My trip to the 10th International Conference on Nitride Semiconductors

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I was lucky enough to be able to attend the 10th International Conference on Nitride Semiconductors (ICNS) held on 25-30th August 2013 in Washington DC. This conference is held every other year, and is the biggest international conference in the nitrides field on the years it is held, alternating with the International Workshop on Nitrides (IWN). It was attended by about 800 delegates, including many influential names in the wider nitrides picture, along with names I am familiar with from the literature within my own research topic.

The dual motivation for my attendance at ICNS-10 was to give an oral presentation of my work on the use of nanorod photonic crystals in GaN/InGaN LEDs for controlling light extraction, and to benefit from the accelerated learning that major conferences enable. Before detailing the huge value I received to my own work from the experience of this conference in particular, I will summarise some of the presentations and sessions which were most interesting to me.

There were 5 plenary sessions, 18 invited talks, ~250 contributed talks and ~500 poster presentations, so I chose to plan my tour around the conference in advance using the online program and abstracts in order to get the most out of the trip. The conference was organised into four separate categories, often running in parallel sessions during the day. These categories were:

- Bulk and film growth
- Optical devices, visible
- Optical devices, UV
- Electrical devices

As my work is in light extraction, both the visible and UV categories immediately stood out as relevant, but upon further investigation there were a good number of presentations in the growth category which were relevant to creating photonic crystal structures – something I am likely to need to do in the near future. I discovered almost everything I particularly wanted to see was in the first two days of the conference – I was in for a busy couple of days!

The first talk I attended was the plenary talk given by M. Krames from Soraa Inc. about the lighting technology they have developed using freestanding GaN substrates. He began by giving an overview of the history and current challenges in meeting white lighting needs, along with justifying why solid state lighting could be the future solution to these needs.

The technology relies on freestanding GaN substrates being available at practical costs, which is something that has been made possible through the development of rapid growth techniques such as HVPE. Krames says that the mass production requirements for high quality GaN films to make violet (405nm) lasers at high yield for the recently emerging Blu-ray market has led to a substantial reduction in the cost and enabled this technology to be practical for commercial GaN LED production. Soraa use a lower carrier density at their specified device operating currents to reduce the effects of efficiency droop seen at higher carrier density. This is achieved by increasing the width of the active region, allowing the devices to be smaller for the same performance seen in other commercial devices.

The LEDs they make are triangular in shape to increase the light extraction through reduction of total internal reflection using chip-shaping, which Krames himself published early practical results on in GaP LEDs. The LED chips are spread out over a host substrate to reduce absorption by neighbouring chips.

The other primary focus of the talk was on the colour-rendering properties they were able to achieve and bring to market in a product. As the devices suffer less droop for the same performance, violet LEDs can be used as a source for down-conversion, leading to a wider and smoother spectrum to illuminate with. This gives a very high colour rendering index.

I found this talk interesting because it showed the way that a commercial product addresses the problems and shortcomings in GaN LEDs which are the subject of much research and debate in a more academic context.

The next plenary talk was given by M. Micovic from HRL laboratories about GaN transistors for efficient operation at microwave and higher frequencies. GaN has many material properties that make it suitable for this application and it is being researched extensively as evidenced by the large number of talks addressing transistors at the conference.

Micovic began by giving an overview of the figures of merit for high frequency performance and some of the physical factors which directly affect these. The parasitic resistances and capacitances must be as low as possible to minimise the time constant which ultimately limits the maximum operating frequency. The capacitance can be reduced by using a T-shaped gate structure which increases the separation of the bulk of the gate from the conducting channel, a technique widely adopted in other material systems. In first generation GaN transistors in the early 1990s, the primary limitation was the parasitic series resistance due to poor contacts. This problem was improved by using higher doping levels which were achieved using plasma assisted MBE growth techniques, additionally giving much smoother surface morphology of the contacts. Further improvements were found by reducing surface leakage currents through regrowth of the device structures rather than etching and surface passivation.

The problem I found most interesting was the limitation reported by Micovic once many of the parasitic resistances and capacitances were reduced sufficiently to give good operation over ~100GHz. He reported that the system becomes limited by the electron velocity – specifically the time it takes for the electrons to travel between the source and drain, producing an interesting analogue to the photon transit time which creates frequency performance limitations in photodiodes. The obvious solution of reducing the source-drain spacing from 1μm used previously was pointed out by Micovic. He estimated that 100nm or smaller would be required for good operation over 500GHz and outlined the many challenges in producing a device geometry of this size as well as presenting results his team had achieved towards 500GHz performance.

The topic of transistors is not directly relevant to my research work, but I did study communications technology as part of my undergraduate degree. As a result, it was interesting to see where the limitations in producing high frequency devices are in practice and how these are being addressed through novel design and ideas in current research.

