The 14th International Conference on Nitride Semiconductors (ICNS-14)

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The 14th International Conference on Nitride Semiconductors (ICNS-14) was successfully held in Fukuoka, Japan, from 12 to 17 November 2023. ICNS is one of the most important international conferences on group-III nitride semiconductors. It presents high-impact scientific and technological advances in materials and devices based on group-III nitride semiconductors. A total of 1241 participants from 32 countries and regions attended ICNS-14. The conference focused on four main topics: growth, characterization, optical devices, and electronic devices. There were 424 oral presentations and 407 poster presentations.

My research work focuses on investigating the structure-property relationships in nitride electronic devices. Recently, I used hyperspectral scanning capacitance microscopy (SCM) to map the threshold voltage (V_{th}) distribution in GaN-based high electron mobility transistors (HEMTs) at the nanoscale. I also directly correlated nanoscale fissure-like defects on the sample surface to local V_{th}, gaining insights into the impact of defects and AlGaN barrier inhomogeneities on local V_{th}. I made an oral presentation about this work at ICNS-14 with the title "Nanoscale Mapping of Threshold Voltage Distribution in GaN-based High Electron Mobility Transistor Structures." After the presentation, many colleagues from other institutes approached my supervisor, Prof Rachel Oliver, and me with further inquiries about this work. Eventually, I was honored with the Best Student Award for my oral presentation. I am very grateful to my team members in this work, especially my supervisor, Prof Rachel Oliver, and my mentor, Dr Saptarsi Ghosh. I also want to thank the UK Nitrides Consortium (UKNC) for awarding me a Phil Dawson Travel Award to fund my attendance at ICNS-14.

Prof Rachel Oliver (right)
Chen Chen (left)

Except for my presentation, the Cambridge Centre for Gallium Nitride also contributed four other excellent presentations. Prof Rachel Oliver gave an invited talk titled “Insights into Porous GaN from Electron Microscopy”. Dr Saptarsi Ghosh presented a poster titled “Optimization of GaN / Porous GaN Distributed Bragg Reflectors Grown on Si”. Dr Martin Frentrup delivered an oral presentation titled “Polarity Determination of Crystal Defects in Zincblende GaN by Aberration-Corrected Electron Microscopy”. Mr Yihong Ji presented a talk titled “Morphological, Structural, and Strain Relaxation Properties of Porous InGaN-Based Pseudo-Substrate for Long Wavelength μ-LEDs”.

In addition to focusing on our Centre’s presentations, I also paid attention to other insightful presentations from different institutes. The following are my notes on some selected talks.

1. N-polar nitrides and N-polar HEMTs

Metal-polar nitride materials and devices have been extensively researched. During the conference, I gained the impression that N-polar nitride materials and devices are emerging as a major research trend for the development of next-generation RF and power electronic devices. Numerous recent studies on both N-polar nitride materials and N-polar HEMTs were presented.

1.1 N-polar nitrides

1.1.1 Large dislocation reduction in N-polar GaN by wet-etch and regrowth

(presented by Pietro Pampili *etc.* from Tyndall National Institute, University College Cork, Ireland)

The reason why N-polar GaN was not widely researched previously was that its crystal quality is still somewhat poorer than that of standard Ga-polar epilayers. The best N-polar samples reported in the literature have X-ray rocking curve full widths at half maximum (FWHMs) around 400 arcsec for symmetric and 600 arcsec for skew-symmetric reflections.

To address this issue, the authors have developed a two-step growth approach. In the first step, N-polar GaN is grown on offcut sapphire, followed by selective wet etching in a KOH-containing solution, and subsequent regrowth to restore a smooth epilayer. A dense array of micro-pyramids after KOH etching acts as the base for subsequent lateral overgrowth until a 2D epilayer is formed again. They found that low-temperature growth in nitrogen favours the immediate expansion of residual $(000\bar{1})$ facets, while standard high-temperature conditions in hydrogen favour the growth on slanted sidewalls and lead to a significant delay in the formation and expansion of $(000\bar{1})$ facets, which is essential for the bending and annihilation of threading dislocations. Thus, high-temperature overgrowth reduced the FWHMs to below 250 arcsec for both $000\bar{2}$ and $10\bar{1}\bar{1}$ reflections.

