RELIABILITY AND DC/RF STRESS INDUCED DEGRADATION IN InAlGaN/GaN HEMTS FOR RF AND TERAHERTZ APPLICATIONS

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CENTRE FOR APPLIED RESEARCH IN ELECTRONICS

INDIAN INSTITUTE OF TECHNOLOGY DELHI

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by

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CENTRE FOR APPLIED RESEARCH IN ELECTRONICS

Submitted

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March 2026

CERTIFICATE

This is to certify that the thesis entitled, **“RELIABILITY AND DC/RF STRESS INDUCED DEGRADATION IN InAlGaN/GaN HEMTS FOR RF AND TERAHERTZ APPLICATIONS”** being submitted by **Mr. SHIVANSH AWASTHI** to the Indian Institute of Technology Delhi for the award of the degree of “**Doctor of Philosophy**”, is a record of bonafide research work carried out by him under my guidance and supervision.

In my opinion, the thesis has reached the standard of fulfilling the requirement of all the regulations regarding to the degree. For the award of Joint degree, the results contained in this thesis have been submitted to National Yang Ming Chiao Tung University as a part of IITD-NYCU Joint Degree Program.

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Shivansh Awasthi

Abstract

Modern wireless systems including 5G/6G transceivers, EHF radar front ends, satellite links, and emerging THz sensors require power amplifiers and receiver devices with high linearity, wide bandwidth, and strong reliability. GaN high-electron-mobility transistors (HEMTs) play a key role due to their high breakdown field, strong polarization-induced 2DEG, and ability to deliver high power at high frequencies. However, challenges such as nonlinear transconductance, hot-electron degradation, surface and buffer trapping, and dynamic reliability effects still limit linearity, gain, and current collapse. This thesis addresses these issues through coordinated device engineering, experimental reliability studies, physics-based TCAD modeling, and machine-learning-based predictive analysis.

The first part investigates electrostatic linearity engineering using a dual-gate (DG) InAlGaN/GaN HEMT architecture that improves g_m flatness and suppresses RF nonlinearities. A source-side secondary gate enhances channel modulation, reduces IMD3, and expands the linear operating range without compromising cutoff or maximum oscillation frequency. Large-signal modeling confirms improved C/I ratio and AM-PM behavior, establishing DG-HEMTs as strong candidates for highly linear RF power amplifiers and V-band front ends.

The second theme examines reliability under extreme RF operation. On-wafer tests on 0.1 μm AlGaN/GaN HEMTs under 60 GHz Class-AB RF stress for over two days and complementary DC stress for five days show stable gate leakage but significant degradation in gain, output power, and PAE, indicating RF-accelerated mechanisms not seen in DC stress alone. A calibrated TCAD reliability model incorporating hot-carrier effects, self-heating, and dynamic trap generation reproduces the degradation and reveals insights into field-induced trap activation, inverse piezoelectric field shifts, and barrier-defect impacts on long-term mm-wave reliability.

In the third part of this thesis, the potential of GaN HEMTs for non-resonant terahertz (THz) detection is investigated using advanced device structures. A dual-gate configuration is introduced to improve responsivity and noise-equivalent power (NEP), with performance compared against multi-channel HEMTs to highlight the benefits of InAlGaN barriers for

enhanced THz detection. The optimized design delivers higher responsivity and lower NEP. A reliability study incorporating trap distributions and temperature variations further confirms the robustness and practical viability of the proposed device for dependable THz detection.

The fourth phase proposes and analyzes a dual-channel graded-barrier (DCGB) GaN HEMT to address buffer-trap-induced current collapse. Transient and electro-thermal simulations show strong suppression of drain-lag degradation due to enhanced charge confinement, a 3D electron gas formed by graded polarization, and spatial decoupling of the upper channel from the Fe-doped buffer. These engineered barrier-grading and multi-channel transport effects significantly mitigate collapse mechanisms, enabling more stable high-power and high-frequency operation.

The final section introduces a machine-learning (ML) framework trained on TCAD-generated data and measured device behavior to predict intrinsic parameters such as threshold voltage (V_{TH}) and transconductance (g_m). Ensemble methods like Random Forest and Gradient Boost surpass conventional regression and match deep-learning accuracy while offering greater interpretability and efficiency. This physics-guided ML approach provides a fast, reliable route for future GaN device optimization and reliability prediction.

Collectively, this thesis provides an integrated understanding of GaN HEMT behavior across linearity, reliability, collapse suppression, THz detection potential, and data-driven modeling. The synergy between experimental measurements, advanced TCAD simulations, and predictive ML tools establishes a robust methodology for engineering next-generation GaN devices for RF, EHF, and THz applications, ultimately contributing to more efficient, reliable, and scalable wireless transceiver technologies.

