Summer Topicals Meeting Series 2015, 13th –15th July, Nassau

Conference report for UKNC
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Introduction

The Summer Topicals Meetings are organized every year by the IEEE Photonics Society to discuss about different topics in the emerging fields of photonics. This year among the six topics, two of them were closely related to nitride materials: Visible Light Communication (VISC), and Ultraviolet Lasers and Light Emitting Diodes (UVLED).

Most of the presentations were 30-minutes invited talks, which from a student perspective was a great opportunity to learn about the state of the art and get an overview of the most recent results directly from the group leaders of the prominent research institutions and commercial companies operating in this field, especially from US and Japan. The six topical meetings were held in parallel and I mostly attended the UVLED one, which consisted of 19 talks plus a final joint section together with the VISC meeting.

I would like to express my sincere thanks to UKNC for their contribution in funding this trip for me. This conference has been a very formative experience as it gave me the opportunity to both deepen my knowledge of the field and give a talk in front of an international community of experts.

Hereafter I have included a short summary of each of the talks of the UVLED section.

MB1

Title: *Direct Observation of Auger Electrons: Identification of the Dominant Efficiency Droop Mechanism in GaN-based Visible LEDs*

Speaker: *James S. Speck*

Affiliation: *University of California, Santa Barbara, CA, USA*

In the first session (UVLED Plenary) Professor Speck reported about an experiment performed in collaboration with the CNRS-Ecole Polytechnique (Palaiseau Cedex, France) about direct measurement of Auger-electrons emitted from a GaN-based LED. It is well-known that Auger recombination is one of the mechanisms which could explain the efficiency droop experienced by all nitride-based light-emitting devices at high current densities. Nevertheless there is still not agreement whether this is the dominant mechanism or not and, before this experiment, all the arguments were based on theoretical calculations or indirect experiments. In order to achieve a direct measurement of Auger-electrons, the authors exploited the characteristic of cesium of being able to confer a negative electron affinity to a p-doped semiconductor surface if properly deposited on it. In order to reach the caesiated surface and, eventually, be collected by a spectrometer and revealed, the Auger-electrons generated in the active region must travel through a 200 nm p-doped GaN layer and most of them will recombine or thermalize to the bottom of the conduction band. Nevertheless the energies of the Auger-electrons are high enough to allow them to populate different valleys of the conduction band and hopefully reach the surface without fully thermalize. The authors reported that when increasing the current in the device the onset of efficiency droop occurred at the same time as the appearance of a high energy peak in the electron spectrum, and concluded that Auger recombination is the dominant mechanism of the efficiency droop.

In my opinion this is certainly an extremely interesting experiment but there are still a few points that need to be further clarified. First of all, the measured energy difference between the Γ point and the closest valley is reported to be about 1 eV, whereas theoretical values based on experimentally well proved models give a two-times bigger value. They don't have any explanation for that, but a similar experiment recently performed by the same group with a completely different structure seems to confirm the same value. Other problems are the very low sensitivity of the experiment (evaluated to be about 10^{-6}), and the lack of full understanding of the effects on the hot electrons of the caesiated surface.

MB2.1

Title: *Quasi-pseudomorphic AlGaN Based Deep Ultraviolet LEDs over Sapphire Substrates*

