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Making 3D Photonic Crystals

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Trieste, Feb 05

Opal: the First Photonic Crystal?

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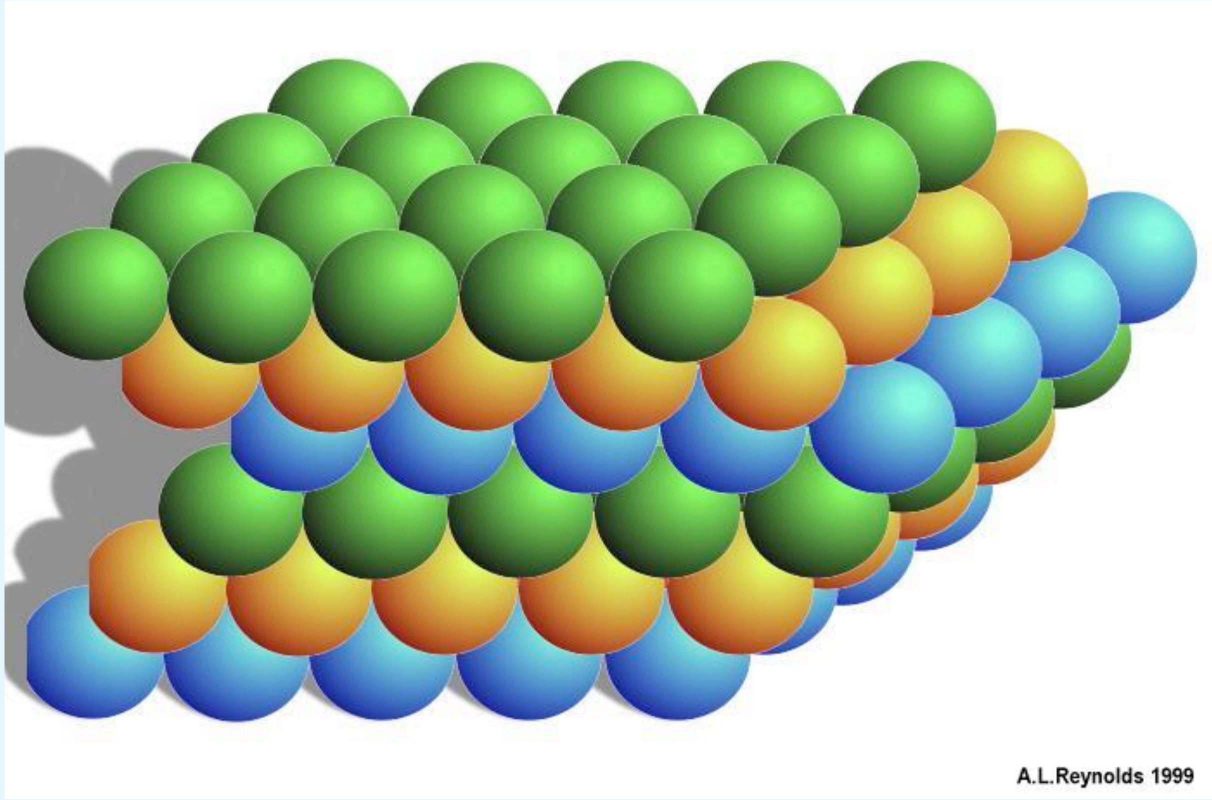
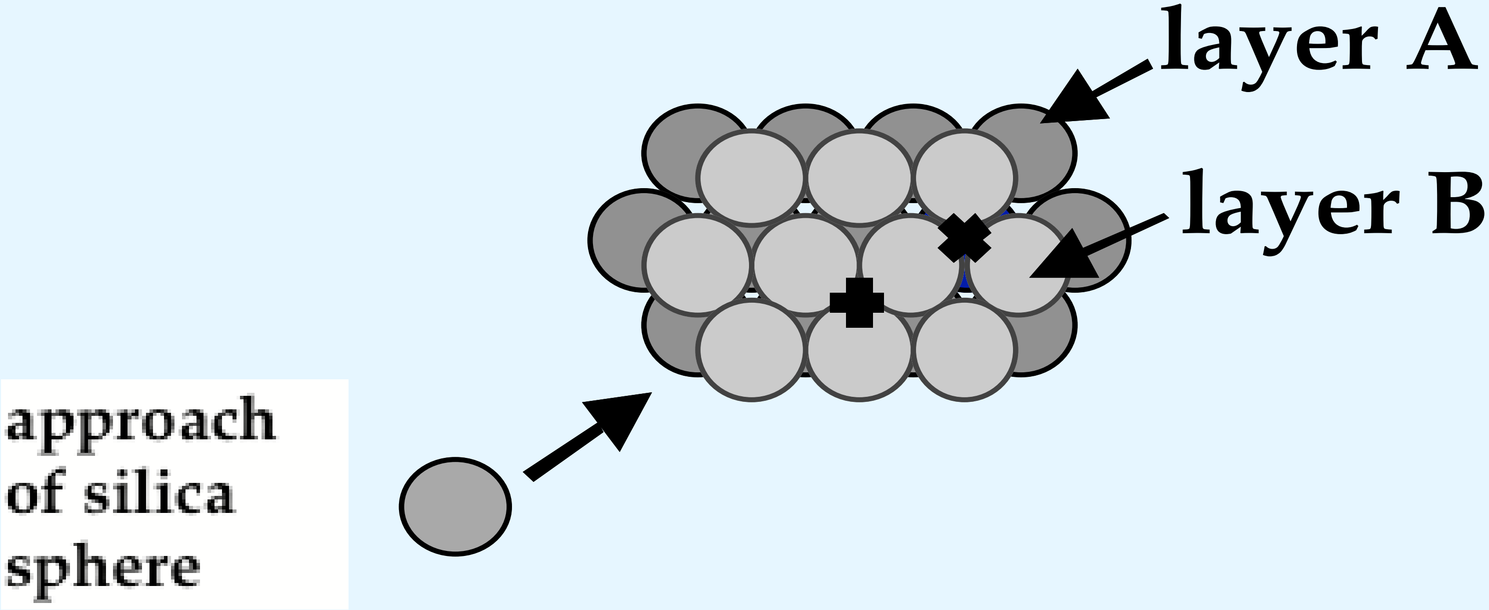
Colloidal formation and self-organised deposition of ~300 nm dia. silica spheres.



Representation due to Andrew Reynolds

Which crystal symmetry?

- Choosing the site(s), as successive layers are deposited, means choosing the crystal symmetry.



✖ A site for ABABAB gives hcp

✚ C site for ABCABC gives fcc

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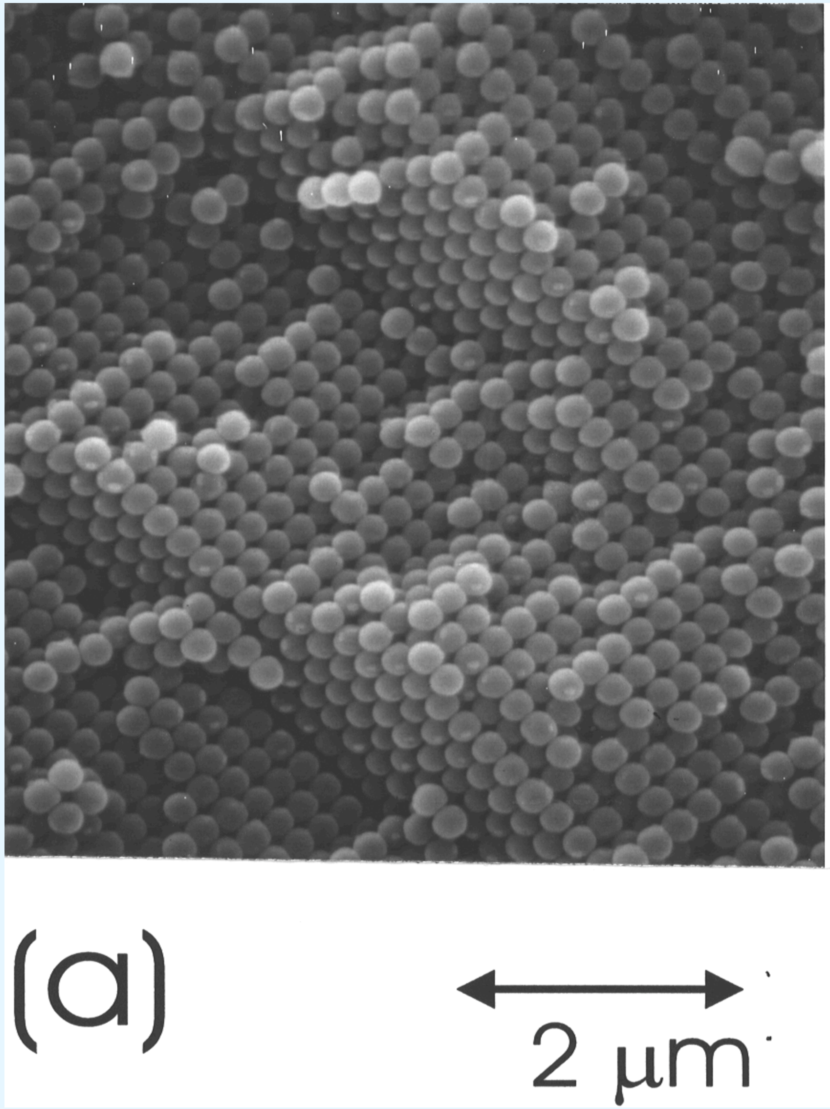
Bare opal: Electron Micrograph

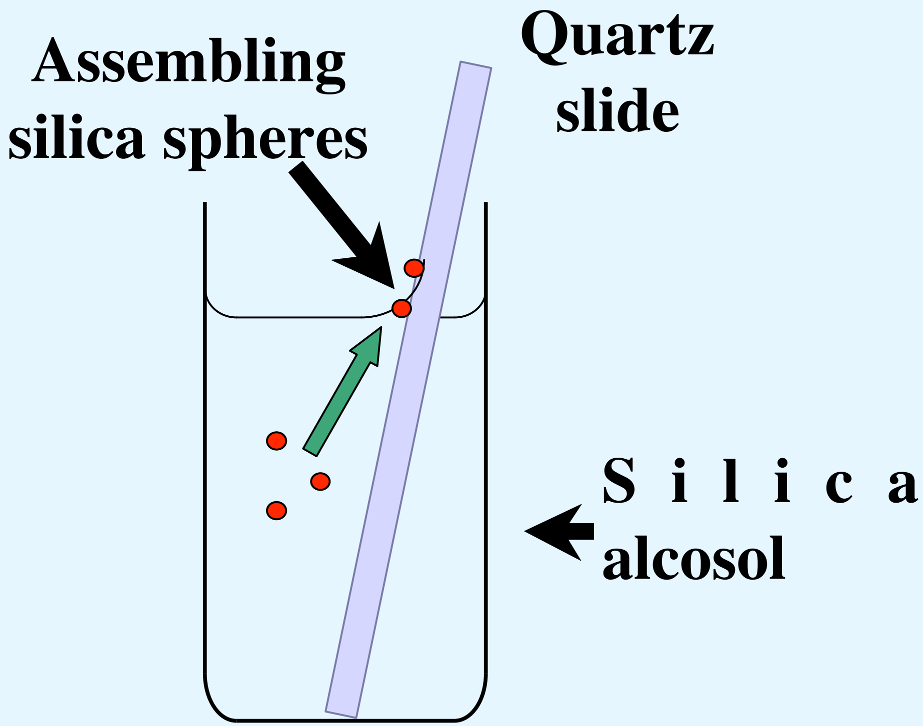
Sub-micrometre (typically ~300 nm dia.) colloidal silica spheres. Cleaved material surface shows both *square* packing associated with (100) planes and *hexagonal* packing associated with (111) planes. Made in Russia.



S.G. Romanov, N.P. Johnson and C. Sotomayor-Torres

Capillary Growth

Evaporation of solvent in a controlled environment.



