Report on the 10th International Conference on Nitride Semiconductors (ICNS-10)

The ICNS-10 was held at the *Gaylord National Hotel and Convention Center* in Washington D.C. from 25-30 August 2013. With over 700 oral and poster presentations and about 1000 attendants from four continents, it provided an outstanding opportunity to get a deeper insight into the multifaceted field of nitride semiconductors. The conference week started with a reception on Sunday evening (which I missed due to issues with my British credit card upon arrival). The scientific program was divided into four sections: A) Bulk and Film Growth, B) Optical Devices: Visible, C) Optical Devices: UV, D) Electrical Devices; while plenary sessions addressed some important issues in various topics, for instance the loss mechanisms in nitride light emitters, analysed in extensive detail by C.G. Van de Walle, or the key challenges and technical breakthroughs that had led to the construction of high frequency GaN HFETs, presented by M. Micovic in a most informative and comprehensive talk. As my research is related to AlGaN/GaN HEMTs, I mostly attended the oral presentations of section D) and some talks in Bulk and Film Growth. Poster sessions were held after the oral presentations on Monday and Tuesday evenings and Wednesday afternoon and allowed researchers to immerse themselves in casual but in-depth conversations about their particular topic of interest and build new relationships while enjoying some delicacies of the American cuisine.

Several presentations of the Electrical Devices section captured my attention. One of these was the very first talk, from D.J. Meyer (*U.S. Naval Research Laboratory (NRL)*). He presented the concept of the nanocrystalline diamond (NCD) heat spreader. NCD layers were grown on AlGaN/GaN HEMTS by PECVD in order to reduce channel temperature, exploiting the high thermal conductivity of diamond. To circumvent the issue of the thermal instability of Schottky gate at the diamond growth temperature, they have invented the 'gate-after-diamond' process, i.e. the gate was deposited after the growth and etching of diamond. Electrical characterisation found that the NCD-coated devices were outperforming the reference ones, for instance, they exhibited 20% higher transconductance. Moreover, they showed 1 W/mm higher output RF output density in 4 GHz load-pull measurements. The research group concluded that the improvement originated in the reduction of channel temperature, i.e. in the mitigation of self-heating effects. Earlier this year I had the opportunity to perform thermal analysis on their devices and it was great to take a look on the project from a different angle.

Quite a few talks of Monday's session (titled *"High-Speed and High Performance Nitride HEMTS and Modeling"*) – and in later sessions during the week too – focused on MISHEMT structures – in particular, various gate insulators – and enhancement-mode devices; clearly these have been hot topics of research recently all over the world. B.P. Downey (also from *NRL*) has reported on the fabrication of InAlN/AlN/GaN MISHEMT with 65 nm T-gate and MBE-grown ultra-thin (1-6 nm) SiN gate insulator. The study's goal was to mitigate the consequences of aggressive scaling, namely the increased leakage current and premature breakdown. SiN was found to suppress gate leakage (10^{-7} A/mm at V_g=-10 V) and induce high electron sheet density, presumably due to positive fixed charge. The fabricated devices exhibited 82 V breakdown voltage and 118 GHz cut-off frequency. Researchers from the *Department of Electronic and Computer Engineering* of the *Hong Kong University of Science and Technology*, too, have observed similar effects on ultra-thin barrier (1.5 nm) AlGaN/GaN MISHEMTs with 7 nm / 3 nm in-situ MOCVD SiN_x gate dielectric that was revealed to reduce leakage current by 7 / 4 orders of magnitude, respectively. Sheet resistance – scaling with SiN_x thickness in their study, too – was shown to be an order of magnitude lower (1300 Ω/sq / 4200 Ω/sq) than on samples without SiN_x.

As for E-mode devices, I have found the concept presented by R. Brown (from *University of Glasgow*) rather interesting, as E-mode devices was realised with gate wrap-around method using simple PECVD-deposited SiO2 with 10 nm/20 nm thickness, resulting in 3 V/2 V threshold voltage, respectively. Clearly the electronic characteristics needed to be improved but the proposed technique seemed to be promising. Y. Zhang (from *MIT*) and his fellow researchers took a different approach to achieve high threshold voltage. He reported on fabrication of flourinated MOSHEMTs with V_{th} higher than 3 V. The flourine plasma (CF_4) etching prior to the atomic layer deposition of the Al_2O_3 gate dielectric, together with the consecutive annealing were assumed to induce negative bulk charge in the oxide. According to their study, the achieved V_{th} was stable up to 250 °C and the HEMTs showed no sing of current collapse.

