GALLIUM NITRIDE VCSELS WITH BURIED DIELECTRIC BRAGG MIRRORS

GR/N07868/01 FINAL REPORT

BACKGROUND/CONTEXT

Light emitting devices based on III-N semiconductors have achieved impressive performances and developed into a major part of the global optoelectronics industry. The performance of GaN-based blue/violet edge-emitting lasers and UV/blue/green/amber LEDs, and the variety of potential applications, continues to improve at a dramatic rate. However, the lack of a viable approach to the fabrication of GaN-based Vertical-Cavity Surface-Emitting Lasers (VCSELs) is a significant shortcoming in III-N device technology, as explained in the application for this grant. Such devices promise a range of advantages over their edge emitting counterparts, the desirability of which has increased over the last few years. For example their increased stability and reduced thresholds are significant for printing/recording/lithographic applications. In addition recent interest in advanced wide-gap microcavity devices, such as the so-called polariton lasers, has added further to the desirability of III-N microcavities of exactly the type required for VCSELs.

Our programme has explored a novel approach to the fabrication of GaN-based VCSELs and related structures. We employed epitaxial layer overgrowth on areally-patterned dielectric Bragg mirrors to seek to combine the benefits of low-loss, highly-reflecting bottom mirror elements for the VCSEL devices with those of improved quality III-N overgrown active regions and microcavities. In addition to the achievements in this area the project was particularly successful in identifying other significant routes to fabricate III-N VCSELs, along with important work underlying this type of device in general. Five of the six original objectives were delivered and surpassed as detailed in the results described below.

Significant steps were taken towards the sixth objective (demonstration of VCSEL operation) although this was not achieved. With the benefit of hindsight and viewed in the context of the worldwide status of development of III-N vertical cavity devices this objective was significantly more demanding than it appeared at the time of writing. Despite efforts over the last few years by leading groups in the US (including Santa-Barbara. Xerox and a collaboration of Brown University/Sandia National Labs/LumiLeds), Japan (including NTT Corporation and the leading Japanese VCSEL group at Tokyo) and Europe a full GaN-based VCSEL has still not yet been demonstrated. As identified in our proposal a fundamental difficulty lies in the fabrication of a lower DBR mirror of suitable quality. We proposed the use of oxide-based mirrors (both top and bottom) as a better route than AlGaN-based Bragg stacks. There have been a number of demonstrations of resonant cavity InGaN LEDs (a non-lasing VCSEL) employing both AlGaN-based lower mirrors [1] and double dielectric mirrors [2] and with electrical pumping [3]. Optically pumped VCSEL operation has been demonstrated using sophisticated AlGaN DBRs [4]. These impressive demonstrations brought into focus the extent of effort needed to achieve suitable AlGaN mirrors and there has been increasing worldwide interest in the double dielectric approach as proposed by ourselves [5]. For example a very recent report describes the removal of SiC substrates to fabricate high-Q GaN microcavities with upper and lower oxide mirrors [6].

KEY ADVANCES AND SUPPORTING METHODOLOGY

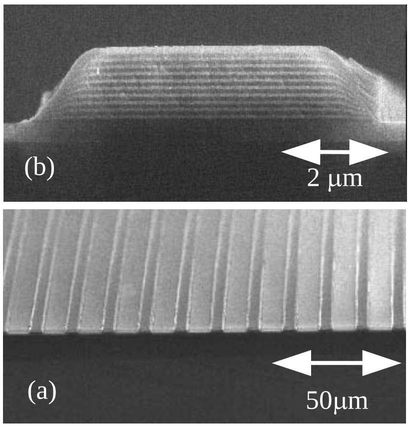

Fig. 1.(a) SiO_2/ZrO_2 DBR on GaN patterned into 4 μm stripes. (b) Sectional view of a 6 μm wide stripe.

