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'Microchip and visible external cavity surface-emitting semiconductor lasers'

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Summary: This report summarises the outputs of a two-year research programme (1st April 2004 to 31st March 2006) in which we sought (i) to extend the concept of semiconductor thin-disk lasers to visible wavelengths and (ii) to develop further our novel concept of a microchip form of such devices. We chose to approach these goals using two separate III-V semiconductor alloy systems, namely AlInGaP for red wavelengths and AlInGaN structures for violet wavelengths. The work on the red lasers has been a great success, with continuous-wave output at the 1.1 Watt level having been demonstrated, together with intracavity frequency doubling to give 120mW at 337nm and microchip devices in various configurations. We have not yet succeeded with the AlInGaN violet devices, whose development we anticipated would be much more difficult. Nevertheless, we have learned a great deal from the work performed, and have some clear pointers to how such devices may be demonstrated in the near future.

1. Background and Context

The field of semiconductor thin-disk lasers, also known as vertical external cavity surface-emitting lasers (VECSELs), dates from the pioneering work of Mooradian and co-workers[1] in 1997, in which these novel devices were first demonstrated. These lasers are, in effect, half-cavity VCSEL structures (a semiconductor Bragg mirror and multi-quantum well active region) with feedback provided by an external optical resonator. Mooradian et al.[1] showed that operating such semiconductor lasers with diode-pumping could simultaneously give efficient mode and wavelength conversion, to provide Watt-level continuous-wave (CW) power outputs in circularly-symmetric TEM_{00} beams. Work in subsequent years, in which the UK groups at Southampton and Strathclyde Universities have played a prominent part, has shown that these lasers are also attractive from the point of view of accommodating intra-cavity optical components, for operation, respectively, as mode-locked[2] or tuneable single-frequency sources.[3,4] The cavities are also suitable to accommodate nonlinear crystals, and due to the high circulating intra-cavity powers (up to ~100W CW) can give efficient, and tuneable, intra-cavity second harmonic generation (SHG). Exploration in many laboratories since 1997 has now firmly established this technology, both commercially and in research. Major areas of interest include; laser projection displays, solid-state laser replacements; lasers for forensic and life sciences applications; and advanced laboratory sources for atomic and molecular spectroscopy, atom optics and Bose-Einstein Condensation (BEC).

A key issue for the above technology, however, is that the vast majority of work[2] has been performed on lasers operating at ~1000nm, and thus coverage in the visible spectral region has been limited to that achievable by the second harmonic generation of such wavelengths. This was the position at the start of the current programme and provided part of the background motivation to the work proposed. Several factors have contributed to this limited wavelength coverage - principally the ready availability and uniquely-favourable structural, thermal and gain characteristics of the InGaAs/(Al)GaAs structures for ~1000nm operation, together with the strong commercial incentive to develop blue and green wavelengths (SHG of 980-1060nm) for laser projection displays. A very important additional factor, however, is that the devices are temperature sensitive; pump-induced temperature rises in the active region of >100K, sufficient to frustrate or greatly impair laser action, are hard to avoid when the main thermal management is via heat extraction through the Bragg mirror and substrate. We had recognised that the above limitation could be tackled by an alternative thermal management approach whereby heat is removed from surface of the active region using an intracavity, optically-transparent heat-spreader bonded to that surface. We had not long adopted this idea, first demonstrated[5] by Sandia Labs. using sapphire, and were extending it to the higher thermal conductivity materials SiC and diamond.[6,7] In addition, it was recognised that such an approach would facilitate a monolithic form of VECSEL where a mirror coating on the outer surface of the heat-spreader would form the compact cavity.[8]

In summary, then, the background to the project was the desirability of extending the limited wavelength coverage of VECSELs, and in particular of the potential to utilize new semiconductor alloy structures and cavity designs for short wavelengths if the intracavity heat-spreader approach was adopted. With this motivation we sought to demonstrate direct generation of visible light for the first time from a VECSEL and to develop novel and compact forms of these devices.