Speaker: *Asif Khan*

Affiliation: *University of South Carolina, Columbia, SC, USA*

In his presentation, Professor Khan started with an interesting introduction about the state of the art of deep-UV LEDs both in the industry and in the research. He pointed out that the use of sapphire as a substrate is still more widespread than bulk material, even among commercial companies (e.g. SETi, Nitek, Dowa, Nikkiso). Considering just the basic device, without any special optimization, all of the existing LEDs on sapphire have more or less the same performances: optical powers of 1.5—2.0 mW at 20 mA, external quantum efficiencies of 2—3% and lifetimes of about 1,000 hours. Then, optimizing the thermal management by using a flip-chip configuration is possible to increase their efficiency up to two times; and by optimizing the light extraction, a further two-fold improvement is also possible. In these devices the n-AlGaN layer is usually 2 μm thick or more, in order to allow for current spreading and thermal management but, as a consequence, relaxation and formation of defects are likely to occur even though this may be partially reduced by using super-lattice layers. Because of the dramatic reduction of dislocations, the use of bulk material as a substrate is claimed to be beneficial for the fabrication of high-performance devices. But, prof. Khan stated, in order to exploit these low defect substrates the n-AlGaN layer needs to be much smaller (usually less than 600—800 nm) and the improvement from the material quality can be hindered by the reduced efficiency of the current spreading layer. From this perspective, the authors decided to investigate whether is possible to grow a good quality thin n-AlGaN layer of the same reduced thickness but directly on the sapphire/AlN template instead than on bulk material. They called this approach *quasi*-pseudomorphic growth, and compared the optical and electric characteristics of a device fabricated in this way with a standard one on sapphire. The latest results, still to be published, account for a device having a 800-nm-thick n-AlGaN layer, able to show almost the same performances as a standard one but obtained with a sensible reduction of growth time.

MB2.2

Title: *Progress of AlGaN-based UV LEDs on Sapphire*

Speaker: *Cyril Pernot*

Affiliation: *Nikkiso Co. Ltd., Japan*

This presentation was from the commercial company Nikkiso, originally founded by two of the three 2014-Nobel prize winners: Professors Amano and Akasaki. Their technology is based on sapphire and flip-chip mounting for improved thermal managements. At the beginning of the talk it was pointed out that UV LEDs have had a really huge improvement in the last 10 years having increased their external quantum efficiency from less than 1% up to 10% or even more, in agreement with Haitz's law, a photonic version of Moore's law. Then the speaker focused on the possible ways for further improvement that are currently under investigation. In particular it was mentioned that in order to reduce the losses in the thin p-GaN layer, usually present in top of the p-AlGaN cladding layer to assure a good ohmic contact, three challenging strategies are studied: the use of a meshed structures good enough for contact purposes but less absorbing, a further reduction of the p-GaN thickness down to 10 nm, and a complete removal of the p-GaN.

MB2.3

Title: *UV LED Performance and Applications*

Speaker: *Max Shator*

Affiliation: *SETi, Columbia, SC, USA*

This was another talk from a commercial company: the SETi, based on Columbia, South Carolina which has a strong collaboration with professor Asif Khan's team of the local university. Same as Nikkiso, their technology is based on sapphire and flip-chip mounting. The speaker described the range of their products and their performances and mentioned about a patent about exploiting inhomogeneity in AlGaN concentration (due to different mobility of Ga and Al adatoms during growth) to obtain more conducting or more transparent layers in different position of the device.

MB3.1

Title: *Deep Ultraviolet LEDs: from Materials Research to Real-World Applications*
Speaker: *Michael Kneissl*
Affiliation: *Technical University of Berlin, Germany*

Professor Kneissl gave a good introduction about all the problems that currently affects UV LEDs and the ways how to solve them. A very interesting comparative graph that shows external quantum efficiency versus emission wavelength of almost all UV LEDs reported in literature was shown; this graph is kept up-to-date and can be freely downloaded from their website.

Their approach is to grow on sapphire but, to improve the quality of their templates, they make use of patterned substrates for which they have developed their own version of Epitaxial Lateral Overgrowth (ELO) technique. The key results of their research in the last few years have been the realization of high conductive n-AlGaN layers, the optimization of Mg-doped Al(Ga)N/AlGaN electron blocking layers, and the use of strained active regions in order to force TE-polarized emission instead of a TM-polarized emission even for high aluminium content AlGaN alloys. Using all these achievements, they were able to demonstrate flip-chip mounted UVB-emitting LEDs with an optical power of 15 mW and more than 10,000 hours of lifetime.

