Conference Report

14^{th} International Conference on Nitride Semiconductors (ICNS)

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The 14^{th} International Conference on Nitride Semiconductors (ICNS) was held from November 12^{th} to 17^{th} in Fukuoka, Japan this year, and this is the first Nitrides-related international conference I've ever attended. This conference covered all aspects of Nitrides in different categories. Various topics include materials growth, characterizations, physical simulation, device fabrications, UV optical devices, RF, HEMT, power electronics, micro-LEDs, lasers, InGaN optical, quantum electronics, bio-compatible devices and so on. Among the various contributed talks, I gave a talk about "Morphological, structural and strain relaxation properties of InGaN-based pseudo-substrates for long wavelength micro-LEDs" and received the "*Best Student Award*" based on the abstract and presentation performance, and I am truly grateful for this honour. Overall, this was a conference that opened my mind, broadened my views and gave me the opportunity to meet and discuss with various researchers internationally. Here, I would like to use this opportunity to report my thoughts and things I've learned from the talks that I am particularly interested in.

November 13^{th}:

(Plenary talks)

Tribute to our predecessor, the late Professor Isamu Akasaki, and the role of nitrides in establishing an earth-friendly, comfortable, convenient and people-friendly society, *Hiroshi AMANO*

The conference was started with the plenary talk that tribute to the GaN predecessor-Professor Isamu Akasaki who passed away from pneumonia on April 1, 2021, at the age of 92. Previously, the only thing I know about him is that he was a Nobel Laureate in Physics. From the talk, I started to know more about him that he has developed the metalorganic vapour-phase epitaxy in growing GaN in 1981 when there was nearly no one continuing the GaN research because they thought it was very difficult to grow single crystal and the p-type GaN growth is nearly impossible. Professor Isamu Akasaki described that time as like “Going alone in the wilderness”. However, what impressed me most and eventually led to his success was his *persistence.* He walked his way without much support and gave up. His endless effort eventually led to the first demonstration of high-quality GaN crystals, p-type GaN and p-n junction GaN LEDs. The “wilderness” that Professor Isamu Akasaki pioneered is now a prosperous and fruitful field where many researchers all over the world gather and bring happiness to the world. This story of Professor Isamu Akasaki truly inspired me to work harder in my daily research and don’t easily give up until we give our best. Always trust the process- “where there is a will, there is a way”.

Controlling electronic polarization in polar and ferroelectric nitride semiconductor heterostructures for electronic and photonic devices, *Debdeep Jena*

Following is the second plenary talk given by Professor D. Jena from the Cornell University. In that talk, he mainly discussed the changes in the understanding of the fundamentals of semiconductor heterostructure physics and device design brought by the polarization field present in the nitrides’ semiconductors.

Besides the 2D electron gas that is introduced by the polarization field discontinuity at sharp heterojunctions of GaN and Al(Ga)N, 2D hole gas can also be formed when implemented correctly such as adopting AlN/GaN/AlN QW on Al-polar AlN, where 2DHG and 2DEG can present simultaneously at the interfaces. The combination of polarization-enabled nFETs and pFETs allows for a new all-nitride high-temperature digital logic platform.

More than that, it was the first time I knew that wz-nitrides can possess ferroelectricity by alloying transition metals into it (my background is mainly focused on long wavelength micro-LEDs). Now, with this property, nitride ferroelectrics hold the possibility of an all-nitride electronic logic + memory system that holds the promise of high-temperature operation.

(Invited and contributed talks)

GaN Power Electronics: Game on!, *Umesh K. Mishra*

The first invited talk given on that day was from University of California, Santa Barbara by Professor Umesh K. Mishra. This talk is very interesting and fresh to me (again, I am not specialize in the GaN electronics), but would be very exciting for the whole GaN community as in that talk, Professor Mishra has busted four **MYTHS** regarding lateral GaN power electronics, which are:

1. GaN is best suited for low power operation and SiC outperforms it for high power

operation (Wrong)

2. Lateral GaN devices do not have the ability of surviving short circuit events (Wrong)
3. Lateral GaN devices cannot provide 1200V blocking capability (Wrong)
4. Cascode normally-off devices are inferior to Emode devices (Wrong)

