Progress towards photonic crystal quantum cascade laser

C.L. Walker, C.D. Farmer, C.R. Stanley and C.N. Ironside

Abstract: The paper describes recent progress in the design, simulation, implementation and characterisation of photonic crystal (PhC) GaAs-based quantum cascade lasers (QCLs). The benefits of applying active PhC confinement around a QCL cavity are explained, highlighting a route to reduced threshold current operation. Design of a suitable PhC has been performed using published bandgap maps; simulation results of this PhC show a wide, high reflectivity stopband. Implementation of the PhC for the device is particularly difficult, requiring a very durable metallic dry etch mask, high performance dry etching and a low damage epilayer-down device mounting technique. Preliminary shallow etched PhC QCLs demonstrated the viability of current injection through the metal etch mask and the device mounting technique. Development of the etch mask and dry etching have demonstrated a process suitable for the manufacture of deep etched PhC structures. All the necessary elements for implementing deep etched PhC QCLs have now been demonstrated, allowing for the development of high performance devices.

1 Introduction

Quantum cascade lasers (QCLs) are mid-to-far infra-red semiconductor lasers, where photons are generated by radiative intersubband transitions in quantum wells [1, 2]. Applications for QCLs include gas sensing, spectroscopy, defence and communications. Quantum cascade lasers suffer from a low radiative recombination efficiency compared to conventional interband semiconductor lasers, resulting in a relatively high threshold current density. The high drive current requirement of QCLs is inconvenient and, as a result of the low efficiency, most of the energy supplied is converted to heat, causing severe device heating problems; for the QCL to achieve its full potential it is imperative that the threshold current be significantly reduced. One possible route to reduce threshold currents is to improve the quality factor, Q, of the resonator cavity by increasing the reflectivity of the mirrors [3]; this reduces the effective mirror loss and allows the overall laser dimensions to be decreased. Progress towards this has already been achieved by using a high reflectivity coating at one end of the resonator [4]. Further progress can be achieved by embedding the QCL cavity in a photonic crystal (PhC) structure [5], where the PhC is designed to form a high reflectivity mirror at the lasing wavelength.

In this paper, we propose a high-Q active photonic crystal quantum cascade laser, demonstrate a method of implementing the design and review the challenges inherent in producing a very low threshold device. Figure 1 shows the concept of the photonic crystal quantum cascade laser. A two dimensional (2-D) PhC forms a high reflectivity mirror around a QCL cavity, thus providing strong confinement of the light; the effective mirror loss and device dimensions can consequently be reduced. Since current is injected into the PhC as well as the central microcavity section, the PhC is active and has the potential to introduce gain into the system, thus counteracting device losses. Eventually, the central microcavity section could be reduced to a small defect state within the PhC, drastically reducing the overall device size, with a corresponding reduction in lasing threshold current and device heating. Furthermore, as a consequence of the transverse magnetic (TM) polarisation of the intersubband transitions in QCLs, the emitted photons cannot couple to any optical modes propagating perpendicularly to the plane of the quantum wells, and hence for QCLs a 2-D PhC structure can act as a quasi-3-D PhC structure.

Photonic crystal research has advanced rapidly over the past few years, driven by the attractive light confinement and guiding properties offered by PhCs [5]. Although the main focus of PhC research is directed towards applications in compact integrated photonics, there is increasing interest in PhC lasers. Indeed, 1-D PhCs have already proved very successful in vertical cavity surface emitting lasers (VCSELs) and distributed feedback (DFB) lasers, both of which have been commercially exploited on a large scale. Further performance improvements can be achieved by employing 2-D PhCs [6] and eventually 3-D PhCs, though many difficulties remain unsolved at present. Of particular interest for PhC lasers are the controllable photon confinement characteristics, which can be exploited to enhance the photon coupling to desired modes while suppressing that of unwanted modes [6]; a natural extension of this concept is the thresholdless laser, where photons can only couple to one possible mode. Although significant progress has been made on active 2-D PhC InGaAsP/InP interband lasers for communication wavelengths, the performance and exploitation of the technology is

