Accurate Modeling of the Self-Heating and Trapping Effects in GaN HEMTs

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Outline

• Introduction of GaN HEMTs modeling and new features in ASM-HEMT 101.4 and MVSG_CMC 3.2.0

• RF parameter extraction package in IC-CAP
  • Parameter extraction flow
  • Thermal extraction
  • Trapping extraction

• Summary
RF GaN is Hot

• RF GaN market will grow from $1.3B to $2.7B by 2028

Source: "RF GaN market broadens its appeal with an appetite for GaN-on-Silicon" - www.yolegroup.com
GaN Model Development History

Phase 1
- 8 candidates
  - Accuracy
  - Convergence
  - Physical nature

Phase 2
- 4 candidates
  - Sponsors
  - Data

Phase 3
- 2 candidates
  - Model evaluation
  - Feedback

Phase 4
- Model support
- Version release

Source: "RF GaN market broadens its appeal with an appetite for GaN-on-Silicon" - www.yolegroup.com
Modeling of Various GaN Device Effects

• **Field-plates** – modeled with computationally efficient formulation

• **Non-linear access region** – physics-based formulation covering linear and saturation

• **Gate-current (IG)** – physics-based formulations covering multiple IG mechanisms

• **Trapping effects** – multiple modes to suit applications and extraction flows

• **Noise** – Physics-based thermal- and flicker noise models

• **Self-heating effect** – modeled with thermal sub-circuits

• **Ambient temperature effects** – modeled with temperature-dependent formulations

• …

Source: Sourabh Khandelwal, “Scalable nonlinear RF modeling of GaN HEMTs with industry standard ASM-HEMT compact model - Enabling new modeling capabilities for GaN” - IMS
ASM-HEMT 101.4 New Features

• New current saturation formulation added to the access region resistance model
• Two new model parameters tepi and asub added to tune the substrate voltage dependence of pinch-off voltage
• Technical manual updated with new section 5.2 describing statical model extraction flow

Source: Release notes of ASM-HEMT 101.4
MVSG_CMC 3.2.0 New Features

• External thermal node added – additional temperature offset can be defined at the netlist level

• Schottky p-GaN implementation to include dynamic Vt effect

Source: release notes of MVSG_CMC 3.2.0
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### ASM and MVSG Modeling Packages Updates in IC-CAP

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**RF package**

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**Keysight Technologies**
Modeling Flow (ASM-HEMT)

Load Meas Data/Setup environment/Model Parameter initialization

Contact resistance from the probe

Initial threshold voltage and mobility

Extract cap by using S-parameters

Extract parasitics using S11 and S22

Self-heating extraction with static and pulsed IV

100, 125, 150 and 175°C

Slope=22K/w

Power

Temp (in Kelvin)
Modeling Flow (ASM-HEMT)

- **Extract DC parameters and RTH0**
  - DC_MODELING
    - ig_vgs_input
    - id_vgs_Tranfer_lin
    - id_vgs_Tranfer_subvOFF
    - id_vgs_Tranfer
    - id_vgs_Output

- **Extract thermal parameters with IdVd at different temperatures**
  - DC_MODELING_TEMP
    - id_vgs_Output_2m25C
    - id_vgs_Output_25C
    - id_vgs_Output_75C
    - id_vgs_Output_100C

- **Extract cap parameters at low voltage and thermal parameters at high voltage**
  - CV_Modeling
    - spar_cap_vg_vds
    - spar_cap_vg_vds1
    - spar_cap_vg_vd
    - spar_cap_vg_vds_high

- **Extract parasitic effect (LG, LD, LS, RG)**
  - SPAR_MODELING
    - init_Spar_Modeling
    - vg_1stswep_vd_2nd
    - vd_1stswep_vg_2nd
    - Spar_all_freq_biases
    - Spar_bias_point
    - Model_Quality_Verification

- **Gate-lag and drain-lag**
  - TRAPPING_MODELING
    - pulsed_vd_50
    - pulsed_vd_40

- **Continues IV for DC modeling & Temperatures**
  - DC_MODELING
    - id_vgs_input
    - id_vgs_Transfer_lin
    - id_vgs_Transfer_subvOFF
    - id_vgs_Transfer
    - id_vgs_Output

- **Self-heating**
  - Plot_ASM_HEMT_MODELING/DC_MODELING/id_vgs_Transfer_paras_vd_vds

- **U0, UA, RDC UTE**
  - VOFF

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*KEYSI*
MVSG_CMC Parameter Extraction in IC-CAP

- Contact Resistances
- Capacitance vs. Voltage
- Pulsed IV for DC
- Thermal Sub Circuit
- S-Parameters
- Trapping Module
- Large Signal Power

UTILITIES: provide GUI and function to help modeling
Self-Heating Effect

- Self-heating effect has become a greater concern for industry in recent years. Since smaller devices, new materials and geometries, resulting in an increase of this effect.

- Self-heating results in an increase of the device temperature will cause mobility reduction, compromised reliability and signal delays.

- In ASM-HEMT and MVSG_CMC models, self-heating effect is modeled by standard R-C network, which contains thermal resistance $R_{TH0}$ and thermal capacitance $C_{TH0}$.

Self-heating Extraction

- We need two types of data:
  - Static $I_dV_d$ at room temperature.
  - Pulsed $I_dV_d$ at various other than the room temperature.
- $V_d0=0V$ and $V_g0=0V$, which are the voltage at low level.