2. Management, Collaboration and Staff

The original project plan was based around the forthcoming availability of a very able Ph.D student, Jennifer Hastie, who was then about to graduate. Jennifer had spent much of her Ph.D work demonstrating 850nm VECSELs with SiC intra-cavity heat-spreaders[6] and, in the very last stages, had performed the first practical demonstration of the microchip VECSEL concept at 850nm and 980nm.[8] She was poised to bring very relevant experience directly to bear. In the event, however, Jennifer applied for, and was awarded, a 5-year Royal Academy of Engineering Research Fellowship which started at the same time as this grant. As she had no associated grant support, it was decided (by her, in consultation with the PI) to dedicate her time to the laser aspects of this project, in which she was later supported by a new Ph.D student, Lynne Morton (2004-2007). This opened the way to utilise the 24 month PDRA time on the grant to support several individuals involved in wafer design and characterisation, development of the capillary bonding technology and heatspreader processing, and gallium nitride structure development and growth. These aspects were deemed essential given the demanding processing and materials development aspects of the programme. The individuals concerned were Chao-Wang Liu, Si-Hyun Park, John-Mark Hopkins and Zheng Gong. Hopkins (1 man month) had performed the original capillary bonding with diamond[7] and transferred this know-how into the project, Liu (3 months) and Gong (11 months) were involved in the gallium nitride structure growth and optical and structural characterisation, and Park (10 months) was dedicated to the processing of GaN-on-Si and GaN-on-sapphire wafers. Park was originator of another microchip VECSEL concept[9] and was an important addition to the team, but was only available from his home institution in Korea (Chosun University) for a limited period of time. Management of the project was undertaken by the PI, in association with co-investigators Erling Riis and Allister Ferguson. This involved day-to-day supervision of the research staff and students and regular project meetings within the team. Riis and Ferguson were simultaneously advancing the single-frequency operation[4] and in-well pumping[10] of VECSELs and brought that expertise into the programme.

The work was undertaken in 3 work-packages. Work package 1, led by Hastie, concentrated on designing AlInGaP/GaAs structures for red VECSEL operation, the demonstration of air-spaced formats of these devices, and achievement of the accompanying red laser milestones. Work package 2, led by Park and then Gong, concentrated on the epitaxial growth of GaN-based VECSEL structures on silicon and sapphire substrates, their capillary bonding to diamond, and attempted optical pumping demonstrations. Work package 3, led by Hastie and supported by Liu, Park and Gong, focussed on the microchip format of VECSELs, the processing of GaN structures, and the further development of microlens technology in diamond.

A key issue for the project was supply of high-quality AlInGaP red VECSEL material to our in-house wafer designs. Sheffield University was the specified supplier, and produced excellent metal-organic chemical vapour deposition (MOCVD) grown material in the second year of the project. In the early stages, during which Sheffield supply was delayed, we were able to approach our longstanding collaborator Prof. Markus Pessa, at Tampere University of Technology, Finland, who produced suitable structures at cost using molecular beam epitaxy (MBE). We were therefore able to make some overall comparisons between the MBE and MOCVD grown wafers. The project fostered close collaborations with growers at both institutions (Krysa and Roberts at Sheffield and Leinonen at Tampere) and several reciprocal visits to/by Sheffield staff and to/by Tampere staff were undertaken to facilitate collaboration.

3. Explanation of Expenditure

The University's budget for this 2-year programme was £191,100. This supported 24 months of PDRA time, allocated as described above, plus 6 months of named technician Lisa Reid, who performed all of the specialised machining work necessary to produce custom sample holders, mounts, stages, laser draft isolation covers, adaptors for the polishing rig, etc.

The equipment budget (£46,413) was spent purchasing a new UV argon ion laser (Coherent Sabre) at a special discounted price and a small chemical-mechanical polishing rig. Although reluctant to commit to new ion laser technology, we felt this to be the best way forward for the project. It was essential to have any chance of demonstrating 'proper' violet VECSEL performance to have the capability of pumping above the bandgap of GaN (350nm) with several Watts of CW power, and all-lines UV power of 3W was available from the ion laser. Furthermore, this laser was reconfigurable to provide very high pump powers at blue and green wavelengths, suitable for exploring power scaling limitation with the red VECSELs. The polishing rig was to allow us to polish the bulk GaN and sapphire substrates for GaN epitaxial growth.

