








Photonic Crystals: Nanostructured Electromagnetic Environment



Control of light propagation

- Guiding, bending and splitting
- Negative refraction
- Self-collimation
- Localization
- Slow light
- Cloaking

Control of light emission

- Spontanteous emission enhancement
- Strong-coupling (Photon – Atom Bound states, Non-Markovian emission process)
- Non-classical light sources

Reference: "Photonic crystals: Molding the flow of light", J.D. Joannopoulos, R.D. Meade, J. Winn, Princeton Univ.Press, NJ(1995)

Photonic Crystals: Periodic dielectric system

Maxwell's Equations

$$\nabla \cdot \mathbf{H}(\mathbf{r},t) = 0 \qquad \nabla \times \mathbf{E}(\mathbf{r},t) + \mu_0 \frac{\partial \mathbf{H}(\mathbf{r},t)}{\partial t} = 0$$

$$\nabla \cdot [\varepsilon(\mathbf{r})\mathbf{E}(\mathbf{r},t)] = 0 \qquad \nabla \times \mathbf{H}(\mathbf{r},t) - \varepsilon_0 \varepsilon(\mathbf{r}) \frac{\partial \mathbf{E}(\mathbf{r},t)}{\partial t} = 0.$$

Harmonic Mode solution

$$\mathbf{H}(\mathbf{r},t) = \mathbf{H}(\mathbf{r}) e^{-i\omega t}$$

$$\mathbf{E}(\mathbf{r},t) = \mathbf{E}(\mathbf{r}) e^{-i\omega t}.$$

Eigen Value Equation

$$\boxed{\nabla \times \left(\frac{1}{\varepsilon(\mathbf{r})} \nabla \times \mathbf{H}(\mathbf{r}) \right) = \left(\frac{\omega}{c} \right)^2 \mathbf{H}(\mathbf{r}).}$$

$$\hat{\Theta}\mathbf{H}(\mathbf{r})$$

Hermitian operator

Reference: "Photonic crystals: Molding the flow of light", J.D. Joannopoulos, R.D. Meade, J. Winn, Princeton Univ.Press, NJ(1998),sec. ed.

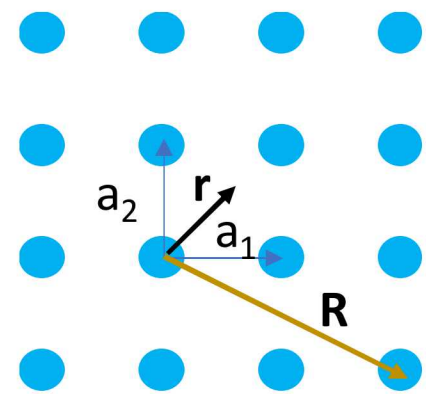
Photonic Crystals: Periodic dielectric system

PhC is periodic system with a discrete translational symmetry

$\varepsilon(\mathbf{r}) = \varepsilon(\mathbf{r} + \mathbf{R})$ where, $\mathbf{R} = \ell \mathbf{a}_1 + m\mathbf{a}_2 + n\mathbf{a}_3$

$\boldsymbol{l}, \boldsymbol{m}, \boldsymbol{n} \in \mathbb{Z}$

Real Lattice



Apply Bloch's theorem:

Field distribution eigen functions are periodic with same period

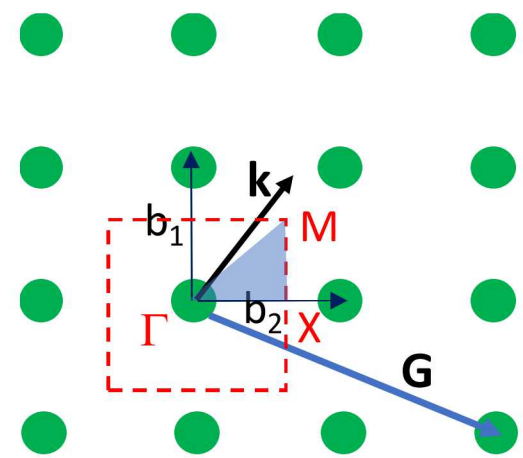
$\mathbf{H}_\mathbf{k}(\mathbf{r}) = e^{i\mathbf{k}\cdot\mathbf{r}}\mathbf{u}_\mathbf{k}(\mathbf{r})$, where, $\mathbf{u}_\mathbf{k}(\mathbf{r}) = \mathbf{u}_\mathbf{k}(\mathbf{r} + \mathbf{R})$

$\mathbf{k} = k_1\mathbf{b}_1 + k_2\mathbf{b}_2 + k_3\mathbf{b}_3$ such that $\mathbf{a}_i \cdot \mathbf{b}_j = 2\pi\delta_{ij}$.

$$\mathbf{H}_\mathbf{k}(\mathbf{r}) = \mathbf{H}_{\mathbf{k}+\mathbf{G}}(\mathbf{r})$$

$\boldsymbol{G} = \mathbf{i}\boldsymbol{b}_1 + \boldsymbol{j}\boldsymbol{b}_2 + \boldsymbol{k}\boldsymbol{b}_3$ $\mathbf{i}, \boldsymbol{j}, \boldsymbol{k} \in \mathbb{Z}$

Reciprocal Lattice

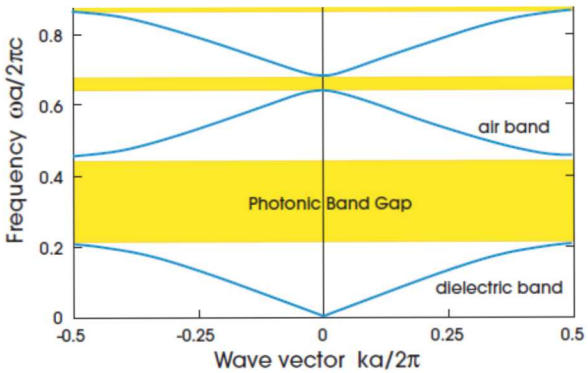


Reference: "Photonic crystals: Molding the flow of light", J.D. Joannopoulos, R.D. Meade, J. Winn, Princeton Univ.Press, NJ(1998),sec. ed.

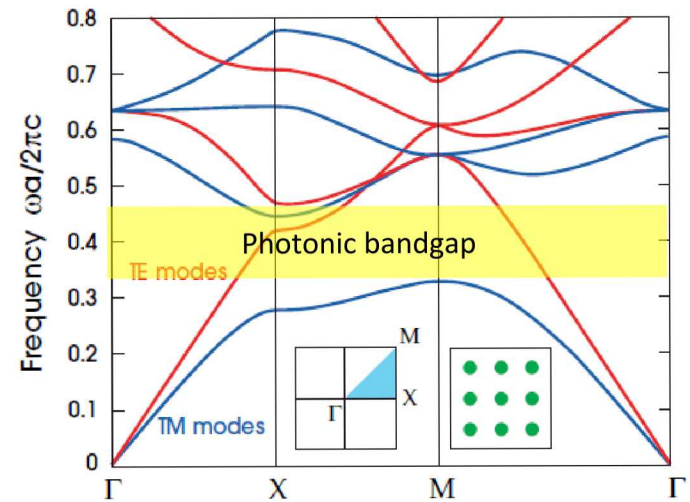
Photonic Crystals: Photonic Band Structure

$$\hat{\Theta}\mathbf{H}_{\mathbf{k}} = (\omega(\mathbf{k})/c)^2\mathbf{H}_{\mathbf{k}}$$

1D

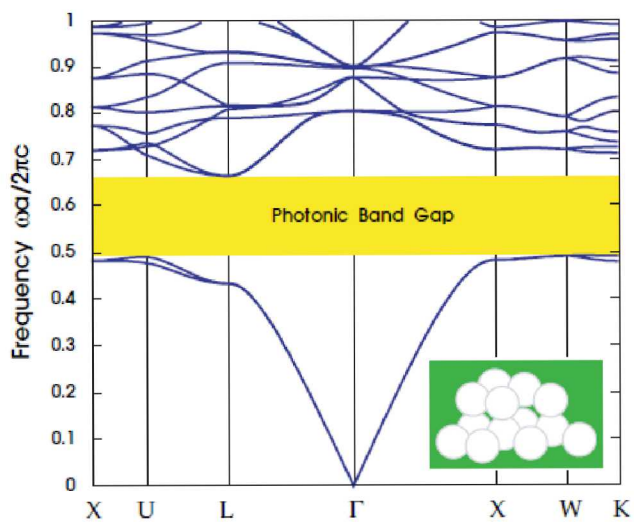


2D



3D

Brillouin zone



Reference: "Photonic crystals: Molding the flow of light", J.D. Joannopoulos, R.D. Meade, J. Winn, Princeton Univ.Press, NJ(1998),sec. ed.

Nanofabrication Example Structures

- **1 D**
  - Multilayer ENZ metal dielectric
- **2D PhCs**
  - GaAs based
    - Cavity
    - WG
  - GaN based
    - Laser
    - Aperiodic
    - Topological
  - SOI based
    - TOP PhC
  - Metal optics
    - Plasmonic (neg resist,pos resist)
    - DG (emphasize different substrate)
- **3D PhC**
  - Si, W
  - Si
  - TiO2
  - GaN
  - Au
- **0D**
  - GaN QD PEC etching

Self – assembly; microsphere lithography

Process Steps for Nanofabrication

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➢ Material growth

- Bulk wafer (e.g., Si, GaAs, InP etc.)
- Epitaxial film growth (e.g. III-V,II-VI semiconductors InGaAs, GaAs, AlGaAs, InGaAsP, InSb, GaN, InGaN etc.)
  - Metal organic chemical vapor deposition (MOCVD)
  - Metal Organic Vapor Phase Epitaxy (MOVPE)
- Thin film growth (e.g., Si, Ge, SiO_2,TiO_2, ZnO, ITO, SiN, TiN, Al_2O_3, HfO , Au, Ag, Pt, Al etc.)
  - Physical vapor deposition (PVD)
    - Evaporation (e-beam, thermal, sputtering, pulsed laser deposition)
  - Chemical vapor deposition (CVD)
    - Diffusion furnace
    - Plasma enhanced chemical vapor deposition (PECVD)
    - Atomic Layer deposition (ALD)
    - Spin coating
    - Electrochemical deposition

Process Steps for Nanofabrication

Sandia National Laboratories

➢ Patterning

- **Optical Lithography**
  - Patterns with > 0.5 μm minimum feature size
  - Fast, simple to operate and easier access
  - Sample sizes small pieces to 6” wafer
  - Predetermined pattern from a mask
- **Electron beam lithography**
  - Patterns with <0 .5 μm minimum feature size
  - Slow, requires training , difficult access
  - Small samples to larger wafers (~ 4”)
  - Computer generated pattern –more flexibility for changes
- **Laser interference lithography**
  - Large area periodic structures
- **Nanoimprint lithography** (Large area nm to submicron patterns)
- Step-and-repeat (large fabs and commercial)

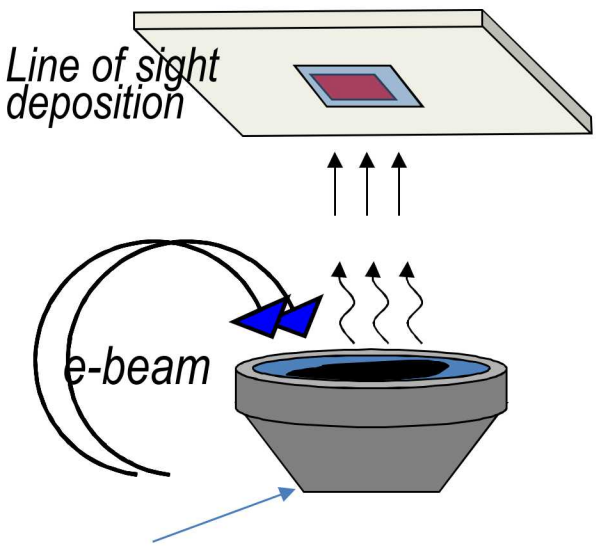
Process Steps for Nanofabrication

- **Etching**
  - **Wet etching**
    - Isotropic and anisotropioc
  - **Dry etching**
    - Reactive ion etching
    - Ion beam etching
    - Deep Reactive Ion etching

Thin Film Deposition

Physical Vapor Deposition (PVD)

Electron beam evaporation



Crucible (W, Mo, Ta,BN, SiO_2,ZrO_2 ,graphite)

- Material inside the crucible(e.g.,W or graphite) is heated by high electron beam current.
- The chamber is typically pumped down to below 10^{-4} Torr (increasing mean free path)
- Electron beam is typicaly swept in a criss-cross or figure '8' pattern for uniformity

Features

- LIne-of-sight deposition – good for lift-off
- Deposition rate 0.1nm/s -1nm/s
- Good for metals (Au, Ag, Pt,), some semiconductors (Si, Ge)
- Compounds and Alloys are trickier due to decomposition
- Oxides are possible with O_2 feed

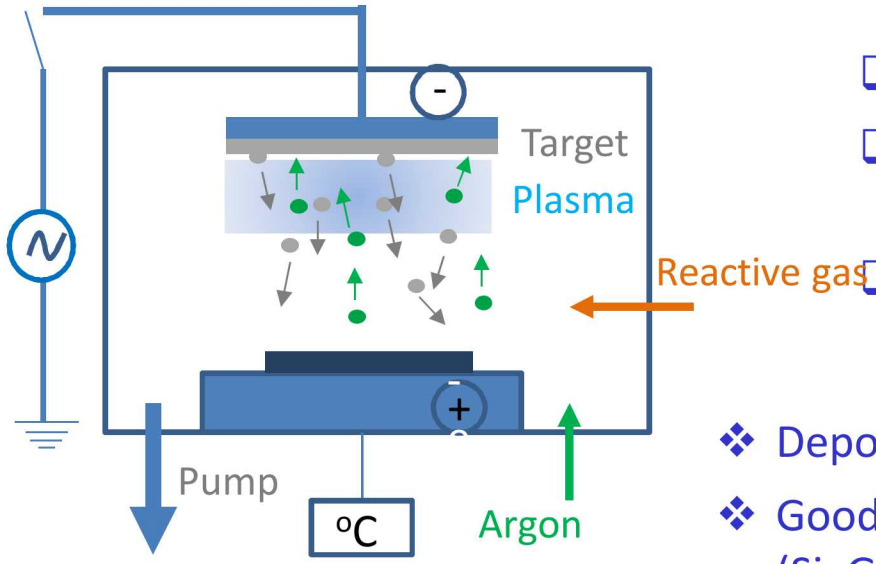
Generates X-rays – so sometimes thermal evaporation is preferred

Introduction to Microfabrication by Sami Franssila Wiley (2010). Sec. Ed.

Thin Film Deposition

Physical Vapor Deposition (PVD)

Sputtering



- Material is placed disc target at the negative electrode
- The chamber is pumped down to ~< 1 mT but operates around 1-10mT
- RF or HVDC is applied to create plasma
- Ar is ionized and hits the target ejecting the atoms that travel towards the substrate
- Atoms from target thermalize and land on wafer

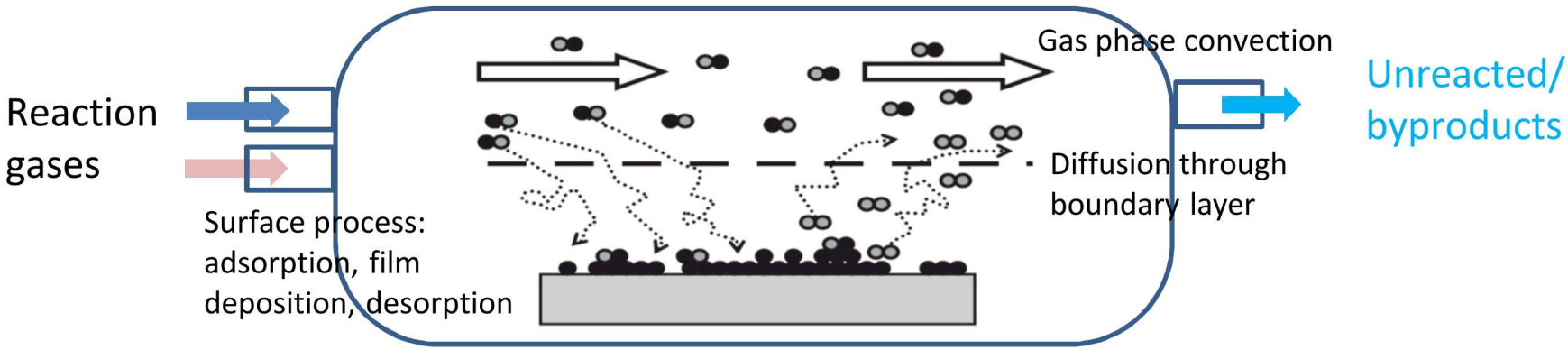
Features

- Deposition rate 1nm/s -10nm/s
- Good for metals (Au, Ag, Pt,), some semiconductors (Si, Ge) and alloys
- Reactive sputtering with introduction of O_2 or N_2 is possible
- The atoms hitting the wafer are more energetic so can damage films but can also knock-off impurities
- Dense films can be obtained

Introduction to Microfabrication by Sami Franssila Wiley (2010). Sec. Ed.

Thin Film Deposition

Chemical Vapor Deposition (CVD)



Si: $SiH_4\ (g) \Longrightarrow Si\ (s) + 2\ H_2\ (g)$ ~600 °C

SiO_2: $SiCl_4\ (g) + 2\ H_2\ (g) + O_2\ (g) \Longrightarrow SiO_2\ (s) + 4\ HCl\ (g)$ ~900 °C

W: $WF_6\ (g) + SiH_4\ (g) \Longrightarrow W\ (s) + 2\ HF + H_2\ (g) + SiF_4\ (g)$

$WF_6\ (g) + 3\ H_2\ (g) \Longrightarrow W\ (s) + 6\ HF\ (g)$

Si_3N_4: $3\ SiH_2Cl_2\ (g) + 4\ NH_3\ (g) \Longrightarrow Si_3N_4\ (s) + 6\ H_2\ (g) + 6\ HCl\ (g)$ ~800 °C

- Source materials are in gas phase, diffuse to the wafer surface and react to deposit film
- By-products and unreacted are pumped away
- Can be 'surface raction limited' or 'diffusion limited'

Features

- Deposition rate 0.1nm/s -10nm/s
- Good for polycrystalline e.g, Si, SiO_2, Si_3N_4, W
- Films are relatively dense

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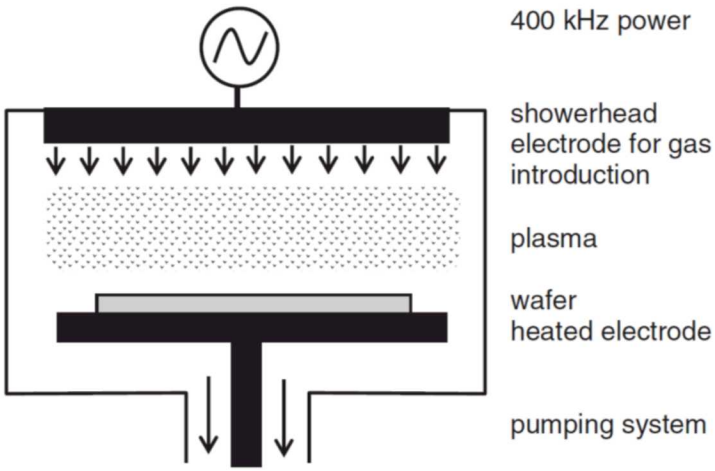
Thin Film Deposition

Plasma Enhanced Chemical Vapor Deposition (PECVD)



- Wafer is placed in the heated bottom electrode
- Source gases are introduced from the top shower head
- RF plasma enhances source gas decomposition
- Chamber, pressure, reactive gas flow rate, RF power can be used to control film dep rate and qualtity

SiO_2 : $SiH_4\ (g) + 2\ N_2O\ (g) \longrightarrow SiO_2\ (s) + 2\ H_2\ (g) + 2\ N_2\ (g)$

Features

- Deposition rate 0.1nm/s -10nm/s
- Lower deposition temperature 300°C
- Less dense films (potential pin-holes) , typically non-stoichiometric
- Can deposit e.g, a:Si, SiO_2, SiN_x, Si_xO_yN, SiC
- Useful for hard mask depostion

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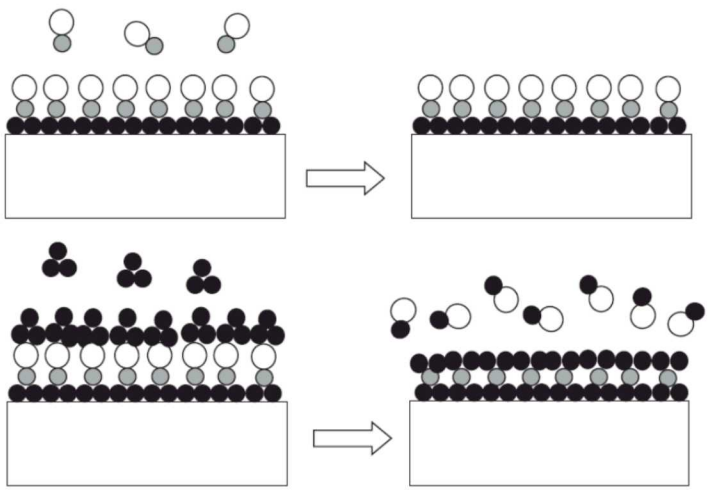
Thin Film Deposition

Sandia National Laboratories

Atomic layer deposition (ALD)



- Material deposited in pulses
  - Chemical bond forms between precursor and surface atom till all reaction sites are occupied
  - Purge N2 pulse removes unreacted precursor
  - Second precursor pulse reacts first monolayer and purge pulse applied
  - Process is repeated

HfO_2 :

$$HfCl_4\ (ad) + 2\ H_2O\ (ad) \Longrightarrow HfO_2\ (s) + 4\ HCl\ (g)$$

Features

- Deposition rate 1A/cycle
- Low deposition temperature (room temp)
- Dense films near-stoichiometric (Al_2O_3, TiN, TiO_2, SiO_2)
- Conformal coverage
- Depends highly on precursors

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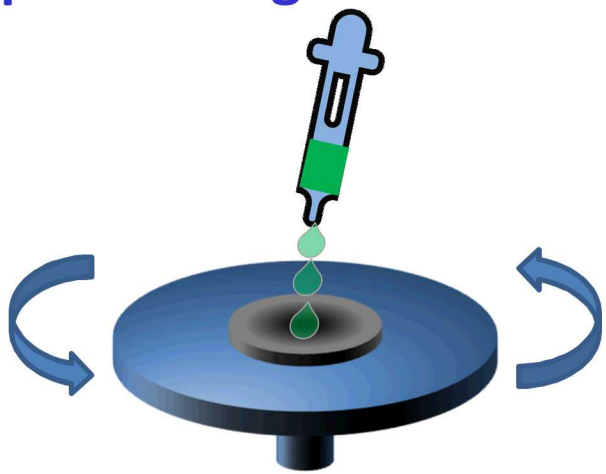
Thin Film Deposition

Spin Coating



- Desired material in the liquid form is uniformly covered over the wafer mounted on spinner
- Wafer is spun at high rate ~ 3000- 5000 rpm for 30-60s
- Solvent evaporates during spin
- Material is baked at medium temperature (90°C to 250°C) on hot-plate to drive-off remainng solvent

Features

- Films can be deposited with high uniformity (< 5nm variation)
- Typically suitable for polymers (e.g. resists)
- Also Spin-on-dielecric : SOG
- High temperature bake can enable phase transition to dense dieletric
- Good via-filling - Useful for planarization
- Simple and easy approach to thin film

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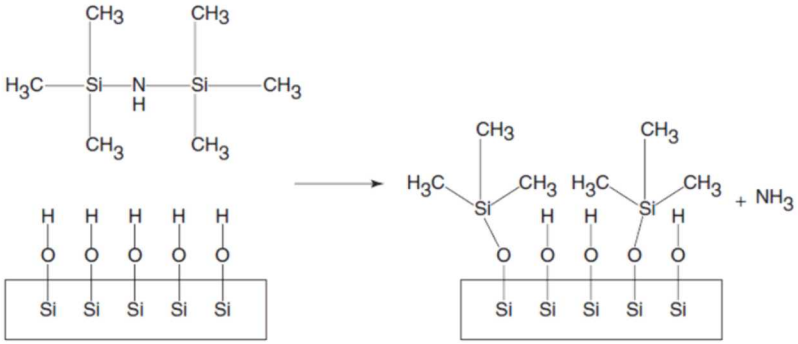
Patterning

Optical Lithography

- Clean wafer (Acetone, Isoproponal and air drying)
  - May need DI H_2O for some cases or RCA clean
- Spin or vapor prime adhesion promoter as needed (HMDS:Hexamethyldisilazane)
- Spin on resist (either positive/negative)
  - Thickness controlled by spin paramaters (rpm, acceleration, time)
- Bake at recommended temperature (80°C to 180°C)
- Clean optical mask containing desired pattern (ACE, IPA)
- Align pattern under the mask aligner
- Expose pattern (time based on resist recommendation)
- Post bake if needed
- Develop in an appropriate developer (e.g. TMAH)

HMDS



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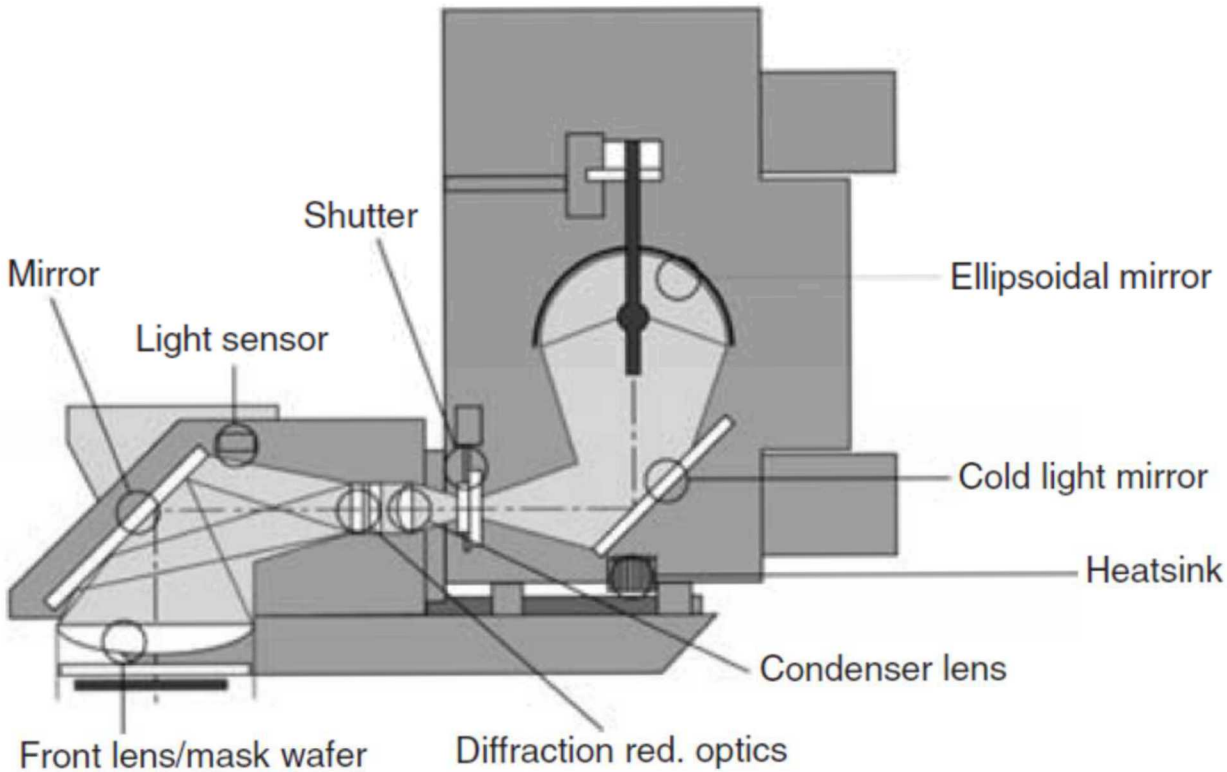
Patterning

Optical Lithography (contd.)

Mask Aligner



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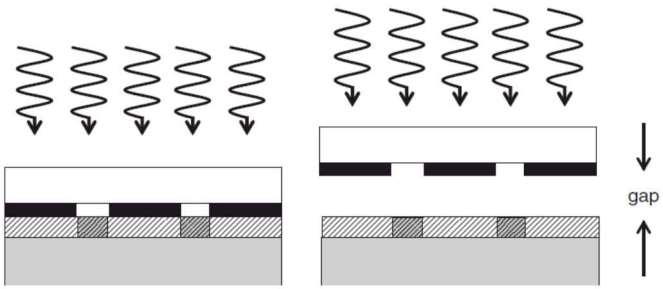
Patterning

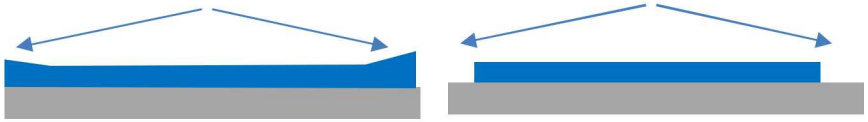
Optical Lithography (contd.)

Contact Lithography

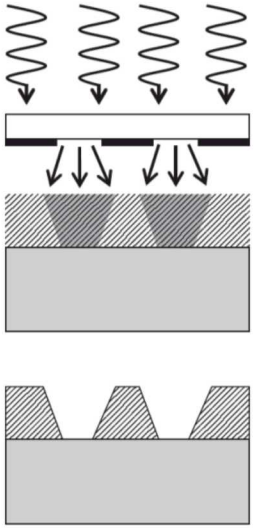


Edge 'bead'

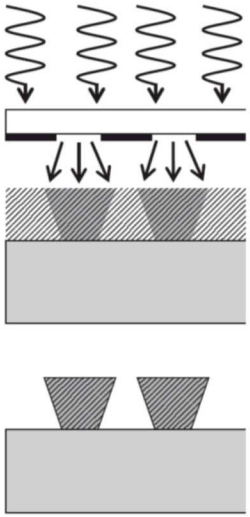
Remove edge-bead with first exposure



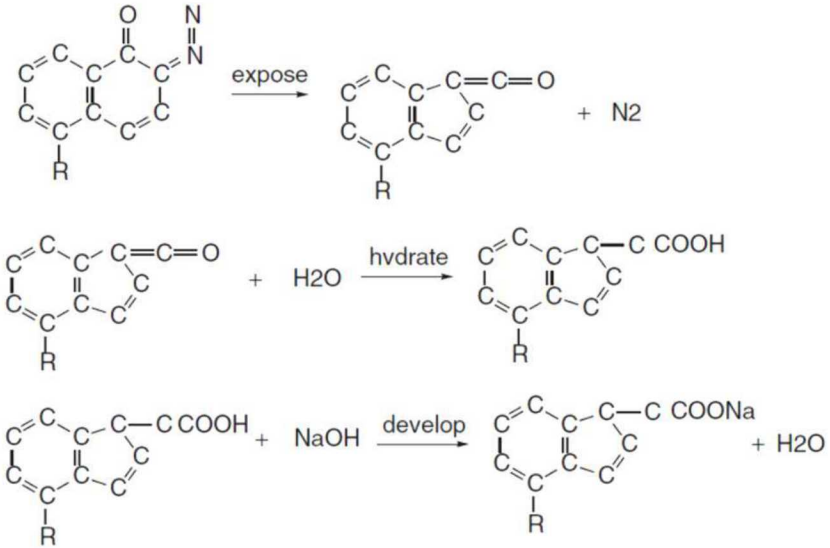
Positive resist



Negative resist



Development



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Patterning

Optical Lithography (contd.)

Features

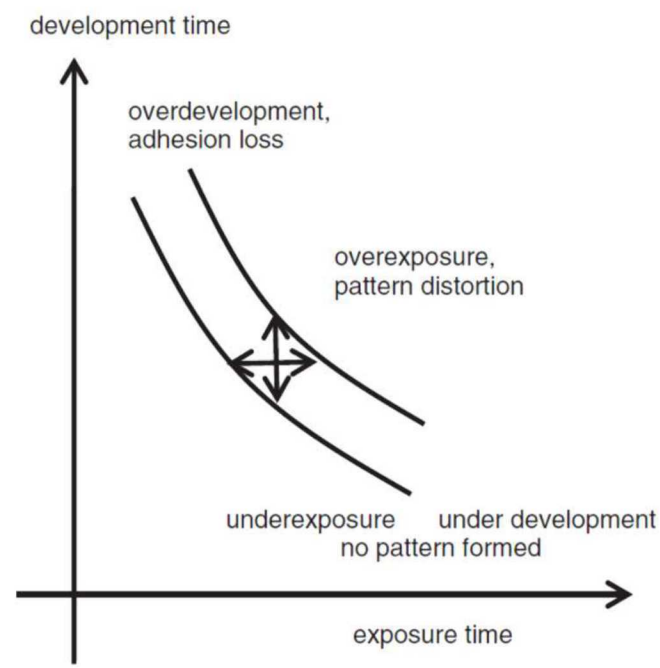
- Relatively 'easy' patterning of features > 0.5 μm
- Quite versatile with many resist choices
- Resist choice is important . Selection criteria:
  - Sensitivity, Tone (+,-), resolution, process lattitude, shelf-life, etch selectivity
- Can be used as a 'mask' for many steps:
  - Ion implant, wet etch, dry etch, evaporation/liftoff, electroplating

$$\text{linewidth} \approx \sqrt{\lambda \times \left(g + \frac{d}{2}\right)}$$

gap

Exp. wavelength

Resist thickness



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Patterning

Electron Beam Lithography

- Clean wafer (Acetone, Isoproponal and air drying)
  - May need DI H_2O for some cases or RCA clean
- Spin or vapor prime adhesion promoter as needed (HMDS:Hexamethyldisilazane)
- Spin on resist (either positive/negative :e.g. PMMA/NEB-31)
  - Thickness controlled by spin paramaters (rpm, acceleration, time)
- Bake at recommended temperature (80°C to 180°C)
- Create pattern to be 'written' in a CAD software (e.g, Autocad® , Design workshop®): creates a '.gds' format file
- Convert pattern into a E-beam machine readable format
- Expose pattern
  - Pattern+ resist sensitvity dictates machine conditions: Current, aperture, exposure dose etc.
- Develop in an appropriate developer (e.g. Methyl isobutyl ketone [MIBK])

Goal in EBL is to write fast with smallest feature sizes

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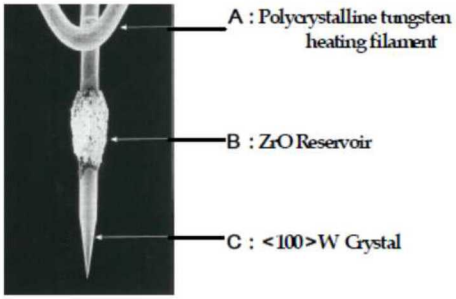
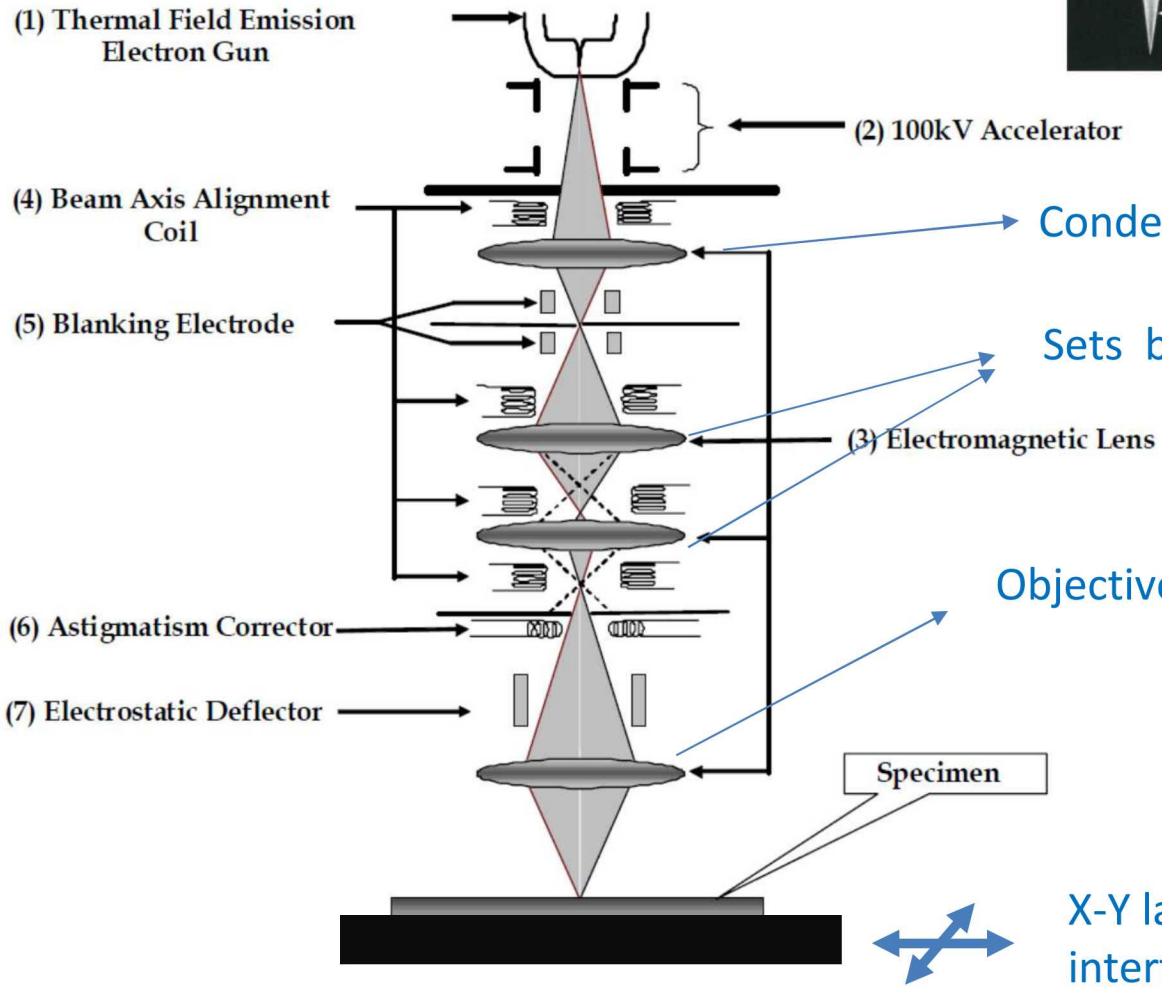
Patterning

Electron Beam Lithography





Accel. Volt 25-100kV

Condenser lens: collects electrons

Sets beam current

Objective lens : focuses e-beam

X-Y laser interferometer stage

Lithography, Ed. By Michael Wang, Intech (2010)

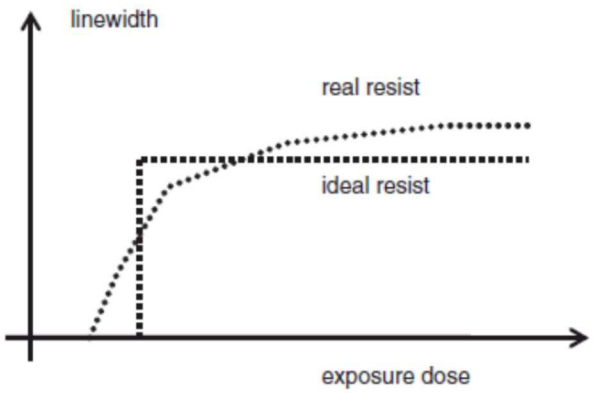
Patterning

Electron Beam Lithography

Resist exposure in e-beam system

- E-beam provides higher resolution than optical litho
  - As small as 5nm
  - Limited not by de-Broglie λ of e- but by electon optics and Coulomb repulsion
- If resist receives sufficient charge dose ($\mu C/cm^2$) to exceed resist sensitivity threshold it is exposed
- Resists are non-ideal so nearby regions are exposed : 'proximity effect'

$$d_{\text{eff}}\ (\text{nm}) = 0.9 \times \left(\frac{t}{V}\right)^{1.5}$$



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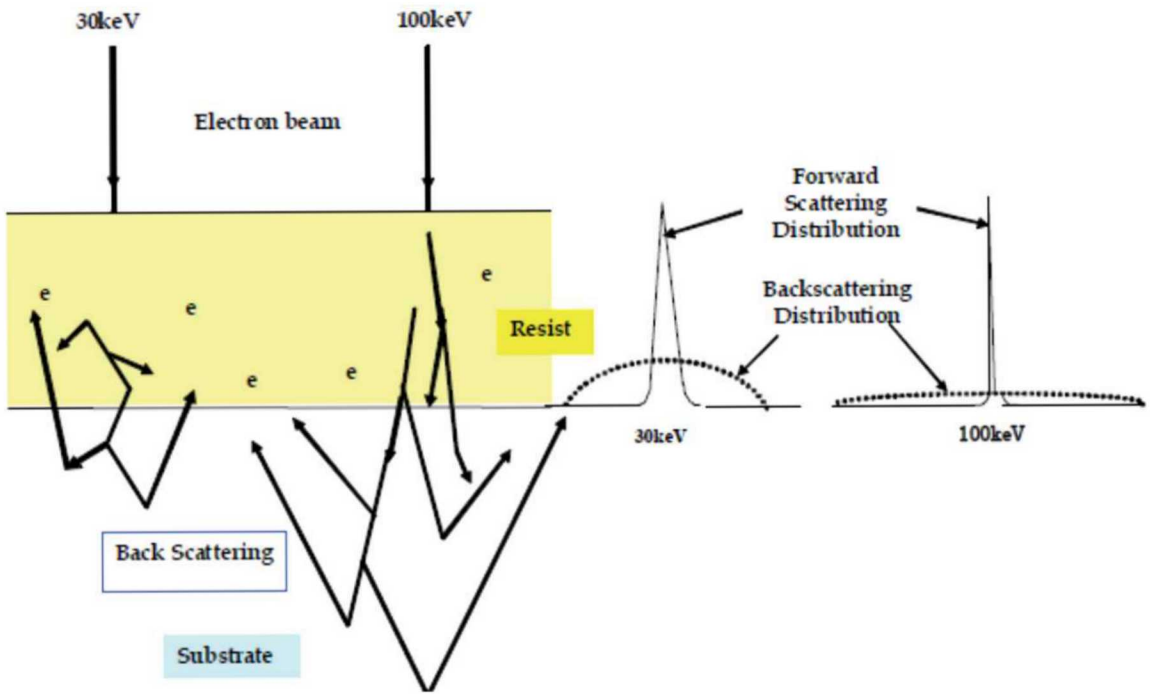
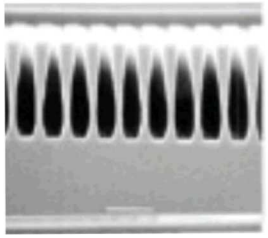
Patterning
Electron Beam Lithography