We fabricated suitable SiO_2/ZrO_2 mirrors on GaN and showed them to be sufficiently robust to withstand conditions simulating overgrowth of a laser cavity. The reflectivity of 10½-period structures exceeded 99% with a high-reflectivity stop-band more than 80 nm wide, exceeding the necessary performance specifications. Despite thicknesses of ~1 μm we successfully patterned these mirrors using a single layer lift-off technique [7]. This circumvented problems associated with dielectric etching and involved overcoming difficulties associated with the relatively high temperatures required for their deposition. Two-inch diameter GaN-on-sapphire wafers were patterned with a range of mirror stripes (widths and spacings between 4 and 10 μm). Careful optimisation enabled a re-entrant photoresist profile to be achieved, suitable for the successful patterning of the narrow mirror stripes as shown in Fig. 1. This achieved the first objective: *Patterning of high-reflectivity dielectric DBR mirrors to ~10μm feature-size*. In addition we showed that neither dry etching nor wet-etching with buffered HF could produce such patterns from initially unpatterned SiO_2/ZrO_2 films, because of the resistance of ZrO_2 to these processes.

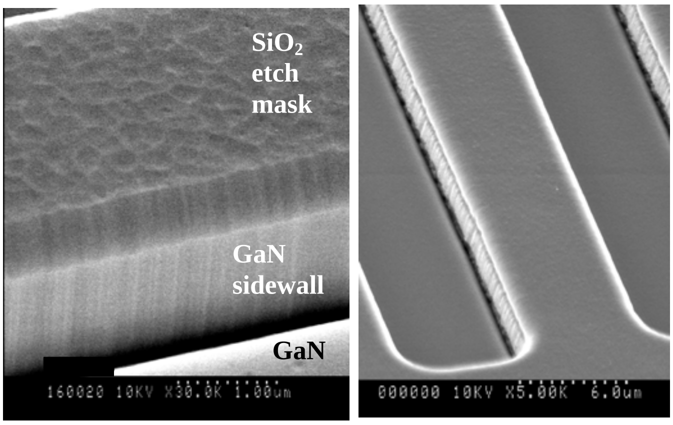

Fig. 2.(a) ICP etched trench in GaN (b) Plan-view of DBR coated ICP-etched GaN trenches and ridges.

The second objective required *high-quality inductively-coupled plasma (ICP) etching of GaN for lateral overgrowth templates and for device contacting*. The etching parameters were explored and optimised and high quality μm-scale trench structures etched into GaN layers as illustrated in Fig. 2. The overgrowth required DBRs, similar to those described above, to be prepared within trenches between narrow ridges of GaN. We envisaged burying these mirror strips by overgrowth of GaN seeded from the ridge sidewalls above the DBRs (pendeoepitaxy). Mirrors were successfully prepared within the GaN trenches but oxide deposits on the sidewalls prevented lateral epitaxy at this stage

[7]. However, as detailed below, a successful method of burying DBR strips by lateral epitaxy was subsequently identified and implemented. This was in fact a hybrid of the two overgrowth mechanisms (LEO and pendeoepitaxy) initially proposed as parallel approaches.

Achievement of the second part of objective two involved the development of etching, contacting and fabrication technology suitable for arrays of GaN surface-emitting devices [e.g. 8]. To date this has been used in very significant demonstrations of micro-LED arrays but the patterning and contacting problems are very similar for VCSELs). ICP etching has been used to produce large scale arrays of sub-10 μm scale micro-disks and –rings generating important scientific results as well as device potential. Individually addressable arrays of up to 128x96 devices represent world leading performance. A novel sloped side-wall mesa etching for conformal metal deposition was developed and implemented for electrical contacting of these arrays.

This work confirmed the importance of ICP etching for the patterning of GaN devices on a sub-μm scale (10's of times faster than RIE and more selective over mask materials). At the same time we explored the use of laser micromachining to pattern GaN [9] and in so doing identified an additional route to the fabrication of GaN microcavity devices, as specified in this project. Laser micromachining offers a rapid and maskless route to producing via holes in the back-side of III-N epitaxial layers opening the way to post-growth dielectric mirror deposition. Optimisation of this technique is part of ongoing work and represents another important development from this project.