- thin films
- single domains (~50-100µm)
- well-ordered
- opalescent

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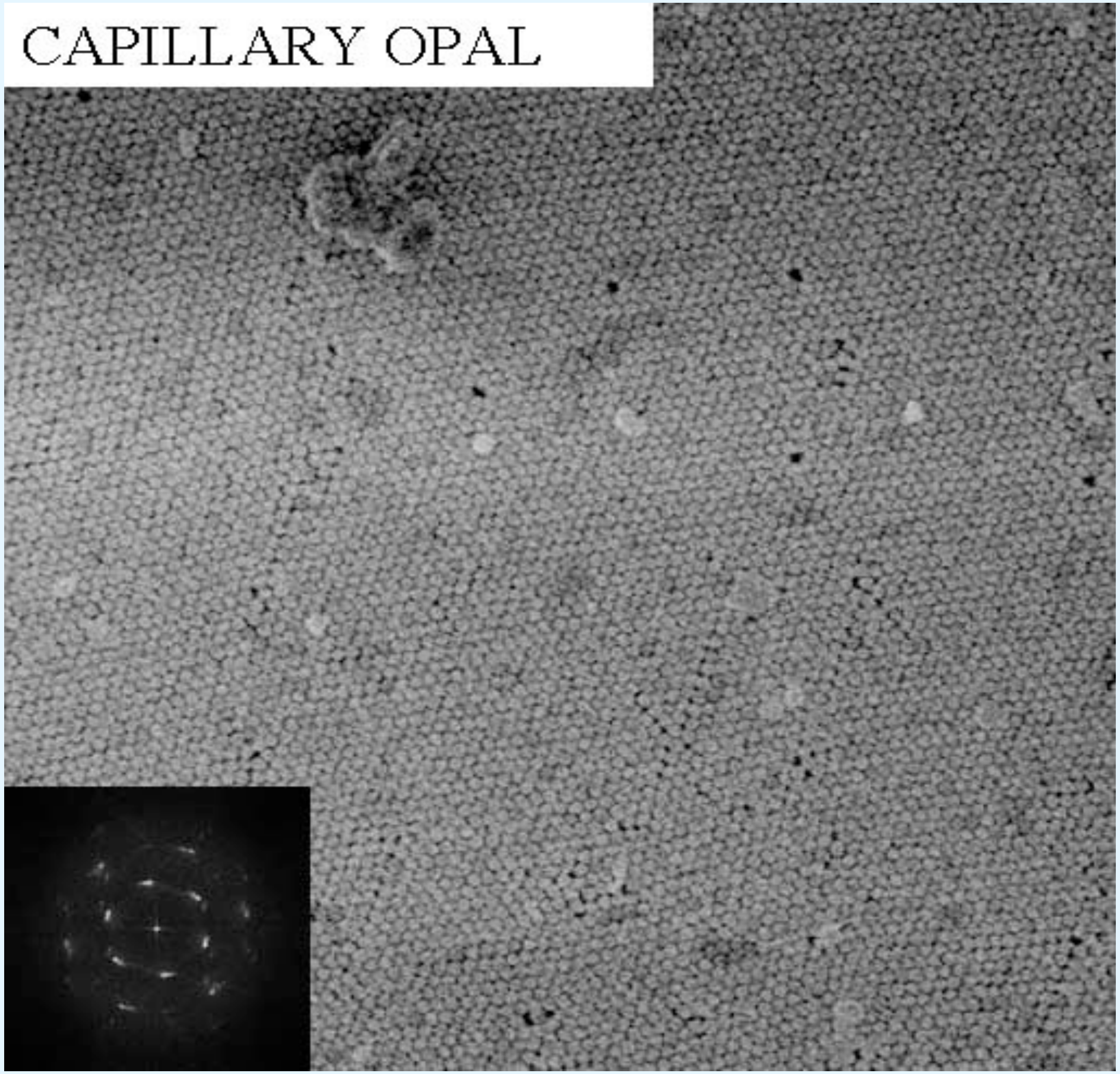
Opal: 'grown in Glasgow'



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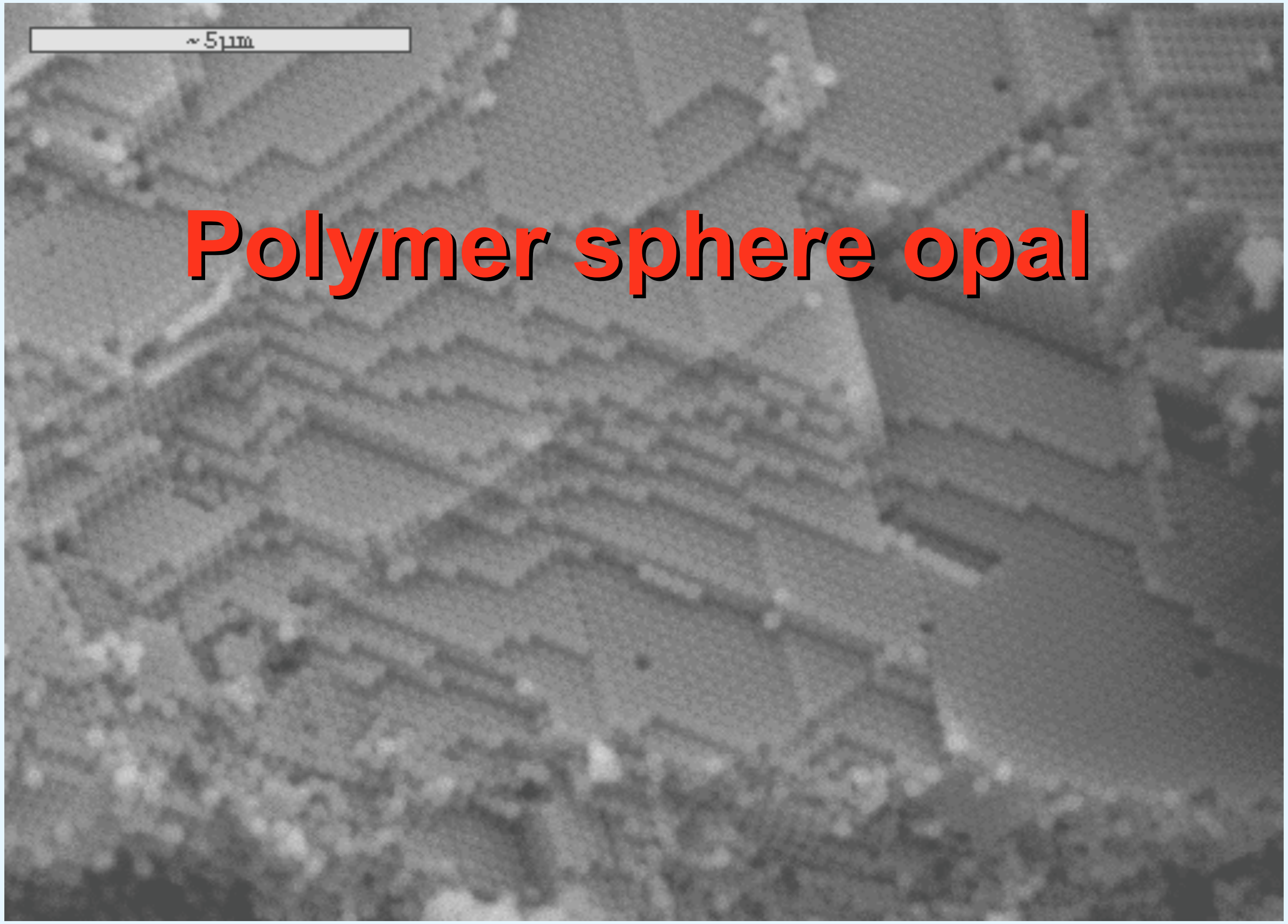
Cleaved colloidal crystals in plastic!

Presented at the ECS Meeting, Paris, April 2003.

McLachlan MA, Johnson NP, De La Rue RM and McComb D.M.,'Thin film photonic crystals: synthesis and characterisation', J MATER CHEM 14 (2): 144-150 2004



Stacked (111) layers perpendicular to substrate.

Sphere diameter 230nm

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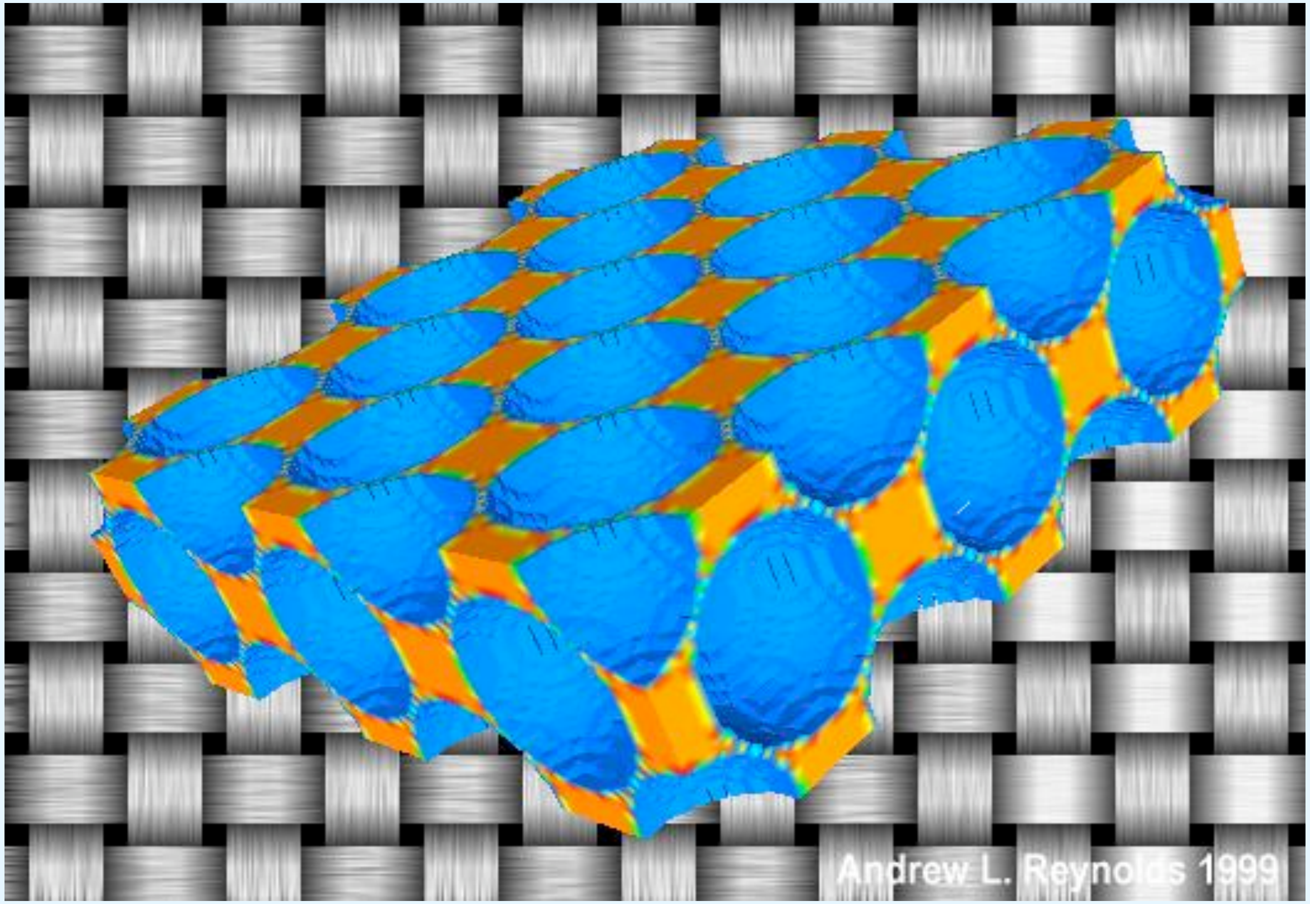
Inverse Opal: a Lattice of "Air" Spheres



Representation due to Andrew Reynolds

Formation of Inverse Opals

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Filling the voids

- Infiltrate small crystals of opal with concentrated solution of precursor - vacuum assisted.

Formation of solid "walls"

- Calcine - atmosphere and temperature

Creation of the "air" spheres

- Polymer opal
  - calcine - air, oxygen
  - solvent extraction
- SiO_2 opal
  - dissolve - HF, NaOH

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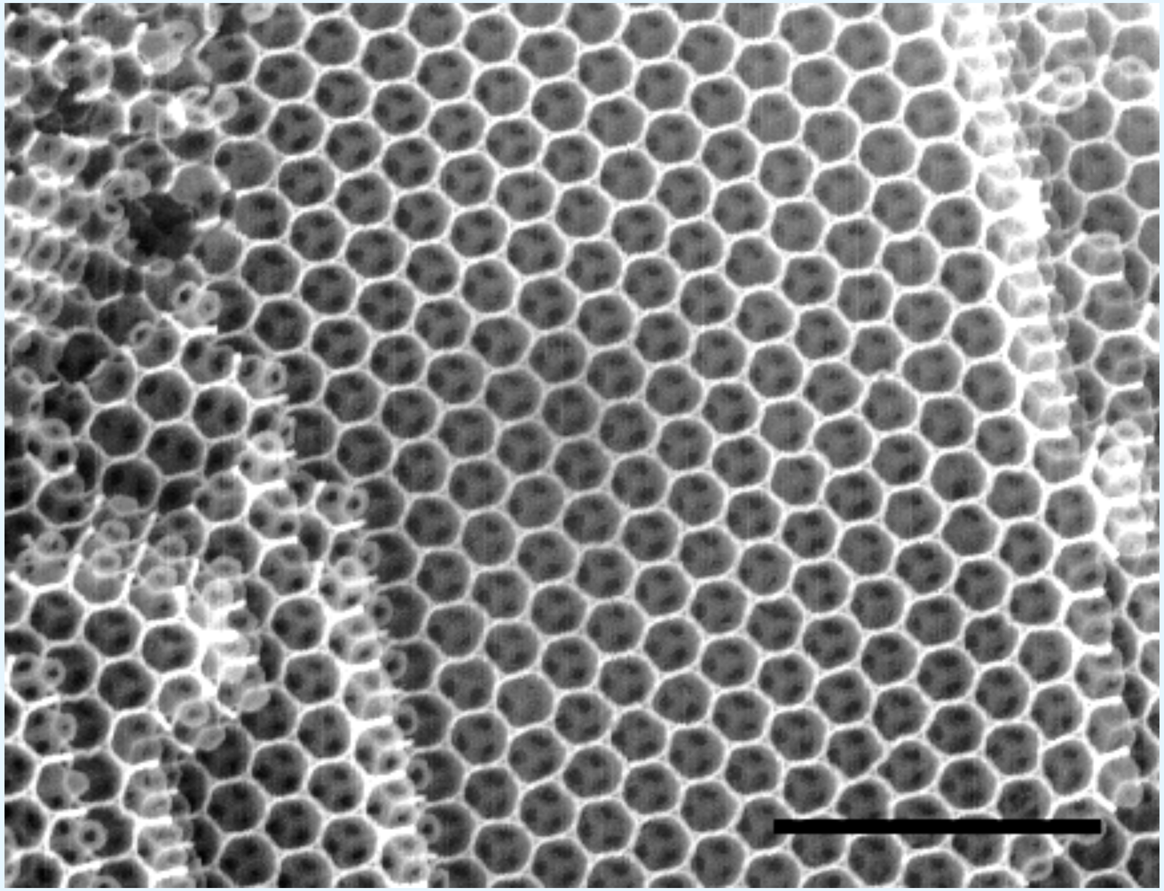
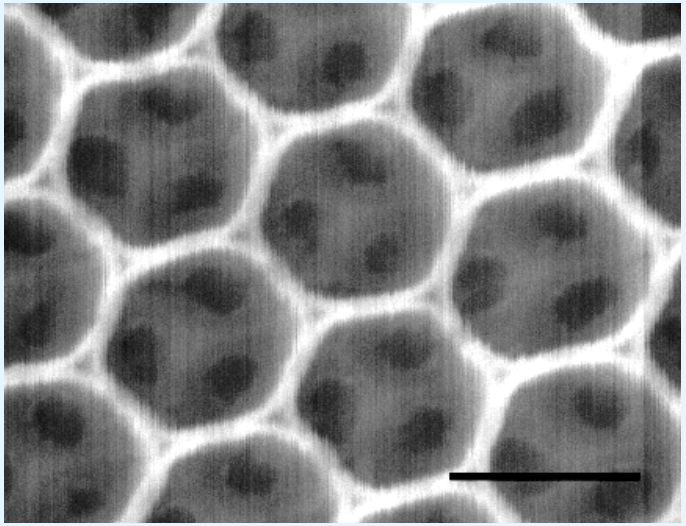
TiO_2 Inverse Opal - SEM



