GaN HEMTS Device Modeling Using ASM Standard-Extraction Flow and Validation

Fréderique SIMBÉLIE & Zacharia OUARDIRHI
Outline

- Hardware Requirements

- Model Extraction flow
  - Small Signal FET modeling
  - Output Current Source
  - Diodes
  - Non-linear capacitances
  - Thermal & trapping effects

- Large Signal Model Validation
Hardware Requirements

Measurement System

• **Short pulse**: Quasi-isothermal conditions
• **Low duty cycle**: Constant mean temperature
• **Quiescent bias point**: Thermal conditions fixed, Traps conditions fixed

Advantages

✓ High power dissipated areas // safe operating conditions
✓ Thermal effects: influence of QP on Idss
✓ Trapping effects (gate-lag & drain-lag)
✓ Precious modeling data inputs
Model Extraction flow

- Small-Signal
- IV Model
- Non-linear capacitances
- Thermal model
- Trapping effects

\[ y = 0.0029x + 0.6375 \]
\[ y = 0.0049x + 0.6889 \]

<table>
<thead>
<tr>
<th>0.4</th>
<th>0.6</th>
<th>0.8</th>
<th>1</th>
<th>1.2</th>
<th>1.4</th>
<th>1.6</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>50</td>
<td>100</td>
<td>150</td>
<td>200</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\[ y = -0.0008x + 1.1543 \]

<table>
<thead>
<tr>
<th>1.02</th>
<th>1.04</th>
<th>1.06</th>
<th>1.08</th>
<th>1.1</th>
<th>1.12</th>
<th>1.14</th>
<th>1.16</th>
<th>1.18</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>50</td>
<td>100</td>
<td>150</td>
<td>200</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\[ I_{ds} = f(V_{gs}, V_{ds}) \]
\[ I_{gs} = f(V_{gs}, V_{ds}) \]
\[ I_g = f(V_{gs}, T) \]
\[ I_{ds} = f(V_{gs}, V_{ds}, T) \]

\[ C_{gs} = f(V_{gs}) \]
\[ C_{gd} = f(V_{gd}) \]
\[ C_{ds} = f(V_{ds}) \]

Opt1:
\[ C_{gs} = f(V_{gs}, T) \]
\[ C_{gd} = f(V_{gd}, T) \]
\[ C_{ds} = f(V_{ds}, T) \]

Opt2:
\[ I_{ds} = f(V_{gs, trap}, V_{ds, trap}, T) \]

Various effects are successively added
Small Signal FET modeling

- **Extrinsic parameters**
  - pad capacitances $C_{pg}$, $C_{pd}$
  - port metallization inductances $L_g$, $L_d$, $L_s$
  - port ohmic resistances $R_g$, $R_d$, $R_s$

- **Intrinsic parameters**
  - channel capacitances $C_{gs}$, $C_{gd}$
  - voltage-controlled current source with transconductance $g_m$ and transit time delay $\tau$
  - ohmic resistances $R_i$, $R_{gd}$
  - output capacitance $C_{ds}$ and resistance $R_{ds}$

$G_m = G_{m0} \times e^{-j\omega\tau}$
Small Signal FET modeling

• Extraction of extrinsic and intrinsic parameters:

Four steps

**Step 1 (optional) - Extrinsic parameters initialization with cold FET measurements using foundry parameters :** $R_c$

\[ Z_{11} = R_g + R_s + \frac{R_c}{3} + \frac{n k T}{q I_g} + j \omega (L_s + L_g) \]

\[ Z_{21} = Z_{12} = R_s + \frac{R_c}{2} + j \omega L_s \]

\[ Z_{22} = R_d + R_s + R_c + j \omega (L_s + L_d) \]

\[ V_{ds} = 0 \text{ V} \]

Channel open \hspace{1em} V_{gs} >> V_p

=> Direct calculus of extrinsic parameters without optimization

\[ R_s = \text{real}(Z_{21})-R_c/2 \]
\[ R_d = \text{real}(Z_{22})-\text{real}(Z_{21})-R_c/2 \]
\[ R_g \approx \text{real}(Z_{11})-\text{real}(Z_{21})+R_c/6 \]

\[ L_s = \text{Im}(Z_{21})/W \]
\[ L_d = (\text{Im}(Z_{22})-\text{Im}(Z_{21}))/W \]
\[ L_g = (\text{Im}(Z_{11})-\text{Im}(Z_{21}))/W \]
Small Signal FET modeling

