Modeling of GaN-based High Electron Mobility Transistors

A Cursory Note on Some Latest Developments

Agilent EEsof EDA

Brian Chen

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GaN-based HEMT Applications

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

	High-power/High-frequency	High-speed/High-voltage
Example	RF Power Amplifiers	Switched-mode power supply
Key FOM	3rd order Intercept Point (IP3) Gain Power-added Efficiency (PAE) 1-dB Gain Compression Point (P1dB) ...	ON Resistance (R_{ON}) Gate Charge (Q_G) $R_{ON} * Q_G$ 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

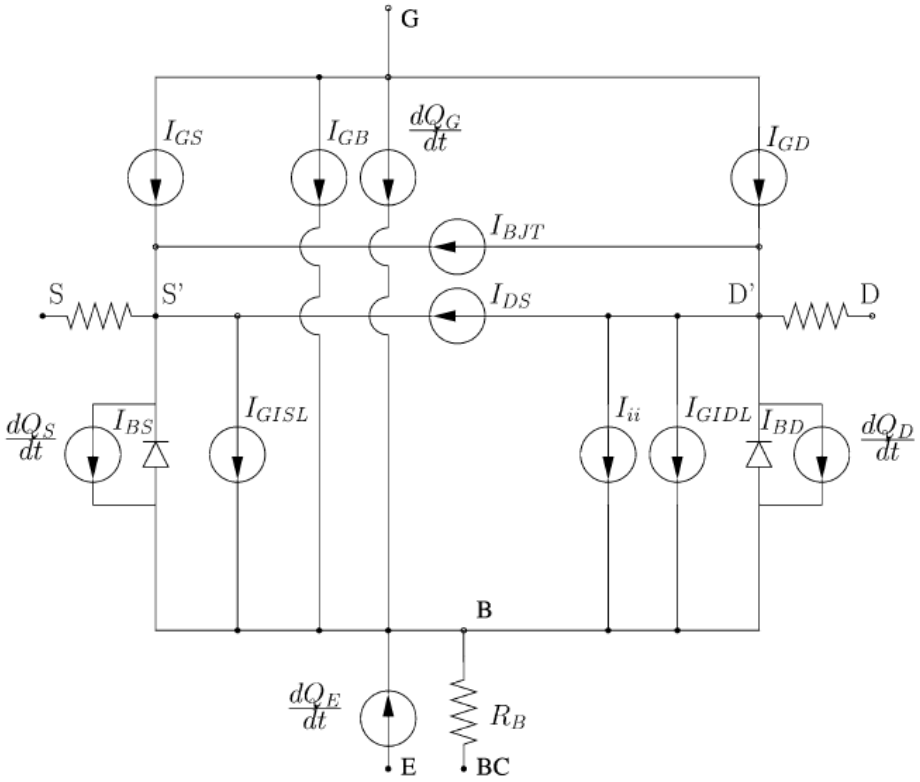
Physics-based Modeling of Silicon MOSFETs

- *Poisson equation*
- *Boltzmann distribution*

- *Surface potential*
- *Quasi − Fermi level*
- *Mobile charge*
- ***Terminal charges*** $(\boldsymbol{Q-V})$

- *Continuity equation*
- *Transport model*

Channel current $(\boldsymbol{I-V})$



Circuit representation of PSP-SOI model*

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

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

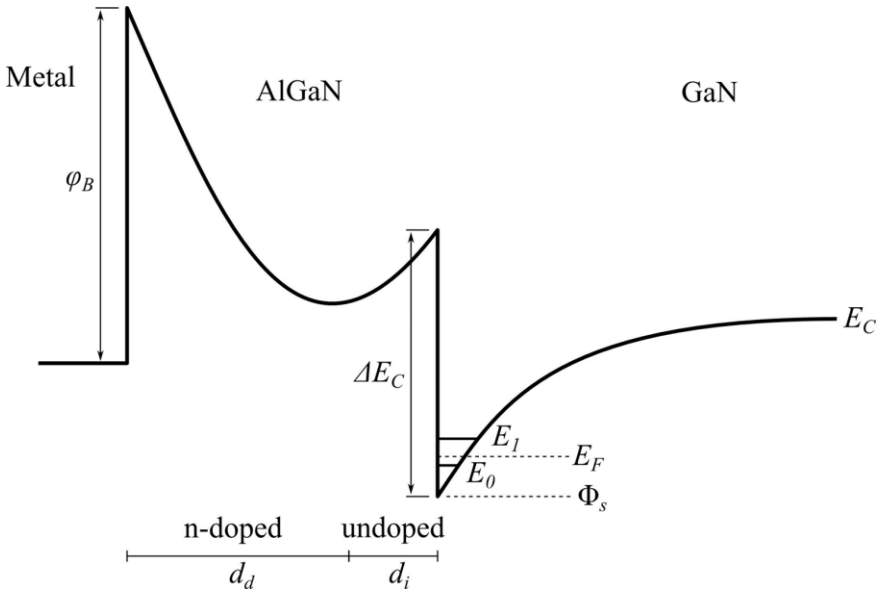
*G. Gildenblat, "Compact Modeling: Principles, Techniques and Applications", Springer, 2010, p. 44.