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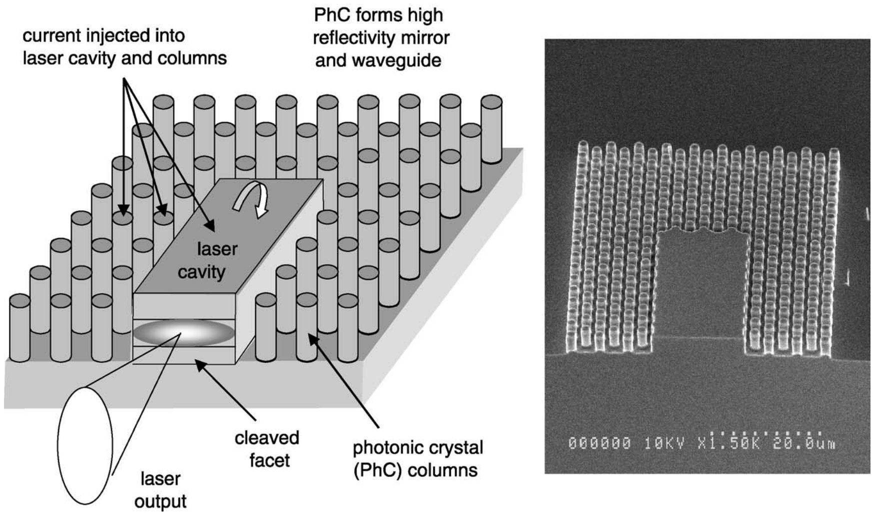


Fig. 1 *Concept of active photonic crystal quantum cascade laser (QCL)*

Eventually the device will consist of a small microcavity defect state within the active photonic crystal, thus allowing very low threshold currents. The SEM image shows a preliminary shallow etched device to give a better visualisation

limited by the following factors [6]: (i) fabrication of the PhC requires high performance nano-technology tools; (ii) scattering losses due to PhC roughness and imperfections; (iii) severe carrier loss due to nonradiative electron–hole pair surface recombination. The first two of these problems are drastically reduced when applying PhC principles to mid-infrared QCLs; the larger wavelength of the QCLs reduces the fabrication tolerances and scattering losses. More importantly, the problem of nonradiative electron–hole pair surface recombination is altogether avoided for the case of QCLs since they are unipolar intersubband lasers, using only a single carrier type (electrons in this case); consequently there will be a negligible electron–hole pair surface recombination carrier loss. These advantages of applying PhC principles to mid-infra-red QCLs, combined with the quasi-3-D confinement offered by a 2-D PhC (as a consequence of the TM polarised intersubband transitions), makes the PhC QCL an ideal candidate for demonstrating the benefits of PhC lasers and low threshold QCLs.

Thus far, quantum cascade lasers have been realised in two material systems: InGaAs/InAlAs lattice matched to InP and AlGaAs/GaAs latticed matched to GaAs [7]. High performance quantum cascade lasers require design of the active region and optical waveguide in addition to laser fabrication [7]. Laser operation at the desired wavelength is achieved by quantum engineering of the active region to enable radiative intersubband transitions of the required energy. Designing a suitable optical waveguide for the laser requires careful analysis of the modal confinement in the active region in addition to the optical loss contributions. The thermal conductivity of the materials must also be considered for effective heat dissipation. Design and optimisation of quantum cascade laser cavities is covered elsewhere, for example [7–9].