The consumables budget (£47,000) was used to purchase AlInGaP and GaN-on-Si wafers, GaN bulk substrates, full mirror sets for 670nm and 420nm, in-house GaN epitaxy consumables, diamond heat-spreader platelets, and general mechanical materials, optical mounts and positional control components.

The travel budget (£3,500) covered visits to Sheffield University (1 person, 1 visit), to Tampere University in Finland (2 persons, 2 visits), to CLEO/QELS 2005 (partial, Hastie) and CLEO/QELS 2006 (Morton).

3. Key Advances and Supporting Methodology

a) Red VECSELs

AlInGaP materials technology has been very well explored for the production of red edge- and surface-emitting diode lasers and for amber and red light-emitting diodes. This material is known to lattice-match to GaAs substrates for the alloy composition $(Al_yGa_{1-y})_{0.51}In_{0.49}P$. The PI had been closely involved in development work on this material at Sharp Laboratories throughout the early 1990's and it was therefore natural to consider applying this technology to visible VECSELs. Our designs were, as usual, governed by optical and structural design factors and compromises and empirical estimates of likely cavity loss and gain per quantum well, all underpinned by transfer matrix and gain modelling. It is worth emphasising that the design criteria are somewhat different to those of VCSELs – especially in terms of accommodating large numbers of wells in an extended active region and allowing for uniform carrier injection through this structure via optical pumping at a known (532nm) wavelength. Balancing these considerations, our resulting design was as follows. The growth took place on 2" diameter (100) GaAs substrates. The DBR mirror had 40 pairs of $Al_{0.45}Ga_{0.55}As/AlAs$ quarter wavelength layers and the gain region 20x 6nm-thick $Ga_{0.46}In_{0.54}P$ compressively-strained quantum wells, grouped in pairs and separated by $(Al_{0.6}Ga_{0.4})_{0.51}In_{0.49}P$ barriers to give half-wavelength spacing for resonant periodic gain (RPG). The RPG wavelength, which determines the output wavelength of the VECSEL, was set to 670nm. The quantum wells were designed for a room temperature peak emission wavelength of 660nm to allow a 'gain offset'. Similar structures were grown by both MBE at Tampere and MOCVD at Sheffield. Samples of 4 x 4 mm^2 were cleaved from the VECSEL wafer and bonded using liquid capillarity to 250µm-thick single-crystal natural diamond (Type IIa) platelets of the same size, which acted as intra-cavity heat-spreaders. The advantages of diamond for such applications had been described in infrared VECSEL work which preceded the start of the project.[7]

Full results obtained with this structure in an extended VECSEL cavity are described in [11]. These include CW power transfer measurements, beam profiling, polarisation measurements, and tuning achieved using an intracavity birefringent filter. As a summary, the beam divergence was 10^{-3} radians with beam propagation ratio (M^2) less than 1.05; the VECSEL was linearly polarized with a measured extinction ratio of ~300:1 and tuning was obtained with 100mW output power over ~7nm around 674nm. More recent power transfer data, taken with the Sheffield MOCVD-grown material and showing maximum output of 1.1 Watts is shown below, together with tuning in a high-reflectivity cavity (HR mirror as output coupler) showing the maximum tuning range for this laser.