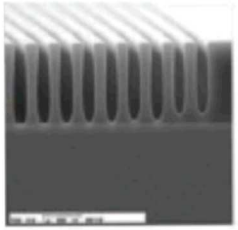
Resist exposure in e-beam system

- Exposure profile depends on accelerating voltage
- Exposure is mainly due to secondary electrons (~ 200-400eV)
- Factors determining exposure dose
  - Resist sensitivity and thickness
  - Atomic number of substrates (backscatter strength)

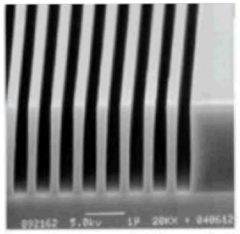




30keV



50keV



100keV

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Patterning

Electron Beam Lithography

Sandia National Laboratories

Features

- Can pattern features ~ 10-20nm
- Computer generated pattern allows for design flexibility
- Extremely useful for prototyping and as a research tool
- Slow (but still a work horse for small volume production)
- Resist choice is important . Selection criteria:
  - Sensitivity, Tone (+,-), resolution, process lattitude, shelf-life, etch selectivity
- Can be also used as a 'mask' for many steps:
  - Ion implant, wet etch, dry etch, evaporation/liftoff, electroplating

SEM with blanker + pattern generator	Dedicated EBL tool
• **Pro**: Inexpensive, easy to implement and operate, nanoscale patterns, rudimentary alignment • **Con:** Low accel voltage – sparse pattern, restricted alignment, small field size (~ 100μm), cannot field stitch	**Pro**: High accel V (dense pattern),~ 20nm placement accuracy, large field (500mm), excellent field stitching. Con: Expensive, difficult to learn and operate, larger infrastructure and maintenance

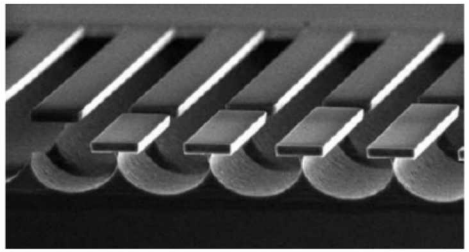
Etching

Wet etching

solid + liquid etchant → soluble products

Isotropic

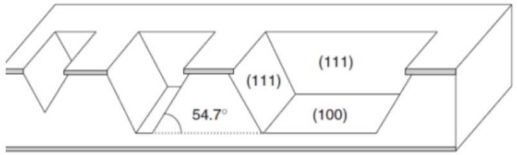
Example : $SiO_2 + 6\ HF \Rightarrow H_2SiOF_6\ (aq) + 2\ H_2O$

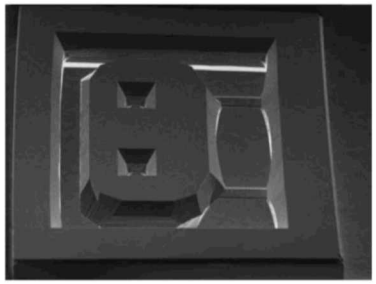


Anisotropic

Example : $Si\ (s) + 2\ OH^- + 2\ H_2O$

$\Rightarrow Si(OH)_2(O^-)_2\ (aq) + 2\ H_2\ (g)$





Features

- Simple approach for pattern transfer
- Undercutting under resist asks
- High etch rates or 100-1000/min
- Deep etches of several 10s to 100s of micron possible
- Etch can be either surface limiting or transport (of etchant) limiting

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Etching

Wet etching

solid + liquid etchant → soluble products

Examples of different etchants

SiO_2	NH_4F:HF (7:1),[a] 35 °C
SiO_2	NH_4F: CH_3COOH:$C_2H_6O_2$ (ethylene glycol): H_2O (14:32:4:50)
Poly-Si	HF:HNO_3:H_2O (6:10:40)
Al	H_3PO_4:HNO_3:H_2O (80:4:16), water can be changed to acetic acid
Mo	H_3PO_4:HNO_3:H_2O (80:4:16)
W, TiW	H_2O_2:H_2O (1:1)
Cr	$Ce(NH_4)NO_3$:HNO_3:H_2O (1:1:1)
Cu	HNO_3:H_2O (1:1)
Ni	HNO_3:CH_3COOH:H_2SO_4 (5:5:2)
Ti	HF:H_2O_2 (1:1)
Au	KI:I_2:H_2O, KCN:H_2O
Pt, Au	HNO_3:HCl (1:3), "aqua regia," H_2O dilution may be used

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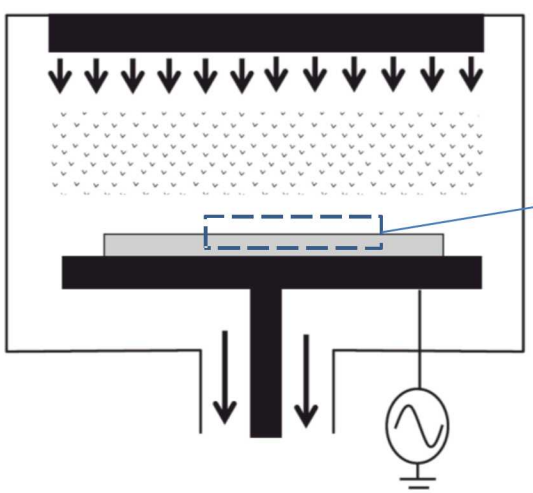
Etching

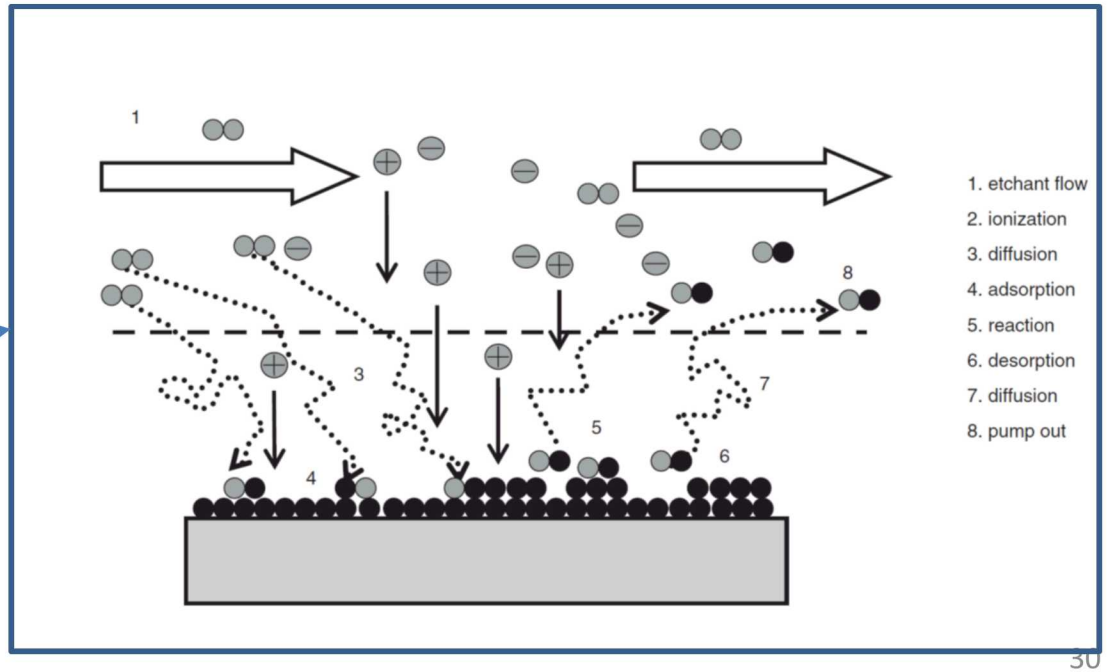
Reactive ion etching

solid + gaseous etchant → volatile products

- Chamber is similar to PECVD
- Wafer is placed in the bottom electrode
- Source gases are introduced from the top shower head
- RF plasma enhances source gas decomposition
- Chamber, pressure, reactive gas flow rate, RF power can be used to control film etch rate and quality

RIE chamber





Etching

Reactive ion etching

- Etching depends on bond energies like in wet etching
- Also depends on the volatility of reaction product gases
- Etch occurs chemically while ion bombardment provides directionality

Bond energies

C–O	1080	Si–F	550
Si–O	470	Si–Cl	403
Si–Si	227	Si–Br	370

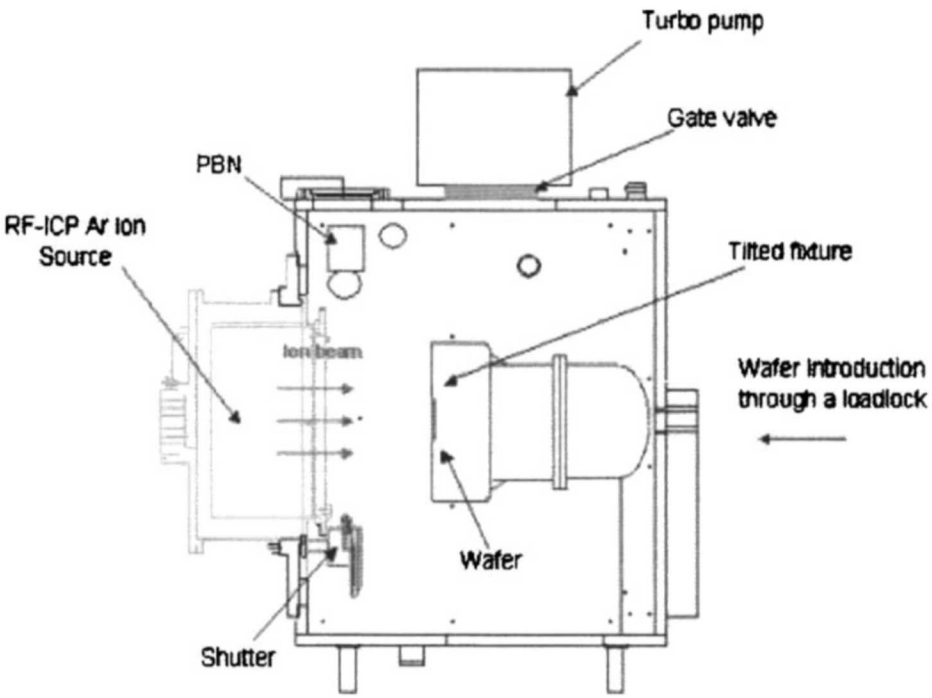
- Si can be etched by halogen
- SiO_2 etch requires flourine

Features

- Etch is typically anisotropic : Key for etching nanoscale features
- Key parameter is the selectivity : mask etch rate vs. material etch rate
- Etch depth depends upon mask thickness as well as etch condition
- Hard mask (e.g. SiO_2 or SiN, Ni, Al) may be sometimes required.
- Deeper etch is possible with modified approaches (ion beam etching)

Etching

Ion beam etching



Chemically assisted ion beam etching

- Chamber pumped down to ~ 10-7 Torr
- High energy Ar ion beam is created using inductively coupled plasma
- Ion is neutralized with a plasma bridge neutralizer
- Etch chemical (eg. Cl_2) is introduced through a ring near the substrate
- Etch occurs due to etch gas while neutral Ar beam enables faster and directional material removal
- Useful for deep etching of III-V compound semiconductors

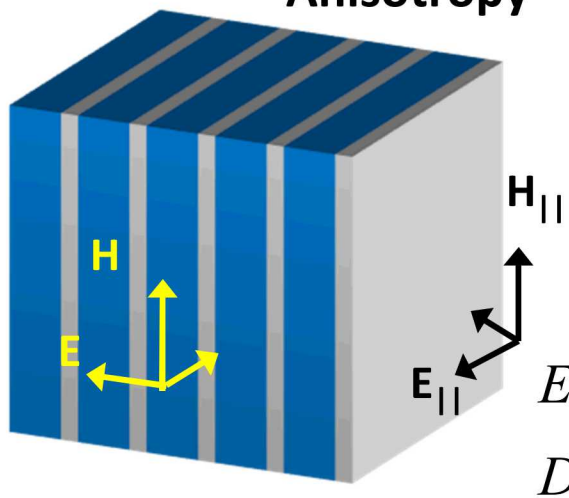
A. Rhallabi, et.al, JVST B: Microelectronics and Nanometer Structures Processing, Measurement, and Phenomena **23**, 1984-1991 (2005).

1D PhC

Visible Frequency Epsilon Near Zero Metamaterial - 1D metal/dielectric stack

$$\frac{1}{\varepsilon_{\perp}} = \frac{f}{\varepsilon_{+}} + \frac{(1-f)}{\varepsilon_{-}}$$

Anisotropy



$$\varepsilon_{\parallel} = f\varepsilon_{+} + (1-f)\varepsilon_{-}$$

$$D_{Avg\perp} = D_{+\perp} = D_{-\perp}$$

$$E_{Avg\perp} = f_{+}E_{+\perp} + (1-f)E_{-\perp}$$

$$\frac{D_{Avg\perp}}{\varepsilon_{eff}} = f\frac{D_{+\perp}}{\varepsilon_{+}} + (1-f)\frac{D_{-\perp}}{\varepsilon_{-}}$$

$$E_{Avg\parallel} = E_{+\parallel} = E_{-\parallel}$$

$$D_{Avg\parallel} = fD_{+} + (1-f)D_{-}$$

$$\varepsilon_{eff}E_{Avg\parallel} = f\varepsilon_{+}E_{+\parallel} + (1-f)f\varepsilon_{-}E_{-\parallel}$$

dielectric

$$\varepsilon_{effective} = f\varepsilon_{+} + (1-f)\varepsilon_{-}$$

metal

Goals

- Minimize losses due to metal
- Effective medium behavior-finer subdivision
- Reduce non-local effects – Smoother field distribution
- Easy fabricate , easy characterization

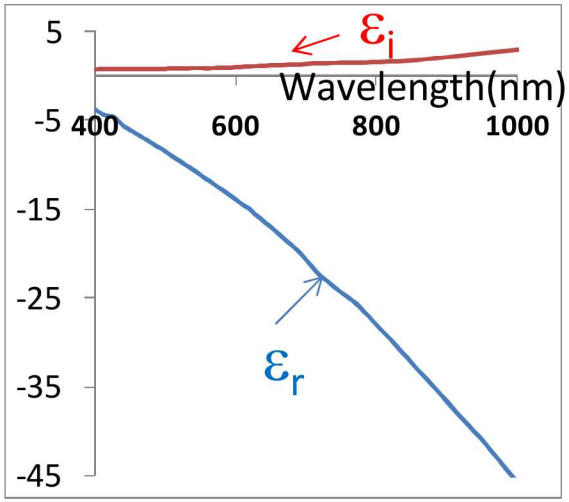
S. A. Ramakrishna, et. al "Imaging the near field," Journal of Modern Optics **50**, 1419-1430 (2003).

Effective Medium Approach to ENZ

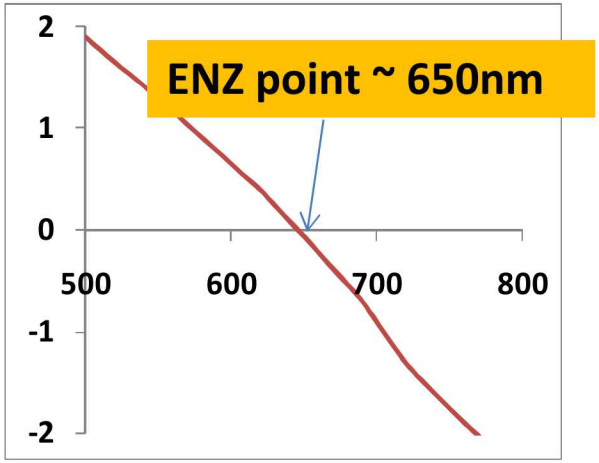
Materials Choice ε_- : Ag and ε_+ **: TiO_2**

Ag (23%) + TiO_2 (77%)

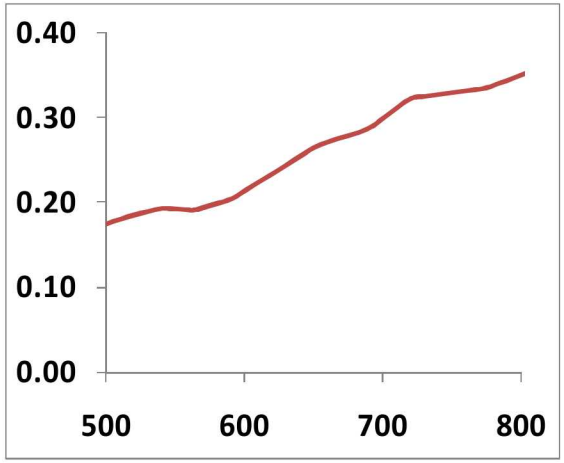
Silver(Ag)dispersion (Palik)



Composite-ε_{real}



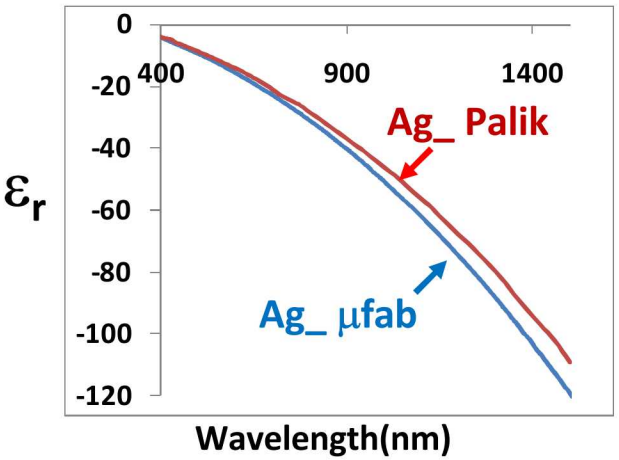
Composite-ε_{imag}

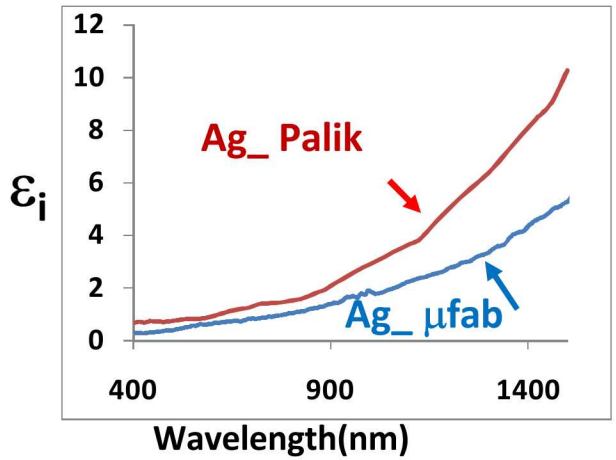


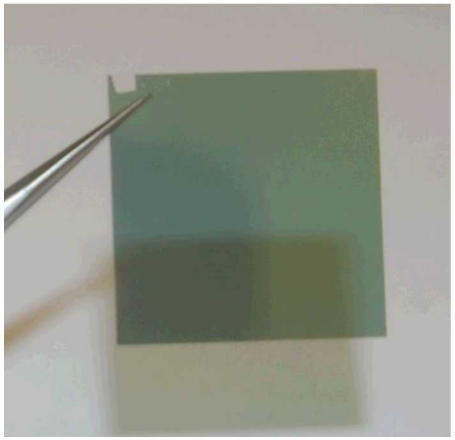
G. Subramania, A. J. Fischer, T. S. Luk , Appl. Phys. Lett. , 101, 241107(2012)

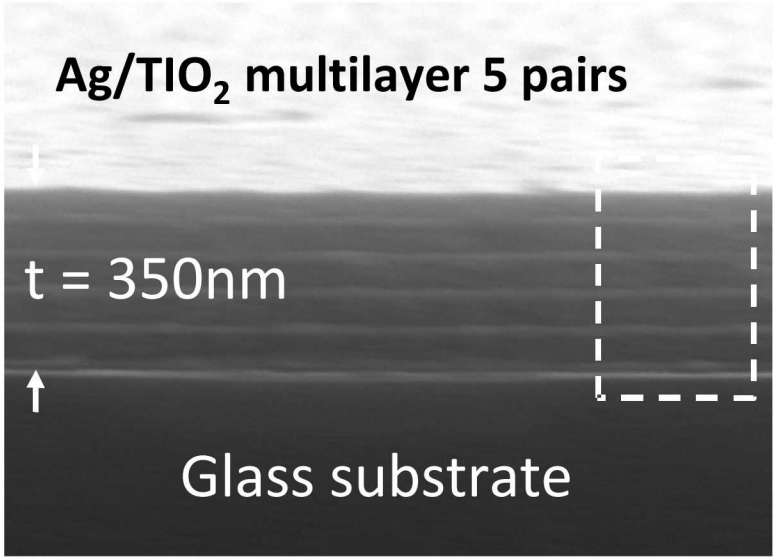
Fabricated ENZ samples

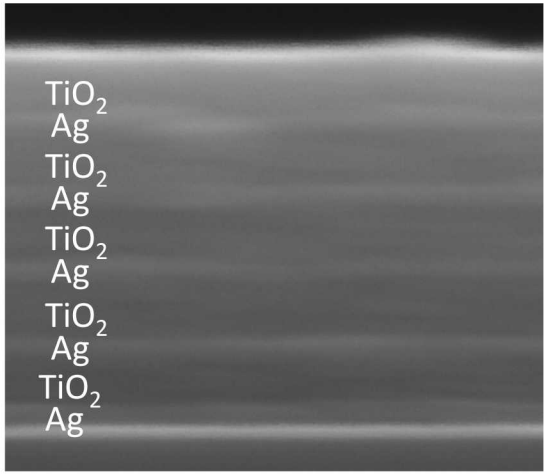
Electron beam evaporation of alternating layers of Ag and TiO_2







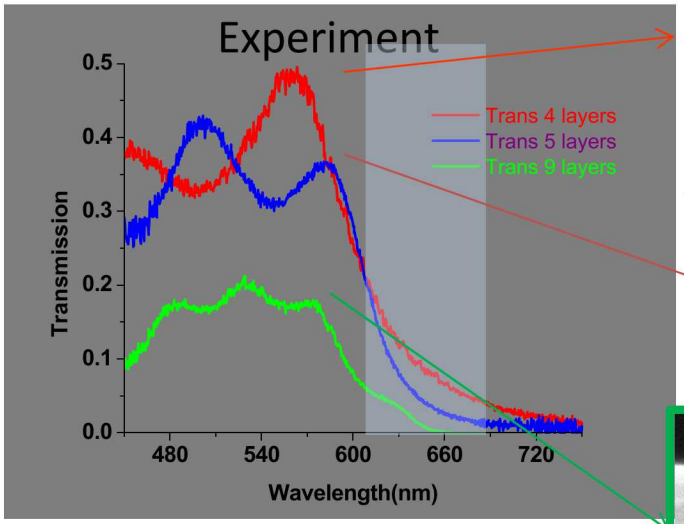




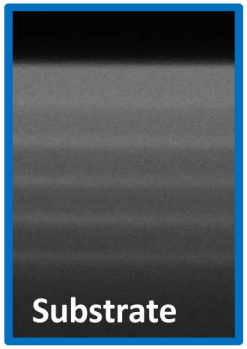
TiO2 = 54nm
Ag = 16nm

G. Subramania, A. J. Fischer, T. S. Luk , Appl. Phys. Lett. , 101, 241107(2012)

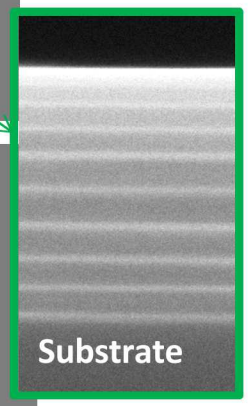
Optical Characterization and FDTD Simulations



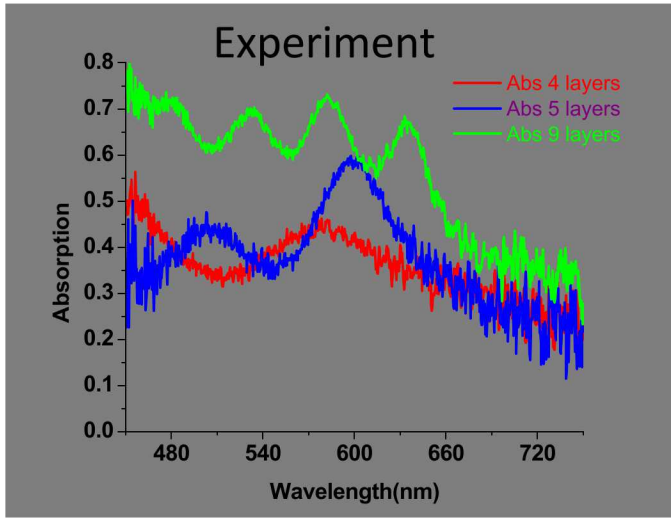
4pairs

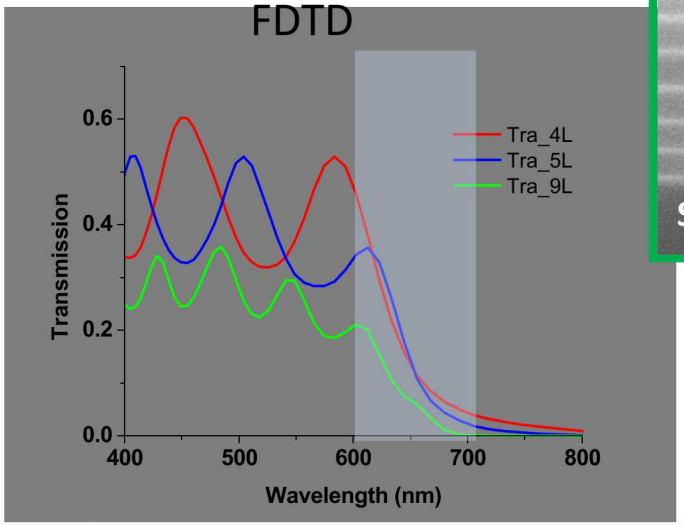


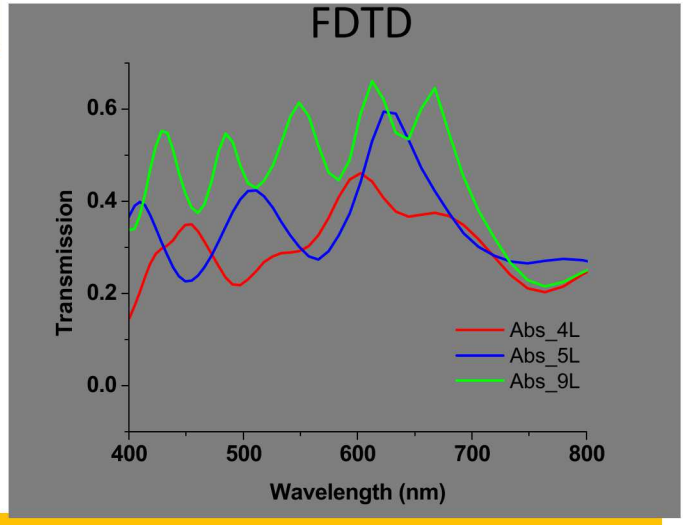
5pairs



9 pairs





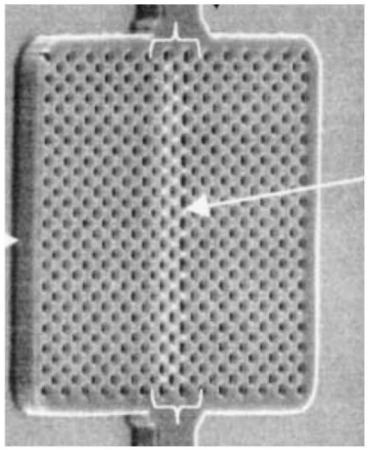


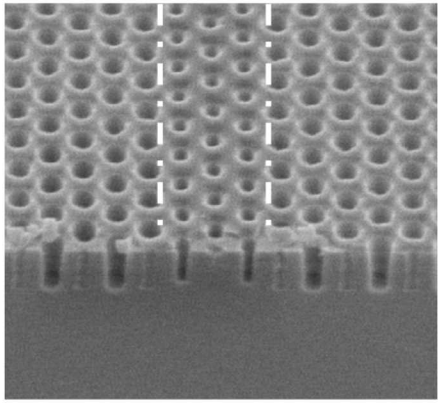
- Transmission reduces with increased number of pairs – Metal absorption
- Experimental absorption about 10% more than FDTD

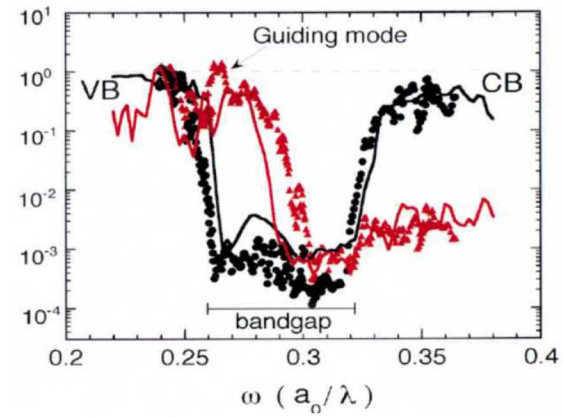
2D PhC

Two-Dimensional Photonic Crystals: GaAs based

PhC Waveguide

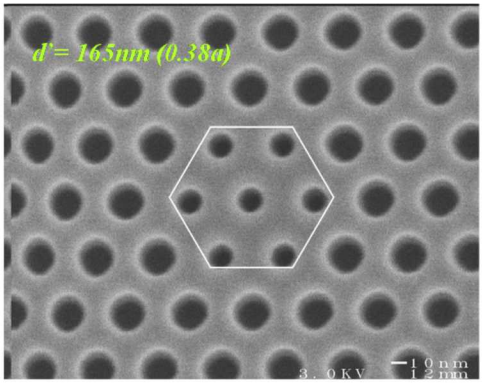


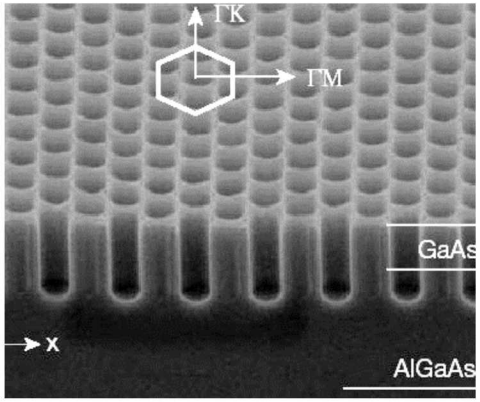


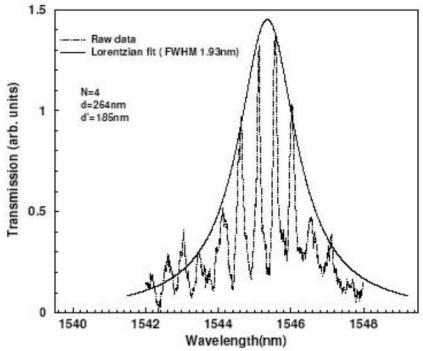


S. Y. Lin, et. al, Opt. Lett. **25**, 1297 (2000).

PhC Cavity







G. Subramania, et. al.,Applied Physics Letters **83**, 4491 (2003).

Fabrication Steps of GaAs based 2D PhC

Sandia National Laboratories

Epitaxially grown wafer stack

Deposit thin hard mask: PECVD

Patterning: E-beam lithography

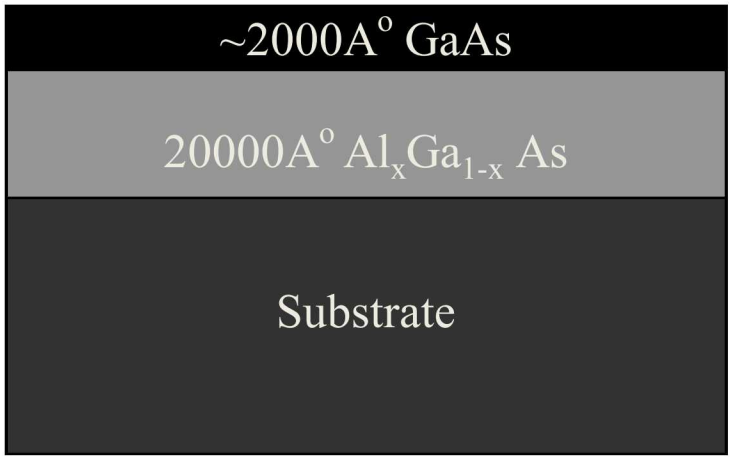
Transfer pattern into hard mask: RIE etch

Pattern transfer to active layer: DRIE etch

Oxidation of bottom cladding layer

Fabrication Steps of GaAs based 2D PhC

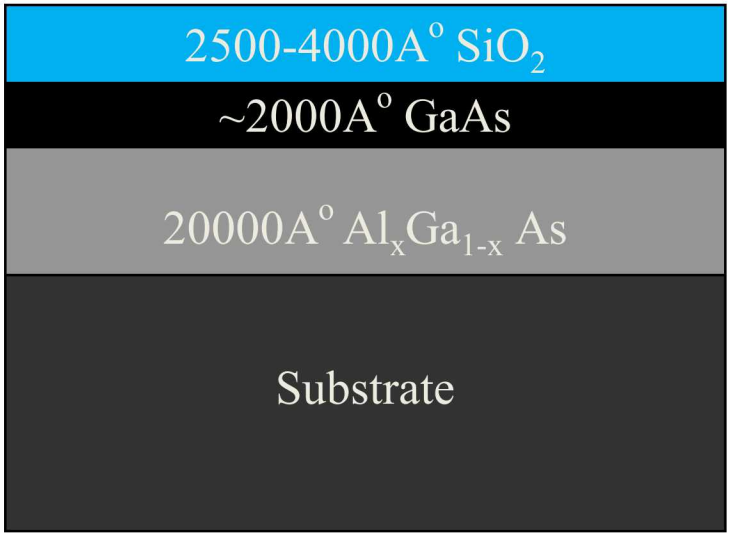
Epitaxially grown wafer stack



- MOCVD grown on GaAs substrate

$Al_xGa_{1-x}As$ substrate isolation layer with x ~ 0.75-0.9

Deposit thin hard mask: PECVD



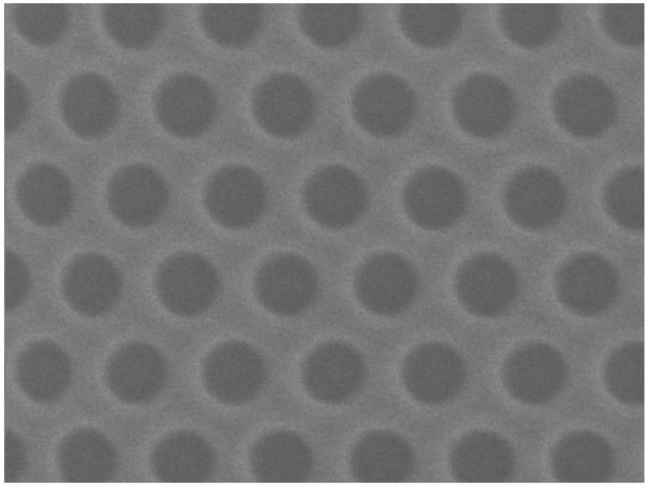
- SiO_2 hard mask needs to be thick enough to survive the subsequent deep reactive ion etch.

Fabrication Steps of GaAs based 2D PhC

Sandia National Laboratories

Patterning: E-beam lithography

- Photonic crystal pattern is first defined on a resist (PMMA) using electron beam lithography
  - typical lattice constant for λ ~ 1550nm "a" = 400-500nm
  - typical bulk hole diameters "d" = 250nm - 350nm
- Other possible resists : ZEP520™
- Choice of resist thickness is important
  - Depends on the size of the features needed to be patterned
  - Also depends on thickness of hard mask and selectivity during the subsequent etch process



G. Subramania, et. al.,Applied Physics Letters **83**, 4491 (2003).

Fabrication Steps of GaAs based 2D PhC

Sandia National Laboratories

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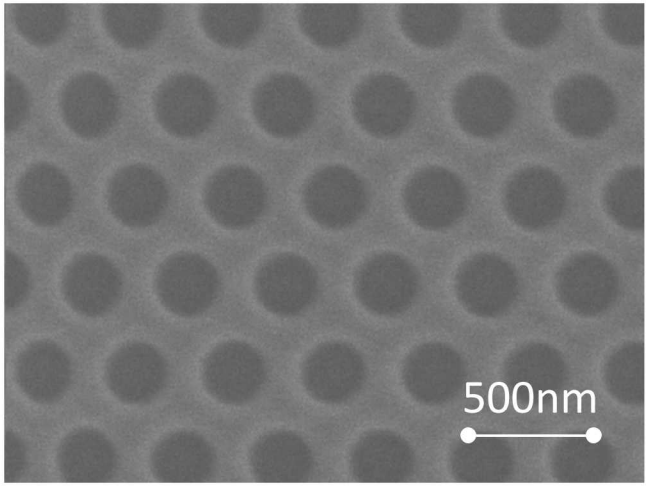
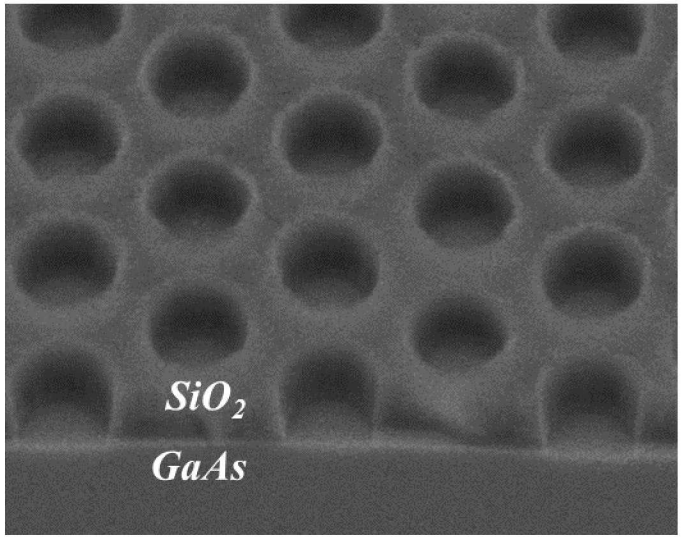


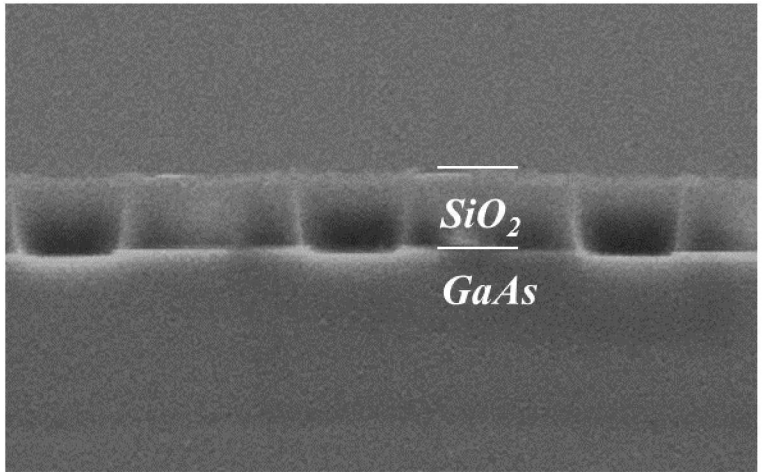
G. Subramania, et. al.,Applied Physics Letters **83**, 4491 (2003).

