Martin Walker,
Martin Cryan,
Patric Strasser,
Kartik Srinivasan

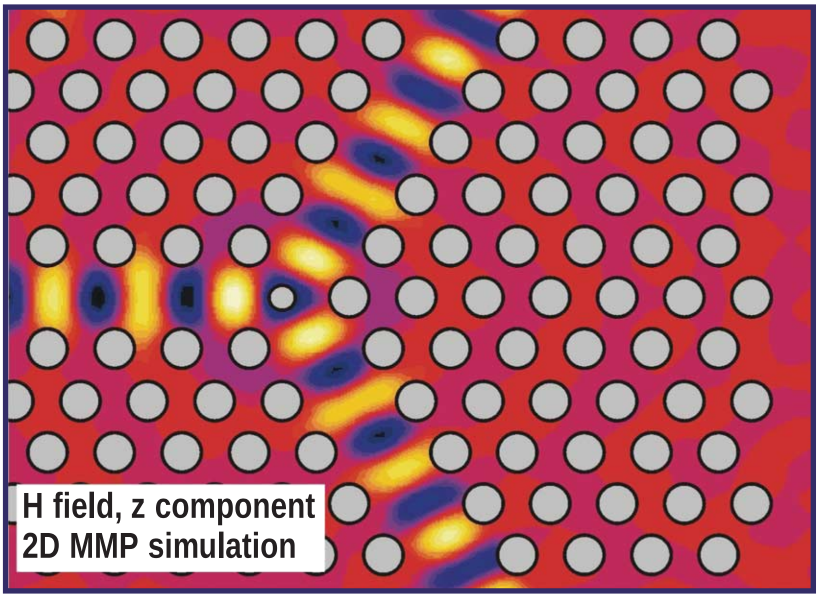
Photonic Crystal structures offer an alternative way of constraining light in optical components. This article draws together work carried out at three key research centres and an equipment vendor, describing how photonic crystals are fabricated, potential processing pitfalls and current applications, including ultra-high speed carrier lifetime determination, quantum cascade microlasers and quantum electrodynamics.

Fabricating photonic crystals in InP

In PhCs, the periodic RI modulation gives rise to a band of forbidden frequencies within which light cannot propagate.

Yablonovitch first suggested the concept of photonic crystals in 1987[i]. The term "Photonic crystals" (sometimes abbreviated to PhCs) was coined in analogy to semiconducting crystals and is simply shorthand for a material with a strong periodic modulation of the refractive index (RI) (usually semiconductor/air) with a pitch of the same order as the wavelength of light being used. This gives rise to a similar effect as seen in semiconductors, where an electronic forbidden bandgap arises due to the periodic potential modulation. In PhCs, the periodic RI modulation gives rise to a band of forbidden frequencies within which light cannot propagate. In three-dimensional PhCs (i.e. with a periodic modulation of RI vertically as well as horizontally, e.g. 'wood-pile structure') the forbidden bandgap opens for any light incidence, but these are very challenging to fabricate. Two-dimensional PhCs can be fabricated in much the same way as conventional planar optical waveguides. The vertical light confinement is achieved by reflection at material interfaces (between low and high refractive index layers). The horizontal confinement is provided by the periodic modulation in the PhCs. This article considers only 2 dimensional PhCs.

Figure 1: Power Splitter formed in photonic crystal (courtesy of K. Rauscher, ETH Zurich)



There are now numerous groups around the world developing technologies for the fabrication of 2D PhCs. Most groups favour the triangular lattice of holes, as this give rise to a large photonic bandgap for TE-polarised light (i.e. with the electric field parallel to the axis of the holes). The introduction of defects (missing or smaller holes) allows light to propagate, while the surrounding PhC stops in-plane leakage and suppresses spontaneous emission. In this way, it is possible to create waveguides, lasers and confined quantum states.

This technique makes possible a range of devices, including ultra-compact power splitters with $R\sim\lambda$ (see Figure 1), while still achieving low losses. This opens the possibility of very dense integration of optical components, necessary for future optical and quantum computing devices.