MB3.2

Title: *Pseudomorphic UVC LEDs on AlN substrate*
Speaker: *Silviu Velicu (substituting Leo Schowalter)*
Affiliation: *Crystal IS, Green Island, NY, USA*

Contrary to Nikkiso and SETi, Crystal IS is a company that focuses on the use of bulk AlN substrate. During the talk their range of products was presented, including both the TO-packaged series called “optan” and the Surface Mount Devices (SMD). Their optical power is in the range of 1—5 mW and have a lifetime of 3,000 hours at 100 mA. They claim to be able to pseudomorphically grow up to 1 µm of material on top of the bulk substrate before the onset of relaxation and increase of defect density. As pointed out by Prof. Khan in presentation MB1.2, being able to increase the thickness of pseudomorphic n-AlGaN, is really a key point for the performance of the device grown on bulk AlN (Prof. Collazo in presentation TuB1.3 (see below) reported the even bigger value of 5 µm).

MB3.3

Title: *Recent Progress of AlGaN Deep-UV LED by Improving Light Extraction Efficiency*
Speaker: *Hideki Hirayama*
Affiliation: *RIKEN research institute, Saitama, Japan*

The approach of RIKEN has been to use sapphire as a substrate and to control the quality of the material growth by using pulsed ammonia flow, and multilayer AlN-buffer techniques; in addition, to enhance the effectiveness of the electron blocking layer they have developed a multiple quantum barriers structure. In this presentation the speaker reported about the most recent achievement of his group. In particular they were able to completely remove the p-GaN layer and still obtain a good ohmic contact on a UV-transparent p-AlGaN. To further enhance the light extraction, they substituted Ni/Au metallization scheme with a Ni/Al metal stack. The latter is not as reflective as pure aluminium but compared to Al/Au is still ohmic and is three times more reflective. The use of photonic nanostructures is expected to improve even further the light extraction efficiency and the target for the near future is to exceed 40% compared with the present average value of about 8%.

MB4.1

Title: *Development and Future of Ultraviolet Light-Emitting Diodes*
Speaker: *Yoshihiko Muramoto*
Affiliation: *Nitride Semiconductors Co. Ltd., Japan*

Nitride Semiconductors is a Japanese company that claims to have developed the world’s first UV LED in 2000, in collaboration with Tokushima University. They are mostly focused on near-UV devices in the range 355—380 nm grown on sapphire substrates. The key points of their technology are the ability to decrease the threading dislocation density in their n-doped layers, and the ability to increase the indium composition variation in the active region in order to enhance carrier localization. To achieve the first point, instead of using Si-doped alloys, they subsequently grow undoped-AlInGaN and pure silicon layers. The material grown in this way still shows n-conductivity (the doping is probably due to Si diffusion into the AlInGaN layers) but the quality is improved. In addition to that, they also use SiN interlayers within their templates. To achieve the second point, they introduced a monolayer of SiN in the active region grown after every barrier before the following well. According to their model, in this monolayer many nanoholes are present and indium and/or gallium adatoms will preferentially move there whereas aluminium adatoms due to the difference in their diffusion mobility will stick indifferently in any point where they have been adsorbed.

MB4.2

Title: *Using Surface Plasmon Coupling for Enhancing the Emission Efficiency of UV LED*

Speaker: *Chun-Han Lin*

Affiliation: *National Taiwan University, Taipei, Taiwan*

In this presentation, Professor Lin reported about the opportunity of exploiting surface plasmons to increase the performances of UV LEDs. Surface plasmons (SPs) are collective electron oscillations at the interfaces between metals and semiconductors strongly coupled with the associated electromagnetic fields producing either Surface Plasmon Polaritons (SPPs) in planar interfaces, or Localized Surface Plasmons (LSPs) when confined into small particles. In their studies the authors performed simulations and experiments involving both SPPs and LSPs at the interfaces between p-AlGaN and aluminium in order to enhance the quantum well efficiency, reduce p-GaN absorption by modifying the emission direction, and minimize the TM-polarized emission. The key point is to reduce as much as possible the distance between the active region and the metal structures in order to maximize the energy transfer to the SPs. It is also important to assure that the SPs can radiate otherwise this would lead to quenching instead of enhancement. LSP can naturally radiate, whereas for SPP a nano-grating approach was chosen to compensate for the k mismatch.

