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UKNC Bursary Report

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Introduction

The International Conference on Nitride Semiconductors (ICNS) is an annual conference highlighting recent developments in Nitride-based semiconductors. The 14th edition of the conference was held this year in Fukuoka, Japan from the 12th to the 17th of November. Various topics were covered including growth, characterisation, optical devices, and electronic devices, in the form of both posters and oral presentations. The oral presentations, lasting 12 minutes, and 30 minutes for invited talks, were run in 6 parallel sessions, with varying specific themes such as power electronics, MOCVD growth, UV LEDs etc.

I would like to thank UKNC for the generous student bursary which helped fund my attendance at this conference, allowing me to share my research with an international audience and learning from students and experts in my research area. I have included a brief summary of some of the research I found particularly interesting.

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, Institute of Materials and Systems for Sustainability, Nagoya University, Furo-cho, Chikusa-ku, Nagoya 464-8601, Japan

This plenary talk from Prof Amano focused on celebrating the life and work of Isamu Akasaki, a pioneer of research in Nitride LEDs. It opened the conference not only on a note of commemoration, but also of excitement for the potential of where we are heading. Professor Akasaki passed away in 2021 at 92 years of age, having won the Nobel Laureate in Physics in 2014 for his work on blue LEDs. The speaker spoke of how Prof. Akasaki began work in this area to the challenges of those around him, initially failing in attempts to realise blue LEDs using GaN grown by MBE. However, not giving up, he persevered in this quest, pursuing alternative methods such as metalorganic vapour phase epitaxy at Nagoya University in 1981. Prof Akasaki is quoted as describing his work as ‘Going alone in the wilderness’, such was the sparse research into this field considered a lost cause. Eventually, he successfully realised the blue LED, shaping the world we live in the today. The relevance of this work was also linked to the conference we were all attending, as Prof. Amano described how Prof. Akasaki led various organising committees for international meetings of researchers in this field that ultimately led to the International Conference on Nitride Semiconductors. Prof. Amano proceeded to discuss the various cuttingedge technologies in Nitride semiconductors, ranging from the domination of GaN-based power electronics, to the recently demonstrated first continuous-wave UVC laser diode operation at room temperature.

This talk was a great lesson for the students in the road that has been travelled to arrive at where we are today. Remembering Prof. Akasaki and his seminal work on blue LEDs provides an appreciation for the challenges that had to be overcome that we now perhaps take for granted.

Electrical properties of dislocations in GaN structures for power devices: an approach based on ultraviolet light assisted Kelvin Probe Force Microscopy

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This presentation discussed the use of a non-destructive surface characterisation technique known as Kelvin Probe Force Microscopy (KPFM) with the assistance of a UV light source. The focus of the work was on the electron-trapping characteristics of GaN for use in power devices. The KPFM technique is a fairly well-established method of surface characterisation, however I found the concurrent use of a UV light very interesting. By exposing the surface to high energy ($> E_g$) photons, electron-hole pairs are generated and a subsequent current flows relative to the surface with the aid of the KPFM setup. Dislocations are of interest to power applications as they result in a severe degradation of performance.

In this work, two GaN samples with varying dislocation densities/types were examined. After UV illumination, the dislocation centres on the surface are shown to trap electrons, which can be inferred from the surface charge profile. Furthermore, they were able to differentiate between edge and screw type dislocations based on the presence of electron trapping. Edge dislocations have been shown to demonstrate this electron trapping, while screw type dislocations do not. After the UV source is turned on, the electrons are trapped in the edge type dislocations, shown by an increase in the surface potential. After turning off the source, the surface potential remains high in the dislocation, indicating the electrons remain trapped. As well as this, the researchers also varied the pumping powers of the source, allowing them to examine the surface recombination characteristics of the electrons in the layer and on the surface.

This work ultimately highlights the need to minimise threading dislocation densities – specifically edge type – in order to improve the performance of GaN power devices.

Characterization of 430nm- InAlGaN laser diode with polarization doped p-cladding layer

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Polarisation doping to enhance *p*-type conductivity in (Al)GaN alloys was largely developed by the work in Debdeep Jena and John Simon in Cornell University. It has allowed for major improvements in hole concentrations achievable in DUV LEDs, playing a major role in their progress witnessed in recent years. By grading the Al composition over a distance *d*, a 3-dimensional negative polarisation field is generated, which must be balanced by the ionising of holes. This alternate ionisation mechanism of holes (field ionisation) has some benefits over conventional thermal ionisation: ionised impurity scattering can be avoided as the need for an impurity dopant can potentially be neglected – resulting in an increased mobility; the hole concentration will be significantly larger as it is not limited by the large energy barriers required to activate a hole from the deep level Mg acceptor state; and the hole concentration can be temperature independent as the field ionisation mechanism is intrinsic to the material.

