12th International Conference on Nitride Semiconductors

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Introduction

The twelfth International Conference of Nitride Semiconductors (ICNS) was held this year in Strasbourg, France, from the 24th to the 28th July. The biennial conference is one of the largest events in the field of nitride semiconductors, together with the alternating biennial International Workshop on Nitrides (IWN).
About 800 oral and poster presentations took place. Over 1000 participants listened to plenary talks given on Monday and Friday, while the days in between were dedicated to more detailed talks in seven different clusters. These were "Materials", "Optical devices", "Electronic devices", "Other devices", "Theory-basics", "Nano" and "Late news".
Below I briefly outline presentations which caught my attention in particular.

Selected Presentations

C. G. Van de Walle **Wide-band-gap semiconductors: present and future** (Plenary oral presentation)

The emission of the nitride family spans the IR (InN) to the UV range (AlN) and its large lattice mismatch result in noticeable piezoelectric polarisation. Furthermore, the extended family members of ScN and BN with both direct and indirect bandgap configurations enrich the picture with possible advantages in the very deep UV emission together with single photon emission (BN) and larger piezoelectric fields (ScN). Then, de Walle focused on three often neglected points. Firstly, the strength of the spontaneous polarisation of a material is always referenced to a second material, which is for Wurtzite GaN commonly the Zinc blende configuration. However, this leads to spurious rest terms and therefore inaccurate spontaneous polarisation in simulations. A proposed 2D hexagonal GaN comparison structure overcomes this problem and gives a value that is one magnitude larger. Next, the importance of Auger processes was underlined. Although energy and momentum conservation imply negligibly low direct Auger rates for wide bandgap materials, indirect processes using a phonon show higher rates. For example, these seem to be mainly responsible for the efficiency droop at high injection currents in nitride LEDs. The strength of direct Auger processes decreases exponentially with increasing bandgap, whereas the indirect one is constant. This leaves no room for engineering the Auger rate by changing the electronic structure. The last part of the talk focused on defect assisted recombination (Shockley-Read-Hall), being a nuisance for LEDs and lasers in particular. This non-radiative recombination is most effective with defects centred in the bandgap. For example, Ga vacancies lie mid-bandgap, requiring a high building energy, lowered for complexes. However, also excited states of defects may be important, as theoretical studies of Fe defects showed.

R. Kirste **A path towards electrically injected AlGaN-based deep UV laser diodes** (Plenary oral presentation)

Deep UV-based lasers will be useful in high density optical data storage, detection of chemicals and bioagents and for sterilisation. However, the problem is the low external

quantum efficiency of high Al-content GaN. This motivated a detailed growth analysis of AlGaN. An AlN substrate was used instead of the cheaper sapphire one to reduce the dislocation density during MOVPE growth. Different growth parameters led to a different surface morphology: 3D or step flow growth. Kirste identified the surface supersaturation and the miscut angle of the substrate as the critical parameters determining the morphology, simplifying the parameter space. Based on this insight the Ga content in AlGaN was studied as a function of the miscut angle, and was found to increase with increasing angle. This was explained with the higher volatility of Ga compared to Al. Then, Kirste explained the problem of doping AlGaN: with increased dopant concentration the carrier density drops above a critical concentration due to self-compensation. Donor electrons can form energetically favoured defects at lower energy, due to the large bandgap. The proposed solution controlled the chemical potential, more precisely the quasi Fermi level of defects. This was achieved by light illumination with a photon energy larger than the bandgap. In practice, the technique resulted in very low defect densities without altering the growth conditions. It was shown to work for both n- and p-doing.