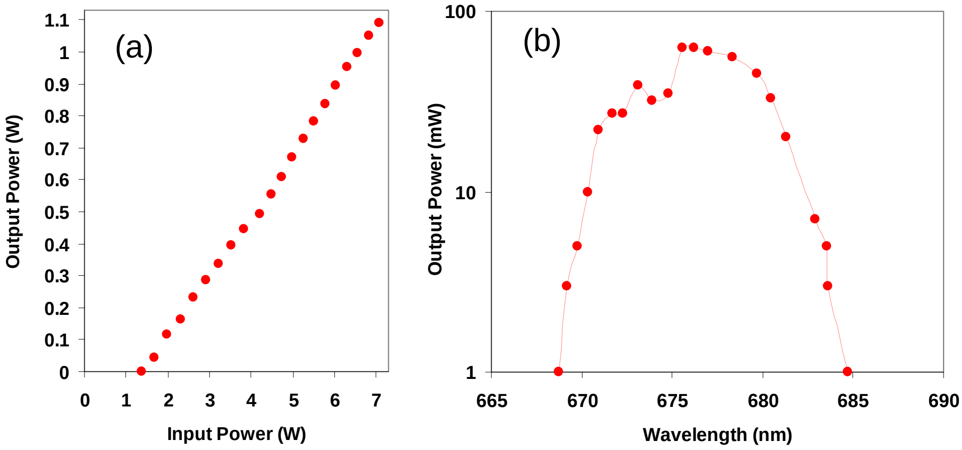

Fig. 1 Best power transfer and maximum tuning of red air-cavity VECSEL.

Please note that these results have been obtained with only one design of structure, and the slope efficiency is less than 20% (double this has been demonstrated in the infrared). Empirical optimisation by growth repetitions while varying number and distribution of wells, should therefore offer much room for further improvement. This laser has the potential to be operated in tunable, single-frequency format (such work is ongoing) and has generated much interest from the atomic spectroscopy community. It covers wavelengths of Li and Sr$^+$ for optical clocks and BECs. Further extension down to ~640nm, covering other atomic transitions e.g. Ca and Ne, should be possible. This work was selected as a recent research highlight in Compoundsemiconductor.net and Laser-Focus World and Photonics Spectra magazines in 2005.

The second phase of this work was to explore the potential of the devices as semiconductor microchip lasers. Here, we take advantage of mirror-coating the outer surface of the diamond heatspreader to produce a monolithic device where the optical field propagates within the diamond (hence the cavity is ~250µm long). We had established this principle shortly before using infrared VECSELs,[8,12] so our purpose here was two-fold, (i) to show that the same general method would work in the red and to characterise the specific results obtained and (ii) to explore the idea that these microchips are 'self-aligned' resonators of large surface area, therefore allowing the possibility of array-format operation if the pump beam was suitably divided. Arrayed laser beams of suitable wavelength, beam quality and optical power are of interest in atom optics and chip-based biosystems and we were keen to explore the potential of microchip VECSELs to fulfil these requirements. The same gain structure as above was used, bonded to a 250µm-thick diamond heatspreader whose outer surface was coated with a dielectric mirror 99% reflecting at 670nm and highly transmitting at the 532nm pump wavelength. The full results obtained are described in [13]. Briefly, with a single 532nm pump beam, 330mW of red output was obtained in a near-Gaussian beam ($M^2<2$). With the pump beam suitably divided by diffractive optical elements (kindly provided by M. Taghizadeh's group at Heriot-Watt University) into suitable pump patterns, 1 x 3 and 2 x 2 array operation of the microchip was also demonstrated (Fig 2). Each individual beam in these cases was Gaussian (M^2 <1.2) and had power per beam ~100mW. This shows that in principle, with suitably optimised microchip structures, large arrays of arbitrary fixed-pattern output could be obtained.

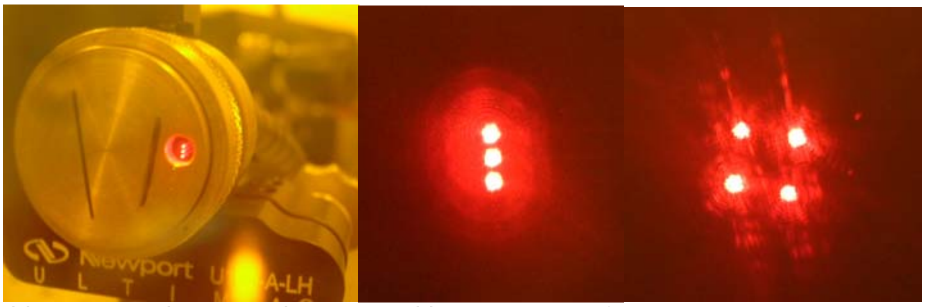

Fig.2 Microchip VECSEL in mount; in 1 x 3 and in 2 x 2 output format.