• **Step 2 (optional)**: Extrinsic parameters initialization with cold FET measurements

\[ \text{Im}(\chi'_{11}) = j\omega (C_{pg} + 2Cb) \]
\[ \text{Im}(\chi'_{21}) = \text{Im}(\chi^*_{12}) = -j\omega Cb \]
\[ \text{Im}(\chi'_{22}) = j\omega (Cb + C_{pd}) \]

\[ V_{ds} = 0 \text{ V} \]

Channel pinch-off \( V_{gs} < V_p \)

=> Direct calculus of extrinsic parameters without optimization

\[ C_{pd} = \frac{(\text{Im}(Y_{22}) + \text{Im}(Y_{21}))}{W} \]
\[ C_{pg} = \frac{((\text{Im}(Y_{11}) + 2\times \text{Im}(Y_{21}))}{W} \]
Small Signal FET modeling

• Extraction of extrinsic and intrinsic parameters:

For a given set of extrinsic parameters, intrinsic admittance matrix of the device is extracted from measured [S] parameters

Condition: There is only one set of extrinsic parameters for which intrinsic parameters are frequency independent.
Small Signal FET modeling

• **Step 3**: Linear model optimization

Comparison and optimization between calculus and measurement can be done for \([S]\), \([Y]\) or \([Z]\) parameters.

After selecting Linear Model, tuning and optimization are accessible.

The final and optimized set of parameters. During the optimization, the updated data are displayed in real time.
Small Signal FET modeling

• Step 4: Multi-bias extraction

To check the good behavior of the linear model with the optimized set of parameters, visualize the intrinsic parameters in multi-bias conditions.

If the intrinsic curves have a good trend, all these parameters can be stored into a buffer or in Netlist file.

Settings: model output, intrinsic parameters; -> linear model extraction
Model Extraction flow

- **Small-Signal**
  - $I_{gs} = f(V_{gs}, V_{ds})$
  - $I_{ds} = f(V_{gs}, V_{ds})$

- **IV Model**

- **Non-linear capacitances**
  - $C_{gs} = f(V_{gs})$
  - $C_{gd} = f(V_{gd})$
  - $C_{ds} = f(V_{ds})$

- **Thermal model**
  - $I_g = f(V_{gs}, T)$
  - $I_{ds} = f(V_{gs}, V_{ds}, T)$

- **Trapping effects**
  - $I_{ds} = f(V_{gs\_trap}, V_{ds\_trap}, T)$

- **Optimization 1**
  - $C_{gs} = f(V_{gs})$
  - $C_{gd} = f(V_{gd})$
  - $C_{ds} = f(V_{ds})$

- **Optimization 2**
  - $I_{ds} = f(V_{gs\_trap}, V_{ds\_trap}, T)$

- $R_s, R_d$

This document may not be reproduced, modified, adapted, published, translated, in any way, in whole or in part, or disclosed to a third party without the prior written consent of AMCAD engineering - © Amcad 2019.
GaN HEMT modeling

ASM linear model is based on extrinsic parameter AMCAD extraction flow in IV CAD

Advanced Spice Model \(^{(1)}\) is a CMC candidate models for industry standardization in 2018

ASM is one of the 2 candidates for the Compact Model Coalition with MIT model (MVSG)

ASM-HEMT Model Overview \(^{(2)}\)

- Analytical Solution of Shrödinger’s & Poisson’s
- 2-DEG charge Fermi-level (Ef), Surface-potential (SP)
- SP-based \(I_d \, I_g\) & charge model real device effects included
- Accurate I-V and C-V physical parameters DIBL, Rs, Vs, ...
- Noise Model, Trapping Effects Model, Self-heating
- DC, AC, Transient, Harmonic Simulations, Noise etc

---

\(^{(1)}\) http://iitk.ac.in/asm/

\(^{(2)}\) Industry Standard GaN HEMT compact model for power electronics and RF applications, Dr Yogesh S. Chauhan
ASM GaN industry standard

- The variation of $E_f$ (Fermi-level) is divided in function of the gate voltage
- A rigorous charge model for all the terminal charge in the device is present

ASM = Physics based-model

Real Device Effects Incorporated into the model:
- velocity saturation effect
- mobility field dependance
- subthreshold-slope degradation
- NL series résistances
- flicker noise
- channel length modulation
- drain-induced barrier lowering
- self-heating effect
- temperature dependance ...

