ASM-HEMT Model for GaN RF and Power Electronic Applications: Overview and Extraction

June 27, 2016

Sheikh Aamir Ahsan
Sudip Ghosh
Yogesh Singh Chauhan
IIT Kanpur

Sourabh Khandelwal
UC Berkeley

MA Long
Keysight Technologies
Contents

– ASM-HEMT Model Overview

– Parameter Extraction
  • DC Model
  • Field Plate Capacitance Model
  • RF Small Signal Model

– Summary
GaN HEMT Model Standardization Effort in CMC

- Compact Model Coalition – an industry body that standardizes and promotes SPICE models for semiconductor devices as well as compiled modeling interface

- Dedicated workgroup for GaN HEMT model standardization launched in Year 2011

- Standardization process
  - Phase I completed: solicitation of models and presentation to CMC.
  - Phase II completed: shortlisted candidate models being examined against fundamental requirements and being fitted to measurement data for CMC evaluation
  - **Phase III is ongoing: evaluation on runtime, convergence, operability, etc.**
    - ASM-HEMT
    - MVSG
  - Phase IV: ballot for standardization (targeting at the end of 2016)

*Compact Model Coalition, https://www.si2.org/cmc_index.php
ASM-HEMT Model Overview

\[ n_s = D V_{th} \left\{ \ln \left[ \exp \left( \frac{E_f - E_0}{V_{th}} \right) + 1 \right] + \ln \left[ \exp \left( \frac{E_f - E_1}{V_{th}} \right) + 1 \right] \right\} \]

\[ E_0 = \gamma_0 n_s^{2/3} \]
\[ E_1 = \gamma_1 n_s^{2/3} \]

\[ n_s = \frac{\varepsilon}{qd} (V_{go} - E_f - V_x) \]

Transcendental

\[ E_{f, \text{unified}} = V_{go} - \frac{2V_{th} \ln \left( 1 + e^{\frac{V_{go}}{2V_{th}}} \right)}{1 + \frac{C_g}{qD} e^{-\frac{V_{go}}{2V_{th}}}} \]

\[ \psi = E_f + V_x \]

\[ \psi = E_f + V_x \]
ASM HEMT Model Overview

Intrinsic Charges

\[ I_d(x) = \mu W N_f Q_{ch} \frac{d\psi(x)}{dx} + \mu W N_f V_{th} \frac{dQ_{ch}}{dx} \]

\[ Q_{ch} = -C_g (V_{go} - \psi(x)) \]

\[ I_d = \frac{W}{L} \mu C_g N_f \left[ V_{go} - \left( \frac{\psi_s + \psi_d}{2} \right) + V_{th} \right] (\psi_d - \psi_s) \]

Incorporating Realistic device effects

\[ I_d = \frac{\mu_{eff}}{\sqrt{1 + \theta_{sat}^2 \psi_{ds}^2}} \frac{W}{L} C_g N_f \left[ V_{go} - \left( \frac{\psi_s + \psi_d}{2} \right) + V_{th} \right] \psi_{ds}(1 + \lambda V_{ds}) \]

\[ Q_{gi} = - \int_0^L W N_f C_g (V_{go} - \psi(x))dx \]

\[ Q_{di} = \int_0^L (x/L) W N_f C_g (V_{go} - \psi(x))dx \]

