Epitaxially Re-Grown Photonic Crystal Surface Emitting Lasers

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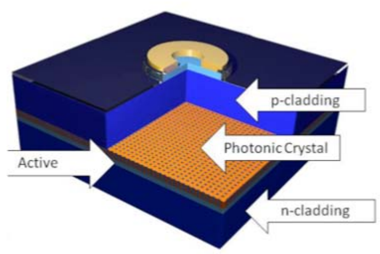

Figure 1. Schematic of the PCSEL

Photonic crystal surface emitting lasers (PCSELs) [1] offer the ultimate in control in semiconductor lasers. PCSELs have been shown to have high power scaling with area, high single-mode powers [2], large scale coherent emission, control of the beam shape and polarization with design of the photonic crystal geometry [3,4], as well as beam steering [5]. The photonic crystal, a two-dimensional variation in refractive index, provides feedback in multiple orthogonal directions. Wave propagating in various directions couple with one another and a 2D standing wave (cavity mode) is constructed over a broad area. These devices have previously been fabricated through wafer fusion or the formation of voids during the re-growth process. The manufacturability of such devices prompted the move towards epitaxially regrown structures that do not contain voids.

University of Sheffield researchers (Williams *et.al.),* have developed all semiconductor PCSELs (i.e. void-free) based on epitaxial regrowth of GaAs/InGaP [6]. The development and optimization of the epitaxial regrowth via MOVPE (Stevens, EPSRC National Centre for III-V Technologies) is a major challenge due to the high aspect ratio of the PC features. There is a tradeoff in the choice of regrowth temperature. High temperatures are required to desorb natural oxides, yet result in As:P exchange, which we aim to minimize. Low temperatures lead to the formation of threading dislocations. These constraints on growth temperature remove an element of freedom when trying to ensure good planarization during the regrowth process. In order to optimize the regrowth process, samples identical to the final PCSEL design were realized that differed by having a PC layer (p-$In_{0.48}\,Ga_{0.52}\,P$) of 300 nm in thickness.

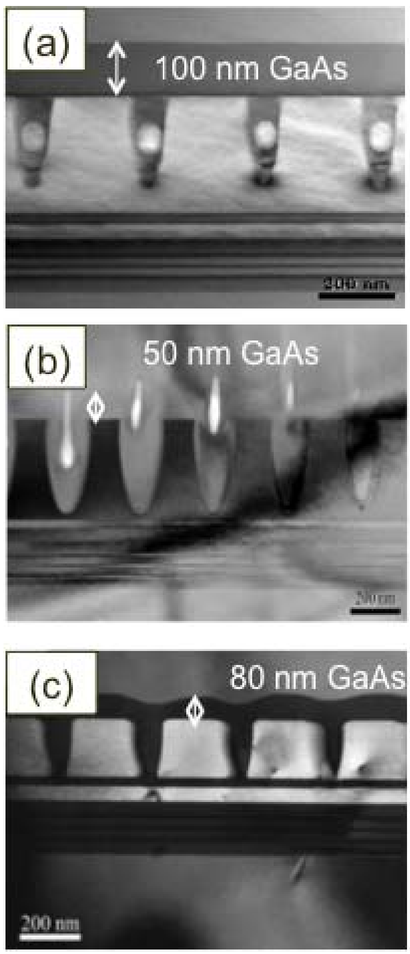

Figure 2. TEM images showing development of the epitaxial re-growth process.

Fig. 2 shows TEM images of 3 different PCSEL overgrowth experiments [7]. In Fig. 2(a) a standard regrowth was used that has been successfully applied to distributed feedback lasers and self-aligned stripe lasers with lower aspect ratio features [8]. In addition to growth temperature, a key parameter in the regrowth process is the surface mobility of gallium, which may be modified by the supply of arsenic (as the available temperature window is narrow). While the overgrowth conditions in Fig.2(a) offer excellent planarisation (evidenced by the upper GaAs/AlGaAs interface), they are observed to give rise to voids within the PC structure. Reducing the arsine flow into the reactor reduces the surface mobility of the gallium. The TEM of a regrown test structure (300 nm p-$In_{0.48}Ga_{0.52}P$) using a reduced arsine flow is shown in Fig. 2(b). We see that the position of voids is displaced vertically, and their shape is modified to be more "teardrop" shaped. Fig. 2(c) shows the overgrowth of our standard structure with a 150-nm-thick

InGaP layer rather than the 300 nm thickness used in test structures, carried out under identical conditions to those used in the regrowth of Fig. 2(b). Here, the infill of the PC is complete, with reasonable planarization as a clear modulation of the upper GaAs/AlGaAs interface is observed, additionally the infill apparently formed without the creation of threading dislocations.