Surface potential calculus

Current & traps

Model for real device effects

http://iitk.ac.in/asm/

Industry Standard GaN HEMT compact model for power electronics and RF applications, Dr Yogesh S. Chauhan
In addition to the existing AMCAD current source model, the ASM (3) model has just been added in IVCAD.

### Output current source: NEW OPTION ➔ ASM

#### Considerations:

#### Model Parameters:

<table>
<thead>
<tr>
<th>Name</th>
<th>Definition</th>
<th>Units</th>
<th>Default</th>
</tr>
</thead>
<tbody>
<tr>
<td>NOF</td>
<td>Number of fingers</td>
<td>none</td>
<td>3.00</td>
</tr>
<tr>
<td>Gate_width</td>
<td>Gate width</td>
<td>m</td>
<td>2.00E-4</td>
</tr>
<tr>
<td>Gate_length</td>
<td>Gate length</td>
<td>m</td>
<td>2.50E-7</td>
</tr>
<tr>
<td>tbar</td>
<td>Barrier layer thickness</td>
<td>m</td>
<td>2.72E-8</td>
</tr>
<tr>
<td>vsat</td>
<td>Saturation velocity</td>
<td>m/s</td>
<td>4.20E6</td>
</tr>
<tr>
<td>at</td>
<td>Temperature dependence coefficient for saturation velocity</td>
<td>none</td>
<td>0.0</td>
</tr>
<tr>
<td>u0Val</td>
<td>Low field mobility</td>
<td>m2/(V*s)</td>
<td>0.18</td>
</tr>
<tr>
<td>ua</td>
<td>Mobility degradation coefficient first order</td>
<td>V-1</td>
<td>4.40E-9</td>
</tr>
<tr>
<td>ub</td>
<td>Mobility degradation coefficient second order</td>
<td>V-2</td>
<td>1.00E-16</td>
</tr>
<tr>
<td>ute</td>
<td>Temperature dependence coefficient of mobility</td>
<td>none</td>
<td>1.00</td>
</tr>
<tr>
<td>imin</td>
<td>Minimum drain current</td>
<td>A</td>
<td>1.00E-15</td>
</tr>
<tr>
<td>voff</td>
<td>Pinch off voltage</td>
<td>V</td>
<td>-2.608</td>
</tr>
<tr>
<td>lambda</td>
<td>Channel length modulation coefficient</td>
<td>V-1</td>
<td>-3.5E-3</td>
</tr>
<tr>
<td>delta</td>
<td>Exponent for Vdeff coefficient</td>
<td>none</td>
<td>0.67</td>
</tr>
<tr>
<td>thesat</td>
<td>Velocity saturation parameter</td>
<td>V-2</td>
<td>1.37</td>
</tr>
<tr>
<td>nfactor</td>
<td>Sub-voft slope parameters</td>
<td>none</td>
<td>4.64</td>
</tr>
<tr>
<td>cdscd</td>
<td>Sub-voft slope change due to drain voltage</td>
<td>None</td>
<td>0.19</td>
</tr>
<tr>
<td>epsilon</td>
<td>Dielectric Permittivity of AlGaN layer</td>
<td>F/m</td>
<td>10.66E-</td>
</tr>
<tr>
<td>etao</td>
<td>DIBL Parameter</td>
<td>none</td>
<td>1E-9</td>
</tr>
<tr>
<td>vdscale</td>
<td>DIBL Scaling VDS</td>
<td>V</td>
<td>5</td>
</tr>
<tr>
<td>gdsmin</td>
<td>Convergence parameter</td>
<td>S</td>
<td>1.0E-12</td>
</tr>
</tbody>
</table>

---

Output Current Source

The extrinsic parameters values are common to the linear and non-linear model.