In this talk, a laser diode emitting at 430 nm was fabricated, which included a polarisation doped *p*-layer. Standard characterisation of the laser was carried out, as well as a temperature-dependent LIV test, down to 77 K. In a conventional impurity-doped structure, the hole concentration would begin to 'freeze-out' around 100-150 K as the thermal energy has been reduced significantly. However, in this work, they showed successful operation of the laser down to 77 K. The threshold current showed a non-monotonic behaviour as the temperature decreased. While their work was recent and further analysis was required, I found this talk very exciting as it is a rare demonstration of cryogenic conduction of holes, as theoretically predicted by Prof. Jena in the early 2000's. This work is related to work I am carrying out currently, so it was interesting to see a similar trend of behaviour change around 150 K. This work highlights the exciting potential of polarisation doping for low temperature operation of wide bandgap optoelectronic devices.

Far-UVC LEDs with high external quantum efficiency by micro LED array design

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As well as poor *p*-type conductivity and internal absorption, extracting the light from UVC LEDs is one of the major challenges specific to this wavelength. As the Al composition increases for lower wavelengths, the polarisation of the light switches from transverse electric (TE) (normal to surface) to transverse magnetic (TM) (parallel to surface). This makes extracting the light from the bottom surface of the LED very challenging. One solution to this is to form parabolic shaped mesas of diameters around 10 µm, which reflect the in-plane photons down and out of the device. This work focused on optimising the materials used in the passivation layer on the sidewalls of the parabolic mesa, to achieve maximum light extraction efficiencies (LEE) in UVC µLEDs. Arrays of 233 nm µLEDs were fabricated, with the passivation coating on the mesa sidewalls investigated.

SiO_2 and SiN were both investigated to examine which resulted in higher light output. It was found that due to its larger refractive index contrast with AlGaN, µLEDs with sidewalls coated with SiO_2 produced an EQE four times larger than the SiN coated ones. While one would think that placing a highly UV-reflective layer of Al on top of this passivation layer would increase the light reflected, the presence of this Al layer had negligible effects on the LEE. This would suggest that the majority of the light is actually reflected at the SiO_2/AlGaN interface due to the contrast in refractive index. Additionally, the light output power from the arrays was increased by condensing the pattern of µLEDs from a grid-style to a diamond-style layout – increasing the density of devices per array. This work shows the importance of increasing the LEE for maximum light output power from UVC LEDs.

Defect-assisted nonradiative recombination in nitrides

Chris G. Van de Walle, University of California, Santa Barbara, USA

This invited talk was given by a leader in the theoretical field of nitride semiconductors, Professor Chris Van de Walle. In it, he discussed the mechanisms and properties of defect-assisted nonradiative recombination in nitride semiconductors. Understanding these sources and mechanisms of defect-related losses has proven much more difficult than in narrower bandgap materials. Theory predicts a decreased rate of electron and hole capture in trap states from the respective bands as the bandgap increases, however, experimentally, it has been observed that these processes do indeed persist. This can be explained by the process of defect-assisted Auger-Meitner recombination.

It is worth noting here the nomenclature of this process. Previously, the mechanism of an electron gaining energy from the relaxation of a nearby electron has been referred to as 'Auger recombination', after French physicist Pierre Auger's discovery in 1923. However, it was later discovered that an Austrian-Swedish physicist Lise Meitner had discovered the process separately, a year prior in 1922. There has been a recent push to refer now to the process as the Auger-Meitner process, to rightly acknowledge the work of Lise Meitner.

Defect states in the mid-gap can degrade the performance of optoelectronic devices. Through allowing the capture of electrons and holes, the states can assist in the occurrence of Auger-Meitner effects. There are four variations of this process, depending on which particles transfer their energy. Prof Van de Walle and his research group developed a first-principles methodology to investigate the defect-assisted Auger-Meitner processes in wide bandgap semiconductors. In their work, they focused on the calcium impurity in InGaN, although their framework can be applied to any material system.

The Auger-Meitner effect along with trap-assisted carrier capture is an important process that must be considered in understanding the performance degradation in nitride semiconductors, and in order to minimise the effect to maximise the radiative recombination, a deep understanding of its causes will allow for practical steps in the growth and fabrication.