Scale bar = 1.8 μm



Scale bar = 300 nm

Richel et al, Appl. Phys. Lett. ***76*** *(2000) 1816*

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Multifunctional Photonic Crystals

- Create inverse structures with **additional functionality**
  - e.g. ferroelectric, magnetic, superconducting
- Most inorganic functional materials contain >2 types of atom
- Can we make a ternary inverse opal ?
  - e.g. $BaTiO_3$

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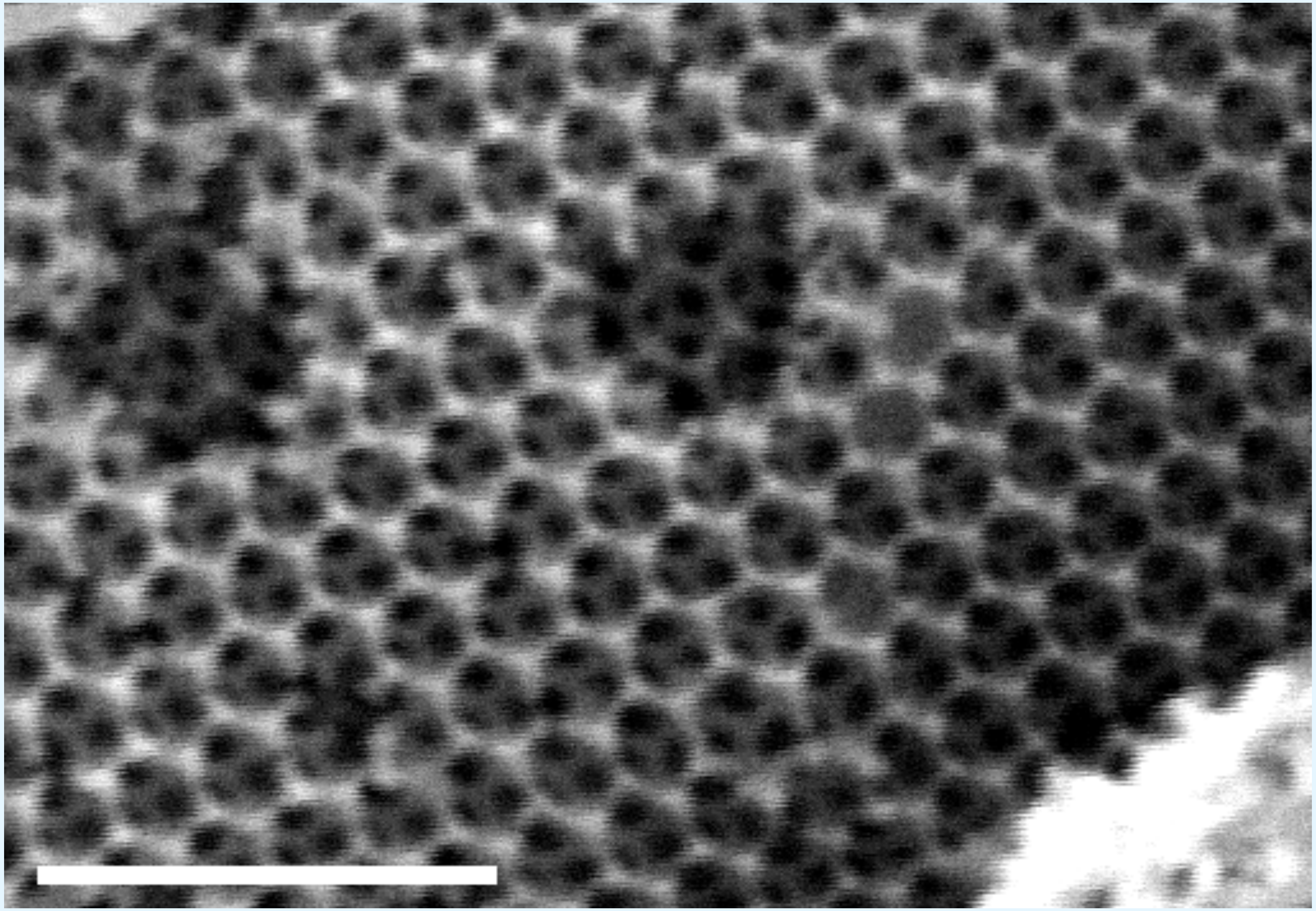
$BaTiO_3$ - 3D Structure



Scale bar = 1.2 mm

Harkins et al, J. Mater. Chem (2002)

Lithographic Template Growth Control

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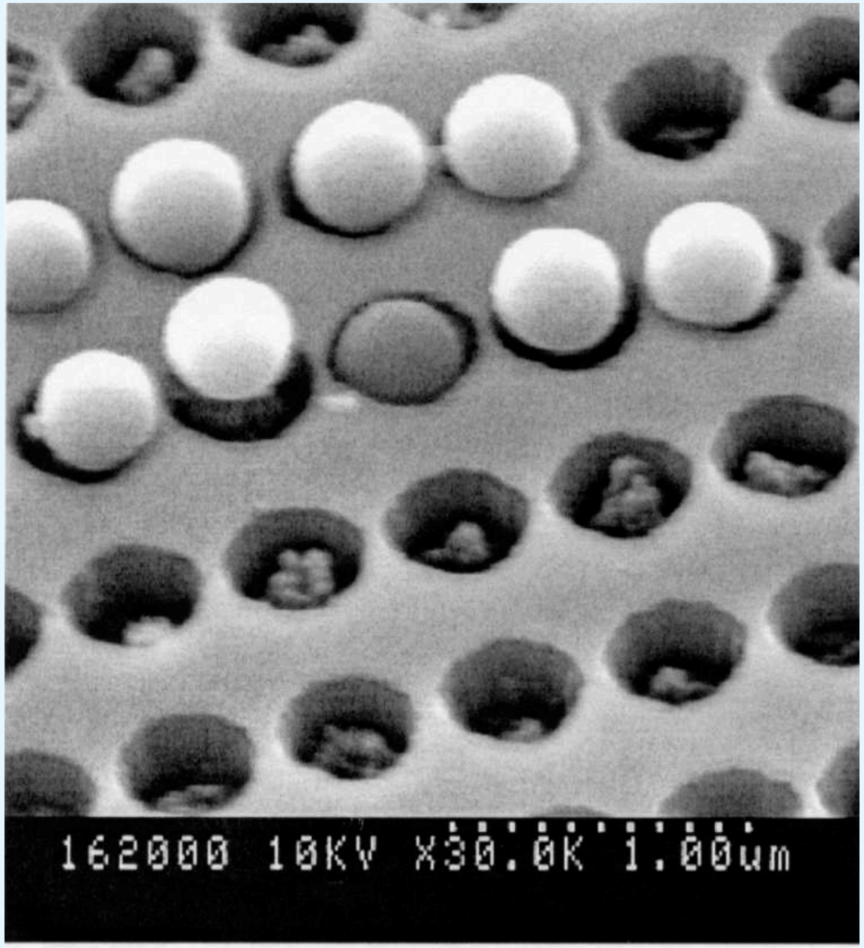
- By initiating sphere-based photonic crystal growth on a lithographically defined template, both symmetry and orientation control may be possible.
- Even controlled insertion of desired defect features could be possible?
- But how important will sphere size control be for success?



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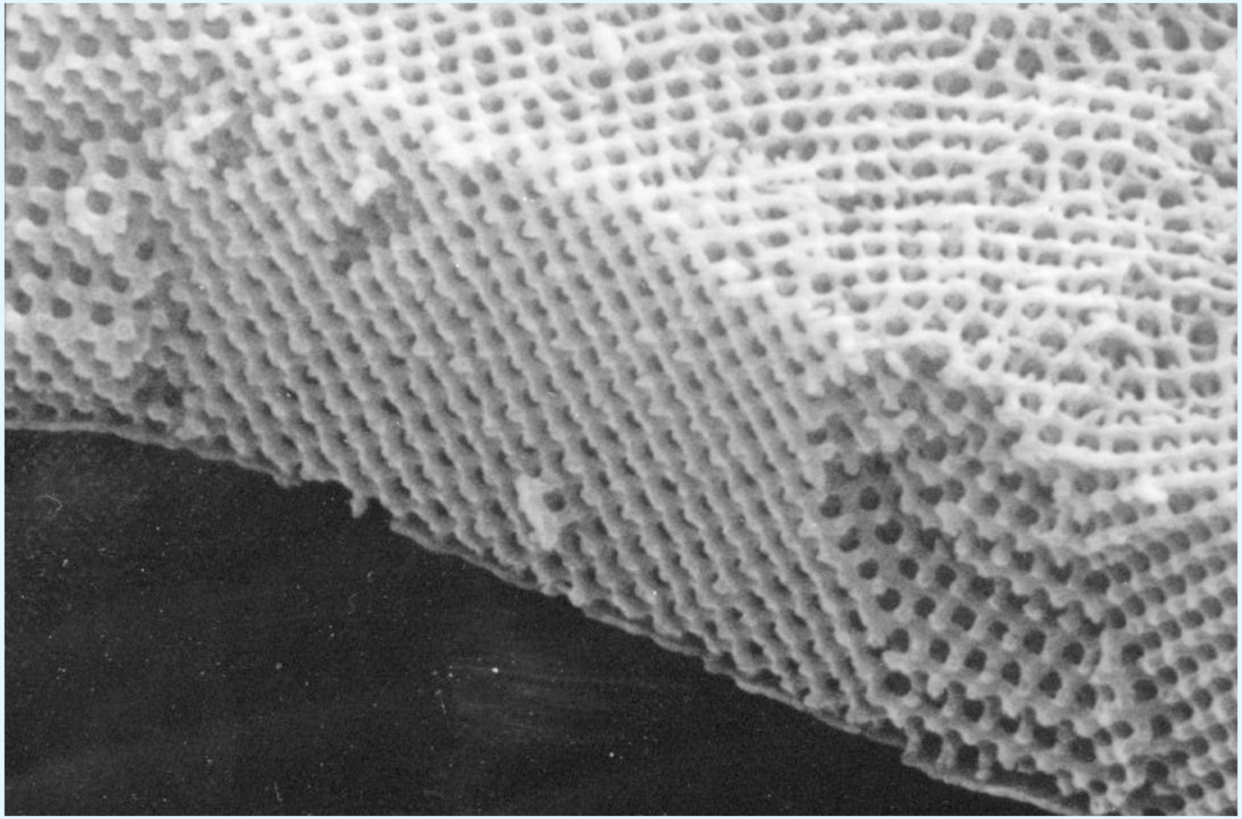
Natural Photonic Crystal: Butterfly Wing

P.Vukusic and J.R. Sambles, University of Exeter, U.K.



Periodic structure with index contrast ~ 1.5:1 gives strongly wavelength selective Bragg reflection. e.g. typically bright blue colour seen in some tropical butterflies. Nature has engineered several other interesting optical effects into butterflies.

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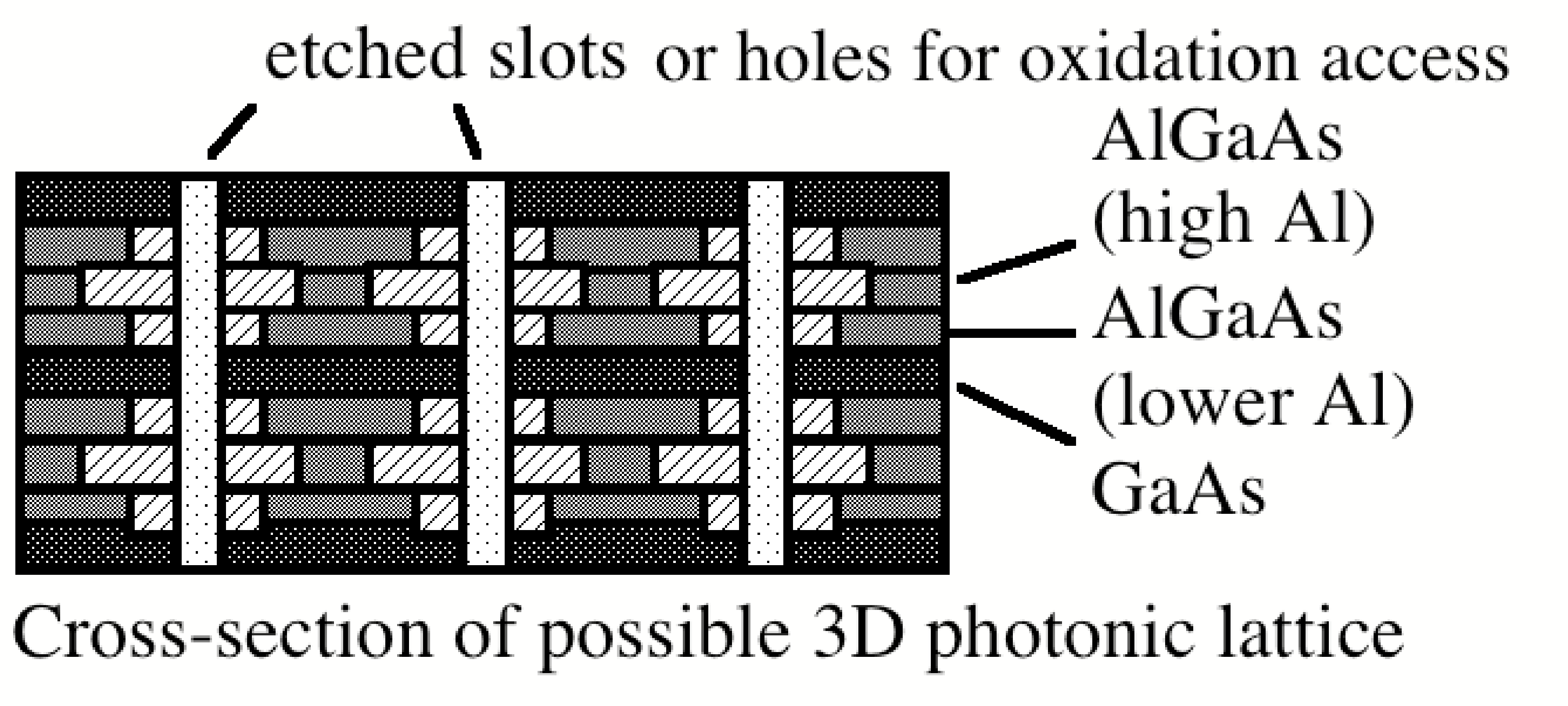
What III-V semiconductor techniques are available for 3D photonic crystal fabrication?