For the nonlinear part it is possible to use the AMCAD model or a custom model.

Equation editor is implemented to allow the customer to build his custom model.
Output Current Source

Model optimization methodology

Locked Parameters

- Physical parameters
- Nominal T° measurements
- Convergence parameters
- Imín : Pinch off Current
- Voff : Pinch off Voltage

...
Diodes: NEW OPTION ➔ ASM

- Gate-drain and gate-source diode equations:

  \[ I_{gs} = w \times l \times n_f \times |t_3| \times (e^{t_0} - 1) \]

  - \[ t_0 = \frac{V_{gsi}}{n_{jgs} \times k_b Q \times T_{dev}} \]
  - \[ t_3 = i_{gsdio} + \left( \frac{T_{dev}}{T_{nom}} - 1 \right) \times k_{tgs} \]

  \[ I_{gd} = w \times l \times n_f \times |t_3| \times (e^{t_0} - 1) \]

  - \[ t_0 = \frac{V_{gsi}}{n_{jgd} \times k_b Q \times T_{dev}} \]
  - \[ t_3 = i_{gddio} + \left( \frac{T_{dev}}{T_{nom}} - 1 \right) \times k_{tgd} \]

<table>
<thead>
<tr>
<th>Name</th>
<th>Definition</th>
<th>Units</th>
<th>Default</th>
</tr>
</thead>
<tbody>
<tr>
<td>igsdio</td>
<td>Gate-source junction diode saturation current</td>
<td>A/m^2</td>
<td>1</td>
</tr>
<tr>
<td>njgs</td>
<td>Gate-source junction diode current ideality factor</td>
<td>None</td>
<td>2.5</td>
</tr>
<tr>
<td>igd dio</td>
<td>Gate-drain junction diode saturation current</td>
<td>A/m^2</td>
<td>1</td>
</tr>
<tr>
<td>njgd</td>
<td>Gate-drain junction diode current ideality factor</td>
<td>None</td>
<td>2.5</td>
</tr>
<tr>
<td>ktgs</td>
<td>Temperature co-efficient of gate-source junction diode current</td>
<td>None</td>
<td>0</td>
</tr>
<tr>
<td>ktdg</td>
<td>Temperature coefficient of gate-drain junction diode current</td>
<td>None</td>
<td>0</td>
</tr>
</tbody>
</table>
Model Extraction Flow

Small-Signal

IV Model

Non-linear capacitances

Thermal model

Trapping effects

$\frac{\text{Rs}}{}$, $\frac{\text{Rd}}{}$

$y = 0.0029x + 0.6375$

$y = 0.0049x + 0.6889$

Opt1:

$C_{gs} = f(V_{gs})$

$C_{gd} = f(V_{gd})$

$C_{ds} = f(V_{ds})$

$R_s = f(T)$

$R_d = f(T)$

Opt2:

$I_{ds} = f(V_{\text{gs,trap}}, V_{\text{ds,trap}}, T)$

$I_{gs} = f(V_{gs}, V_{ds})$

$I_d = f(V_{gs}, V_{ds})$

$I_g = f(V_{gs}, T)$

$I_{ds} = f(V_{gs}, V_{ds}, T)$

$C_{gs} = f(V_{gs})$

$C_{gd} = f(V_{gd})$

$C_{ds} = f(V_{ds})$

$I_{gs} = f(V_{gs}, V_{ds})$

This document may not be reproduced, modified, adapted, published, translated, in any way, in whole or in part, or disclosed to a third party without the prior written consent of AMCAD engineering © Amcad 2019.
Non-linear capacitances: NEW OPTION ➔ ASM

$C_{gs}$

- Input capacitance $C_{gs}$ is strongly influenced by $V_{gs}$ and weakly influenced by $V_{ds}$.
- In ASM model the $C_{gs}$ capacitance depends on both $V_{gs}$ & $V_{ds}$, 2D capacitance.

