INVESTIGATION OF TRAPS INDUCED RELIABILITY ISSUES IN GAN HIGH ELECTRON MOBILITY TRANSISTORS

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By

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Dedicated to

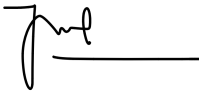
My Parents, My Husband,

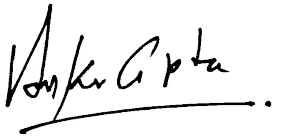
&

Three Cute Kids - Kanha, Guddan, and Aadu

Certificate

This is to certify that the research work presented in this thesis titled **"Investigation of Traps Induced Reliability Issues in GaN High Electron Mobility Transistors"**, being submitted by **Ms. Shradha Gupta** for the award of degree of **Doctor of Philosophy** to Indian Institute of Technology Delhi. The work embodied in this dissertation is a record of bonafide research carried out by her under our guidance and supervision. This thesis to the best of our knowledge does not contain any results which have been submitted in part or full for a degree or diploma at any other University or Institute.





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Shradha Gupta

Abstract

GaN-based High Electron Mobility Transistors (HEMT) are excellent candidates for high-frequency and high-power applications due to their wide bandgap, high breakdown voltage, and high output power. However, the increasing requirement of reduced length for high-volume production introduces various issues within the device and affects its reliability. Several reliability issues depend on the presence of electrically active defects in AlGaN/GaN HEMTs during the epitaxial layer growth and at each processing step of fabrication. However, the physical presence and location of these defects are still unclear and need further investigation. The trapping/de-trapping of the electron into these defects causes adverse effects, which includes current collapse, kink effect, instability of leakage, and threshold voltage at different operating condition. Therefore, studying such reliability issues becomes essential for the GaN HEMTs to outperform the competitors in the semiconductor industry. This thesis work studies the factors affecting the long-term reliability of GaN HEMTs.

A two-dimensional analytical model was proposed to explain the drain current collapse and its subsequent recovery in the output I-V curve. The effect of parasitic resistance on the output I-V curve was presented. The drain current collapse was explained using the proposed virtual gate model. The virtual gate was formed due to the capture and movement of electrons among donor surface states from the gate edge towards the drain via hopping conduction. Later, the multi-phonon tunneling process's involvement leads to electron emission from the donor surface states at high static electric fields and recovers the drain current. The variation in leakage current with temperature confirmed the evidence of the multi-phonon tunneling process. This work also observed the self-heating effect at high drain voltages due to the increase in the channel temperature.

The deep traps were identified in AlGaN/GaN HEMTs using thermal admittance and deep-level transient spectroscopy. The occupancy of defects was determined using the measured transient admittance at different frequencies and temperatures. The on-state temperature dependence of leakage current was explained using trap-assisted and phonon-assisted tunneling currents. However, the previous model could not explain the leakage current and output IV curve near the pinch-off. Therefore, the previous model was extended to explain the complete kink contour in output IV characteristics' full gate voltage range. The virtual gate model was further modified

with real-time characteristics of surface states. The model incorporates the breakdown of the virtual gate region at a high electric field due to a reduction in the barrier height of the virtual gate. This phenomenon initiates with channel impact ionization and is later controlled through multi-phonon ionization.

The temperature-dependent off-state stress measurements were performed to explore further the effect of threshold voltage instability in AlGaN/GaN HEMTs. The in-house fabricated devices having different layer quality were utilized in this work. The change of subthreshold slope in the measured $I_{DS} - V_{GS}$ characteristics was used to estimate the interface trap densities in the AlGaN barrier and GaN buffer. It was observed that the change in the interface trap density with the temperature is the reason for the threshold voltage instability. Moreover, the capture barrier was experienced by the deep defects in that device which have a great amount of threshold voltage shift after stress with temperature. Pertaining to smaller interface trap density and insignificant shift in threshold voltage with temperature before and after off-state stress, the device with improved layer quality shows better electrical performance.

