Critical RFCMOS IC Simulation Improvements Through New Industry Standard MOSFET and MOS Varactor Models

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Outline

• Compact Model Council: Industry Standardization Body for compact models
• PSP: Next Generation Industry Standard MOSFET Model
  – Physical improvements important for nanometer RF
  – Circuit examples
• MOSVAR: Industry Standard MOS Varactor Model
  – Motivation
  – Details
  – Results
Compact MOSFET Models: Brief History

- BSIM3 gains traction for sub micron technologies in early to mid 1990s
- BSIM3 becomes 1st Compact Model Council (CMC) industry standard model in 1995
- BSIM4 developed to extend life of BSIM architecture, adding new effects like halo implants, gate current...
- BSIM4 becomes 2nd CMC industry standard model in 2000
- CMC solicits next generation standard MOSFET model to address nanometer technology and overcome shortcomings of BSIM platform
- PSP becomes next generation, the 3rd CMC industry standard MOSFET model in June 2006
What is the Compact Model Council?

- Industry body that recommends and develops standard models for the semiconductor industry
- Members consist of IDMs, fabless design companies, foundries, and EDA vendors
- All major IDMs, foundries, and EDA vendors are members
- CMC Standard models provide following advantages
  - Best modeling community in the world drives effort
  - Portability and consistency of models among simulators

INTEL  NEC
Mentor  INTEL
NXP  Toshiba
Toshiba  TI
Agilent  Broadcom
Freescale  JAZZ
MAXIM  National
RFMD  TSMC
ADI  Cadence
Synopsis
BSIM vs. PSP: Key Things to Know

- Vth based, model genesis is
  
  \[ I_{ds} = \beta \left( V_{gs} - V_{th} - \frac{V_{ds}}{2} \right) \cdot V_{ds} \]

  Etc…

- Regional model with different equations for subthreshold, inversion, and saturation connected with empirical smoothing functions

- Inconsistent IV and CV models

- Insufficient modeling of overlap regions, including CV

- Discontinuous at Vds=0

- Poor, unphysical noise modeling

- Drift-diffusion equations based on surface potential \( \Psi_s \)

  \[ I_d = \mu W \left( -QI \frac{d\Psi_s}{dx} + \phi_l \frac{dQI}{dx} \right) \]

  - Continuous model across all regions

  - Consistent IV and CV models

  - Physical modeling of overlap regions through surface potentials (key for short channels)

  - Continuous at Vds=0, key for RF

  - Physics-based noise modeling
Moderate Inversion: Dominate for Low Vdd

\[ I_{DS} = I_{drift} + I_{diff} \]

PSP \( \Psi^s \)-Based
Moderate Inversion Physical

BSIM \( V_{th} \) Based
Moderate Inversion Empirical

Reprinted courtesy Gennady Gildenblat, Arizona State University
Improved Physical Modeling with PSP

PSP coulomb scattering provides improved Gm fitting

PSP halo implant modeling provides improved Gds fitting over geometry

PSP: Precise CV with physical parameters Tox, VFB, Nsub
Gummel Symmetry: $V_{ds}=0$ Exposed!

**Diagram:**

- BSIM
- PSP

**Equations:**

- $V_{gb0}$
- $V_{b0}-V_x$
- $V_{b0}+V_x$

**Drain Current Graphs:**

- Two graphs showing the drain current ($I_{ds}$) as a function of the gate-source voltage ($V_{gs}$) for BSIM and PSP models.
Gummel Symmetry: Vds=0 Exposed!

1\textsuperscript{st} Derivative

**BSIM**

\[ \frac{d}{dV_d} AV \]

\[ V_{gs} \rightarrow V_{gd} \text{ switching in model at } V_x=0 \]

**PSP**

\[ \frac{d}{dV_d} AV \]
Gummel Symmetry: Vds=0 Exposed!

2nd Derivative

BSIM

PSP

Vgs→Vgd switching in model at Vx=0
Gummel Symmetry: Vds=0 Exposed!

3rd Derivative

BSIM

PSP

Vgs→Vgd switching in model at Vx=0
PSP vs. BSIM Distortion Simulation for RF Attenuator

BSIM IP3 NOT constant!  
PSP IP3 constant

BSIM IM3 slope=2!  
Caused by non existent 2nd order derivative at Vx=0

PSP IM3 slope=3

Variables (dBVp)

Pin (dBVp)
RFCMOS Switch

- BSIM unphysical third order harmonic simulation render RFCMOS Switch design with BSIM unpractical
- PSP required for RFCMOS design of switch, passive mixer, Gm amps/attenuators, ....