Quantum cascade lasers ($\lambda \approx 9.4\,\mu$m) with monolithic air–semiconductor Bragg reflectors have been successfully demonstrated, where due to the finite lateral dimensions of the structure the Bragg reflector represents a 1-D PhC mirror [3]. This 1-D PhC quantum cascade laser showed reduced threshold current operation compared to a cleaved device as a consequence of reduced mirror losses; the reflectivity of the 1-D PhC mirror is in the range $R = 80\%$ compared to $R = 23\%$ for the cleaved facet. The laser was implemented in the AlGaAs/GaAs material system. Fabrication of the air–semiconductor 1-D PhC mirror was achieved by focused ion beam (FIB) processing, giving a smooth, vertical, etch profile. Distributed feedback (DFB) quantum cascade lasers have also been demonstrated, employing metallised surface relief gratings for optical feedback [10]. Although 1-D PhC mirrors enable improved QCL operation, the application of 2-D PhC structures offers much greater potential for device miniaturisation and superior QCL performance. A quantum cascade surface-emitting photonic crystal laser employing a 2-D PhC structure has recently been demonstrated, where the PhC is used to create a micro-resonator [11]. This electronically pumped laser operates in the band-edge mode of the PhC. A hexagonal etched array of air holes is used to create the PhC, where the etch penetrates through the lower cladding. This PhC simultaneously provides optical feedback and vertical out-coupling of light. Wavelength tunability was achieved by varying the PhC dimensions.

The research described in this paper follows on from the work on coatings we employed on AlGaAs/GaAs quantum cascade laser operating at $\sim 11\,\mu$m [4]. The AlGaAs/GaAs material system is suitable for photonic crystal fabrication since it has an established dry etching technology that can give the necessary vertical etch profile. The overall aim is to demonstrate a low threshold PhC QCL, which requires the following objectives to be achieved: (i) design and simulation of a suitable PhC for the device; (ii) development of the necessary fabrication techniques; (iii) a solution for suitable device mounting. This paper addresses these objectives, outlines the difficulties faced and future research to be undertaken. Our laser is based on defect mode operation as opposed to the band-edge mode operation of the surface-emitting PhC QCL [11].

2 Photonic crystal design and simulation

Designing the optimum device requires careful analysis of the PhC structure, laser operation, and fabrication requirements; many of the issues involved are disparate and therefore a suitable compromise must be chosen. Since the PhC is electrically active it is imperative that the overall pumped area be kept to a minimum to achieve a low threshold current. Maintaining a small cavity volume is also desirable for minimising the number of cavity modes; ideally only a single cavity mode would be supported.

The number of lattice repeats required to achieve a high reflectivity stopband must also be kept to a minimum, meaning that a high index contrast PhC is necessary [3, 12]. Fabrication of the high index contrast PhC requires etching vertically through the semiconductor material to give a periodic structure consisting of the semiconductor material and the airgap [3, 12]. For the quantum cascade material used in this research, it is necessary to etch through the upper cladding, waveguide core and lower cladding. Although a high index contrast can be achieved by stopping the etch in the waveguide core or lower cladding, the optical mode interaction with surface would cause scattering losses, and consequently it is desirable to etch through the entire waveguide structure. The large wavelength of QCLs makes the epitaxial material very deep and thus an etch depth in the region of 10 μm is necessary. Such a deep etch requirement has a large impact on the design, fabrication and structural integrity of the PhC QCL.

Laser emission from the QCL is TM polarised, and therefore, from inspection of published photonic bandgap maps [5], a triangular lattice of high index columns separated by airgaps appears the most appropriate configuration. This gives the largest stopband region, reducing the fabrication tolerances and offering a high PhC reflectivity. Although the majority of PhC research in integrated optoelectronics focuses on using a lattice of air holes, the TM polarisation of the QCL makes such a configuration a poor choice for this case; a lattice of air holes has a relatively small stopband for TM polarisation, and the diameter of the hole is similar to the period, consequently approaching the hole touching condition. The recently reported quantum cascade surface-emitting photonic crystal laser [11] is mounted epilayer-up, thus requiring the PhC structure to be electrically connected for injection into the device. They therefore adopted a hexagonal etched array of air holes for their PhC; however, this PhC does not form a full 2-D bandgap for TM polarised light, hence their laser operates in the bandedge mode. In contrast, our approach is to mount our device epilayer-down for the following reasons: (i) superior thermal dissipation; (ii) current can be injected into a lattice of high index columns, where the columns are electrically connected by the metal bonding layer. Our epilayer-down approach therefore allows a PhC structure based on a triangular lattice of high index columns separated by airgaps, giving a full 2-D bandgap for TM polarised light, and consequently our device is a defect mode PhC laser.

