International Workshop on Nitride semiconductors 2008, Montreux, Switzerland Travel Bursary Report

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I. INTRODUCTION

The International Workshop on Nitride semiconductors 2008 (IWN2008) was held in Montreux, Switzerland between the 6th and 10th of October and was the fifth in a series of biennial workshops. IWN2008 was attended by over 700 participants, from various countries, including 35 invited speakers. The four day event comprised of over 500 presentations, and additionally over 250 posters were on display in 3 sessions. IWN2008 consisted of a forum for presenting state-of-the-art results, the latest advances and future trends in research and technology of group III-nitrides and related semiconductors. The format of this workshop included presentations of invited (35 min), contributed (15 min), and late news (15 min) lectures in plenary sessions, seven focused workshops on specific topics of nitride research, poster presentations and an industrial exhibition. Lastly, the main conclusions of the workshop sessions were presented in the closing day of the conference, aiming to share the highlights of the focused workshop sessions among all participants of IWN2008. This report is designed to provide a summary of the recent research progress on nitride semiconductors and is organized into the themes of the parallel workshop sessions.

II. SUBSTRATES FOR NITRIDE EPITAXY

In the workshop "substrates for nitride epitaxy" and in two of the plenary sessions the following themes were discussed: GaN bulk crystal grown by hydride vapor phase epitaxy (HVPE) and ammonothermal method, free-standing GaN, silicon and AlN substrates, non-polar substrates, semi-polar substrates, and new approaches. From these talks the important things to consider for substrate growth is the lattice and thermal mismatch, conduction properties, growth rate, cost, wafer size or crystal size and shape and the resulting crystallinity, dislocation density, roughness, pits, cracks and bowing. In the future it is predicted that GaN bulk crystals will be grown at a lower cost (currently at ∼$10,000 a wafer), with better quality and in larger wafers (currently GaN wafers are 2 inch diameter).

III. CHALLENGING MATERIALS ISSUES

A. InN and high In content alloys

In the workshop session "challenging materials issues: InN and high In content alloys" and in four of the plenary sessions the following topics were discussed: higher precision InN band gap determination, advances in growth of InN by plasma assisted molecular beam epitaxy (PAMBE), metal-organic chemical vapor deposition (MOCVD) and metal-organic vapor phase epitaxy (MOVPE), understanding the propensity for n-type, achieving and analysing p-type InN, the effect of residual donors and dislocations, analysing bulk, surface and interface properties and fabrication of InN nanostructures.

Approximately seven years have passed since the revision of the InN band gap and InN still remains the least studied material in the group III-nitrides. Goldhahn *et al.* and Schley *et al.* have studied the band structure of InN by optical measurements and determined the fundamental band gap, E_0 of wurtzite and zinc-blende InN to be 0.678 eV and 0.595 eV, respectively.[1–3] It was also noted at IWN2008 that band gap renormalization (BGR) should be taken into account, since InN has a high carrier concentration. Currently there are two methods of estimating the extent of BGR and Goldhahn *et al.* stated that taking into account many-body interactions was considered the more accurate method. Determination of the band gap also requires incorporation of the non-parabolicity of the conduction band and the conduction band filling, where the Fermi level in InN is generally high in the conduction band and hence a Burstein-Moss shift is observed in absorption spectroscopy.

InN is known to exhibit extreme electronic properties and it is difficult to grow high quality InN with low electron concentrations and high mobilities. This is due to InN growth requiring a low growth temperature, $\sim 500°C$ due to a low InN dissociation temperature, a high equilibrium nitrogen vapor pressure over the InN film and also

because of the large lattice and thermal expansion coefficient mismatch between InN and any candidate substrates. High quality InN films on sapphire have been grown by PAMBE[4–8], MOCVD[9] and MOVPE[10] and the properties of these materials are greatly dependent on layer thickness, substrate material (buffer layers), growth temperature, stoichiometry and polarity. Yamguchi *et al.* demonstrated a new growth method that used In-rich conditions of growth followed by a nitrogen-plasma treatment. The excess In was observed as In droplets on the surface and after the nitrogen-plasma supply In droplets were no longer seen and the thickness of InN was increased by 160 nm. Krischok *et al.* have studied the surface properties of clean InN by combining growth with surface studies in one ultra-high vacuum chamber and have observed a (2×2) or $(\sqrt{3} \times \sqrt{3})$R30° surface reconstruction, dependent on the substrate growth temperature (440°C or 450°C).