Select almost all the I(V) points

Reuse of the current source parameters

<table>
<thead>
<tr>
<th>Name</th>
<th>Definition</th>
<th>Units</th>
<th>Default</th>
</tr>
</thead>
<tbody>
<tr>
<td>QM0I</td>
<td>Charge centroid parameter - starting point for QME in inversion</td>
<td>none</td>
<td>1E-3</td>
</tr>
<tr>
<td>BDOSI</td>
<td>Charge centroid parameter - slope of CV curve under QME in inversion</td>
<td>none</td>
<td>1</td>
</tr>
<tr>
<td>ADOSI</td>
<td>Quantum mechanical effect pre-factor cum switch in inversion</td>
<td>none</td>
<td>0</td>
</tr>
<tr>
<td>cgso</td>
<td>Gate-source overlap capacitance</td>
<td>F</td>
<td>0.0E-18</td>
</tr>
<tr>
<td>cfgd</td>
<td>Fringing capacitance parameter</td>
<td>F</td>
<td>1E-13</td>
</tr>
</tbody>
</table>
Non-linear capacitances: NEW OPTION ➔ ASM

\( C_{gs} \)

- Input capacitance \( C_{gs} \) is strongly influenced by \( V_{gs} \) and weakly influenced by \( V_{ds} \).
- In ASM model the \( C_{gs} \) capacitance depends on both \( V_{gs} \) & \( V_{ds} \), 2D capacitance.

Select almost all the I(V) points

\( C_{gs} \) capacitance extracted on the entire I(V) network

<table>
<thead>
<tr>
<th>Name</th>
<th>Definition</th>
<th>Units</th>
<th>Default</th>
</tr>
</thead>
<tbody>
<tr>
<td>QM0I</td>
<td>Charge centroid parameter - starting point for QME in inversion</td>
<td>none</td>
<td>1E-3</td>
</tr>
<tr>
<td>BDOSI</td>
<td>Charge centroid parameter - slope of CV curve under QME in inversion</td>
<td>none</td>
<td>1</td>
</tr>
<tr>
<td>ADOSI</td>
<td>Quantum mechanical effect pre-factor cum switch in inversion</td>
<td>none</td>
<td>0</td>
</tr>
<tr>
<td>cgs0</td>
<td>Gate-source overlap capacitance</td>
<td>F</td>
<td>0.0E-18</td>
</tr>
<tr>
<td>cfgd</td>
<td>Fringing capacitance parameter</td>
<td>F</td>
<td>1E-13</td>
</tr>
</tbody>
</table>
**Non-linear capacitances**: NEW OPTION ➔ ASM

- Feedback capacitance $C_{gd}$ is a strong function of drain voltage. Inclusion of this effect is necessary to fit large-signal data.

<table>
<thead>
<tr>
<th>Name</th>
<th>Definition</th>
<th>Units</th>
<th>Default</th>
</tr>
</thead>
<tbody>
<tr>
<td>vdsatcv</td>
<td>Saturation voltage on drain side in CV Model</td>
<td>V</td>
<td>100</td>
</tr>
<tr>
<td>cgdo</td>
<td>Gate-drain overlap capacitance</td>
<td>F</td>
<td>0.0E-18</td>
</tr>
<tr>
<td>cgdl</td>
<td>Vds bias dependence of parasitic gate drain overlap capacitance</td>
<td>F</td>
<td>0.0E-15</td>
</tr>
<tr>
<td>cfgd</td>
<td>Fringing capacitance parameter</td>
<td>F</td>
<td>1E-12</td>
</tr>
<tr>
<td>ktcfgd</td>
<td>Temperature dependence of Fringing capacitance</td>
<td>F</td>
<td>0</td>
</tr>
<tr>
<td>cfgdsm</td>
<td>Capacitance smoothing parameter</td>
<td>F</td>
<td>1E-24</td>
</tr>
</tbody>
</table>

Reuse of $C_{gs}$ capacitance parameter

Select almost all the I(V) points

$C_{gd}$ capacitance extracted on the entire I(V) network
Non-linear capacitances: NEW OPTION ➔ ASM

- It is possible to have a $C_{ds}$ capacitance function of the $V_{ds}$ voltage.