A sizeable effort within this project was directed at conventional lateral epitaxial overgrowth (LEO) using single-layer SiO_2 patterned masks, both in preparation for overgrowth of DBR stripes and to optimise overgrown III-N structures. High-quality overgrowth was demonstrated with standard thin (~200nm) and novel thick (~500nm), with the latter designed to mimic the thicker mirror-based masks. This work included the first analysis of in-situ reflectivity monitoring of lateral overgrowth [10], which proved important for early indication of the point of coalescence of the two growth fronts. Rapid and complete coalescence of the growth fronts was an important requirement for microcavities produced by this route. Optimisation of the growth parameters enables void-free GaN layers to be produced as shown in Fig. 3. A considerable enhancement in the PL intensity was demonstrated for the laterally overgrown regions, in comparison to the seed regions. This can be imaged with the necessary spatial resolution using cathodoluminescence spectral imaging, which also reveals details of very small changes in strain within the III-N layer. AFM studies of conventionally overgrown GaN assisted in the understanding and optimisation of the process. This work addressed objective 4: *Optimisation of the overgrowth of AlGaInN active regions and contact layers.*

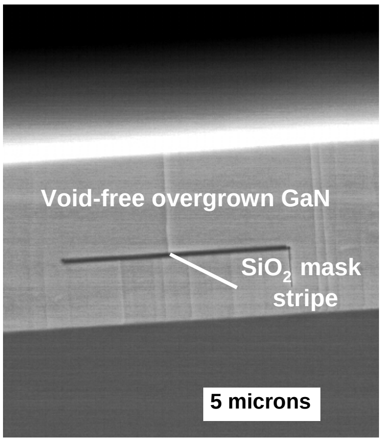

Fig. 3. Conventional GaN overgrowth showing the absence of a void above the mask

A number of attempts were made to grown GaN by LEO over patterned dielectric mirror stripes. Although some areas have shown successful LEO, delamination of the dielectric stripes at the elevated temperature within the reactor proved a difficult problem to overcome. A series of experiments involving treatment of mirror layers in different ambients and at high temperature shed some light on the nature of the problem but did not indicate an easy solution. The mirror-coated GaN structures were analysed using a number of techniques, including XRD, TEM and Secondary Neutral Mass Spectrometry (SNMS). The major difficulty was with the ZrO_2 layers but trials with HfO_2/SiO_2 DBRs showed similar delamination. The solution DBRs within the trenches were then “sealed” in place using an extra layer of SiO_2. The GaN ridges were then exposed by removal of excess SiO_2 and the unwanted DBRs, and then used to seed the hybrid overgrowth. Initial results were very promising as illustrated in Fig. 4, which shows a DBR mirror element buried by ~6 μm of GaN. A small void is visible above the buried mirror but the other features visible within the overgrown GaN are due to the nature of the cross-section (produced by fracture!). The luminescence from the overgrown GaN and from InGaN wells embedded within it, was investigated using CL and PL before and after deposition of a second oxide DBR mirror on the top surface. The cavities fabricated thus far are too long (>5 μm) but, as shown in Fig. 4(b) the integrity of the lower mirror is evident by the increased amplitude of the cavity modes within the CL spectra from the laterally grown regions. The above addresses objective 3: *Overgrowth of high-quality GaN above patterned mirrors using LEO and/or pendeoepitaxy.*