For each one of them, Professor Mishra has presented data to support his claims. The dominant advantages of GaN-based power electronics lie in the fact that the existence of 2D electron gas (~1E13cm^{-2}) with high mobility (~2000$cm^2V^{-1}s^{-1}$) gives a low sheet resistance of 300ohms/sq in normally-on channels. Lateral GaN devices with short-circuit survivability of >3 ms can easily beat SiC. GaN on sapphire enables it to achieve 1200V switch. On the other hand, SiC has a larger charge accumulation than GaN, and therefore it will have a higher loss in the high-voltage operating end. Lastly, he discussed that Cascode devices are actually better than Emode devices due to the larger operating window for the on-state (8-20V). Finally, he concludes that ***"If it can be done by Silicon, it will be done by Silicon. Of the rest, if it can be done by GaN, it will be done by GaN."***

Effect of underlying layer on red GaInN-based multi-quantum shells on hexagonal nanopyramid structures, *Ayaka Shima*

Compared with their c-plane counterpart, semipolar GaN is expected to provide high emission efficiency due to reduced polarization field and threading dislocations. However, low In incorporation on such plane limits its further application. In this study, the authors introduced a hexagonal nanopyramid structure dominated by (1-101) planes and an n-InGaN underlayer between the n-GaN nanowires (NWs) and multiple-quantum shell (MQS). The have grown two type of samples with and without the n-InGaN nanopyramid as the underlayer. The scanning electron microscopy (SEM) observations showed n-InGaN nanopyramids had nan almost perfect hexagonal pyramid shape with almost no (0001) planes observed, while n-GaN nanopyramids had residue (0001) planes at the top of the NW. The cathodoluminescene (CL) results showed that at the top of (1-101) plane, the peak wavelength of the n-InGaN nanopyramid (620 nm) was about 80 nm longer than that of the n-GaN nanopyramid, despite the same MQS growth conditions. Furthermore, the CL peaks of the two samples on the top of (1-101) plane are almost the same, suggesting that the emission efficiency of MQS on n-InGaN nanopyramids is high enough in red emission region. The results in my opinion show a promising way in achieving high efficiency long wavelength emission micro-LEDs, however, the reason for the red shift of n-InGaN is remain unclear. For this, more characterizations can be done such as TEM and EDX.

Improvement of Optical Properties of InGaN-based Red Multiple Quantum Wells,

Xin Hou

Similar to the previous talk, in this study, the author adopted a low-indium (In) content pre-well layer to improve the crystal quality by relaxing the residual stress. In the meantime, they found a higher growth temperature and growth rate can improve the uniformity of the In content and the crystal quality of the red QWs, enhancing the photoluminescence (PL) emission intensity. In my opinion, for this work, there is no AFM, XRD or other microscopy data to support their PL data, and there are many variations between the two samples they used in their study. Therefore, the conclusion is not definitive.

Monolithic Full-color InGaN-based LED with Si-doped Interlayers, *Koji Okuno*

In this talk, the authors proposed a monolithic LED fabricated by forming a mesa in an epitaxial structure comprising active layers emitting red, green, and blue wavelengths, followed by re-growth the p-layer. The unique design in their structure is that they inserted n-$In_{0.01}Ga_{0.99}N$/u- $In_{0.01}Ga_{0.99}N$ interlayers in between the blue/green and green/red active regions, and these interlayers can serve as hole-blocking layers, impeding the diffusion of the holes beyond the n-InGaN interlayers towards the n-side. In this way, they were able to control the sole emission from red and green active regions. Furthermore, they found that the injection of carriers into each active layer can be regulated by adjusting the Si concentration within the interlayers separating the active layer. The extent of the hole barrier decreased with decreasing the Si concentration in the n-InGaN interlayer, resulting in light emission from multiple active layers.

Evaluation of radiative and non-radiative recombination lifetimes in c-plane InGaN quantum wells with different In composition, *Keito Mori-Tamamura*

The reason why I am interested in this talk is that they used photoacoustic (PA) measurement to measure the non-radiative recombination efficiency. Conventionally, the low radiative recombination efficiency in c-plane GaN could be due to two reasons: the increased separation between electron and hole wavefunction overlap caused by piezo-electric field or high defect density generated by the large lattice mismatch between InGaN/GaN. A common way for the non-radiative recombination is through defect-assisted recombination and the energy will be released in the form of heat (acoustic vibration). In this study, they used such PA measurement to measure the non-radiative recombination lifetime for five InGaN-QWs with different In compositions. The results show that the drop of the emission efficiency is due to the decrease of the radiative recombination probability. Though I admire the method they used to measure the non-radiative recombination efficiency, however, a Auger-Meitiner recombination efficiency is another type of non-radiative recombination which does not release the energy in the form of heat. Besides that, I would expect more characterizations such as XRD, EDX and TEM to support their conclusions.