- **Multilayer Growth** (Heteroepitaxy): MBE or MOVPE.
- **Lithography:** electron beam lithography or deep UV. Implementation of deep UV will enable mass-replication.
- **Dry etching:** reactive ion etching (RIE), chemically assisted ion beam etching (CAIBE), inductively coupled plasma (ICP).
- **Selective Wet Oxidation** in high (differential) Al-fraction arsenides and phosphides.
- **Quantum Well/Superlattice intermixing** techniques: using localised implantation, diffusion, laser (PAID) and sputtering (plasma?) processes.

3D photonic crystal via epitaxial III-V semiconductor technology?



Richard M. De La Rue and Thomas F. Krauss, NATO ASI Series E, 324, pp.175-192, 1996, Edited by J. Rarity and C.Weisbuch.

3D PC in epitaxial semiconductor

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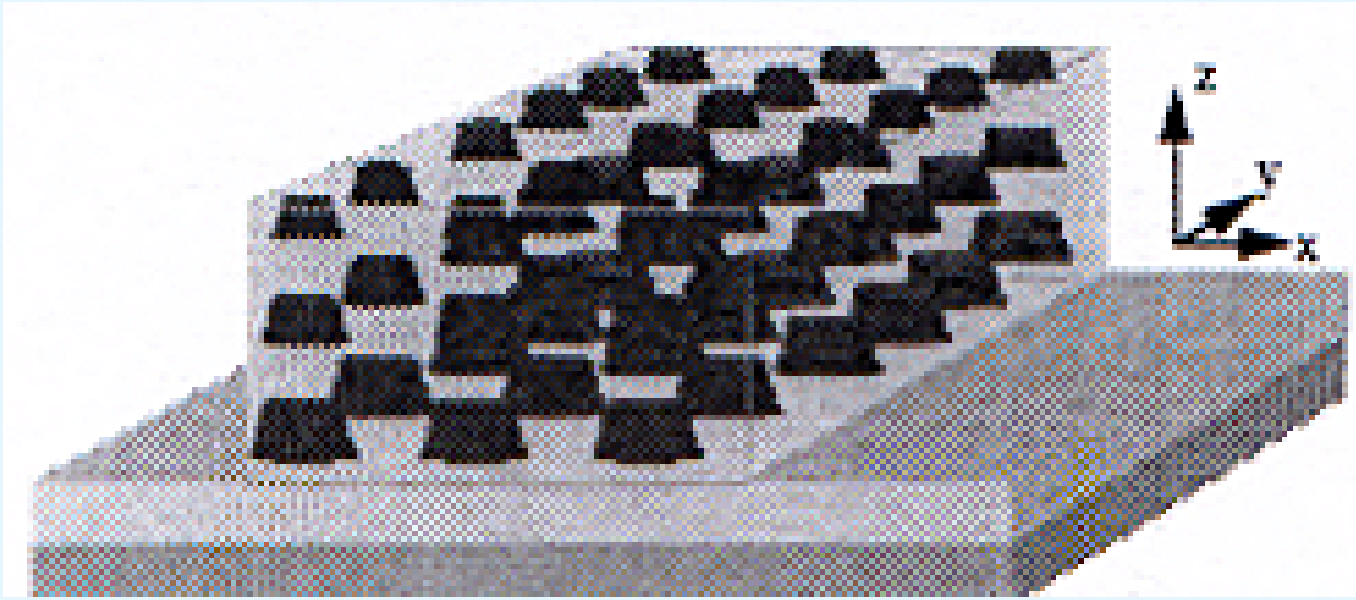

- Selective oxidation, e.g of AlAs, gives porous, insulating and low index 'AlOx' material. Oxidation rate depends exponentially on Al-fraction,

- Selective oxidation can proceed rapidly and selectively along high Al-fraction layers, if thick enough. Intermixing can locally amalgamate super-lattice to radically change oxidation rate.

P.Bhattacharya et al., APL, 75, pp.1670-1672, (Sept 1999).

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Photonic Crystals, Photonic Wires and Photonic Bandgaps: Devices for Light Emission and Filtering

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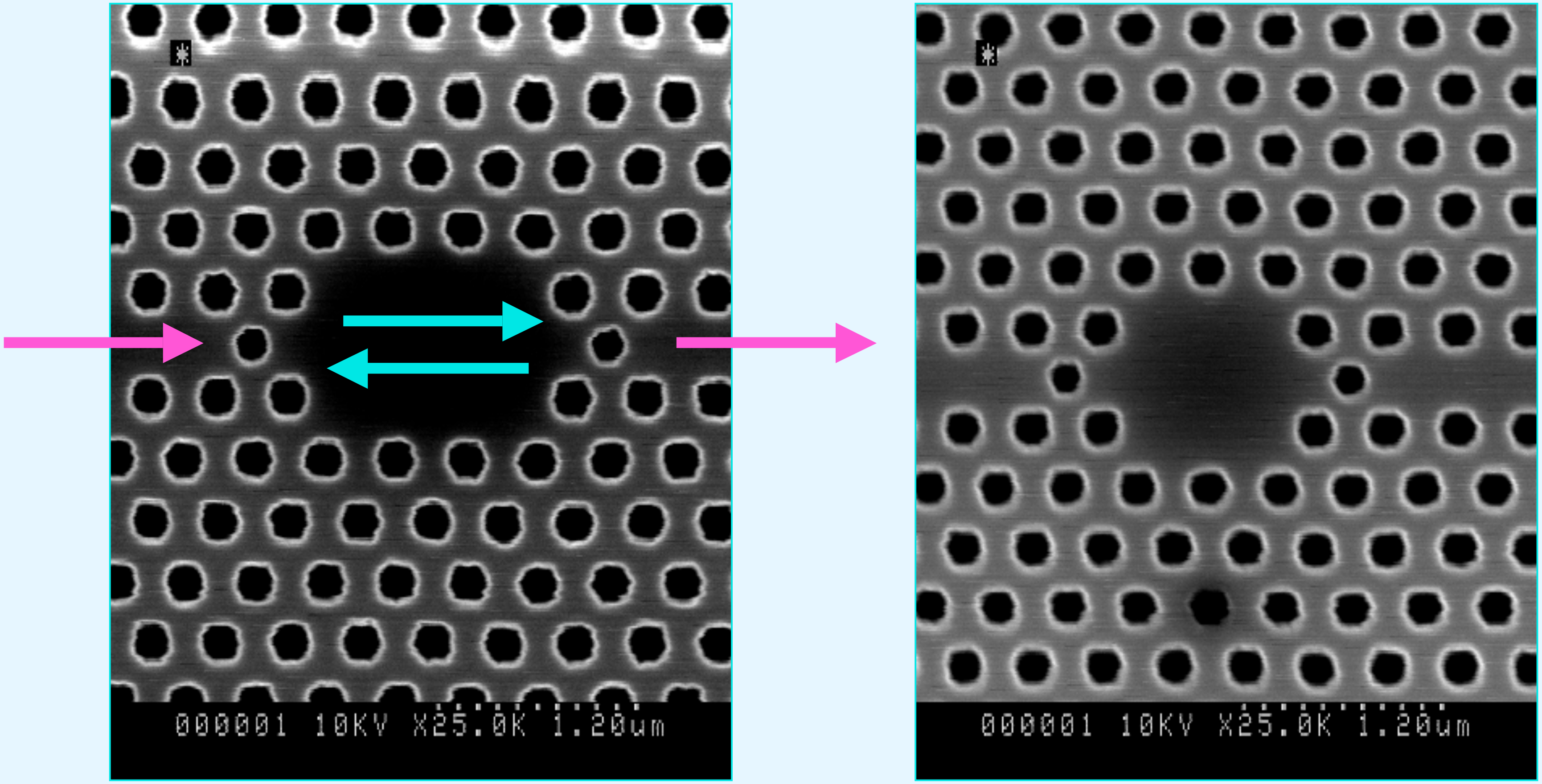
Cavities in SOI material for wavelength demultiplexers and channel add / drop filters

Direct coupling to cavity



(a) Elongated cavity

(b) Hexagonal cavity

Direct coupling to cavity with in-filling holes of 185 nm diameter

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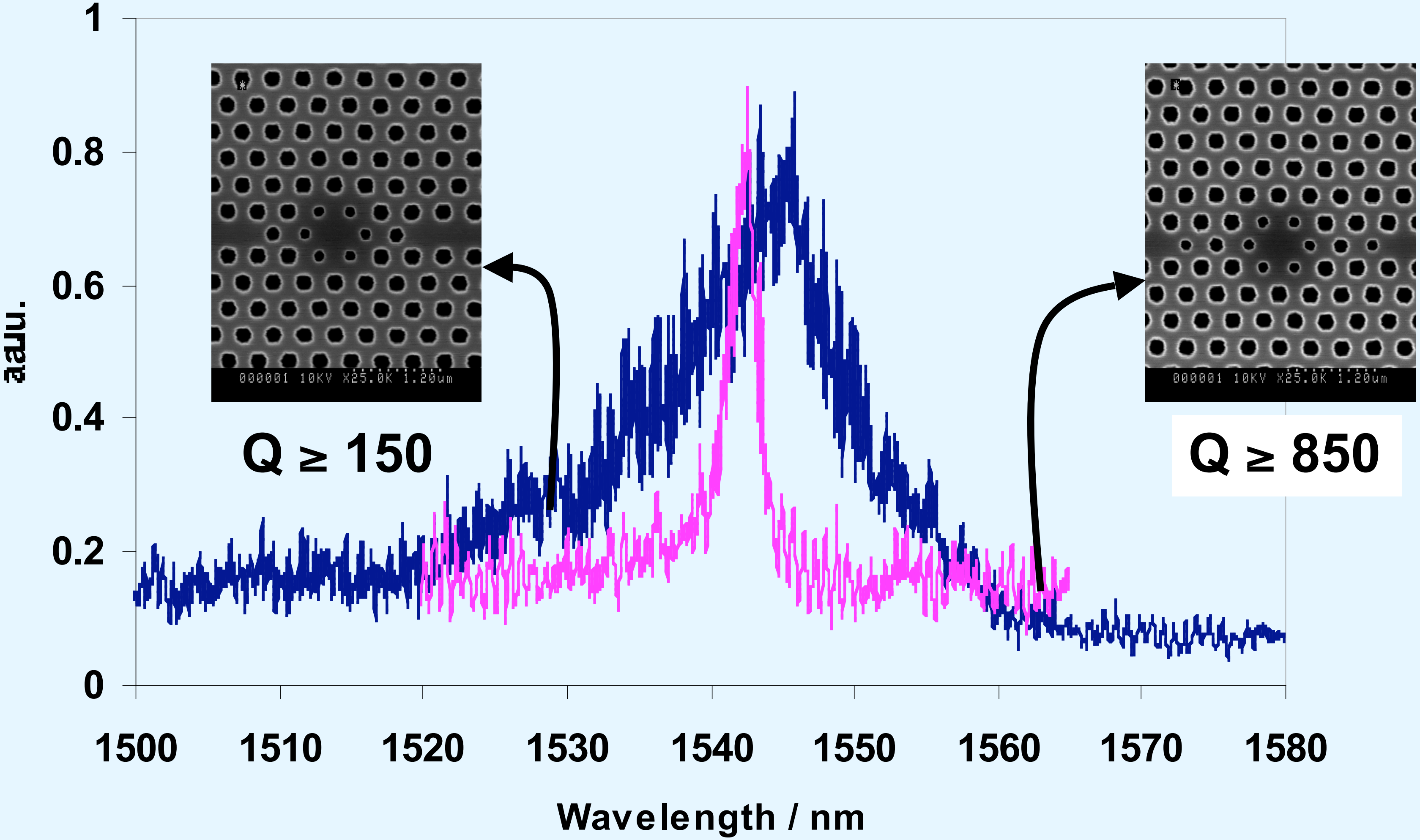
H. Chong et al, PD paper, ECIO, Prague, April 2003