Following regrowth, discrete devices were formed by etching a 50 µm mesa in the p+GaAs contact layer above the center of the PC. An annular gold contact was defined, providing a 25 µm aperture for light extraction. The electrically driven re- gion (50 µm diameter plus current spreading) is smaller than the regrown PC (150 µm × 150 µm). Room temperature lasing was observed with narrow (~1 degree) divergence, and measured band structure in excellent agreement with theory, as shown in Fig 3.

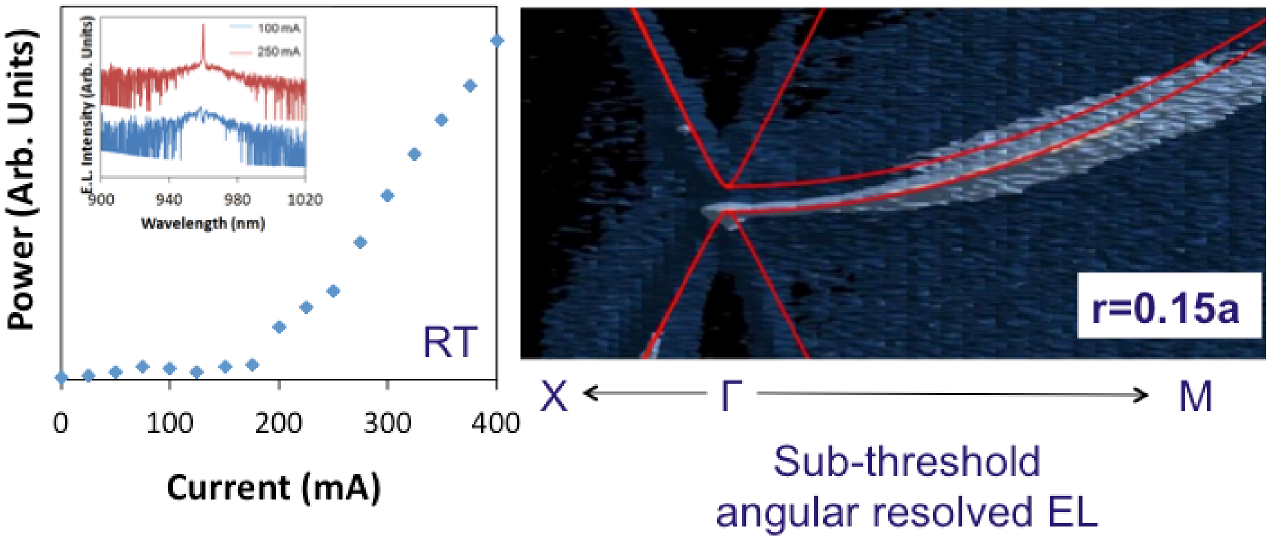

Figure 3. L-I characteristics of PCSEL with inset showing emission spectrum. Sub threshold angular dependence of the EL shows excellent agreement with simulation.

Simulation of all semiconductor photonic crystals [9] has shown them to have coupling which is *higher* to that of void containing structures. A high coupling coefficient is required to increase the power emitted per unit area. Figure 4 shows the modelled mode profile of an all semiconductor and void containing PCSEL, overlaid on the PCEL structure, showing how the mode overlaps with the PC region. Within void containing structures the low refractive index of the PC region "pushes" the mode away from the PC. This is not the case for the all semiconductor PC and the higher coupling is due to strong modal overlap with the PC region, which compensates for the smaller contrast between the mark and space. Simulation of PCSELs in other materials systems is underway, but preliminary results indicate that all semiconductor structures have higher coupling irrespective of the materials chosen, and hence operating wavelength.

Acknowledgements

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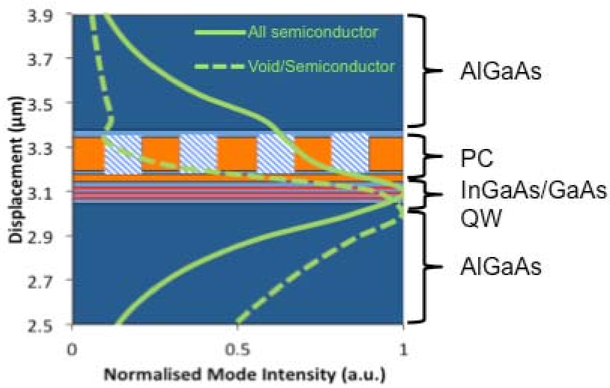

Figure 4. Simulation of mode within all semiconductor and void/semiconductor PCSEL operating at 980nm