A further refinement of this idea was to use a spatial light modulator in the pump beam to demonstrate pattern-programmable operation. This was also successful and is described in full in the paper, where one red laser spot was shown to 'orbit' around a fixed central red laser spot. We believe these demonstrations to be interesting and a proof-of-principle of more sophisticated array and pattern-programmed operation that should be possible in future. An important point here is that the individual pump beams sample defined local areas of gain and, in contrast to doped dielectric gain media, the properties of these local gain regions can be controlled. Techniques such as quantum well intermixing,[14] for example, would ensure that different spots had different wavelengths. This becomes even more interesting in the dynamic case, where the pump beams are moving over the laser gain area at variable speeds, sampling the local gain as they move.

Note that the microchip VECSEL approach originally suggested in the proposal required micro-lenses to be etched into the diamond. In the event, we found that plane-plane cavities sufficed with thermal lensing contributing to cavity stability. We devoted some project time to further advancing the diamond microlens technology,[15] however, to facilitate a future variant of the micro-chip VECSELs.

In the final and most recent part of the red VECSEL work, we have made initial demonstrations of intracavity frequency doubling. The significance of this work is that it is the first extension of VECSEL operation into the ultraviolet, showing a combination of performance characteristics unusual for UV lasers, namely high-power CW operation with wavelength tunability in a high-quality beam. Up to 120mW around 338nm was obtained (Fig.3) in this first demonstration using plane- and Brewster-cut

$3 \times 3 \times 7$ mm^3 BBO crystals, giving an overall pump-to-UV conversion efficiency of ~2%. A report on this work has been submitted to Applied Physics Letters.[16]

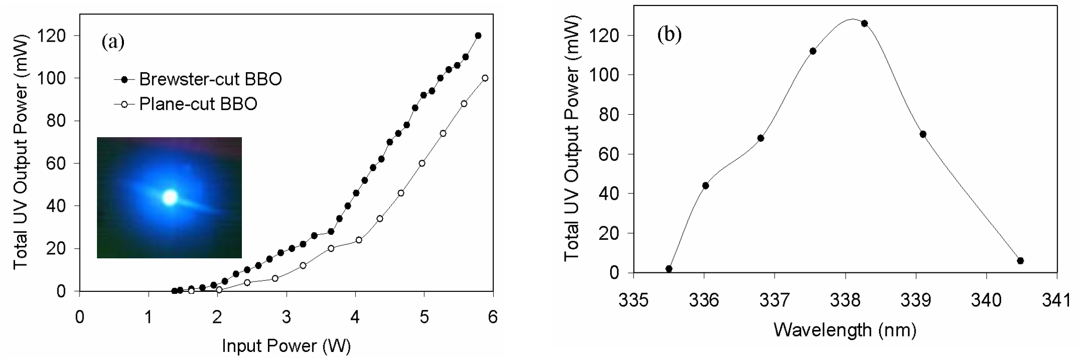

Fig.3 Intra-cavity SHG of red VECSEL, showing (a) power transfer and (b) tuning range.

(b) Violet VECSELs

The challenges in producing violet VECSELs have much in common with those of producing a viable gallium nitride VCSEL technology. The latter has yet to emerge, despite more than 8 years of effort by the international research community. Major issues shared by both include the lack of a suitable, structurally-compatible semiconductor lower DBR mirror technology (only limited success has been achieved to date with AlGaN/GaN and AlInN/GaN approaches) and difficulties in achieving resonant periodic gain and appropriate pump-field and cavity-field distributions in a cavity having minimised optical and non-radiative carrier losses. The approaches to GaN VCSELs and microcavities which we have pursued for several years have in common the use of a lower dielectric DBR, and have concentrated on means to incorporate this DBR into a monolithic GaN structure in a manner which promotes or retains low optical and carrier loss. In earlier work, we concentrated on various forms of epitaxial lateral overgrowth as a means of 'burying' a dielectric mirror element within an epitaxial GaN film. In the current programme we have pursued two additional approaches, namely (i) use of AlInN layers for wet-chemical lift-off of homoepitaxial GaN thin-film structures grown on GaN substrates and (ii) the use of GaN-on-Si templates to allow wet-chemical etching of a rear "via hole" for dielectric mirror deposition. In both cases, the idea has been to define the cavity thin-film structure by a wet chemical process and to capillary bond the epitaxial surface of such structures to diamond (to function as intracavity heatspreaders in the manner of our longer-wavelength VECSELs). It should be noted here that the advantageous properties of diamond further appertain to gallium nitride devices – diamond has a close refractive index match to GaN (~2.5) at violet wavelengths, and retains its high optical transparency in this wavelength range, whilst also, of course, having the very high thermal conductivity essential for heat-spreading. In the programme, we have successfully demonstrated diamond capillary bonding to GaN-on-sapphire films, a major development which has broader implications than just for VECSELs. However, as described below, we have not yet succeeded in doing this in the GaN substrate or GaN-Si cases.

