

**MOVPE GROWTH OF III-NITRIDE
BASED ADVANCED HETEROSTRUCTURES**

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MOVPE Growth of III-Nitride based Advanced Heterostructures

by

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Dedicated to Readers & Researchers

Certificate

This is to certify that the research work presented in this thesis entitled “**MOVPE Growth of III-Nitride based Advanced Heterostructures**”, being submitted by **Mr. Kapil Narang** for the award of the degree of **Doctor of Philosophy** to the Indian Institute of Technology Delhi is a record of bonafide research carried out by him under our guidance and supervision. He has fulfilled the requirements, which to our knowledge have reached the requisite standard for the submission of the thesis.

To the best of our knowledge, this thesis does not contain any results which have been submitted in part or full at any other Institute or University for the award of any degree or diploma.

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ABSTRACT

III (Al, Ga, In)-Nitride (N) family material hetero-structures have emerged as an important building block for the next generation opto-electronics and electronics applications. Among many devices, AlGaIn/GaN HEMT (High Electron Mobility Transistor) has been widely used for high frequency, high power RF applications. It is the inherent material properties such as large energy bandgap, high breakdown field, high peak electron velocity and very high 2DEG concentration $\sim 1 \times 10^{13} \text{ cm}^{-2}$ even without intentional doping which make it superior to its other technological counterparts such as Si and III-As. However, there are various unsolved challenges in the epitaxial growth of crack-free, high-quality III-N based epi-layers and HEMT structures. Hence, to utilize the full potential of III-N, a systematic strategy is adopted to address several challenges related to III-N hetero-epitaxy on SiC substrate in this dissertation. The strategy involved in-depth research on III-N hetero-epitaxy followed by fine-tuning of different growth parameters at different layers/stages of HEMT structure. This leads to repeatable and sustainable material development and growth processes.

The brief details about the growth technique to grow III-Nitride hetero-epitaxy on SiC substrate i.e. MOVPE (Metal Organic Vapour Phase Epitaxy) and characterization tools to characterize structures are also discussed.

The work reported in this dissertation is focused on the improvement of quality (crystalline, surface and interface) of AlN nucleation layer, AlGaIn and InAlN barrier layers of HEMT structures. Hence, the work reported in this dissertation highlights the importance of growth parameters to achieve high quality (crystalline, interface and surface) epi-layers of III-Nitride based HEMT structure.

The work reported in this dissertation has resulted an optimized AlGaIn/GaN and InAlN/GaN HEMT structures with step-flow surface morphology with excellent electrical and structural characteristics. The achieved 2DEG mobility is $2050 \text{ cm}^2/\text{V}\cdot\text{s}$ with $1 \times 10^{13} \text{ cm}^{-2}$ 2DEG concentration in AlGaIn/GaN while $1500 \text{ cm}^2/\text{V}\cdot\text{s}$ with $2.4 \times 10^{13} \text{ cm}^{-2}$ in lattice matched InAlN/GaN HEMT structures respectively

This dissertation also focuses on the growth of AlGaIn/GaN HEMT structure with thin-GaN ($\sim 200 \text{ nm}$) buffer and compared its material and device characteristics with conventional-GaN ($\sim 2 \mu\text{m}$) based HEMT structure.

The work reported in this dissertation has resulted a similar material and device characteristics of conventional-GaN and thin-GaN based AlGaIn/GaN HEMT structure.

सारांश

III (Al, Ga, In)-नाइट्राइड (N) पारिवारिक सामग्री हेटेरो-स्ट्रक्चर अगली पीढ़ी के ऑप्टो-इलेक्ट्रॉनिक्स और इलेक्ट्रॉनिक्स अनुप्रयोगों के लिए एक महत्वपूर्ण बिलिंग ब्लॉक के रूप में उभरा है। कई उपकरणों में, AlGaIn/GaN HEMT (उच्च इलेक्ट्रॉन गतिशीलता ट्रांजिस्टर) का व्यापक रूप से उच्च आवृत्ति, उच्च शक्ति RF अनुप्रयोगों के लिए उपयोग किया गया है। यह अंतर्निहित सामग्री गुण हैं जैसे कि बड़ी ऊर्जा बैंडगैप, उच्च ब्रेकडाउन फील्ड, उच्च शिखर इलेक्ट्रॉन वेग और बहुत उच्च 2DEG सांद्रता $\sim 1 \times 10^{13} \text{ cm}^{-2}$ डोपिंग के बिना भी जो इसे अपने अन्य तकनीकी समकक्षों जैसे Si और III-As से बेहतर बनाती है। हालांकि, दरार-मुक्त, उच्च-गुणवत्ता वाले III-N आधारित एपि-लेयर्स और HEMT संरचनाओं के एपिटैक्सियल विकास में विभिन्न अनसुलझी चुनौतियाँ हैं। इसलिए, III-N की पूरी क्षमता का उपयोग करने के लिए, इस शोध-कार्य में SiC सबस्ट्रेट पर III-N हेटेरो-एपिटैक्सी से संबंधित कई चुनौतियों का समाधान करने के लिए एक व्यवस्थित रणनीति अपनाई गई है। HEMT संरचना की विभिन्न परतों/चरणों पर विभिन्न विकास मापदंडों के फाइन-ट्यूनिंग के बाद III-N हेटेरो-एपिटैक्सी पर गहन शोध में शामिल रणनीति है। यह दोहराने योग्य और टिकाऊ भौतिक विकास और विकास प्रक्रियाओं की ओर जाता है।