MB4.3

Title: *High-reflection Si/SiO_2 Bragg Reflector via Membrane Transfer Printing*

Speaker: *Zhenqiang Ma*

Affiliation: *University of Wisconsin, Madison, WI, USA*

In the first part of his talk Professor Ma reported about the results achieved by his group in manipulating nano-membranes for photonic applications. In particular they were able to obtain silicon nano-membranes with a silicon dioxide layer grown in top and stack few of them using transfer printing technology in order to obtain a very efficient distributed Bragg reflector.

Transfer printing is a technology that by exploiting the adhesion characteristics of a particular elastomer can be used to transfer devices or membranes in top of virtually any substrate. In the second part of his presentation, the speaker discussed how this technology can be used to improve UV LEDs. Professor Ma and their team think the poor quality of the p-GaN is the main reason for efficiency droop (poor hole injection and hence electron overflow). As a possible solution for that, they propose to transfer print a p-Si layer on top of the device to substitute for the p-GaN layer. So far they were only able to put a p-Si layer in top of a still existing p-GaN layer, but they claim they were already able to obtain a device which showed no efficiency droop until 800 A/cm^2.

TuB1.1

Title: *Optically Pumped Low-Threshold UV Laser*

Speaker: *Russell D. Dupuis*

Affiliation: *Georgia Institute of Technology, Atlanta, GA, USA*

Professor Dupuis reported about the study performed by his group in collaboration with Arizona State University and Technical University of Berlin regarding an optically pumped laser emitting at 249 nm. The substrate used for the growth is sapphire without any use of patterned surface. To control the quality of their AlN-template they used instead an optimized growth recipe in three steps with different growth rates in order to obtain a good trade-off between material quality and growth time. They achieved a threshold optical power of about 100 kW/cm^2 and, based on their experience, they claim sapphire is a perfectly suitable substrate for deep-UV lasers.

TuB1.2

Title: *350-nm Band Edge-Emitting Laser Diodes Enabled by Low-Dislocation-Density AlGaN Templates*

Speaker*: Mary H. Crawford*

Affiliation*: Sandia National Laboratories, Albuquerque, NM, USA*

In my opinion this was one of the best talk of the whole conference for the richness of the presented results spanning from improvement of material quality; defect characterization; design, simulation and testing of the final device.

Having decided to use sapphire as a substrate, to achieve a good quality of their AlN-template and consequently of their n-AlGaN, they used a patterned-substrate approach. But, instead of using the standard epitaxial lateral overgrowth, which is more difficult to achieve for AlGaN than it is for InGaN and leads to a poor uniformity of the defect density, they tried to develop the results originally published by Amano at Nagoya University. The key point of this approach is the use of a special patterning at submicron scale. The quality of the AlN-template grown in this way was in the range of 2—3 x 10^8 cm^{-2}.

In order to achieve this result they also optimized the growth temperature by studying its correlation with the different types and concentrations of defect investigated by using the Deep Level Optical Spectroscopy technique, which is similar to the more common Deep Level Transient Spectroscopy but uses optical instead than thermal stimulation.

Different solutions about doped versus undoped waveguide and electron blocking layer were experimentally analysed by optically pumping the devices. The final device was a laser diode emitting at 352 nm, electrically pumped with a current density threshold of about 22 kA/cm^2.

