MVSG Model for RF Applications: Thermal, Scalability and Parasitic Modeling

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RF-Electronic Design Using III-V Semiconductors

- **Ron vs. BV tradeoff**: HV devices
- **Switching losses**: HV devices
- **f_max vs. BV tradeoff**: RF devices

GaN enabled

High power density and frequency

RF-electronics
Vehicular Communication Using GaN-Electronics

IEEE802.11P for real time traffic management

- Wireless access in vehicular environments (WAVE)
- Licensed ITS band (5.85-5.925 GHz) and range of up to 300 m
- Smaller and efficient systems: Integration in mobile phones (V2V, V2H)

V2V wireless communication with 9000 intelligent vehicles, U-M Transportation research institute and U.S. DoT, 2012
Communication Using Cellphones

GaN: Form factor, efficiency and output power

From ‘iFixit iPhone 7 teardown’

Bottleneck of form-factor & power consumption

Application
Network
MAC
PHY

Application Processor
Digital Communication Processor
DAC
ADC
RF Transceiver
RF FEM (PA & passive)

CMOS
CMOS
CMOS or SiGe
III-V

Better power density and efficiency than CMOS
From Physics-Modeling to Industry Standard

MVSG model chosen as GaN industry standard model

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

Phase-II
- 4 candidates
- Sponsors: ADI, TI, Toshiba
- Data: Triquint, Toshiba

Phase-III
- 2 candidates
- Model evaluation
- Feedback

Phase-IV
- Model support
- Version release
GaN HEMT: Carrier Transport

**RF-GaN HEMT**
- Source access region
- Intrinsic transistor
- Drain access region

**HV-GaN HEMT**
- GaN (3 nm)
- Al\textsubscript{0.26}Ga\textsubscript{0.74}N (18 nm)
- GaN 1.2\(\mu\)m

**DD transport**
- \(V_{S}\)
- \(V_{D}\)
- \(V_{l_g}\)
- \(V_{g}\)
- \(V_{Si}\)
- \(V_{Df}\)
MVSG Model: Device Currents

**Accuracy**
- MVS approach
- V, T, f dependence
- Extensive calibration
- Circuit evaluation

**Convergence**
- Charge-based
- Nodal symmetry
- Low node-count
- Verilog-A

\[ I_D / W = \frac{V_{sat} (Q_{inv,s} + Q_{inv,d})}{2} \]

Saturation velocity

Source and drain end charge

Function for transition from short to long gate lengths

- Charge-based model
- Source/Drain symmetry ensured
- DD-to-ballistic transport covered
MVSG Model: Gate-Length Scaling

- 1 μm HV-devices
- Full region of operation

- 40nm RF-devices
- Device physics: SCE, DIBL, Access regions
- Quasi-ballistic transport
MVSG Model: Width Scaling

Model captures width-scalability for large devices

- Wide devices
  : RF-PAs and HV-FETs

- Simple scaling
  : $R_{th}$ scaling
  : $C_{of}$ scaling
  : $Q_{inv}$ scaling

- $W/N_{gf}$ effects similar
MVSG Model: High-Frequency Modeling

Large signal estimations do not require any fitting
MVSG Model: $S$-parameter Scaling

**Model captures width-scalability for large devices**

- High-frequency behavior against large-W devices

- Simple scaling:
  - $R_{th}$ scaling
  - $C_{of}$ scaling
  - $Q_{inv}$ scaling

- $W/N_{gf}$ effects similar
 Thermal and shot noise sources added to the model

 Compared with on-wafer RF noise measurements at 6 GHz

\[ I_{S,th}^2 = \frac{4kT}{R_S} \quad I_{D,th}^2 = \frac{4kT}{R_D} \quad I_{G,th}^2 = \frac{4kT}{R_G} \quad I_{ch,th}^2 = 4kTg_m(q_s + q_d) \quad q_s(d) = \frac{Q_s(d)}{Q_{inv,s(d)}} \]

\[ I_{GD,shot}^2 = 2qI_{GD} \quad I_{GS,shot}^2 = 2qI_{GS} \]

- IEDM 2014
MVSG Model: RF Noise Model

- Thermal and shot noise sources added to the model
- Compared with on-wafer RF noise measurements at 6 GHz
IEEE802.11P: First Fully Integrated GaN RF-front-end
MVSG Model: RF-Circuit Level Validation

Enabling RF-circuit design through dedicated physics-modeling

PA: $P_{\text{sat}} = 28.8$ dBm, PAE = 50%

LNA: NF = 3 dB, OIP3 = 22 dBm

MIT virtual source GaNFET-RF compact model for GaN HEMTs: From device physics to RF frontend circuit design and validation
- U. Radhakrishna, P. Choi, S. Goswami, LS. Peh, T. Palacios, D. Antoniadis, 2014 IEEE IEDM.
MVSG Model: Thermal modeling

Carrier velocity

\[ v_{sat}(T) = \frac{v_{sat}(T_o)}{1 + \eta_v \Delta T} \]

Effective mobility

\[ \mu_{eff}(T) = \frac{\mu_o(T_o)}{1 + \eta \mu \frac{\Delta T}{T_o}} \]

Electrostatic parameters

\[ S(T) = S_o(T_o) \left(1 + \frac{\Delta T}{T_o}\right) \]
\[ V_T(T) = V_T(T_o) \left(1 + \eta_{vt} \Delta T\right) \]

- Additional parameters: \(v_{sato}, \mu_o, \eta_v, \eta_\mu, \eta_{vt}, \varepsilon\)
MVSG Model: Thermal modeling

- Model calibrated against two $T$
- Temp-cos extracted
- Captures 2 other $T$
- Self-heating removed: pulsed IV
Self-heating: Bias Dependence

- Channel temperature (\(T_{eq}\)) by electrical methods show little bias dependence.

- Thermal measurements show bias dependence (Same Pdiss, different Vg, Vd, \(\rightarrow\) different T profile).


Heat generation in the channel is highly non-uniform. Which temperature determines the current degradation?
Self-heating: Equivalent Channel Temperature

Equivalent channel temperature $T_{eq}$: interpolation of electro-thermal current from single-$T$ currents

For short-gate RF HEMTs, $T_{eq}$ lies in the source access region.

Self-heating: Equivalent Channel Temperature

Temperature affects the low-field region (through mobility) much more than the high-field region (through saturation velocity).
Self-heating: $T_{eq}$ in HV HEMTs

For long-gate HV HEMTs, $T_{eq}$ lies around the source-side gate edge.

For HV FETs with longer Lg: bigger part of the gated channel is also low-field.
Summary

- MVSG model as a design tool for both device and circuit design
- MVSG model captures: DC, small and large-signal AC, noise, thermal
- Verified against various fabricated device data
- RF-circuit design validation using commercial foundry process
- Studied GaN HEMT self-heating mechanisms
- Explained difference between “electrical” temperature and “physical” temperature