Significant Design Success Reported in Silicon Distortion match to Simulation
Noise Modeling: NFmin

- Default BSIM under predicts NFmin, missing several effects
- BSIM with HF noise extensions is better, does not match bias dependence accurately
- PSP model accurately matches bias dependent NFmin with no extra parameter tuning from DC/RF data needed

PSP Includes
- Physical models for induced gate noise and correlation to drain noise
- Physical dependence of channel noise on velocity saturation
- Accurate NQS models, results in physical values for device parasitics
Noise Modeling: Equivalent Noise Resistance $R_n$

- Default BSIM under predicts $R_n$
- BSIM with HF noise extensions is better, does not match bias dependence accurately
- PSP model accurately matches $R_n$ with no extra parameter tuning from DC/RF data needed
Significant differences in predicting RFCMOS LNA noise performance

PSP provides most accurate simulations
• **GOAL of Statistical Modeling:**
  Accurate simulation of PCM distribution caused by process variation

• Achieve **GOAL** through statistical infrastructure called Backward Propagation of Variance (BPV)

• **BPV Requirement:** Scalable models which simulate physical sensitivities of the PCM to variations in process and geometry model parameters

• **PSP** provides vastly improved physical mapping compared to $V_{th}$ based models
Backward Propagation of Variance (BPV)

Model Parameters

- $V_{FB}$
- $N_{SUB}$
- $\Delta L$
- $dV_{FBL}$
- $\mu_0$

 PCM

- $I_{dsat_S}$
- $I_{dsat_L}$
- $V_{th_S}$
- $V_{th_L}$
- $KB$

Measured PCM

FPV

RFIC Workshop 2007, James Victory
Backward Propagation of Variance (BPV)

Model Parameters:
- $V_{FB}$
- $N_{SUB}$
- $\Delta L$
- $dV_{FBL}$
- $\mu_0$

GOAL MET!

PCM
- $I_{dsat_S}$
- $I_{dsat_L}$
- $V_{th_S}$
- $V_{th_L}$
- $K_B$

Measured PCM
- PSP
- BSIM

RFIC Workshop 2007, James Victory
PSP Simple BPV Matrix Example

Variances of PCM (e)

\[
\begin{align*}
\sigma_{\delta V_{il}}^2 &= \left( T_{ox} \frac{\partial V_{il}}{\partial T_{ox}} \right)^2 \sigma_{\delta T_{ox}}^2 \frac{T_{ox}}{T_{ox}} \\
\sigma_{\delta Id_{il}}^2 &= \left( T_{ox} \frac{\partial Id_{il}}{\partial T_{ox}} \right)^2 \sigma_{\delta T_{ox}}^2 \frac{T_{ox}}{T_{ox}} \\
\sigma_{\delta K_{bl}}^2 &= \left( T_{ox} \frac{\partial K_{bl}}{\partial T_{ox}} \right)^2 \sigma_{\delta T_{ox}}^2 \frac{T_{ox}}{T_{ox}} \\
\sigma_{\delta V_{ts}}^2 &= \left( T_{ox} \frac{\partial V_{ts}}{\partial T_{ox}} \right)^2 \sigma_{\delta T_{ox}}^2 \frac{T_{ox}}{T_{ox}} \\
\sigma_{\delta Id_{ds}}^2 &= \left( T_{ox} \frac{\partial Id_{ds}}{\partial T_{ox}} \right)^2 \sigma_{\delta T_{ox}}^2 \frac{T_{ox}}{T_{ox}}
\end{align*}
\]

Sensitivities obtained from within Model (Spectre)