Fabrication Steps of GaAs based 2D PhC

Transfer pattern into hard mask: RIE etch

- Anisotropic dry etch of SiO_2 hard mask in a Reactive ion etch plasma chamber
- Etch chemistry
  - CF_4/O_2 or CHF_3/O_2 or CHF_3/ Ar
  - Oxygen is introduced at a small partial pressure ~ 15% to remove polymer formation
  - Alternatively Ar can also be used to sputter of the polymer
  - Total pressure (10mT – 50mT)
  - RF power (100W-300W)
  - The above numbers need to be adjusted depends on the chamber and RF circuit design and needs to be adjusted
  - Other possible etch chemistry: BCl_3



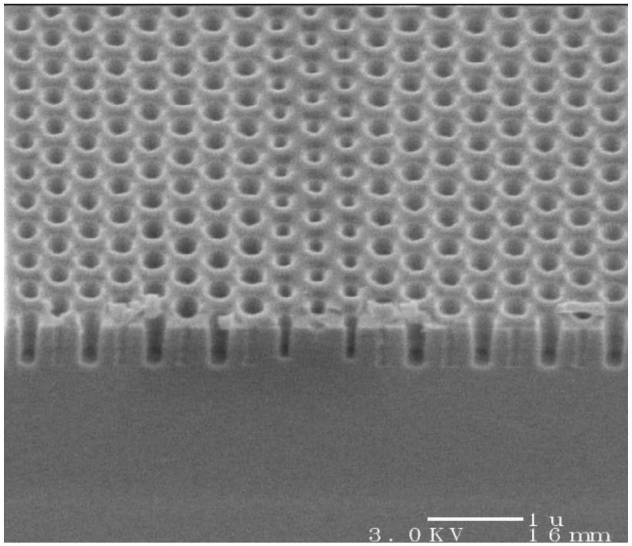


G. Subramania, et. al.,Applied Physics Letters **83**, 4491 (2003).

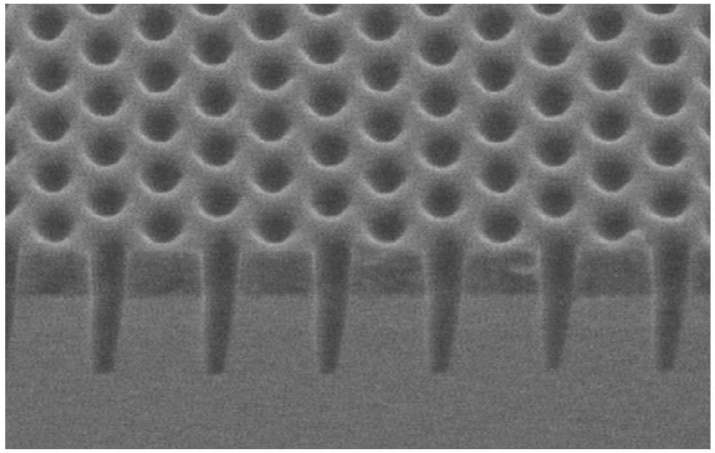
Fabrication Steps of GaAs based 2D PhC

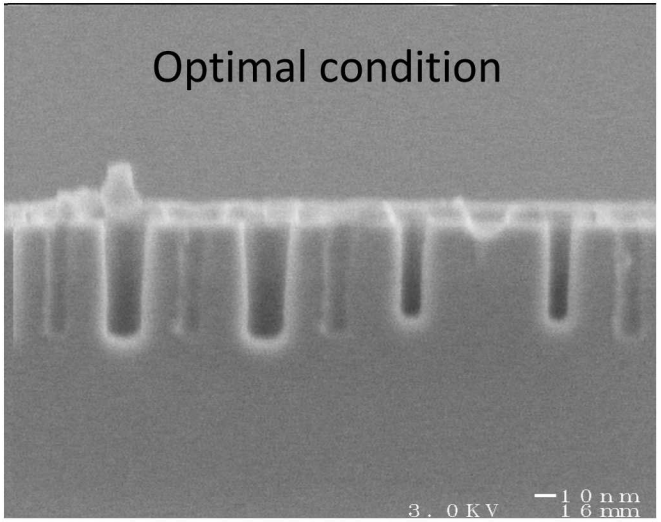
Pattern transfer to active layer: DRIE etch

- The photonic crystal patternis etched into the GaAs / AlxGa1-xAs layer underneath the SiO2 mask layer using a Cl_2/Ar based deep reactive ion etch with Ar ion beam
- Typical etch depth 0.6-1.0 μm
- Complete removal of the SiO2 in the hole region during the reactive ion etch process is essential for a vertical etch profile



Not optimal condition



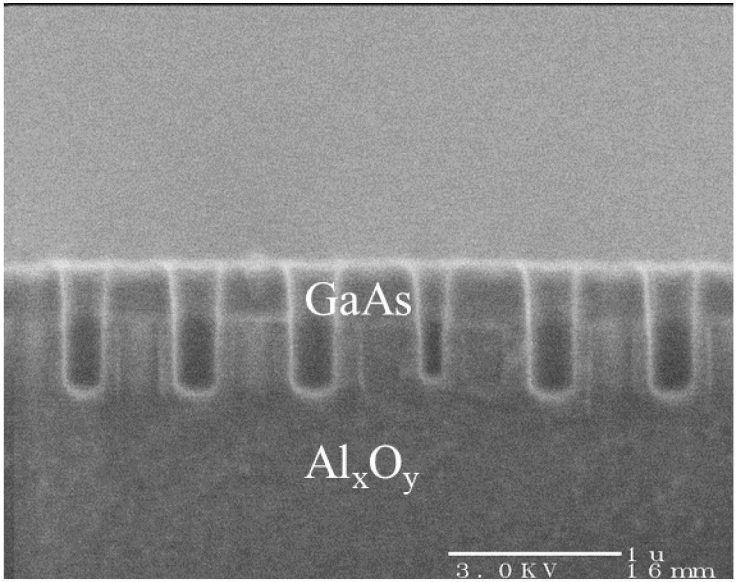


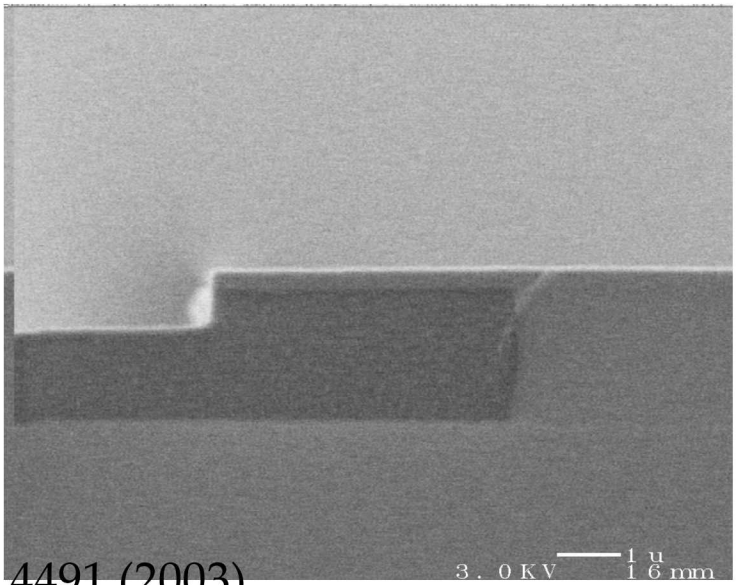
G. Subramania, et. al.,Applied Physics Letters **83**, 4491 (2003).

Fabrication Steps of GaAs based 2D PhC

Oxidation of bottom cladding layer

$Al_xGa_{1-x}As$ layer is wet- oxidized to Al_xO_y at 420-440°C to obtain a lower index cladding layer (n ~ 1.5)

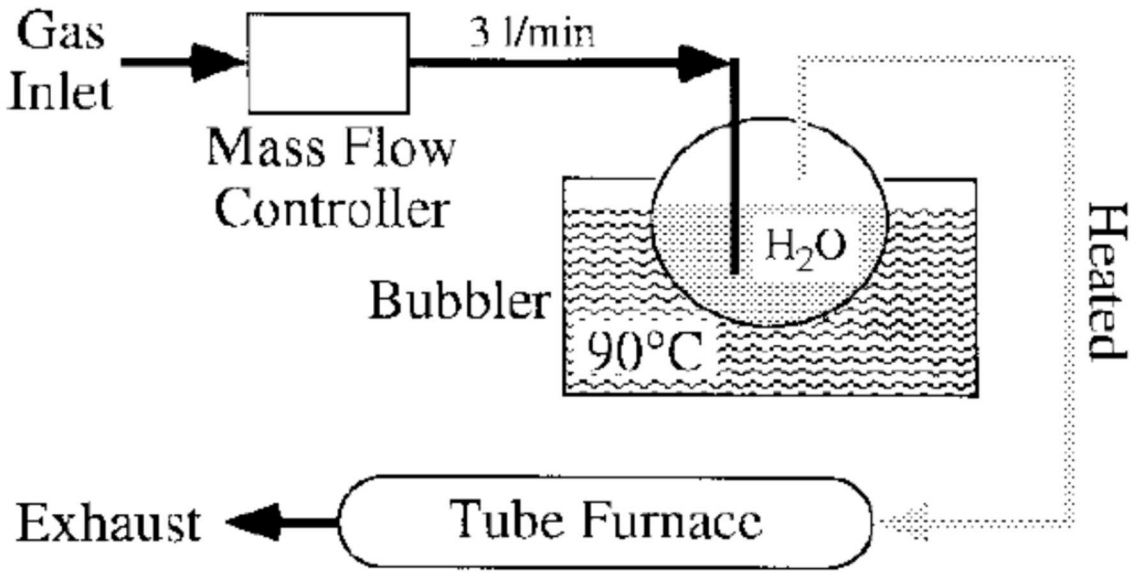




G. Subramania, et. al.,Applied Physics Letters **83**, 4491 (2003).

Oxidation of $Al_xGa_{1-x}As$

- Concept: Aluminum in the AlxGa1-xAs layer to water vapor carried in an inert gas within an elevated temperature
- Possible carrier gases : N_2 or Ar or H_2/N_2

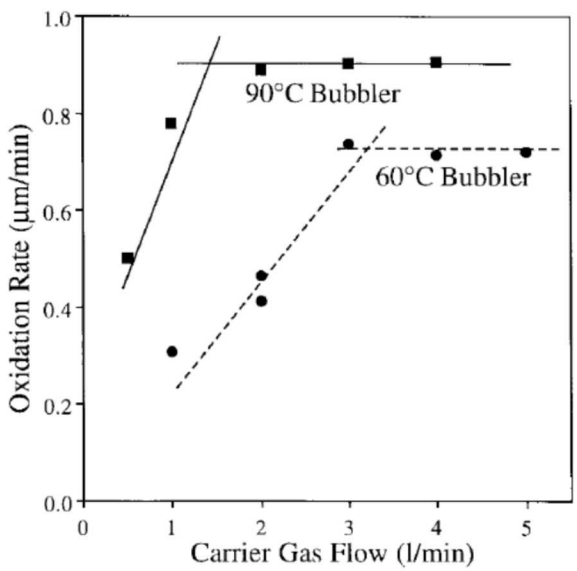


K. D. Choquette et. al., IEEE Journal of Selected Topics in Quantum Electronics 3, 916-926 (1997).

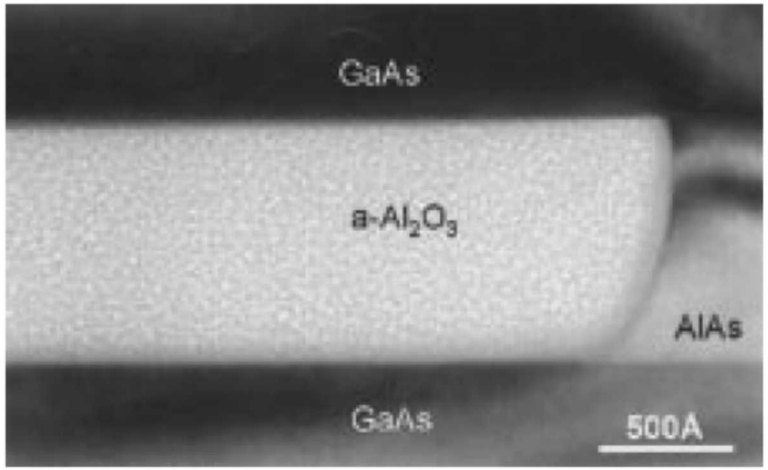
Oxidation of $Al_xGa_{1-x}As$

Reaction

$$2\ AlAs + 6\ H_2O(g) = Al_2O_3 + As_2O_{3(l)} + 6\ H_2$$
$$\Delta G^{698} = -473\ \text{kJ/mol} \quad (1)$$
$$As_2O_{3(l)} + 3\ H_2 = 2\ As + 3\ H_2O(g)$$
$$\Delta G^{698} = -131\ \text{kJ/mol} \quad (2)$$
$$As_2O_{3(l)} + 6\ H = 2\ As + 3\ H_2O(g)$$
$$\Delta G^{698} = -1226\ \text{kJ/mol.} \quad (3)$$



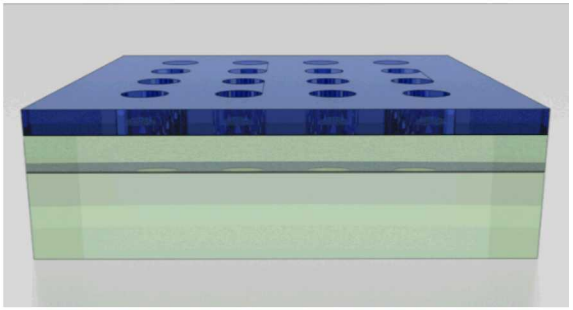
Oxidation rate depends on flow rate and bubbler temperature



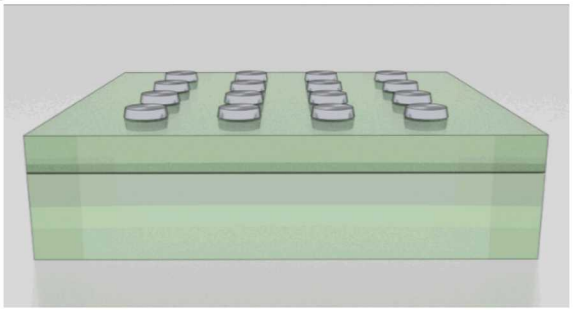
K. D. Choquette et. al., IEEE Journal of Selected Topics in Quantum Electronics 3, 916-926 (1997).

Fabrication Steps of GaN based 2D PhC

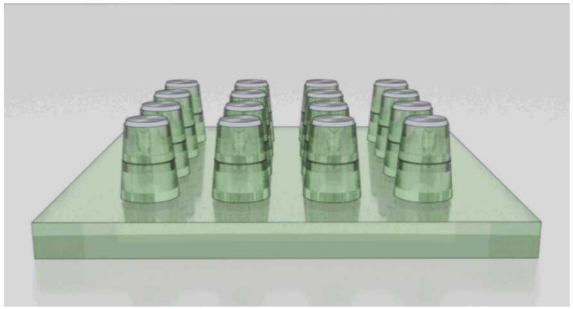
EBL pattern in PMMA



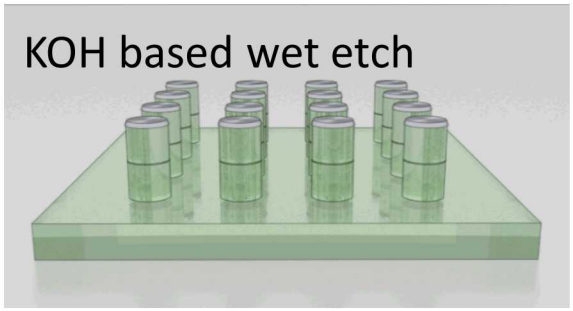
Ni evaporation and lift-off



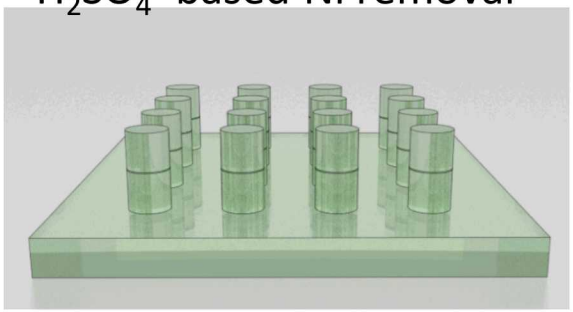
Cl2 based dry etch



KOH based wet etch

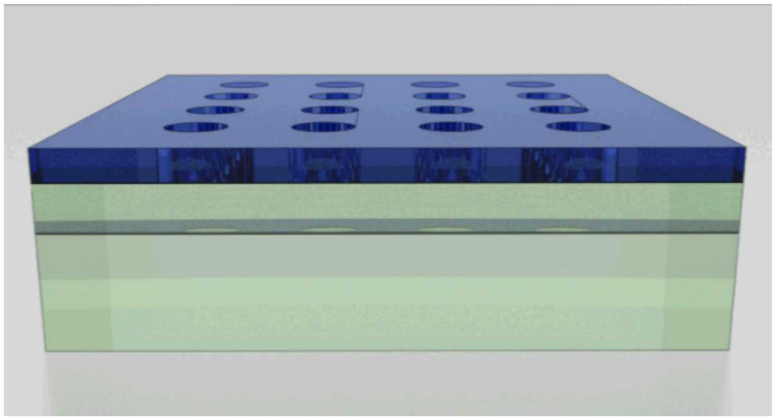


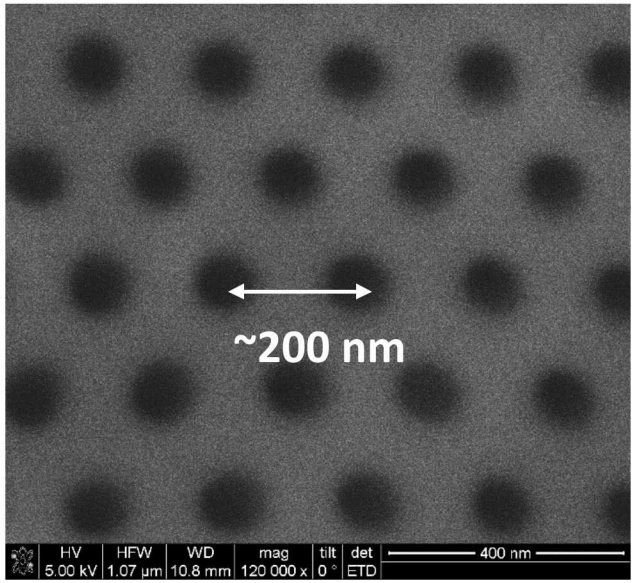
H_2SO_4–based Ni removal



Fabrication Steps of GaN based 2D PhC

EBL patterning

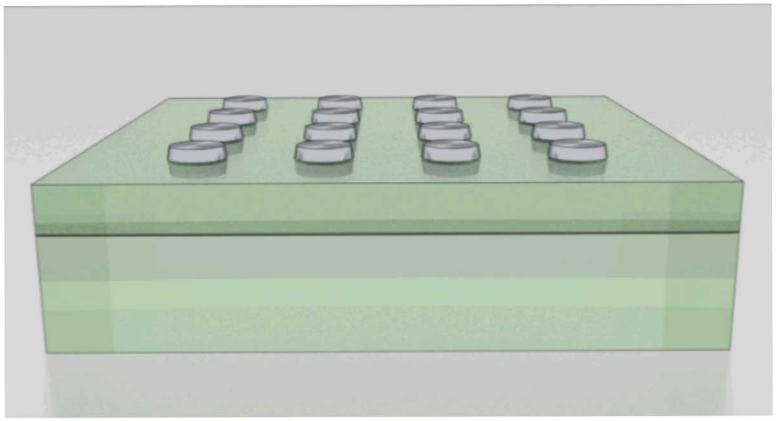


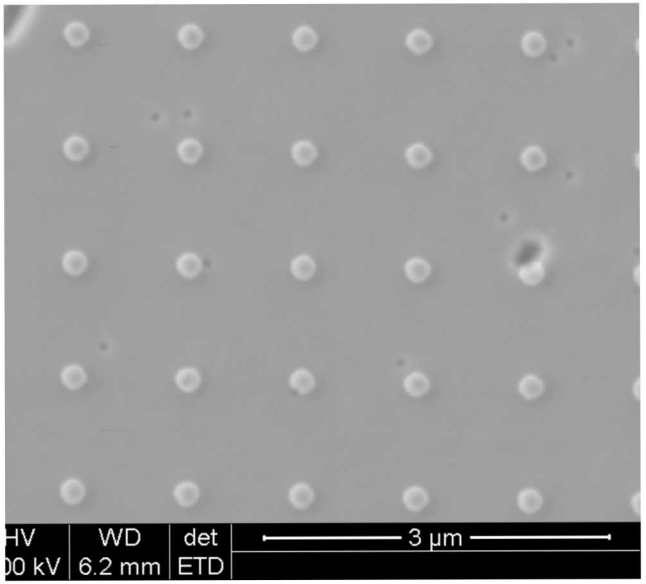


- PMMA resist 150-250nm thick
- Hole array patterns can be formed 20nm – 300nm
- Typically III-nitrides are grown on sapphire substrate which is non-conducting
- Requires a charge dissipation layer
  - Thermally deposited Au 100A thick
  - Also spinnable conducting polymer

Fabrication Steps of GaN based 2D PhC

Ni evaporation and lift-off

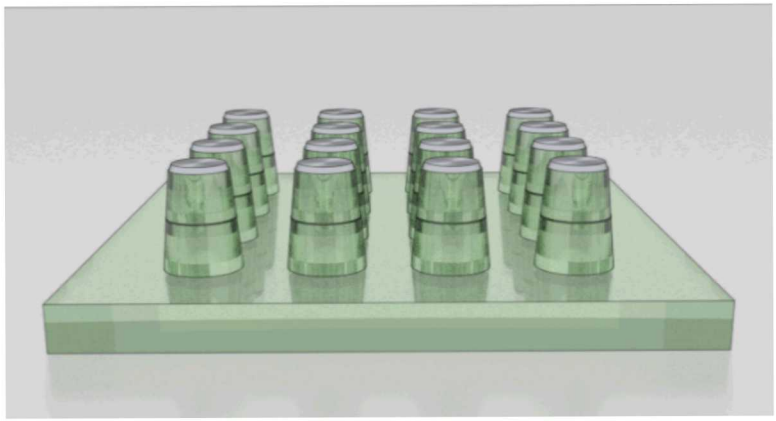


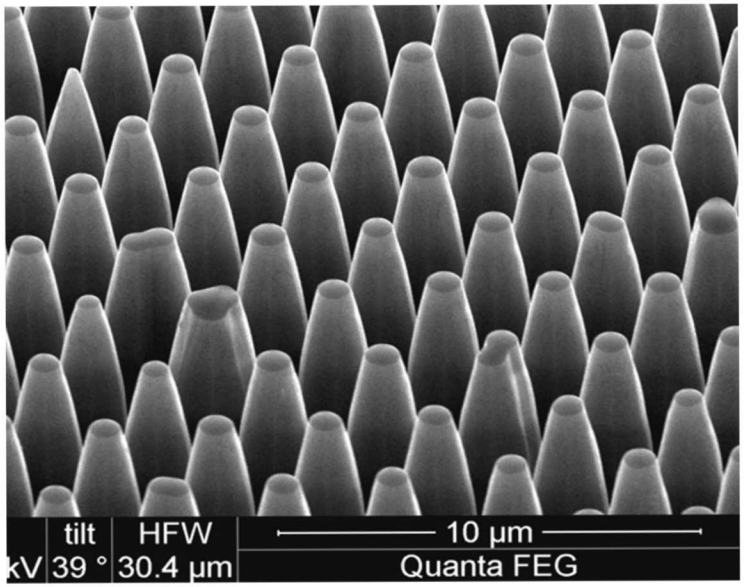


- Electron beam evaporation of Ni hard mask ~70-100nm thick
- Lift-off by soaking in Acetone for ~ 1hr
  - Can use medium strength ultrasonication
- or hot (80°-90°C) n-Methyl-2-Pyrrolidone (NMP)

Fabrication Steps of GaN based 2D PhC

Cl_2 based dry etch

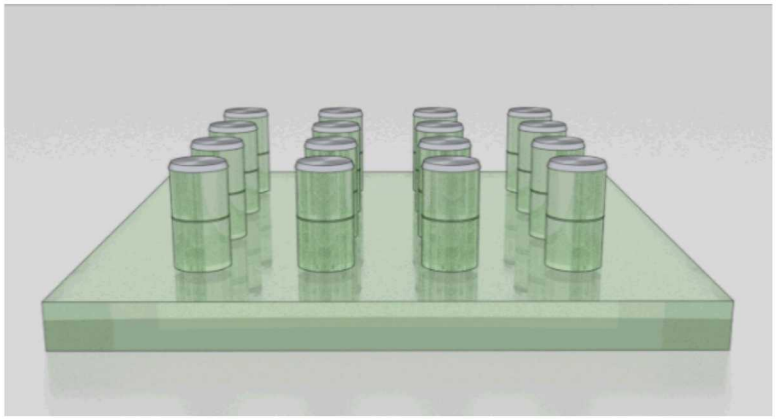


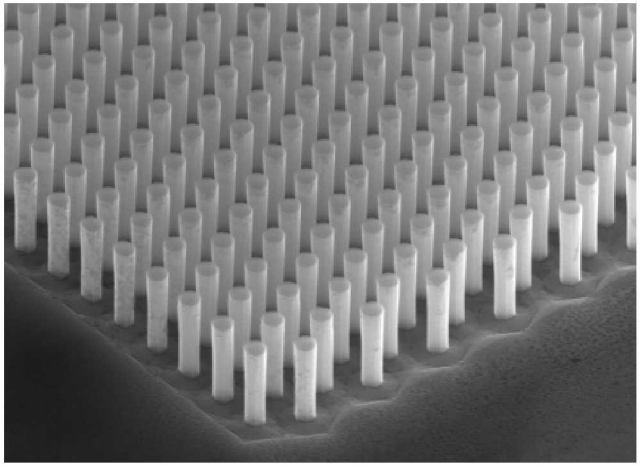


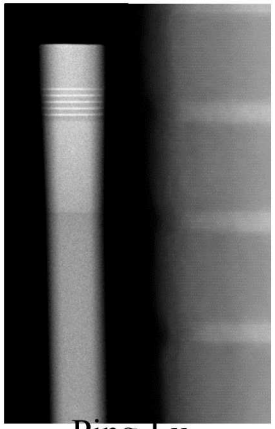
- Anisotropic dry etch -Inductively coupled plasma etch
- Cl_2/BCl_3 based etch
- Results in a conical shape of the III-N rods
- Etch selectivity of > 10 can be achieved

Fabrication Steps of GaN based 2D PhC

KOH based wet etch







Ping Lu, Sandia

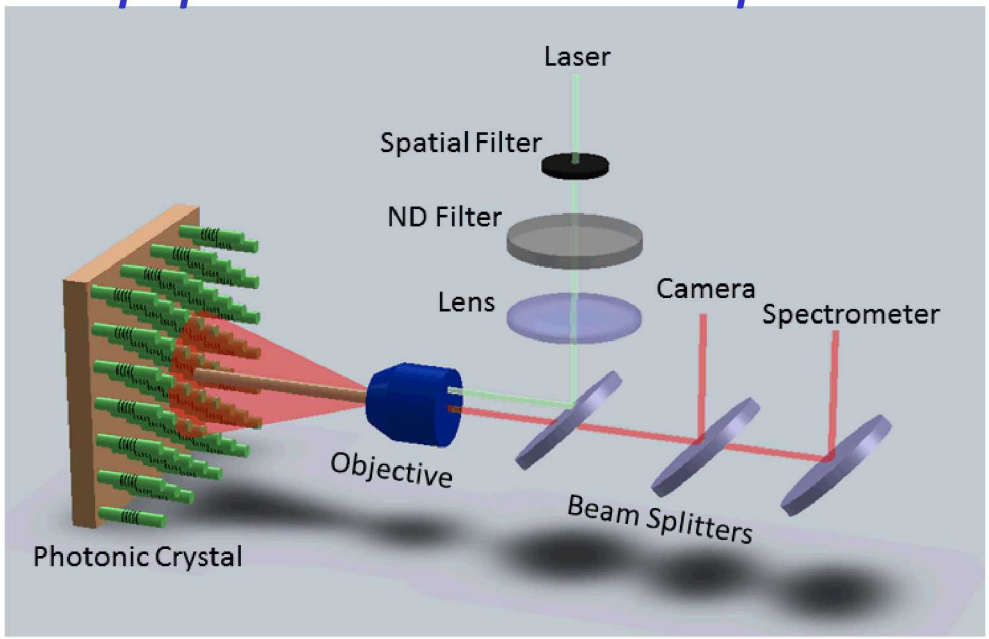
- The dry etch is followed by a wet etch in KOH for ~3-5min at 60°-70°C
- Wet etch selectively etches away plasma damged c-plane regionleaving nanorods of cylindrical morphology
- The surfaces are atomically smooth
- The remaining Ni hard mask can be

J. B. Wright et. al. Sci. Rep. **3**, 2982 (2013).

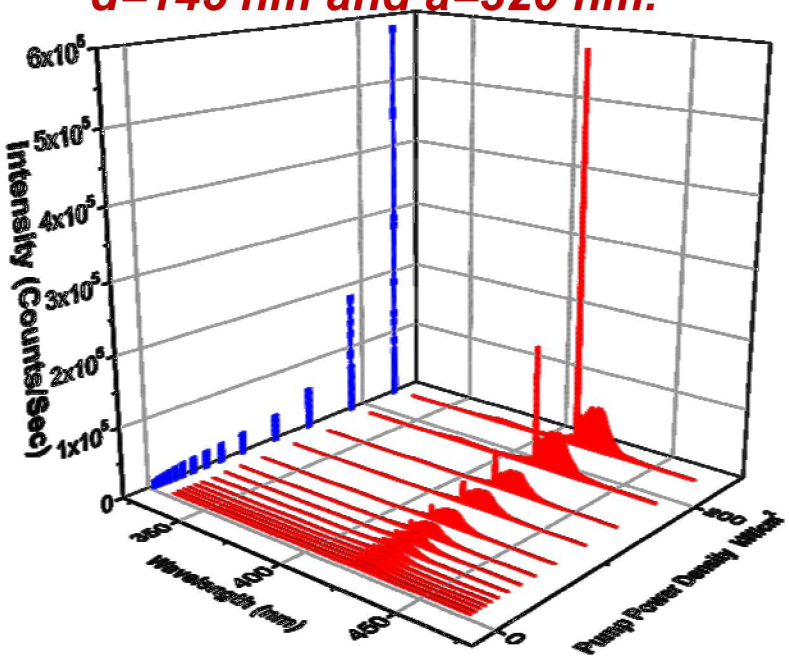
P. D. Anderson, .. and G. Subramnia , Optical Materials Express **7**, 3634-3642 (2017).

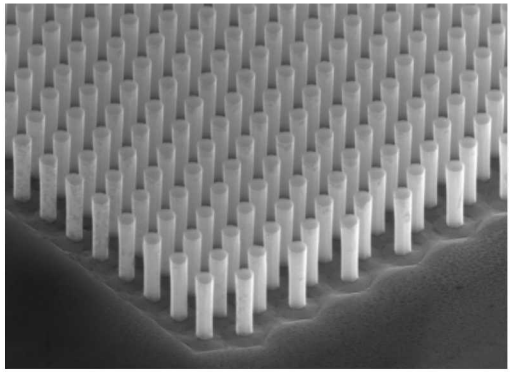
2D PhC for low threshold lasing

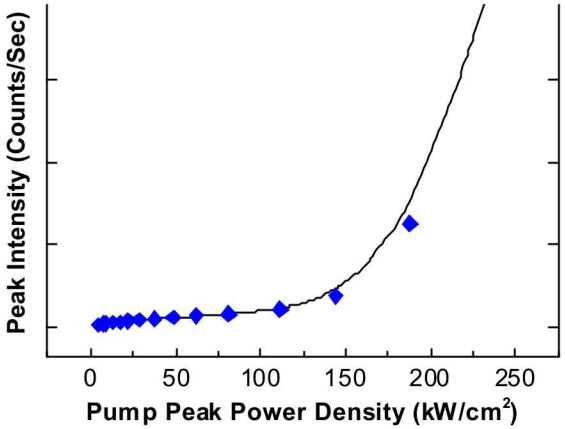
Pump spot is tunable in size and power density.



Array Element Dimensions: d=145 nm and a=320 nm.

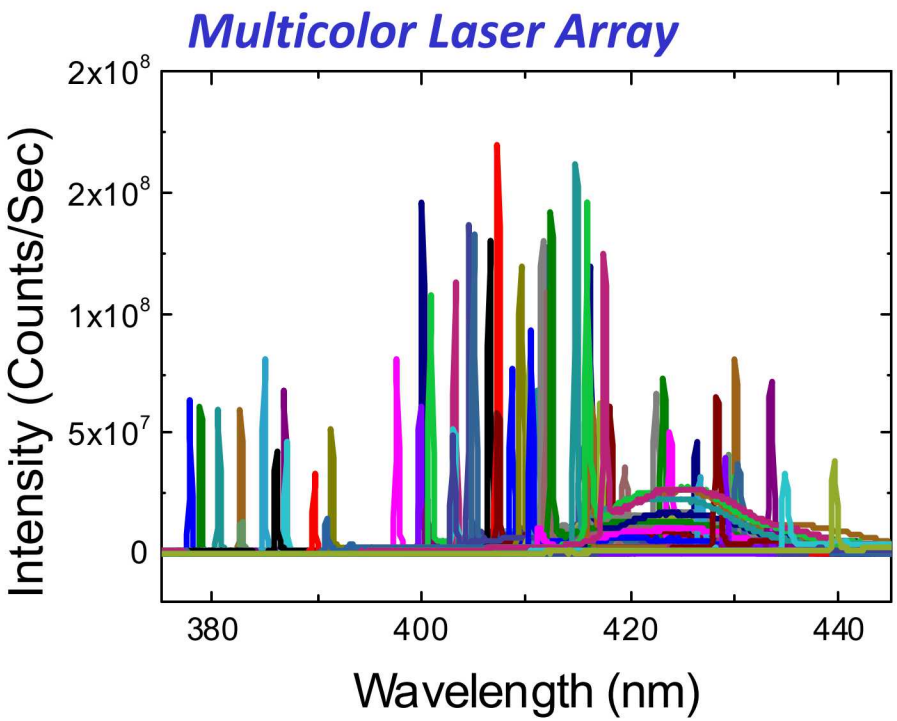


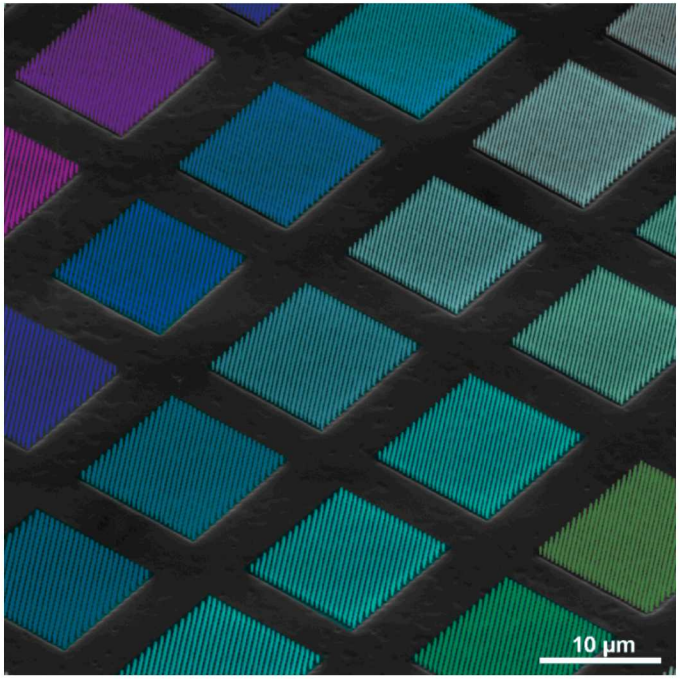




A low lasing threshold is achieved with < 500kW/cm2 for all PC lasers fabricated.

2D PhC for low threshold lasing



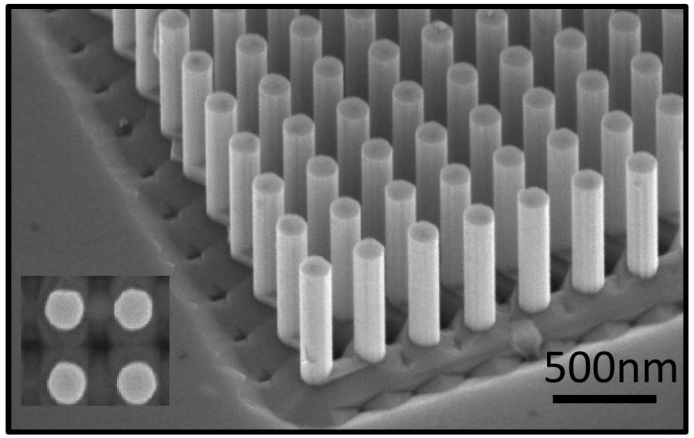


- *Wavelength tunability (lattice constant and nanowire diameter).*
- *Multiple color laser emission on a single epitaxial wafer covering a spectral range from 380-440nm.*

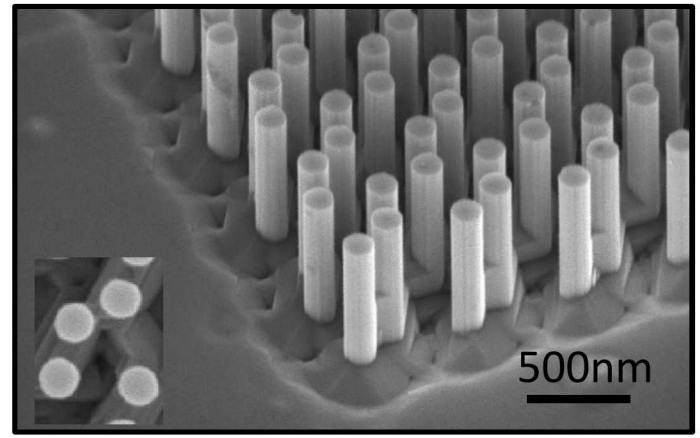
J. B. Wright et. al. Sci. Rep. **3**, 2982 (2013).

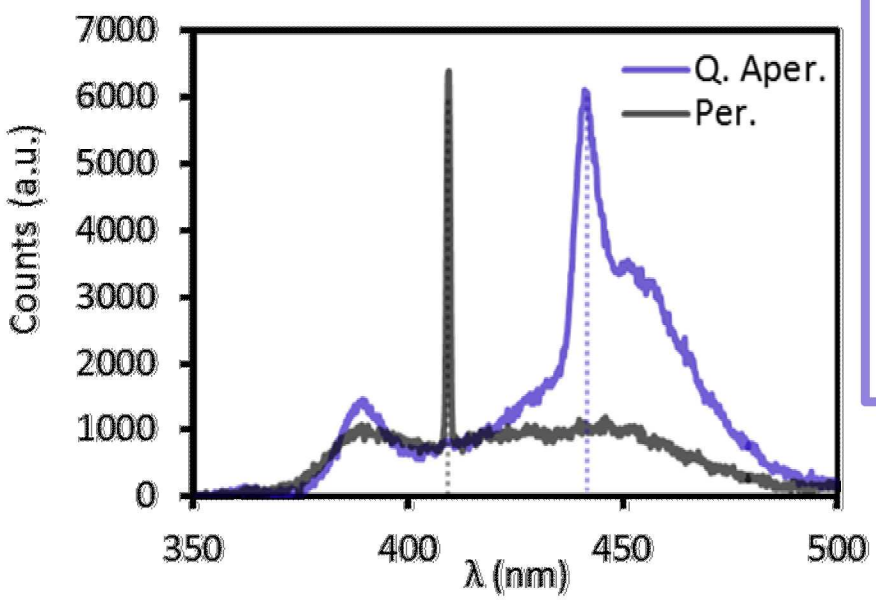
2D PhC for Farfield Beam Shape Control

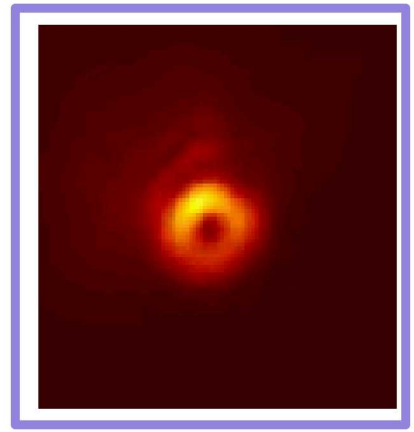
Periodic

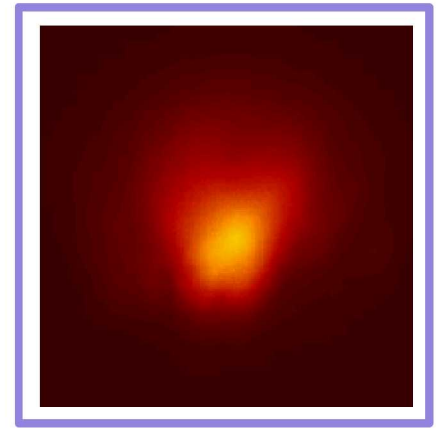


Quasi Periodic





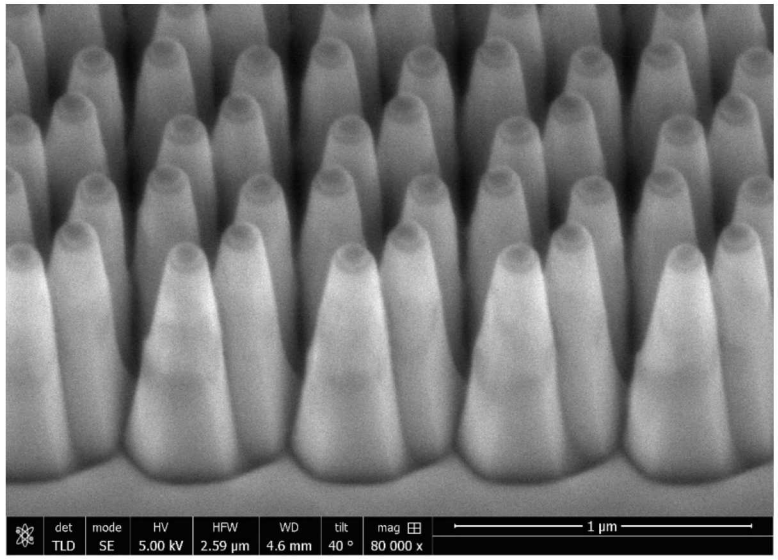


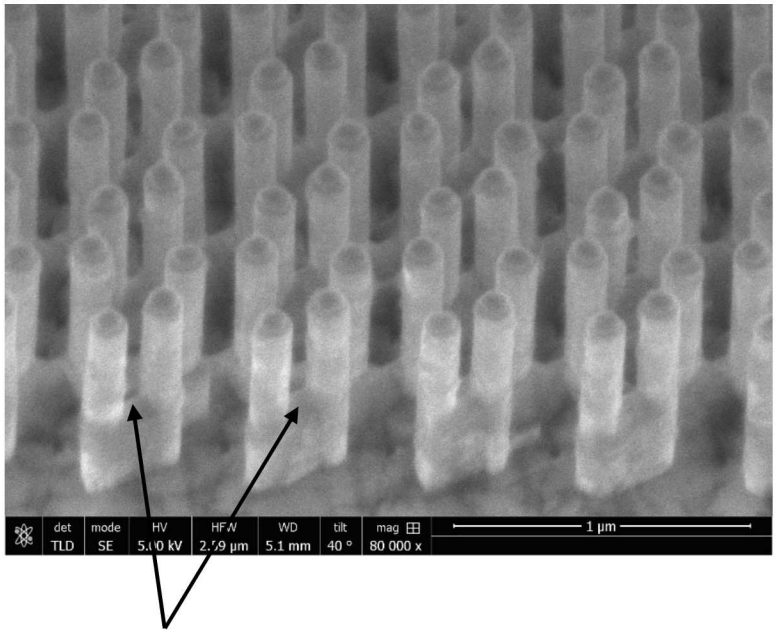


P. D. Anderson, . . and G. Subramania, Optical Materials Express **7**, 3634-3642 (2017).

2D PhC for Farfield Beam Shape Control

- Example : lattice spacing (average) 280nm ; rod design radius 60nm
- Proximity of rods can affect dry etch profile
- Subsequently affects wet etch depth – ‘bridging interconnects’

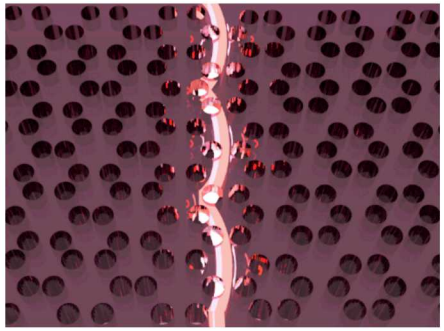




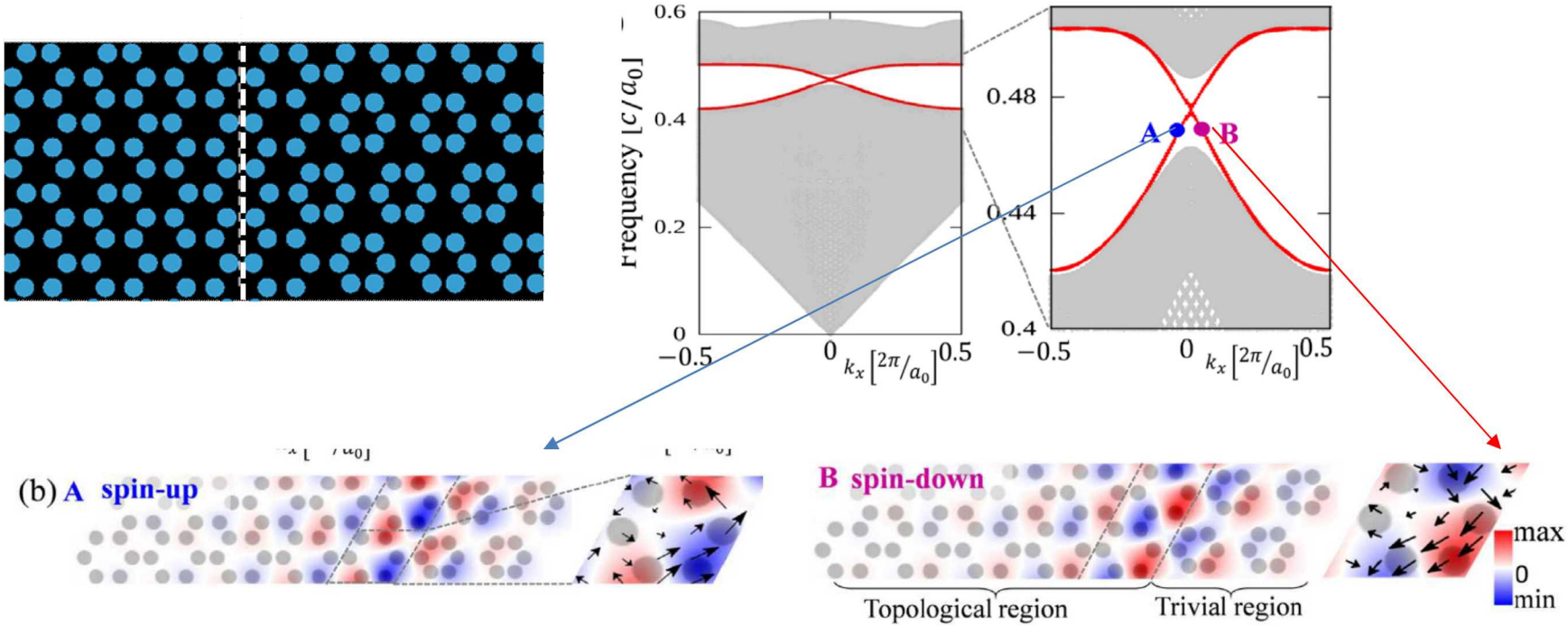
‘bridging interconnects’

P. D. Anderson, .. and G. Subramnia , Optical Materials Express **7**, 3634-3642 (2017).

Topological Photonics

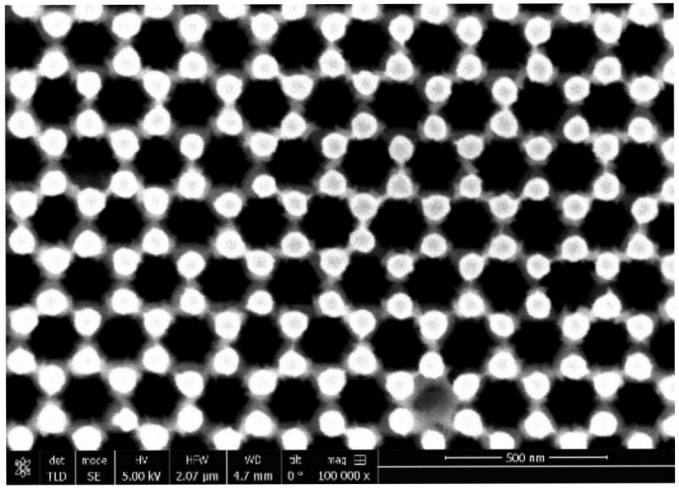


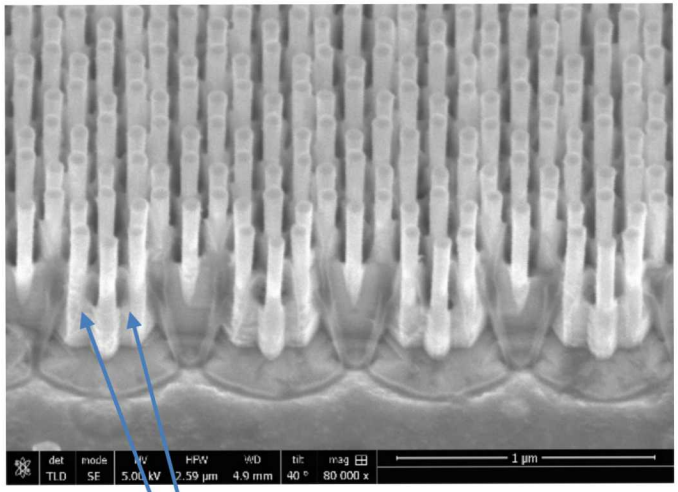
An interface between a PhC of topologically trivial and non-trivial bandgaps can have pseudo-spin dependent unidirectional edge states

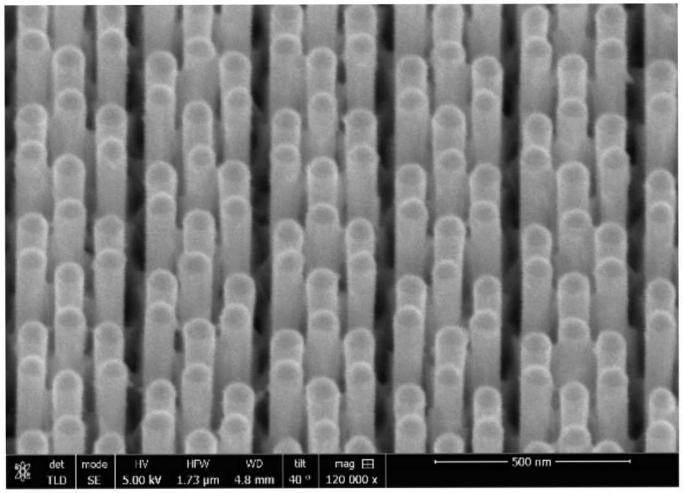


L.-H. Wu, and X. Hu, "Scheme for Achieving a Topological Photonic Crystal by Using Dielectric Material," Phys. Rev. Lett. **114**, 223901 (2015).