One of the most commercially significant wavelengths for telecommunications is λ=1550nm. Indium Phosphide is almost transparent at this wavelength and allows integration of both active devices (lasers, amplifiers) and passive devices (diplexers, filters etc.). The fabrication of InP-based PhCs is therefore very attractive. In this material system, the vertical light confinement is provided by an InP/InGaAsP waveguide. However, this scheme has the drawback to offer a very low refractive index contrast, which results in a large penetration of the optical mode into the substrate. For this reason, holes need to be etched as deep as 3.5μm in order to achieve a sufficient modal overlap, or a membrane structure must be used. Additionally, the PhC lattice constant needs to be of the order of the effective wavelength in the materials (~450nm) to provide the desired functionality. This implies that hole diameters of between 150nm and 350nm are required, fabricated with an accuracy of 10nm. This accuracy has recently become available through the use of state-of-the art photolithography tools. The required aspect ratios (15:1 or higher) cannot be obtained using isotropic wet etching, while crystallographic-direction sensitive anisotropic wet etching cannot provide the shapes needed. However, recent advances in high-density plasma reactive ion etching (driven by requirements in micromechanics) have made possible the necessary aspect ratios in silicon. Similar results are now being published for other materials, including InP.

Fabrication flows

There are many ways to fabricate photonic crystals in InP. Here are three examples, from three different research groups currently publishing work in this area.

Focused Ion Beam Patterning, Slab Waveguide based systems

This technique has been developed by M. Hill and co-workers at the Centre of Communication Research, University of Bristol, England.[ii] The simplest form uses a highly focused beam of Ga^+ ions to ablate a pattern into the sample surface. This technique is almost material independent, with etch rates and profiles changing only slightly with material. This is good for multi-layer structures such as the InP/InGaAsP/InP used for these photonic crystals. The disadvantage with this process is the lack of profile control, which makes it difficult to achieve good side-wall verticality in holes, leading to losses in PhC structures.

A variant on this process uses the focused ion beam to pattern a metal layer, which is then used as a mask for an RIE process, which transfers the image into an underlying oxide layer. This is then used as the mask for an etch process removing InP (and InGaAsP) by ICP-RIE. This final process can produce good sidewall verticality, which results in improved PhC device performance.