सार

मॉडर्न वायरलेस सिस्टम—जिसमें 5G/6G ट्रांसीवर, EHF रडार फ्रंट एंड, सैटेलाइट लिंक और नए THz सेंसर शामिल हैं—को हाई लीनियरिटी, वाइड बैंडविड्थ और मज़बूत रिलायबिलिटी वाले पावर एम्पलीफायर और रिसीवर डिवाइस की ज़रूरत होती है। GaN हाई-इलेक्ट्रॉन-मोबिलिटी ट्रांजिस्टर (HEMTs) अपने हाई ब्रेकडाउन फील्ड, मज़बूत पोलराइजेशन-इंड्यूस्ड 2DEG और हाई फ्रीक्वेंसी पर हाई पावर देने की क्षमता के कारण अहम भूमिका निभाते हैं। हालांकि, नॉनलीनियर ट्रांसकंडक्टेंस, हॉट-इलेक्ट्रॉन डिग्रेडेशन, सरफेस और बफर ट्रैपिंग, और डायनामिक रिलायबिलिटी इफेक्ट्स जैसी चुनौतियां अभी भी लीनियरिटी, गेन और करंट कोलैप्स को सीमित करती हैं। यह थीसिस कोऑर्डिनेटेड डिवाइस इंजीनियरिंग, एक्सपेरिमेंटल रिलायबिलिटी स्टडीज़, फिजिक्स-बेस्ड TCAD मॉडलिंग और मशीन-लर्निंग-बेस्ड प्रेडिक्टिव एनालिसिस के ज़रिए इन मुद्दों को सुलझाती है।

पहला भाग डुअल-गेट (DG) InAlGaN/GaN HEMT आर्किटेक्चर का इस्तेमाल करके इलेक्ट्रोस्टैटिक लीनियरिटी इंजीनियरिंग की जांच करता है जो gm फ्लैटनेस को बेहतर बनाता है और RF नॉनलीनियरिटी को दबाता है। सोर्स-साइड सेकेंडरी गेट चैनल मॉड्यूलेशन को बढ़ाता है, IMD3 को कम करता है, और कटऑफ या मैक्सिमम ऑसिलेशन फ्रीक्वेंसी से समझौता किए बिना लीनियर ऑपरेटिंग रेंज को बढ़ाता है। लार्ज-सिग्नल मॉडलिंग बेहतर C/I रेश्यो और AM-PM बिहेवियर को कन्फर्म करता है, जिससे DG-HEMTs को बहुत ज़्यादा लीनियर RF पावर एम्पलीफायर और V-बैंड फ्रंट एंड के लिए मज़बूत कैंडिडेट के तौर पर स्थापित किया गया है।

दूसरी थीम बहुत ज़्यादा RF ऑपरेशन के तहत रिलायबिलिटी की जांच करती है। 0.1 μm AlGaN/GaN HEMTs पर 60 GHz क्लास-AB RF स्ट्रेस के तहत दो दिनों से ज़्यादा और कॉम्प्लिमेंट्री DC स्ट्रेस के तहत पांच दिनों तक ऑन-वेफर टेस्ट से स्टेबल गेट लीकेज दिखता है, लेकिन गेन, आउटपुट पावर और PAE में काफी गिरावट आती है, जो ऐसे RF-एक्सेलरेटेड मैकेनिज्म को दिखाता है जो सिर्फ DC स्ट्रेस में नहीं दिखते। हॉट-कैरियर इफ़ेक्ट, सेल्फ़-हीटिंग और डायनामिक ट्रैप जेनरेशन को शामिल करने वाला एक कैलिब्रेटेड TCAD रिलायबिलिटी मॉडल, गिरावट को दोहराता है और फ़ील्ड-इंड्यूस्ड ट्रैप एक्टिवेशन, इनवर्स पीज़ोइलेक्ट्रिक फ़ील्ड शिफ़्ट और लंबे समय तक चलने वाली mm-वेव रिलायबिलिटी पर बैरियर-डिफ़ेक्ट के असर के बारे में जानकारी देता है।

इस थीसिस के तीसरे हिस्से में, एडवांस्ड डिवाइस स्ट्रक्चर का इस्तेमाल करके नॉन-रेज़ोनेंट

