

MODELING AND SIMULATION OF BIAS DEPENDENT BEHAVIOR IN GaN HEMT FOR RF APPLICATIONS

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CENTRE FOR APPLIED RESEARCH IN ELECTRONICS (CARE)

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by

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CENTRE FOR APPLIED RESEARCH IN ELECTRONICS

Submitted

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Dedicated to My Family and Friends.....

Certificate

This is to certify that the thesis entitled “**Modeling and Simulation of Bias Dependent Behavior in GaN HEMT for RF Applications**” being submitted by **Pragyey Kumar Kaushik** to the Centre for Applied Research in Electronics (CARE), Indian Institute of Technology Delhi for the award of degree of ‘**Doctor of Philosophy**’ is a record of bonafide work carried out by him. He has worked under my supervision and guidance, and has fulfilled the requirement for the submission of this thesis, which in my opinion has reached the requisite standard. The results contained on this work has not been submitted, in part or full, to any other University or Institution for the award of any degree or diploma.

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Abstract

In the present thesis, we have probed the AlGaIn/GaN HEMTs device modelling and simulation to extract the bias dependency of different parameters associated with the devices. The presence of surface traps is an important phenomenon in AlGaIn/GaN HEMT. The analysis shows that from deep to shallow surface donors, the percentage change in electron density in 2DEG gets saturated (near 8 %) with change in aluminum concentration. The depth of the quantum potential well below the fermi level is also analysed and is found to get saturated (near 2 %) with aluminum percentage when surface donor states energy changes to deep from shallow. In this part, the effect of surface donor traps on the surface potential also have been discussed in detail. These surface states are modeled as donor states. Deep donor ($E_C - E_D = 1.4$ eV) to shallow donor ($E_C - E_D = 0.2$ eV) surface traps are thoroughly studied for the donor concentration of 10^{11} to 10^{16} cm⁻². This study involves an aluminum concentration variation from 5 % to 50 %.

By using this TCAD calibrated platform, we have generated the I_{DS} vs V_{GS} and I_{DS} vs V_{DS} of the HEMT device. It is observed that the parasitic R_D/R_S (drain/source) resistances of AlGaIn/GaN HEMT are gate bias dependent. A different methodology is being adopted to extract these source/drain (R_D/R_S) resistance variation with low gate voltage over a wide range of temperatures with single device DC characterization data. Extraction of source and drain resistance by this methodology takes only single device data which reduces the sample to sample variation in resistance calculation. The reliability of the adopted methodology used to extract the parasitic resistance is found in tune with the reported results. The extraction of these parasitic resistance is also extracted through modified RF technique.

The previously proposed models assumed a constant value of inductance, but recent a strong dependency of bias on extrinsic inductances (L_s , L_g , and L_d) are reported, which leads to the deviation in simulated and measured values of intrinsic Y-parameters. This deviation in simulated and measured values suggests that the circuit structure should be modified for small-signal modelling of AlGaIn/GaN HEMTs. This bias dependency on the extrinsic parameters can be eliminated by introducing a novel channel resistance (R_L) and an inductance (L_{ds}) in the intrinsic part of the small-signal model of AlGaIn/GaN HEMT. These reports analysed the effect of R_L and L_{ds} at higher gate bias, but its impact at low gate bias and on the other parameters (like R_{ds} and C_{ds}) in the intrinsic part of the small-signal model have not been explored. We have studied three main aspects of modified SSM for GaN HEMTs: First,

variation of R_L with respect to low gate voltage, second, Effect of R_L on parameters such as R_{ds} and C_{ds} , and third, Study of intrinsic Y-parameters deviation from measured data with R_L and without R_L .

The short circuit current gain (h_{21}) is one of the RF parameters which is used to evaluate the cut-off frequency. The cut-off frequency defined the upper limit of frequency operation in GaN HEMT. In general, this h_{21} decreases with the rate of -20 dB/decade of frequency; nonetheless, sometimes this standard roll-off in h_{21} deviates from its ideal behaviour beyond the cut-off frequency. This deviation in short circuit current gain h_{21} owing to have the peak beyond the cut-off frequency called current gain peak. In this part, we are reporting the effect of the low gate bias condition on these current gain peaks. A small-signal equivalent model (SSEM) has been adopted to extract the value of the parameter at different low gate bias conditions. These parameters are then used to predict the behaviour of these double peaks in AlGaIn/GaN HEMTs. It is observed that there are two peaks. First peak is associated to the resonance frequency (48 GHz to 53.5 GHz) of the dip in open-circuit output impedance Z_{22} . Whereas, the second peak of h_{21} associated to the resonance frequency (75.2 GHz) of open circuit forward transfer impedance Z_{21} . Simulation says that the first peak of h_{21} having magnitude as well as resonance frequency (Δh_{21fp} , $\Delta f_{rffp} \neq 0$) window with respect to low gate bias but the second peak have only magnitude window ($\Delta h_{21sp} \neq 0$) not resonance frequency ($\Delta f_{rfsp} = 0$) window.