One of the strengths of PhCs is their scalability, where a change in frequency can easily be accommodated by scaling the PhC accordingly. Owing to the complexity of QCL design and epitaxial wafer growth, obtaining the exact design wavelength can be difficult, and consequently the approach adopted here is to develop the design and fabrication process for a high reflectivity PhC structure at a wavelength of 10 μm, then simply scale the PhC to match the exact peak gain wavelength of the specific QCL wafer.

Having chosen the high index contrast triangular lattice of columns as the most appropriate configuration for this device, the next step requires selection of the column radius (r) and lattice period (a). Fortunately, 2-D photonic crystal bandgap maps with a suitable index contrast for GaAs based semiconductor-to-air PhC structures have been published [5], providing a good starting point for the PhC design. The development of a high performance PhC is an iterative process, requiring feedback from device fabrication and characterisation. Considerable care must be exercised when using the 2-D PhC bandgap for designing the real devices; although the 2-D bandgap map provides a valuable insight

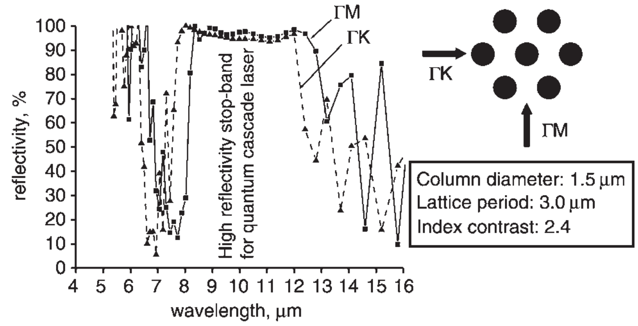


Fig. 2 *Simulation results (2-D) showing reflectivity of a triangular lattice of high index columns as a function of wavelength for both crystal orientations*

into the PhC operation, it does not account for many of the issues in the fabrication and operation of the real device. Inspection of the 2-D bandgap map for the triangular lattice of high index columns reveals several regions of bandgap operation for TM polarisation [5]. Selecting where to operate within the bandgap is a compromise between opposing issues. Achieving a small electrically injected area requires a small radius, but this leads to a low radius-to-period ratio, which consequently increases the out-of-plane diffraction losses. From a fabrication point of view, a large column radius improves the device structural integrity, but the resulting large radius-to-period ratio tends to cause dry etch problems related to removal of etch products. Considering these various factors, an initial design was developed with a column radius and lattice period of 0.75 μm and 3.0 μm, respectively; this design operates in the largest TM bandgap region and offers a wide stopband with reasonable fabrication tolerances. Simulation of the photonic crystal was performed using the finite difference time domain (FDTD) method. Figure 2 shows the simulation results for both crystal orientations; the plots show the photonic crystal reflectivity as a function of wavelength. Care must be taken when interpreting the simulation results; the further away from the 10 μm wavelength, the less accurate the results become, and since the simulations must have finite dimensions and time, this limits the accuracy. Additionally, the simulation is only 2-D, and thus ignores out-of-plane losses; 3-D simulations were too computationally intensive to be of practical use. Nevertheless, the 2-D results clearly show a high reflectivity PhC for both crystal orientations. The high reflectivity window of operation is centred near 10 μm as expected, with a stopband width of ~4 μm. These reflectivity plots are promising, especially since the wide window of useable operation makes matching the region of photonic bandgap operation to the lasing wavelength relatively easy, and allows for fabrication inaccuracies.

3 Shallow etched photonic crystal laser

Achieving the goal of a compact, low threshold PhC QCL requires a number of technological issues to be addressed. Preliminary shallow etched PhC devices were investigated to gain an understanding of these issues and develop appropriate solutions. Optimised deep etched PhC devices can subsequently be developed using the knowledge gained. In particular, the fabrication process, device mounting and current injection through the metal etch mask required investigation.

