Advanced MOSFET Modeling for RF IC Design

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Outline

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Introduction

- Booming wireless communication market asks for alternative technology such as CMOS for low power and low cost solutions.

- RF IC designers need MOSFET models at RF to verify their design.

- Compared with table look-up model, physical and scalable compact models are preferred.

- Continued efforts are required to have an RF MOSFET model with good accuracy over bias, frequency and geometry
Modeling at High Frequency

- At high frequency, parasitic capacitance and resistance components need to be accounted for in the model.

- Non-Quasi Static effects become significant for $f > f_{T/5}$

- Good continuity, accuracy and scalability are the essential requirements.

- Predicts accurately the bias dependence of small signal parameter at HF operation.

- Describes correctly the non-linear and distortion behavior of the device.

- Models accurately the noise characteristics.
AC Small Signal Modeling

- Modeling of gate resistance
- Modeling of substrate resistance
- Modeling of capacitive components.
- Modeling of NQS effects
- Results and Discussions.
Parasitic Components in a MOSFET

Diagram showing the parasitic components and labels:
- G: Gate
- D: Drain
- S: Source
- B: Body
- N+: N-type doping near the gate
- N-: N-type doping near the substrate
- P+: P-type doping near the substrate
- P-SUB: P-type substrate
- RSB: Source-Body resistance
- RD: Drain-Body resistance
- RDS: Drain-Source resistance
- RDB: Drain Body resistance
- RGS: Gate-Source resistance
- CGS: Gate-Source capacitance
- CGD: Gate-Drain capacitance
- DSB: Source-Body diffusion capacitance
- DBD: Drain-Body diffusion capacitance
- RBDS: Body-Drain diffusion capacitance
- CGSO: Gate-Source overlap capacitance
- CGDO: Gate-Drain overlap capacitance
Modeling Gate Resistance

\[ R_g = R_{g, \text{poly}} + R_{g, \text{nqs}} \]

- **\( R_g \):** Total gate resistance
- **\( R_{g, \text{poly}} \):** Poly-silicon gate resistance
- **\( R_{g, \text{nqs}} \):** Effective gate resistance caused by NQS effect. It becomes dominant in devices with longer channel length
Modeling Substrate Resistances

Signal at the drain coupling to the nearby source diffusions and to the substrate terminal through the junction capacitance and substrate resistance
Modeling Capacitive Components

- "Tox" or "Tox,eff"? And hence "Cox" and "Cox,eff"?
- The influence of Poly-depletion and channel quantization!
- Extrinsic capacitance becomes critical, especially in 0.13 and below technologies.
- Csub can be ignored when $f<10\text{GHz}$. 
**Subcircuit Model**

- All parasitic components are scalable and extracted from data.
- The capacitance of CGSP and CGDP can be embedded into the core model, if it is sufficient for the geometry and bias dependence.
The model accuracy in terms of frequencies, biases and different device geometries is important for the model to predict the large signal behavior.
The subcircuit model predicts the $f_T$ characteristics well at different bias conditions.
The model without the consideration of NQS effect cannot predict the HF behavior of a device with a longer channel length.

- NQS effect results in a significant change in both real and imaginary parts.
Noise Modeling

• Noise sources in a MOSFET

• Flicker noise modeling

• Comparison of different channel thermal noise models

• Induced gate noise discussion
Noise Sources in a MOSFET

\[ \frac{i_g^2}{i_g^2} \quad \frac{i_s^2}{i_s^2} \quad \frac{i_d^2}{i_d^2} \quad \frac{i_{SUB}^2}{i_{SUB}^2} \quad \frac{i_d^2}{i_d^2} \quad \frac{i_g^2}{i_g^2} \]

- Noise contributed by gate poly-resistance
- Noise contributed by source series resistance
- Noise contributed by drain series resistance
- Noise contributed by substrate resistance
- Noise contributed by channel resistance
- Induced Gate Noise
HF Noise Prediction by Subcircuit Model

- The model needs to be improved in predicting HF noise behavior
**HF Noise Simulations**

- Inaccurate noise prediction by traditional noise models.