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***

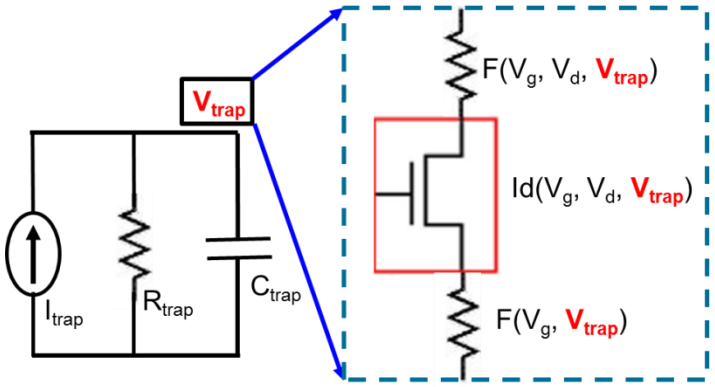


Energy band diagram in GaN HEMT**

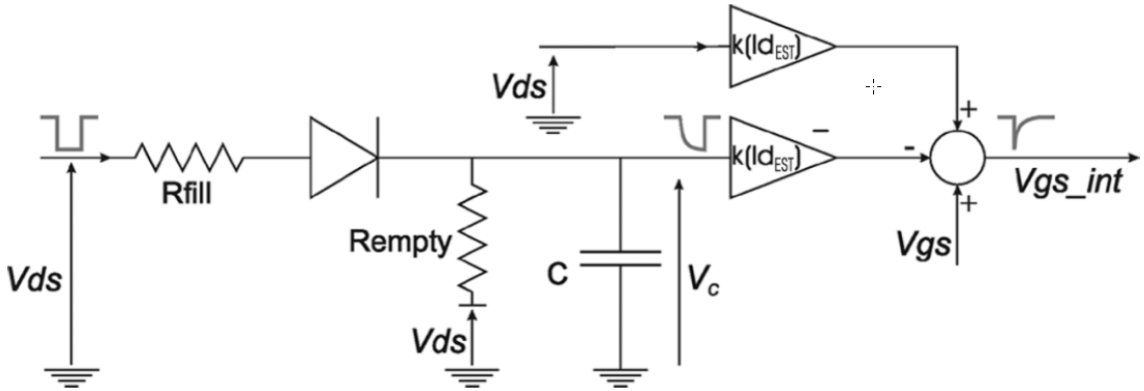
- *S. Khandelwal et al., IEEE MTT, vol. 61, no. 9, 2013
- **P. Martin, "HSP: A Surface-Potential-Based Compact Model of AlGaN/GaN HEMTs Power Transistors," MOS-AK, Bordeaux, Sep. 2012.
- ***X. Cheng, et al., "A Surface Potential Based Compact Model for AlGaN/GaN MODFETs," IEEE Transactions on Electron Devices, vol. 58, no. 2, pp. 448-454, Feb. 2011.

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
- **O. Jardel, et al., "An Electrothermal Model for AlGaN/GaN Power HEMTs Including Trapping Effects to Improve Large-Signal Simulation Results on High VSWR," IEEE MTT, vol. 55, no. 12, Dec. 2007

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*

- *D.E. Root, et al., "Technology Independent Large-Signal Non Quasi-static FET Models by Direct Construction from Automatically Characterized Device Data," Proc. 21st European Microwave Conference, pp.927-932, 1991.