November 14th:

(Invited and contributed talks)

Revisiting the determination of the carrier diffusion length in GaN from cathodoluminescence spectroscopy, *Jonas Lähnemann*

A crucial parameter for the design of any bipolar semiconductor device is the carrier diffusion length, and the most popular approach to determine this value is through the cathodoluminescence (CL) intensity profile across the threading dislocations. However, the author noticed that this intuitive approach could yield spurious results as the dark spot size from the threading dislocations does not increase with the temperature T, which is abnormal according to the diffusion model. Hence, the author tried a new method that considers the piezoelectric field to quantify the diffusion length.
In the talk, their presentation shows that the dark spot size is controlled by the spatial extent of the piezoelectric field, and to a lesser degree by the lateral width of CL generation volume. They have determined the actual diffusion length from the dipolelike energy shift at the dislocation outcrop and found that it varies by a factor of 5 between temperature 10 and 300 K, in excellent agreement with the values derived independently from the CL intensity profiles across the buried quantum wells. The T dependence of the diffusion length obtained on the QW agrees quantitatively with the deduced from the exciton energy shift observed in hyperspectral cathodoluminescence maps. This shift is caused by the strain-induced variation in the band gap around dislocations with an edge component.
I really appreciate their work as it provides new thoughts for the new studies related to diffusion length determination.

Recent advances in nitride LED technology for green-to-red wavelengths, *Robert Armitage*

I am interested in this talk because the speaker is from Lumileds, and he gave a presentation about the recent advances of long wavelength of LEDs from a commercial and industrial perspective.

In the talk, he mainly discussed the present status of nitride LEDs in the green-to-red spectral range, including factors that limit efficiency and performance compared to requirements for different applications (high-power illumination and μLED displays). From their perspective, the EQE of commercial green LEDs is limited by the intrinsic Auger recombination due to high carrier densities reached in polar quantum wells with small electron-hole wavefunction overlap. Therefore, they exploit the V-defects to bypass carrier injection and inter-well transport barriers associated with polarization charges, achieving more evenly distributed carriers among multiple quantum wells. They have demonstrated that green LEDs with excellent droop of 45% EQE at 40A/cm^2, but one thing associated with that is the trade-off between EQE droop and forward voltage.

Another important idea I picked up from this talk is the term "dominant wavelength". According to his talk, most of the red emissions shown in published papers are actually the peak wavelength, which does not meet the display gamut requirements.

Origins of High-Energy Electroluminescence Peaks in Long-Wavelength InGaN LEDs, *Yi Chao Chow*

This talk overlaps with my research interest as it is focused on the emission from the defects, especially V-pits, in InGaN-based long wavelength micro-LEDs. In that presentation, the speaker showed two high-energy electroluminescence (EL) emission peaks from the samples with thicker QWs and higher indium composition, in addition to the ground state emission. According to their simulation, the lower high-energy peak is attributed to the transitions involving excited states due to slower ground state transition in thick QWs that causes a carrier density build-up. The higher high-energy peak is attributed to the emission from the thinner and lower indium content QWs in the semipolar sidewalls of V-defects.

Recent Advances in III-Nitrides for MicroLEDs and Laser Diodes, *Jake Ewing*

This talk mainly discussed the high-performance InGaN-based RGB micro LEDs. They have achieved external quantum efficiencies as high as 58% at 450nm by using tunnel junction, novel processing and transparent packaging. Typically, efficiency drops with the shrink of size due to surface leakage current. They demonstrated efficient III-Nitride-based micro LEDs at dimensions as small of 1 micron using ALD passivation, which is more superior than the PECVD. Using strain relaxation methods such as porous GaN, they have fabricated a 640nm InGaN red micro-LED with efficiency of 6%.

Rump session

This is the first time for me to join such a session at a conference. This session aims to invite speakers from either industry or academia to share their opinions about the development of a certain research field in the near future and hopes to trigger discussions between the panel and audiences. I joined the Rump session named: *How nitrides put micro-LEDs forward?* There were 6 invited speakers who shared their thoughts， here I will list the questions and ideas that enlightened me the most:

TV size has increased through the years, but what about the power consumption? Micro LEDs may achieve lower consumption without circularized polarization, but the issue is that the number of the wafers required per colour is huge and hence we need innovative mass production in epi/wafer process.