Fabrication of Topological Photonic Structures in III-nitride

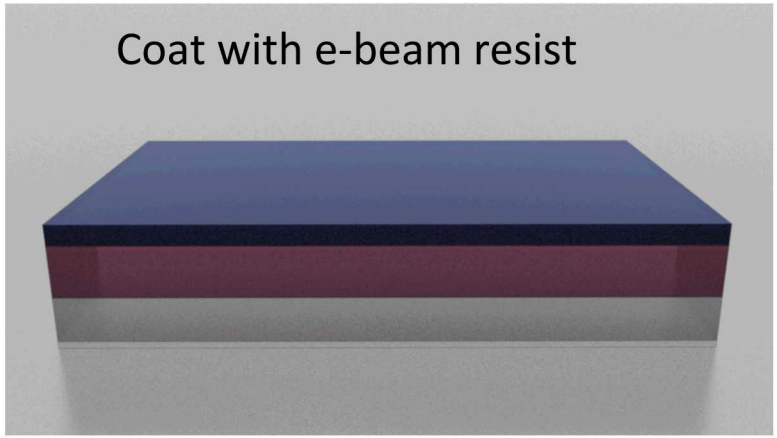


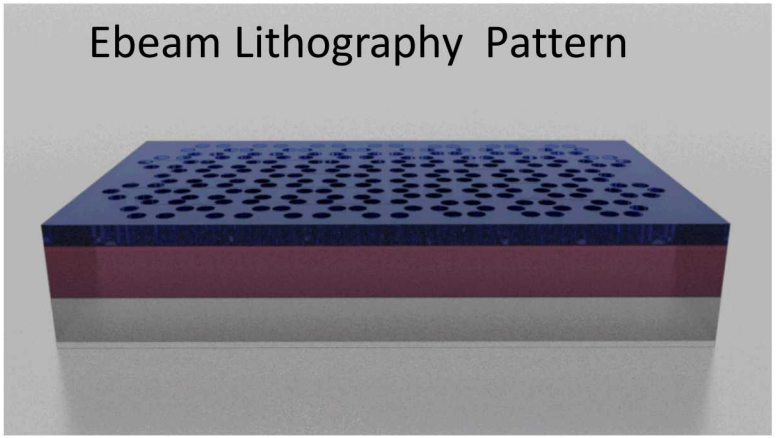


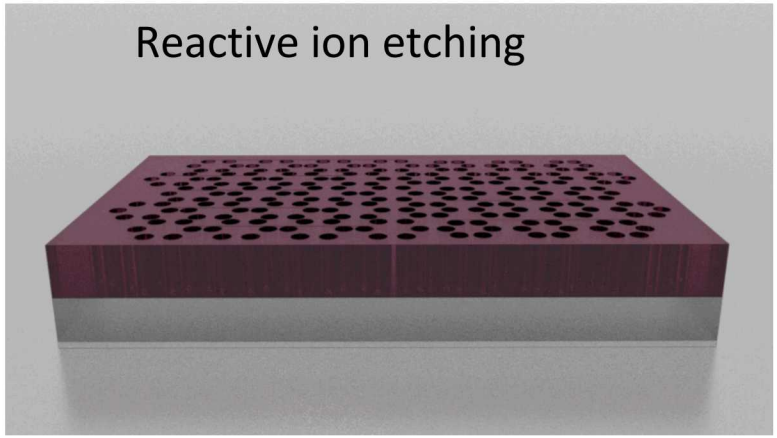


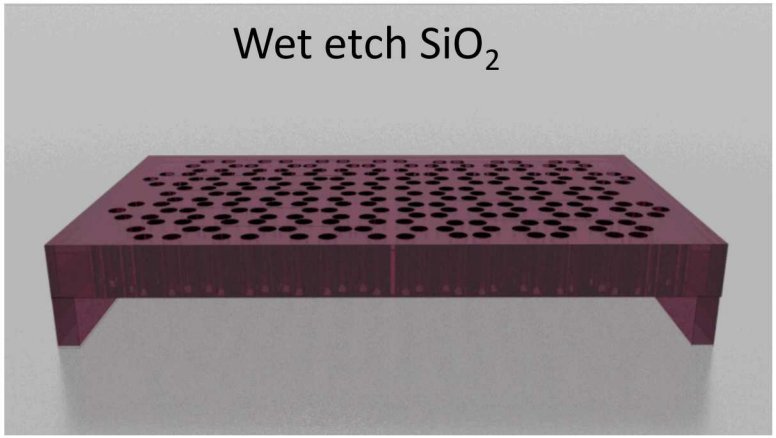
Bridging interconects

Fabrication of Topological Photonic Structures in Silicon-on-insulator





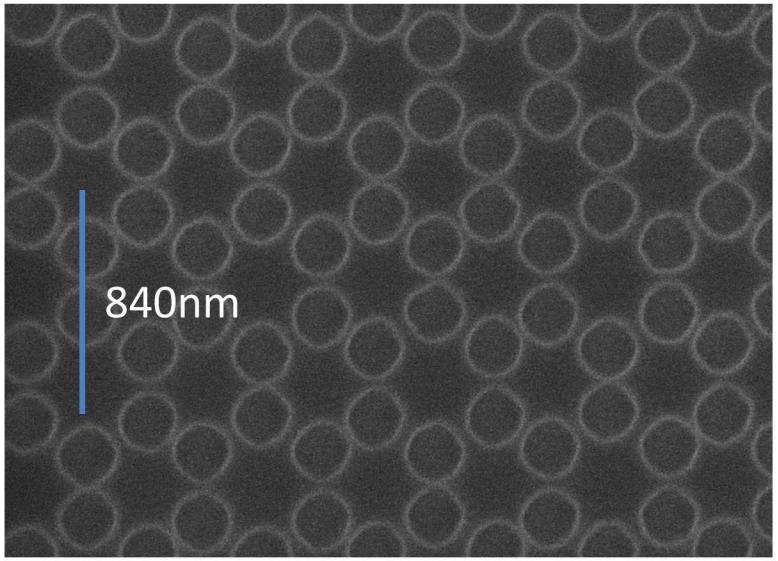




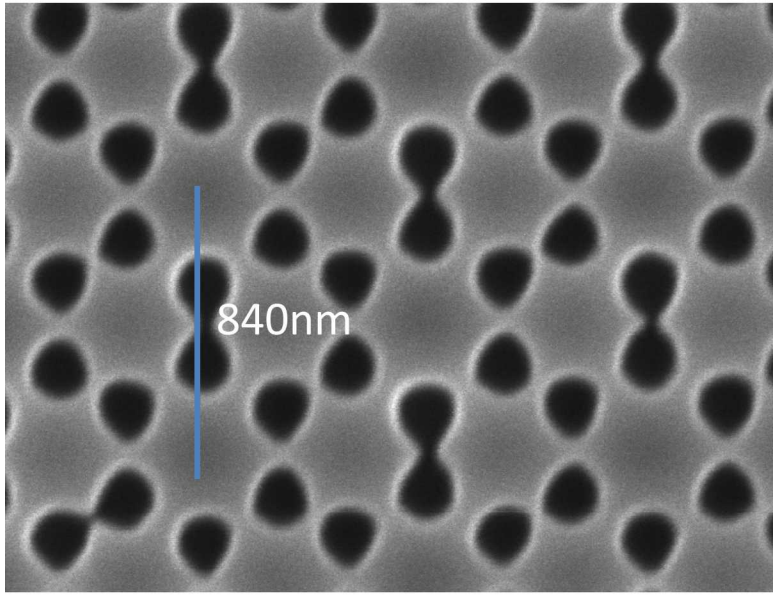
Fabrication of Topological Photonic Structures in Silicon-on-insulator

- Hole radius ‘r’= 0.13*840= 110nm or ‘d’ ~ 220nm
  - Typical feature sizes at the necks ~ 30-50nm

After pattern write in resist



After pattern transfer

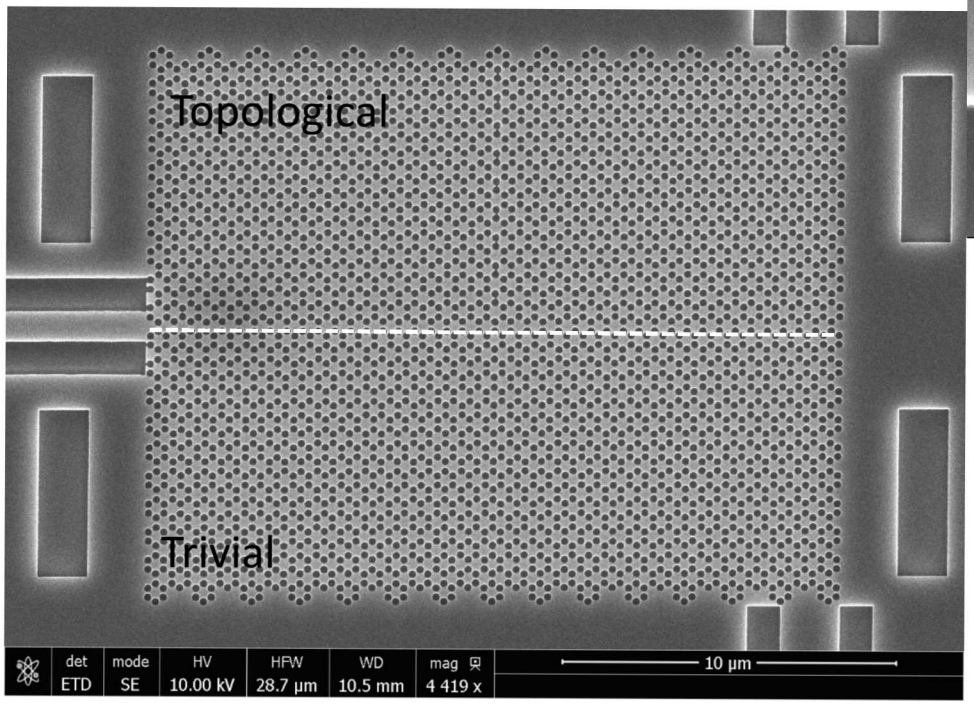


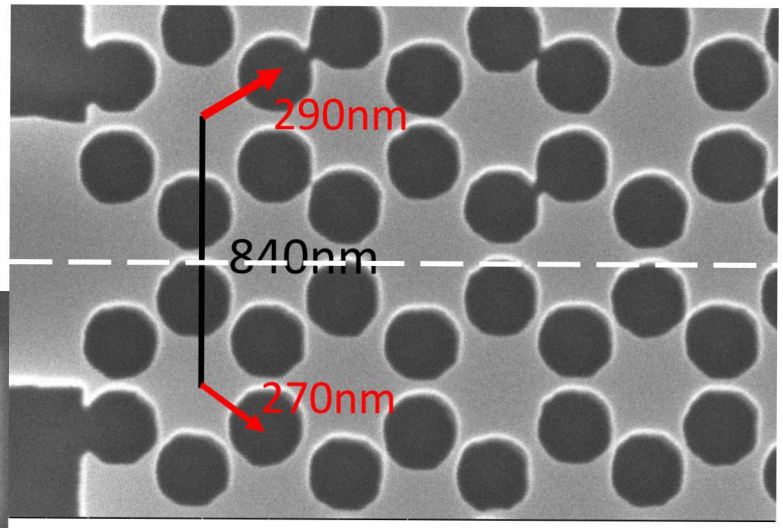
Issues with ‘necking’ of adjacent holes - addressed with SiO2 hard mask

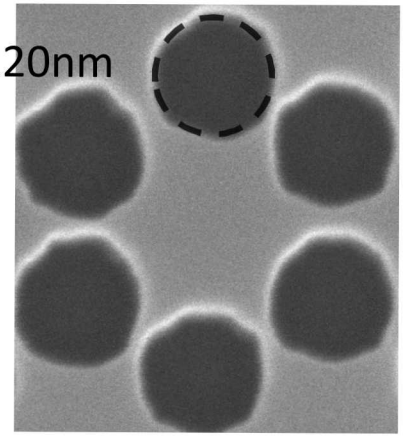
Fabrication of Topological Photonic Structures in Silicon-on-insulator

Pattern transfer to Si

- ~ 50 nm SiO2 is used as hardmask for pattern transfer
- Highly selective HBr based RIE for Si etch

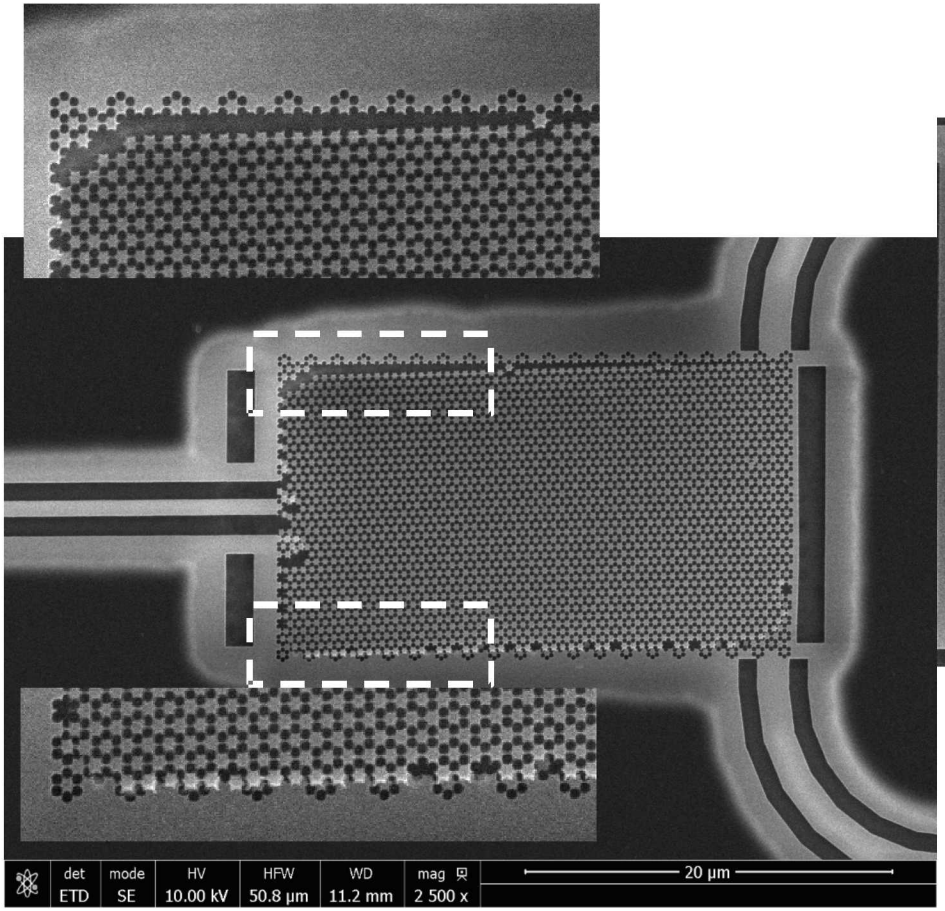


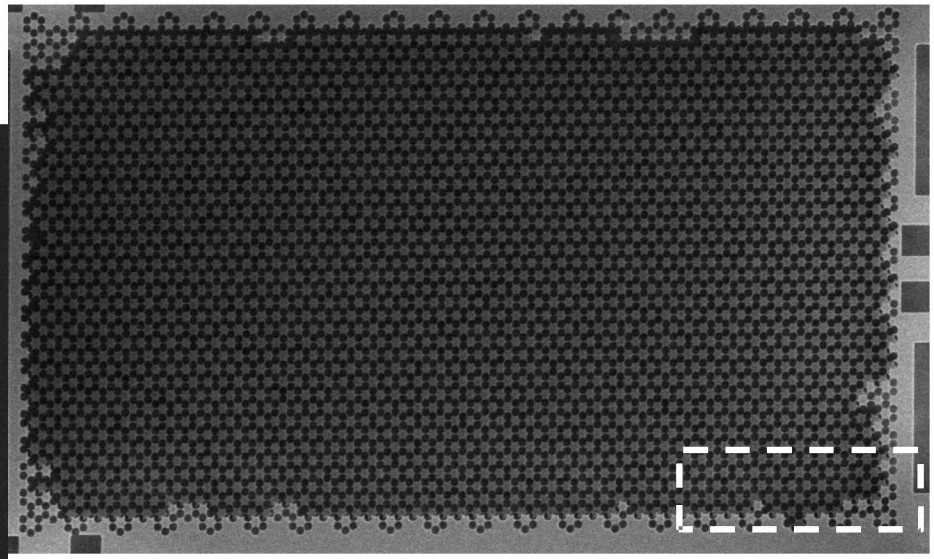


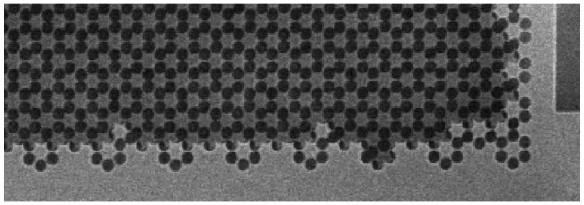


Fabrication of Topological Photonic Structures in Silicon-on-insulator

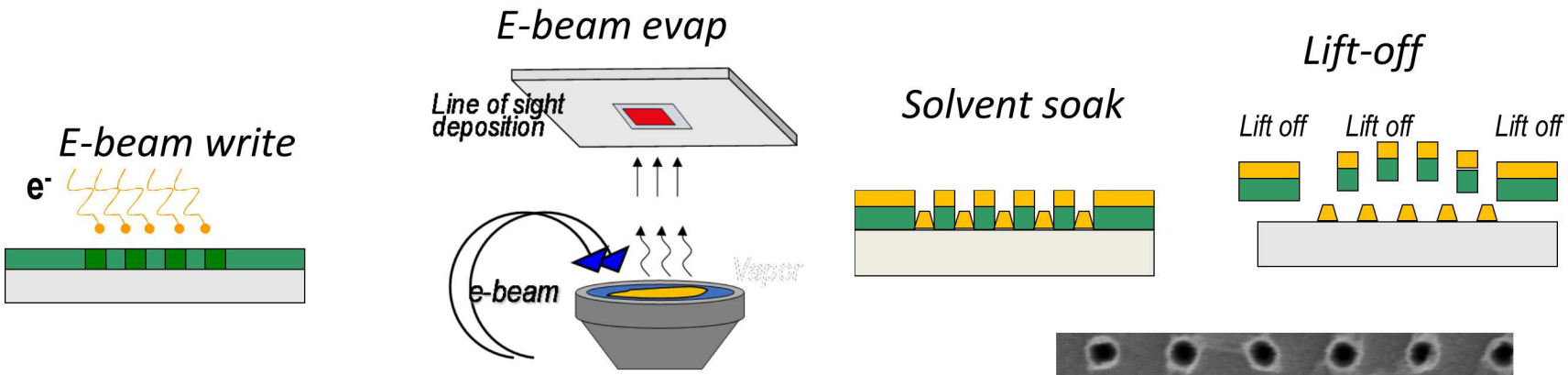
- Wet etch in buffered oxide etchant for 15-20min : 1.6 to 1.8 μm deep
- Narrow bridge necks + Si epi stress causes some challenges

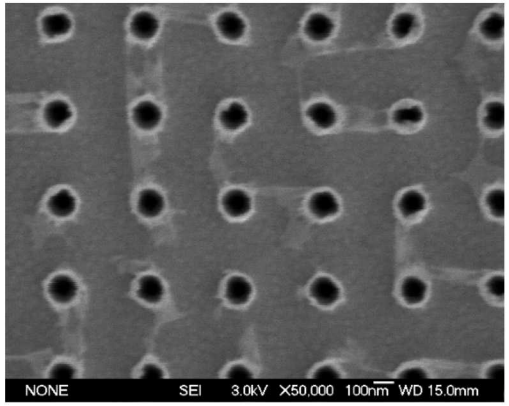


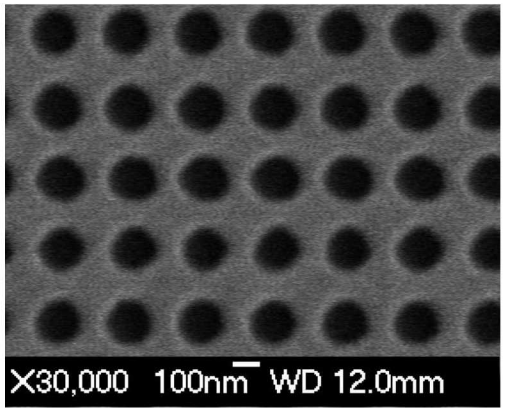




Nanofabrication of Metal Nanostructures

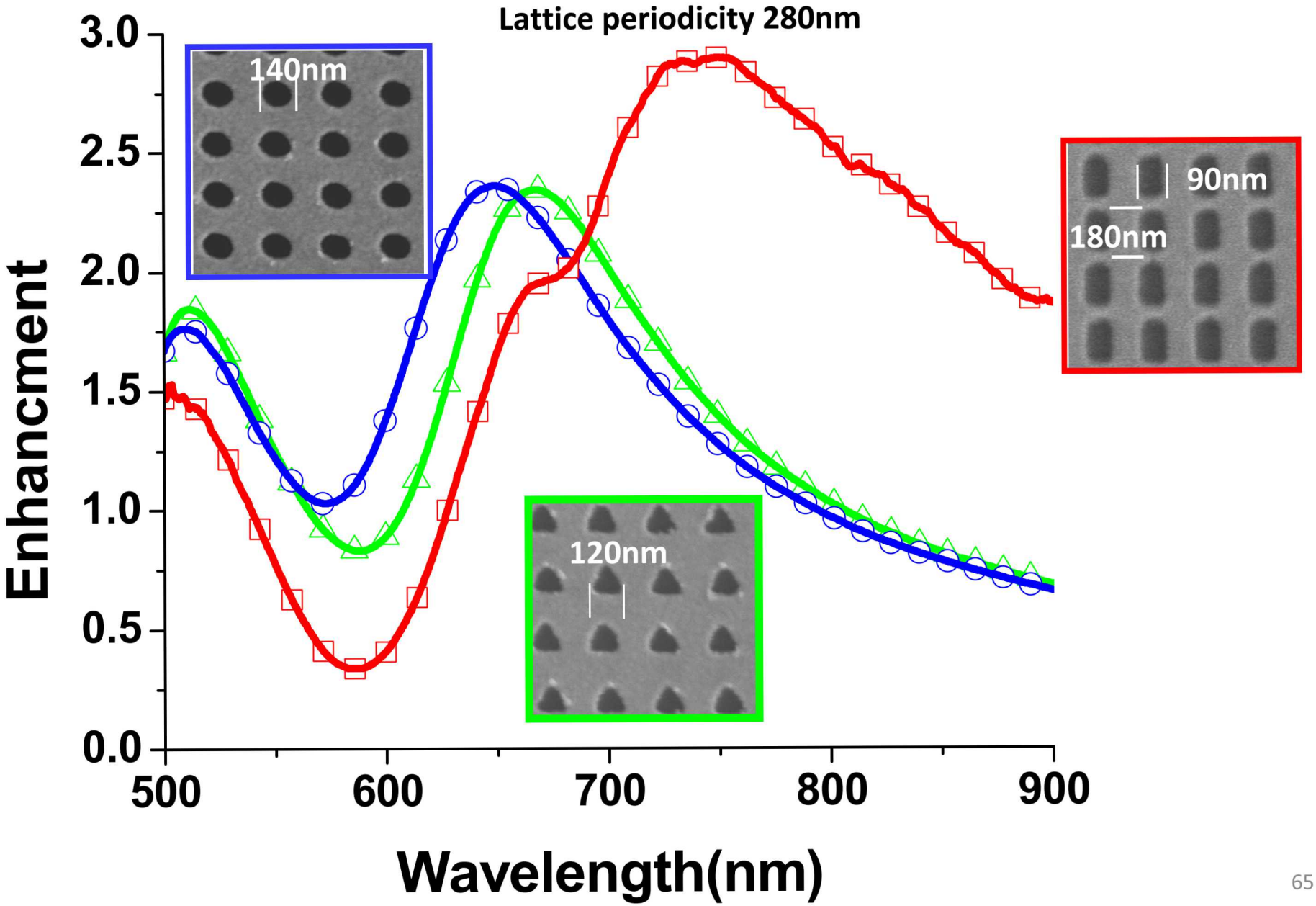




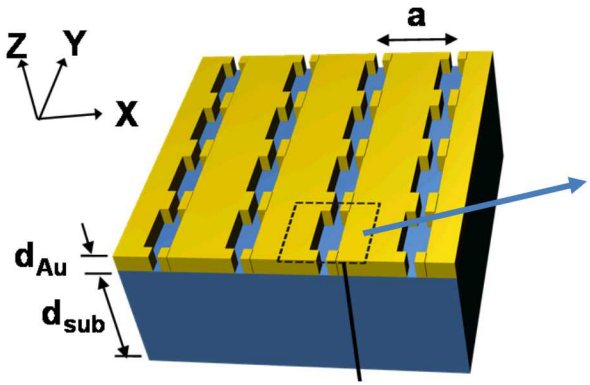


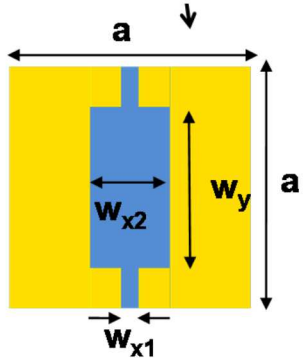
- For holes in continuous metals one can write aperture pattern in negative tone resist, deposit metal and perform lift-off
  - Faster write, e-beam negative resists sensitive -hole size harder to control, lift-off difficult
- Alternatively you can expose everything outside the aperture region , deposit metal and perform lift-off
  - Slower, better dose latitude better control of hold shape and size

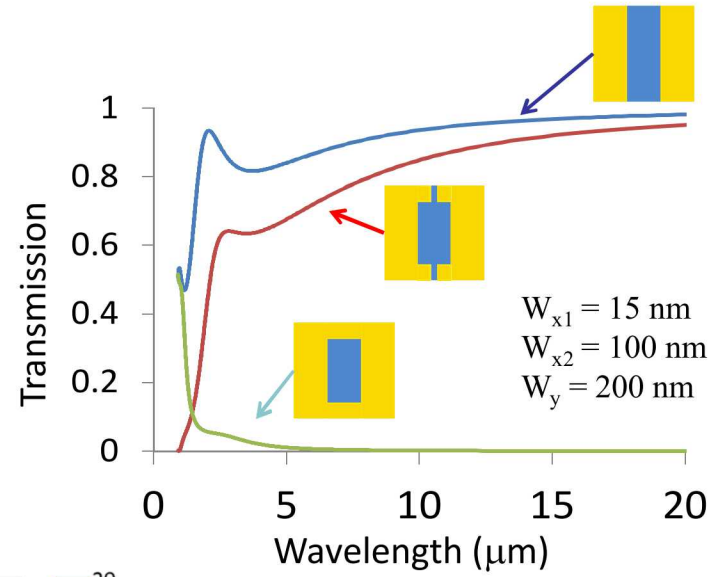
Metal nanostructures for Extraordinary Optical Transmission

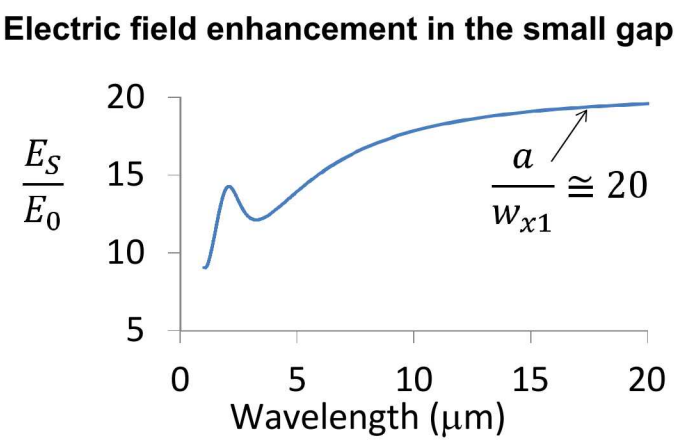


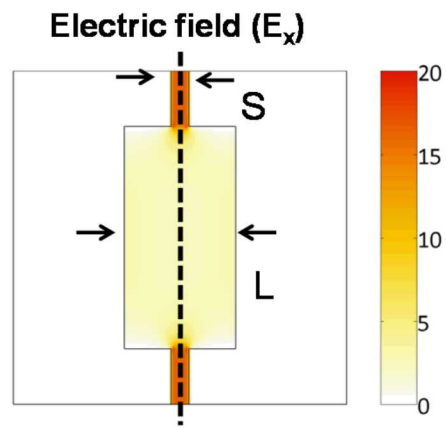
Non-resonant Broadband Ultra-subwavelength Light confinement

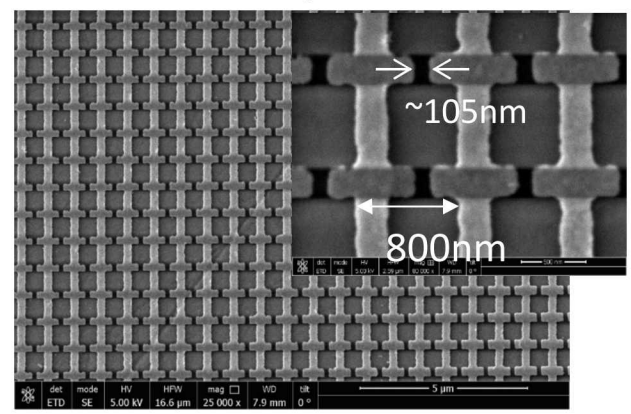












- Broadband transmission and electric field enhancement
- Ultrasubwavelength confinement : $(\lambda/250)^2$ (@ 10 μm)

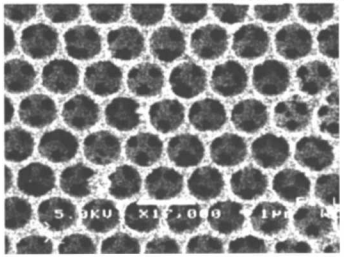
G. Subramania, S.Foteinopoulou and I. Brener, Phys. Rev. Let., 107, 163902(2011).

3DPhC

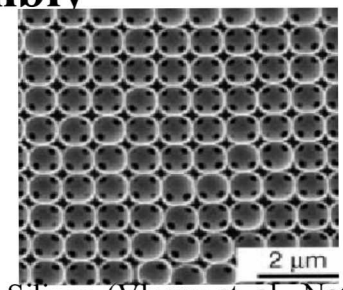
Methods for 3D Photonic Crystals

Sandia National Laboratories

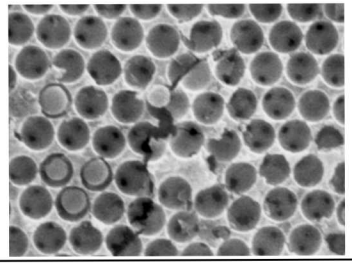
Self- assembly



TiO_2 (Subramania et.al., APL,**74**,1999)

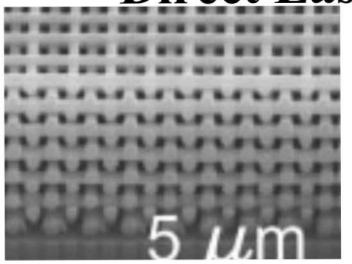


Silicon (Vlasov et. al., Nature, **281**, 2001)



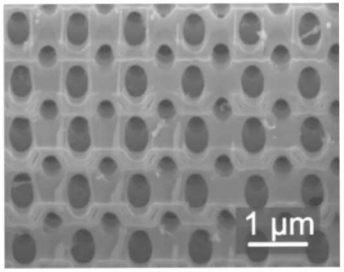
CdS (Braun et. al., Nature, **402**, 1999)

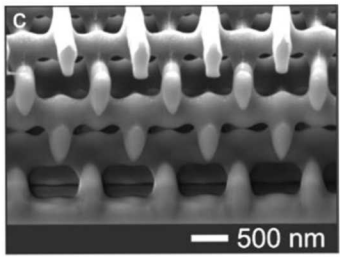
Direct Laser/Ink Writing



Silicon (Hermatschweiler et. al., Adv. Fun. Mat, **17**, 2007)

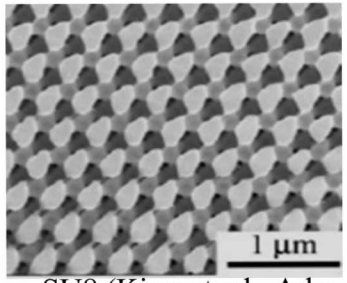
TiO2 (Duoss et. al., Adv. Mat, **19**, 2007)





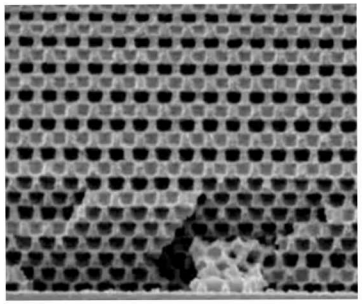
As2S3 (Wong et. al., Adv. Mat, **18**, 2006)

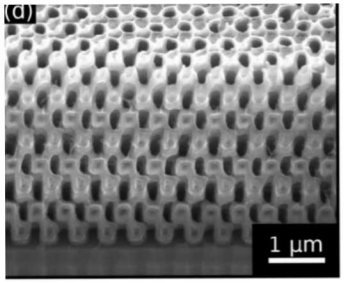
Interference/ Phasemask lithography



SU8 (King et. al., Adv. Mat, **18**, 2006)

Silicon (Ramanan et. al., APL, **94**, 011101,2008)





Silicon (Ramanan et. al., APL, **92**, 2008)

Goals: Large area, multiple layers, single step, inexpensive

Challenges: Large index contrast, minimum feature size, defect introduction

PhC can Control Spontaneous Emission

A complete three-dimensional photonic bandgap can suppress all emission in all direction.

A highly sought after goal !

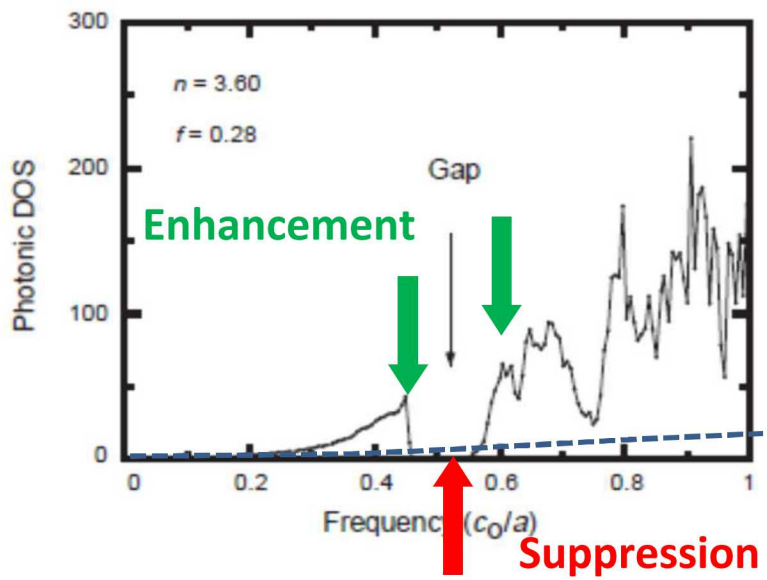
Radiative rate of an emitting dipole in an EM field (Fermi's Golden Rule)

$$\Gamma_r(\omega) = \frac{\pi\omega\mu^2}{3\varepsilon_0\hbar}\rho(\omega)$$

Photonic Density of States (PDOS)

$$\rho_f(\omega) = \frac{\omega^2}{\pi^2 c^3}$$

in free space



Radiative rate modification

$$\frac{\Gamma_{r\_PC}(\omega)}{\Gamma_{r\_free}(\omega)} = \frac{\rho_{PC}(\omega)}{\rho_f(\omega)}$$

Local Photonic Density of States (LDOS)

$$\rho_L(\boldsymbol{r},\omega) = \sum_n \int_{1stBZ} d^3k \left|\overline{\mu}\cdot\boldsymbol{E}_{n,\boldsymbol{k}}(\boldsymbol{r})\right|^2 \delta(\omega^2 - \omega_{n,\boldsymbol{k}}^2)$$

Logpile Three-dimensional PhC

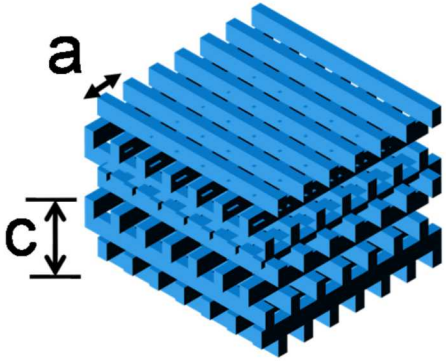
Not all structures give a complete three dimensional photonic band gap !