The preliminary shallow etched device is very similar to the SEM image shown in Fig. 1, except that the real device is much longer. The device has one PhC reflector made by

7 to 8 column repeats, with the other mirror created by cleaving. The waveguide is formed by embedding a nonetched defect region of width ~16 μm within the PhC; the waveguide is surrounded on either side by six PhC column repeats. The PhC orientation is ΓK with respect to the direction of propagation of the light in the resonator. The columns have a diameter of 1.5 μm with a period of 3.0 μm. The total length of the device is ~1500 μm and the total width ~44 μm. Although the device is much larger and has more lattice repeats than is envisaged for the optimised device, it provides a valuable insight for future development.

Fabrication of the PhC QCL has a number of challenging aspects. In particular, the definition and dry etching of deep, vertical, smooth, high-aspect-ratio columns is difficult. The etch mask is critical since it must withstand the dry etch process used to create the 10-μm-deep PhC columns and form a good electrical contact to the semiconductor. Consequently, the mask must be metallic and highly resilient to the dry etch process. Owing to the high durability of nichrome (NiCr) in silicon tetrachloride ($SiCl_4$) reactive ion etching (RIE) used to etch GaAs/AlGaAs, a 100 nm NiCr layer was chosen. Accurate definition of the structures was achieved using an electron beam lithography (EBL) lift-off process. After EBL, metallisation and lift-off, the sample was dry etched using $SiCl_4$ RIE; the etch process is highly vertical and non-selective for GaAs/AlGaAs. For the preliminary shallow etched devices the etch depth was ~4 μm; this depth was chosen since smooth, vertical columns could be reliably etched to this depth whilst still maintaining sufficient metal etch mask for electrical injection. Material for the shallow etched PhC QCL was very similar to that previously published [8, 13] and has a lasing wavelength of ~11.2 μm. The $Al_{0.33}Ga_{0.67}As$/GaAs QCL structure is grown by molecular-beam epitaxy on an n^+-GaAs substrate and has 40 periods of alternating active and injector regions. Optical waveguiding is achieved by sandwiching the active region between Si doped GaAs cladding layers.

Device mounting is critical to achieve high performance devices; damage of the fragile PhC columns during mounting must be avoided. The devices must be mounted epilayer-down, and we have opted to use gold plated copper mounts coated with an indium bonding layer. However, pure indium has a thin surface oxide layer, which should ideally be removed before device mounting. A flux cannot be used since this would penetrate the PhC structure, consequently damaging device performance. Cold welding the devices by pressing them into the indium layer, thus breaking through the oxide layer, would damage the PhC columns, and therefore is not a realistic option. The preferred solution was to heat the mount in a forming gas (H_2/N_2) while gently pressing the device into the indium bonding layer; since the indium layer is softened by the heating, damage to the PhC columns is prevented. Device mounting was carried out by the QCL group at Thales.

Figure 3 shows the light/current (L/I) characteristic of the shallow etched device; characterisation of the device was performed at the University of Sheffield, UK. Since the PhC is only shallow etched to a depth of ~4 μm, the index contrast is very low and consequently the PhC performs poorly as a reflector. For this device it is not clear whether the return reflection is due to the PhC reflector or the cleaved facet. Even so, the device shows laser operation when cooled, at a lasing wavelength expected for this wafer. Although deep etching through the waveguide layers of the PhC structure results in a large index contrast between semiconductor column and airgap, consequently giving a