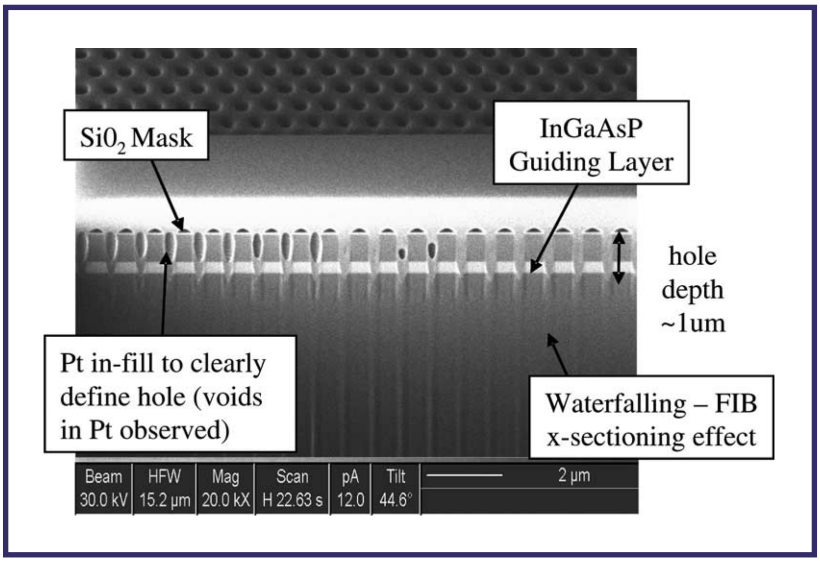


Figure 2: Photo courtesy of M. Cryan at University of Bristol, UK

E-beam & ICP, Slab Waveguide based system

An alternative technique for creating PhCs is used by the Communication Photonics Group, Electronics Laboratory (IfE), ETH Zurich, Switzerland. Instead of FIB techniques, PhC structures in InP/InGaAsP/InP are fabricated using e-beam lithography to pattern a layer of PMMA e-beam resist.[iii] The pattern is then transferred into a multilayer hard mask consisting of 30nm Ti and 400nm SiN_x on top of the semiconductor material. The thin titanium layer is etched using RIE in an SF_6/N_2 mixture, following Ar sputtering in order to reliably break the top TiO_x layer. The SiN_x layer is then etched using O_2/CHF_3 plasma. Finally, the semiconductor layers are etched using $Cl_2/Ar/N_2$ chemistry with the SiN hard mask in an ICP-RIE system. This process achieves etch depths of greater than 3μm for 200nm diameter holes. The difference in the etch rates of the InP and the InGaAsP layers is insignificant. Lastly, the remaining SiN_x mask material is removed with a hydrofluoric acid dip before the characterisation of the PhC structures. ETH Zurich uses the internal light source[iv] technique, in collaboration with partners from the Swiss Federal Institute of Technology in Lausanne, to measure the photonic bandgap and characterise the fabrication. For the device characterisation, we use the endfire technique (port-to-port measurement with two optical fibres). Light in- and out-coupling is reliably controlled using a

> ***The next few years will be crucial, as to whether PhCs manage to move out of the laboratory and start to appear in commercial products.***

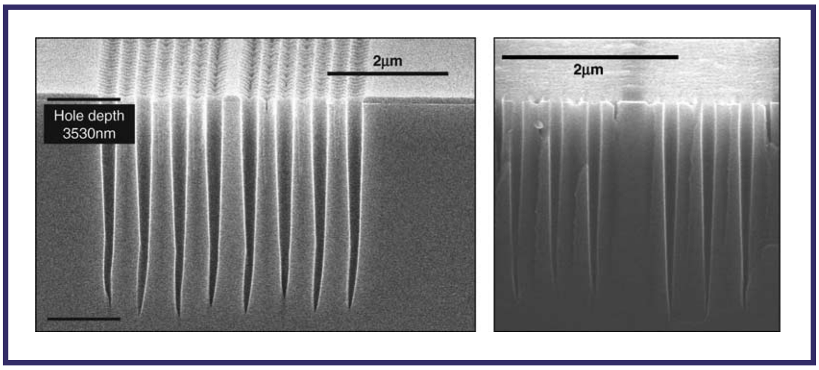


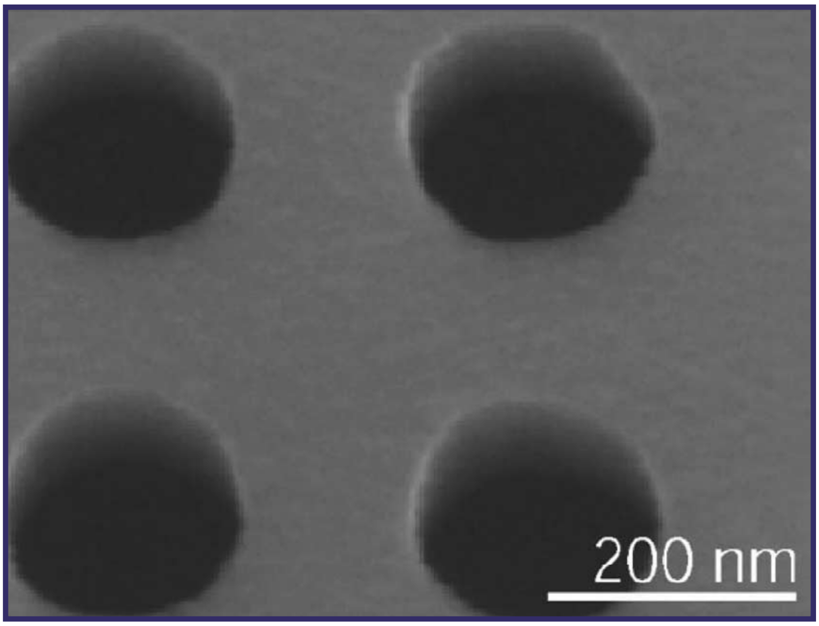
Figure 3: Photos courtesy of P. Strasser at ETH, Zurich

mix&match technology for the integration of photo and e-beam lithography.