A good part of the talk was devoted to address different fabrication issues. In particular they reported about the optimization of etching techniques as a way to obtain the facets for the cavity, a much more effective and reproducible solution than the standard cleaving used other groups. Two different approaches were presented: dry ICP-etching and wet etching in KOH. The first one gave better results with increased temperature (up to 250°C, limited only by the equipment). The second one (which gave even better results) is based on the work originally published by Stocker in 2000 and basically consists of a photo-enhanced electrochemical etch (which is able to etch c-plane nitride-material even though the facet quality is usually poor) followed by a wet etch in molten KOH to smooth down the non-polar surfaces.

TuB1.3

Title: *Status and Challenges in Deep UV Semiconductor Lasers*

Speaker*: Ramón Collazo*

Affiliation*: North Carolina State University, Raleigh, NC, USA*

The key point of this talk was to stress out the importance of using bulk AlN substrate for sub-300-nm UV-lasers, hence advocating the opposite approach as the one discussed by professor Dupuis (see talk TuB1.1). The main reasons for that choice being: a threading dislocation density less than 10^3 cm^{-2} compared with values larger than 10^9 cm^{-2} for templates on sapphire substrates, the possibility of pseudomorphically grow AlGaN up to a thickness of 5 µm (instead of less than 1 µm as generally believed; see MB1.2 and MB3.2), and the possibility to obtain TE-polarized emission even for high-aluminium-content AlGaN alloys. About the latter point, the speaker reported a very peculiar behaviour of their lasers that showed 100% TE-polarized emission for wavelengths longer than 240 nm and 100% TM-polarized for shorter wavelengths, whereas many other groups obtained partial polarization above threshold. The optically pumped devices fabricated this group showed a room temperature lasing at wavelengths from 237 to 281 nm with a threshold optical power below 60 kW/cm^2.

TuB2.1

Title: *Polarization Engineered Deep Ultraviolet Nanowire LEDs Integrated on Silicon and Metal Substrates*

Speaker*: Roberto Myers*

Affiliation*: Ohio State University, Columbus, OH, USA*

The speaker reported about the results of his group in the field of nanowire-based UV LEDs. They are specialized in using the polarization-doping technique (invented by Prof. Debdeep Jena originally at University of Notre Dame, now at Cornell) and applying it to AlGaN nanowires grown by Molecular Beam Epitaxy. According to them, this approach is particularly effective in nanowires because of their ability to better withstand strains even at large aluminium contents. They have demonstrated p-down/n-up structured nanowires grown on different substrates such as: p-doped silicon, directly on metal (molybdenum) and on n-doped silicon forming tunnel junctions. The last two achievements are the most recent ones and have just been submitted for publication.

TuB2.2

Title: *AlGaN Nanowire Ultraviolet Lasers on Si*

Speaker*: Zetian Mi*

Affiliation*: McGill University, Montreal, Canada*

The laser reported in this presentation is a so-called "random laser" in which instead of a conventional cavity the light is confined using a random distribution of scattering elements as a result of a phenomenon known as Anderson localization of light. To achieve that, they grew AlGaN nanowires on silicon that spontaneously formed using radio-frequency plasma-assisted MBE without using any foreign metal catalyst. Thanks to the very high-Q cavity obtained with this approach and to the electron/hole confinement in the active region of the nanowires due to a naturally occurring Al concentration inhomogeneity, they were able to demonstrate lasing at low temperature (6—180 K) in the range 320—340 nm with a threshold current density of about 10 A/cm^2, almost three order of magnitude lower than what usually reported.

TuB2.3

Title: *III-Nitride Nanowires for UV-Visible Optoelectronics*

Speaker*: George T. Wang*

Affiliation*: Sandia National Laboratories, Albuquerque, NM, USA*

Key point of this presentation is the development of a new method of producing nanowires. Instead of the common bottom-up method in which the nanowires are grown over a patterned substrate using special conditions (usually low temperature and low V-III ratio) in order to suppress sidewall growth, they developed a top-down method that can lead to a better material quality. The problem with this approach is that the quality of the etched surfaces is usually quite poor. The novelty of their work is the use of a second wet-etching step using a KOH-based chemical (dip in the resist developer AZ400K at 65°C for a few hours) to improve sidewall quality by removing dry-etched-damaged material and allowing for a very high aspect ratio. They further studied the nanowires produced using this method and the speaker reported about single mode control via geometry modifications, wavelength tuning via both photonic-crystal-structures and by applying pressure (using a diamond anvil equipment).