During the mid UV lasers and photodetectors session, several talks detailing results on UVC lasing were presented. Achieving lasing at wavelengths less than 300nm is particularly challenging for a number of reasons. All the presentations used the $Al_xGa_{1-x}N$ system, which seems to be considered the best way to approach the problem. The growth of high-quality AlN films is challenging and not as well investigated as in GaN. The presentations titled *"Lasing and Cavity Modes in Photo-Pumped Deep UV AlGaN Heterostructures"* given by R. Collazo and *"UV-C AlGaN Quantum Well Lasers Grown on Sapphire and Bulk AlN Substrates"* given by M. Martens both compared results using bulk AlN and sapphire substrates, producing AlN films with very different defect densities. Both groups did not observe the characteristics of lasing on the sapphire substrate, but did with the bulk AlN substrate under photoluminescence. Martens did observe a lasing threshold on another sample; low defect density AlN grown by ELOG which they claim to be the shortest wavelength (272nm) lasing reported on a sapphire substrate. These presentations seemed to demonstrate that the lasing threshold is highly dependent upon the defect density of the materials; presumably due to the increased optical absorption (and so lower gain) with more defects.

Electroluminescent lasing at UVC wavelengths has not yet been demonstrated and was commented as a "next-step" by several of the presenters in the session. This is even more challenging than photoluminescent lasing as it is also sensitive to the material quality and doping outside the gain region – p-type doping of AlN is difficult and typically degrades the material quality. Coupled with the poor conductivity of AlN at low doping levels and poor material quality, this makes achieving population inversion under electrical injection very challenging.

The invited talk entitled *"High-Performance Nanowire III-N LEDs"* given by N. Gardner from Glo USA Inc. presented performance figures for core-shell nanowires grown using a "bottom-up" approach with good lateral uniformity. The nanowires are grown using MOCVD through holes in a nano-imprinted mask, with active and then p-type layer shells grown laterally once the wires are formed. An electrical contact has been made by filling the gaps between the wires and using lateral contacting techniques. Some impressive optical images taken using a solid immersion lens were presented, allowing imaging of individual nanowires (with diameters of <800nm) and showing good uniformity of emission wavelengths wire-to-wire. The performance devices were tested under various environmental parameters and found to behave with good stability, which I have not seen considered before in other reports on nanorods/wires and is promising for commercial viability.

The rest of the Nano LEDs and Lasers session was very interesting as it is particularly relevant to my research. Different groups took different approaches towards characterising and creating these structures. J. Ledig presented *"Electro-Optical Characterisation of Single InGaN/GaN Core-Shell LED Structures"* which investigated the properties of individual core shell LEDs using nano-probes inside a SEM setup, showing poor current spreading in thin p-type layers around the outside of core shell nanorods. The presentation *"Fabrication and Characterisation of Axial and Radial III-Nitride Nanowire LEDs"* by G. Wang investigated nanorods formed using a 2-step "top-down" process where the nanowires are ICP-etched from a planar template and then wet-etched to remove damage and control the diameter of the wires. Axial core-shell structures are regrown after this surface preparation. *"Regularly Patterned Core-Shell InGaN/GaN Quantum-Well Nanorod Light-Emitting Diode Arrays"* given by C. Liao presented results on "bottom-up" nanorods using MBE-grown GaZnO coalesced between the rods to act as a transparent contact to all the rods, whereas Wang's results used coalesced growth of p-GaN to connect the rods. This allowed both groups to perform electrical characterisation using conventional planar techniques. Liao concludes that there is an insignificant quantum confined Stark effect as no spectral shift is seen with increased current. All three presentations reported difficulties getting a good contact and current spreading in/to the p-type layer, which is a significant challenge to this technology.

H. Kong from Cree Inc presented an invited talk on the *"Status of GaN/SiC-based LEDs and their Application in Solid State Lighting"*, using SiC substrates for their LEDs. Details of SiC technology are not often reported as Cree have concentrated on commercialising and protecting this technology. Kong outlined the advantages of SiC as a substrate – it is transparent, it has good thermal conductivity and a reasonable lattice match to GaN. Cree produce everything in-house from the SiC substrates to the luminaire hardware which allows their production to be highly competitive. Kong said Cree have achieved 88% light extraction on 1mm^2 devices using a thin film flip-chip configuration and a combination of a shaped chip and surface roughening.