\[ Q_{si} = -Q_{gi} - Q_{di} \]
# List of Parameters

## Core Model Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>VOFF</td>
<td>-2.0</td>
<td>Cut-off voltage</td>
</tr>
<tr>
<td>VTH</td>
<td>170.00e-3</td>
<td>Low field mobility</td>
</tr>
<tr>
<td>UA</td>
<td>0.0e-9</td>
<td>Mobility Degradation coefficient first order</td>
</tr>
<tr>
<td>UB</td>
<td>0.0e-10</td>
<td>Mobility Degradation coefficient second order</td>
</tr>
<tr>
<td>VSAT</td>
<td>1.9e5</td>
<td>Saturation Velocity</td>
</tr>
<tr>
<td>DELTA</td>
<td>2.0</td>
<td>Exponent for Vsat</td>
</tr>
<tr>
<td>AI</td>
<td>0.0</td>
<td>Temperature Dependence for saturation velocity</td>
</tr>
<tr>
<td>UIE</td>
<td>-0.8</td>
<td>Temperature dependence of mobility</td>
</tr>
<tr>
<td>LAMBDA</td>
<td>0.0</td>
<td>Channel Length Modulation Coefficient</td>
</tr>
<tr>
<td>ETAO</td>
<td>1.00e-9</td>
<td>DIBL Parameter</td>
</tr>
<tr>
<td>VDScale</td>
<td>5.0</td>
<td>DIBL Scaling VDS</td>
</tr>
<tr>
<td>K1</td>
<td>0.0e-3</td>
<td>Temperature Dependence for VOFF</td>
</tr>
<tr>
<td>THESET</td>
<td>1.0</td>
<td>Velocity Saturation Parameter</td>
</tr>
<tr>
<td>NFACTOR</td>
<td>0.5</td>
<td>Sub-VOFF Slope parameters</td>
</tr>
<tr>
<td>CSDC</td>
<td>1.00e-3</td>
<td>Sub-VOFF Slope Change due to Drain Voltage</td>
</tr>
<tr>
<td>IMIN</td>
<td>1.00e-15</td>
<td>Minimum Drain Current</td>
</tr>
</tbody>
</table>
List of Parameters II

Access Region and Temperature Parameters

- `parameter integer BDSMOD = 1;` from `[0:1];` //Switch for external source and drain resistances
- `parameter real VSATACC = 50.0e3` from `[0.0:inf];` //Saturation Velocity for access region: Source Side
- `parameter real NSOACCS = 5.0e17` from `[1.0e5:inf];` //2-DEG Charge Density in per square meter in Source access region
- `parameter real NSOACCDD = 5.0e17` from `[1.0e5:inf];` //2-DEG Charge Density in per square meter in Drain access region
- `parameter real KACC = 0.0` from `[0.0:inf];` //Vg dependence parameter of source side access region 2-DEG charge density
- `parameter real KACCD = 0.0` from `[0.0:inf];` //Vg dependence parameter of drain side access region 2-DEG charge density
- `parameter real UGACC = 155e-3` from `[0.0:inf];` //Access region mobility source-side
- `parameter real UGACCD = 155e-3` from `[0.0:inf];` //Access region mobility drain-side
- `parameter real MEXPACCS = 2.0` from `[0.0:inf];` //Exponent for access region resistance model
- `parameter real MEXPACCDD = 2.0` from `[0.0:inf];` //Exponent for access region resistance model
- `parameter real LS = 1.0e-8` from `[0.0:inf];` //Length of Source-Drain Access Region
- `parameter real LDG = 1.0e-6` from `[0.0:inf];` //Length of Drain-Gate Access Region or Length of drain side access region
- `parameter real RSC = 1.0e-4` from `[0.0:inf];` //Source Contact Resistance
- `parameter real RDC = 1.0e-4` from `[0.0:inf];` //Drain Contact Resistance
- `parameter real KNS0 = 0.0` from `[0.0:inf];` //Temperature Dependence for 2-DEG charge density at access region
- `parameter real AT3 = 0.0` from `(-inf:inf);` //Temperature Dependence for saturation velocity at access region
- `parameter real UTES = 0.0` from `(-inf:inf);` //Temperature dependence of mobility at access region: Source Side
- `parameter real UTFED = 0.0` from `(-inf:inf);` //Temperature dependence of mobility at access region: Drain Side
- `parameter real KNSC = 0.0` from `[0.0:inf];` //Temperature dependence of Source Contact Resistance
- `parameter real KNSD = 0.0` from `[0.0:inf];` //Temperature dependence of Drain Contact Resistance
- `parameter integer SHMOD = 1;` from `[0.0:inf];` //Switch to turn on and off self-heating model
- `parameter real RTHO = 5.0` from `[0.0:inf];` //Thermal Resistance
- `parameter real CTHO = 1.0e-9` from `[0.0:inf];` //Thermal Capacitance
Parameter Extraction I