The proposed analytical and physical model in this thesis work shows an excellent agreement with the measured data. This work fills the unexplained void in the literature, such as the effect of the leakage current on the virtual gate, the breakdown of the virtual gate, the electron emission at a high electric field using multi-phonon ionization, and a complete understanding of kink contour in output IV curve.

Keywords: Leakage Current; Current Collapse; Kink Effect; Multiphonon Ionisation; Trap Assisted Tunneling current; Phonon Assisted Tunneling current; Impact Ionization; Thermal Admittance Spectroscopy; Deep Traps; Activation Energy; Capture cross-section; DLTS

Abstract (सामान्य सारांश)

गैलियम नाइट्राइड (GaN) आधारित उच्च इलेक्ट्रॉन मोबिलिटी ट्रांजिस्टर (HEMT) उच्च आवृत्ति और उच्च शक्ति अनुप्रयोगों के लिए उत्कृष्ट उम्मीदवार हैं इसके विशाल बैंडगैप, उच्च ब्रेकडाउन वोल्टेज, और उच्च आउटपुट पावर के कारण। हालांकि, उच्च मात्रा में उत्पादन के लिए छोटी लंबाई की बढ़ती आवश्यकता ने इस डिवाइस में विभिन्न मुद्दे पैदा किए हैं और इसकी प्रतिस्थापना प्रक्रिया के हर पदावनत चरण पर इसकी प्रतिस्थापना प्रभावित करती है। उत्तोदित परत विकसान और उसके हर प्रक्रिया चरण में विद्युतीय गतिविधियों की मौजूदगी पर कई नियमितता सम्बंधित समस्याएं प्रभावित होती हैं। हालांकि, इन दोषों की भौतिक उपस्थिति और स्थान अभी भी अस्पष्ट हैं और इसके लिए और अध्ययन की जरूरत है। इन दोषों में इलेक्ट्रॉन के इन गतिविधियों में फंसना / छूटना नकारात्मक प्रभाव डालता है, जिसमें विभिन्न संचालन स्थिति में विद्युत विस्फोट, तीव्र विस्फोट प्रभाव, स्रवण के अस्थिरता, और थ्रेशोल्ड वोल्टेज शामिल होते हैं। इसलिए, सेमिकंडक्टर उद्योग में प्रतिस्थापना संबंधी इस प्रकार के दोषों का अध्ययन करना गैलियम नाइट्राइड HEMTs के लिए प्रतिद्वंद्वियों को पीछे छोड़ने के लिए महत्वपूर्ण होता है।

एक (two-dimensional analytical) मॉडल का प्रस्तावना किया गया था जो आउटपुट I-V कर्व में drain current collapse का संक्षेपण और उसकी उपशोधनीय प्राप्ति को समझाने के लिए किया गया था। आउटपुट I-V कर्व पर पैरासाइटिक रेसिस्टेंस के प्रभाव को प्रस्तुत किया गया था। Drain current collapse को प्रस्तुत करने के लिए प्रस्तावित वर्चुअल गेट मॉडल का उपयोग किया गया था। वर्चुअल गेट का निर्माण गेट की किनारे से ड्रेन की ओर इलेक्ट्रॉनों के परिवहन और आंतरिक स्थितियों के बीच कूदने के माध्यम से होता है। बाद में, बहु-ध्वनिक प्रक्रमण की शामिलता से इलेक्ट्रॉन उत्सर्जन होता है, जो गेट की ओर से होता है, जो उच्च स्थिर विद्युत फ़ील्ड में गहरी स्थिति से उत्पन्न होता है और drain current collapse को बहाल करता है। तापीय विद्युतीय क्षेत्रों में बहु-ध्वनिक प्रक्रमण के साथ गेट के सतहीय अवस्थाओं की परिवर्तन लीकेज विद्युत में बदलाव की पुष्टि करता है। इस काम में उच्च ड्रेन वोल्टेज के कारण स्वयं-गर्म होने का भी अध्ययन किया गया।