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***

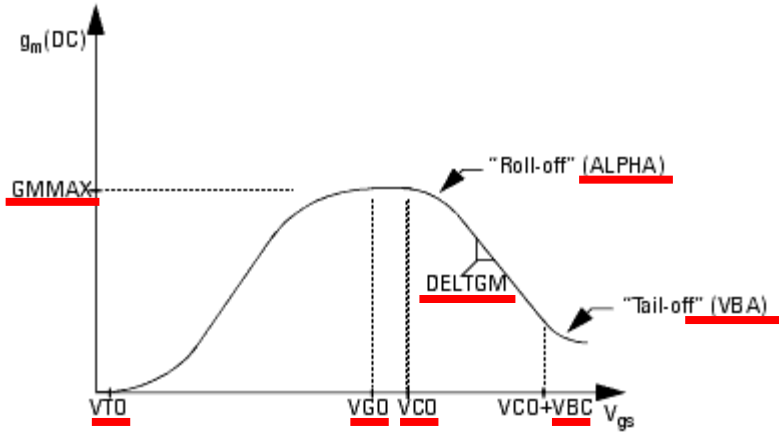
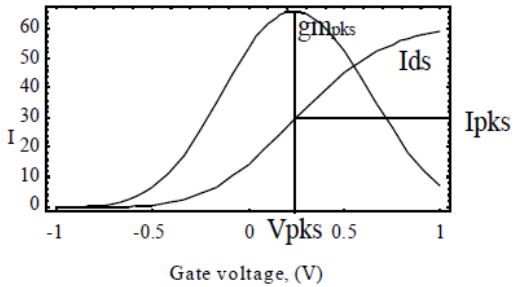
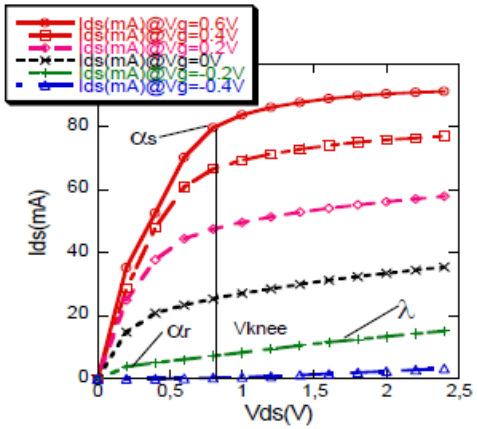


Illustration of some DC parameters in Agilent EEHEMT1 model*





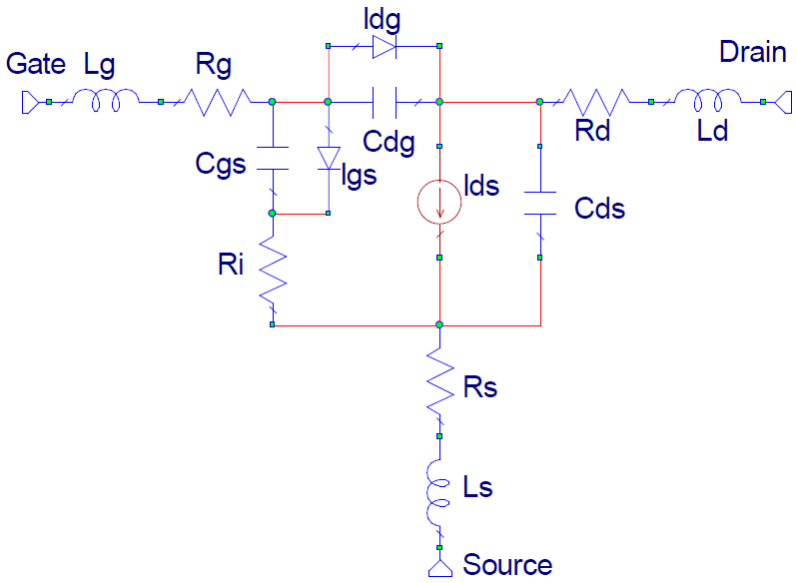
- $I_{ds} = I_{pks}\left[1 + tanh\left(\Psi_p\right)\right]tanh(\alpha_s V_{ds})(1 + \lambda V_{ds})$
- $\Psi_p = P_{1m}\left(V_{gs} - V_{pks}\right)$

Illustration of channel current formulation in Angelov-GaN model**, *****

- *Agilent IC-CAP EEHEMT1 Package User Guide, qthelp://iccap.2013.01/doc/mesfet/Agilent_EEHEMT1_Model_Equations.html.
- **Agilent IC-CAP Angelov-GaN Package User Guide, qthelp://iccap.2013.01/doc/angelov/Parameter_Extraction_Flow_Example.html.
- ***I. Angelov, "Compact, Equivalent Circuit Models for GaN, SiC, GaAs and CMOS FET," MOS-AK, Baltimore MD, Dec. 2009.