The slow desorption of $InCl_3$ from InP at low temperatures dramatically reduces the etch rate. Therefore, elevated temperatures are used in order to obtain deep holes and smooth sidewall etching. The addition of nitrogen in the plasma provides sidewall passivation due to the formation of stable N-P bonds.[v] However, a delicate balance needs to be achieved, as too little N_2 results in underetching, while too much N_2 causes increased sidewall roughness.

A limiting factor for deep holes is the lag effect (aspect-ratio dependent etching). The etch rate of InP will decrease significantly at high aspect ratio (a result of small hole diameters), much as it does in silicon etching. This needs to be taken into account for the design of PhC devices where small diameter holes are often used to provide additional functionality.

Figure 4: Holes etched into InAsP/InGaAsP/InP by ICP/RIE at Caltech



Similar work has been done by Caltech in collaboration with Bell Labs, creating photonic crystal microcavity lasers in a quantum cascade epitaxy.[vi] These devices were electrically injected to stimulate lasing.

E-beam and ICP, Membrane waveguide based system

This alternative strategy has been very successfully pursued by the Department of Applied Physics, California Institute of Technology, USA, (Caltech) working with Lucent Technologies. They have designed a PhC structure using an air interface to achieve vertical light constraint. Their device is fabricated as a multilayer structure of InAsP/InGaAsP on top of InP. A subsequent wet etch process removes the InP under the photonic devices, creating a membrane structure.

The process flow is as follows:

- PECVD of SiO_2 (200nm) for hard mask
- Apply e-beam resist (ZEP-520A) and expose
- RIE using C_4F_8 to transfer the pattern into the oxide
- Solvent removal of remaining resist
- ICP-RIE using Ar/Cl_2 chemistry and local surface heating
- HF removal of remaining oxide
- Undercut of the structure using $HC1/H_2O$ (4:1)

The wet etching in HCl/H_2O attacks the InP much faster than the Al bearing layers, leaving a 252nm thick free-standing InAsP/InGaAsP membrane.[vii] This has been used to create the microcavities used for Quantum electrodynamics experiments.These devices are optically pumped to stimulate lasing.

Applications

Ultrafast Carrier Dynamics

All-optical switches in the InP system are required for all-optical networks. Ultra-fast switching can be achieved if both fast turn-on and turn-off times are available. Interband or intersubband transitions in quantum wells are potential candidates for ultrafast switches with carrier lifetimes in the ps range. This is much faster than the ns range achieved in bulk InP layers (due to a slow surface recombination velocity). Apart from compactness, PhCs therefore also have the potential to reduce carrier lifetime due to enhanced surface-to-volume ratios and increased surface recombination processes at surface states of the dry etched sidewalls.

The carrier lifetime has been measured by Holzman et al[xiii] on PhCs fabricated in InP as described previously (E-beam and ICP, Membrane waveguide based system), using a triangular lattice of holes. A simple relationship between carrier lifetime and etched sidewall area was demonstrated, from which a surface-recombination velocity of 1 x 10^5 cm/s was extracted. The best performing samples displayed a carrier lifetime below 100 ps (down from 8 ns for bulk InP).

Quantum Cascade Photonic-crystal microlaser

This device, fabricated by Bell Labs and Caltech, demonstrated lasing in a quantum cascade PhC microcavity. It was the first electrically injected PhC microcavity laser of any type. A very important application of this device is in trace gas sensing. Using PhC techniques to create quantum cascade lasers opens the possibility of integrating such devices with other optoelectronic components, including the opportunity of creating multi-wavelength laser arrays on a single chip.