The talk entitled *"Violet Vertical-Cavity Surface-Emitting Laser Structures Based on an AlInN/GaN Distributed Bragg Reflector"* given by C. Berger stood out as displaying thorough investigation into device engineering design. Their structure design consisted of a lattice-matched AlInN/GaN DBR below an active gain region consisting of many quantum wells, followed by a dielectric Ta_2O_3/SiO_2 DBR above. They systematically went through each layer to determine its optimal design and function before combining them together in the final device. Berger began with the AlInN/GaN DBR which consisted of 50 pairs, characterising the composition and the optical behaviour using XRD and reflectivity studies respectively. In a laser it is desirable to have as large an active region as possible to increase the optical gain as the photon/exciton coupling scales with the square of the number of quantum wells. However, as more quantum wells are grown on a non-lattice matched template, their strain gradually changes with distance from the template. This shifts their band gap, in turn changing their gain at the intended lasing wavelength. This effect was studied in the report using PL and spatially resolved CL studies, looking at the shift in the wavelength of emission over many quantum wells grown on the DBR structure. Berger determined that 13 quantum wells was the optimal number where they remain fully strained without significant PL wavelength shift. Finally the top DBR was optimised, requiring only 10 pairs due to the higher refractive index contrast between the two dielectrics. Berger reported that the final design produced a device that appeared to lase under high enough PL excitation with a linewidth of 0.09nm and a very low spontaneous emission coefficient of 7×10^{-3}.

The invited talk on *"III-Nitride Photonic Cavities"* given by N. Grandjean gave a fantastic overview of photonic crystal technology in the III-N material system, with many references given for me to look at later. I learnt many useful things, such as that III-Ns typically have a very low temperature dependence of their refractive index and that III-N suspended photonic crystal slabs have been fabricated using undercut selective etching of silicon templates. Grandjean also described quantitatively the difficulties with DBRs in the material system – to get a higher refractive index contrast, the difficulties with growing non-lattice matched materials on top of each other at high qualities must be faced, whereas the maximum contrast possible when lattice matched is ~10% using AlInN/AlGaN. As all good review papers, it left me with many questions nagging me to investigate in the numerous references provided.

The poster sessions on Monday, Tuesday and Wednesday were a good opportunity to discuss the days' presentations with friends old and new, as well as locate people from specific research groups to discuss their work in a less formal context.

The poster *"Comparison of Light Extraction Efficiency between the Vertical Light-Emitting Diodes with Surfaces of Periodic and Rough Structures"* given by C. Lin presented a novel fabrication technique for producing periodic patterning more cheaply than many conventional techniques. A photo-electrochemical assisted etch process was used, with an inferometer in the illumination path to produce the periodic patterning. This created a linear grating which was found to out-perform the light extraction from similar surface roughened vertical LEDs.

"Atom Probe Tomography Analysis of a Gallium-Nitride-Based Commercial Light-Emitting Diode" given by Y. Prosa presented a reverse-engineering study of an OSRAM LED. The atomic probe tomography (APT) technique was used, which allows a 3D reconstruction of the atoms in a sample to be created. It is an particularly exciting technique which was used to produce a few results at the conference as its 3D abilities allow advanced analysis of the arrangement of atoms in a sample, potentially in the future identify the physics behind observed behaviours at device-scale. The poster specifically presents the results as an example of APT use for competitive analysis of existing products, along with identification of failure modes on the atomic scale. Additionally, some stunning visualisations of the device they tested were presented, along with comments on the epitaxial structure and doping densities in the OSRAM LED.

The poster which particularly stood out to me was *"Monolithic III-Nitride Multi-Color Laser Arrays"* by J. Wright from Sandia National Laboratories. This was closely linked to the earlier talk by G. Wang and used the same two-step "top down" fabrication process which allows the group precise geometric control over nanowire structures. Using electron-beam lithography they were able to create photonic crystal lasers at different wavelengths by changing the planar geometry of the nanowires, lasing from photonic crystal modes. Without giving too much away here, this was very interesting as it is highly relevant to my future work on manipulating these photonic crystal modes for highly directional LEDs. The opportunity to discuss their work in context with mine allowed me to gain several starting points, hopefully saving me some time for the challenges ahead as well as some more insight into the physics behind the vertical confinement seen in their structures.

The talk I gave was entitled *"Photonic Crystal Effects in Regular Arrays of Core Shell and Quantum Disc InGaN/GaN Nanorods"* and presented experimental evidence that Bloch modes can be set up in these structure in some conditions, apparently depending upon the device geometry. We were able to present experimental results with striking similarity to an earlier theoretical study by A. David, whose PhD thesis I have spent many hours poring over. The primary unrepeatable and invaluable experience that being able to attend this conference gave me is meeting with David after my talk and discussing the similarities between our investigations, the physics which may or may not drive the behaviour and many other elements of our work into photonic crystals. Amongst many others, this contact furthering my personal corner of the UK's research would not have been possible without the financial support from the UKNC bursary.