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**



Large-signal equivalent circuit in Tajima model **

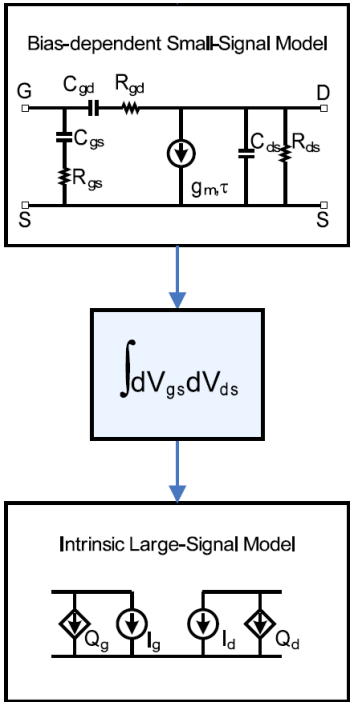
- *I. Angelov, “Compact, Equivalent Circuit Models for GaN, SiC, GaAs and CMOS FET,” MOS-AK, Baltimore MD, Dec. 2009.
- **Y. Tajima, “Progress in GaAs PHEMT, GaN Modeling,”, EDICON 2013.

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***

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

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



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

- *D.E. Root, et al., "Technology Independent Large-Signal Non Quasi-static FET Models by Direct Construction from Automatically Characterized Device Data," Proc. 21st European Microwave Conference, pp.927-932, 1991.
- **J. Wood and P.H. Aaen, "On the Modeling of LDMOS RF Power Transistors," IEEE CICC, San Jose, CA, Sep. 2010.
- ***I. Angelov, "Compact, Equivalent Circuit Models for GaN, SiC, GaAs and CMOS FET," MOS-AK, Baltimore MD, Dec. 2009

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

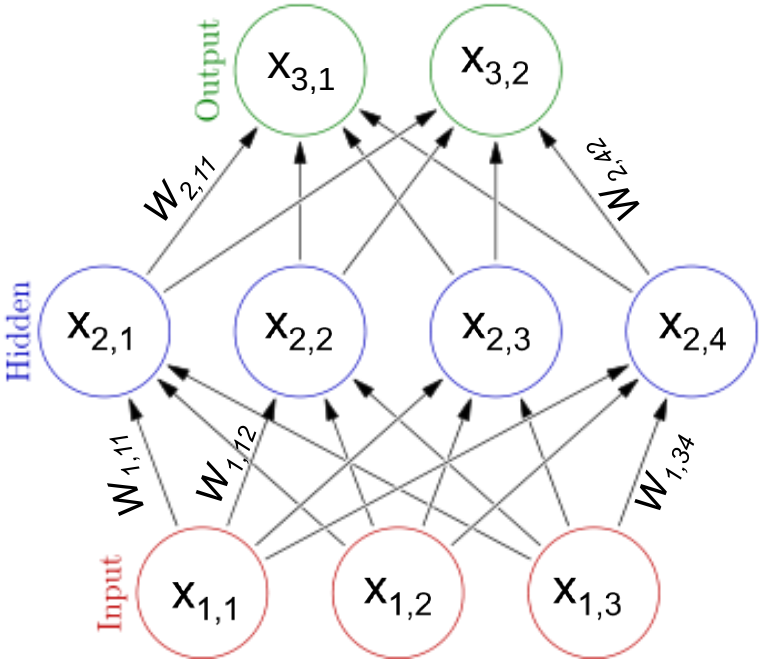


Illustration of an artificial neural network with one hidden layer of four neurons

$$x_{L,j} = \sum_{i=1}^{N_{L-1}} sigmoid\left(w_{L-1,ij} * x_{L-1,j} + b_{L,j}\right)$$

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

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

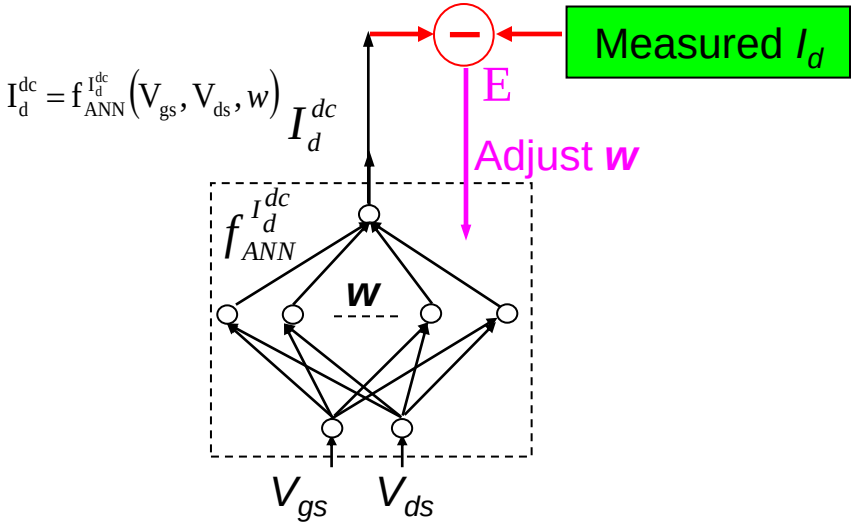


Diagram of NeuroFET's ANN structure of DC current model and its training*

$$I_g(t) = I_g^{dc}(V_{gs}(t), V_{ds}(t)) + \frac{dQ_g(V_{gs}(t), V_{ds}(t))}{dt}$$