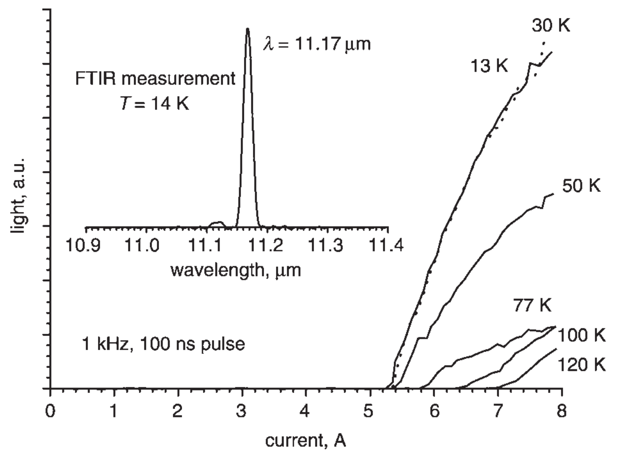


Fig. 3 *Light/current (L/I) characteristic of shallow etched PhC QCL*

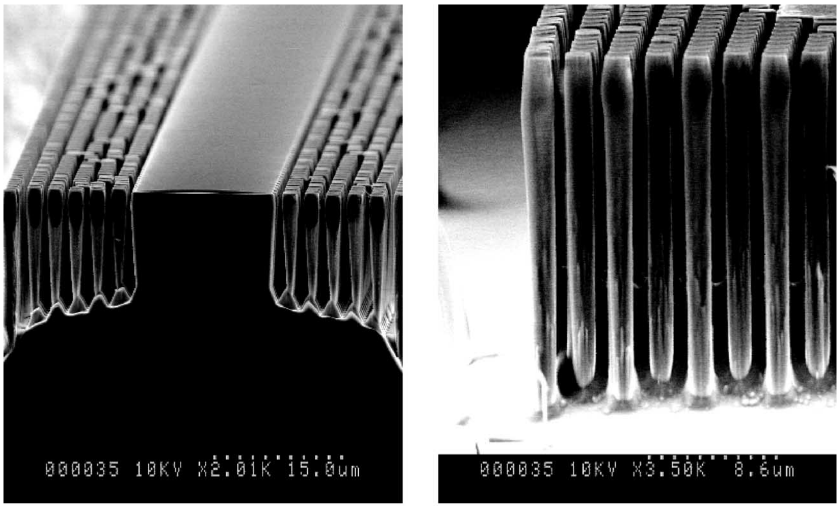
Inset shows the lasing spectrum; the lasing wavelength for this wafer was 11.2 μm

full bandgap for TM polarised light, the effects of shallow etched PhC structures are less clear. For shallow etched PhC devices the etch does not propagate through the entire vertical waveguiding structure, resulting in a much lower index contrast and consequently a poorer bandgap. As the etch depth is increased the vertical waveguiding mechanism underneath the etched region is disrupted; for a sufficiently deep etch the vertical waveguiding mechanism is no longer sufficient to form a wavguide and the mode is no longer supported. For the 4-μm-deep shallow etched PhC QCLs reported in this paper the etch depth is believed to be sufficiently deep to significantly perturb the optical mode underneath the shallow etched region, though it is unclear whether a mode can still be supported underneath the etched region. Since the PhC columns are only shallow etched, current spreading occurs, and therefore the effective current injected region is ~1500 μm by 44 μm. At 77 K, the threshold current density for the shallow etched PhC QCLs was 8.8 kA/cm^2. Previous measurements on this wafer for standard 2000 μm by 20 μm devices gave a threshold current density of 5.4 kA/cm^2 at 77 K. The increase in threshold current density can be attributed to additional losses incurred as a consequence of the poor reflectivity from the shallow etched PhC. An increase in threshold current density was also observed for the quantum cascade surface-emitting photonic crystal laser [11].

Results from the shallow etched PhC QCL are very promising for the future development of low threshold deep etched PhC QCLs. Although the device suffered from a high threshold current density, this can be explained by the poor reflectivity of the shallow etched PhC. A fully deep etched PhC offers much improved light confinement and reduced current spreading, consequently leading to greatly reduced threshold currents. The critical fabrication issues of epilayer-down device bonding and current injection into the active PhC through the metal etch mask have been resolved.