1.1.2 Pushing the Mg doping limit in N-polar GaN by controlling self-compensation

(presented by Masahiro Kamiyama *etc.* from Department of Materials Science and Engineering, North Carolina State University, USA)

To realize N-polar nitride devices, it is necessary to achieve controllable p-type doping in N-polar GaN. Similar to Ga-polar GaN, N-polar GaN exhibits a maximum achievable carrier concentration followed by a drop in carrier concentration with Mg doping. This phenomenon is often referred to as the knee behavior. The authors investigated the doping limit and the nature of compensation that leads to this knee behavior in Mg-doped N-polar GaN. They found that a large fraction of Mg atoms was incorporated in electrically inactive states, and the formation of the neutral $3Mg\text{-}V_N$ defect complex is mainly responsible for the knee behavior. Based on compensation control, the p-type carrier concentrations achieved in their study are comparable to the more mature Ga-polar technology, supporting the possibility for next-generation devices based on N-polar GaN.

1.1.3 Demonstration of Controllable Si Doping in N-polar AlN by Plasma Assisted Molecular Beam Epitaxy

(presented by Md Irfan Khan *etc.* from Department of Electrical Engineering and Computer Science, University of Michigan, USA)

N-doping of AlN is challenging in both N-polar and Ga-polar materials. In this study, the authors demonstrated controllable Si doping in N-polar AlN films grown on a single-crystal AlN substrate by plasma-assisted molecular beam epitaxy (PAMBE). They revealed that Si incorporation dramatically decreases at a high growth temperature (950°C). To enable higher silicon incorporation, low-temperature growth of high-quality AlN films was developed using Ga as a surfactant. By lowering the growth temperature of AlN to 750°C, they successfully incorporated Si with concentrations as high as 2×10^{20} cm^{-3} and demonstrated an electron concentration as high as 1×10^{19} cm^{-3} at room temperature.

1.2 N-polar HEMTs

1.2.1 High-quality N-polar GaN/AlGaN/GaN/AlN HEMTs by multistep temperature and supersaturation regime growth on off-cut SiC substrates

(presented by Ingemar Persson *etc.* from Center for III-Nitride Technology, Linköping University, Sweden)

High-quality N-polar GaN-based HEMTs were also demonstrated. N-polar HEMTs have many advantages. They feature a 2DEG situated in the top GaN channel layer above the natural back-barrier layer (the 2DEG is situated below the front barrier layer in metal-polar HEMTs), providing better 2DEG confinement and reducing short-channel effects. Moreover, low-ohmic contact resistivity is attainable. However, the growth of N-polar device structures still presents significant challenges associated with rough surfaces (step-bunching) or high levels of impurities (e.g., oxygen) and, most importantly, polarity inversions.

The authors reported the development of a multi-step temperature growth strategy to achieve high-quality N-polar GaN on low-temperature GaN buffer layers via hot-wall metal-organic chemical vapor phase deposition (MOCVD) on 4H-SiC with various low off-cut angles towards the a-plane and m-plane. A high growth rate of 50 nm/min and fairly low dislocation densities (3.0×10^{8} cm^{-2} for screw and 1.0×10^{9} cm^{-2} for edge type) were achieved. Furthermore, step-bunching was eliminated. The root mean surface roughness for N-polar GaN grown on a- and m-plane mis-cut substrates is 1.4 nm and 0.5 nm, respectively. Finally, they also demonstrated N-polar GaN-based HEMT structures with high charge carrier density (Ns ~1.0×10^{13} cm^{-2}) and electron mobility (μ ~1400 $cm^{2}V^{-1}s^{-1}$).

1.2.2 Low Sheet Resistance N-Polar InAlGaN/GaN HEMT

(presented by Robert Hamwey *etc.* from Department of ECE, University of California, Santa Barbara, USA)

The authors reported the fabrication and results of the first N-polar InAlGaN HEMT. AlGaN/GaN HEMTs demonstrate considerably smaller 2DEG densities compared to other III-nitride heterojunctions. As a result, alternative high-charge heterostructures have been investigated. InAlGaN/GaN, in particular, has emerged as a promising candidate. Hall measurements showed a 2DEG density of 2.85×10^{13} cm^{-2} and a bulk mobility of 1048 $cm^{2}V^{-1}s^{-1}$. Transfer length method measurements demonstrated a low sheet resistance of 179 Ω/☐ in the source-drain direction.