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

- *J.J. Xu and D. Root, "Measurement-based FET modeling using Artificial Neural Networks (ANNs)," Innovations in EDA Webcast, Feb., 2012, http://www.home.agilent.com/agilent/eventDetail.jspx?cc=US&lc=eng&ckey=2068731&nid=-34161.0.08&pid=0000100020022:atg:pgr
- J.J. Xu, et al., "Exact Adjoint Sensitivity Analysis for Neural-Based Microwave Modeling and Design," IEEE Trans. Microwave Theory and Techniques, vol. 51, no. 1, Jan. 2003.

Measurement-caused Modeling Challenges for RF PA Applications

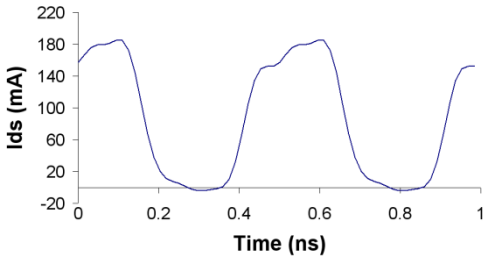
- Actual operating conditions of an RF PA often not attainable for modeling measurement
  - Current/voltage/power constrains define DC SOA
  - Pulsed measurement limited by pulse width
- Ultimate model validation done on RF PA under large-signal operation
- Often times a model just tuned to fit load-pull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

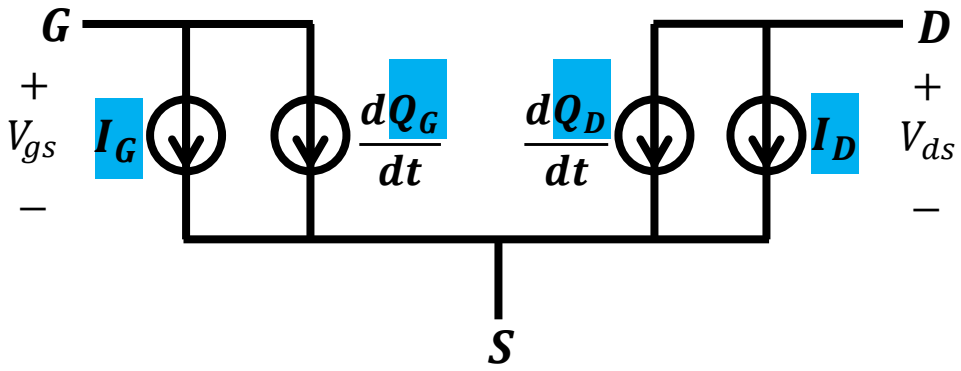
Agilent DynaFET Model*,**

DC/S-parameter measurement data across ambient temperature

NVNA waveform measurement data across

- DC bias
- RF power
- RF frequency
- Load condition
- Ambient temperature





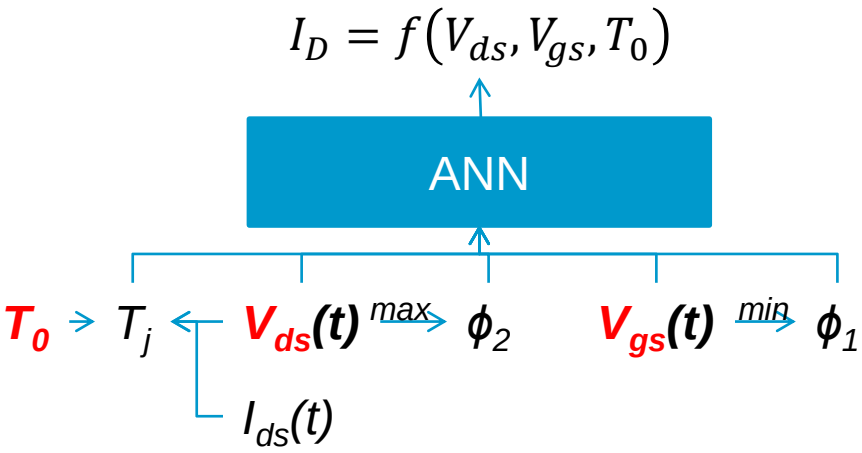
DynaFET model structure where I_G, I_D, Q_G, and Q_D are formulated using ANNs