TuB2.4

Title: *p-Type AlN Nanowires and AlN Nanowire Light Emitting Diodes on Si*

Speaker*: Zetian Mi*

Affiliation*: McGill University, Montreal, Canada*

In this presentation the speaker reported about efficient p-doping of AlN nanowires which is possible thanks to higher magnesium incorporation in these structures than in planar material. The growth is similar to what already presented in talk TuB2.2 and here the focus was on characterize the effective activation energy using temperature dependent PL and IV measurements. The results show a 0.5 eV activation energy at temperature higher than 500 K, as expected from other studies in planar p-AlN. On the other hand, at lower temperatures for sufficiently high doping concentrations an effective activation energy of about 50 meV was measured which is compatible with hopping conduction in the impurity band. Using the same approach they were able to demonstrate an AlN nanowire-based LED with a turn-on voltage of 6 V, much smaller than the values around 20 V usually reported in literature for planar AlN devices

TuB3.1

Title: *Hexagonal Boron Nitride for Deep UV Photonics*

Speaker*: Hongxing Jiang*

Affiliation*: Texas Tech University, Lubbock, TX, USA*

In this talk the speaker reported about the studies performed by his group in order to characterise hexagonal boron nitride (hBN) and exploring the opportunity of using it in conjunction with the standard nitride materials for deep UV photonic devices. The presentation focused mainly on optical characterization of MOVPE-grown hBN, but his group is also trying to investigate the effect of Mg doping and the feasibility of using p-doped hBN as a substitution for p-doped Al-rich AlGaN. A structure consisting in p-hBN/n-AlGaN junction and exhibiting a diode behaviour was demonstrated.

TuB3.2

Title: *Advantages and Limitations of UV optoelectronics on AlN substrate*

Speaker*: Ramón Collazo*

Affiliation*: North Carolina State University, Raleigh, NC, USA*

This presentation was about the work performed in collaboration with HexaTech, a company specialized in the production of AlN bulk substrates, and focused mainly on the issue of optical transparency in the UV region which is one of the major problems affecting this technology. The speaker explained that this strong absorption in the <280-nm-region is due to the presence of carbon that originates from the equipment used in the physical vapour transport process. In particular the tantalum carbide susceptor is likely to be the most important source of carbon atoms. Because it is not possible to reduce the carbon contamination, they developed a different solution consisting in co-doping with both carbon and silicon impurities. Experimental and simulation studies showed that the single-atom carbon and silicon impurities are likely to bond together forming a new stable point-defect with a higher absorption energy shifting the absorption band of the material at shorter wavelengths in the <250-nm-region.

TuB3.3

Title: *Ammonia Molecular Beam Epitaxy Technology for UV Light Emitters*

Speaker*: Erin C. Young*

Affiliation: *University of California, Santa Barbara, CA, USA*

In the first part of this talk, the speaker introduced the growth technique of ammonia-based Molecular Beam Epitaxy (MBE). Compared with the more common plasma-enhanced MBE in which the source of active nitrogen is the plasma itself, the ammonia-MBE is to some extent more similar to Metal Organic Vapour Phase Epitaxy (MOVPE) and allows for higher growth temperatures. This relatively new technique has proven very interesting and, so far, holds the world's record for the highest carrier mobility in a GaN-based high electron mobility transistor (HEMT). The second part of the talk was about preliminary results regarding the use of a n+/p GaN tunnel junction as a way to overcome the problem of inefficient hole injection due to poor p-doping. Following the work of professors Myers and Rajan's group from Ohio State University, they tried to combine this approach with ammonia-MBE. After the first results obtained for visible devices, they are now trying to extend this approach to UV LEDs.