Y-Junction with smaller hole (dia. ~ 132 nm) at the waveguide junction

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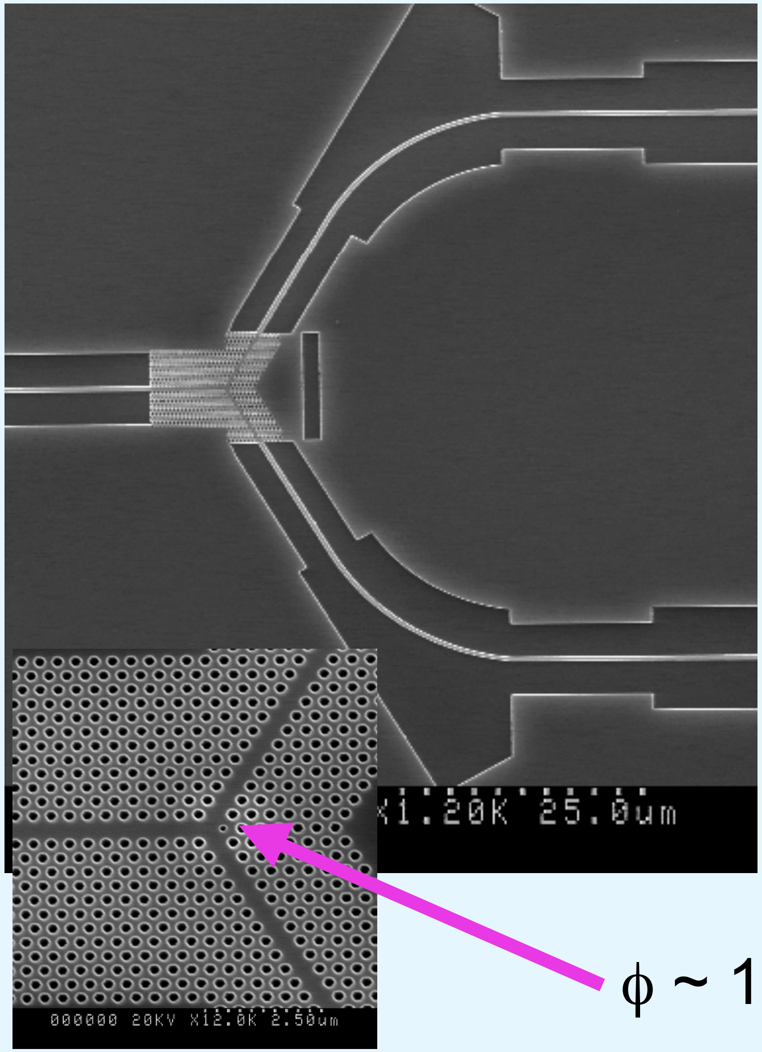
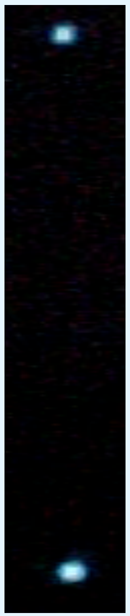
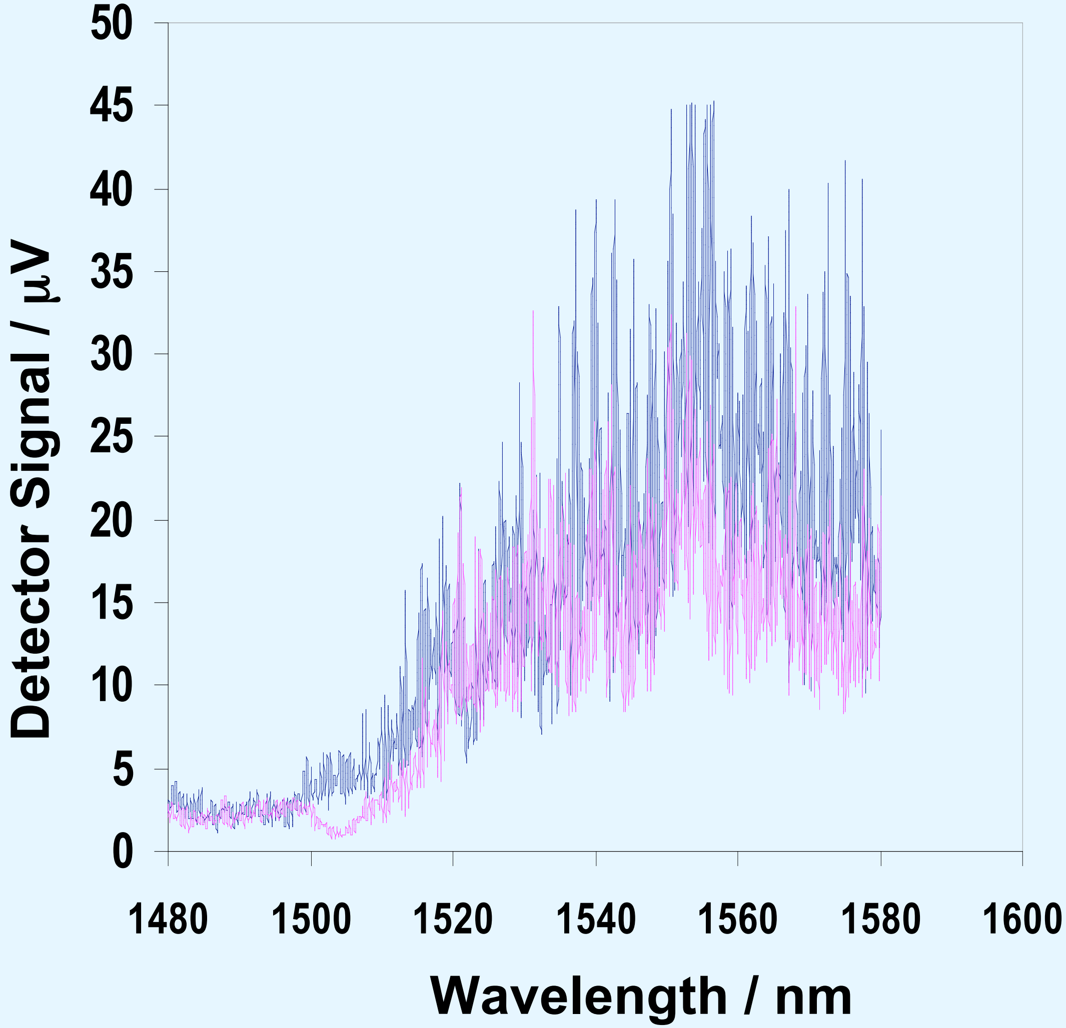


Red



Blue



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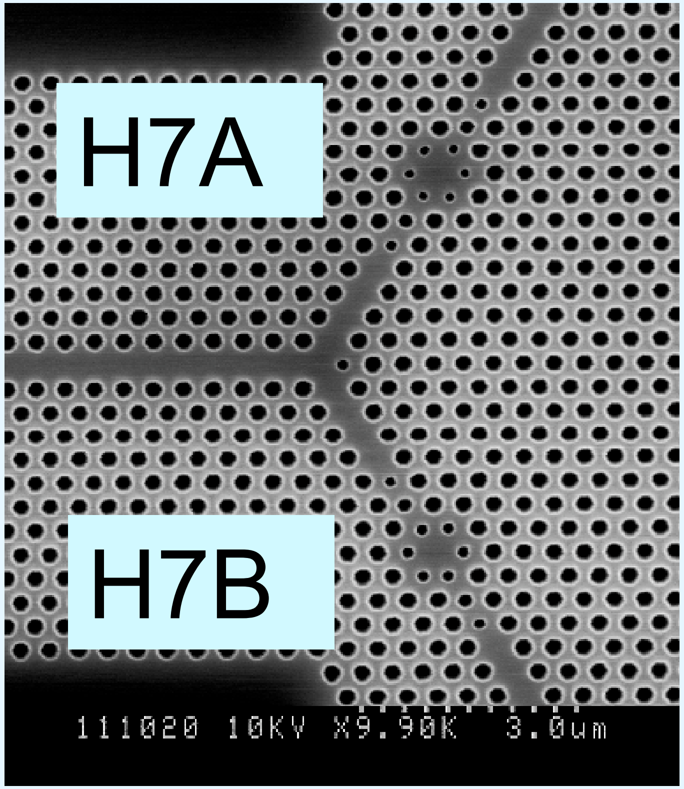
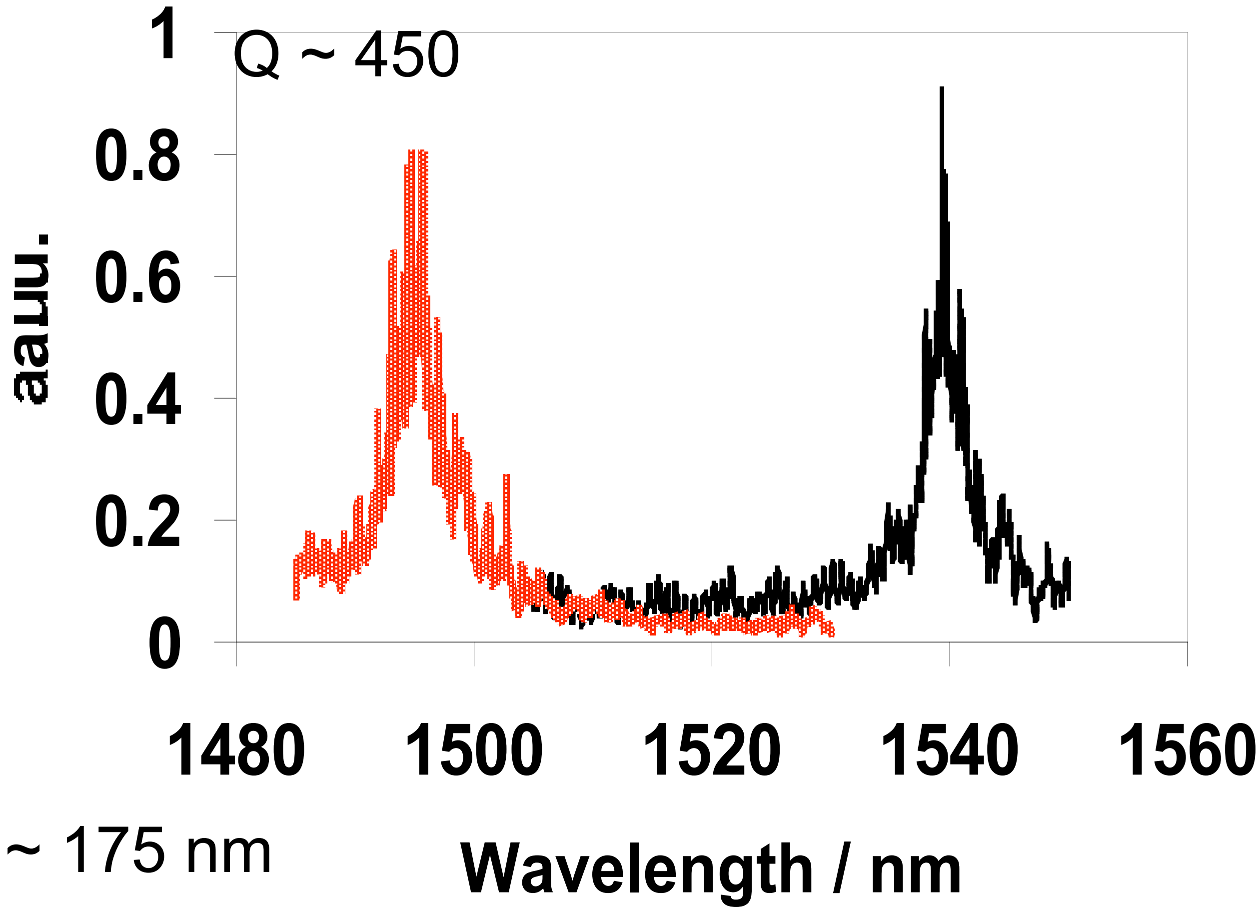
Measurement of H7 μ-cavities with Y-junction with smaller hole (ϕ ~ 150 nm) at the waveguide junction