Major capabilities:

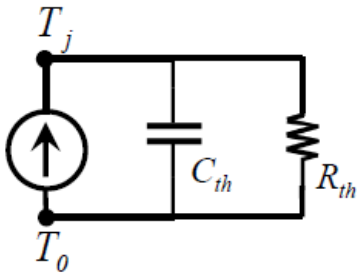
- *Trapping/de-trapping modeling*
- *Self-heating modeling*

- *J. Xu, et al., "Large-signal FET Model with Multiple Time Scale Dynamics from Nonlinear Vector Network Analyzer Data," IMS 2010, Anaheim CA
- **J. Xu, et al., "Dynamic FET Model – DynafET – for GaN Transistors from NVNA Active Source Injection Measurements," IMS 2014, Tampa Bay FL.

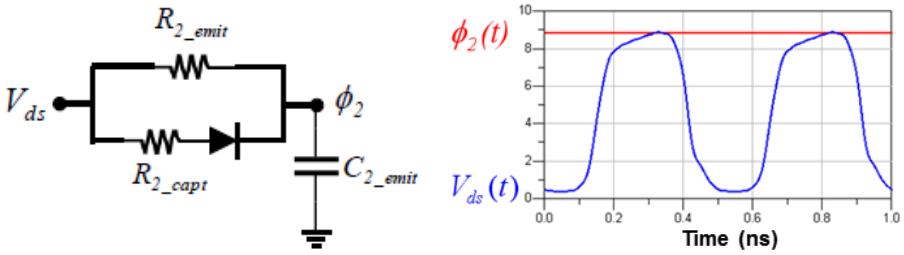
ANN Model Extraction in DynaFET



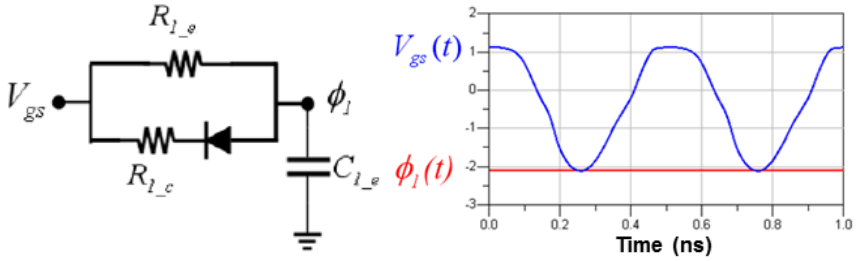
Simplified ID ANN extraction scheme



Self-heating subckt



Drain lag subckt &
Approximation for trap state ϕ_2



Gate lag subckt &
Approximation for trap state ϕ_1

- *J. Xu, et al., "Large-signal FET Model with Multiple Time Scale Dynamics from Nonlinear Vector Network Analyzer Data," IMS 2010, Anaheim CA
- **J. Xu, et al., "Dynamic FET Model – DynafET – for GaN Transistors from NVNA Active Source Injection Measurements," IMS 2014, Tampa Bay FL.

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

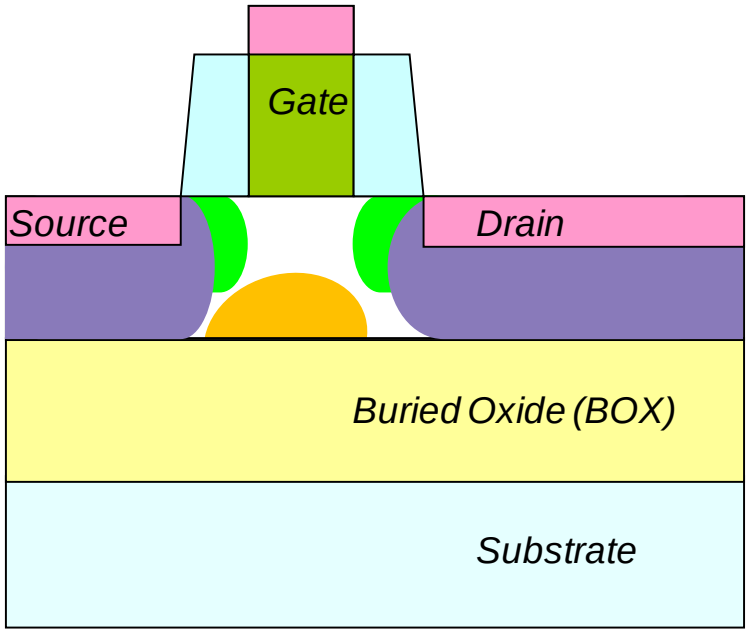
For helpful discussions and sharing expertise

