Modeling of GaN-based High Electron Mobility Transistors

A Cursory Note on Some Latest Developments

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GaN-based HEMT Applications

- High-power/high-frequency
- High-speed/high-voltage

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<th>High-power/High-frequency</th>
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<td>RF Power Amplifiers</td>
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<th>Key FOM</th>
<th>3rd order Intercept Point (IP3)</th>
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<td>Breakdown Voltage (BV)</td>
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- ON Resistance ($R_{ON}$)
- Gate Charge ($Q_G$)
- $R_{ON} \times Q_G$
- Breakdown Voltage (BV)
GaN HEMT Model Standardization Effort

- Compact Model Coalition – compact model standardization body for industry standard models for silicon MOSFETs, BJTs, resistors, varactors and compiled modeling interface

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

- Requirements for the core model
  - As exact, complete, and simple a representation of physical GaN HEMT behavior as possible.
  - Extensibility of the model from GaN to all III-V FET/HEMT structures would be an added benefit but is not a strict requirement
  - Physically correct in all operating regions
  - No unphysical behavior
  - As computationally efficient as possible
  - Model should be charge based and not capacitance based, and charge conserving
Examples of GaN HEMT Models

- CMC candidate models as of December 2013
  - Angelov-GaN model: Prof. I. Angelov, Charlmes University
  - COMON model*: URV, Prof. B. Iniguez
  - HKUST model**: Hong Long University of Science and Technology, Prof. M. Chan
  - HSP (HEMT Surface Potential) model, CEA-Leti, Dr. P. Martin
  - MIT Unified VS GaNFET (MVSG) model: MIT, Prof. D. Antoniadis
  - NCSU model: North Carolina State University, Raleigh, Prof. R.J. Trew
  - RPI model: Rensselaer Polytechnic Institute, Prof. M. Shur
  - U. Connecticut model: University of Connecticut, Prof. M. Anwar
- Many other models..

*Initial model development done by Dr. S. Khandelwal and Prof. T. Fjeldly at UniK
**Initial model development done by Tsinghua University
Broad Categories of Modeling Approaches

- Physics-based models
- Empirical models
  - Empirical DC current modeling
  - Empirical charge modeling
  - Advanced empirical modeling with ANNs
- Frequency-domain empirical models
  - S-parameter models
  - X-parameter models
Physics-based Modeling of Silicon MOSFETs

- Poisson equation
- Boltzmann distribution

- Surface potential
- Quasi – Fermi level
- Mobile charge
- Terminal charges (Q – V)

- Continuity equation
- Transport model

**Channel current (I – V)**

- Charges are formulated directly in the model
- Charges and channel current are formulated consistently
- Capacitances are just observable derivatives

\[ C_{mf} = \begin{cases} \frac{-\partial Q_m}{\partial V_f}, & m \neq f \\ \frac{\partial Q_m}{\partial V_f}, & m = f \end{cases} \]

Physics-based Modeling of GaN HEMT

- Self-consistent solution of Schrodinger and Poisson equations using triangular well approximation for 2DEG electron concentration
  
  - Poisson equation
  - Schrodinger equation

- Examples:
  - COMON model
  - HSP model
  - HKUST model

Energy band diagram in GaN HEMT

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*S. Khandelwal et al., IEEE MTT, vol. 61, no. 9, 2013


Modeling of Dynamic Trapping Effects

• Common approach
  • Use RC networks to determine effective gate and drain bias values during dynamic operation

Dynamic trapping modeling in COMON model

Example of drain-lag related trapping modeling

- S. Khandelwal et al., IEEE MTT, vol. 61, no. 9, 2013
Empirical DC Current Modeling – Table-based Approach

- The DC currents for the model are taken directly from DC measurements and stored in table form as functions of the two independent terminal voltages ($V_{gs}$, $V_{ds}$).

- Ex.: Agilent Root model

Empirical DC Current Modeling – Analytical Approach

- Channel current model is constructed by explicitly capturing geometrical characteristics of output/transfer behavior
  - Ex.: Agilent EEHEMT1 model, Angelov-GaN model

\[
I_{ds} = I_{pks} \left[ 1 + \tanh(\Psi_p) \right] \tanh(\alpha_s V_{ds})(1 + \lambda V_{ds})
\]

\[
\Psi_p = P_{1m}(V_{gs} - V_{pks})
\]

Illustration of some DC parameters in Agilent EEHEMT1 model

Illustration of channel current formulation in Angelov-GaN model

Empirical Charge Modeling – Capacitance-only Approach

- No charge model is formulated in this case
- Capacitances used explicitly to construct the model are non-linear, i.e. dependent on terminal voltages
  - Ex.: Angelov-GaN model\(^*\), Tagima model\(^**\)

Empirical Charge Modeling – Capacitance-Integration Approach

• Bias-dependent small-signal capacitances integrated over bias space to obtain charge models to ensure charge conservation