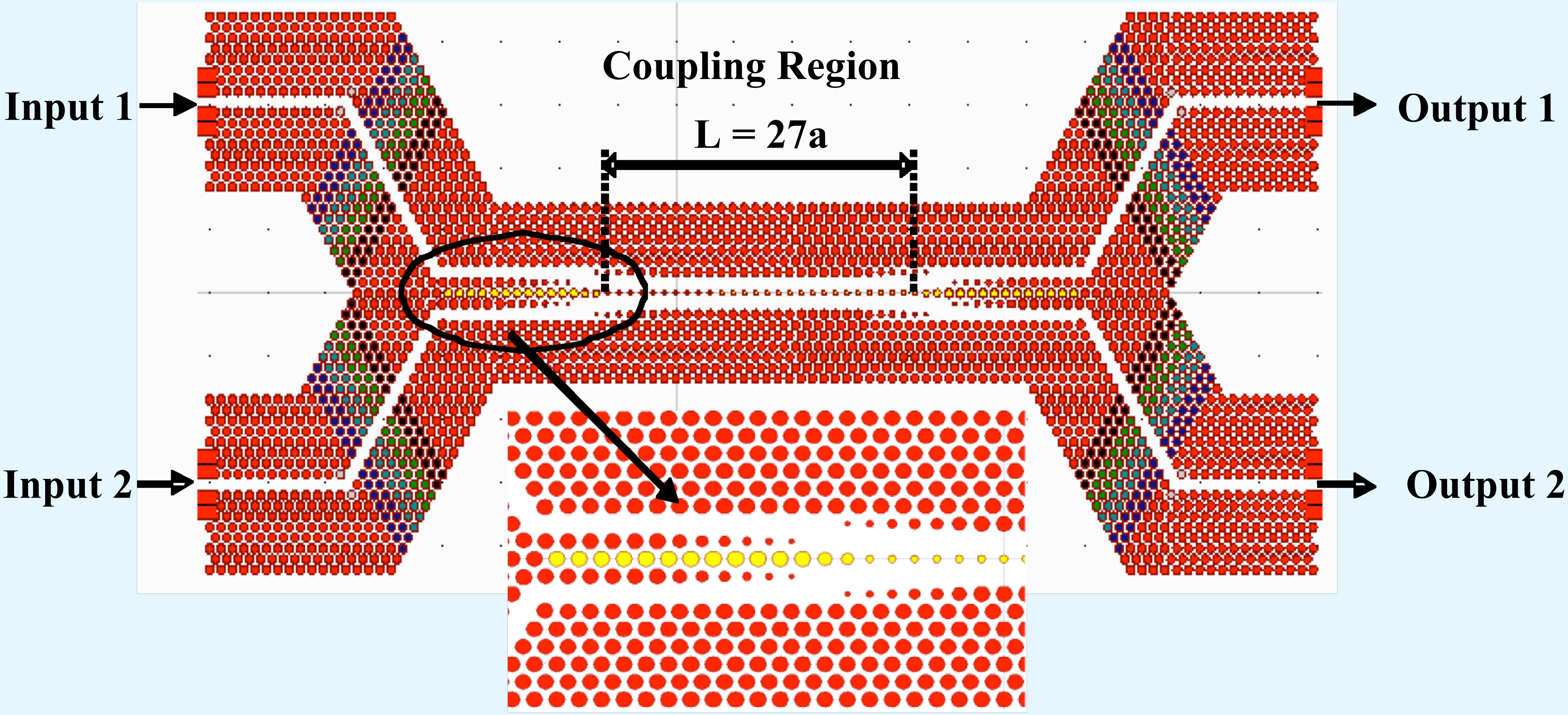
Black, λ ~ 1539.6 nm for ϕ ~ 145 nm





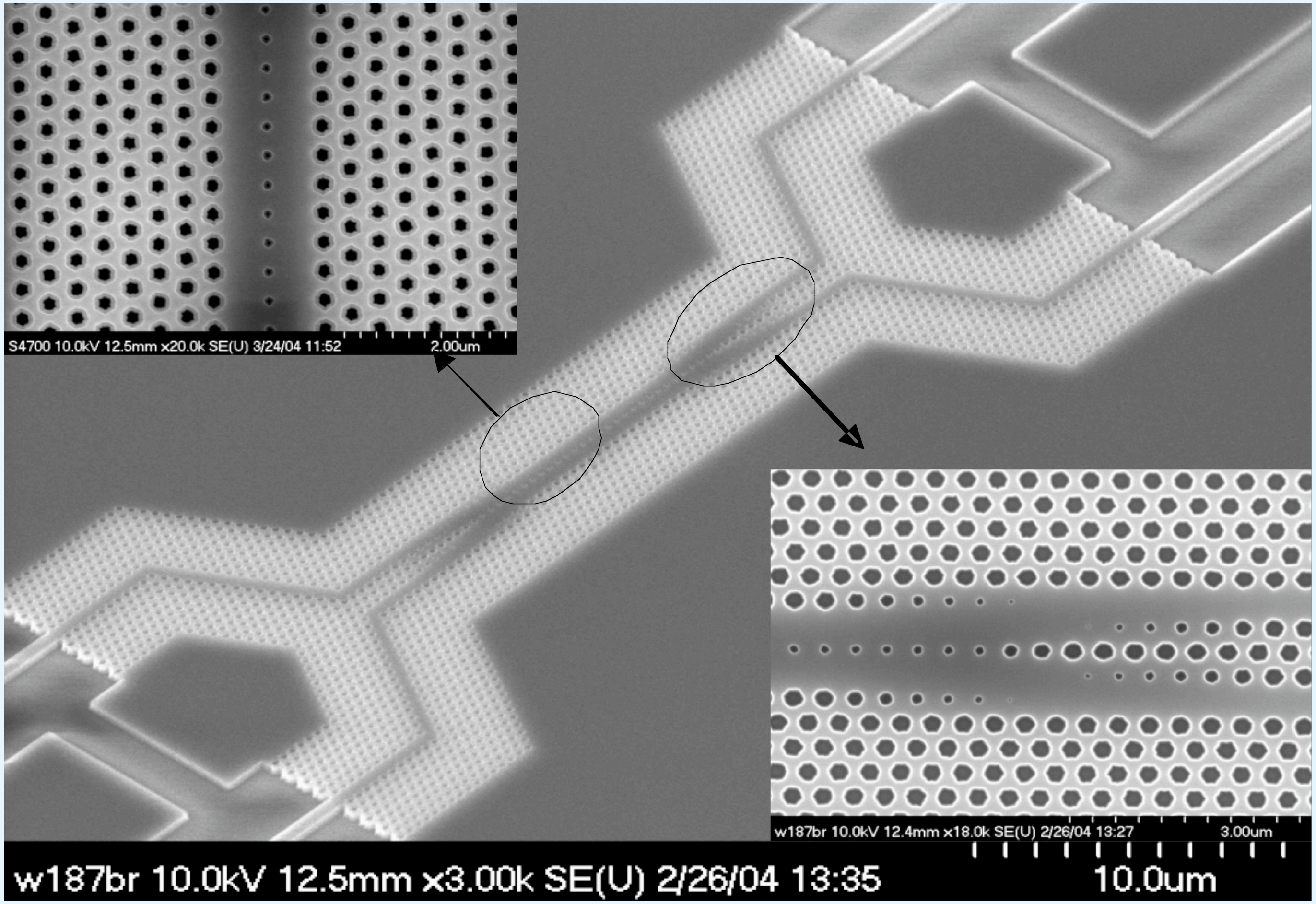
Red, λ ~ 1495.4 nm ϕ ~ 175 nm

• The structure

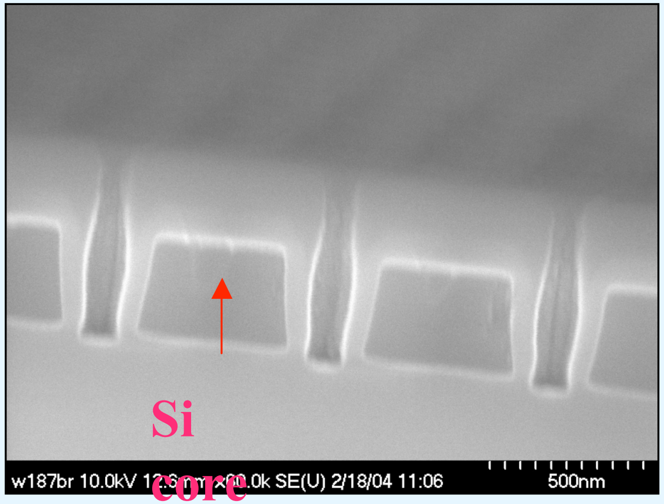


Mode Conversion Region

•Fabrication Process



- *Etching profile*



Microcavity LED with2D photonic-crystal light-extractor

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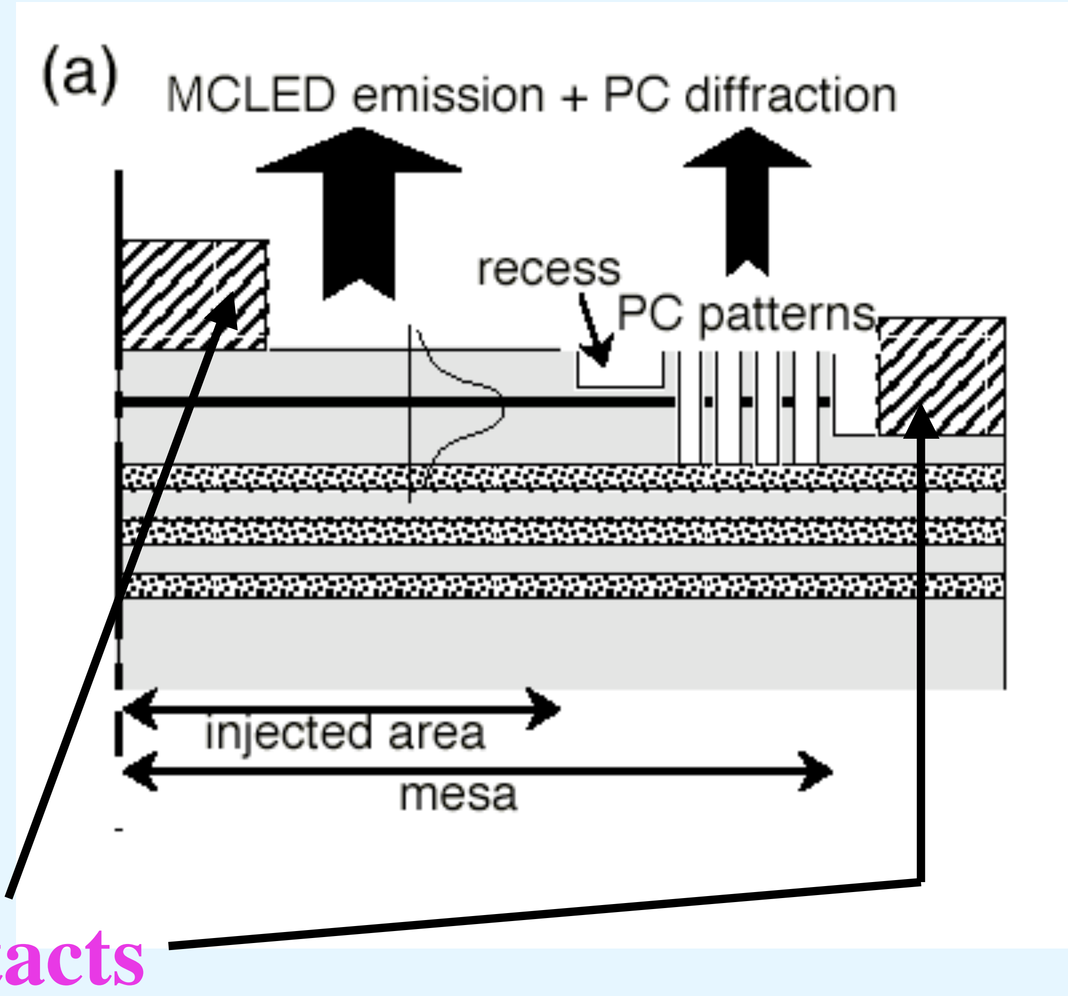
Half Cross-Sectional View of Circular Geometry Device

- **All top-contact device. Mirror stack uses selective oxidation ('Alox' process). Transverse current flows through photonic crystal region to outside contact.**
- M. Rattier et al, "High extraction efficiency, laterally injected, light emitting diodes combining microcavities and photonic crystals," Optical and Quantum Electronics, **34**, (2002), 79 - 89.



Selectively Grown Large-Bandgap Nitride Micro-cavities -> Nanocavities?

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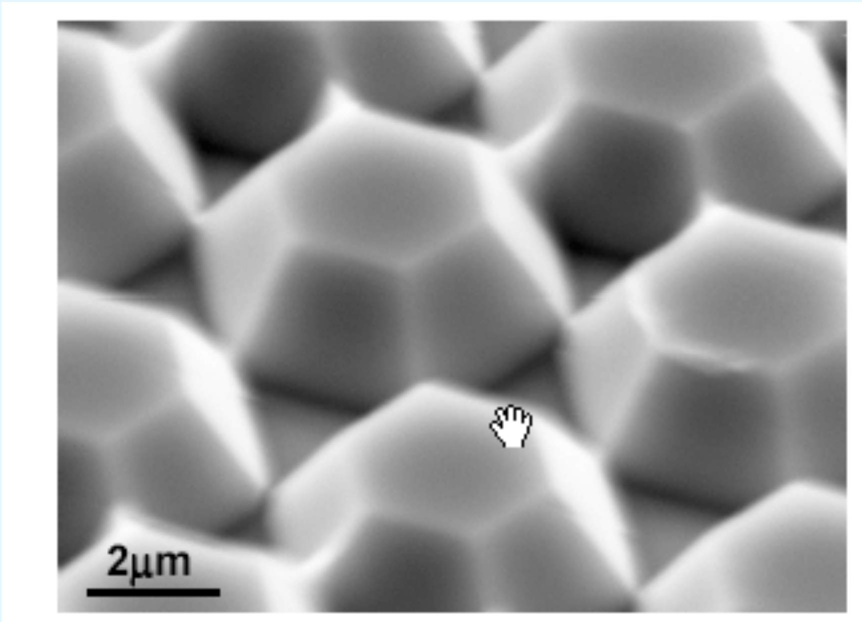
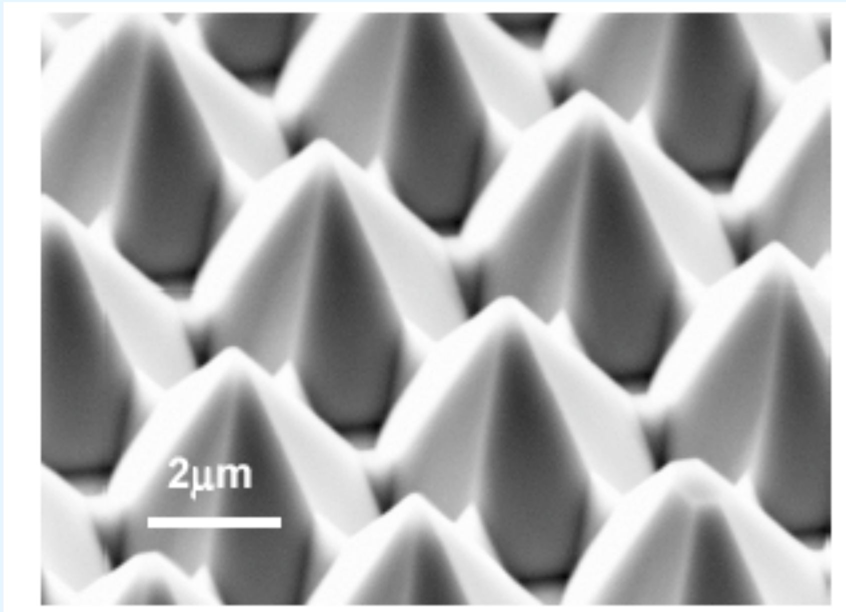
Structures produced by growing through hole array in silica layer on top of GaN epi-layer grown on sapphire substrate.