सार

वर्तमान शोध प्रबंध में, हमने उपकरणों से जुड़े विभिन्न मापदंडों की पूर्वाग्रह निर्भरता को निकालने के लिए AlGaIn / GaN एचईएमटी डिवाइस मॉडलिंग और सिमुलेशन की जांच की है। सतही जालों की उपस्थिति AlGaIn/GaN एचईएमटी में एक महत्वपूर्ण घटना है। विश्लेषण से पता चलता है कि गहरे से उथले सतह दाताओं तक, 2DEG में इलेक्ट्रॉन घनत्व में प्रतिशत परिवर्तन एल्यूमीनियम एकाग्रता में परिवर्तन के साथ संतृप्त (लगभग 8 %) हो जाता है। फर्मी स्तर से नीचे क्वांटम क्षमता की गहराई का भी विश्लेषण किया जाता है और यह पाया जाता है कि जब सतह दाता ऊर्जा को उथले से गहरे में बदलता है तो एल्यूमीनियम प्रतिशत के साथ संतृप्त (लगभग 2 %) हो जाता है। इस भाग में, सतही क्षमता पर सतह दाता जाल के प्रभाव पर भी विस्तार से चर्चा की गई है। इन सतह जालों को दाता जालों के रूप में तैयार किया गया है। गहरे डोनर ($E_C-E_D=1.4$ eV) से उथले डोनर ($E_C-E_D=0.2$ eV) सतही जाल का 10^{11} से 10^{16} सेमी⁻² की दाता एकाग्रता के लिए पूरी तरह से अध्ययन किया जाता है। इस अध्ययन में 5 % से 50 % तक एल्यूमीनियम सांद्रता भिन्नता शामिल है।

इस TCAD संशोधित मंच का उपयोग करके, हमने एचईएमटी डिवाइस के आईडीएस बनाम वीजीएस और आईडीएस बनाम वीडीएस उत्पन्न किया है। यह देखा गया है कि AlGaIn/GaN एचईएमटी के परजीवी R_D/R_S (अपवाहिका /स्रोत) प्रतिरोध गेट पूर्वाग्रह पर निर्भर हैं। एक डिवाइस डीसी लक्षण वर्णन जानकारी के साथ तापमान की एक विस्तृत श्रृंखला पर कम गेट वोल्टेज के साथ इन स्रोत/अपवाहिका (R_S/R_D) प्रतिरोध भिन्नता को निकालने के लिए एक अलग पद्धति अपनाई जा रही है। इस पद्धति द्वारा स्रोत और अपवाहिका प्रतिरोध का निष्कर्षण केवल एक उपकरण जानकारी लेता है जो नमूना को प्रतिरोध गणना में नमूना भिन्नता को कम करता है। परजीवी प्रतिरोध को निकालने के लिए अपनाई गई पद्धति की विश्वसनीयता रिपोर्ट किए गए परिणामों के अनुरूप पाई जाती है। इन परजीवी प्रतिरोधों का निष्कर्षण भी संशोधित आरएफ तकनीक के माध्यम से निकाला जाता है।

पहले प्रस्तावित तंत्र ने प्रेरक का एक निरंतर मूल्य ग्रहण किया था, लेकिन हाल ही में बाह्य प्रेरकों (L_s , L_g , और L_d) पर पूर्वाग्रह की एक मजबूत निर्भरता की सूचना दी गई है, जो आंतरिक वाई- पैरामीटर के सिम्युलेटेड और मापा मूल्यों में विचलन की ओर जाता है। नकली और मापा मूल्यों में यह विचलन बताता है कि AlGaIn/GaN एचईएमटी के छोटे-सिग्नल मॉडलिंग के लिए तंत्र संरचना को संशोधित किया जाना चाहिए। बाहरी मापदंडों पर इस पूर्वाग्रह निर्भरता को AlGaIn / GaN एचईएमटी के छोटे-सिग्नल मॉडल के आंतरिक भाग में एक उपन्यास चैनल प्रतिरोध (R_L) और एक प्रेरक (L_{ds}) की शुरुआत करके समाप्त किया जा सकता है। इन रिपोर्टों ने उच्च गेट पूर्वाग्रह पर R_L और L_{ds} के प्रभाव का विश्लेषण किया, लेकिन छोटे-सिग्नल मॉडल के आंतरिक भाग में कम गेट पूर्वाग्रह और अन्य मापदंडों (जैसे R_{ds}