![Graph showing noise simulations](image)

- $N_f = 10$
- $W = 12 \mu m$
- $L = 0.36 \mu m$
- $V_{DS} = 1V$

- Extracted from measured data

- Subcircuit RF model

- $8kT^* (g_m + g_{ds})/3$
- $8kT^* g_m/3$
- $8kT^* g_{ds}/3$

- $I_{DS}$ (mA)
- $i_d^2 (10^{-22} \text{Amp}^2/\text{Hz})$
**Induced Gate Noise**

- **Induced gate noise is only important in either device with long channel lengths or very high frequency.**

- **For devices with minimum channel length (0.18um), the induced gate noise can be ignored for a frequency range up to 10GHz.**
Status of Induced Gate Noise Model

- No induced gate noise models in commercial circuit simulators.
- Not dominant at the operating frequency range of most RF circuits
- Modeling difficulty to obtain physical and accurate correlation with channel thermal noise
- Implementation difficulty in the circuit simulator
- Different modeling approach without induced gate noise
Large Signal Modeling

- “Low Frequency Limit” behavior of MOSFET
- Modeling methodology for large signal behavior
- Example and Discussions.
Distortion Behavior: MOSFET versus BJT

MOSFET is much more linear than BJT.
BJT distortion behavior exhibits a much stronger frequency dependence.

Moving valleys!
Low Frequency Limit (LFL)

- A MOSFET exhibits a much higher low-frequency limit (LFL) than a BJT.

- The LFL is a frequency under which the distortion behavior is mostly dictated by the device characteristics at DC (static) and low-frequencies.

- A BJT has a strongly nonlinear AC component, i.e. the bias-dependent diffusion change accumulated in the quasi-neutral base and collector at high currents, while a MOSFET has a relatively linear counterpart.

- The strong nonlinear diffusion charge contributes to the strong frequency dependence of the distortion behavior of Bipolar transistors.

- Such high LFL enables a static/quasi-static modeling strategy for MOSFET distortion.
Modeling Methodology

• Use a subcircuit-based composite model with BSIM3V3 as the core component.
  • Enable a precise DC extraction. Most essential for MOSFET distortion prediction.
  • Use external components to better represent the device parasitic components and distributed behavior at higher frequencies

• Quasi-static extraction methodology
  • Require only typical measurement setup: DC, AC, and S-parameters
  • Sufficient distortion prediction of MOSFET up to frequencies of interest, where the devices are still capable of delivering a decent gain.

• No fine-tuning of model parameters with respect to distortion is needed.
DC Model Verification

Accurate DC ($G_m$ and $G_{out}$) modeling is essential to distorting modeling.

- $L_f = 0.36\, \mu m$
- $W_f = 12\, \mu m$
- $N_f = 2$

- $V_{ds} = 0.5$
- $V_{ds} = 1.0$
- $V_{ds} = 1.5$

- $V_{gs} = 0.5$
- $V_{gs} = 1.0$
- $V_{gs} = 1.5$
Distortion Prediction I: Pin=-10dBm

Modeled (solid lines) and measured (symbols) $P_{out}$'s versus drain current $I_{ds}$ for the 10x12x0.36 device at different frequencies when $V_{ds}=0.5V$ and $P_{in}=-10$dBm.
Distortion Prediction II: Pin=0dBm

Modeled (solid lines) and measured (symbols) $P_{out}$’s versus drain current $I_{ds}$ for the 10x12x0.36 device at different frequencies when $V_{ds}=1.0V$ and $P_{in}=0dBm$
Discussions

- The proposed methodology is sufficient for MOSFET distortion prediction.

- Accurate $f_T$ model is less essential to the distortion prediction of MOSFET than to that of BJT, while the high-frequency current gain is still strongly dependent on it.

- The distortion behavior observed from the given measurement setup is more of a function of $G_m$ than $G_o$. Very useful for application such as cascode amplifiers and active mixers, whose distortion behavior is mostly dictated by $G_m$.

- Need further verification for inter-modulation prediction.

- Need further work for the distortion prediction of a passive mixer, where a symmetrical model is preferred.
Summary

• RF model development is important for IC design

• Reasonable fitting can be achieved by a subcircuit model with the existing intrinsic MOSFET model in predicting DC, AC small signal and distortion.

• Further modeling work need to be continued to develop better models to predict NQS, noise and distortion behavior in addition to the DC and AC small signal behavior.