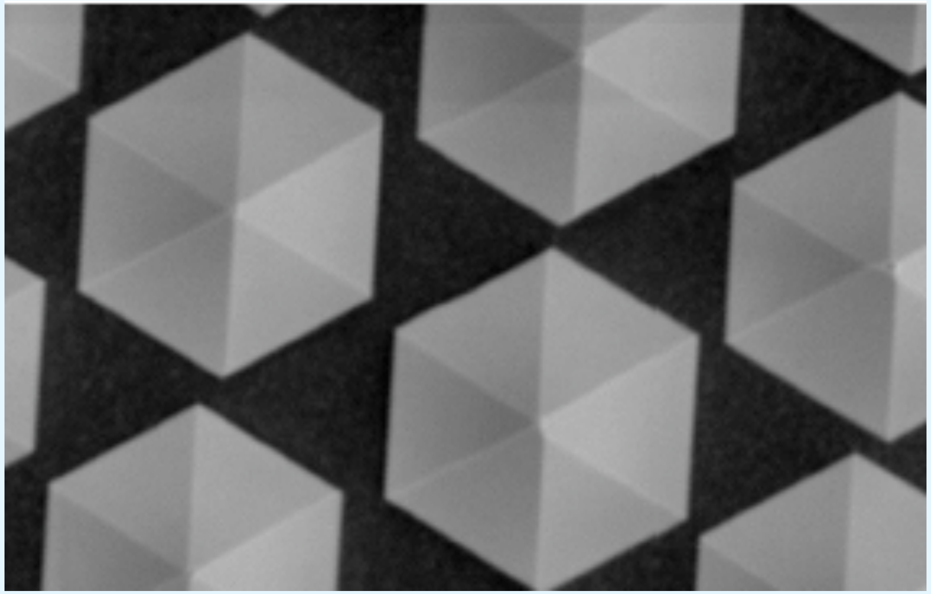




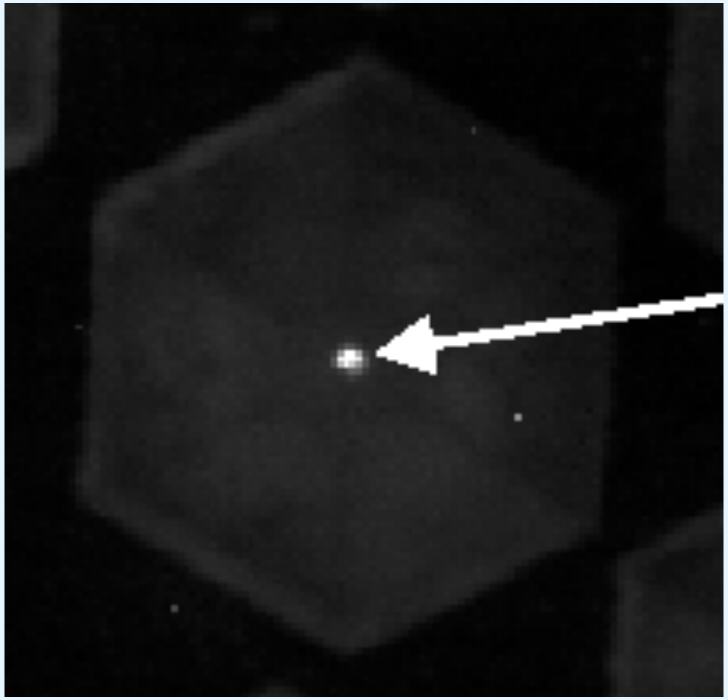
Flat-top or near-pointed pyramidal shape depends on growth interruption timing. Hexagonal geometrical form reflects *atomic* crystal symmetry of GaN grown on sapphire substrate.

Localisation of luminescence

R.W. Martin et al, 'Cathodoluminescence ….', EMAG'09, Oxford UK, Sept 2003.



SE micrograph of microcavity array



Most intense emission from pyramid tip region

Epitaxial Structure Schematics for GaN 'Hex' Pyramids

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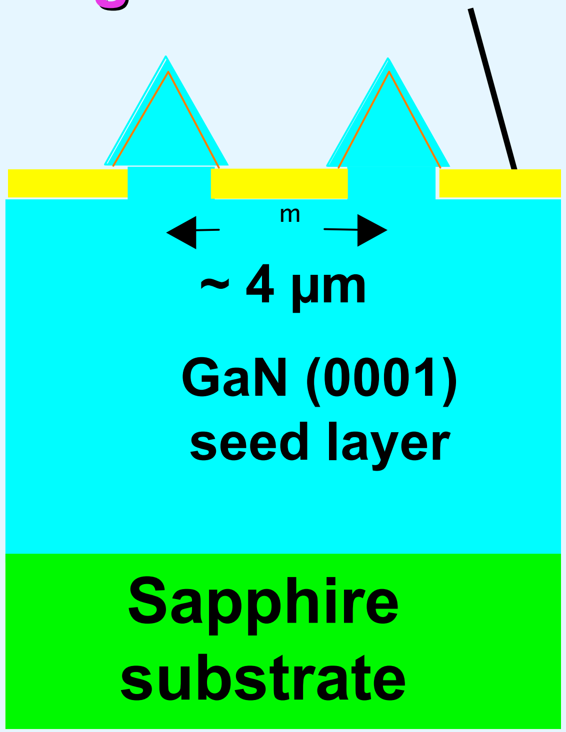
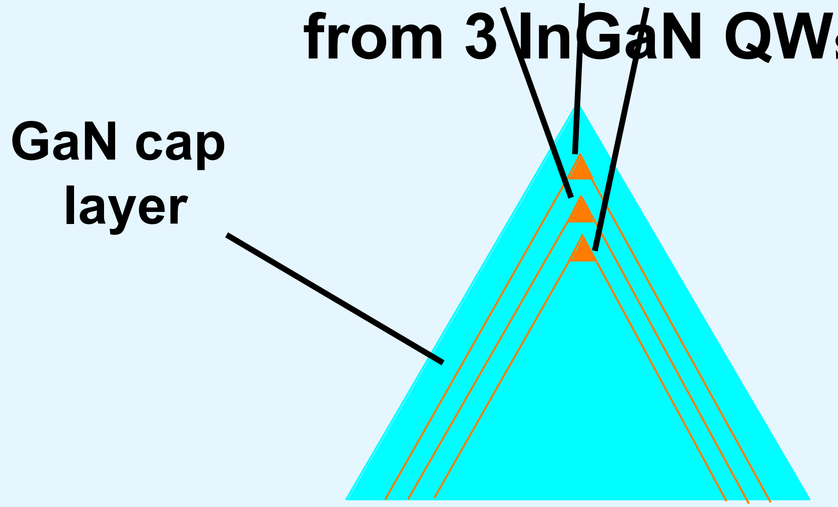
Cross-sectional view of whole epitaxial structure

Thin amorphous silica mask layer deposited and patterned for **selective area growth: SAG.**



QDs near pyramid tip, formed from 3 InGaN QWs



View of GaN pyramid structure

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Relevant Recent Publications: PhC Structures in Large-Bandgap Nitrides

- A. Mills, 'First time III-Nitride photonic crystals', III-Vs Review, 17(1), pp.39-40, (Feb 2004).
- T.N. Oder et al, 'III-Nitride photonic crystals', APL, 83(6), pp. 1231-1233, (11 Aug 2003).
- J.J. Wierer et al 'InGaN/GaN quantum-well heterostructure LEDs employing PhC structures' APL, 84(19), pp. 3885-3887, (10 May 2004).
- R.W. Martin et al, 'Cathodoluminescence spectral mapping of selectively grown III-Nitride structures', EMAG2003, Oxford, IoP conf. Series No. 179: Section 2, pp.135-137, (2003).

Interim Conclusions

- Many Photonic Bandgap Device Concepts have now been demonstrated.
- The III-V semiconductor base is important, but silicon also has potential.
- Silicon is a (potentially) good material for all(?) photonics.
- Microcavity LED/Lasers plus PhC light extractors are promising.
- Large band-gap III-Nitrides continue to be very interesting.
- True PBG type PhC Blue/UV electroluminescent light-emitters have not yet arrived.
- BUT: Demonstrations of large emission enhancements due to better out-coupling of generated light have now been made in this area.

Photonic Wire Waveguide

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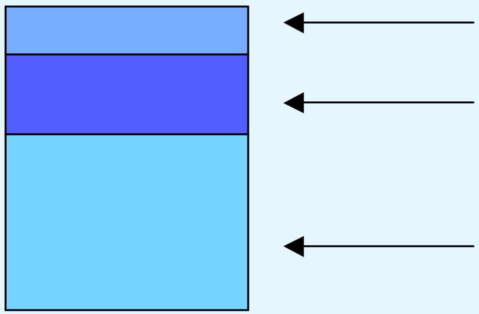
- High aspect ratio narrow ridge waveguide.
- High refractive index contrast material with highly confined fundamental mode in the guiding core.
- Low loss single mode operation.
- Silicon-on-insulator material.



PECVD SiO_2 200 nm

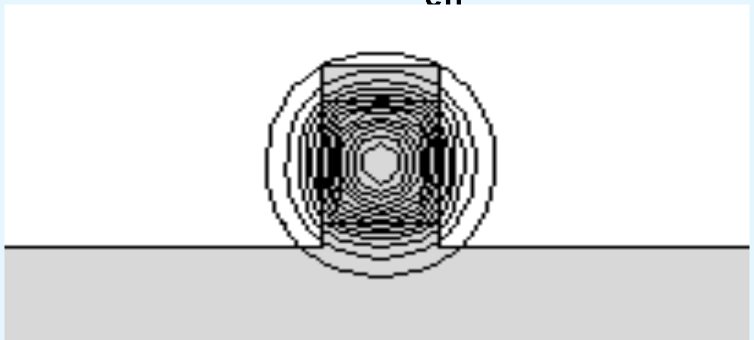
Si Guiding Core 340 nm

SiO_2 Lower Cladding 3000 nm

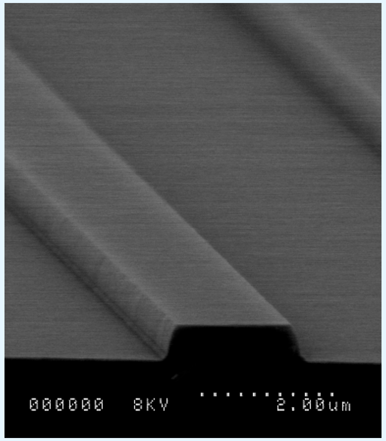
Not to scale

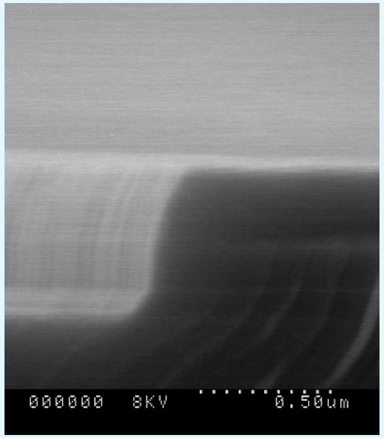
Photonic Wire Waveguide

- n_{eff} calculation using commercial software: Fimmwave™. The n_{eff} for a 300 nm wide wire is ~ 2.97.



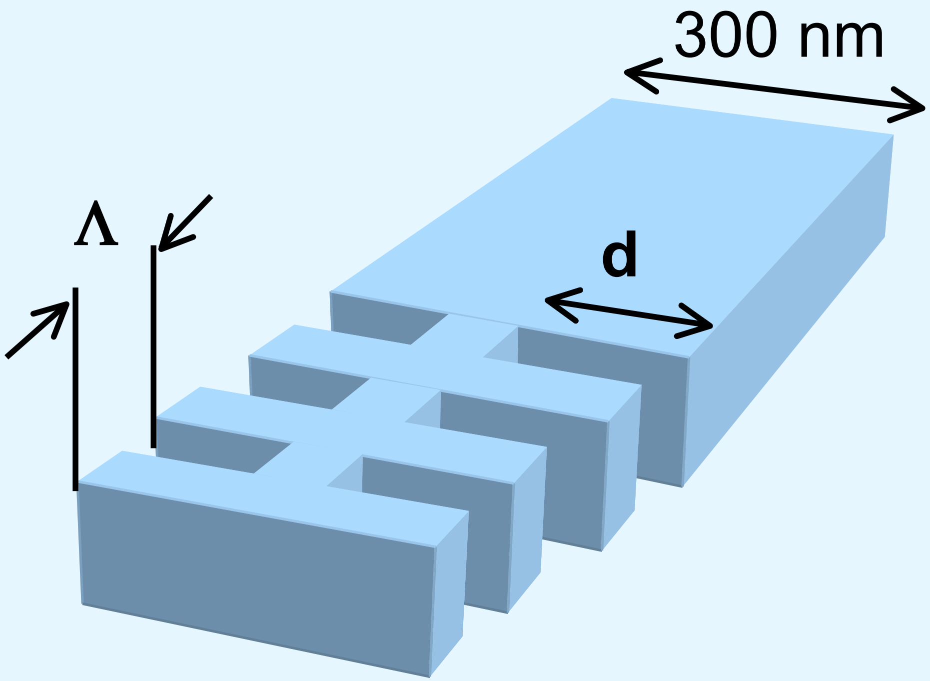
- Dry etch process pattern transfer from resist to silica mask and then to silicon core.





Sidewall Bragg Gratings

- Period, Λ = λo / 2 neff at λo = 1300 nm
- Λ = 220 nm and d = Lateral recess depth



- H. Chong, G. Gilabert-Garcia, S. Kim, A. C. Bryce, J. H. Marsh, M. Sorel and R. M. De La Rue, Photonic Wire Bragg Grating Reflector and Microcavity, ECOC 2003, Rimini.