और C_{ds}) पर इसके प्रभाव का पता नहीं लगाया गया है। हमने GaN एचईएमटी के लिए संशोधित SSM के तीन मुख्य पहलुओं का अध्ययन किया है: पहला, कम गेट वोल्टेज के संबंध में R_L की भिन्नता, दूसरा, R_{ds} और C_{ds} जैसे मापदंडों पर R_L का प्रभाव, और तीसरा, मापा से आंतरिक वाई-पैरामीटर विचलन का अध्ययन R_L के साथ और R_L के बिना।

लघु परिपथ धारा लाभ (h_{21}) RF मापदंडों में से एक है जिसका उपयोग कट-ऑफ आवृत्ति का मूल्यांकन करने के लिए किया जाता है। कट-ऑफ आवृत्ति ने GaN एचईएमटी में आवृत्ति ऑपरेशन की ऊपरी सीमा को परिभाषित किया। सामान्य तौर पर, यह h_{21} आवृत्ति के -20 dB/दशक की दर से घटता है; फिर भी, कभी-कभी h_{21} में यह मानक रोल-ऑफ कट-ऑफ आवृत्ति से परे अपने आदर्श व्यवहार से विचलित हो जाता है। शॉर्ट सर्किट करंट गेन h_{21} में यह विचलन कट-ऑफ आवृत्ति से परे शिखर होने के कारण धारा लाभ शिखर कहलाता है। इस भाग में, हम इन धारा लाभ चोटियों पर निम्न गेट पूर्वाग्रह की स्थिति के प्रभाव को प्रतिवेदित कर रहे हैं। विभिन्न निम्न गेट पूर्वाग्रह स्थितियों पर पैरामीटर के मूल्य को निकालने के लिए एक छोटा-सिग्नल समकक्ष मॉडल (एसएसईएम) अपनाया गया है। इन मापदंडों का उपयोग तब AlGaIn/GaN एचईएमटी में इन दोहरी चोटियों के व्यवहार की भविष्यवाणी करने के लिए किया जाता है। यह देखा गया है कि दो शिखर हैं। पहला शिखर ओपन-सर्किट आउटपुट प्रतिबाधा Z_{22} में डुबकी की अनुनाद आवृत्ति (48 GHz से 53.5 GHz) से जुड़ा है। जबकि, ओपन सर्किट फॉरवर्ड ट्रांसफर प्रतिबाधा Z_{21} के अनुनाद आवृत्ति (75.2 GHz) से जुड़े h_{21} की दूसरी चोटी। सिमुलेशन कहता है कि h_{21} की पहली चोटी में परिमाण के साथ-साथ अनुनाद आवृत्ति (Δh_{21fp} , $\Delta f_{rffp} \neq 0$) विंडो कम गेट पूर्वाग्रह के संबंध में है, लेकिन दूसरी चोटी में केवल परिमाण खिड़की ($\Delta h_{21sp} \neq 0$) है, अनुनाद आवृत्ति खिड़की नहीं ($\Delta f_{rfs} = 0$)।

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Abbreviations

Si	Silicon
SiO ₂	Silicon dioxide
FET	Field Effect Transistor
MOSFET	Metal Oxide Semiconductor Field Effect Transistor
C-MOS	Complementary- Metal Oxide Semiconductor
GaN	Gallium Nitride
AlGaN	Aluminium Gallium Nitride
AlN	Aluminium Nitride
InN	Indium Nitride
SiC	Silicon Carbide
GaAs	Gallium Arsenide
Al ₂ O ₃	Aluminium Oxide
MESFETs	Metal Semiconductor FET
MISFET	Metal Insulator Semiconductor FET
HBT	Heterojunction Bipolar Transistor
HEMT	High Electron Mobility Transistor
DC	Direct Current
RF	Radio Frequency
LED	Light Emitting Diode
MOVPE	Metal-Organic Vapor Phase Epitaxy
2-DEG	Two-Dimensional Electron Gas
CAGR	Compound Annual Growth Rate
D-mode	Depletion-mode
E-mode	Enhancement-mode
TCAD	Technology Computer Added Design
DD	Drift and Diffusion
SRH	Shockley-Read-Hall

ADS	Advanced Design System
SSM	Small-Signal Model
SSEM	Small-Signal Equivalent Model
CGP	Current-Gain Peak
FCGP	First Current-Gain Peak
SCGP	Second Current-Gain Peak
P_{SP}	Spontaneous Polarization
P_{PE}	Piezoelectric Polarization
TLM	Transmission Line Method
ECF	Equivalent Circuit Parameter
TRL	Thru Reflect Line
VNA	Vector Network Analyser
SSPL	Solid-State Physics Laboratory
DRDO	Defence Research Development Organisation