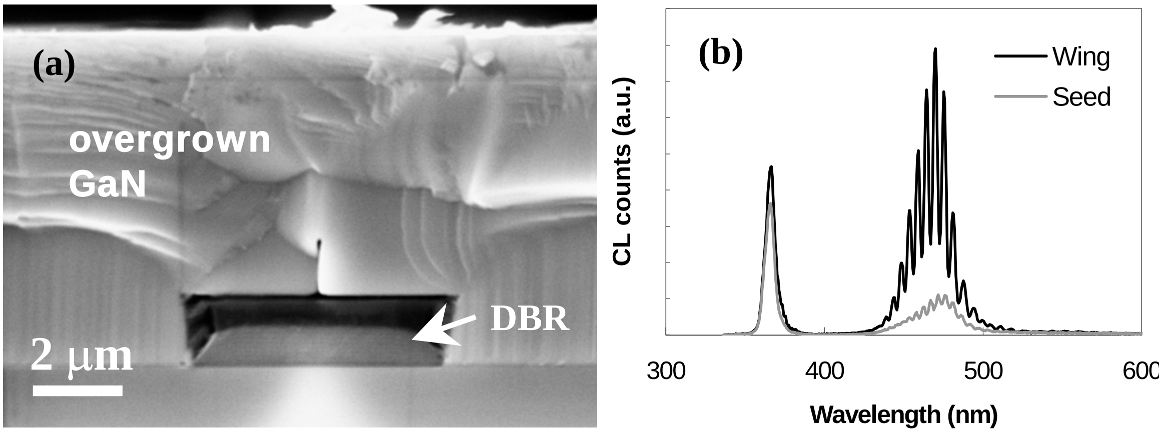

Fig 4. (a) overgrown GaN above a buried oxide DBR (b) RT CL spectra from regions above (enhanced intensity and cavity-induced interferences) and between the buried mirror stripes (lower intensity, weaker fringes)

While working towards “double oxide DBR” GaN microcavities using lateral overgrowth we maintained a search for other viable routes to achieve the same goal and the best microcavities delivered in the frame of this project came from one of these. This involved the separation of epitaxial III-N structures, grown at Strathclyde, from their sapphire substrates using a laser lift-off technique accessed by collaboration with a group at Berkeley. We fabricated high-finesse GaN microcavities by deposition of SiO_2/ZrO_2 DBRs above and below the lifted-off membrane and in addition demonstrated control of the microcavity length using an ICP etch-back [11]. The best cavity Q-factor achieved was ~750, comparable to the best published results to date.

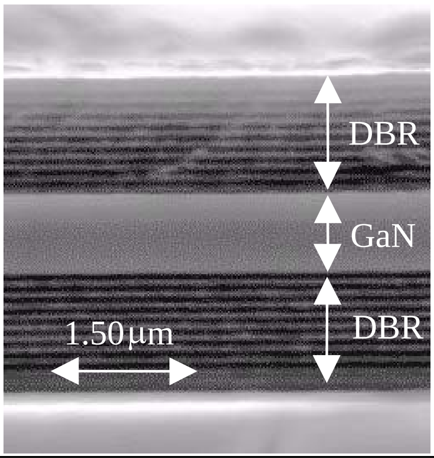

Fig. 5. GaN microcavity, ~800 nm thick, formed by laser-lift off and ICP etching

Similar cavity finesses were measured for 2 µm and 0.8 µm GaN cavities fabricated from the same wafer (see SEM images in Fig. 5) indicating that the etch-back has had little effect on microcavity quality. For InGaN quantum well samples the etch-back is shown to allow the controllable reduction of cavity length. Two etch steps of 100 nm were demonstrated with an accuracy of approximately 5 %. The etch-back, achieved using inductively coupled plasma and wet chemical etching, allows removal of the low-quality GaN nucleation layer, control of the cavity length and modification of the surface resulting from lift-off. In this case the etching did degrade the luminescence linewidth but in the best (unetched) case the PL FWHM narrowed from 13.4 nm for the as-grown quantum well to 0.6 nm for the microcavity sample, indicating a cavity finesse of ~ 50 and a resonance quality factor, Q, of ~ 750. This finesse corresponds to a combined mirror reflectivity of ~ 97%.

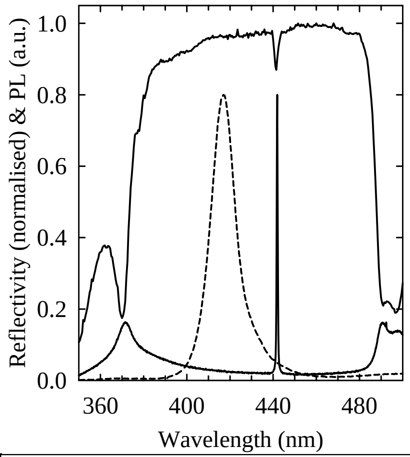

Fig. 6. RT reflectivity and PL data (solid lines) from a microcavity containing a single InGaN quantum well The dashed line shows RT PL from the as grown wafer.