Gallinant *et al.* have examined the origin of the unintentionally high electron concentrations in In-face InN, which could originate from unintentionally incorporated impurities and/or from threading dislocations. Nanishi *et al.* concluded in his talk that dislocations are probably not responsible for the propensity for n-type. Darakchieva *et al.* have used optical Hall effect measurements to study the variation of the bulk free electron concentration with film thickness. The work by Darakchieva *et al.* suggests that N vacancies do not wholly account for the carrier concentrations and that H donors are good candidates. Tuomisto *et al.* have investigated vacancy formation under different growth conditions with positron annihilation spectroscopy. In vacancies and vacancy clusters have been observed and correlate with the free electron density.[11] Tuomisto *et al.* found that the In vacancy concentration is not dependent on the growth stoichiometry suggesting that extended defects and strain are more crucial in vacancy formation than growth thermodynamics. Tuomisto *et al.* also examined the vacancy-type defects in irradiated InN and observed negative non-open volume defects, possibly N interstitials were formed by He irradiation to compensate n-type conductivity. Gorczyca *et al.* reported that In clustering in InAlN and InGaN will theoretically decrease the band gap and hence the band gap bowing parameter will increase. While Broesler *et al.* have reported that they find the bowing parameter for InAlN to be 4.6 ± 3.0 eV.

Veal *et al.* reported the valence band offsets (VBO) of InN/GaN and InN/AlN to be 0.58 eV and 1.52 eV, respectively.[12,13] Previous measurements of the VBO yield a large range of values that are attributed to growth quality, incorrectly accounting for strain-induced piezoelectric fields, neglecting the effects of the hybridization of the In 4*d* and Ga 3*d* peaks and the spin-orbit split d-level character of these peaks, lifetime broadening effects and inelastic losses due to conduction band plasmons.

Unlike the majority of semiconductors, InN exhibits a surface electron accumulation region.[14,15] Bailey *et al.* presented an investigation into determining the composition of InGaN at which the transition from an electron accumulation at the surface of In-rich InGaN to an electron depletion at the surface of Ga-rich InGaN occurs.[16] Ager III *et al.* have investigated the electrical properties of InGaN-Si heterojunctions. The conduction band minimum (CBM) of $In_{0.45}Ga_{0.55}N$ is aligned with the valence band maximum of Si and hence a small degree of band bending at the interface and efficient electron-hole recombination is predicted. While Yu *et al.* have discovered that irradiating InN results in the Fermi level increasing until it saturates at the Fermi stabilization energy, also called the branch point energy or charge neutrality level. This increase in the Fermi level can be explained by the extremely low CBM and with the amphoteric defect model that describes the formation energy and character of the dominant native defects. King *et al.* have determined the charge neutrality level to lie 1.83 ± 0.10 eV above the valence band maximum of InN.[17] Surface states will be primarily donor-like (acceptor-like) when the Fermi level is below (above) the charge neutrality level. For InN, the Fermi level position is usually below the charge neutrality level, enabling the existence of unoccupied donor-like surface states. These positively charged states pin the surface Fermi level position near the charge neutrality level, resulting in the Fermi level increasing at the surface of InN. Alternatively, this can be viewed as the conduction and valence bands bending downward with respect to the Fermi level at the surface of InN. Hence an electron accumulation layer is formed at the surface of InN. There is intense interest in the microscopic origins of the electron accumulation layer and it has been suggested that the donor-like surface states originate from In-In bonds in a surface In-adlayer[18], unintentional H doping, In and N vacancies, and oxygen incorporation. The InN film polarity is determined by growth conditions and substrate and has been shown to have very little influence on the electron accumulation layer.[19] Krischok *et al.* have also demonstrated that the surface Fermi level is pinned even during growth. Nanishi *et al.* attempted to remove the electron accumulation layer by growth of a-plane InN. Unfortunately, the Fermi level in as-grown non-polar InN is still pinned high above the CBM. Surface preparations (N^+-ion bombardment, Ar^+-ion bombardment, HCl etching, atomic hydrogen cleaning) alter the electronic properties slightly. However, treated InN samples still exhibit a surface electron accumulation layer. Gwo *et al.* reported that the Fermi level is unpinned at *in situ* cleaved a-plane InN surfaces resulting in flat surface bands.[20] This is the first observation of flat band InN but unfortunately when *in situ* cleaved a-plane InN is removed from vacuum or material is deposited onto this sample, donor-like surface states are expected to form and hence