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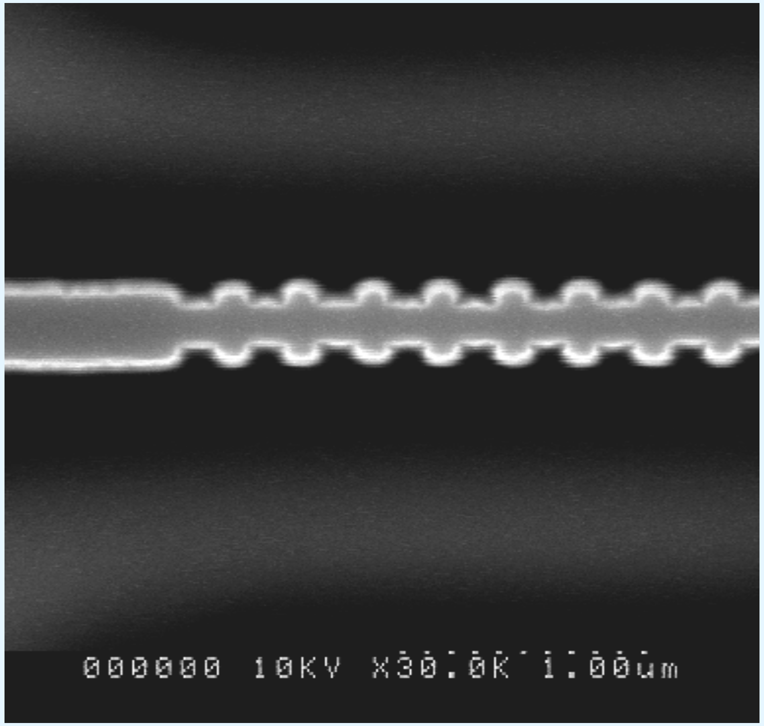
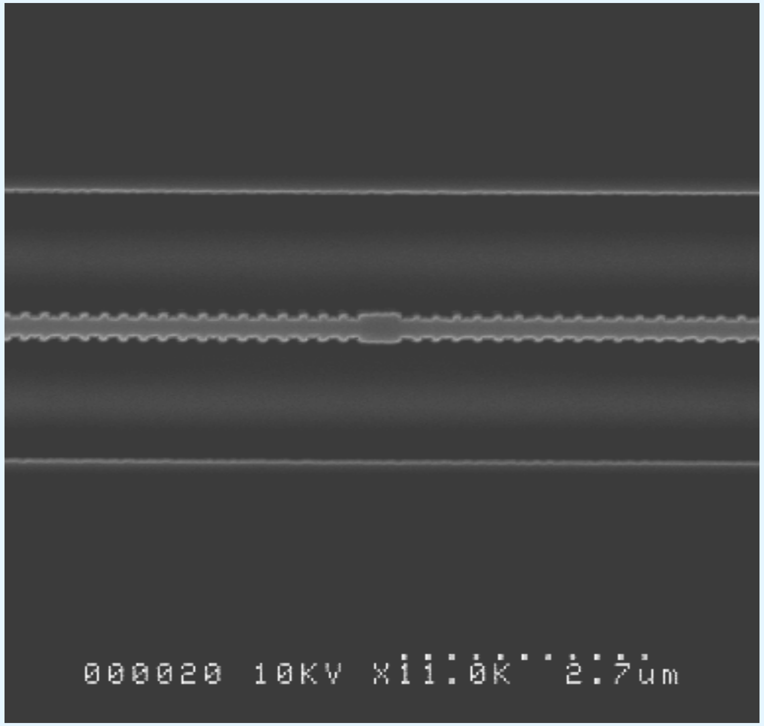
Bragg Gratings plus Spacer = Microcavity

H. Chong et al, 'Photonic Wire Bragg Grating Reflector and Microcavity' ECOC 2003, Rimini.



Photonic wire with lateral sidewall recess



Bragg gratings with $\lambda/4$ shift microcavity

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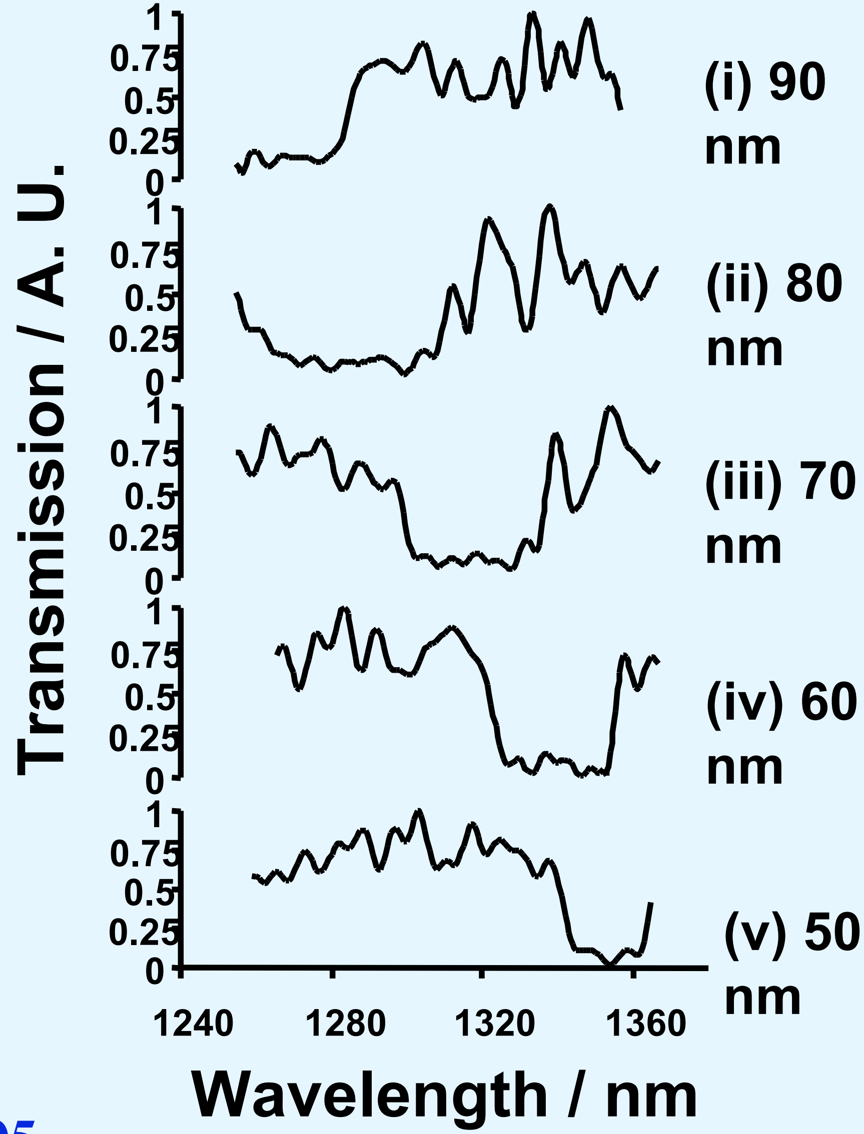

Measurement of the transmission characteristics of 128 periods long photonic wire Bragg gratings with sidewall recess values, d.

Measurement of the $\lambda/4$ shifted microcavity in a 128 period long grating

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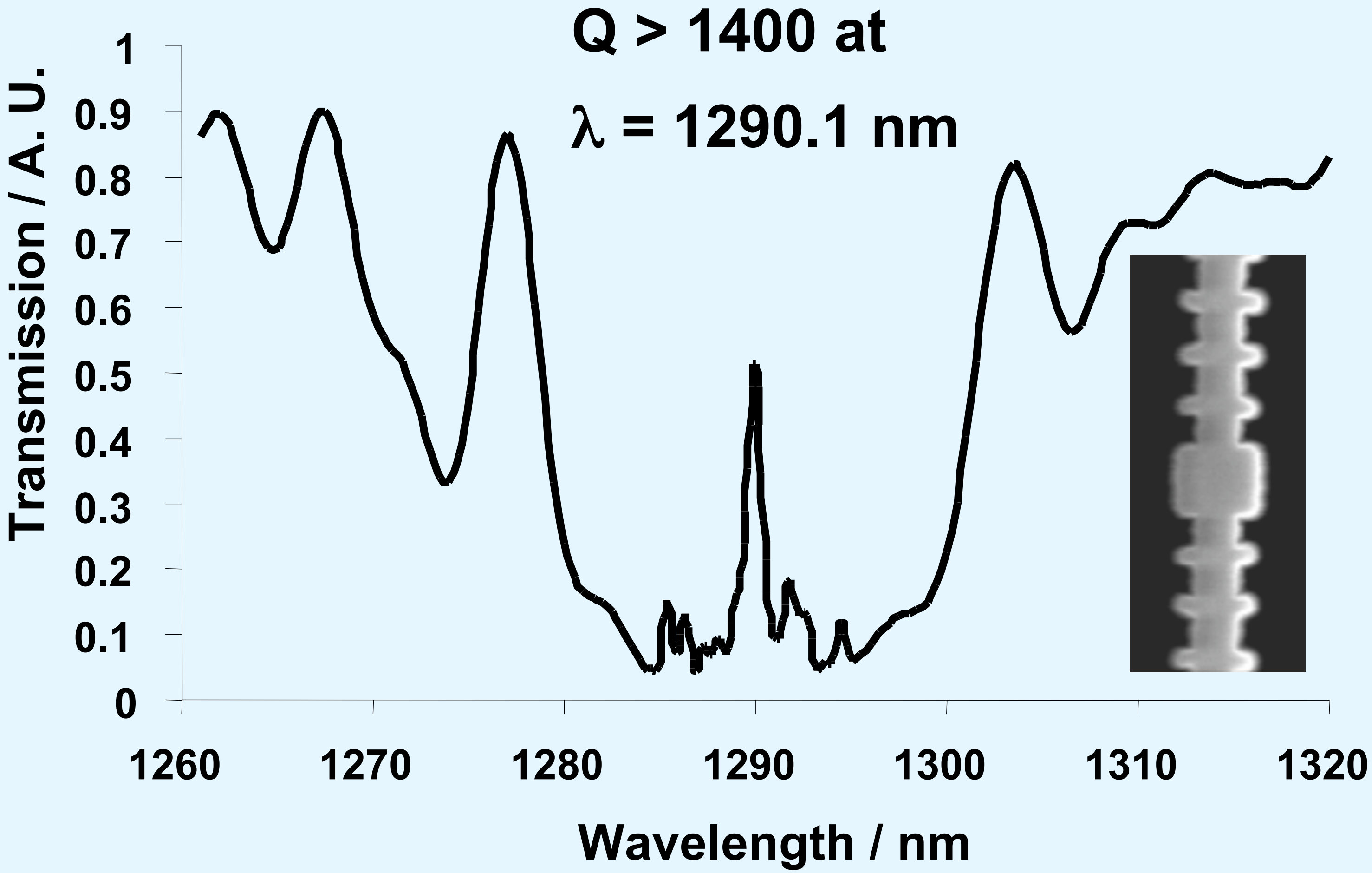

Conclusions

- Techniques for controlling the formation of 3D photonic crystal structures continue to develop.
- Some potential microcavity components for compact and complex planar OEICs/PICs based on photonic crystals have been demonstrated.
- *Photonic wire* structures will compete successfully with photonic crystal waveguide structures in some (possibly many?) situations.
- Bragg-grating structures in photonic wire geometry demonstrate that 1D-periodicity may be sufficient for some applications.

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More Conclusions

- Planar (waveguide) photonic crystals offer lots of potential device functionality. Two-dimensional thinking can go a long way for understanding and for formulating device concepts.
- The functionality available may lead to exploitation of photonic bandgap behaviour, (a) within the stop-band spectrum (including defect states), (b) around the edges of the stop-band spectrum or even (c) outside the stop-band.
- The technology required to realise photonic bandgap components already exists in substantial measure, but more is needed.
- III-V semiconductors continue to have pre-dominant importance, at least for structures involving light emission.

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Some Recent Publications from GU

- McLachlan MA, Johnson NP, De La Rue RM, et al.,Thin film photonic crystals: synthesis and characterisation, J MATER CHEM 14 (2): 144-150 2004.
- Coquillat D, Torres J, Peyrade D, et al., Equifrequency surfaces in a two-dimensional GaN-based photonic crystal, OPT EXPRESS 12 (6): 1097-1108 MAR 22 2004.
- Ntakis I, Pottier P, De La Rue RM, Optimization of transmission properties of two-dimensional photonic crystal channel waveguide bends through local lattice deformation, J APPL PHYS 96 (1): 12-18 JUL 1 2004.
- Pottier P, Ntakis I, De La Rue RM, Photonic crystal continuous taper for low-loss direct coupling into 2D photonic crystal channel waveguides and further device functionality, OPTICS COMMUNICATIONS, 223 (4-6): 339-347 AUG 1 2003.
- Chong H.M.H., De La Rue R.M., Tuning of photonic crystal waveguide microcavity by thermooptic effect, IEEE Photonic Tech L 16 (6): 1528-1530 Jun 2004.
- Camargo EA, Chong HMH, De la Rue RM, 2D Photonic crystal thermo-optic switch based on AlGaAs/GaAs epitaxial structure, OPT EXPRESS 12 (4): 588-592 FEB 23 2004.
- Jugessur AS, Pottier P, De La Rue RM, Engineering the filter response of photonic crystal microcavity filters, OPT EXPRESS 12 (7): 1304-1312 APR 5 2004.
- Kim S, Chong H, De La Rue RM, et al. Electron-beam writing of photonic crystal patterns using a large beam-spot diameter. NANOTECHNOLOGY 14 (9): 1004-1008 SEP 2003.