Upper oxide mirrors of suitable quality were successfully deposited on both the lift-off and overgrown cavities. Together with the demonstration of device quality electrical contacts for the microLED arrays discussed earlier this provided achievement of the 5th objective : *deposition of “top” dielectric mirrors and electrical contacts of suitable device quality.*

As discussed in the introduction the sixth objective (*demonstration of VCSEL operation)* was not achieved (and with hindsight was not realistically achievable) but significant steps have been taken towards the demonstration of a GaN VCSEL. The cavity Q-factor achieved for the lift-off cavities should be sufficient for optically pumped lasing but our attempts to achieve this were frustrated by the fragility of the structures. The other approaches discussed above are more suitable for viable GaN-based VCSEL devices and a very important aspect of this project has been in clarifying some of the requirements needed for such a device and indicating likely routes to its achievement. In addition an important set of fabrication skills and characterisation facilities suitable for GaN microcavity devices has been established.

PROJECT PLAN REVIEW

The project proceeded without major problem. The project plan anticipated more progress in this research field than transpired, despite significant effort worldwide. However, the main unplanned events were in fact the range of significant new research possibilities that were spawned from this project. The management proceeded successfully and as planned despite the departure of the Glasgow University PI early in the project. Prof. Richard De La Rue took over as PI at Glasgow and the work there was enhanced by the addition of Dr. Catrina Bryce to the project team. The grant was able to support more individual researchers than first envisaged at Strathclyde because of supplementation by European Regional Development Funds over part of the project. The principle of making more than one postdoctoral appointment, so as to recruit individuals with complementary skills, was explicitly approved in advance by the EPSRC.

RESEARCH IMPACTS AND BENEFITS TO SOCIETY

As indicated on the report form, the project team has reported results in numerous international journal articles and conference presentations. Several of the latter have been selected for oral presentation, for example at the 5th International Conference on Nitride Semiconductors. Results were also disseminated widely through meetings of UK and Scottish-sector networks, notably the UK Nitrides Consortium. Collaborations with two industrial partners are also noteworthy. Samsung Advanced Institute of Technology (SAIT), Seoul, provided a significant cash contribution. The 2-year secondment of a SAIT employee, Taek Kim, to the Institute of Photonics also overlapped with the initial phase of the project. Dr Kim submitted a PhD thesis ‘Developments in gallium nitride vertical cavity surface emitting laser technology’ in February 2001. The collaboration with SAIT initiated continuing links between the Institute and academic and industrial groups in Korea, including the 18-month appointment of Dr Ki-Sung Kim under the title grant. Collaboration with the UK company PRP Ltd has been important in more recent work concerning micro-LED arrays. PRP’s in kind contribution has included wire bonding, and critical evaluations of device performance.

REFERENCES

[1] N Nakada et al., *Appl. Phys. Lett.* **76** 1804 (1999)
[2] Y-K Song et al., *Appl. Phys. Lett.* **74** 3441 (1999)
[3] M Diagne et al., *Appl. Phys. Lett.*, **79**, 3720 (2001)
[4]. Someya et al. *Science* **285** 1905 (1999) and Y-K Song et al., *Appl. Phys. Lett.* **76** 1662 (2000)
[5] RW Martin et al., *phys. stat. sol. (a),* **176** (1999)
[6] T Tawara et al., *Appl. Phys. Lett.* **83** 830 (2003)
[7] RW Martin et al., *phys.stat. sol.(a)*, **183**, 145 (2001)
[8] HW Choi et al., *IEEE Photonics Tech. Lett.* **15** 510 (2003) and *J. Appl. Phys.* **93** 5978 (2003)
[9] T. Kim et al., *Mat. Sci. Eng.*, **B82**, 262 (2001)
[10] IM Watson et al. *phys.stat.sol.(a)*, **188**, 743 (2001)
[11] RW Martin et al. *Appl. Phys. Lett.*, **79**, 3029 (2001)