Id-Vg Linear and Log Scale (Linear Vd Condition)

VOFF
NFACTOR
ETAO
VDSCALE
CDSCD

U0
Parameter Extraction II

Id-Vgs, gm-Vgs and Id-Vds, gds-Vds

Adjust Ron using

NS0ACCS

NS0ACCD
Parameter Extraction III

Id-Vgs, gm-Vgs and Id-Vds, gds-Vds

Fit Saturation Current by adjusting VSATACCS

VSAT should remain more or less the same since it is a material dependent parameter and should not vary much for different GaN Technologies
Parameter Extraction IV

Id-Vgs, gm-Vgs and Id-Vds, gds-Vds

Fine tune Contact Resistance parameters

RDC

RSC

To further fit the Ron
Self Heating and Temperature Related Parameters

RTH0

Id (A) (m/s)

Vd (V) [E+0]

KT1
AT
ATS
KRSC
KRDC
UTE
Field Plate Capacitance Model

Terminal Capacitances

\[ \text{Ciss} = \text{Cgs} + \text{Cgd} \]
\[ \text{Crss} = \text{Cgd} \]
\[ \text{Coss} = \text{Cds} + \text{Cgd} \]

FP Modeled as an intrinsic HEMT

Each HEMT governed by \( \psi \) Calc.
Field Plate MOD Parameter Extraction I

Ciss – Vgs
-150V < Vgs < 0V
Vds = 0
Crss, Ciss, Coss versus Vds
0V < Vds < 300V
Vgs = -15V
GFPMOD = SFPMOD = 1
Field Plate MOD Parameter Extraction II

VOFFGFP – sets the rise of the hump

ADOS – Smoothens the hump

CFGD

Gate FP - Drain
Fringing capacitance

CFGD0
Optimize the following

AJ, CJ0, MZ, VBI

CFD
ASM HEMT - Small Signal Representation

\[
Y_{11} = \frac{j\omega(C_{gs} + C_{gd})}{1 + \omega^2(C_{gs} + C_{gd})^2 R_g} + \frac{\omega^2(C_{gs} + C_{gd})^2 R_g}{1 + \omega^2(C_{gs} + C_{gd})^2 R_g}
\]

\[
Y_{12} = -j\omega C_{gd} - \omega^2 C_{gd}(C_{gs} + C_{gd}) R_g
\]

\[
Y_{21} = [g_m - \omega^2 C_{gd}(C_{gs} + C_{gd}) R_g] - j\omega \{C_{gd} + g_m(C_{gs} + C_{gd}) R_g\}
\]

\[
Y_{22} = g_{ds} + j\omega \{C_{ds} + C_{gd}(1 + g_m R_g)\}
\]
De-embedded Y-Parameters (0.5-10 GHz)

\[ \text{imag}(Y_{11}) = C_{gs} + C_{gd} \]
\[ \text{imag}(Y_{22}) = C_{ds} \]

\[ \text{real}(Y_{21}) = g_m \]
\[ \text{real}(Y_{22}) = g_{ds} \]
Broadband S-Parameters (0.5-50 GHz)

$S_{11}$

$S_{12}$

$S_{21}$

$S_{22}$

$Y_{11}$

$Y_{12}$

$Y_{21}$

$Y_{22}$

Real

Imag
Load-Pull and Harmonic Balance Simulations

Contours $P_{out}$

- Measured
- Model

Contours PAE

- Measured
- Model
Summary

– As one of the candidates for CMC GaN HEMT, ASM-HEMT is a physical model based on surface potential analytical calculation.

– Model extraction procedure
  • DC parameter extraction – Focused on key parameters
  • Model field plate as a transistor and perform capacitance parameter extraction
  • RF modeling
    - Broadband S-Parameters and Y-Parameters
    - Large signal load pull and harmonic balance power sweeps

– The model is developed by using Keysight’s IC-CAP and ADS software. Good fitting is achieved with industry measured data.
References