downward band bending will be observed.

The surface electron accumulation layer is also predicted to be present at the surface of p-type InN and hence an inversion layer is formed. This results in the surface of p-type InN being electrically isolated from the p-type bulk, preventing direct electrical measurements of p-type InN. Electrochemical capacitance voltage (ECV) measurements have shown that Mg doping introduces acceptors, suggesting that InN:Mg are p-type in the bulk.[21–24] Brown *et al.* have used ECV measurements combined with Hall effect measurements to decrease the extent of the surface electron accumulation layer and measure the transport properties. Measurements of the Seebeck coefficient or thermopower were used by Miller *et al.* to determine the charge of the majority mobile carriers. Miller *et al.* demonstrated the presence of mobile holes and with n-type InN samples obtained a best fit electron effective mass of $0.05m_e$. Ishitani *et al.* estimated that the hole mobility is 15–33 cm^2/Vs. Wang *et al.* reported that not all Mg-doped InN samples exhibit p-type behavior and Yoshikawa *et al.* have found that complex defects, such as In and multiple N vacancies are the cause of n-type doping in overdoped-Mg InN samples.[21]

Yoshikawa *et al.* have also reported the realization of novel InN/GaN monolayer quantum wells.[25] Grandal *et al.* showed InN nanocolumns grown on a-plane GaN exhibited different transport behavior than InN nanocolumns grown along the c-plane on GaN. InN presents "challenging material issues" and much progress has been made since the band gap revision. Yoshikawa stated that "InN is now well understood in terms of bulk and surface properties." Therefore it is expected that in the future InN will be implemented into more device ideas.

B. AlN and high Al content alloys

In the workshop session "challenging materials issues: AlN and high Al content alloys" the following subjects were discussed: point defects and threading dislocations in AlN, growth by HVPE and molecular beam epitaxy, AlN grown on novel substrates, AlN films on Si, SiC substrates, AlInN/GaN quantum well structures, p-type AlGaN:Mg and deep ultra-violet light emitting diodes (LEDs). Future trends expected in this field are reduction of the dislocation density, controlling point defects in AlN, improvement in p-type doping, and the quality of deep ultra-violet LEDs.

C. Non-polar epitaxy

The "challenging materials issues: non-polar epitaxy" workshop session and a plenary session included presentations about: epitaxy on different substrates ($LiAlO_2$, SiN_x masks, m-SiC, ZnO), improvement by interlayers, non-polar AlN, AlN and GaInN on ZnO, growth by MOVPE, HVPE, PAMBE and pulsed laser deposition, semi-polar facet LEDs, high intensity yellow LEDs, controlling optical anisotropy (strain at barriers), doping and activation energy of Mg in GaInN, x-ray diffraction for non-polar substrates, In incorporation in non-polar planes (theory) and better green light emission and polarization. It is predicted that in the future work will concentrate on non-polar substrates and incorporating high In concentrations.

IV. NANOSTRUCTURES

The type of nanostructures discussed in the workshop session "nanostructures" included quantum wells, quantum dots, quantum dashes, nanoislands, nanocolumns/nanorods, and nanowires. The topics discussed ranged over growth and characterization, optical measurements, theoretical studies, a new class of nanostructure: quantum dashes, diffusion on non-polar surfaces, InGaN quantum dot lasers, growth on a Si substrate, patterned substrates for nanowires, electrical properties of nanowires, and the challenges associated with doping. Predicted for the future are single photon emitters at room temperature, quantum dot laser diodes, nanowire transistors and nanowire LEDs.