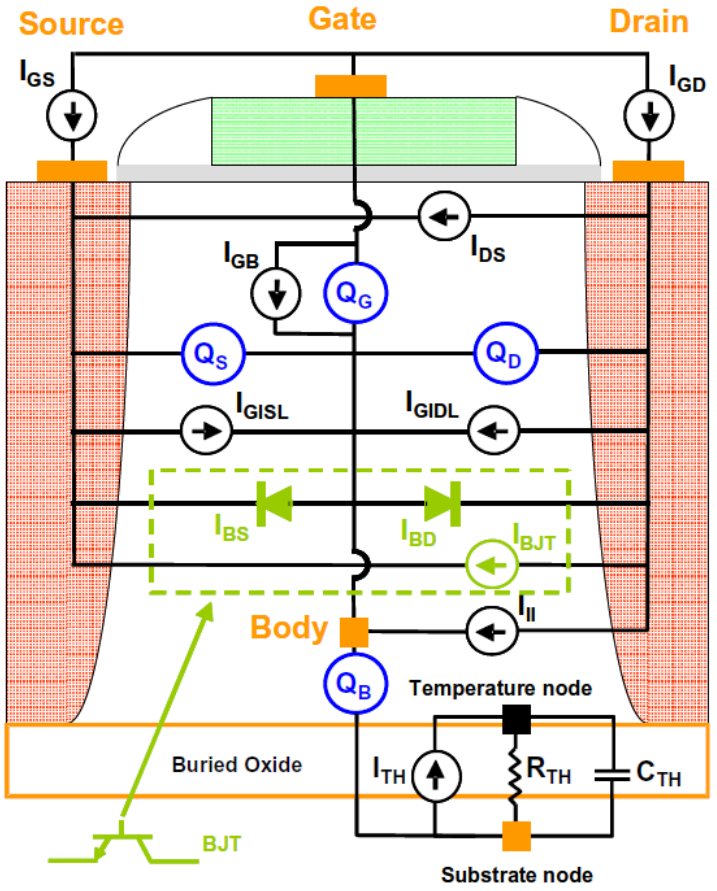
- Dr. David Root, Agilent
- Dr. Jianjun Xu, Agilent
- Prof. Iltcho Angelov, Chalmers University
- Prof. Benjamin Iniguez, Universitat Rovira i Virgili
- Dr. Samuel Mertens, Agilent
- Dr. Patrick Martin, CEA/Leti
- Dr. Sourabh Khandelwal, University of California, Berkeley

BASED ON PD SOI MODELING RETROSPECTIVE..

Most Probably, Yes!

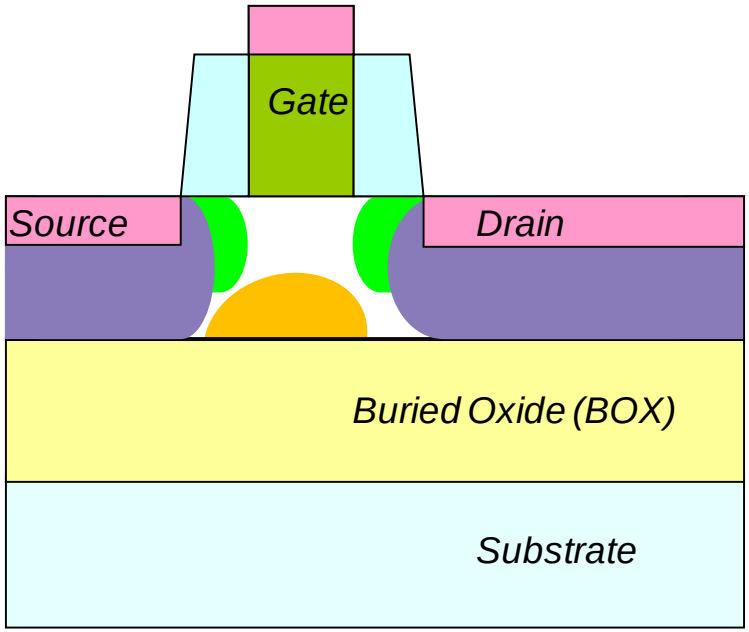
- "Weird" curves to model?
  - Kink effect
  - Bimodal g_m vs. V_{gs}