OLED improved very fast in recent years, can the micro-LED really able to replace that? And how long does it take to achieve it?

Too much power is consumed by the backplane, how can we solve this issue? Care needs to be taken for the non-uniform leakage current for RGB in a lower current regime.

November 15th:

(Invited and contributed talks)

InGaN-based LEDs on arbitrary three-dimensional GaN templates toward tailored spectral control, *Mitsuru Funato*

It is well known that InGaN quantum well (QW) parameters such as barrier and well widths and In compositions highly depend on crystallographic orientations. The three-dimensional (3D) micro-nanostructures therefore offer unique opportunities to control the optical properties of InGaN-based light emitters. For example, selective area growth (SAG) on patterned dielectric masks generates 3D structures composed of energetically stable facet planes such as (0001), (11-22) and (1-101), the polychromatic emission including white without using colour-converting phosphors has been achieved.
Furthermore, in addition to those spontaneously formed 3D structures formed 3D structures, the speaker described an artificially formed 3D structures via photo-

lithography techniques. These 3D structures with arbitrary crystal tilts were formed through grayscale lithography or thermal reflow of photoresist and subsequent reactive ion etching. One disadvantage of these structures is that they are relatively unstable compared with the spontaneously formed ones. However, in my opinion, considering this artificial structure is designable, a more controllable and stable structure can be achieved via further optimization.

Red emitting InGaN nanopyramids grown on graphene/SiC, *A. Dussaigne*

One way to reduce the strain in the active region is by using a relaxed InGaN pseudo-substrate. 2D material should be able to provide a strain and defect-free buffer layer grown on its top due to the van der Waals gap formation allowed by the absence of dangling bonds at the surface of the 2D material.
In this talk, the speaker introduced a red-emitting InGaN nanopyramids (NPs) that were grown on epitaxial graphene on SiC. The graphene surface was treated with NH_3, and NPs with different base diameters were grown. The STEM images reveal that the InGaN nucleation started on a small aperture on SiC through the graphene. The same In content of 13% at the base of the InGaN NP above both the aperture and the graphene may indicate the same strain relaxation on both areas. Red-emitting InGaN/InGaN quantum wells (QWs) were then grown on the NP sidewalls. Interestingly, QW emission from blue to red depends on the NP diameter and density. A red emission at the wavelength of 620 nm was achieved, and the measured corresponding In content was 35%, which was thought to be underestimated due to the absence of electric field according to the speaker. In my opinion, this may not be underestimated because of the inefficient InN incorporation of semi-polar planes. Another highlight of their research is they mapped the internal electric field using the electron holography.

November 16th:

(Invited and contributed talks)

Modelling nonradiative recombination at individual point defects in an InGaN/GaN quantum well, *Thomas F. K. Weatherley*

Point defects (PDs) have been unveiled as critical non-radiative recombination centres in InGaN/GaN quantum wells (QWs), which can lead to at least an order-of-magnitude reduction in the internal quantum efficiency of blue-emitting diodes (LEDs). A deeper insight into these PDs requires a proper modelling of the nanoscale dynamics of nonradiative recombination at individual PDs. According to the speaker, the traditional model that assumes the instantaneous recombination when a carrier strikes the PD capture cross-section does not the match the experimental results, indicating that they need to account for the time required for the PD to relax via multiple phonon emission in between carrier capture events. Upon adapting the model to include such a PD relaxation time, an excellent match can be achieved to the experimental data.

Defect-assisted nonradiative recombination in nitrides, *Chris G. Van de Walle*

Defect-assisted nonradiative recombination is a key mechanism limiting the efficiency of optoelectronic devices. The defect level increases with the In content, and the energy difference between it and the valence band maximum stays approximately the same, whereas the energy difference between it and the conduction band minimum decreases. Therefore, in the lower In content region (blue or ultra-violet emission), the defect-assisted multiphonon process becomes inefficient for the capture of electrons. Experimentally, however, defect-assisted recombination is observed to persist in these shorter wavelength emission ranges. In the talk, the speaker described a trap-assisted Auger-Meitner recombination process that can be used to explain the phenomenon we observed experimentally. They developed a practical first-principle methodology to determine the trap-assisted Auger-Meitner recombination rate for defects and impurities in semiconductors. According to their calculations, the combination of hole capture by multiphonon emission and electron capture by trap-assisted Auger-Meitner results in recombination rates orders of magnitude larger than the recombination rate governed by multiphonon emission alone.