In the Monday poster session I presented a poster which I was a co-author of, as the first author, Ashu Wang could not attend the conference due to issues with the visa (what seemed to be a general problem for attendants of Chinese nationality). Our poster, titled *Impact of Intrinsic Stress in Diamond Capping Layers on the Electrical Behaviour of AlGaN/GaN HEMTs*, presented a joint work of *Universidad Politécnica de Madrid* and the *NRL* – supported by Raman stress measurements performed at our group – that explored how the aforementioned NCD heat spreaders influenced the stress in the coated devices. The finite element simulations suggested that partly the induced inhomogeneous stress was responsible for the observed improvement in electrical characteristics. This poster has attracted some interest, along with other related works from *NRL*, which I had a chance to get acquainted with in detail. These posters, presented by Marko Tadjer, focused on the rather exciting concept of thermal vias, that were etched through the SiC (Si) substrates and then coated with PECVD-diamond, in order to facilitate effective heat extraction from power devices. Apart from the cost, a key advantage of selective diamond thermal via approach over large area diamond substrates is the manageability of the stress induced by thermal expansion mismatch. Using this method, the group managed to largely eliminate wafer bow.

One of the most interesting talks of the Tuesday morning session (titled *"Characterization of Nitride Electronic Devices"*) was presented by Bumho Kim (from *Energy Semiconductor Research Center, Advanced Institute of Convergence Technology, Republic of Korea*), who reported on the investigation of individual leakage paths in GaN by means of conductive-AFM and TEM. Their study identified three kinds of defects acting as leakage current paths: atomic step edges, pure screw dislocations and large pits. Selective etching analysis and TEM revealed that large pits were open-core screw dislocations. My colleague, Miguel B. Montes gave an excellent presentation in a similar topic, he investigated the formation mechanisms of pits forming at the gate edge in AlGaN/GaN HEMTs during off-state stress, which, too, acted as leakage current paths and corresponded with EL spots. He found that at least in some cases the pit formation could be induced by threading dislocations terminating on the surface in the proximity of the gate edge. Our group is currently carrying out further investigations to understand the role dislocations have to play in gate leakage and soft breakdown.

For some reason my own talk was scheduled in the session titled *"Subtrates and Epitaxial Integration for Nitride Electronic Devices"* on Tuesday afternoon. I introduced our novel technique called *diamond Raman micro-thermometer* that enabled accurate time-resolved measurement of the gate temperature in HEMTs. Combined with standard Raman thermography, it improved the accuracy of peak channel temperature estimations, and proved to be especially useful in case of field-plated and metal-covered devices. Despite the unlucky time slot – just before the afternoon coffee break – my talk has attracted some interest some of what will hopefully lead to fruitful collaborations. I was also a co-author of another presentation in the same session, given by Glen David Via (from U.S. Air Force Research Laboratory). He reported on the fabrication AlGaN/GaN HEMTs on diamond substrate via epitaxial transfer. The epitaxial layers were grown on Si, which was etched away along with the nucleation layer, then the layer structure was transferred onto diamond substrate, followed by device fabrication. I have contributed to their study with thermal characterisation and it was found that using the high thermal conductivity diamond substrate resulted in low thermal resistance (8 K/(W/mm)).

For me the ultimate highlight of Wednesday's session (*"Novel Nitride Devices and Electronic Concepts"*) was the invited talk from Umesh K. Mishra (*University of California-Santa Barbara*), titled *Novel Device Concepts in GaN Electronics*. In his usual refreshing style, he elaborated on the inherent structural advantages of the N-polar devices, such as improved electron confinement, low contact resistance, flexibility in channel scaling. He also provided some examples of recent developments in the field of N-polar devices, such as demonstration of MISHEMTs with 5.4 nm GaN channel and InGaN/AlGaN back barrier, grown by MOCVD on sapphire, exhibiting 1.89 S/mm transconductance, 4 A/mm drain current density and 0.23 Ωmm on-resistance. He also analysed the concept of nitride-based hot electron transistors (HETs), that could potentially enable operation at very high frequencies.

Naturally, several of this session's presentations addressed exciting topics. I found Eng Fong Chor's talk on thermally stable RuO_x Schottky gates particularly intriguing as I believe that thermally stable gate would be advantageous for fabricating heat-extracting structures on top of the device. E.F. Chor and her team at the *National University of Singapore* found that after annealing RuO_x gates in nitrogen at 800 °C, the leakage current was as low as 10^{-5} Acm^{-2} and decreased with subsequent high temperature exposure, in contrast to conventional Ni/Au gates.

Two really interesting concepts were presented by researchers of the *Department of Electrical and Computer Engineering* at the *Ohio State University* the GaN/AlN nanowire-based resonant tunnelling Schottky diodes (Y. Shao), and the MoS_2/GaN heterojunction (E.W. Lee). In the latter talk, a potential new class of semiconductor heterostructures was outlined, that could arise from the integration of transition metal dichalcogenides, possessing 2D structure and unique properties, and 3D nitrides. Such structures could give rise to novel devices and applications. In this study, Nb-doped p-type single crystal MoS_2 was grown on GaN by CVD and rectifying behaviour was observed. CV measurements indicated low interface state density on the heterointerface.