A. di Carlo **The Role of Random Alloy Fluctuations in the InGaN/GaN LED** (Invited oral presentation)

This study tried to uncover the influence of random alloy fluctuations in InGaN LEDs on the efficiency droop at high injection currents. For the active QW layer, an atomistic tight-binding model was used together with a Monte Carlo simulation of the distribution of the In atoms. The actual device was added into the model in 1D as a continuum. The simulation showed confinement of both holes and electrons due to random In scattering and band discontinuities at material interfaces. The calculated internal quantum efficiency dropped for longer emission wavelengths. This droop was determined to be mostly due to the quantum confined Stark effect (QCSE), but 20% were due to random In distribution. Then, the possibility of non-uniform fluctuation, that is clustering, was included into the simulation. Indeed, this produced a broader spectrum fitting better the experimental results and also explained the temperature dependence of the radiative recombination efficiency.

M. Dawson **GaN micro-LED arrays for multi-Gb/s visible light communications** (Invited oral presentation)

LEDs revolutionised the lighting market, with benefits in energy efficiency, colour rendering and health aspects. Now, it develops into the direction of lighting as a service, where modulated light offers high speed wireless communication, in addition to WiFi, and indoor navigation. So far white LEDs offer only limited bandwidths of a few tens of MHz. Nitride micro LEDs, like the ones shown in this talk, can outperform those with a 10x to 1000x higher bandwidth. Due to the small LED size even subnanosecond pulses could be achieved. Communication protocols can be as simple as on-off. However, for Gb/s data transmission rates different modulation schemes must be used. Dawson reports for example on orthogonal frequency division multiplexing that allowed a rate of 3Gb/s with a bandwidth of 100MHz. Here, AC signals were used for communication and a DC offset maintained the lighting function. A different approach benefited from the compact layout of the small LEDs, such that their emission merged in the far field. Turning on individual LEDs increased the brightness, which could be used for multilevel communication protocols. The receiving side could also distinguish the single LEDs with suitable imaging, and could be trained to decode the transmitted message. An impressive film footage was the transmission of an HD film over a few meters in the lab. Blocking the beam resulted in stopping the film. A second

demonstration featured structured illumination for smart lighting, which enabled continuous recognition and position measurement of an object within the illuminated area. Smart patterns (Hadamard) needed to be used to ensure the lighting function.

K. Chung **LED based microdisplays with integrated collimating lenses** (Oral presentation)

LED microdisplays offer high intensity and contrast, which could be used in various kinds of reality augmentation. Up to date, the challenge lies in the production of different colours. Here, this was addressed by the use of the QCSE in strain engineered nanopillars. Conventionally grown samples showed emission in a range of 400-650nm. A model was developed to predict the LED emission energy based on the pillar diameter. It uses a 1D array of mechanical springs, of which the total elastic energy is minimised. Surprisingly, this simple, non-quantum model is able to accurately fit the experimental data. Furthermore, the only free fit parameter is proportional to the In content. The smaller the diameter, the larger is the strain relaxation, which leads to a lower QCSE and therefore a lower emission energy. For adjustment of individual colour brightness, pulse width modulation was used to circumvent changes in the emission energy for different driving voltages. Mixing the different colours covered a relatively wide colour range. Finally, a proof-of-principle of integrated condenser lenses for a collimated output was shown. Lenses were fabricated based on SiN, which is close to index-matched to GaN. An e-beam resist on top of the SiN was shaped via reflow. This shape was then transferred on the SiN via reactive ion etching. Results showed a high directionality of the emission. The future challenge is the dependence of the focal length on the colour.

K. Matsumoto **Reduction of Dislocations in GaN on Silicon Substrate Using In-situ Etching** (Oral presentation)

The growth of GaN on Si is advantageous due to big wafer size, low cost and easy integration into existing Si technology. However, the lattice mismatch and the mismatch of the thermal expansion coefficients result in a high density of dislocations. This impacts negatively on LED performance as they act as non-radiative recombination sites. Therefore, techniques for the reduction of the dislocation density are in demand. Epitaxial lateral overgrowth with SiN stripes gave no overall improvement, as dislocations propagated through the window regions. Here, an additional etching process was used. A layer sequence of Si/AlN/GaN was used with SiN in stripes on top. Then followed etching down to the AlN layer and growth of a second layer SiN. Subsequent regrowth of GaN yielded a low dislocation density, but a rough surface when grown under a 100% H_2 atmosphere. Addition of 1% NH_3 improved the surface morphology. The reduction of dislocation density was explained by the blocking action of the second SiN layer, inhibiting dislocation propagation. This method would be fully integrable in normal growth procedures within a growth reactor.