Requirements:

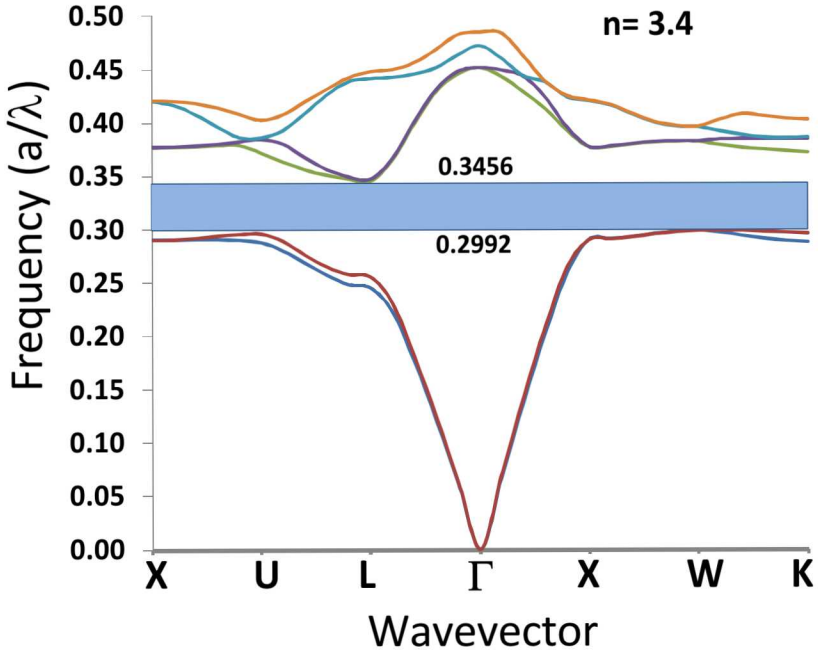
- Lattice structure → ✓ Diamond-like
- Sufficient refractive index → ✓ n > 2.0

Logpile PhC

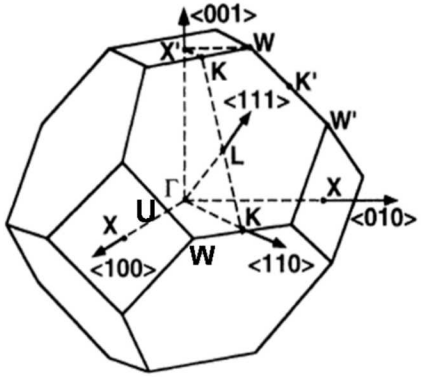
* K.M.Ho et.al. , Solid State Comm., **89** ,413(1994)



Photonic Band Structure



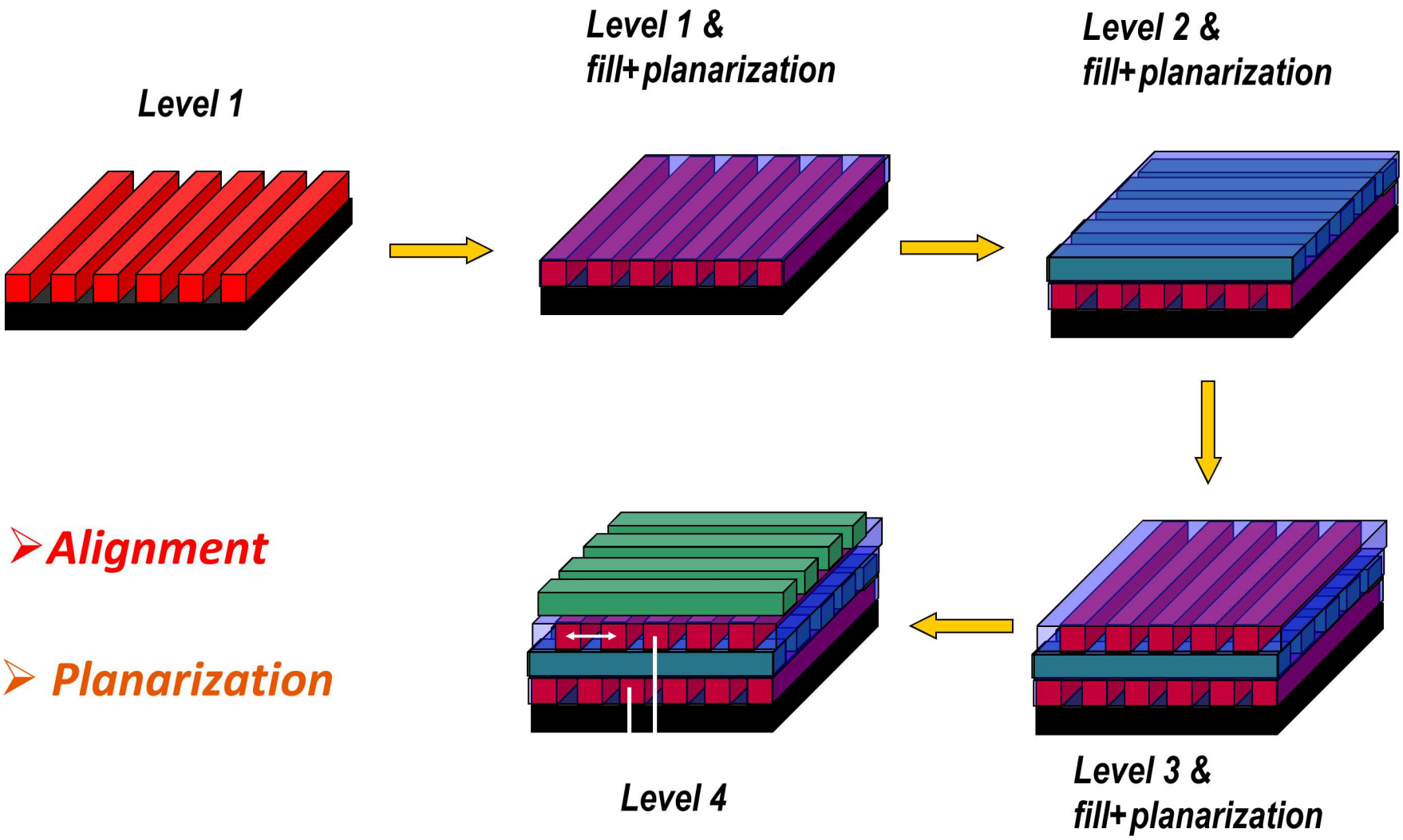
First Brillouin Zone



Logpile PhC can be fabricated one layer at-a-time : Lithography

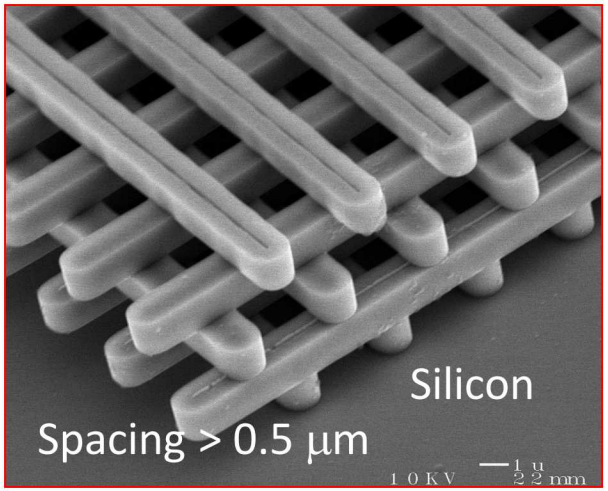
Layer-by-layer Lithographic Nanofabrication

- *Lithographic approach enables PhC fabrication one layer at a time with high precision with standard cleanroom techniques*

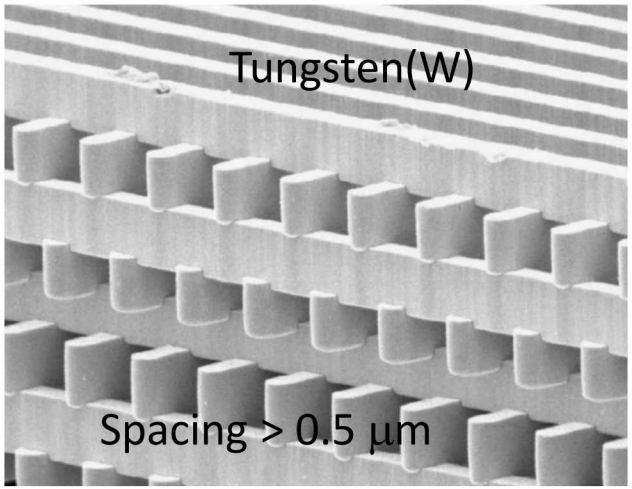


- ***Alignment***
- ***Planarization***

Optical Lithographic approaches of 3D Photonic Crystals



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



S.Y. Lin et.al. Opt. Lett., **28**, 1683(2003)

Advantages

- Accurate feature size and shape control
- Speed : Step-and-repeat lithography
- Clean room compatible
- Flexibility of materials, crystal lattice
- Variable periodicity in each layer
- Controlled introduction of defects for devices

Disadvantages

- Expensive
- Limited accessibility

- **Lattice spacing ~ 0.5 μm**
- **Bandgap: Mid infrared approaching near-IR**
- **Need different approach for beyond near-IR and visible bandgap**

Layer-by-layer Lithographic Nanofabrication

Sandia National Laboratories

Multilevel Electron beam lithography

Excellent for prototyping visible and near-IR 3D gap photonic lattices and devices with precision

Advantages

- **Ultrasmall periodicity: > 200 nm Near -IR and visible 3D gaps !**
- **Ultrasmall feature sizes: ~ 50nm**
- **Ultrasmall overlay accuracy ~ 20nm**

Disadvantages

- **Slow : Fewer devices (about 25-40 per wafer)**
- **Smaller device area : Typically 50-200 mm on a side → Not a problem with microspectrometry**

Key factors to address

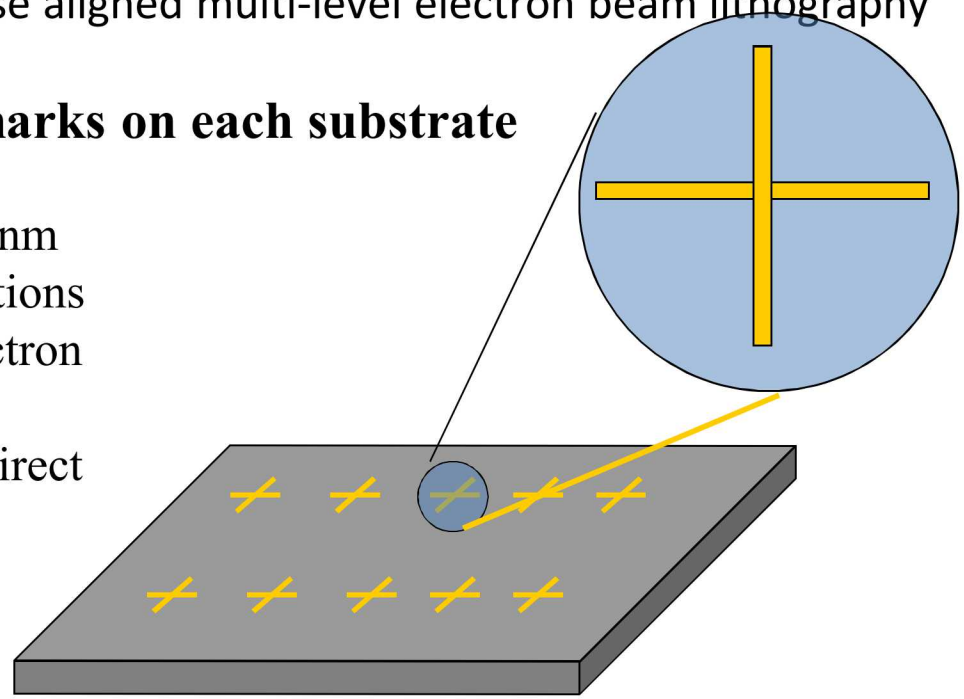
- Alignment between layers
- Planarization
  - Lift-off
  - Etch
  - Self-planarizing

Layer-by-layer Lithographic Nanofabrication

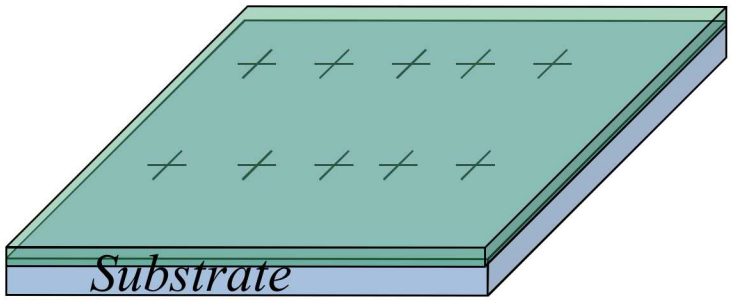
For 3DPhCs with sub-micron structures use aligned multi-level electron beam lithography

Step1: Define chip alignment marks on each substrate

Cross-hair patterns made of gold ~50nm thick are placed at required chip positions on substrate. Gold, due to is high electron backscatter is an ideal material for registration marks in electron beam direct write systems.



Step2: Spin on e-beam resist (polymethyl methacrylate) on the substrate



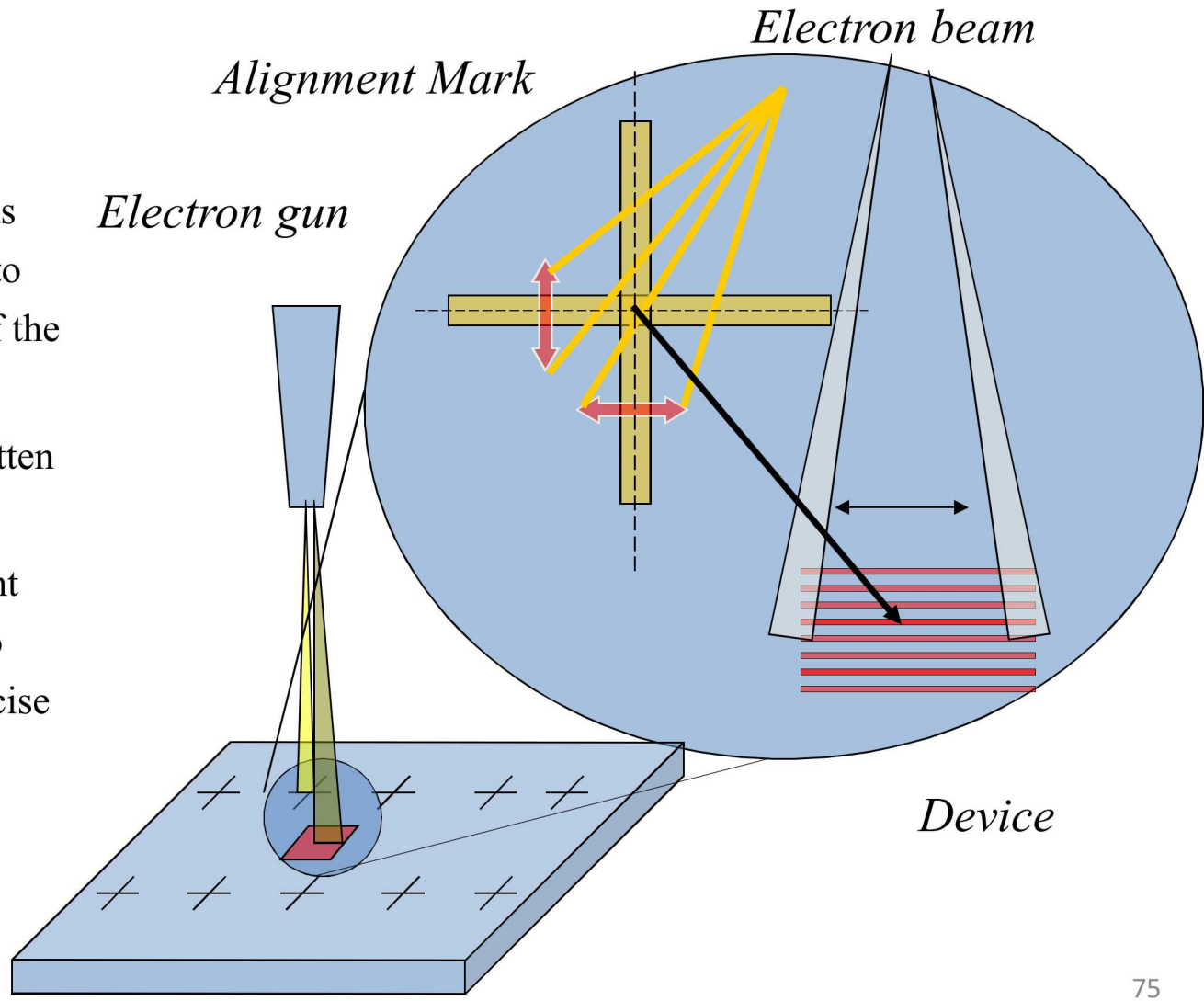
Polymethyl methacrylate (PMMA) ~500nm thick

Layer-by-layer Lithographic Nanofabrication

For 3DPhCs with sub-micron structures use aligned multi-level electron beam lithography

Step3: Pattern exposure using JEOL JBX-5FE electron beam direct write system

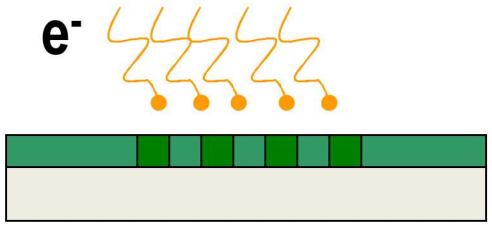
- The electron beam system scans each arm of the gold cross hair to precisely determine the center of the cross hair
- Each device pattern is then written in reference to that position
- The edges of the each alignment mark must be extremely sharp to within a few nanometers for precise determination of the center
- This is also crucial for precise alignment of subsequent layers



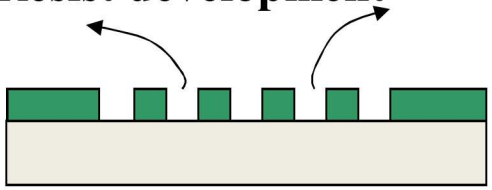
Photonic Crystal Fabrication: Lift-off Technique

Sandia National Laboratories

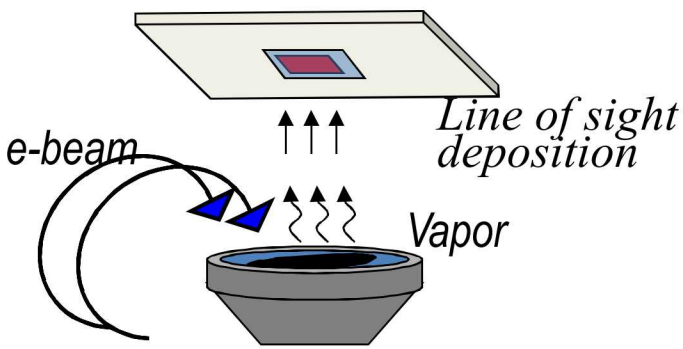
1. Resist Patterning (e-beam write)

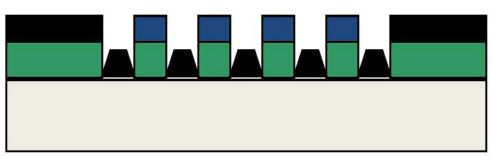


2. Resist development



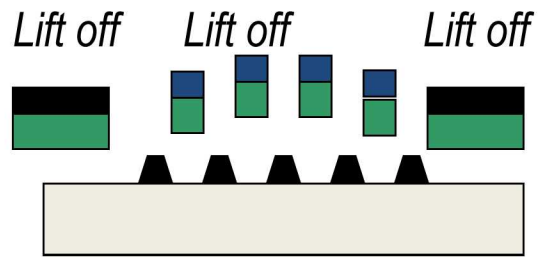
3. E-beam or thermal evaporation



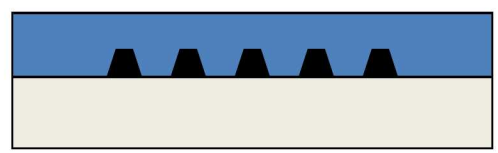


Typically suitable for difficult to etch materials (e.g. metals)

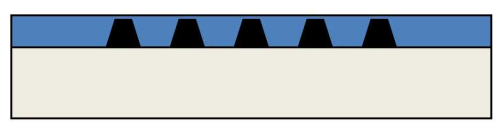
4.Soak in solvent (e.g. acetone)



5.Planarization



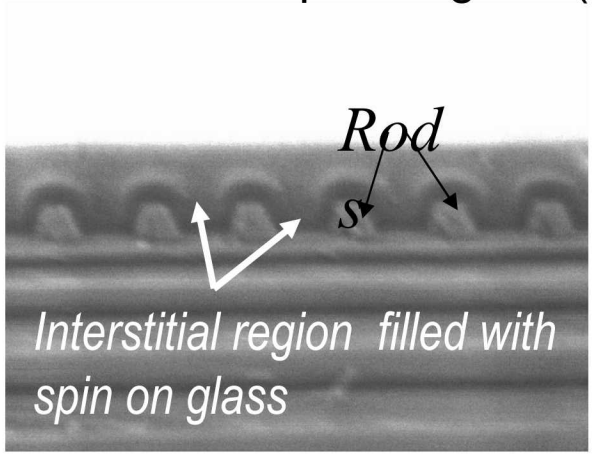
6. Etch back

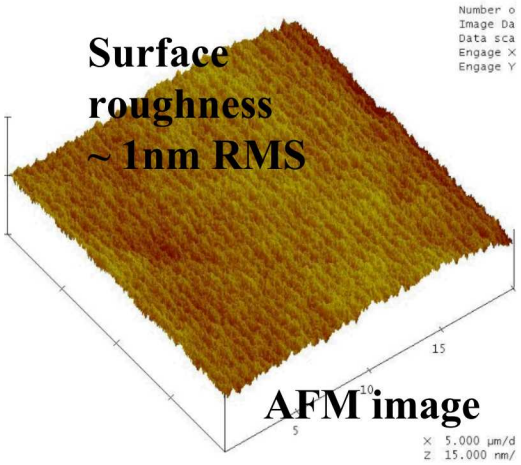


Photonic Crystal Fabrication: Lift-off Technique

Fill in the trenches with planarizing material (e.g. spin-on-glass) and planarize

T-12B series spin-on-glass (Honeywell)





Desirable properties of planarizing dielectric

- *Good filling of nanometer vias*
- *Easy removal : e.g. dry etch, selective wet etching*
- *Chemical, mechanical and thermal stability to subsequent processing*

Local degree of planarization:

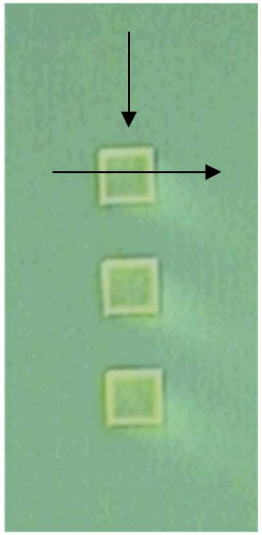
$$DOP_L(\%) = (1 - \delta/d) \times 100$$

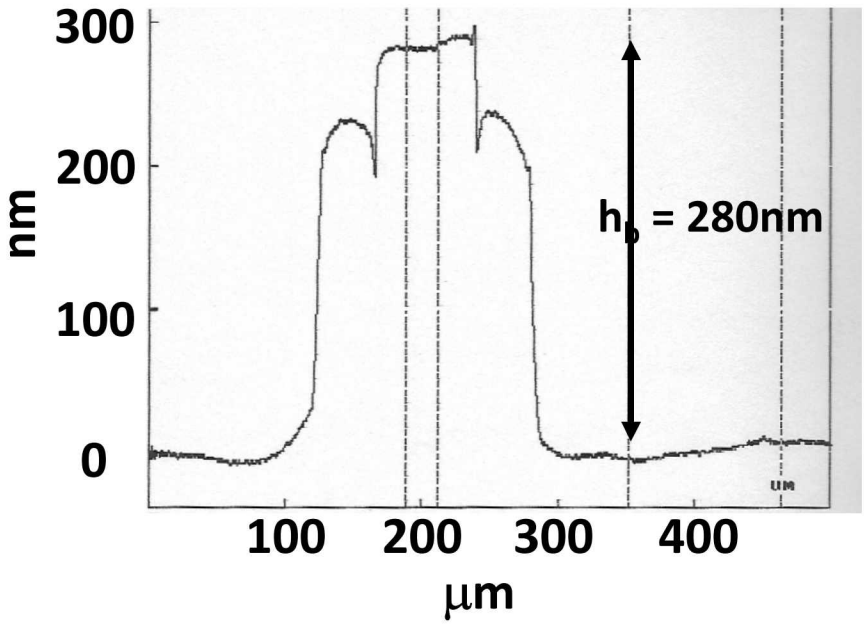
$$DOP_L(\%) = 99.5\ \%$$

- Dry etch excess planarizing dielectric to ready the sample for next layer
- Continue with next layer process

G. Subramania , Nanotechnology, **18**, 035303(2007)

Photonic Crystal Fabrication: Lift-off Technique



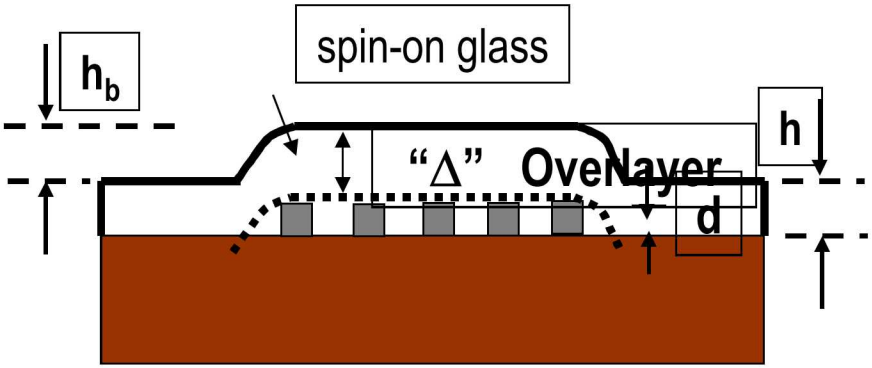


Global degree of planarization:

$$DOP_G(\%) = (1 - h_b/d) \times 100$$

with h_b~ 280nm and d = 230nm

$DOP_G(\%) = -22\ \%$

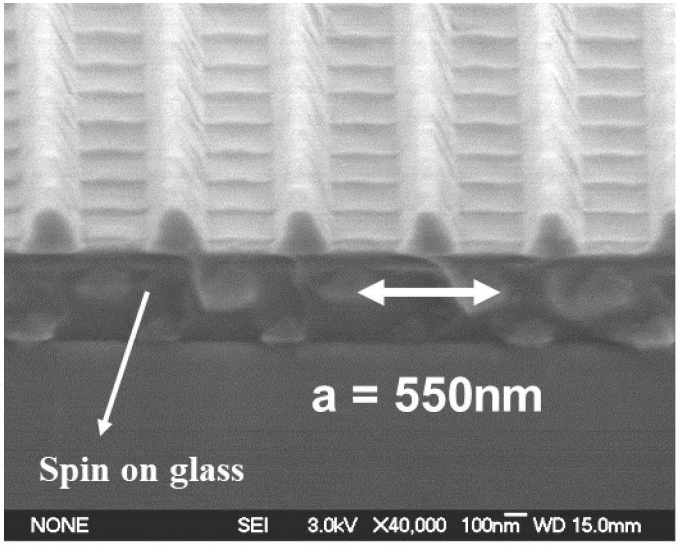


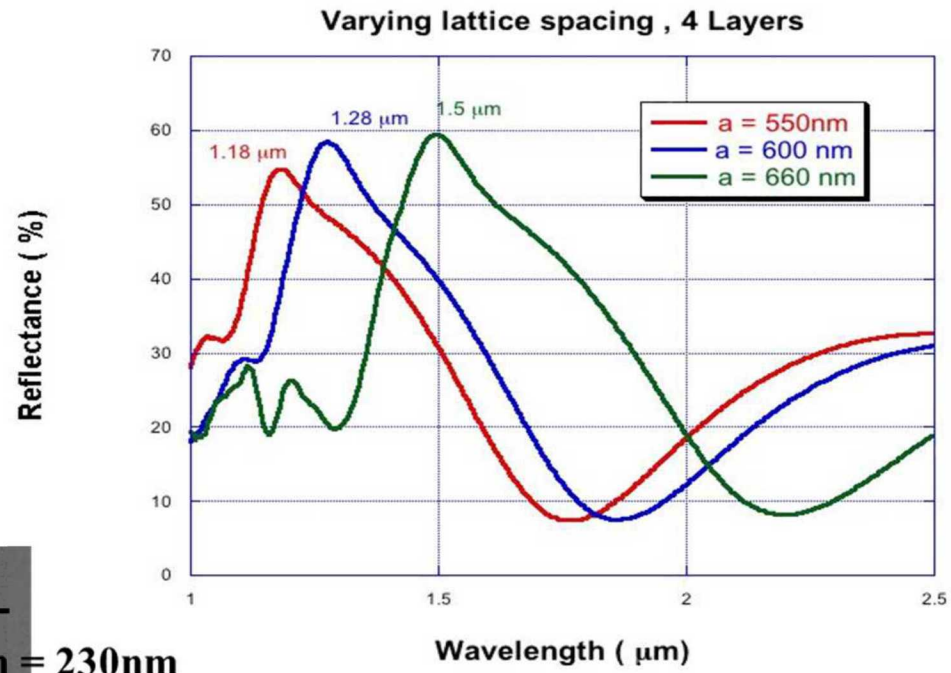
G. Subramania , Nanotechnology, **18**, 035303(2007)

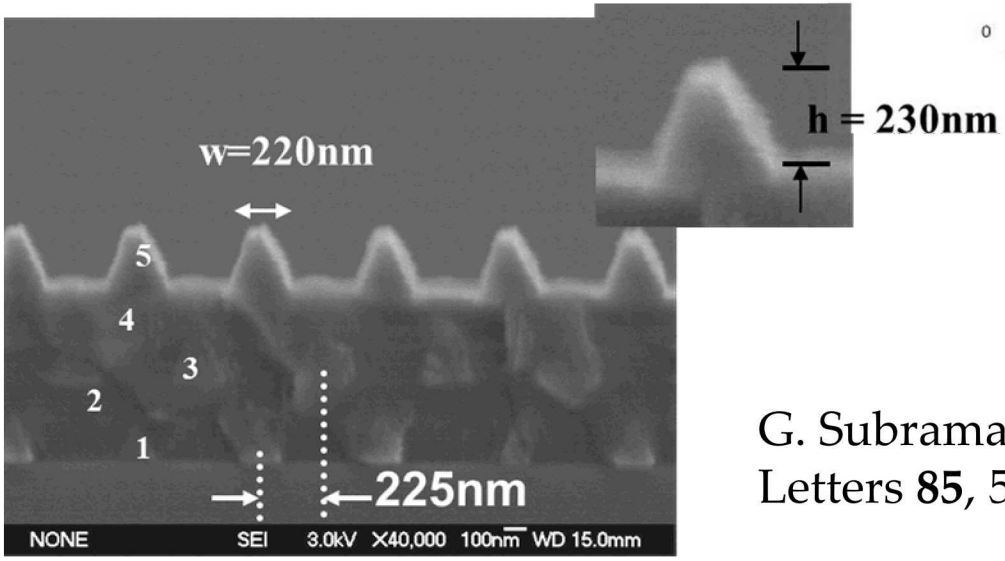
Photonic Crystal Fabrication: Lift-off Technique

Silicon 3D PhC

- Fabricated with e-beam evaporate Si source



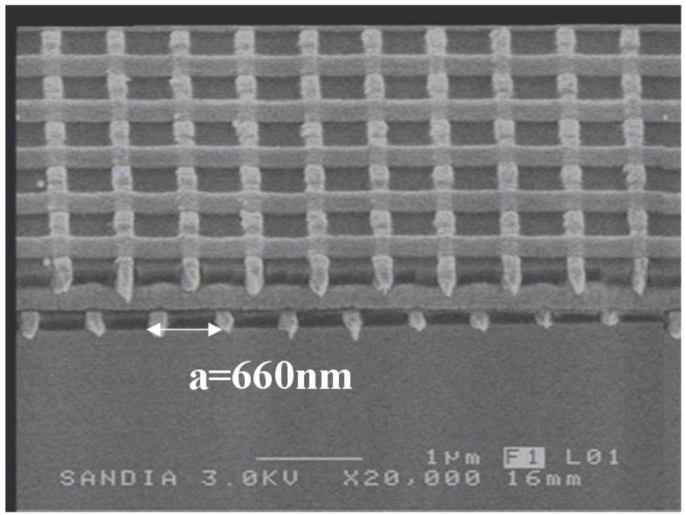


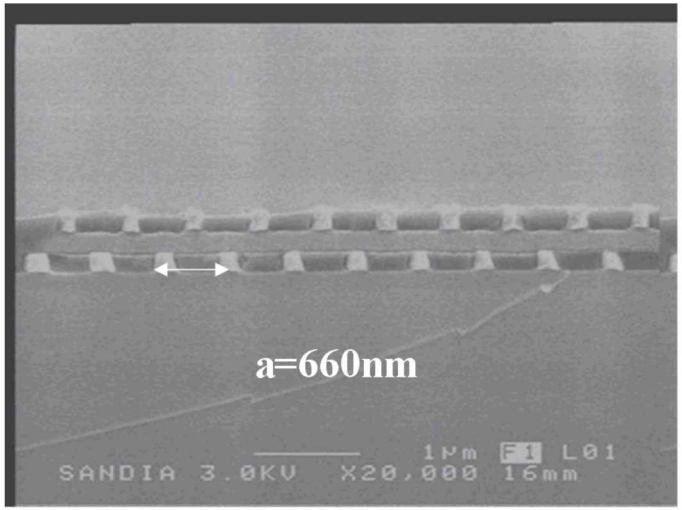


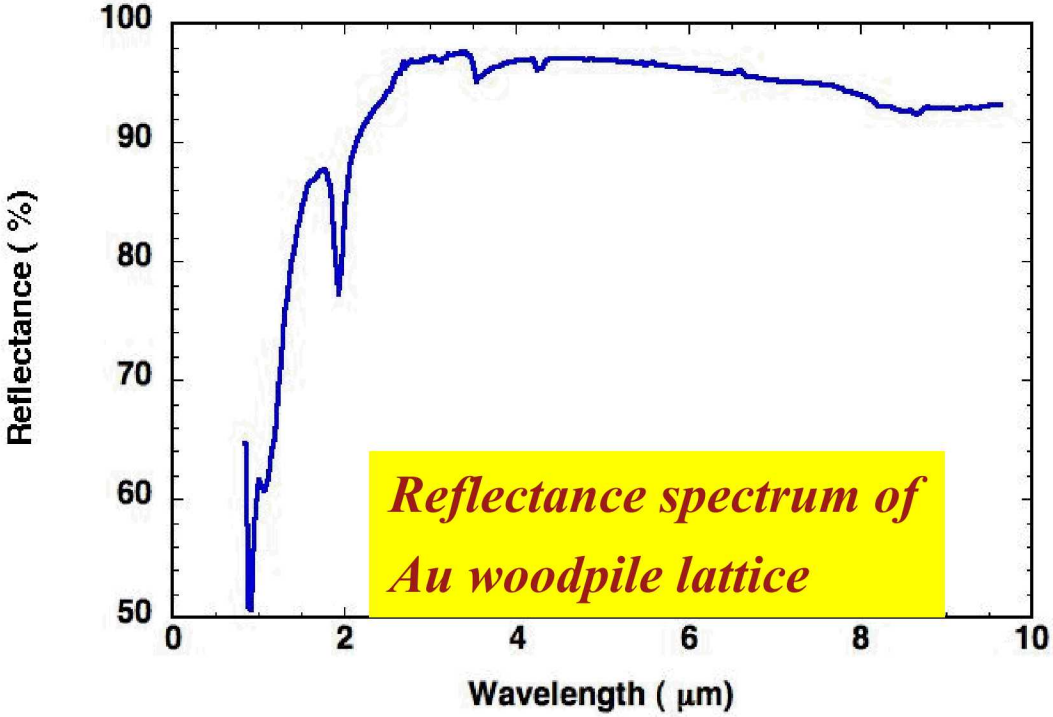
G. Subramania, and S. Y. Lin, Applied Physics Letters **85**, 5037-5039 (2004).