थर्मल अधिकार्यता (Thermal Admittance) और डीप लेवल ट्रांसिएंट स्पेक्ट्रोस्कोपी (Deep Level Transient Spectroscopy) का उपयोग करके AlGaN/GaN HEMTs में गहरी फंदों (Deep Traps) की पहचान की गई। विभिन्न तारंगता और तापमान पर मापी गई अस्थायी अडमिटेंस का उपयोग करके दोषों का आवासन निर्धारित किया गया। उद्दीप्त स्थान पर टपकाने वाली विद्युत धारा के तापमान निर्भरता को ट्रैप सहायित और फोनोन-सहायित टनलिंग धाराओं का उपयोग करके समझाया गया। हालांकि, पिंच ऑफ (Pinch off) के पास लीकेज धारा और आउटपुट I-V कर्व को पूर्णतः समझाने के लिए पिछला मॉडल सामग्री नहीं कर सका। इसलिए, पिछले मॉडल को बढ़ाकर आउटपुट I-V विशेषताओं के पूर्ण गेट वोल्टेज विसंचिका में पूर्णतः किंक संरेखण (Kink effect) का समझाया गया।वर्चुअल गेट मॉडल को सतही कणों की वास्तविक समय विशेषताओं से आगे संशोधित किया गया। यह मॉडल वर्चुअल गेट के बैरियर ऊंचाई में कमी के कारण एक उच्च विद्युत फ़ील्ड में वर्चुअल गेट क्षेत्र के विघटन को शामिल करता है। यह प्रक्रिया चैनल प्रभाव आयननीकरण के साथ प्रारंभ होती है और बाद में मल्टी-फोनोन आयननीकरण द्वारा नियंत्रित की जाती है।

AlGaN / GaN HEMT एचईएमटी में थ्रेशोल्ड वोल्टेज अस्थिरता के प्रभाव की अध्ययन के लिए तापमान-विपरीत स्थिति तनाव माप लिए गए। इस शोध में घरेलू निर्मित उपकरणों का उपयोग किया गया जिनमें विभिन्न परत गुणवत्ता थी। मापी गई $I_{DS} - V_{GS}$ curve विशेषताओं में सबथ्रेशोल्ड स्लोप के परिवर्तन का उपयोग करके AlGaN बैरियर और GaN बफर में इंटरफ़ेस फंदों की

घनत्व का अनुमान लगाने में किया गया। यह देखा गया कि तापमान के साथ इंटरफ़ेस दष्टता में परिवर्तन थ्रेशोल्ड वोल्टेज अस्थिरता का कारण है। इसके अतिरिक्त, उस उपकरण में गहरे दोषों द्वारा जो पक्षाधार वोल्टेज तापमान के साथ तनाव के बाद अधिक मात्रा में शिफ्ट करते हैं, उन्हें कैप्चर बैरियर का सामना करना पड़ा। तापमान से पहले और बाद में ऑफ-स्टेट तनाव के साथ थ्रेशोल्ड वोल्टेज में छोटे से इंटरफ़ेस फंद घनत्व और अनगिनत वोल्टेज स्थानांतरण के संबंध में, उन्हें सुधारित परत गुणवत्ता वाले उपकरण के द्वारा बेहतर विद्युतीय प्रदर्शन प्रदान किया गया।

इस शोध प्रबंध में प्रस्तावित विश्लेषणात्मक और भौतिक मॉडल ने मापे गए डेटा के साथ अत्यंत संतुलन दिखाया है। यह काम साहित्य में अनुसंधान के अनसमझित खाली स्थानों को भरता है, जैसे वर्चुअल गेट पर लिकेज धारा के प्रभाव, वर्चुअल गेट का विघटन, बहु-फोनोन आयननीकरण का उपयोग करके उच्च विद्युत फ़ील्ड में इलेक्ट्रॉन उत्सर्जन, और आउटपुट I-V कर्व में किंक संरेखण का पूर्ण समझौता।

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