MOVPE (मेटल ऑर्गेनिक वेपर फेज एपिटैक्सी) से SiC सबस्ट्रेट पर III-नाइट्राइड हेटेरो-एपिटैक्सी को विकसित करने के लिए विकास तकनीक के बारे में संक्षिप्त विवरण और संरचनाओं की विशेषताओं को निरूपित करने के लिए लक्षण वर्णन उपकरण पर भी चर्चा की गई है।

इस शोध-कार्य में बताया गया तरीके HEMT संरचना की विभिन्न परतों (AlN न्यूक्लियेशन परत, AlGaIn और InAlN बाधा परतों) की गुणवत्ता (क्रिस्टलीय, सतह और इंटरफ़ेस) के सुधार पर केंद्रित है। इसलिए, इस शोध-कार्य में बताए गए तरीके III-नाइट्राइड आधारित HEMT संरचना की उच्च गुणवत्ता (क्रिस्टलीय, इंटरफ़ेस और सतह) एपि-लेयर प्राप्त करने के लिए विकास मापदंडों के महत्व पर प्रकाश डालते हैं।

इस शोध-कार्य में रिपोर्ट किए गए कार्य के परिणामस्वरूप उत्कृष्ट विद्युत और संरचनात्मक विशेषताओं के साथ कदम-प्रवाह सतह आकृति-विज्ञान के साथ एक अनुकूलित AlGaIn/GaN और InAlN/GaN HEMT संरचनाएं हुई हैं। AlGaIn/GaN में $1 \times 10^{13} \text{ cm}^{-2}$ 2DEG सांद्रता के साथ प्राप्त 2DEG गतिशीलता $2050 \text{ cm}^2/\text{V}\cdot\text{s}$ है जबकि लैटिस कॉन्सटेंट मिलान InAlN/GaN में $2.4 \times 10^{13} \text{ cm}^{-2}$ 2DEG सांद्रता के साथ प्राप्त 2DEG गतिशीलता $1500 \text{ cm}^2/\text{V}\cdot\text{s}$ है।

यह शोध-कार्य थिन-GaN ($\sim 200 \text{ nm}$) बफर के साथ AlGaIn/GaN HEMT संरचना के विकास पर भी केंद्रित है और पारंपरिक-GaN ($\sim 2 \mu\text{m}$) आधारित HEMT संरचना के साथ इसकी सामग्री और उपकरण विशेषताओं की तुलना करता है। इस शोध-कार्य में रिपोर्ट किए गए कार्य के परिणामस्वरूप पारंपरिक-GaN और थिन-GaN आधारित AlGaIn/GaN HEMT संरचना की समान सामग्री और उपकरण विशेषताएँ सामने आई हैं।

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Abbreviations

MOCVD	Metal Organic Chemical Vapour Deposition
MOVPE	Metal Organic Vapour Phase Epitaxy
MBE	Molecular Beam Epitaxy
CCS	Close-Coupled Showerhead
NL	Nucleation Layer
TMG	Trimethyl Gallium
TMA	Trimethyl Aluminium
TMI	Trimethyl Indium
III-N	Three Nitride
NH ₃	Ammonia
V/III	Mole fraction ratio of Group-V to Group-III precursors
HEMT	High Electron Mobility Transistor
2DEG	Two-Dimensional Electron Gas
HRXRD	High Resolution X-Ray Diffraction
XRC	X-Ray Rocking Curve
XRR	X-Ray Reflectivity
FWHM	Full Width at Half Maximum
TDD	Threading Dislocation Density
AFM	Atomic Force Microscopy
RMS	Root Mean Square
R _q	RMS Roughness
SEM	Scanning Electron Microscopy
CL	Cathodo-Luminescence
X-CL	Cross-sectional Cathodo-Luminescence
SIMS	Secondary Ion Mass Spectroscopy