Photonic Crystal Fabrication: Lift-off Technique

Au 3D PhC







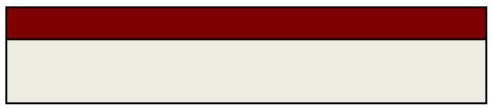
- **Broad band reflectors, selective emitters**
- **Substrate for 3D SERS reproducible SERS sensor**

G.Subramania, et.al., MRS. Symp. Proc. **846**,DD12.3(2005)

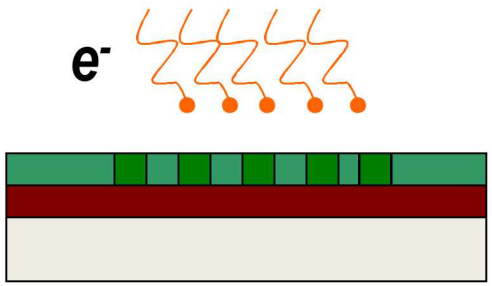
Photonic Crystal Fabrication: Etch Technique

Sandia National Laboratories

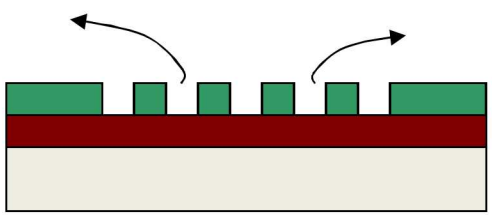
1.Film deposition (e.g. TiO2, Si, ZnO)



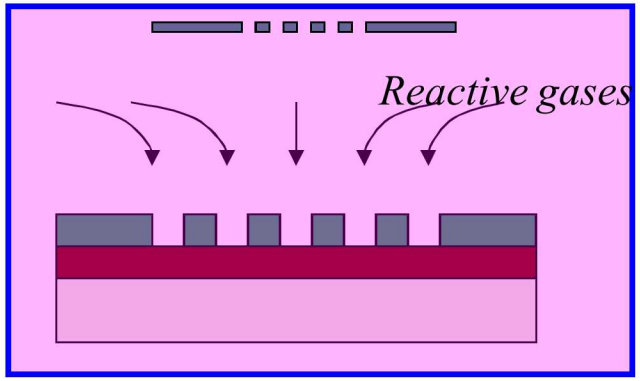
2.Resist Patterning (e-beam write)



3.Resist development

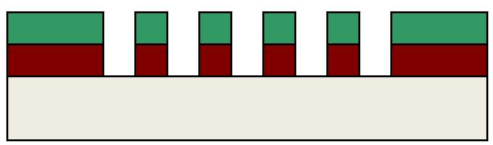


4.Reactive ion etch

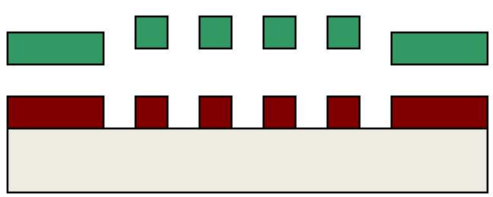


Suitable for dielectrics and semiconductors

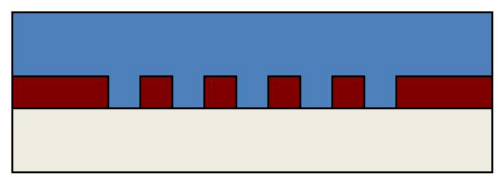
5.Post etch



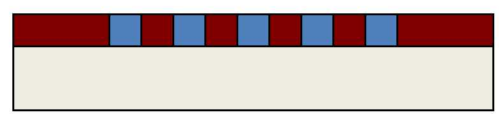
6.Soak in solvent (e.g. acetone)



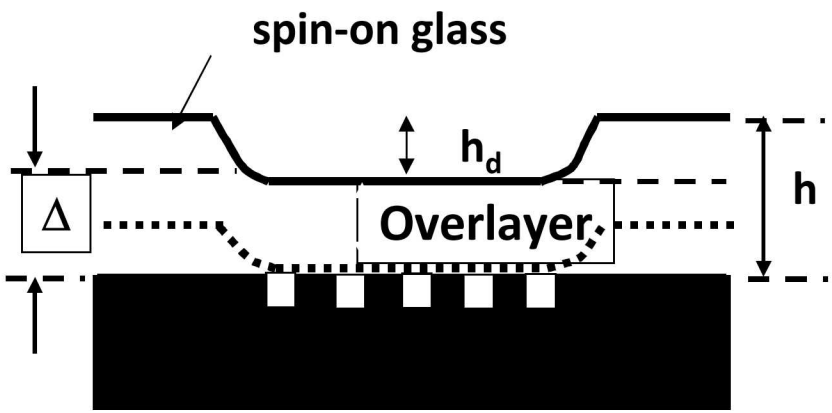
7.Planarization

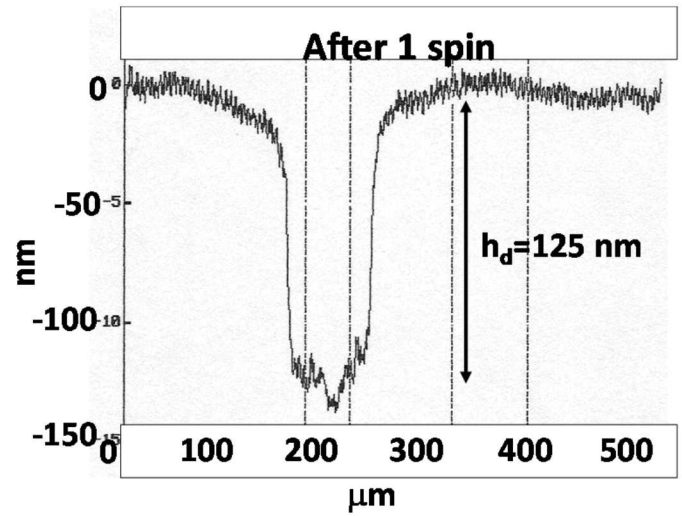


8.Etch back



Photonic Crystal Fabrication: Etch Technique





Good local planarization, poor local planarization

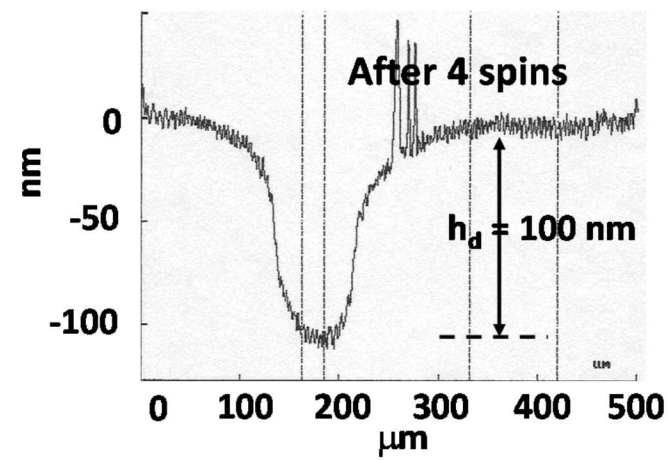
Global degree of planarization:

$DOP_G(\%) = (1 - h_d/h) \times 100$

1 spin with h_d~ 125nm and d =165nm

$DOP_G(\%) = 24.2\ \%$

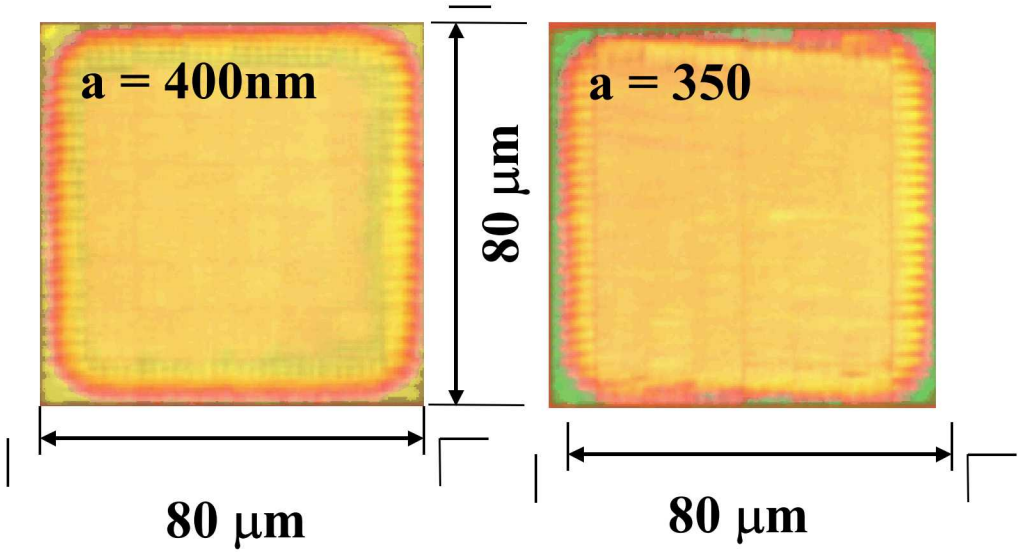
Even with 4 spins $DOP_G(\%) = 15\ \%$

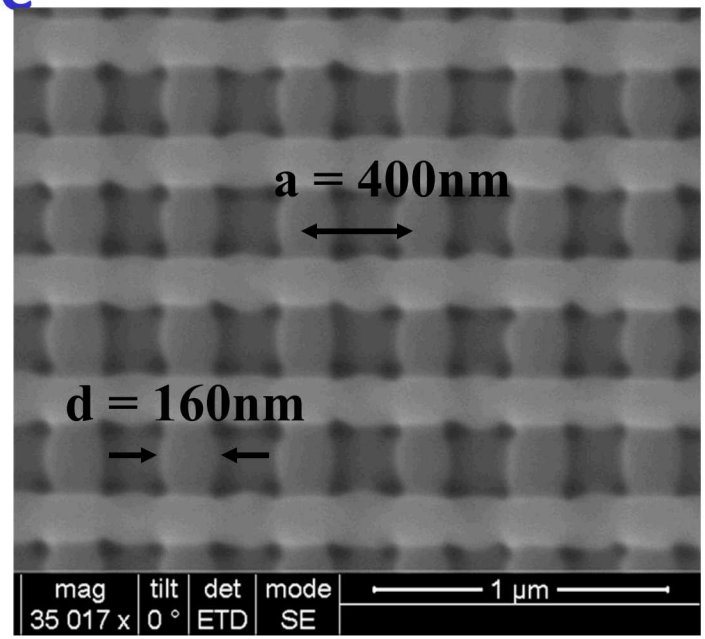


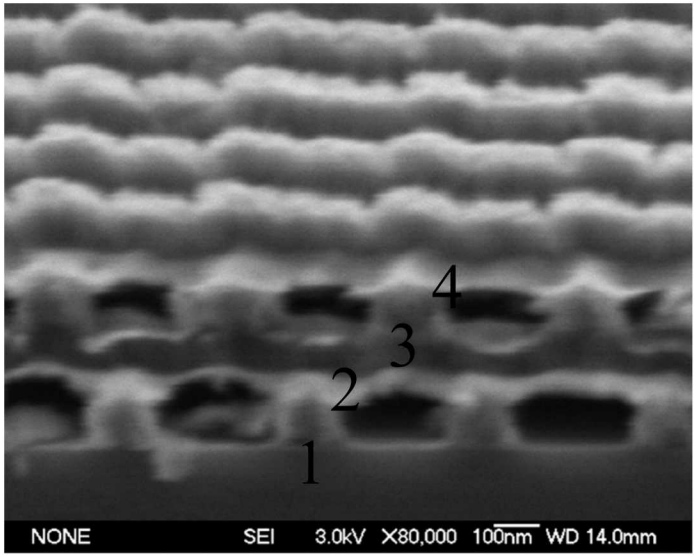
G. Subramania , Nanotechnology, **18**, 035303(2007)

Photonic Crystal Fabrication: Etch Technique

TiO_2 logpile PhC







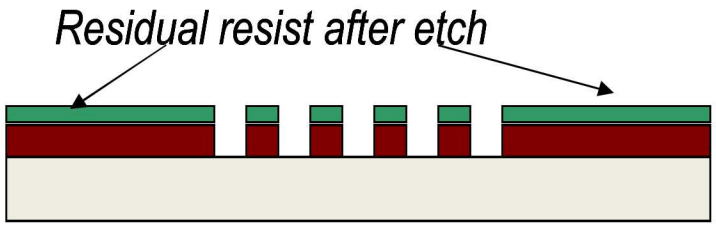
Process

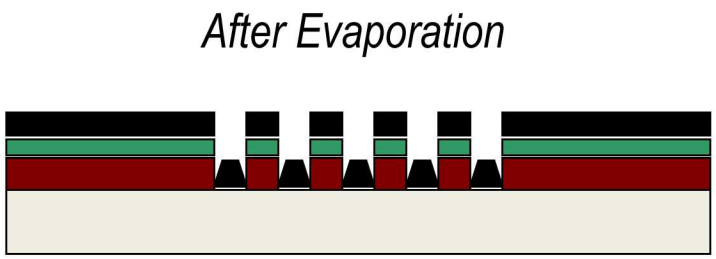
- TiO_2 deposition : Reactive sputtering of Ti target in O_2 flow (150W/15mT)
- Reactive ion etch of TiO2 in CHF3/Ar plasma
- Planarization with T-12B spin-on-glass (Honeywell)
- SiO_2 etch with 6:1 BOE

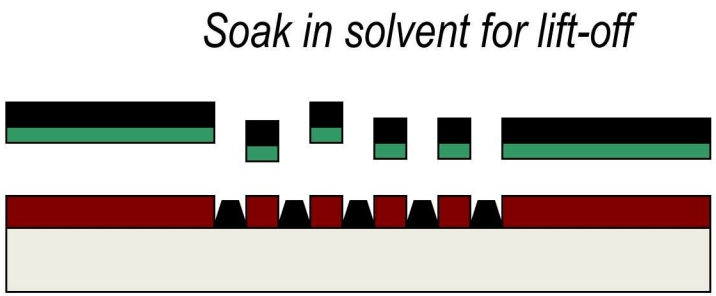
G. Subramania et al., Optics Exp. **15**,13049 (2007)

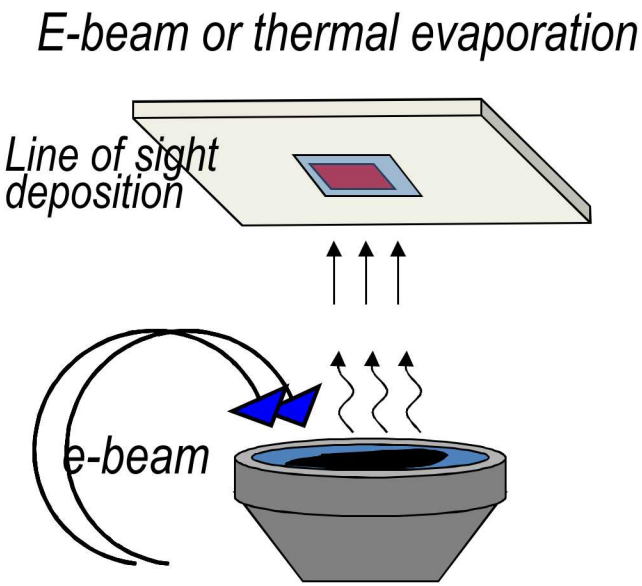
PhC Fabrication: Pre-fill and Etch back

Avoid separate planarization step if feature sizes sufficiently small (< 300nm) and low aspect ratio etch (~< 1:1)





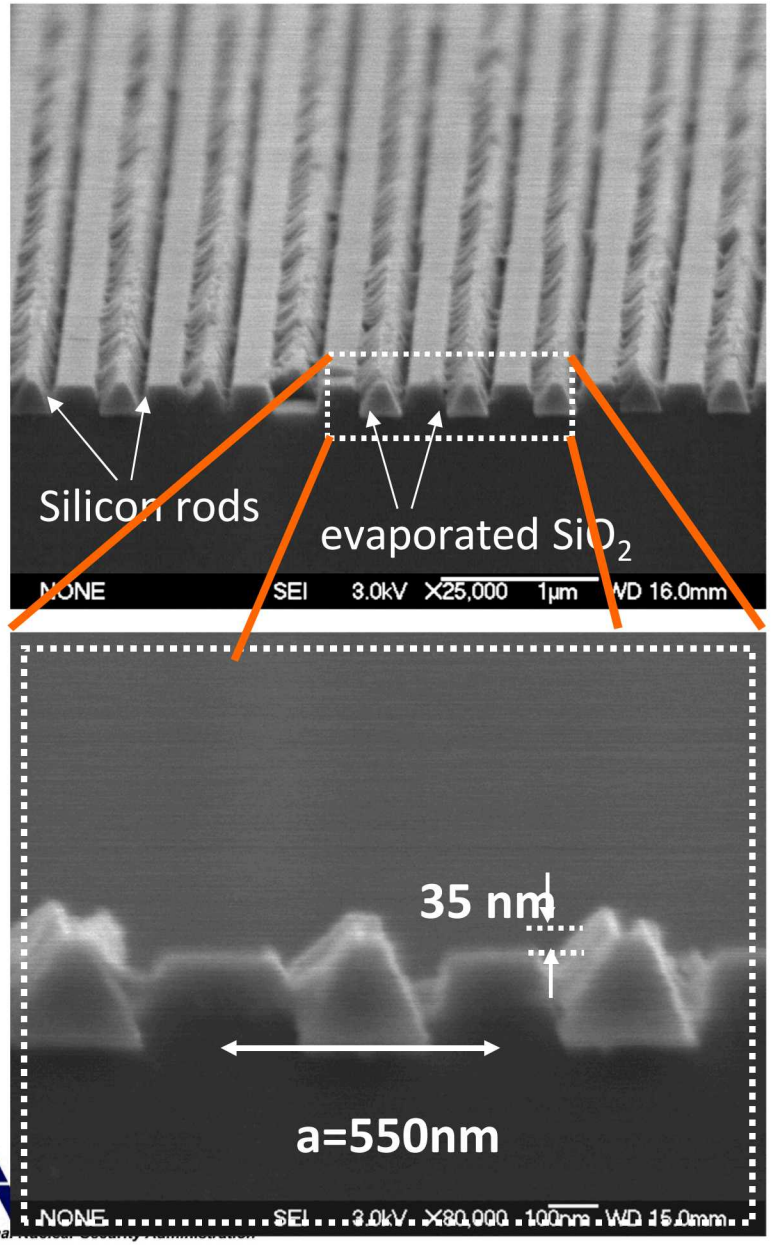


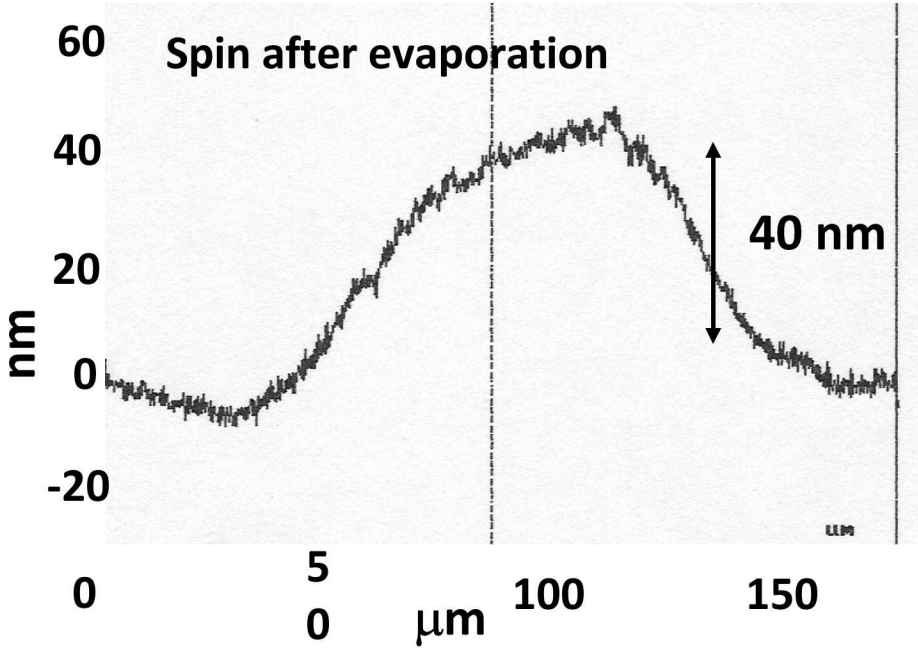


Sufficient residual resist thickness ~1.5x trench depth

- Good adhesion and filling of evaporated material
- Suitable etch profile

PhC Fabrication: Pre-fill and Etch back

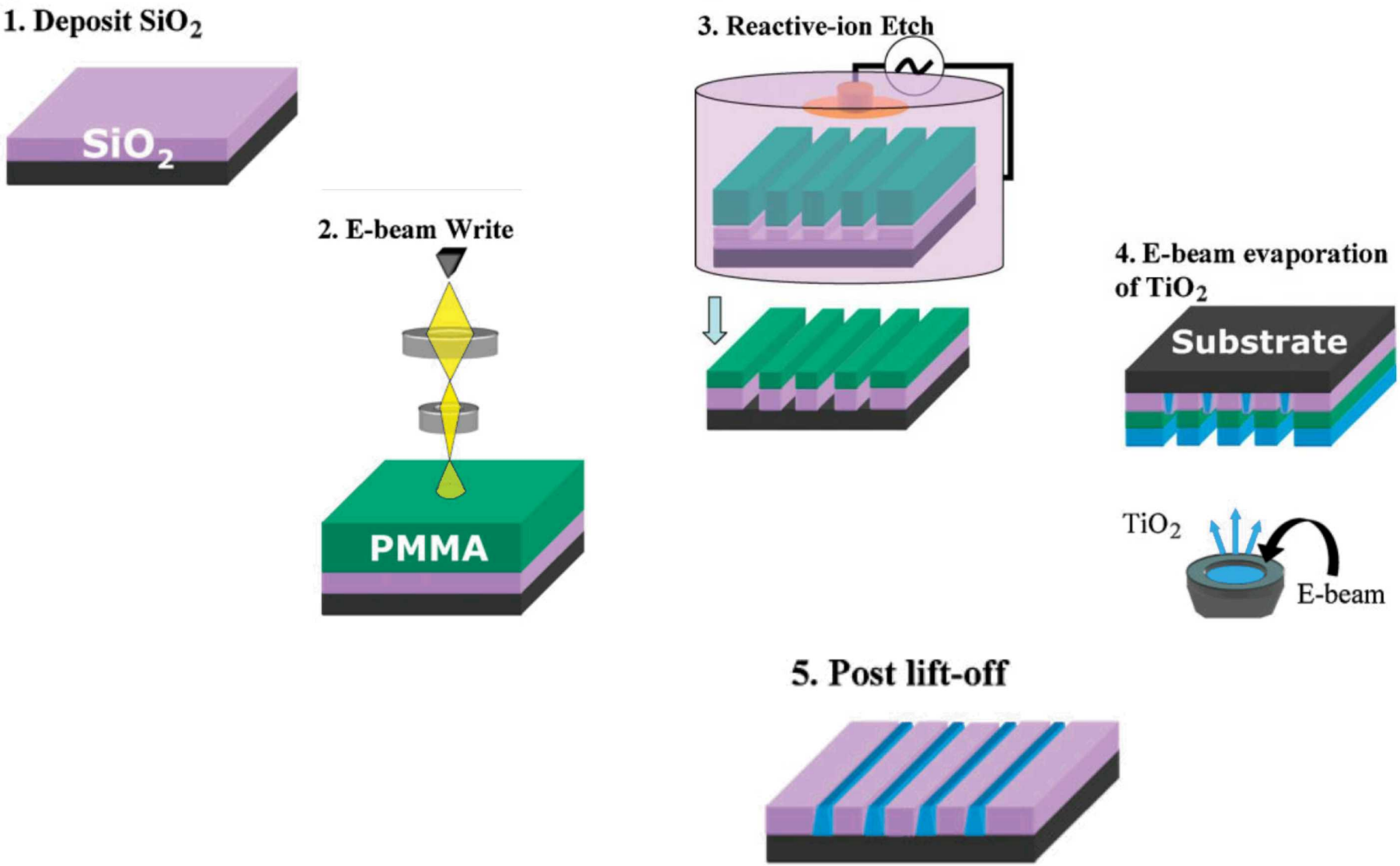




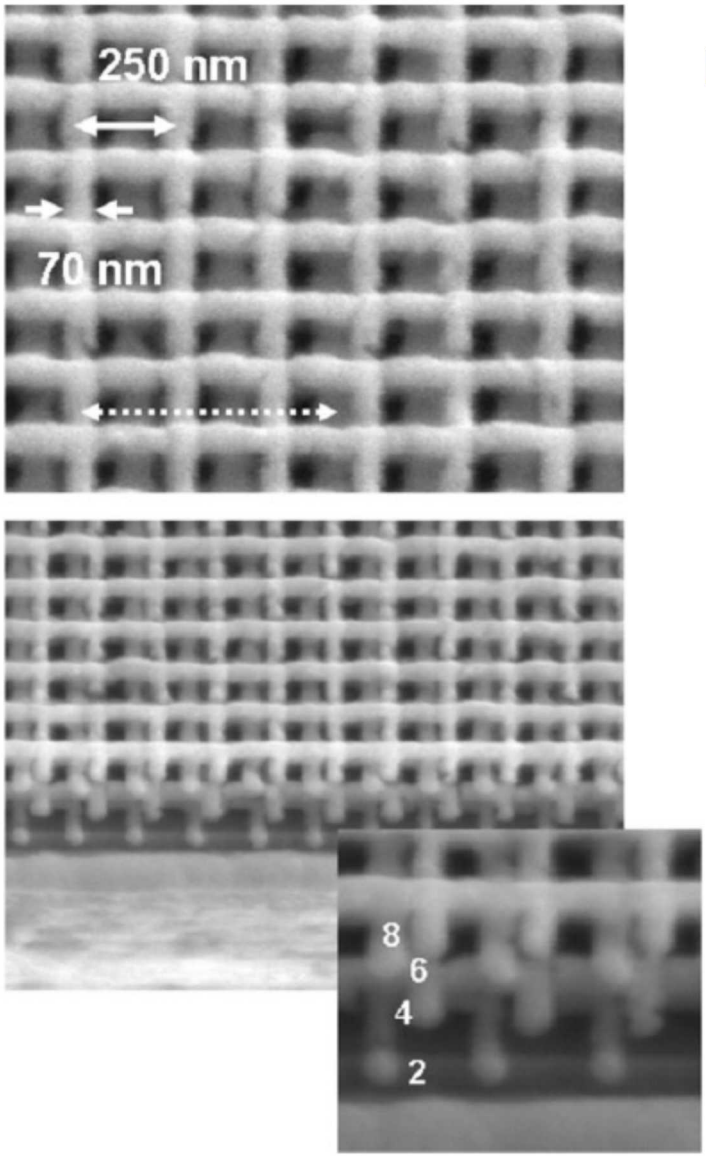
- *Inversion of spin on profile from a trench to relief*
- *Global degree of planarization: 24% --> 76 %*

TiO2 Logpile PC Fabrication Procedure

Single Layer Fabrication

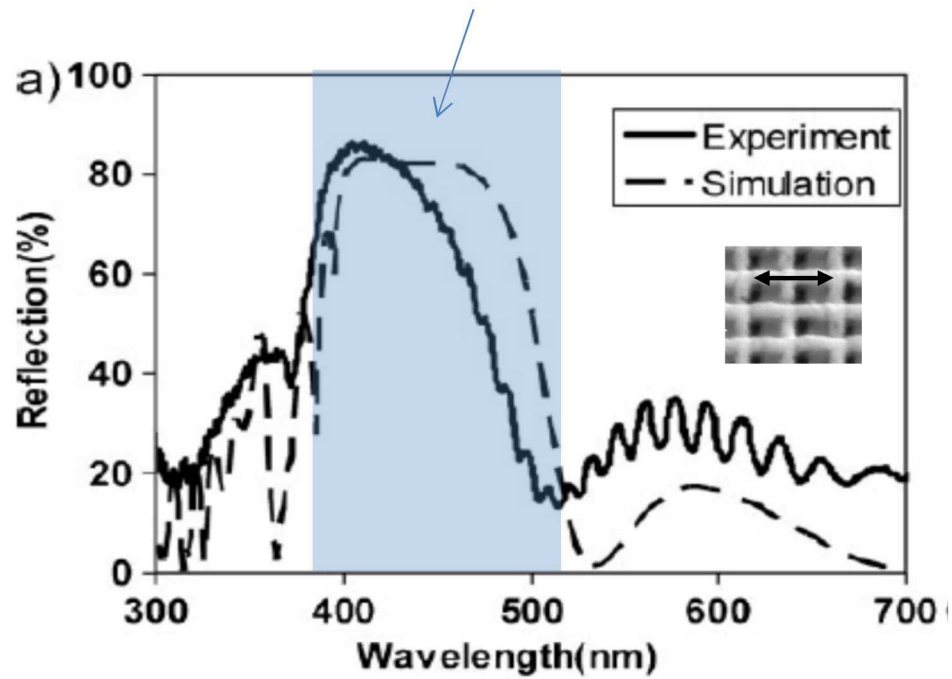


PhC Fabrication: Pre-fill and Etch back



Nine layers visible/near –UV TiO_2 logpile PhC

Normal direction stop gap

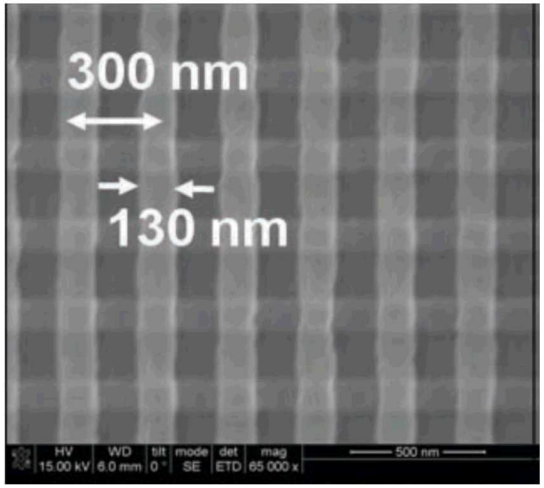


G. Subramania, Y.-J. Lee, A. J. Fischer, and D. D. Koleske, Advanced Materials **22**, 487 (2010)

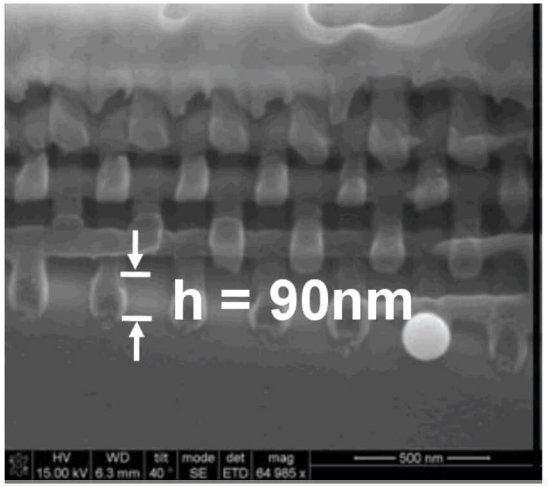
PhC Fabrication: Pre-fill and Etch back

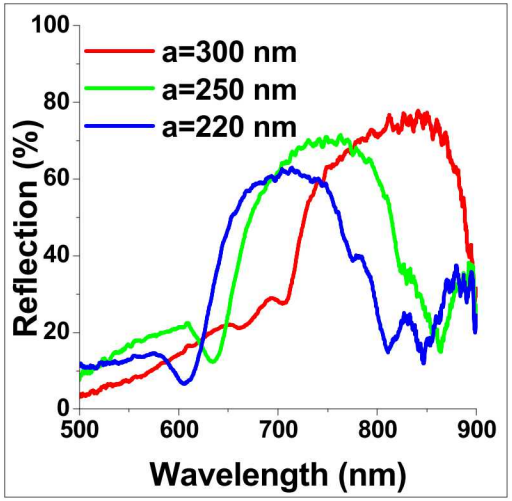
Silcon logpile PhC in at visible frequencies

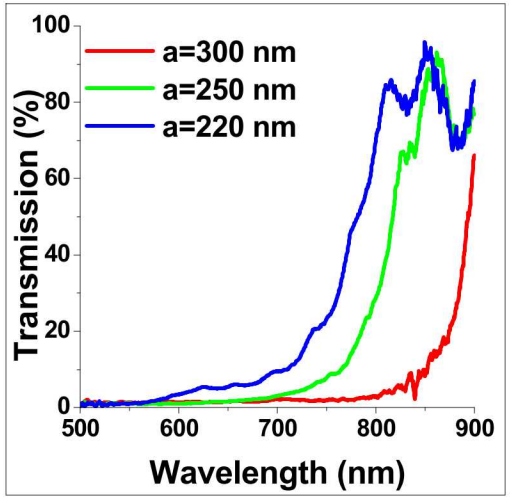
Top View



Cross-section View



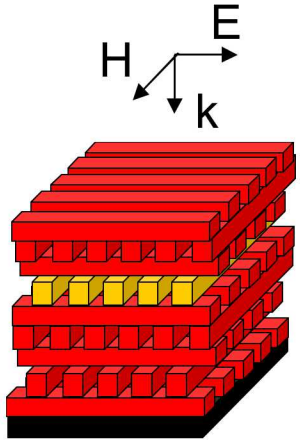


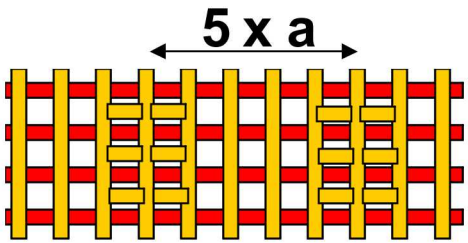


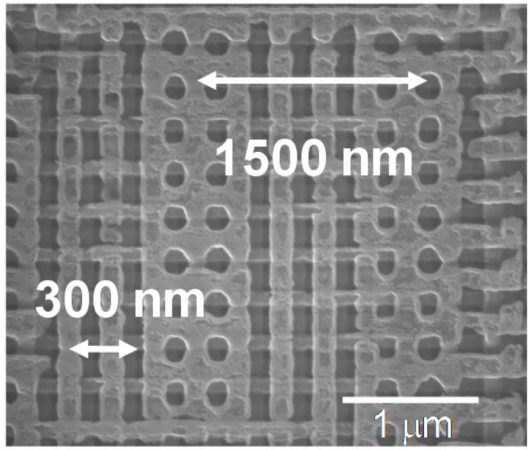
G. Subramania, Y-J Lee, and A.J. Fischer, Advanced Materials **22**, 4180-4185 (2010)

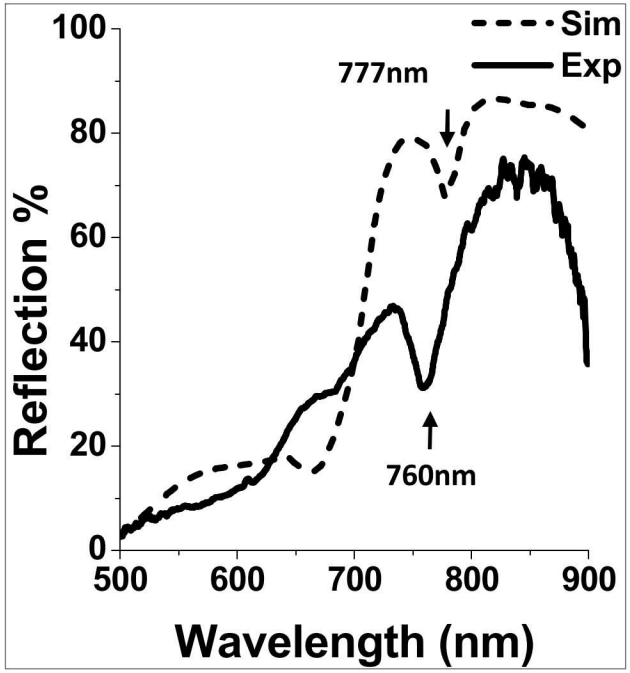
PhC Fabrication: Pre-fill and Etch back

Si 3DPhC 'defect' cavity

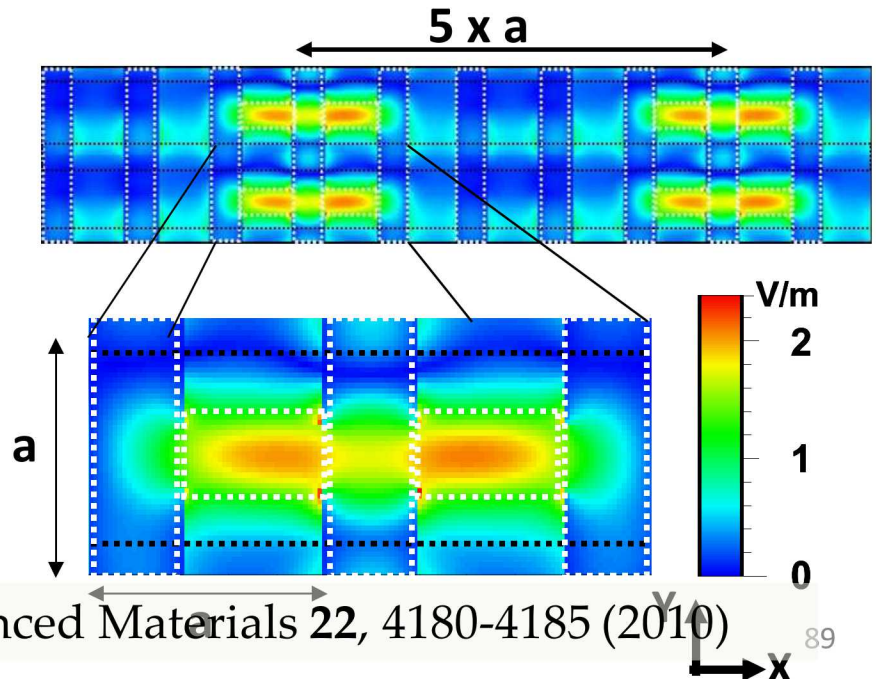








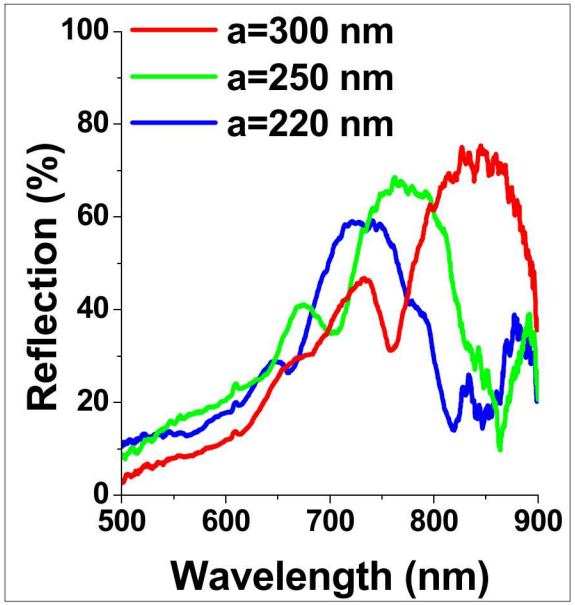
Electric field (E_x) distrubution

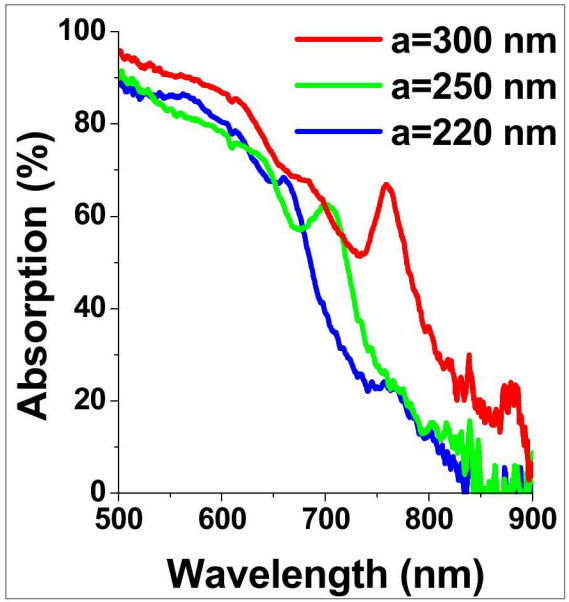


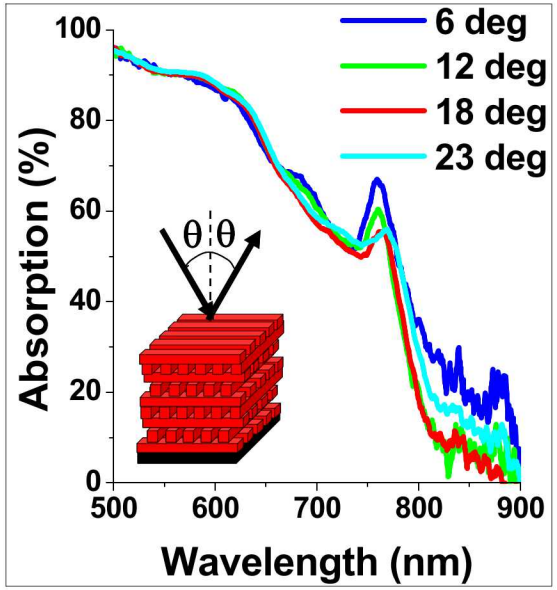
G. Subramania, Y-J Lee, and A.J. Fischer, Advanced Materials **22**, 4180-4185 (2010)

PhC Fabrication: Pre-fill and Etch back

Absorption enhancement at 'defect' cavity





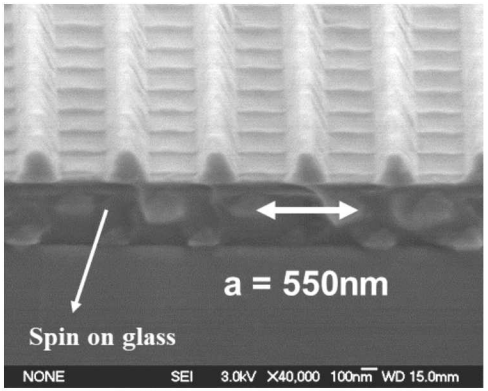


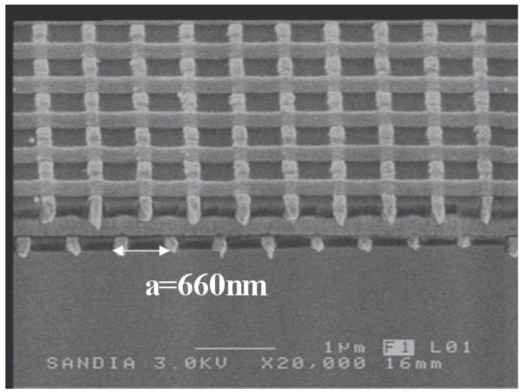
- Cavity mode becomes less prominent as lattice constant decreases
- Enhanced absorption at cavity mode : Slow group velocity
- Absorption wavelength relatively constant for incidence angles upto 23°

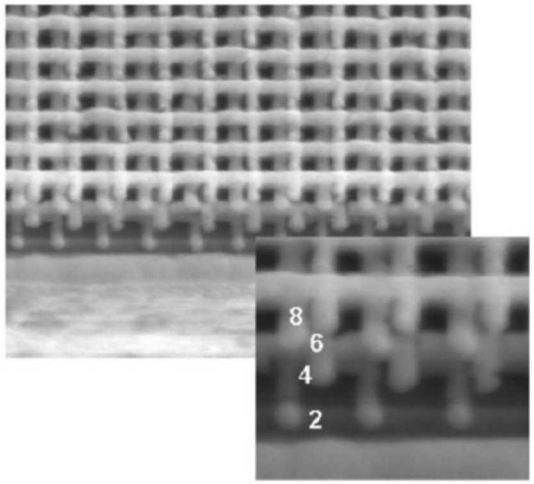
G. Subramania, Y-J Lee, and A.J. Fischer, Advanced Materials **22**, 4180-4185 (2010)

Nanolithographic PhC Fabrication : Epitaxial

Examples shown thus far are made with amorphous or polycrystalline materials





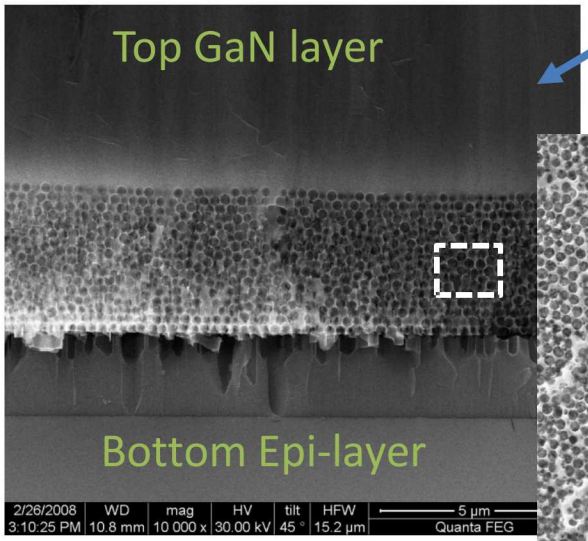


Q: Can we make PhCs with single crystal materials?

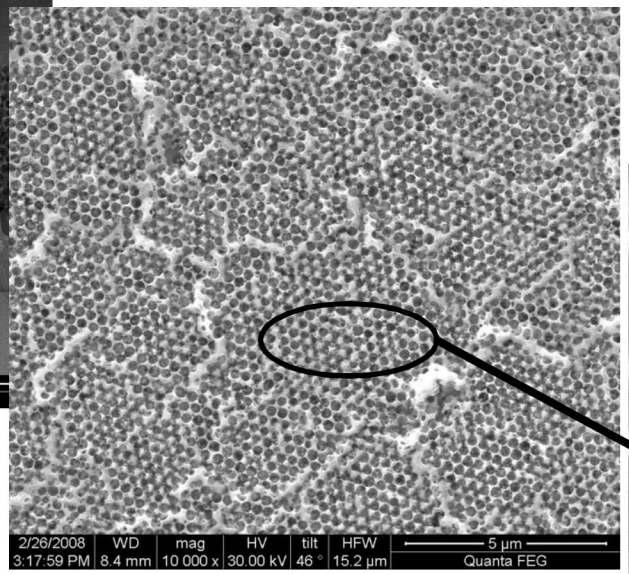
A: Yes !

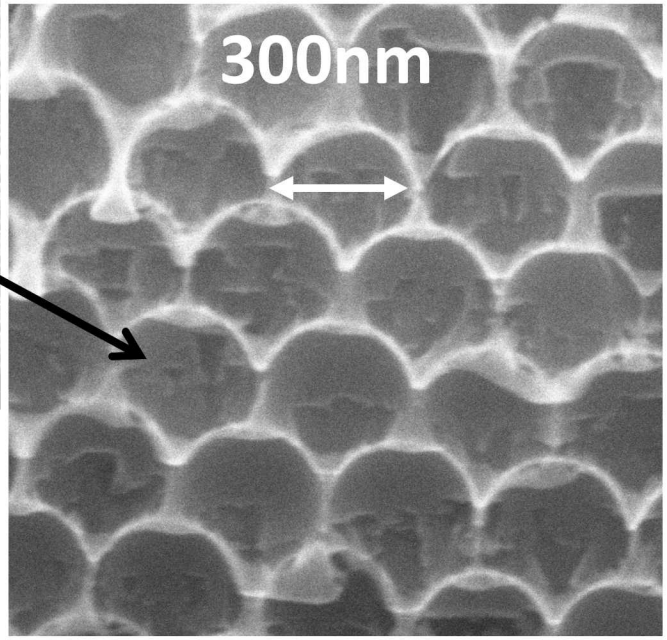
Epitaxial Growth Through Microscopic Template

Semiconductor materials such as GaN can be grown epitaxially though 3D microscopic template such as silica opal.



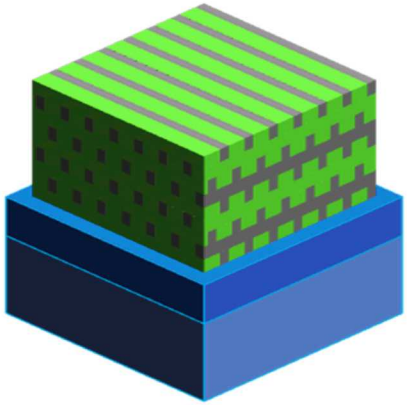
Reduces dislocation density of the top GaN layer



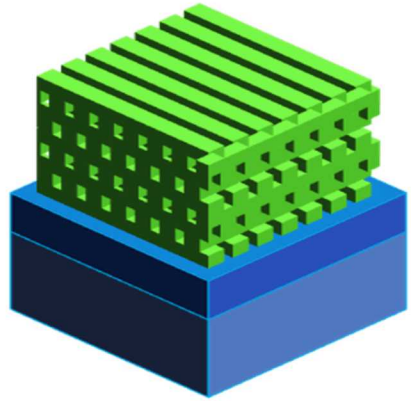


Qiming Li et. al., Appl. Phys. Lett. 94, 231105(2009).