4 Deep etched PhC laser development

Investigation of the shallow etched PhC QCLs highlighted the need for an improved fabrication process for deep etched device manufacture. Although the single layer of NiCr proved a durable etch mask and allowed current injection into the device, NiCr deposited on GaAs or polymethyl methacrylate (PMMA) resist suffers from stress, resulting in



a *b*

Fig. 4 *SEM images of PhC columns created using $SiCl_4$ RIE*
Both images are from the same etched sample
a Image taken at a cleaved facet
b PhC column at edge of array

poor adhesion and fracturing. This limits the NiCr layer thickness to $\sim$100 nm, which is insufficient to etch the columns to the necessary depth of $\sim$10 μm. A more durable and flexible metal etch mask was developed, allowing a thicker layer of NiCr whilst alleviating the problems associated with NiCr stress. The composite multilayer etch mask has the following layer sequence: Ti (20 nm)/Au (40 nm)/NiCr (200 nm). The Ti layer is to provide good adhesion to the GaAs or PMMA surface. The Au layer provides stress relief to eliminate the fracturing problems caused by the NiCr layer. Finally, the NiCr layer is used to provide a very resilient etch mask, suitable for deep etching of GaAs/AlGaAs. The thickness of the NiCr can be varied depending on the required etch depth.

Dry etch tests were performed on samples patterned with the new etch mask. A nonselective $SiCl_4$ RIE process was used to transfer the etch mask pattern into the semiconductor. Figure 4 shows SEM images from a sample etched for approximately 2 h. At the edge of the PhC array the columns are smooth, perfectly vertical and very deep, with an etch depth of $\sim$23 μm. Within the PhC array the column depth is reduced to a minimum of 13 μm next to the laser cavity, and the columns have a slightly nonvertical profile with an undercut incline of $< 2^\circ$. We believe that the deterioration of the dry etch profiles within the PhC array may be due to the restricted outflow of the gaseous reaction products and to ion scattering/recoil. The new composite multilayer metal etch mask proved very durable, meeting the dry etch requirements and thus demonstrating a process suitable for deep etched PhC QCL device manufacture.

Careful inspection of Fig. 4*a* shows that a few columns are damaged and appear slightly out of place. Structurally, the columns are inherently delicate due to the required dimension; the problem is further exacerbated by the slight nonvertical etching within the PhC array. The poor structural integrity of the columns has a great impact on the device fabrication and mounting processes, and great care must be taken to protect the columns from damage. As a result, the device fabrication sequence must be heavily modified such that the dry etching of the columns becomes the last fabrication step before cleaving, thus minimising the potential for structural damage.

5 Conclusions

In conclusion, we have described the motivation and recent progress towards realising high performance photonic crystal quantum cascade lasers. The ultimate aim is to reduce the QCL device to a small defect state within the active PhC to enable very low threshold current operation. Achieving the potential benefits of PhC QCLs requires the key issues of PhC design, device fabrication and device mounting to be addressed. This paper has discussed these issues and demonstrated laser operation from preliminary devices.

Using published bandgap maps [5], a triangular lattice of high index columns separated by airgaps was chosen to give the largest stopband region for the TM polarised QCL emission, thus reducing the fabrication tolerances and offering a high PhC reflectivity. A suitable PhC was designed using the bandgap map, and FDTD simulation results showed a wide high reflectivity stopband. Realising a high performance PhC requires a high index contrast, consequently meaning that the dry etch used to define the PhC must etch through the upper cladding, waveguide core and lower cladding, thus demanding a very durable metallic etch mask and high performance dry etch technology. Results from preliminary shallow etched devices showed laser operation, thus demonstrating the viability of current injection through the metal etch mask and the epilayer-down mounting technique. Development of a composite multilayer etch mask allowed improved PhC manufacture using $SiCl_4$ RIE, with sufficiently deep columns to form the PhC. Following the demonstration of the design and simulation of the PhC, in addition to the fabrication viability using the new metal etch mask, $SiCl_4$ RIE of the columns, and the device mounting technique, the next step is to implement fully deep etched high performance PhC QCLs. This should allow the realisation of QCLs with significantly improved performance.

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