I particularly enjoyed the Rump Session, held on Wednesday evening, where prominent figures of semiconductor industry – namely Toshishide Kikkawa from *Fujitsu*, Umesh Mishra from *UCSB*, Charles Eddy from *NRL*, Steve Stoffels from *IMEC* and Michael Briere from *International Rectifier* – presented us with an inside view on the current state, prospects, challenges, doubts, and obstacles of industrial application of nitride electrical devices, accompanied by the unfailingly delightful showmanship of T. Paul Chow ("*otherwise known as the Equal Opportunities Offender*"[1]). We have learned that even though nitride technology was still far from maturity and there was plenty of room for improvement, most of the initial problems had been addressed and AlGaN/GaN power devices were ready to compete with their state-of-art Si-based counterparts. They had already entered the commercial market and have been gaining popularity – especially in Japan – and all the major manufacturers planned to increase production in coming years. For me, the potential for GaN power devices were especially illuminated by the fact that about one quarter of the world's energy consumption is switching loss. To illustrate the capabilities of nitride technology, GaN and Si based power electronics were compared in terms of physical size and output characteristics. The former were shown to be superior, e.g. for application in electric powertrains, therefore they could play a significant role in the long-awaited advent of electric vehicles. All panelists agreed in the promising future, but the limits of nitride devices and the applications where they might prove to be inferior to SiC devices were disputed. Steve Stoffels mentioned that he expected diamond devices to play a certain role in the future. Researchers from MIT raised the rather surprising issue that it was increasingly hard to find PhD students for nitride-related projects as due to the industry's communication students tended to believe that in this field all the exciting scientific challenges had been solved. Michael Briere expressed his doubts whether enhancement-mode devices were ever to become suitable for real-life applications, due to their low threshold voltage. Concluding the session, he took the opportunity to remind the audience of the importance of respecting IP laws.

In Thursday's session (titled *GaN on Silicon Electronic Devices and Process Innovations*), too, I found the invited talk the most interesting. Farid Medjdoub (*Institute d'Electronique, de Microelectronique et de Nanotechnologie, France*) reviewed the potential applications for GaN-on-Si in mm-wave electronics and analysed the technical issues that GaN-on-Si technology needed to overcome, such as the problem of self-heating, consequence of poor thermal conductivity of Si. He also reported on some of the recent improvements in this field, with particular focus on novel devices with ultra-thin barriers that enabled operation above 100 GHz. The last talk of the session – presented by Marko Tadjer from *NRL* – also captured my attention as it focused on AlN passivation layers on AlGaN/GaN HEMTs (as an alternative to the conventional SiN passivation) deposited by atomic layer epitaxy at various temperatures. These passivation capping layers were found to reduce the degradation of dynamic on-resistance and AlN-passivated devices exhibited lower off-state leakage current and higher breakdown voltage than SiN-passivated ones.

On Thursday I also attended the talks of R. Webster and I. Griffith, from our research group (*Micro- and Nanostructural Materials, University of Bristol*), who both gave excellent and very informative presentations on transmission electron microscopy of nitride nanorods in section A). The day was concluded by the conference banquet where it was announced that Beijing had been chosen for the location of ICNS-11.

As the Electronic Devices section ended on Thursday, I attended the Growth session on Friday morning and found the presentation of V. Wheeler (from *NRL*) really fascinating, as it focused on the growth of nitride semiconductors on fluorine-functionalised graphene. She and her colleagues demonstrated the growth of good quality GaN by MOCVD, applying ALN nucleation layers deposited with ALE on graphene. These graphene interlayers could serve as the base layer for hot electron transistors but also could have interesting effects on the thermal boundary resistance between semiconductor and substrate. Hopefully our group can establish a collaboration and investigate the vertical thermal transport in graphene in such samples.

After the morning session the conference was concluded by a series of plenary talks.

In conclusion, ICNS-10 was a fantastic experience where I have learned a great deal about nitride devices and gained invaluable insight into various topics of this field. I have seen numerous presentations that were truly inspiring and helped me see certain aspects of my own research in a new light. Hopefully, I managed to draw some attention to the work of our group and establish some new scientific relationships. I believe the coming years will be eventful and exciting for the whole field and will completely redraw the map of markets of electronics and lighting. The proverbial genie of nitrides is out of the bottle; for me, this was the main message of the ICNS-10. I would like to thank the UKNC for the financial support that made my participation in this amazing conference possible.

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[1] T.P. Chow, humorously introducing himself in the Rump Session on 28th August