Select almost all the I(V) points

$C_{ds}$ capacitance extracted on the entire I(V) network

<table>
<thead>
<tr>
<th>Name</th>
<th>Definition</th>
<th>Units</th>
<th>Default</th>
</tr>
</thead>
<tbody>
<tr>
<td>cdso</td>
<td>Cds capacitance parameter</td>
<td>F</td>
<td>0E-18</td>
</tr>
<tr>
<td>vbi</td>
<td>Built in potential</td>
<td>V</td>
<td>0.9</td>
</tr>
<tr>
<td>cj0</td>
<td>Zero bias depletion capacitance</td>
<td>F</td>
<td>0E-15</td>
</tr>
<tr>
<td>mz</td>
<td>Grading factor of depletion capacitance</td>
<td>None</td>
<td>0.5</td>
</tr>
<tr>
<td>aj</td>
<td>Limiting factor of depletion capacitance in forward bias region</td>
<td>None</td>
<td>100E-3</td>
</tr>
<tr>
<td>dj</td>
<td>Fitting parameter</td>
<td>None</td>
<td>1</td>
</tr>
</tbody>
</table>
Model Extraction Flow

Small-Signal

IV Model

Non-linear capacitances

Thermal model

Trapping effects

Opt2: \( I_{ds} = f(V_{gs\_trap}, V_{ds\_trap}, T) \)

Opt1:

- \( C_{gs} = f(V_{gs}) \)
- \( C_{gd} = f(V_{gd}) \)
- \( C_{ds} = f(V_{ds}) \)

\[ g = f(V_{gs}, T) \]
\[ I_{ds} = f(V_{gs}, V_{ds}, T) \]

\[ R_s = f(T) \]
\[ R_d = f(T) \]
Thermal effects with IVCAD

- Temperature dependence with ambient or chuck temperature

IVCAD can be used to model thermal effects on different parameters of current source and capacitances.
Model Extraction Flow

Small-Signal
- $R_g$, $C_{pg}$, $L_s$, $C_{pd}$, $L_d$, $R_s$, $R_d$

IV Model
- $I_{gs} = f(V_{gs}, V_{ds})$
- $I_{ds} = f(V_{gs}, V_{ds})$

Non-linear capacitances
- $C_{gs} = f(V_{gs})$
- $C_{gd} = f(V_{gd})$
- $C_{ds} = f(V_{ds})$

Thermal model
- $I_g = f(V_{gs}, T)$
- $I_{ds} = f(V_{gs}, V_{ds}, T)$

Trapping effects
- Opt1: $C_{gs} = f(V_{gs})$
- $C_{gd} = f(V_{gd})$
- $C_{ds} = f(V_{ds})$
- $R_s = f(T)$
- $R_d = f(T)$

Opt2: $I_{ds} = f(V_{gs_trap}, V_{ds_trap}, T)$

This document may not be reproduced, modified, adapted, published, translated, in any way, in whole or in part, or disclosed to a third party without the prior written consent of AMCAD engineering - © Amcad 2019.
Thermal and Trapping effects

- Thermal and Trapping effects require a time-based simulator. IVCAD software does not have an on-board simulator. That’s why, the thermal and trapping effect included in AMCAD models are implemented using commercial software like Advanced Design System.

Trapping Effects:
  ➔ Gate-lag & Drain-Lag measurements.

Thermal resistance extraction ➔ Coincidence method / Del Alamo method
Thermal impedance extraction ➔ Drain long pulse characterization

\[ R_{th} = \frac{\Delta T}{\Delta P} \]

\(@ V_{gs} = 0 \text{ V} \)

DC, Tchuck1 = 25°C
Pulsed from (0,0), Tchuck2 = 100°C
Small-Signal

IV Model

Non-linear capacitances

Thermal model

Commercial Simulators
To export the nonlinear model, select only one point of the I(V) network.
Large Signal model validation

Empiric Load Pull measurements at the extrinsic planes

Gate

Intrinsic Drain

Extrinsic Drain

Drain

Tuner f0, 2f0, 3f0

50Ω

Tuner f0

CW or Pulse RF signal

φ_{Ref}
Application specific Load Pull Validation: ASM model

Modeling and validation flow
Q&A

Thank you

Visit Booth # 328 for more!!

Web Site: www.amcad-engineering.com