DC, $T_1=25^\circ C$
Pulsed from $(0,0)$, $T_2=100^\circ C$
DC curve: $T_1 = T_{1_{ambient}} + RT_H0 \cdot P_{diss1}$
Pulsed curve: $T_2 = T_{2_{ambient}} + RT_H0 \cdot P_{diss2}$
$RT_H0 = (T_{1_{ambient}} - T_{2_{ambient}})/P_{diss1}$

\[Temp (in \ Kelvin)\]
\[Power\]

\[Slope=22K/w\]
Introduction of Trapping Effect

Charge trapping in the buffer layer and AlGaN/GaN interface layer cause a reduction in 2DEG channel charge density, causing a modulation of drain current $I_D$.

The trap model accurately captures Dynamic-$R_{ON}$ and knee walkout.

Gate-lag
- $V_{dq} = 0V$
- $V_{gq} = \text{Deep OFF condition}$: A strong field through the AlGaN layer. No field through buffer (since $V_{ds} = 0$). Only surface traps activated.

Drain-lag
- $V_{dq} = A \text{ significantly positive voltage}$
- $V_{gq} = \text{Deep OFF condition}$: A strong field through the AlGaN layer as well as the buffer. Both surface and buffer traps activated.

Pulsed IV Measurements

- Decrease of Ion, increase of Ron and Vdsat
- After voltage stress is removed, a non-negligible time is required for the 2DEG to regain charge.
- Critical for circuit dynamic operations for RF.

• Increase of Ron and cut-off voltage


Trapping Extraction

ASM-HEMT Trapping Model 1 and 2

- TRAPMOD=0
  - Trapping model turns off

- TRAPMOD=1
  - A single RC sub-circuit
  - Trap voltage $V(\text{trap}1)$ will feed back into model
  - $v_{off\_cap}$, $\eta_0\_cap$, $r_s\_cap$, $r_d\_cap$ changing due to the trapping

- TRAPMOD=2
  - Two RC sub-circuits are used
  - $V_{\text{trap}1}$ and $V_{\text{trap}2}$ will feed back into model
  - $V_{off\_trap}$, $r_{on\_trap}$, $c_{dscd\_trap}$, $\eta_0\_trap$ changing due to the trapping

Source: S. Khandelwal, J. Hodges, and N. Reddy, ASM-HEMT 101.3.0 Advanced SPICE Model for HEMTs Technical Manual, Macquarie University
Trapping Extraction
ASM-HEMT Trapping Model 3 and 4

• TRAPMOD=3
  • Single RC sub-circuit
  • Recommended for GaN power device dynamic ON-resistance
  • Only **drain-side resistance** is affected

• TRAPMOD=4
  • Two RC sub-circuits are used
  • Model drain-lag and gate-lag with most flexibility
  • **voffgflag, u0gflag, vsatgflag** changing due to gate-lag \( (V_{G,\text{eff}}) \)
  • **voffdflag, ns0sdlag, ns0ddlag** changing due to drain-lag \( (V_{D,\text{eff}}) \)
Trapping Extraction

MVSG_CMC Charge Trapping Model

- **TRAPSELECT=0**
  Trapping model turns off

- **TRAPSELECT=1**
  A single RC network with a constant time \( \tau \) is used for modeling trapping and de-trapping constant time.

- **TRAPSELECT=2** *(new)*
  Two parallel R-branches in an RC network with an ideal series diode on one of the resistance branches.
  Two-time constants are used.
  Recommended due to more flexibility

\[ \tau_{\text{capture}} \approx R_{\text{capture}} C \] in forward-biased
\[ \tau_{\text{emission}} \approx R_{\text{emission}} C \] in reverse-biased

Trapping Extraction (ASM-HEMT)

Gate Lag Trapping Extraction

- TRAPMOD=4 is used
- Gate-lag-related parameters can be tuned.
- \( v_{offlag}, u_{0lag}, v_{satlag} \) related trapping parameters

Extraction flow

\[ V_{gp} = -10V \]

\[ V_{gq} = 0, -1.4, -2.6 \text{ V} \]
Drain Lag Trapping Extraction

- TRAPMOD=4 is used
- Drain-lag-related parameters can be tuned.
  - $v_{offdlag}$, $n_{s0sdlag}$, $n_{s0ddlag}$ related trapping parameters

Extraction flow:

$V_{dq} = 0, 10, 20, 30, 40, 50 \text{ V}$

$V_{dp} = 1 \text{ V}$

Drain-Lag trapping

$V_{D, eff}$
Summary

- The latest version of ASM-HEMT 101.4 and MVSG_CMC 3.2.0 is implemented in ADS 2024 update 1.
- The RF package with ASM-HEMT 101.3 and MVSG_CMC 3.1.0 is implemented in IC-CAP 2023 and newer version.
- Both ASM-HEMT and MVSG_CMC have good performance on GaN HEMTs modeling:
  - Core model for DC
  - CV and S-parameters
  - Thermal extraction – implemented in both ASM-HEMT and MVSG_CMC parameter flow.
  - Trapping extraction – implemented in MVSG_CMC parameter flow
    will implement in ASM-HEMT parameter flow soon.
Thanks

• Thanks to Prof. Sourabh Khandelwal, developer of ASM-HEMT, for his help in the development of ASM-HEMT parameter flow in IC-CAP

• Thanks to Prof. Lan Wei, developer of MVSG_CMC, for her help in the development of MVSG_CMC parameter flow in IC-CAP
Thank you
We select new trapping model with TRAPSELECT=2

Mainly parameters can be used: rcapture=rslow, remission=rfast, vdltrapth

Gate-Lag trapping
Drain Lag Trapping Extraction

- We select new trapping model with TRAPSELECT=2
- Mainly parameters can be used: rcapture=rslow, remission=rfast, vgltraph