Microcavity Laser

The group at Caltech fabricated a lasing microcavity in multi-quantum well InP, based on a graded square lattice PhC. This device was first described by Colombelli et al[vii] and further fabrication details have been published[ix]. This device showed subthreshold linewidths of $\Delta\lambda$=0.10 nm, corresponding to a cavity Q of 1.3 x 10^4. When this was pumped with a broad beam, an estimated laser threshold of 360μW was indicated. A focused pump beam gave an even lower lasing threshold, with power levels as low as ~100μW.

Optical Cavity Quantum Electrodynamics (cQED)

The microcavity described above can be combined with a quantum dot, with energy transfer being achieved by resonance. Light can be coupled in and out of the structure by integrating the cavity with an on-chip PhC waveguide, then using optical fibre tapers to couple onto and off of the chip.[x] This will allow interactions between single photons and single quantum dots to be explored. The ultimate goal of this research is the development of quantum networking and computing.

Dispersion Compensation

PhC waveguides can provide very strong dispersion in very small device areas. Thus by correct design of such waveguides there is potential for using them in a number of different dispersion compensation applications. At St Andrew's University, Scotland, a PhC Coupled Cavity Waveguide (CCW) has been designed to have around 10^6 times stronger dispersion than standard single mode fibre at 1536nm[xi]. Pulse compression of 40% has been shown experimentally using an 8μm long GaAs/AlGaAs based CCW. More recently other dispersion compensation applications have been studied. T. Cao et al have shown modelled results[xii] whereby a PhC waveguide is integrated with a Semiconductor Optical Amplifier (SOA) in order to correct for the chirp induced by the SOA. They have shown pulse compression ratios of around 3.2:1. Other applications include optical delay lines and optical memory.

The future for InP PhCs

At present, photonic crystals are confined to R&D labs around the world. However, the fabrication techniques are being refined and the applications are being developed, to the point where new, high performance components can be produced commercially. The next few years will be crucial, as to whether PhCs manage to move out of the laboratory and start to appear in commercial products. Initial devices will simply use the waveguide properties to achieve high-density integration of optoelectronic components, combining lasers, beam-splitters and filters. Further ahead lies the prize of all-optical switching on-chip, and even quantum computing.

Further ahead lies the prize of all-optical switching on-chip, and even quantum computing.

References:

[i] E.Yablonovitch et al. Phys. Rev. Lett. 58, 2059 (1987)

[ii] M.Hill et al, ESPC2004, Poland, July 2004

[iii] P. Strasser et al, 17th Int. Conf. Indium Phosphide Related Materials, May 8-12, Glasgow, UK, 2005

[iv] R. Ferrini et al, IEEE J. Quantum Electron., Vol.38-7 (2002), 786-799

[v] Y. Suzuki et al, Applied Surface Science 162-163 (2000), 172-177

[vi] R.Colombelli et al, Science vol 302(5649), pp.1374-1377 (2003)

[vii] K Srinivasan et al, Appl. Phys. Lett., Vol.83, 1915 (2003)

[viii] J.F.Holzman et al, Nanotechnology 16 (2005) 949-452

[ix] K Srinivasan et al, J.Vac.Sci.Technol.B 22(3) 875-879 (2004)

[x] K Srinivasan et al, phys.stat.sol (b) 242(6) 1187-1191 (2005)

[xi] T.J.Karle et al, IEEE J. Lightwave Technology, Vol.22-2 (2004), 514-519

[xii] T. Cao et al, CLEO Europe, Munich, June 2005

Authors:
Martin Walker
Oxford Instruments
Plasma Technology, UK

Martin Cryan
University of Bristol, UK

Patric Strasser
ETH Zurich, Switzerland

Kartik Srinivasan
California Institute of
Technology, USA