टेराहर्ट्ज़ (THz) डिटेक्शन के लिए GaN HEMTs की क्षमता की जांच की गई है। रिस्पॉन्सिविटी और नॉइज़-इक्विवेलेंट पावर (NEP) को बेहतर बनाने के लिए एक डुअल-गेट कॉन्फ़िगरेशन पेश किया गया है, जिसमें बेहतर THz डिटेक्शन के लिए InAlGaN बैरियर के फ़ायदों को हाईलाइट करने के लिए मल्टी-चैनल HEMTs के मुक़ाबले परफ़ॉर्मेंस की तुलना की गई है। ऑप्टिमाइज़्ड डिज़ाइन ज़्यादा रिस्पॉन्सिविटी और कम NEP देता है। ट्रैप डिस्ट्रिब्यूशन और टेम्परेचर वेरिएशन को शामिल करने वाली एक रिलायबिलिटी स्टडी, भरोसेमंद THz डिटेक्शन के लिए प्रस्तावित डिवाइस की मज़बूती और प्रैक्टिकल वायबिलिटी को और कन्फ़र्म करती है।

चौथा फेज़ बफ़र-ट्रैप से होने वाले करंट कोलैप्स को ठीक करने के लिए एक डुअल-चैनल ग्रेडेड-बैरियर (DCGB) GaN HEMT का प्रस्ताव और एनालिसिस करता है। ट्रांजिएंट और इलेक्ट्रो-थर्मल सिमुलेशन, बढ़े हुए चार्ज कन्फाइनमेंट, ग्रेडेड पोलराइज़ेशन से बनी 3D इलेक्ट्रॉन गैस, और Fe-डोप्ड बफ़र से ऊपरी चैनल के स्पेशल डीकपलिंग के कारण ड्रेन-लैग डिग्रेडेशन को मज़बूती से दबाते हैं। ये इंजीनियर्ड बैरियर-ग्रेडिंग और मल्टी-चैनल ट्रांसपोर्ट इफ़ेक्ट कोलैप्स मैकेनिज़्म को काफ़ी कम करते हैं, जिससे ज़्यादा स्टेबल हाई-पावर और हाई-फ़्रीक्वेंसी ऑपरेशन मुमकिन होता है।

आखिरी सेक्शन एक मशीन-लर्निंग (ML) फ्रेमवर्क पेश करता है जो TCAD से बने डेटा और मापे गए डिवाइस बिहेवियर पर ट्रेन किया गया है ताकि थ्रेशोल्ड वोल्टेज (VTH) और ट्रांसकंडक्टेंस (gm) जैसे इंट्रिंसिक पैरामीटर्स का अनुमान लगाया जा सके। रैंडम फ़ॉरेस्ट और ग्रेडिएंट बूस्ट जैसे एनसेंबल मेथड पारंपरिक रिग्रेशन से आगे निकल जाते हैं और डीप-लर्निंग एक्यूरेसी से मेल खाते हैं, साथ ही ज़्यादा इंटरप्रिटेबिलिटी और एफ़िशिएंसी भी देते हैं। यह फ़िज़िक्स-गाइडेड ML अप्रोच भविष्य के GaN डिवाइस ऑप्टिमाइज़ेशन और रिलायबिलिटी अनुमान के लिए एक तेज़, भरोसेमंद रास्ता देता है।

कुल मिलाकर, यह थीसिस लीनियरिटी, रिलायबिलिटी, कोलैप्स सप्रेशन, THz डिटेक्शन पोटेंशियल और डेटा-ड्रिवन मॉडलिंग में GaN HEMT बिहेवियर की एक इंटीग्रेटेड समझ देती है। एक्सपेरिमेंटल मेज़रमेंट, एडवांस्ड TCAD सिमुलेशन और प्रेडिक्टिव ML टूल्स के बीच सिनर्जी RF, EHF और THz एप्लीकेशन के लिए नेक्स्ट-जेनरेशन GaN डिवाइस की इंजीनियरिंग के लिए एक मज़बूत मेथडोलॉजी बनाती है, जो आखिर में ज़्यादा एफिशिएंट, रिलायबल और स्केलेबल वायरलेस ट्रांसीवर टेक्नोलॉजी में योगदान देती है।

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LIST OF ABBREVIATIONS

HEMT	High Electron Mobility Transistor
RF	Radio Frequency
2DEG	Two-Dimensional Electron Gas
EHF	Extremely High Frequency
GaN	Gallium Nitride
SiC	Silicon Carbide
InAlGaN	Indium Aluminium Gallium Nitride
AlGaN	Aluminium Gallium Nitride
Thz	Terahertz
AlN	Aluminium Nitride
DC	Direct Current
TCAD	Technology Computer Aided Design
ML	Machine Learning
ANN	Artificial Neural Network
GVS	Gate Voltage Swing
MC-HEMT	Multi-Channel HEMT
ADG-HEMT	Asymmetric Dual Gate HEMT