Dualtronics: Expanding the functionality of polar substrates, *Len van Deurzen*

This talk is very interesting and their Dualtronic design is very novel. They introduces a novel approach to expand the functionality of polar substrates by leveraging the epi-readiness of both growth fronts. In their Dualtronics, the epitaxial growth on both sides of c-plane GaN substrates enables the integration of the N-polar (Al,Ga)N/GaN high electron mobility transistors (HEMTs) and metal-polar blue (Al,In,Ga)N light-emitting diodes (LEDs). Using this design, they demonstrated the high-frequency optical modulation by utilizing the HEMTs to drive the LEDs monolithically. The application of such design could be Li-Fi communication systems and micro-LED displays, enabling a monolithic integration of the logic unit with the display.

November 17th:

(Invited and contributed talks)

Evidence of Lateral Injection at V-Defect Sidewalls in III-Nitride Light Emitting Diodes Using Electron Emission Microscopy, *Tanay Tak*

This talk also overlaps with my research interests. In recent years, V-defects have been proposed as a solution to the excess driving voltage of long-wavelength nitride-based light-emitting diodes, a source for their diminished efficiency. In their talk, they studied the effects of the V-defects by using electron emission microscopy (EEM). EEM is a self-emissive electron microscopy technique that images hot electrons emitted from electrically driven devices whose surface has been activated to negative electron affinity. They claimed that for LEDs, the EEM images the electrons generated by eeh Auger-Meitner processes that cross the diode junction, diffuse through to the top p-GaN and then escape out the surface. From the EEM, they observed non-electron emitting regions (dark spots) with a density of $\sim\ 3 \times 10^8\ cm^{-2}$, identified as V-defects. They attributed the measured lack of electron emission directly from the V-defect sidewalls to carriers fast travelling through the V-defect sidewalls and injecting laterally and efficiently into planar quantum wells as well as fewer minority carriers surviving the diffusion through the thicker p-GaN in the V-defect before escaping. And they think the stronger electron emission observed at the ridges of most V-defects is the evidence of lateral injection as larger injected carrier densities present outside the V-defect sidewalls.

My question to this is how they can know the large densities of carriers outside the V-defects are caused by the lateral injection, not the screening effect introduced by the thinner QWs on the sidewall of the V-defects?

Plenary talks

Vertical-cavity surface-emitting lasers at the end of the rainbow, *Åsa Haglund*

In this talk, the speaker described recent developments in short-wavelength vertical-cavity surface-emitting lasers (VCSEL). VCSELs could offer several advantages such as a low-divergent circular-symmetric beam, a low threshold current, single-mode emission, and two-dimensional array compatibility. These qualities are of interest for applications such as retinal scanning displays, laser-based lighting, ultraviolet (UV) curing and gas sensing. The first blue-emitting VCSELs operating under electrical injection were demonstrated in 2008, and they could conceivably be commercialized by 2025 if they follow the same timeline trajectory as that of near-infrared VCSELs. Besides the blue VCSELs, the ultraviolet UVB (280-320 nm) and UVC (<280 nm) VCSELS have been demonstrated as well. Despite of these developments, many different concepts are currently being investigated in parallel to circumvent the material

limitations imposed by III-nitrides. For example, epitaxial distributed Bragg reflectors (DBRs), nano-structured mirrors (porous DBRs and high contrast gratings) and all-dielectric DBRs enabled by different substrate removal techniques exemplify different approaches explored to achieve high reflectivity mirrors with sufficiently accurate cavity length control.
As my background is not in VCSELs, this talk is like an introductory lecture to me and I've learned a lot from this!

Revisiting the physics of III-Nitrides LEDs: myths and facts, *Aurelien David*

This talk overlaps with my research interests and is very enlightening. The speaker discussed our insights into the underlying device physics related to the myths and defects in III-Nitrides LEDs. Firstly, he reviewed some peculiar properties of III-Nitrides that make them stand out against conventional III-V semiconductors, such as polarization, point defects, V-pits, droop current, and random alloy distribution. After that, he showed the progress in materials, characterization, and modelling. The community's improved understanding of device physics with the related progress in device performance was also shared.