D. Wang **Low-Threshold lasing in InGaN/GaN Quantum Dot Micro-Ring Cavities** (Oral presentation)

For lasing, micro-disk cavities are advantageous due to high quality factors, low mode volumes and few modes. During the turn-on process, the dominating mode was seen to hop from a low energy mode to a high one. This was explained with mode competition, which increased the lasing threshold. Since the modes of micro-disks are only situated at their edge, one would expect that the mode competition could be reduced by removing the centre part of the micro-disk. This was studied with different inner removal diameters. The so-fabricated micro-ring cavities showed a lower lasing threshold, but also a lower slope efficiency with

increasing inner diameter. The slope efficiency is linked to the cavity photon loss. Surprisingly, the quality factor remained almost the same compared to a micro-disk cavity. Also, the threshold should increase with an increased cavity photon loss. However, simulations showed that the loss arises from higher order modes, which extend more into the centre part of the cavities. This explained the lower slope efficiency. At the same time, the first order mode did not change in the simulation as it located close to the edge, away from the centre. Therefore, the quality factor of the micro-ring cavity was almost the same as the one of a micro-disk cavity.

J. Hite **Developments in Periodically Oriented GaN** (Poster presentation)

Periodically oriented GaN is interesting for quasi phase matching for frequency mixing, as it has a larger transparency window (0.36-7µm) and higher thermal conductivity compared to the most commonly used materials $LiNbO_3$ and GaAs. To this end, MOCVD grown n-polar GaN on a sapphire substrate was used. SiN was patterned into stripes with conventional photolithography. A thin layer of AlN stripes led to inversion. Subsequent GaN growth resulted in p-polar GaN on top of the AlN stripes and n-polar GaN on the AlN-free regions. This alteration of p- and n-polar GaN changes the χ^2-component perpendicular to the stripes and could therefore be used for quasi phase matching. Second harmonic generation in the infrared was demonstrated with 4% conversion efficiency. This could possibly be enhanced with a higher quality substrate. In principle, fanned-out structures are possible instead of parallel stripes, enabling continuously tuneable phase matching of broadband pulses.

K. Gao **Nanosecond spectral diffusion in a single photon emitting GaN quantum dot** (Poster presentation)

Interface GaN quantum dots were fabricated in AlGaN. The high crystal quality resulted in low dislocation densities, having a positive influence on the QD linewidth. Commonly, the QCSE changes the QD emission energy due to trapping and untrapping of carriers in neighbouring defects (spectral diffusion). Since the timescale is shorter than the spectrum integration time, the measured QD linewidth appears to be much broader than the Fourier limit. Typical values are ~1meV. However, here ~100ueV were reported. The time scale of spectral diffusion was measured with an autocorrelation measurement of only a spectral part of the QD emission. Jittering of the emission in and out of the measurement window resulted in bunching at short delay times seen in the autocorrelation. The extracted decay time of bunching of 22ns may allow for generation of indistinguishable photons within a few nanoseconds.

Concluding remarks

I am grateful to the UKNC for providing me with the opportunity to attend this conference, being my first international one. I was amazed about the breadth of topics ranging from *deep UV laser pumped by electron beams* over *high volume communication via modulated LEDs* to *InGaN LEDs in horticulture*. Both poster and oral presentations including afterwards discussions proved to be fruitful for further understanding and developing future experiments.

Next year, the 10th IWN will be held in Kanazawa, Japan. The 13th ICNS will happen in 2019 in Seattle, USA.