V. NOVEL PHYSICAL CONCEPTS AND DEVICES

The "novel physical concepts and devices" workshop session included topics on spintronics, plasmonics, microcavities, photonic crystals, distributed Bragg reflectors, photon propagation and management, slow light, rare-earth dopants, electro-opto-mechanical devices, ferromagnetism and spin effects in nitrides, and the electronic levels of Mn, Fe and Nd^{3+} in GaN. Devices considered were ultra-violet imaging arrays, light emitting high electron mobility transistors (HEMTs), intersubband devices and photo-induced etching.

VI. OPTO 1: MATERIALS AND PHYSICS AND OPTO 2: TECHNOLOGY AND DEVICES

The two workshop sessions on opto-electronics discussed the following themes: localization effects, structural characterization, quantum hetero-structures, threading dislocations, device processing, LED and laser performance, light extraction, high current injection, thermal management, packaging, green laser diodes, efficiency droop, LED light extraction, high brightness LEDs, high efficiency deep ultra-violet emitters, laser diode degradation and novel laser structures.

VII. ELECTRONIC DEVICES

The electronic devices considered in the session "electronic devices" and two plenary talks included: two dimensional electron gas transport, high electron mobility and bipolar transistors, technology, sensors, high power switches, HEMTs, metal-oxygen-semiconductor field effect transistors, quantum dot sensors, RF devices, power switching devices, metal-oxygen-semiconductor gate technology, and surface passivation. In the future further improvement in epitaxial growth and material quality, reliability and stability (understanding the mechanisms, passivation and metal insulator semiconductor gates), and using vertical structures are predicted.

VIII. CONCLUSION

To summarize, IWN2008 was an excellent workshop to gain knowledge on the extreme electrical properties of InN, in particular the origins of n-type doping and understanding the difficulties p-type doping InN using the branch point energy concepts. Many other presentations focused on substrates, growth, characterization, nanostructures and device design of the III-N materials. The report above describes some of the highlights of the conference and the most topical research work that has special relevance to my own work. The conference provided an excellent opportunity to extend my knowledge and interact with other researchers working within the field, a number of new contacts have resulted from IWN2008. The mixture of plenary and focused workshops was especially valuable to myself and the poster sessions were also very useful, inducing many helpful discussions. I am very grateful to the UK Nitrides Consortium for the travel bursary funding to assist attendance to IWN2008.

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[1] R. Goldhahn, P. Schley, A. Winzer, G. Gobsch, V. Cimalla, O. Ambacher, M. Rakel, C. Cobet, N. Esser, H. Lu, et al., Phys. Stat. Sol. A **203**, 42 (2006).

[2] P. Schley, R. Goldhahn, C. Napierala, G. Gobsch, J. Schrmann, D. J. As, K. Lischka, M. Feneberg, and K. Thonke, Semicond. Sci. Technol. **23**, 055001 (2008).

[3] P. Schley, C. Napierala, R. Goldhahn, G. Gobsch, J. Schrmann, D. J. As, K. Lischka, M. Feneberg, K. Thonke, F. Fuchs, et al., Phys. Stat. Sol. C **5**, 2342 (2008).

[4] C. S. Gallinat, G. Koblmuller, J. S. Brown, S. Bernardis, J. S. Speck, G. D. Chern, E. D. Readinger, H. Shen, and M. Wraback, Appl. Phys. Lett. **89**, 032109 (pages 3) (2006).

[5] G. Koblmüller, C. S. Gallinat, S. Bernardis, J. S. Speck, G. D. Chern, E. D. Readinger, H. Shen, and M. Wraback, Appl. Phys. Lett. **89**, 071902 (2006).

[6] I. Gherasoiu, M. O'Steen, T. Bird, D. Gotthold, A. Chandolu, D. Y. Song, S. X. Xu, M. Holtz, S. A. Nikishin, and W. J. Schaff, Phys. Stat. Sol. C **5**, 1642 (2008).