  • Ex.: Root Model’, Freescale RF power LDMOS model”, Angelov-GaN model”

\[
Q_g (V_{gs}, V_{ds}) = \int_{V_{gs0}}^{V_{gs}} \left[ C_{gs} (v_{gs}, V_{ds0}) + C_{gd} (v_{gs}, V_{ds0}) \right] dv_{gs} - \int_{V_{ds0}}^{V_{ds}} C_{gd} (V_{gs}, v_{ds}) dv_{ds} + Q_g (V_{gs0}, V_{ds0})
\]

\[
Q_d (V_{gs}, V_{ds}) = \int_{V_{gs0}}^{V_{gs}} \left[ C_{m} (v_{gs}, V_{ds0}) - C_{gd} (v_{gs}, V_{ds0}) \right] dv_{gs} + \int_{V_{ds0}}^{V_{ds}} \left[ C_{ds} (V_{gs}, v_{ds}) + C_{gd} (V_{gs}, v_{ds}) \right] dv_{ds} + Q_d (V_{gs0}, V_{ds0})
\]

Large-signal model obtained by integration over the bias voltage space”


Artificial Neural Networks (ANN) Methodology

- An ANN is a parallel processor made up of simple, interconnected processing units, called neurons, with weighted connections.

- ANN training (aka ANN model extraction or model generation): determination of weights ($w$) and offsets ($b$) to fit outputs to known quantities.

\[
x_{L,j} = \sum_{i=1}^{N_{L-1}} \text{sigmoid}(w_{L-1,ij} * x_{L-1,j} + b_{L,j})
\]

Output value of the $j^{\text{th}}$ neuron of the $L^{\text{th}}$ layer

Illustration of an artificial neural network with one hidden layer of four neurons
**Agilent NeuroFET Model**

- Use ANNs to build the current and charge models based on DC and S-parameters
  - Charge models formulated directly instead of through integration of capacitances
  - Charges and currents infinitely differentiable with respect to terminal voltages

\[
I_g(t) = I_{dc}^g(V_{gs}(t), V_{ds}(t)) + \frac{dQ_g(V_{gs}(t), V_{ds}(t))}{dt}
\]

\[
I_d(t) + \tau \frac{dI_d(t)}{dt} = I_{dc}^d(V_{gs}(t), V_{ds}(t)) + \tau \frac{dI_{hf}^d(V_{gs}(t), V_{ds}(t))}{dt} + \frac{dQ_d(V_{gs}(t), V_{ds}(t))}{dt} + \tau \frac{d^2Q_d(V_{gs}(t), V_{ds}(t))}{dt^2}
\]

Measurement-caused Modeling Challenges for RF PA Applications

- Actual operating conditions of an RF PA often not attainable for modeling measurement
  - Current/voltage/power constrains define DC SOA
  - Pulsed measurement limited by pulse width
- Ultimate model validation done on RF PA under large-signal operation
- Often times a model just tuned to fit load-pull contours without regard to its DC and S-parameter fitting
DynaFET model structure where $I_G$, $I_D$, $Q_G$, and $Q_D$ are formulated using ANNs

Major capabilities:
- Trapping/de-trapping modeling
- Self-heating modeling

DC/S-parameter measurement data across ambient temperature

NVNA waveform measurement data across
- DC bias
- RF power
- RF frequency
- Load condition
- Ambient temperature

J. Xu, et al., “Large-signal FET Model with Multiple Time Scale Dynamics from Nonlinear Vector Network Analyzer Data,” IMS 2010, Anaheim CA

ANN Model Extraction in DynaFET

\[ I_D = f(V_{ds}, V_{gs}, T_0) \]

\[ T_0 \rightarrow T_j \leftarrow V_{ds(t)}^{\text{max}} \phi_2 \quad V_{gs(t)}^{\text{min}} \phi_1 \]

\[ I_{ds(t)} \]

Simplified ID ANN extraction scheme

- Drain lag subckt & Approximation for trap state \( \phi_2 \)

- Gate lag subckt & Approximation for trap state \( \phi_1 \)

- J. Xu, et al., “Large-signal FET Model with Multiple Time Scale Dynamics from Nonlinear Vector Network Analyzer Data,” IMS 2010, Anaheim CA
Conclusions

- Fragmented solution space for GaN HEMT modeling: various models developed for specific applications (RF PA, RF switch, passive mixer, power switching, etc.)

- A general model framework is still being sought after that allows in a single model card scalability over
  - Geometry (finger width, number of fingers, drain-gate spacing, etc.)
  - Bias ($V_{gs}$, $V_{ds}$)
  - Frequency
  - Temperature
  - Load impedance

- Is the above goal attainable?
Acknowledgment

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- Dr. Samuel Mertens, Agilent
- Dr. Patrick Martin, CEA/Leti
- Dr. Sourabh Khandelwal, University of California, Berkeley
BASED ON PD SOI MODELING RETROSPECTIVE..
Most Probably, Yes!

- “Weird” curves to model?
  - Kink effect
  - Bimodal $g_m$ vs. $V_{gs}$
Most Probably, Yes!

- Self-heating? – Modeled
- Charging/discharging? – Modeled
- Memory effect? – Captured
Most Probably, Yes!

- Circuit-level correlation for high-frequency, large-signal application?
  - Ring oscillators operating at multi GHz