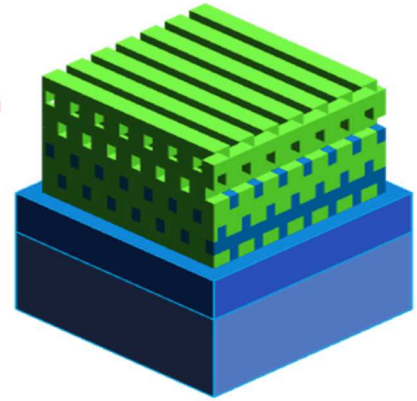
GaN Growth Through Logpile Template



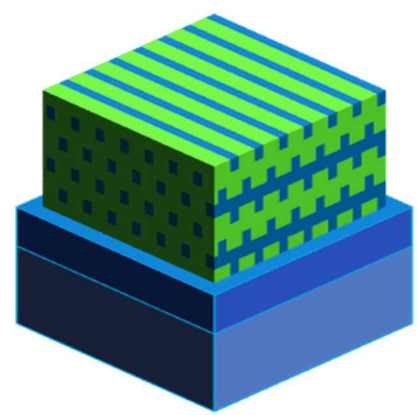
1. Si/SiO_2 logpile PC



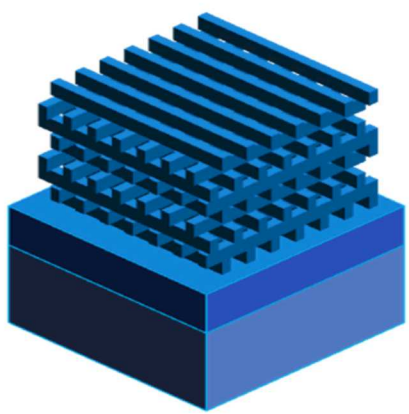
2. After Si is removed with KOH.



3. MOCVD GaN growth through SiO_2 template



4. After complete GaN infiltration into SiO_2 logpile template



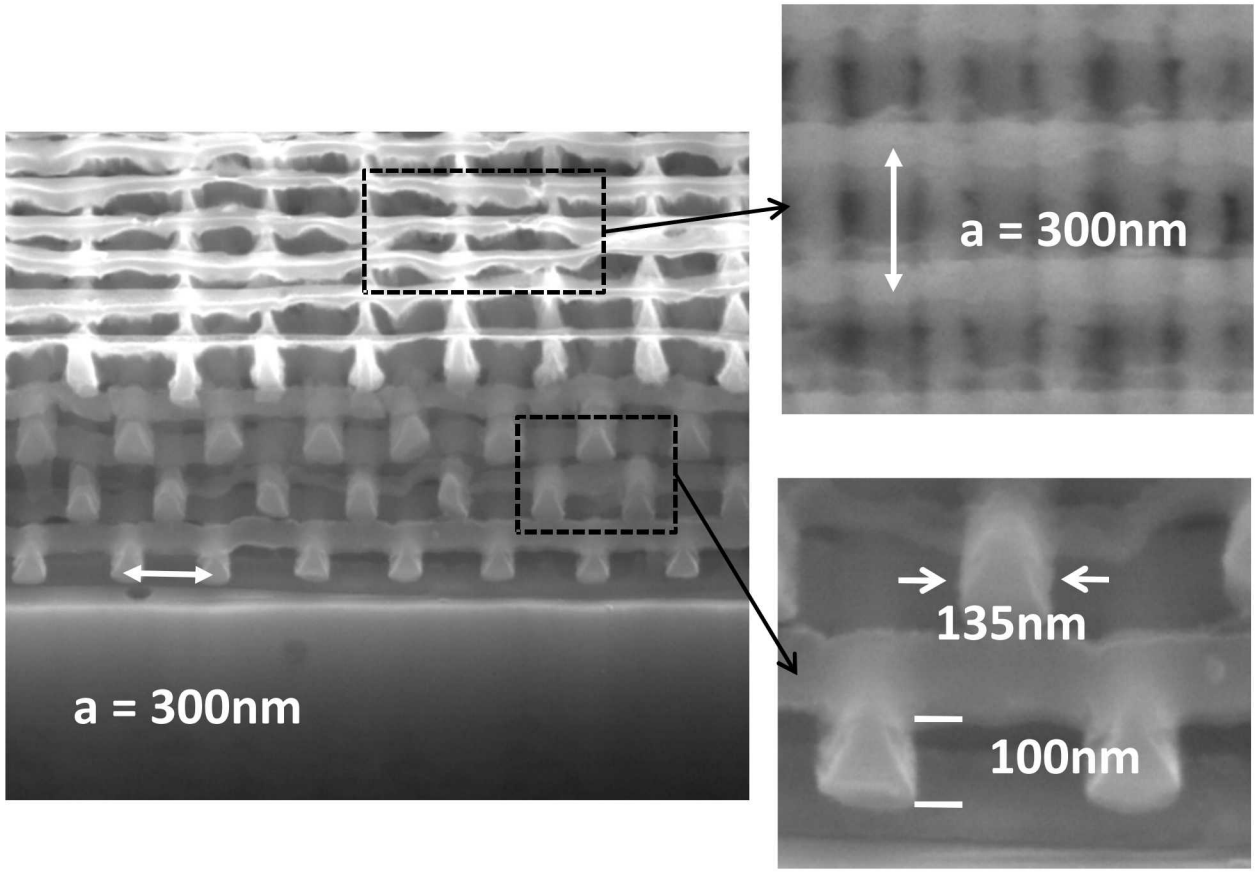
5. GaN logpile PC after SiO_2 logpile template removal

- Sapphire
- GaN
- Si
- SiO_2

With appropriate growth conditions …

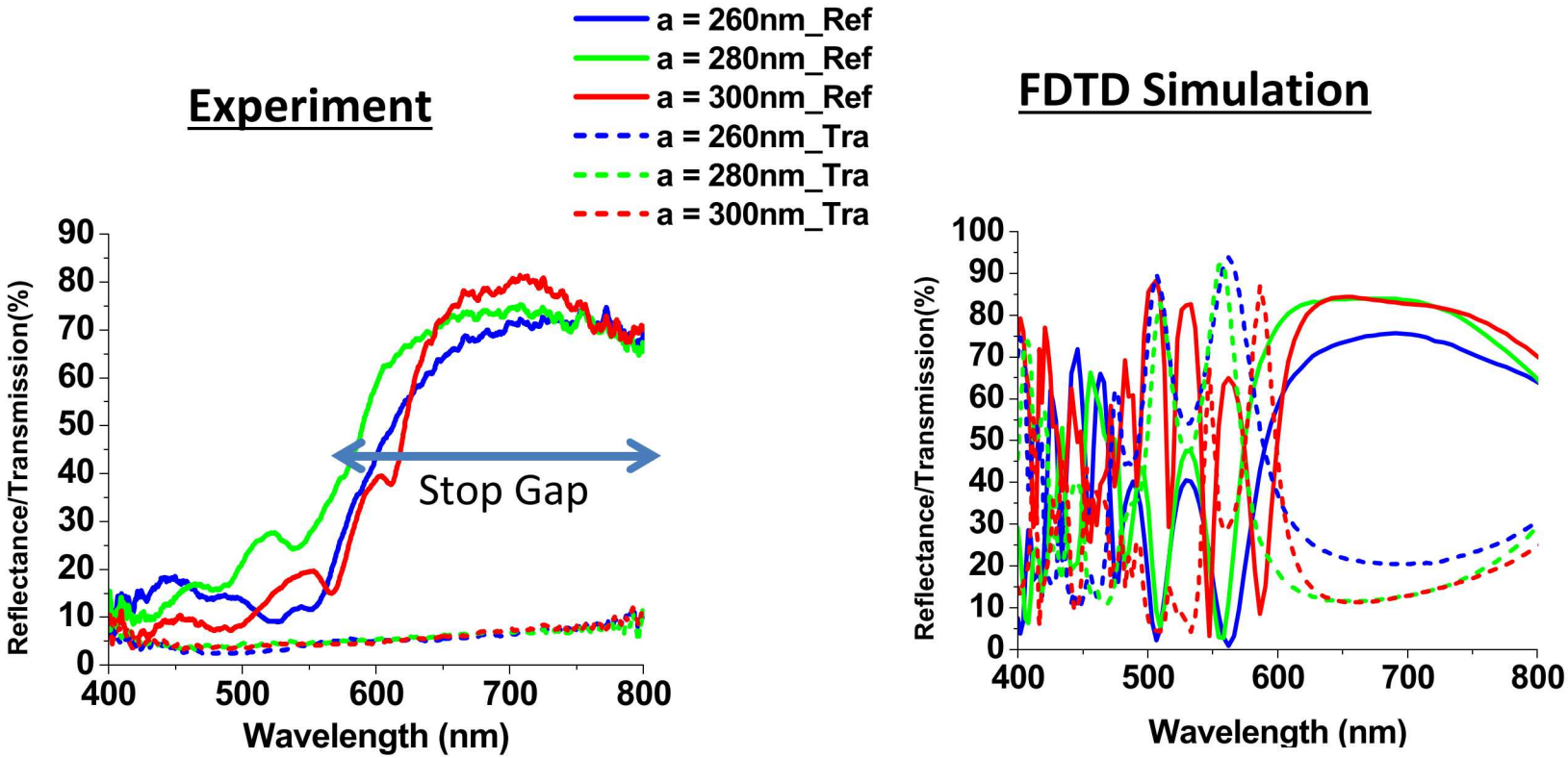
Optimize Growth conditions

- **Gas mixture:**
  TMGa, NH3 (~ 4 SLM), H2, and N2 (~ 100 sccm)
- **Temperature range:**
  1000C-1075C
- **Pressure range:**
  7 torr-30 torr



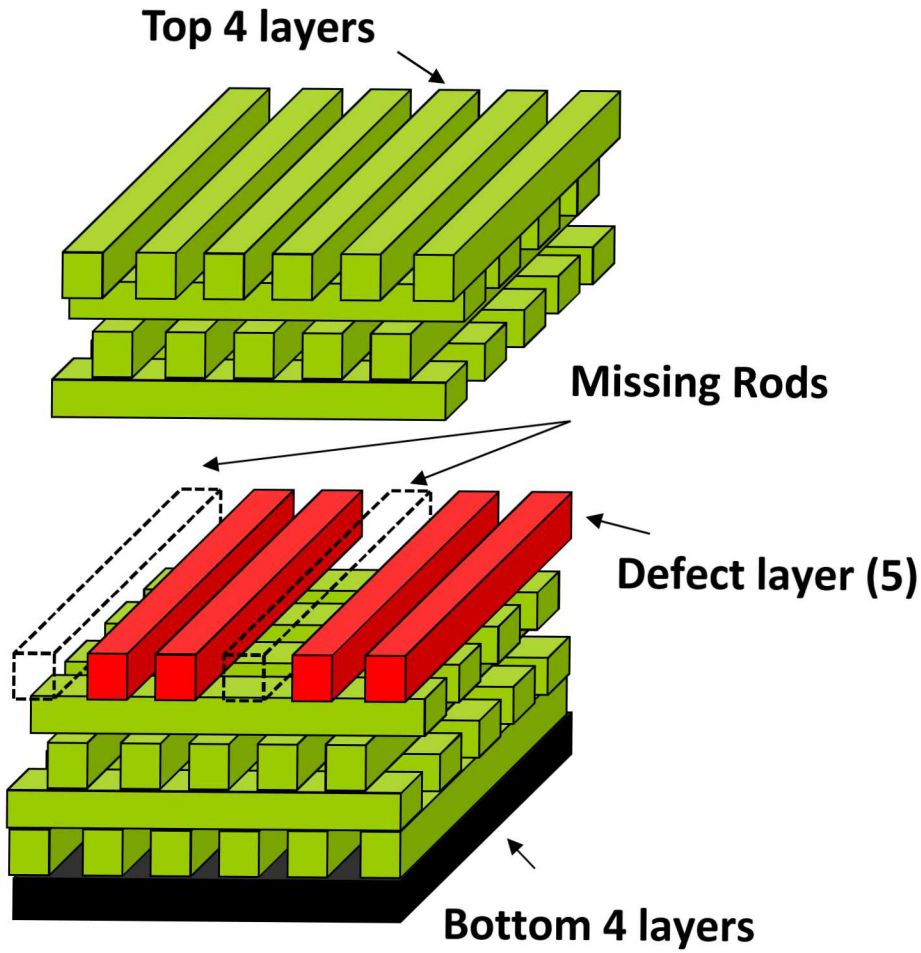
G. Subramania, Q. Li, Y.-J. Lee, J. J. Figiel, G. T. Wang, and A. J. Fischer, Nano Lett. **11**, 4591 (2011).

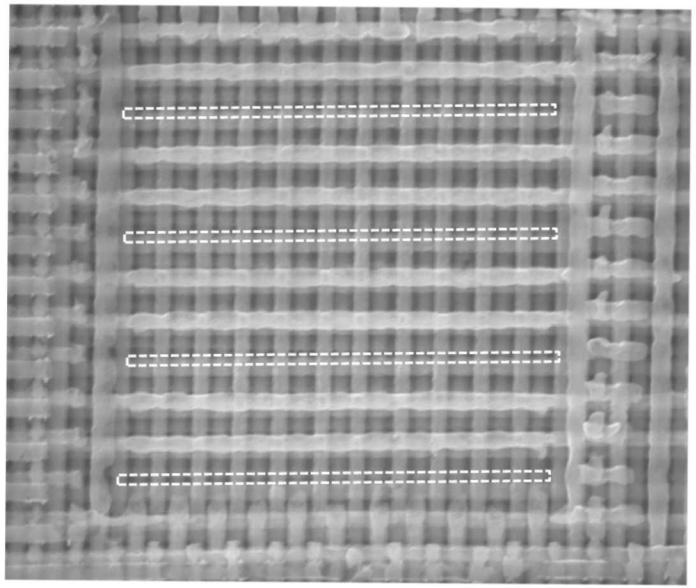
Optical Response of logpile GaN 3D PhC

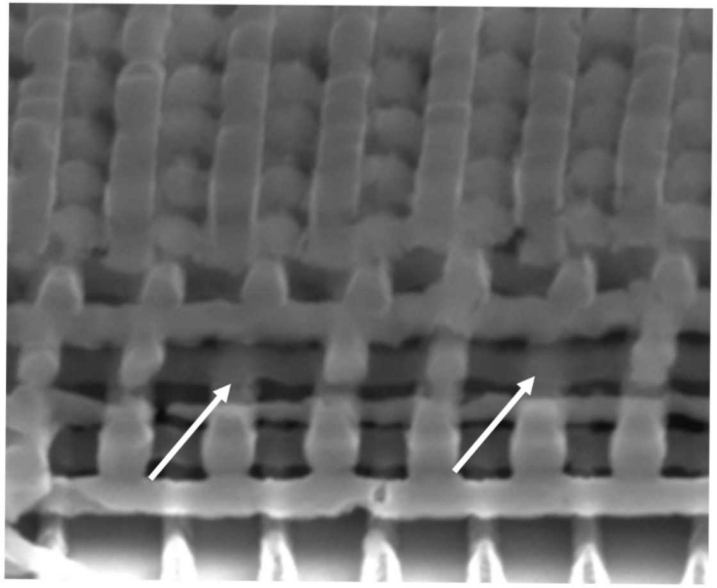


G. Subramania, Q. Li, Y.-J. Lee, J. J. Figiel, G. T. Wang, and A. J. Fischer, Nano Lett. **11**, 4591 (2011).

GaN Logpile PhC defect Cavity





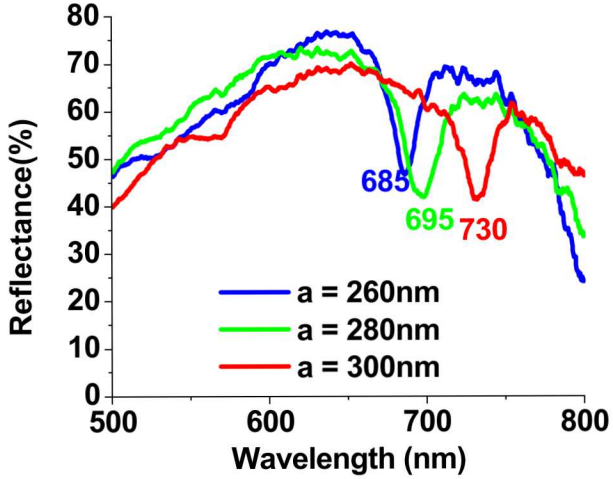


Logpile PC Cavity Optical Response

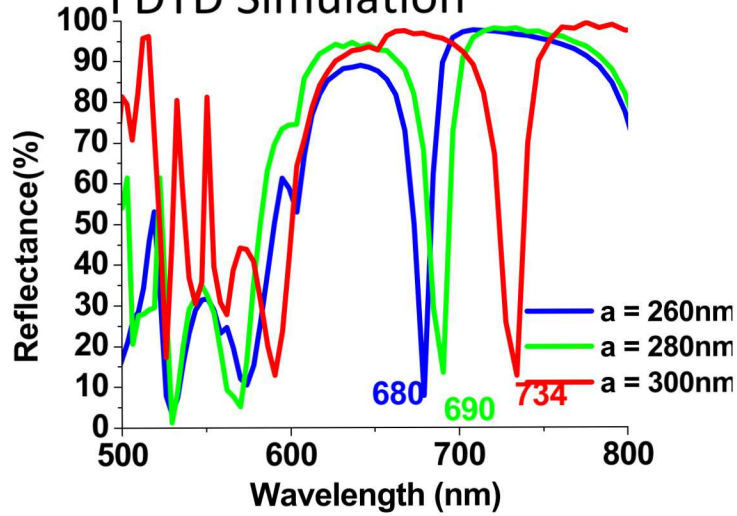
Sandia National Laboratories

Reflection

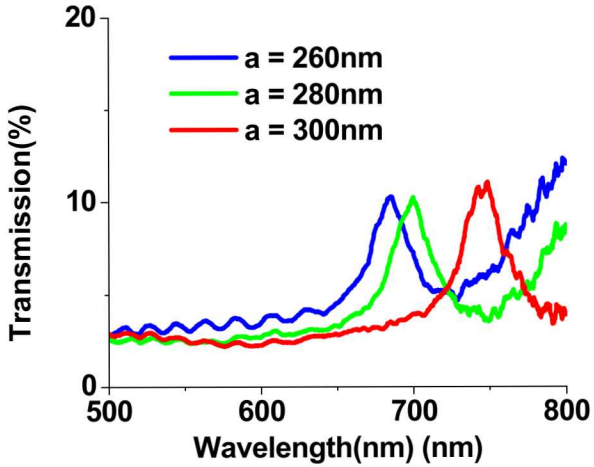
Experiment

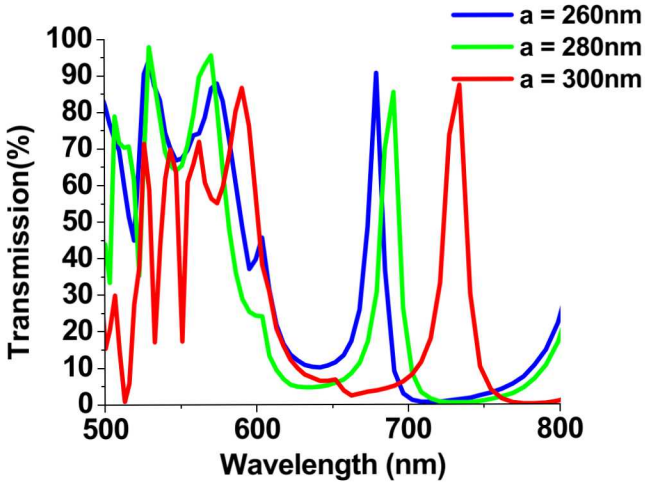


FDTD Simulation



Transmission





G. Subramania et. al. , Nano Lett. **11**, 4591 (2011).

Thank you for your attention!

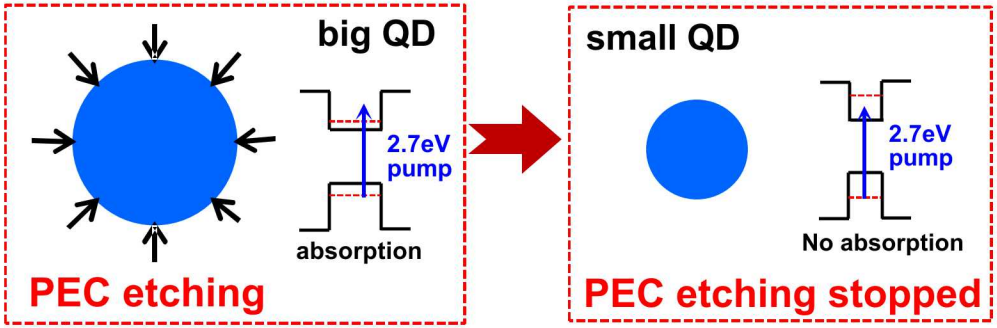
If extra time

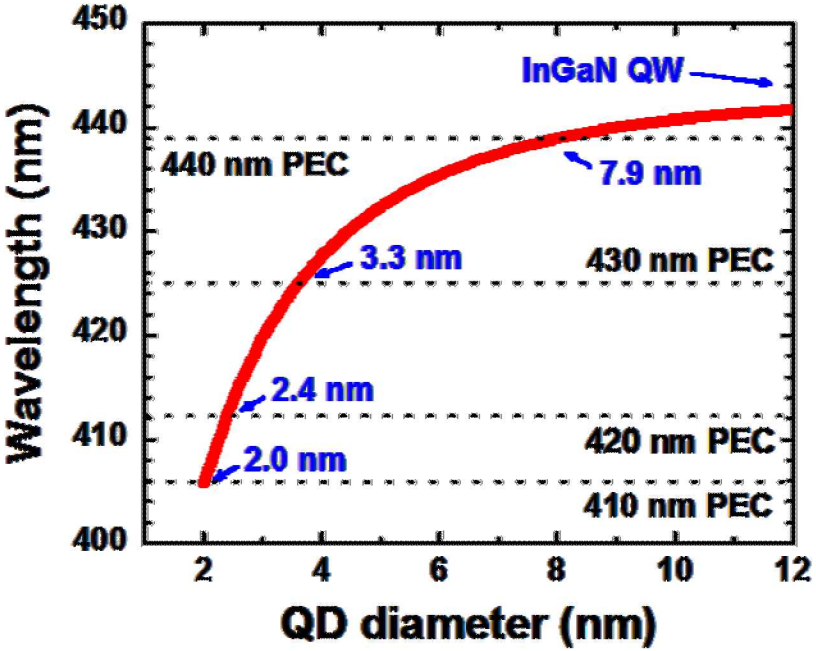
Quantum Dots for Single Photon Sources

Fabrication of InGaN QDs via PEC etching

Quantum Size Control: Use size quantization to control QD size

Self-limiting PEC etch process:





G. Pellegrini, et al., Journal of Applied Physics 97, 073706 (2005).

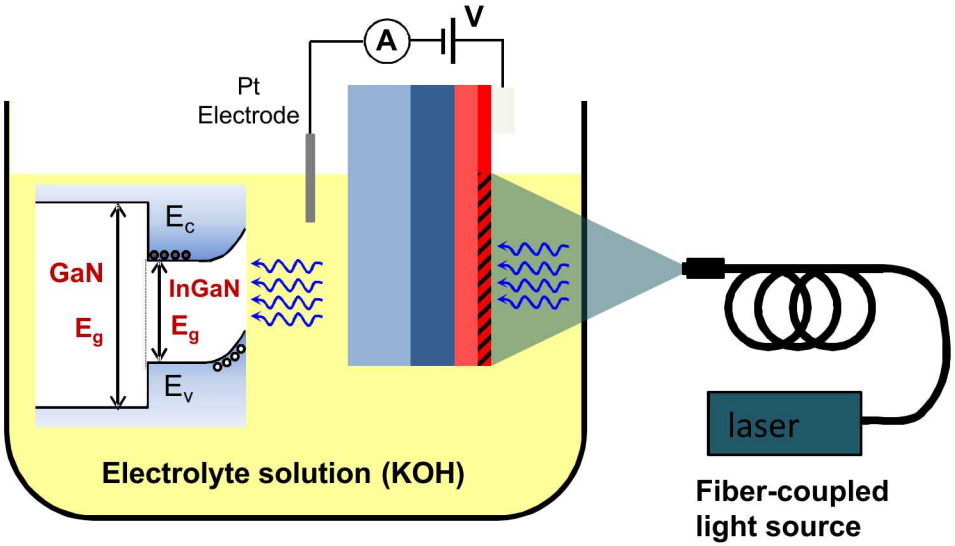
- For QDs, band gap depends on size
- As etch proceeds,
  - QD size gets smaller, band gap goes up
  - Etch terminated for $E_g > E_{photon}$ pump
- Self-terminating etch process
- Band gap selective
- QD size depends on PEC wavelength
- Monodisperse QD distributions ??

Xiao, X. *et al.* Quantum-Size-Controlled Photoelectrochemical Fabrication of Epitaxial InGaN Quantum Dots. *Nano Lett.* **14**, 5616-5620, doi:10.1021/nl502151k (2014).

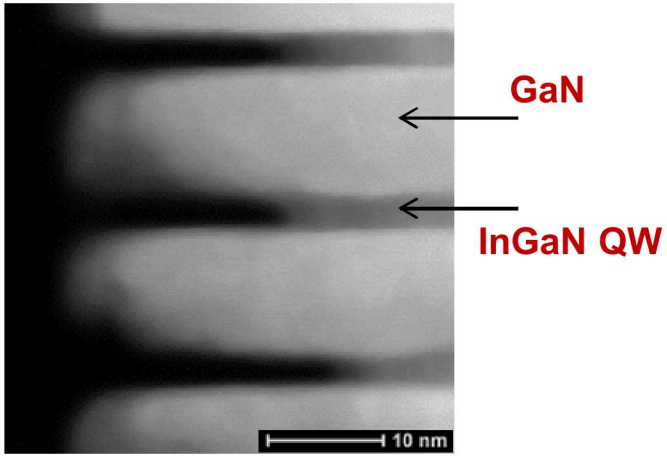
InGaN Photoelectrochemical (PEC) Etching

Photoelectrochemical (PEC) Etching:

- Very few wet etches work for III-nitrides
- Band gap selective (Etch InGaN over GaN)
- Dopant selective, light intensity dependent, etch current can be monitored
- Laser or lamp excitation (Xe arc lamp, tunable ps Ti:S)
- KOH (~0.1M) typically used as electrolyte



PEC etched InGaN/GaN QWS

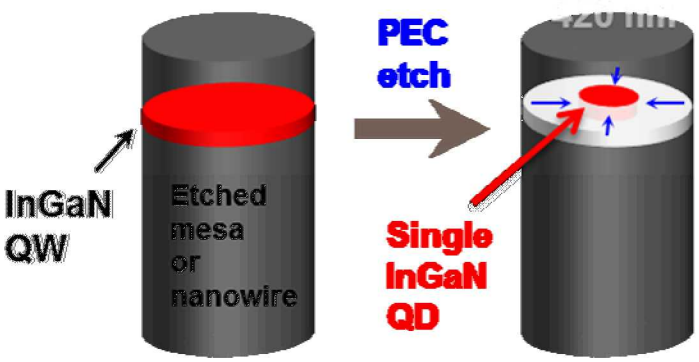


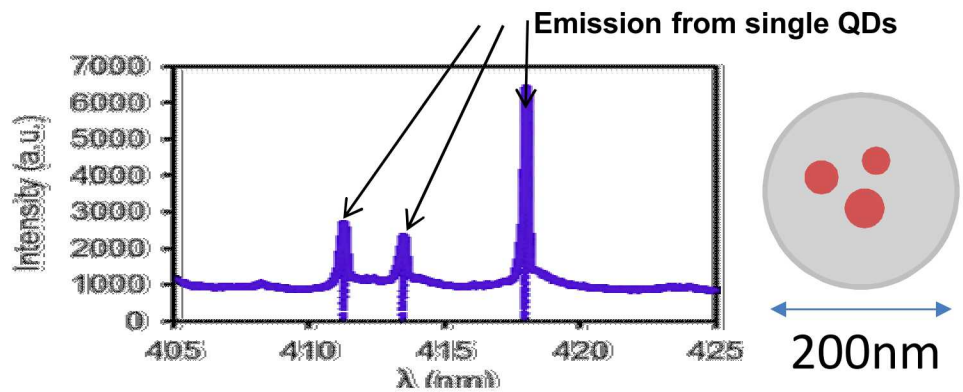
PL from InGaN QDs

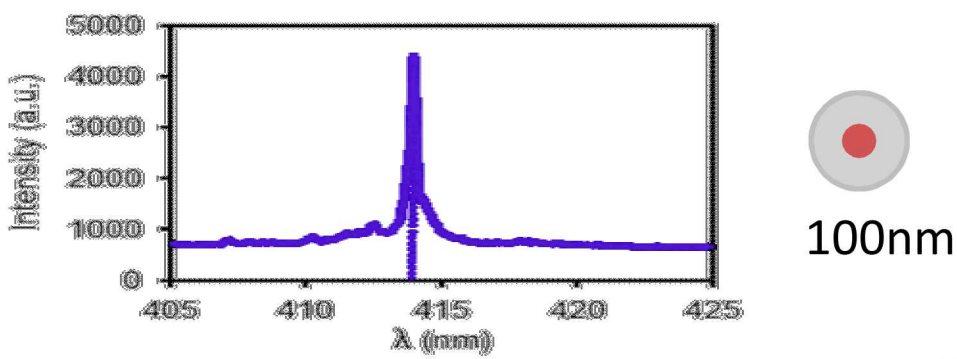
Capped InGaN QW

- Posts (150 – 200 nm) patterned with e-beam lithography
- Thicker GaN capping layer (~ 30 nm)
- Narrow PL emission (<1 nm FWHM) observed
- Better ratio of single QD mission to background

Fabrication of single InGaN QDs (methodology)







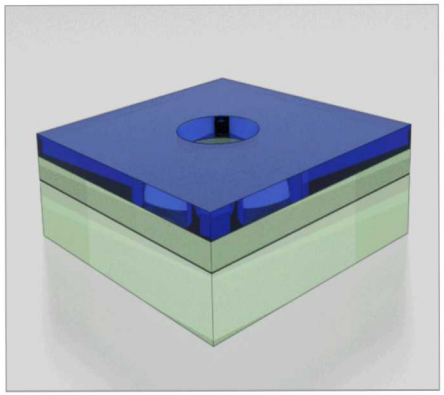
A.J. Fischer et. al. submitted

Patterned fabrication of InGaN QDs

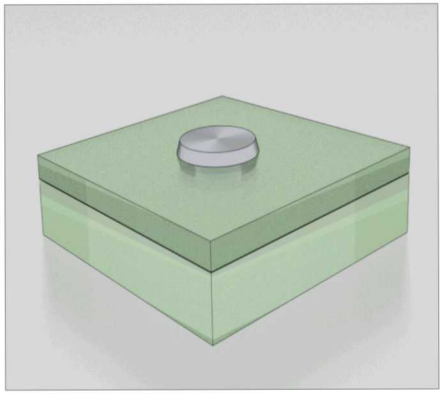
Sandia National Laboratories

- Deterministic placement

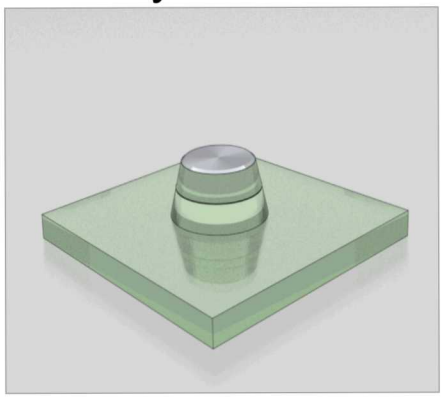
EBL Patterning



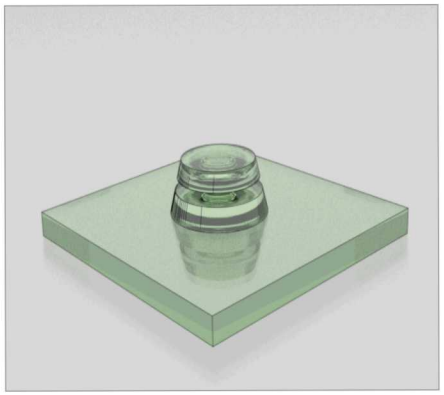
Metal Evaporation + Liftoff

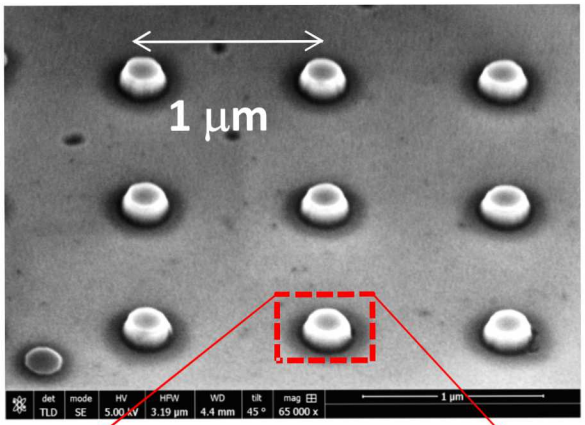


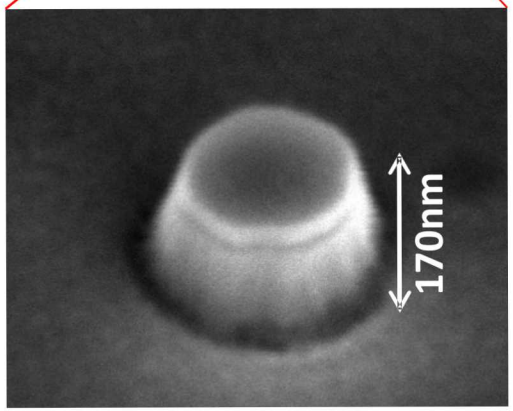
Dry Etch



Ni removal + PEC Etch

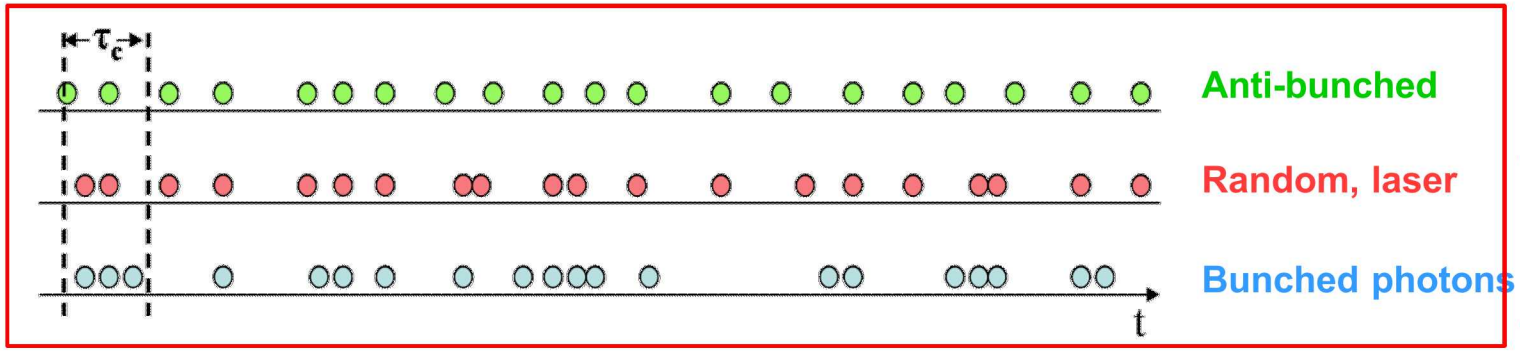






A.J. Fischer et. al. submitted

Single Photon Source: Photon Statistics



Quantum
g(2)(t = 0) <1
e.g., SPS

Classical
g(2)(t = 0) ≥ 1
e.g.,Thermal,LED , Laser

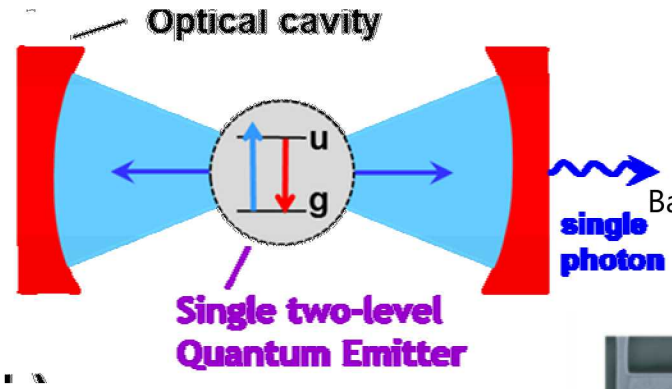
source: J.S. Lundeen

- **Quantum communication**
  - High bit rates than attenuated laser
  - Long distance secure comm.
  - Quantum repeaters (with indistinguishability)
- **Quantum metrology**
  - Measurement of low absorption
  - Single molecule level detection (in combination with high efficiency SPD)
- **Quantum computing**
  - Qubit operations
  - 'flying' qubits

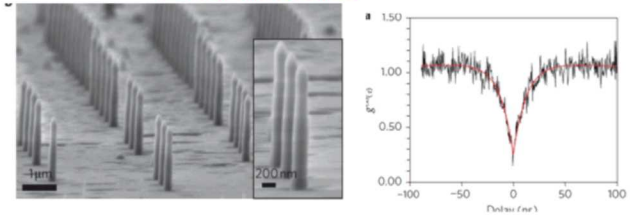
Desired properties of practical single photon sources (SPS)

- Near 100% probability of emitting single photon : $g_2(0)$~0
- High single photon rates
- High extraction or collection
- Mode quality
- Room temperature operation
- Electrical injection
- ~ 100% indistinguishability

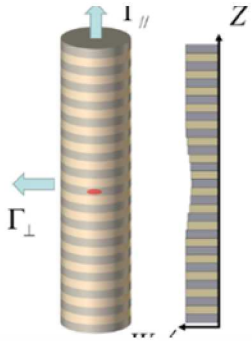
Single Photon Source based on Quantum Dots



Diamond

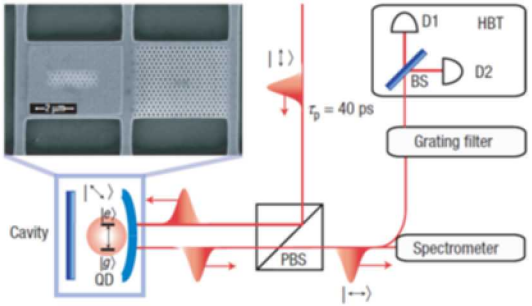


Babinec, T. M. *et al. Nat Nano* **5**, 195-199 (2010).

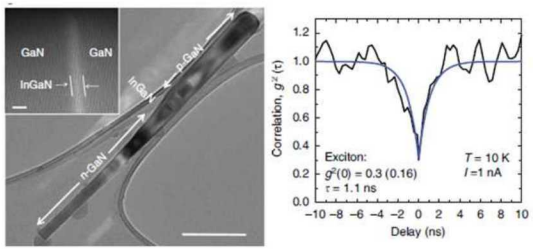


Portalupi, S. L. *et al. Nano Lett.* **15**, 6290-6294, d (2015).

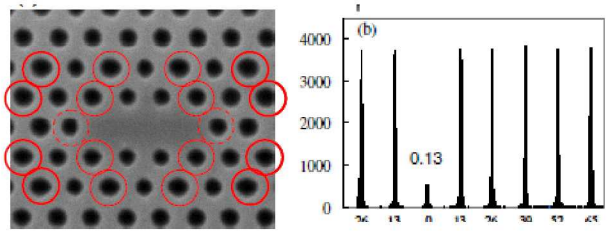
III-V



Faraon, A. *et al.Nat. Phys.* **4**, 859-863, (2008).

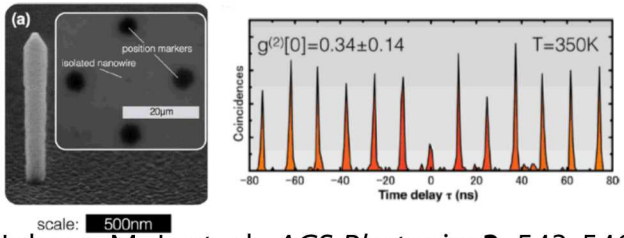


Deshpande, S., Nat.com. **4**, 1675(2013)

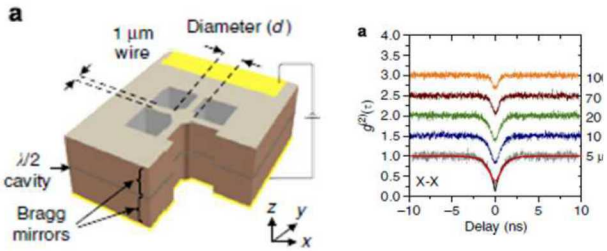


Toishi M., et. al, J. Opt. Exp., **17** , 146185(2009)

III-N



Holmes, M. J., et. al., *ACS Photonics* **3**, 543-546, (2016).