[7] H. Lu, W. J. Schaff, J. Hwang, H. Wu, W. Yeo, A. Pharkya, and L. F. Eastman, Appl. Phys. Lett. **77**, 2548 (2000).

[8] Y. Saito, N. Teraguchi, A. Suzuki, T. Araki, and Y. Nanishi, Jpn. J. Appl. Phys. Part 2 **40**, L91 (2001).

[9] O. Briot, B. Maleyre, and S. Ruffenach, Appl. Phys. Lett. **83**, 2919 (2003).

[10] M. Jamil, R. A. Arif, Y.-K. Ee, H. Tong, J. B. Higgins, and N. Tansu, Phys. Stat. Sol. A **205**, 1619 (2008).

[11] F. Tuomisto, A. Pelli, K. M. Yu, W. Walukiewicz, and W. J. Schaff, Phys. Rev. B **75**, 193201 (2007).

[12] P. D. C. King, T. D. Veal, C. E. Kendrick, L. R. Bailey, S. M. Durbin, and C. F. McConville, Phys. Rev. B. **78**, 033308 (2008).

[13] P. D. C. King, T. D. Veal, P. H. Jefferson, C. F. McConville, T. Wang, P. J. Parbrook, H. Lu, and W. J. Schaff, Appl. Phys. Lett. **90**, 132105 (2007).

[14] H. Lu, W. J. Schaff, L. F. Eastman, and C. E. Stutz, Appl. Phys. Lett. **82**, 1736 (2003).

[15] I. Mahboob, T. D. Veal, C. F. McConville, H. Lu, and W. J. Schaff, Phys. Rev. Lett. **92**, 036804 (2004).

[16] L. R. Bailey, T. D. Veal, P. D. C. King, C. F. McConville, J. Pereiro, J. Grandal, M. A. Sánchez-García, E. Muñoz, and E. Calleja, J. Appl. Phys. (in press).

[17] P. D. C. King, T. D. Veal, P. H. Jefferson, S. A. Hatfield, L. F. J. Piper, C. F. McConville, F. Fuchs, J. Furthmüller, F. Bechstedt, H. Lu, et al., Phys. Rev. B **77**, 045316 (2008).
[18] T. D. Veal, P. D. C. King, P. H. Jefferson, L. F. J. Piper, C. F. McConville, H. Lu, W. J. Schaff, P. A. Anderson, S. M. Durbin, D. Muto, et al., Phys. Rev. B **76**, 075313 (2007).
[19] P. D. C. King, T. D. Veal, C. F. McConville, F. Fuchs, J. Furthmüller, F. Bechstedt, P. Schley, R. Goldhahn, J. Schörmann, D. J. As, et al., Appl. Phys. Lett. **91**, 092101 (2007).
[20] C.-L. Wu, H.-M. Lee, C.-T. Kuo, C.-H. Chen, and S. Gwo, Phys. Rev. Lett. **101**, 106803 (2008).
[21] X. Wang, S.-B. Che, Y. Ishitani, and A. Yoshikawa, Appl. Phys. Lett. **91**, 242111 (pages 3) (2007).
[22] R. E. Jones, K. M. Yu, S. X. Li, W. Walukiewicz, J. W. Ager III, E. E. Haller, H. Lu, and W. J. Schaff, Phys. Rev. Lett. **96**, 125505 (2006).
[23] J. W. Ager III, R. E. Jones, D. M. Yamaguchi, K. M. Yu, W. Walukiewicz, S. X. Li, E. E. Haller, H. Lu, and W. J. Schaff, Phys. Stat. Sol. B **244**, 1820 (2007).
[24] X. Wang, S.-B. Che, Y. Ishitani, and A. Yoshikawa, Appl. Phys. Lett. **92**, 132108 (2008).
[25] A. Yoshikawa, S. B. Che, N. Hashimoto, H. Saito, Y. Ishitani, and X. Q. Wang, J. Vac. Sci. Technol. B **26**, 1551 (2008).