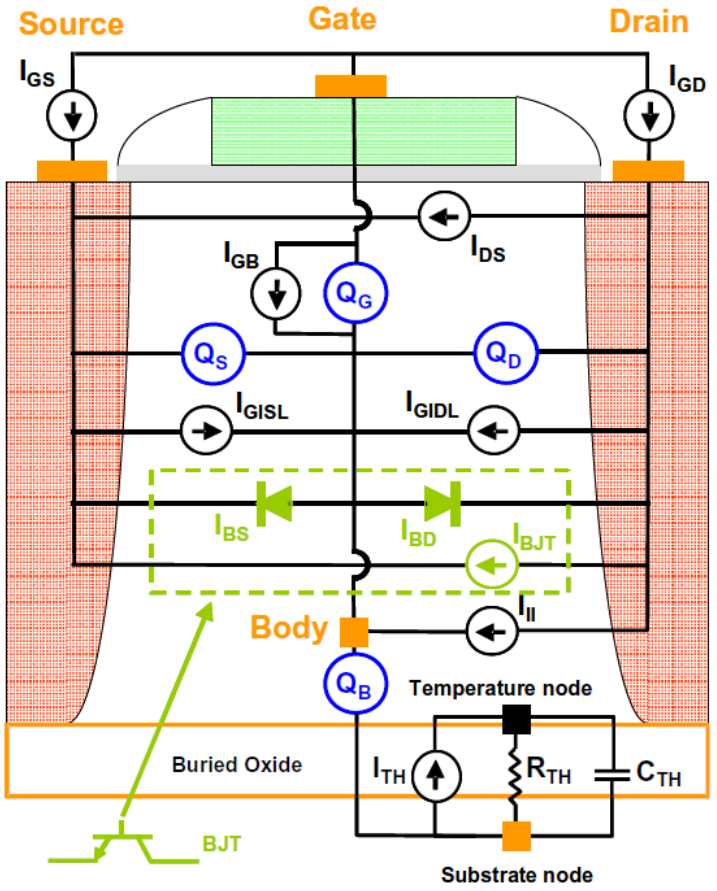


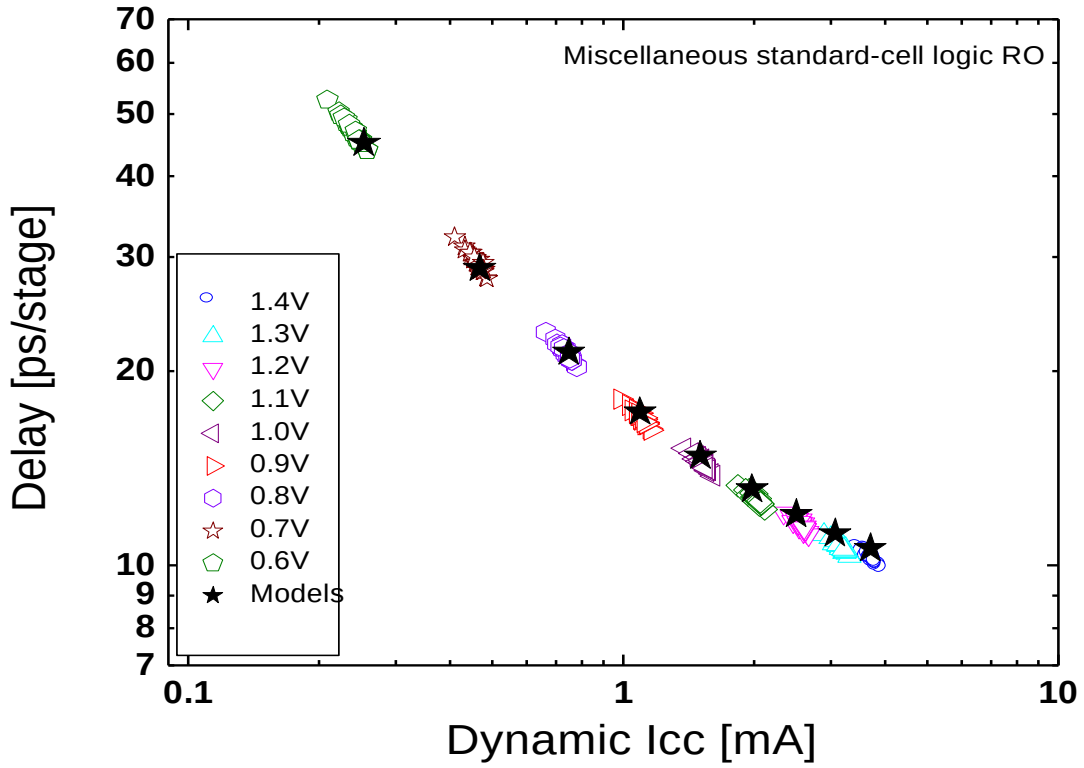


Most Probably, Yes!

- 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