Nowak, A. K. et al.. Nat.com. **5**, 3240(2014)

Motivation for InGaN Quantum Dot SPS

Sandia National Laboratories

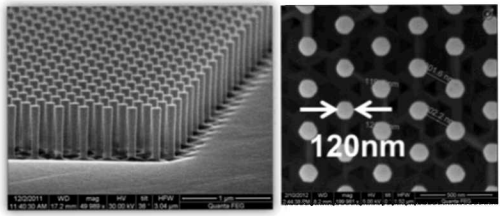
Goal: Room temperature, electrically-injected, chip-scale single photon source

III- N quantum dots have :

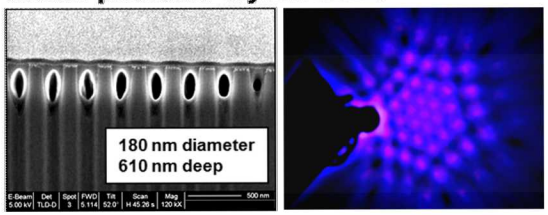
- Large exciton binding energy so can enable room temp. operation
- Path to electrical-injection/chip-scale integration
- Deterministic Source: on demand
- Triggered emission within radiative lifetime
  - Short emitter lifetime (~ 1 ns) → Fast rep. rate

- *Isolate emission from a single quantum dot*
- *Leverage prior expertise/experience*

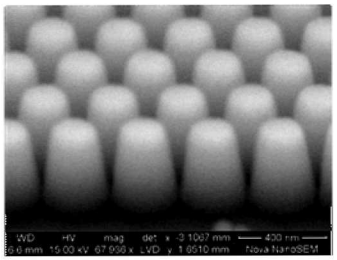
GaN nanowire arrays



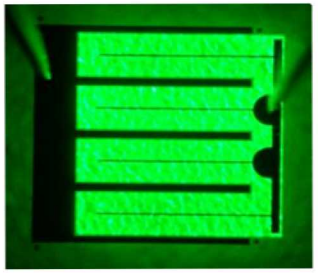
InGaN photonic crystal LEDs



InGaN nano-LED array



Green InGaN LEDs

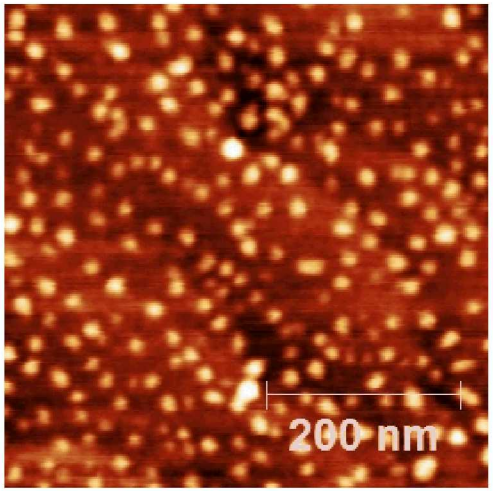


Atomic Force Microscope (AFM) Measurements

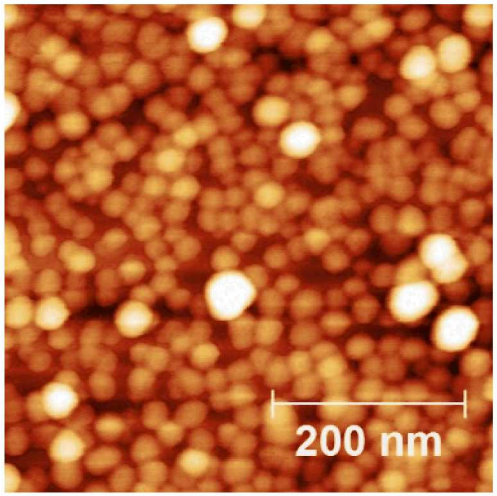
Uncapped InGaN QW

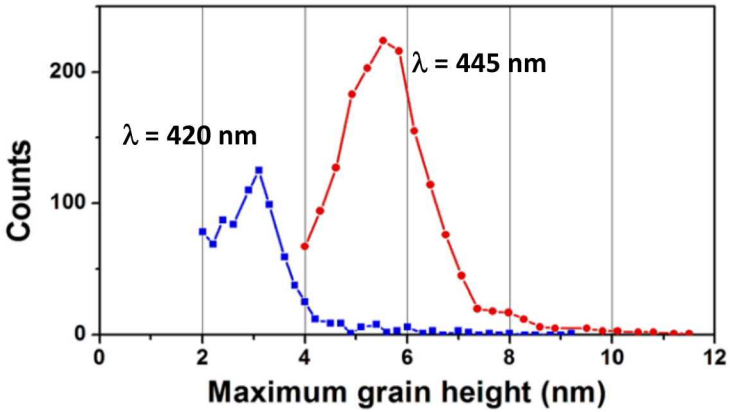
- Samples etched for two hours at 420 nm and 445 nm
  - Laser power density: ~ 3 mW/cm^2
- High dot density: 10^{11}/cm^2
- Some big dots (10-20 nm) remain: due to dislocations?
- QD size depends on PEC etch wavelength

PEC etch→ λ = 420 nm



PEC etch → λ = 445 nm

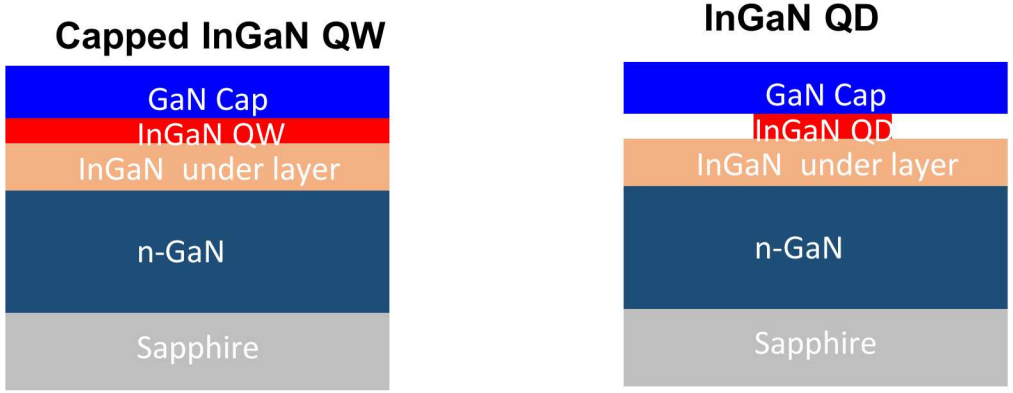


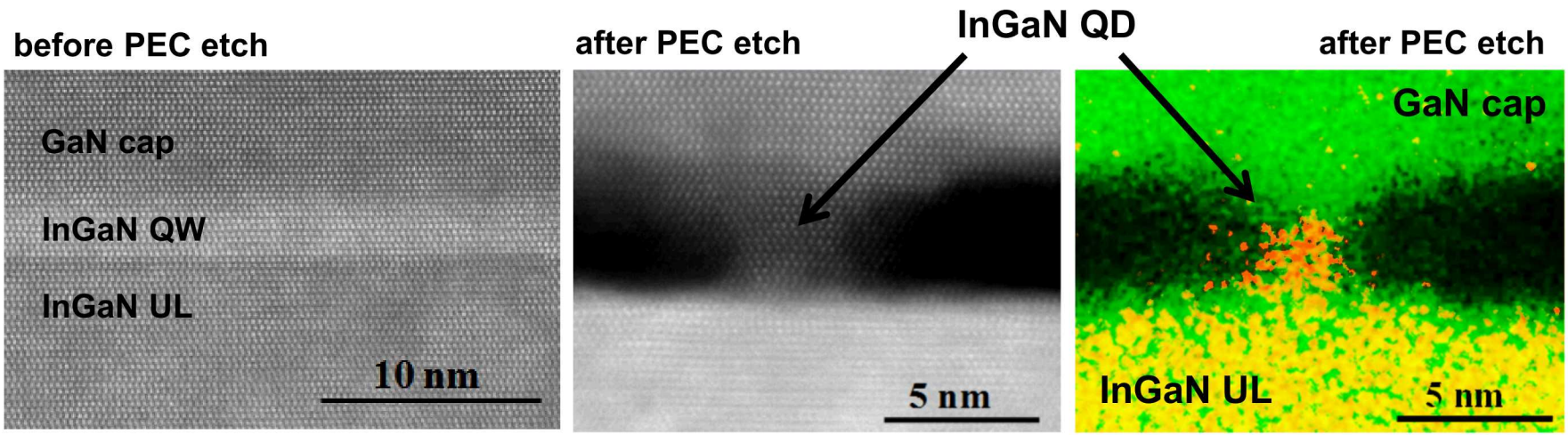


Transmission Electron Microscope Images

Sandia National Laboratories

- High-angle annular dark-field (HAADF) TEM images
- Sample etched at 420 nm
- EDX mapping shows that dots are InGaN
- InGaN QDs are epitaxial to the underlying GaN
- 2% InGaN underlayer + GaN cap
- GaN cap provides partial passivation

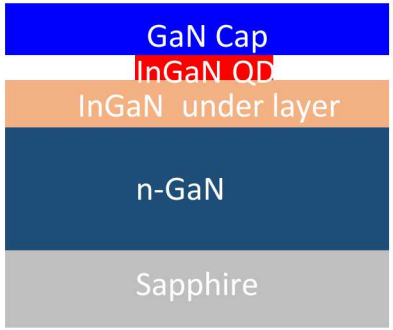




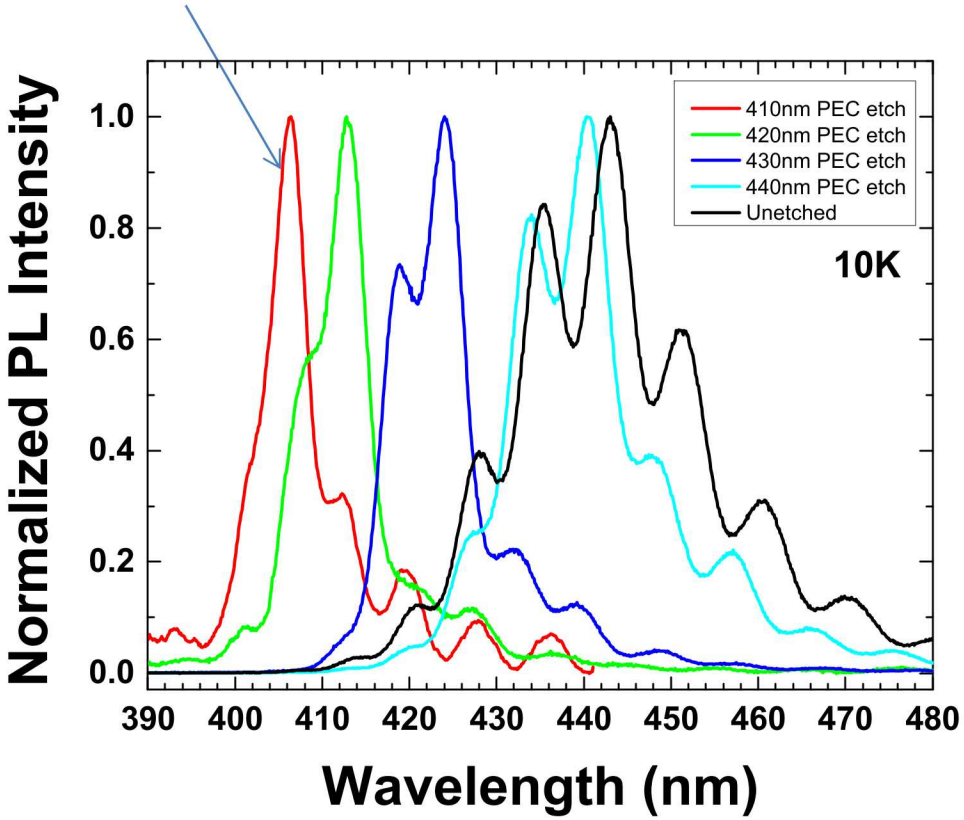
Xiao, X. *et al.* Quantum-Size-Controlled Photoelectrochemical Fabrication of Epitaxial InGaN Quantum Dots. *Nano Lett.* **14**, 5616-5620, doi:10.1021/nl502151k (2014).

Photoluminescence from fabricated InGaN QDs

Capped InGaN QW



As narrow as **6 nm** FWHM is consistent with a narrowing of the QD size distribution



Photoluminescence (PL) data:

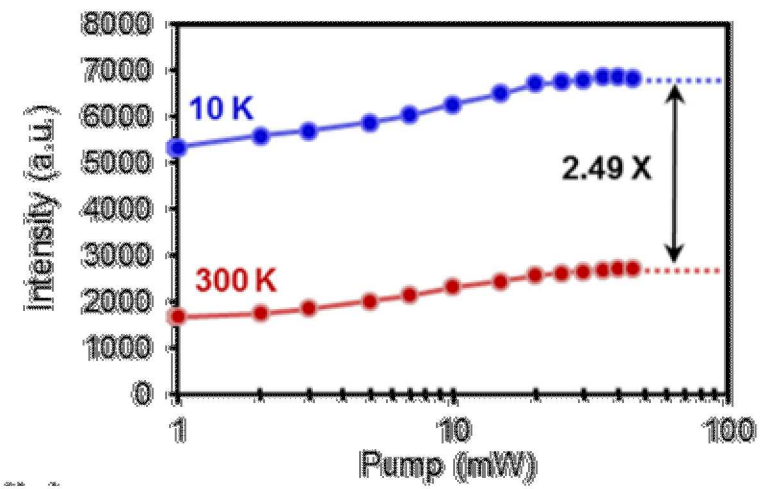
- **375 nm pump (ps pulsed)**
- **10K PL data**
- **PL wavelength determined by PEC etch wavelength**
- **PL linewidth: 24 nm → 6 nm**
- **Quantum size-controlled PEC etching works!**

Xiao, X. *et al.* Quantum-Size-Controlled Photoelectrochemical Fabrication of Epitaxial InGaN Quantum Dots. *Nano Lett.* **14**, 5616-5620, doi:10.1021/nl502151k (2014).

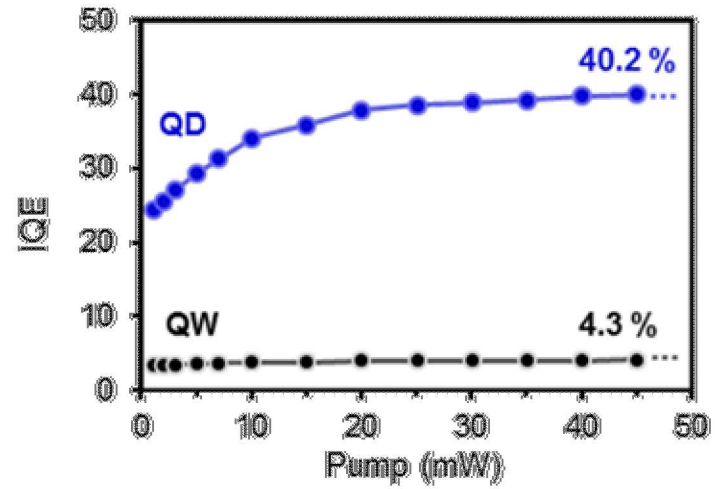
IQE from InGaN QW vs QDs

Sandia National Laboratories

QD PL pump dependence



IQE QD vs QW



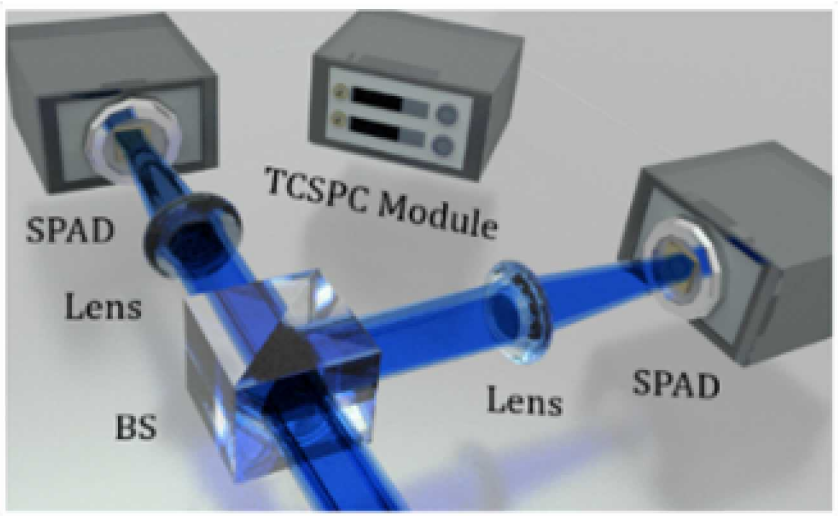
- Significant improvement in IQE between QW and QDs
- <u>Cause:</u> QDs are efficient emitters ; Also poor material etched away

A.J. Fischer et. al. submitted

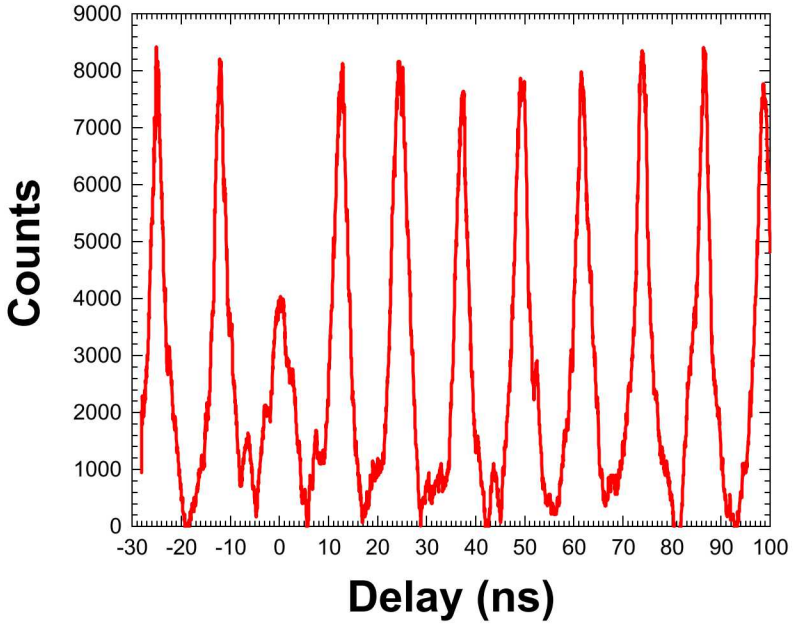
Single Photon Measurement: HBT experiment

- Observation of antibunching : g2 ~ 0.5 for PEC-etched InGaN QDs
- Next steps:
  - Thicker GaN cap
  - Reduce nanowire radius
  - Emission rate enhancement
  - Enhanced light extraction

HBT Experimental Set-up



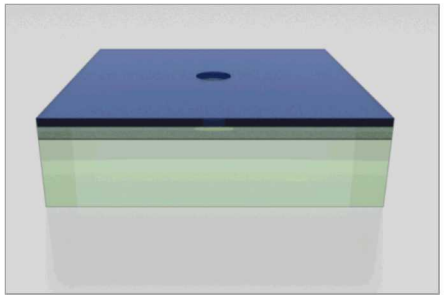
Pulsed g2 data



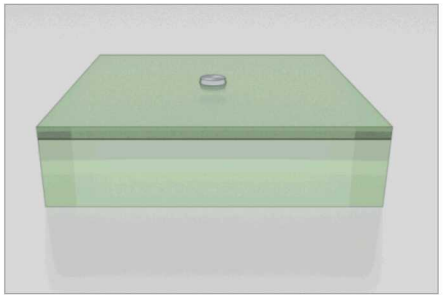
A.J. Fischer et. al. submitted

Nanofabrication Approach

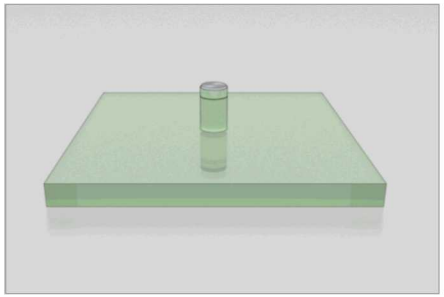
EBL Patterning



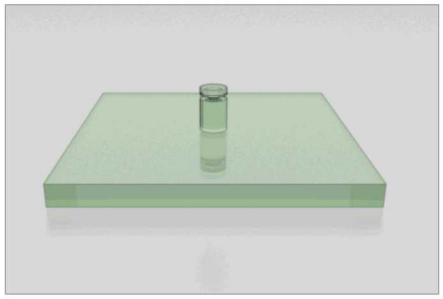
Metal Evap. + Liftoff



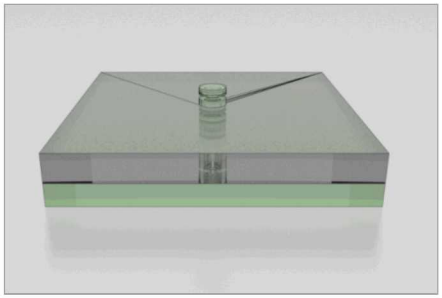
Dry + Wet Etch



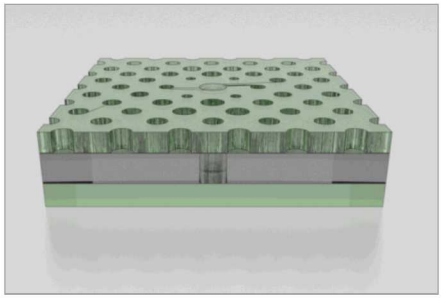
PEC Etch



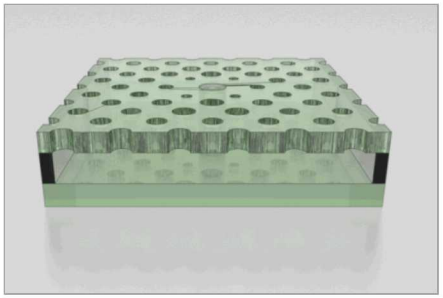
Spin-coat FOX16



TiO_2 dep. + EBL



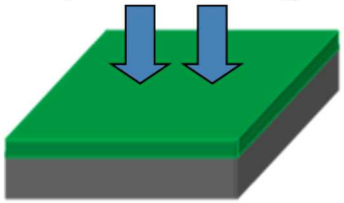
Membrane formation



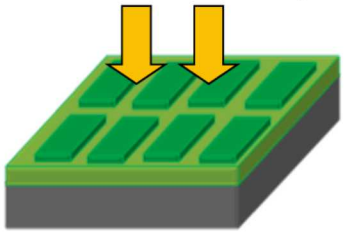
Potentially all III-nitride solution is possible but fabrication is more challenging

Fabrication- Some recent results

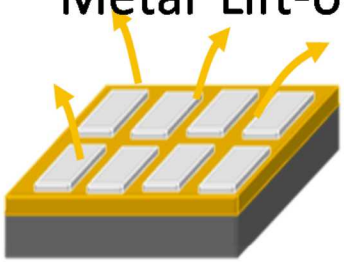
Electron beam patterning of PC

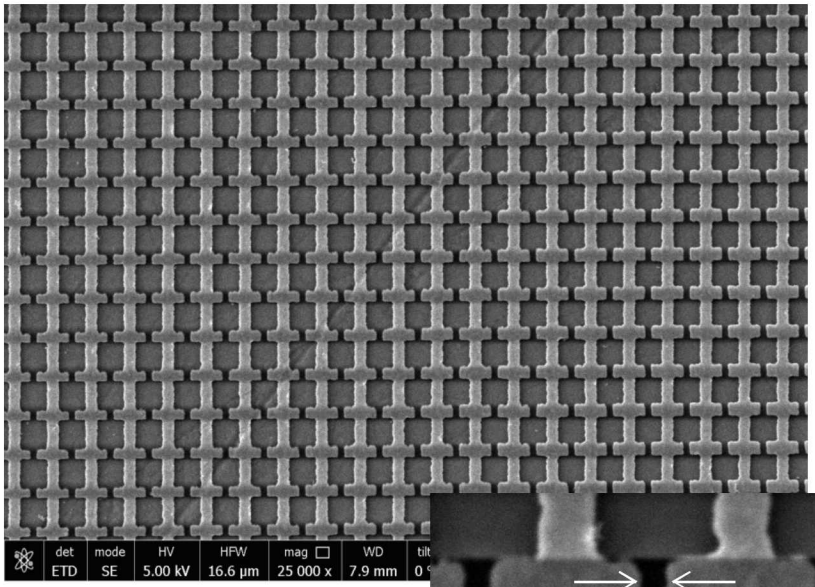


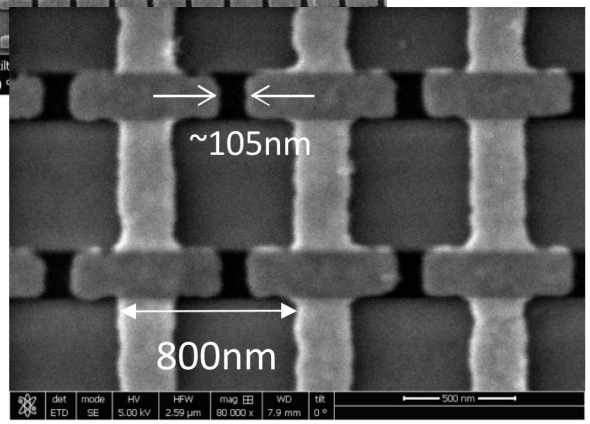
Metal deposition



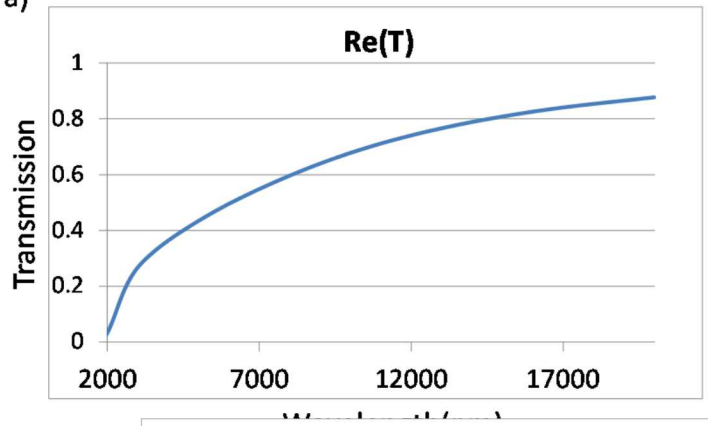
Metal Lift-off



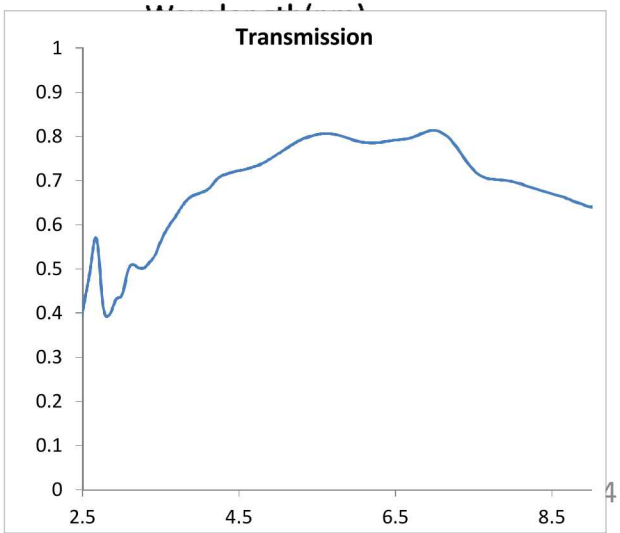




a)



b



Summary / Future Possibilities

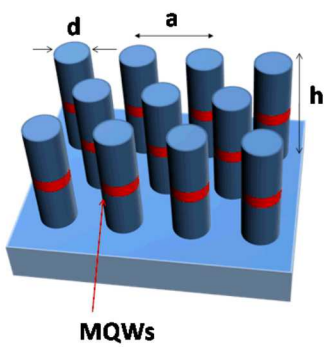
GaN

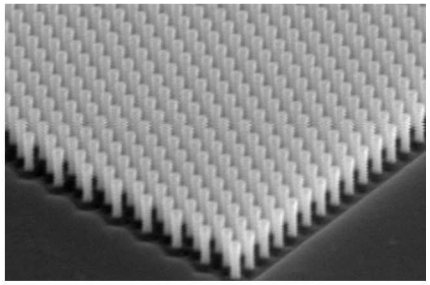
- Nanotemplated 3DPC growth possible (also demonstrated by UIUC group in GaAs)
- The GaN grows epitaxially maintaining crystallinity

- Solid state lighting app.
- Introducing InGaN QW emitters within the 3DPC during growth
- Newer QW geometries ? (axial vs. radial)
- Electrical injection

Fabrication is time consuming and challenging at this point !

Investigating 2DPC GaN nanopillar array based light emission





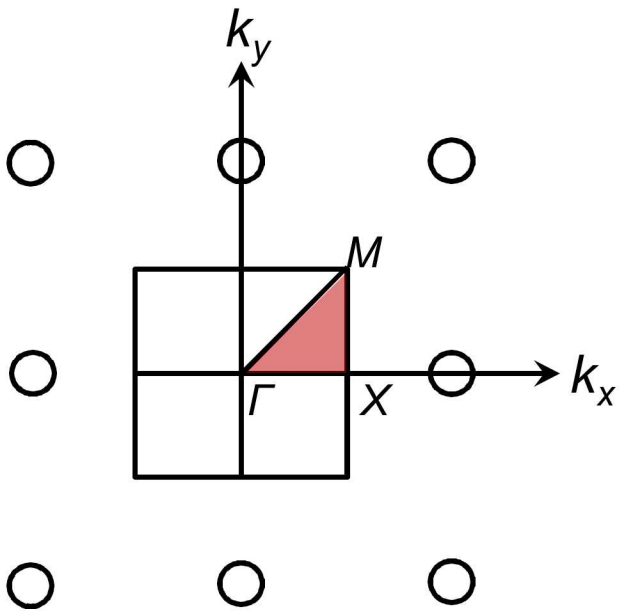
w/ G. Wang , I. Brener, T.S. Luk

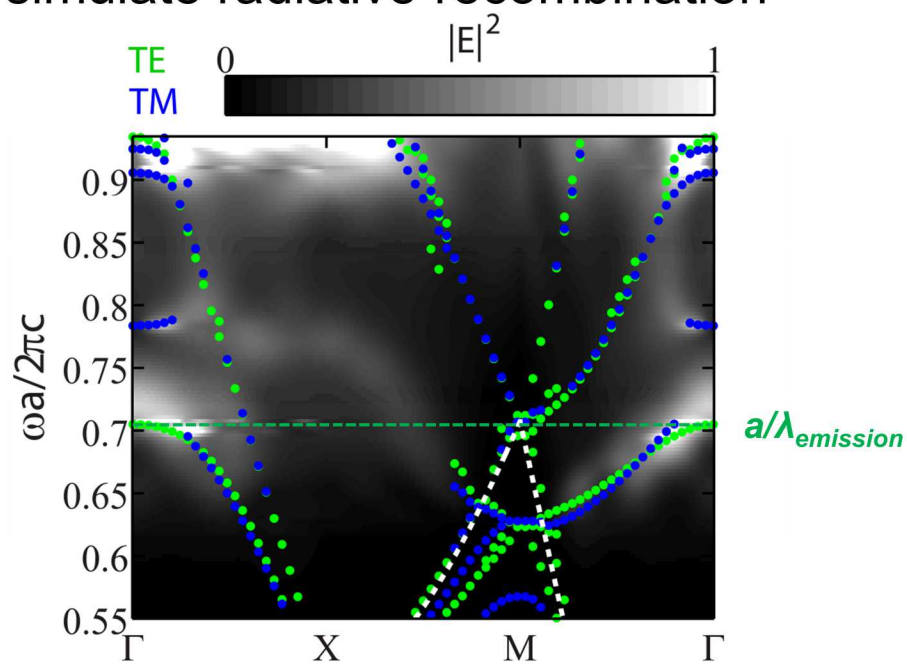
Emitted far-field and bandstructure

In collaboration with M. Povinelli

Structure: Square array of GaN nanorods (r/a = 0.268, h/a = 0.5)

Simulations (FDTD): electric dipoles simulate radiative recombination



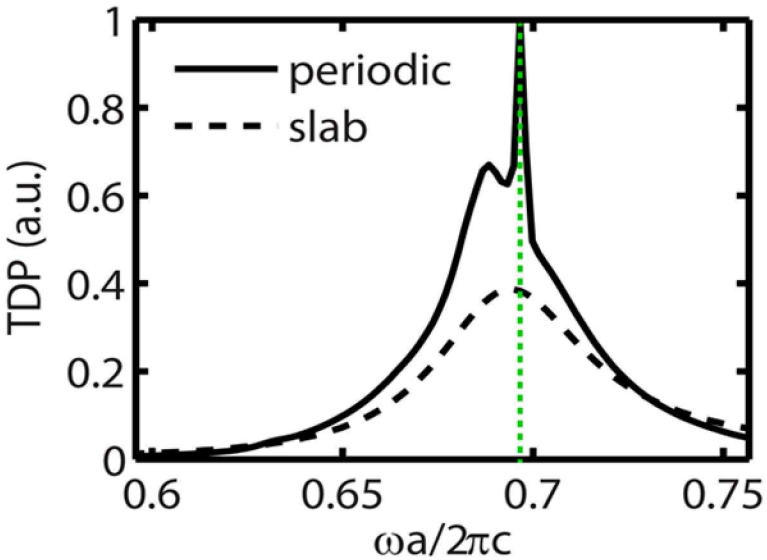


Align emission with lowest-order Γ-point mode

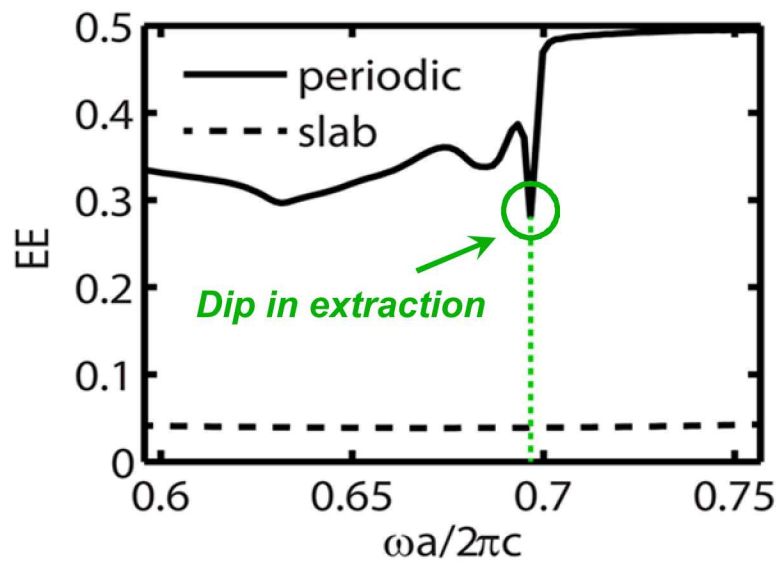
Anderson et al., *Appl. Phys. A.* 117: 1879 (2014)

Emission and extraction efficiency

Resonant enhancement in emission



Improvement in light extraction



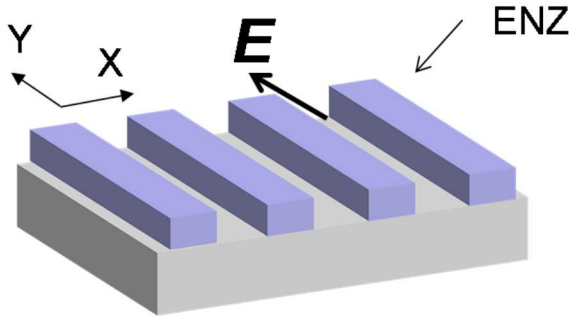
Resonance is forbidden by symmetry to along Γ-point: *uncoupled mode*

Combine enhanced emission with larger light extraction?

Anderson et al., *Appl. Phys. A.* 117: 1879 (2014)

Approach to Reducing Metal Absorption effects

G. Subramania, A. J. Fischer, T. S. Luk *Applied Physics Letters* **101**, 241107 (2012).

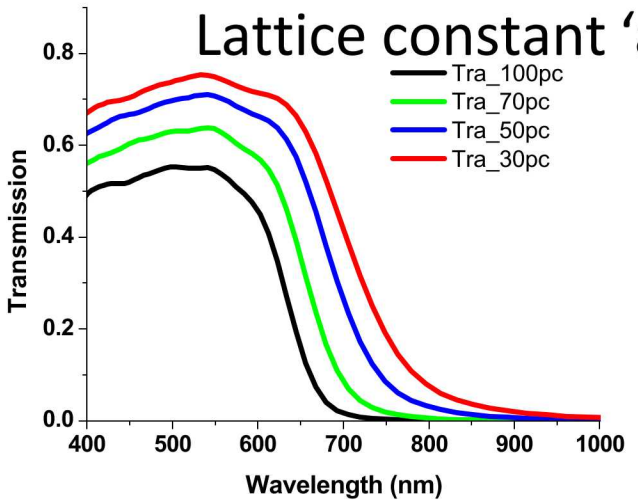


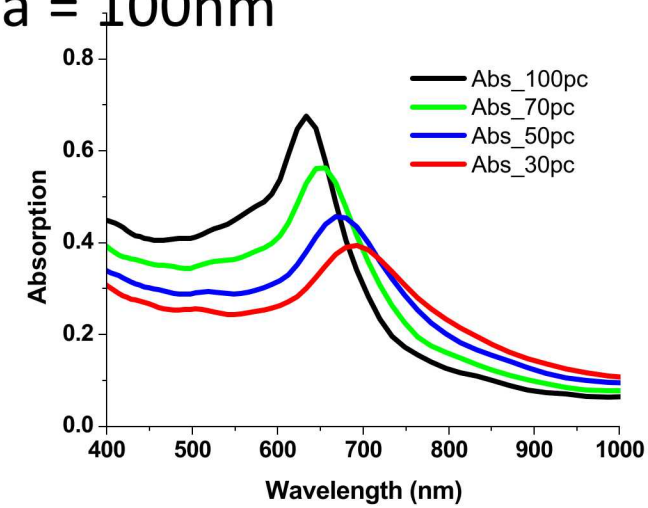
dielectric

$$\varepsilon_{effective} = f\varepsilon_{+} + (1 - f)\varepsilon_{ENZ}$$

- Light polarized along the grating
- Ideally, grating period as small as possible for effective medium
- Increased transmission
- ENZ wavelength redshifts with grating duty cycle

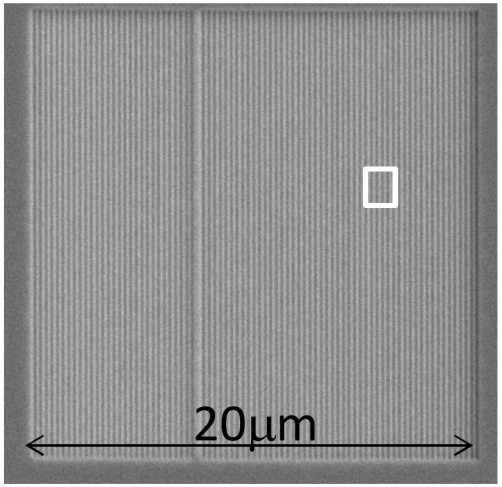
Lattice constant 'a'= 100nm

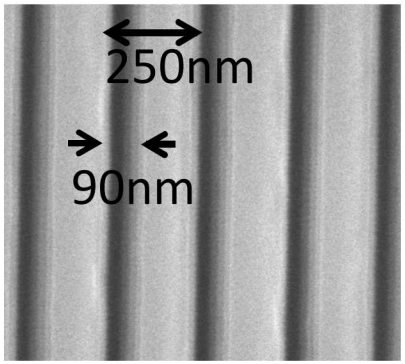


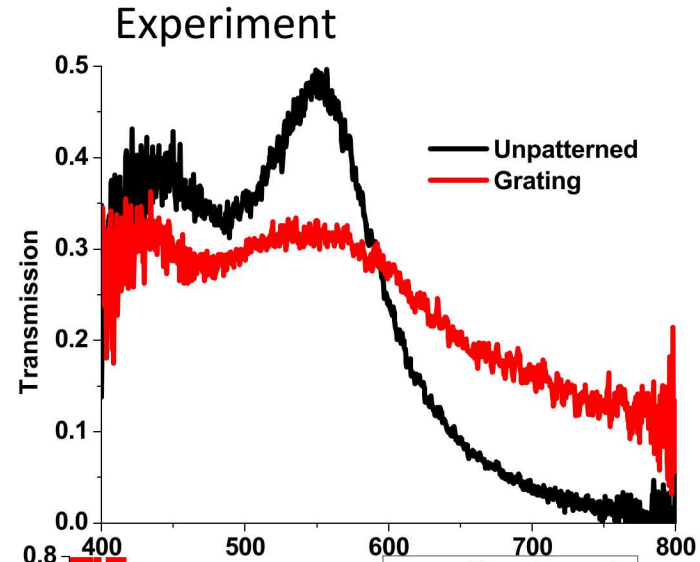


Grat	λ_{ENZ}	Trans
100	660	~0.1
70	690	~0.12
50	725	~0.17
30	800	~0.09

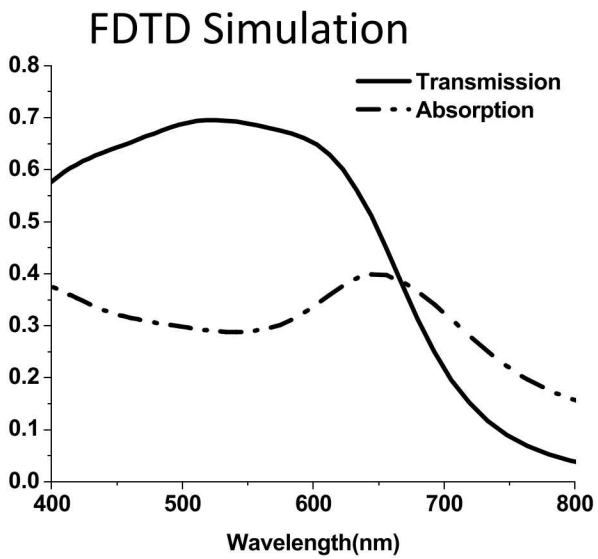
Fabrication - Characterization

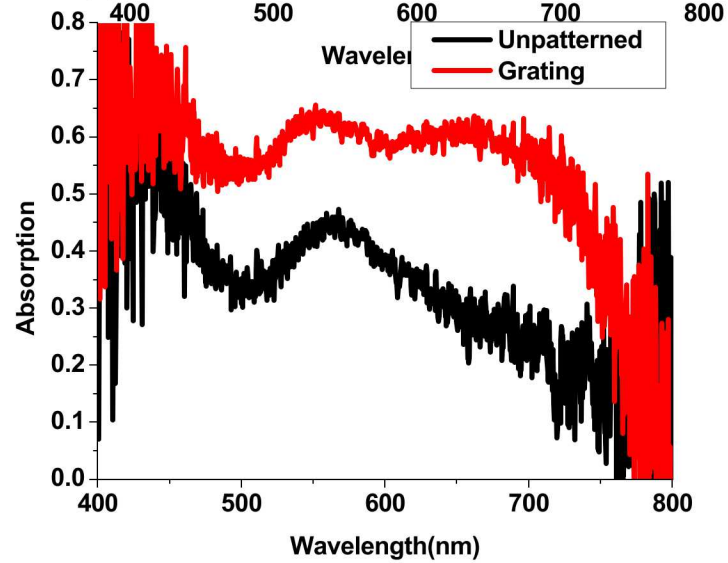






- Fabrication using Focused Ion Beam (FIB)





G. Subramania, A. J. Fischer, T. S. Luk *Applied Physics Letters* **101**, 241107 (2012).

Collaborators

- Art Fischer
- Dan Koleske
- Duke Anderson
- George Wang
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- Igal Brener
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- Stavroula Foteinopoulou
- Jon Wierer
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- Weng Chow
- Mike Coltrin
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- Thomas Beechem
- Paul Clem
- Jeff Brinker
- Bernadette Sanchez
- John Nogan
- Ed Gonzales
- Cathy M
- Doug Pete
- Carlos Sanchez
- Tony Coley
- Travis Young

TiO_2 Photonic crystal