2. Two-dimensional hole gas (2DHG) in nitride heterostructures

The 2DEG, observed in AlGaN/GaN heterostructures, for example, has been well-researched. At the conference, I got the impression that 2DHG may become the next big research topic, as many recent works on 2DHG were presented.

2.1 Generation of 2DHG

2.1.1 Band engineering of polarization induced 2D hole gases in GaN/AlGaN heterostructures

(presented by Pengfei Shao *etc.* from Nanjing University, P. R. China)

Two-dimensional hole gases (2DHGs) induced by polarization at the GaN/AlGaN heterointerface are attractive for GaN p-channel transistors, necessary for GaN complementary logic integrated circuits. In this work, the authors investigated 2DHGs in GaN/AlGaN/GaN heterostructures grown by plasma-assisted molecular beam epitaxy. In terms of energy band engineering for III-nitride heterostructures, they identified various approaches to increase the 2DHG density on the GaN/AlGaN/GaN platform by modulating the energy band profiles around the 2DHG. For instance, introducing Mg doping in the barriers to push up the valence band (VB), or incorporating a thin, very-high-Al-composition Al(Ga)N polarization insertion layer. The highest 2DHG density they achieved is beyond 10^{14} cm^{-2}, the mobility reaches 28 $cm^{2}V^{-1}s^{-1}$, and a record low sheet resistance of 4.7 kΩ/☐ is obtained.

2.1.2 A new insight on the co-existence of two-dimensional electron- and hole gases and their properties in III-N heterostructures

(presented by R. Lingaparthi *etc.* from Temasek Laboratories, Singapore)

For the development of GaN-based complementary electronics, an $Al_xGa_{1-x}N/GaN/Al_xGa_{1-x}N$ heterostructure is a viable option to achieve 2DEG and 2DHG in the same structure. In this work, the authors studied the coexistence of 2DEG and buried 2DHG using three different $Al_xGa_{1-x}N/GaN/Al_xGa_{1-x}N$ heterostructures. Depth profiles of carrier concentration demonstrated that 2DEG and buried 2DHG do not coexist in the $Al_xGa_{1-x}N/GaN/Al_xGa_{1-x}N$ heterostructure, regardless of whether GaN is relaxed or coherently grown. They also show that the absence of sources to supply holes to the quantum well resulted in the absence of buried 2DHG.

2.2 Characterisation of 2DHG

2.2.1 Weak antilocalization and spin-orbit coupling in 2DEG and 2DHG in GaN/AlN heterostructures

(presented by Chuan Chang *etc.* from Cornell University, USA)

The authors presented an analysis of low-field magnetoconductivity measurements of polarization-induced 2DHG. They grew a GaN/AlN sample on a single-crystal AlN substrate using molecular beam epitaxy (MBE). Then, they used a characterization technique called angle-resolved photoemission spectroscopy (ARPES) to characterize the sample. ARPES is a powerful technique for directly observing the electronic structure with energy- and momentum-resolved information. It has played a central role in the discovery, characterization, and understanding of quantum materials. They successfully observed the 2DHG at the GaN/AlN heterostructure. The quality of the 2DHG was also observed to be high: ($\mu_h^{300K} = 32\ cm^2V^{-1}s^{-1}$, $p_h^{300K} = 4.0 \times 10^{13}\ cm^{-2}$, $\mu_h^{2K} = 722\ cm^2V^{-1}s^{-1}$, $p_h^{2K} = 2.1 \times 10^{13}\ cm^{-2}$). As I had noticed some potential 2DHG in my samples previously, I will try to use more convenient characterization techniques (e.g., hyperspectral SCM) to verify 2DHG systematically.

Conclusion

In conclusion, as I observed during the conference, topics such as N-polar nitrides, N-polar HEMTs, and 2DHG in nitride heterostructures may deserve more attention in the future.