This work package was the focus of much concentrated effort during the 2 year programme. In case (i) we have been one of the main groups to exploit the realisation that AlInN can be lattice-matched to GaN whilst retaining structural integrity of a multi-layer epi-structure above. In addition, it possesses a refractive index contrast of ~7% to GaN, allowing optical in-situ monitoring during MOCVD growth of GaN microcavities, itself a major advance, together with a chemical etch selectivity suitable for the further step of lift-off separation of the epitaxial film. Full results of this work have been reported in [17], where we also demonstrated an RPG gain structure in the multi-quantum well active region. Unfortunately, the challenges of etching and lifting-off a membrane of suitable area (> 200µm x 200µm^2) for optical pumping, and the methodology of bonding such membranes to diamond, were not possible to address during the programme (these are the subject of ongoing work). The achievements to date have been encouraging, however, and are also influencing our work on GaN microcavities for selective light-matter coupling.

In case (ii), we were quick to realise the potential of GaN-on-Si templates, which became commercially available in the early stages of the project, and changed our plans to incorporate this approach. We used a significant amount of our consumables budget (~£12k) to purchase these templates. The essential idea here was that, because Si can be readily wet-etched, it should be possible to grow a thin-film InGaN gain structure on the template, then form a rear via by etching through an aperture mask into the silicon, removing the silicon to form a suspended InGaN membrane above. This membrane could then be back dielectric mirror coated and bonded to diamond. In repeated efforts over a period of almost 1 year, we succeeded[18] in all of these steps bar the last, producing beautiful GaN via membranes of diameter up to 2mm. Unfortunately, these films were strained, and were found to shatter on the further step of capillary bonding to diamond. Full results of this work have also been published recently.[18] We did try to optically pump the stand-alone membrane/dielectric back-mirror structures (without the diamond) using the UV argon ion laser. This produced copious amounts of blue photoluminescence at pump powers up to 1 Watt, clear optical feedback in an external cavity, but sadly no lasing. In each case, the pump beam eventually punched a hole in the membrane.

In summary, the problem of InGaN VCSELs/VECSELs remains a very tough one, and must continue to be the subject of intensive international effort for success to be assured. Our approach (i) shows real promise. Approach (ii), where we were initially quite confident of success, has proven very difficult to embody in practice. We have in any case obtained major pointers for the future from this work.

4. Research Impact and Benefits to Society: Further Research

The initial reluctance of the semiconductor laser community in the late 1990's to embrace VECSELs as a viable semiconductor laser technology has now largely been overcome. This is a credit to these devices' unique combination of wavelength versatility and tuning, power scaling in high-quality beams and flexibility of operating regimes. Impact to society has already been achieved through adoption of these devices in spectroscopy and instrumentation research and in increasing commercial 'replacement' for inefficient and cumbersome visible-wavelength gas laser technology. The direct demonstration of visible VECSELs should continue this trend. As noted, the wavelengths covered are of direct relevance to the atomic spectroscopy, atom optics and BEC research communities and tie in with the long-term societal benefits anticipated for this work. In addition, areas such as photodynamic therapy and biomedicine should benefit. The opening up of the ultraviolet to VECSEL technology greatly expands the number of these potential applications.

We are continuing this work under an EPSRC first grant awarded to Jennifer Hastie (EP/0061032/1), mentored by MDD, and it links closely into an EU FP6 STREP project "NATAL" on integrated forms of visible VECSEL with novel modes of spectral control. The gallium nitride work continues under an EU STREP project "STIMSCAT", where the focus is on the further development for InGaN microcavity technology of the advances we have made.

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