\[
\begin{align*}
\left( \frac{\partial V_{il}}{\partial V_{fb}} \right)^2 & \left( \frac{\partial V_{il}}{\partial \mu_0} \right)^2 & \left( \frac{\partial V_{il}}{\partial N_{sub}} \right)^2 & \left( \frac{\partial V_{il}}{\partial V_{fbl}} \right)^2 & \left( \frac{\partial V_{il}}{\partial \Delta L} \right)^2 \\
\left( \frac{\partial Id_{il}}{\partial V_{fb}} \right)^2 & \left( \frac{\partial Id_{il}}{\partial \mu_0} \right)^2 & \left( \frac{\partial Id_{il}}{\partial N_{sub}} \right)^2 & \left( \frac{\partial Id_{il}}{\partial V_{fbl}} \right)^2 & \left( \frac{\partial Id_{il}}{\partial \Delta L} \right)^2 \\
\left( \frac{\partial K_{bl}}{\partial V_{fb}} \right)^2 & \left( \frac{\partial K_{bl}}{\partial \mu_0} \right)^2 & \left( \frac{\partial K_{bl}}{\partial N_{sub}} \right)^2 & \left( \frac{\partial K_{bl}}{\partial V_{fbl}} \right)^2 & \left( \frac{\partial K_{bl}}{\partial \Delta L} \right)^2 \\
\left( \frac{\partial V_{ts}}{\partial V_{fb}} \right)^2 & \left( \frac{\partial V_{ts}}{\partial \mu_0} \right)^2 & \left( \frac{\partial V_{ts}}{\partial N_{sub}} \right)^2 & \left( \frac{\partial V_{ts}}{\partial V_{fbl}} \right)^2 & \left( \frac{\partial V_{ts}}{\partial \Delta L} \right)^2 \\
\left( \frac{\partial Id_{ds}}{\partial V_{fb}} \right)^2 & \left( \frac{\partial Id_{ds}}{\partial \mu_0} \right)^2 & \left( \frac{\partial Id_{ds}}{\partial N_{sub}} \right)^2 & \left( \frac{\partial Id_{ds}}{\partial V_{fbl}} \right)^2 & \left( \frac{\partial Id_{ds}}{\partial \Delta L} \right)^2
\end{align*}
\]

Variances of process model parameters (p)

\[
\begin{align*}
\sigma_{\delta V_{fb}}^2 \\
\sigma_{\delta \mu_0}^2 \\
\sigma_{\delta N_{sub}}^2 \\
\sigma_{\delta V_{fbl}}^2 \\
\sigma_{\delta \Delta L}^2
\end{align*}
\]

Direct PSP model parameters
NO mapping required

\[
\sigma_{\delta e_i}^2 = \sum_k \left( \frac{\partial e_i}{\partial p_k} \right)^2 \sigma_{\delta p_k}^2
\]
PSP Statistical Match to Data

Long Device

Short Device

Accurate Prediction of Correlations Over Geometry
MOSVAR
Industry Standard MOS Varactor Model
Motivation for CMC Standard Model

- MOS Varactor is typically only tuning element in RFCMOS PDKs
  - Multiple voltage range devices offered based on Tox levels
- Clear need for model meeting CMC high standard for model quality
- CMC MOSVAR Subcommittee formed in April 2006, model developed by Victory, Yan, Gildenblat, McAndrew, Anderson et.al. chosen as base. (EDL May 2001, TED August 2005)
- Model code unified with PSP model wherever possible
  - Provides natural consistency and statistical harmony between MOS devices in process
  - New gate current formulations derived since poly-well configurations different in MOS varactor
- Model available now to CMC members in verilogA and shared libraries in spectre
- CMC standardization set for October 2007
  - EDA vendor implementation underway
MOS Varactor

- Intrinsic C generated from frequency dependent surface potential formulation
- Scalable parasitic models ensure accurate CV and Quality Factor (Q) simulation
- Physical Gate Current models critical for 130nm and below technologies
- Layout parasitics, substrate network part of extrinsic model
Frequency Dependent Inversion Charge

- QI thermally generated, not supplied by source/drain regions as in MOSFET
- In VCO design DC biased in inversion, inversion charge can form, altering frequency response
- Depletion width small due to high doping
- Negligible compared to Well thickness
- Ignore voltage dependence of $R_{sub}$
- Accumulation Charge $Q_{ac}$ calculated directly from surface potential
- Voltage dependent surface scattering included in mobility $\mu_{acv}$

$$R_{sub} = R_{S HS} \cdot \frac{L_g}{(12 \cdot W_g \cdot M)}$$
Bias Dependent Well Resistance

- Depletion width small due to high doping
- Negligible compared to Well thickness
- Ignore voltage dependence of $R_{\text{sub}}$

- Accumulation Charge $Q_{\text{ac}}$ calculated directly from surface potential
- Voltage dependent surface scattering included in mobility $\mu_{\text{ac}}$
Bias Dependent Well Resistance

- Depletion width small due to high doping
- Negligible compared to Well thickness
- Ignore voltage dependence of $R_{\text{sub}}$

- Accumulation Charge $Q_{ac}$ calculated directly from surface potential
- Voltage dependent surface scattering included in mobility $\mu ac_v$

\[
R_{ac} = \left( \frac{L_g}{W_g \cdot \mu ac_v \cdot Q_{ac} \cdot M} \right)
\]
\[
R_{\text{sub}} = \text{RSHS} \cdot \left( \frac{L_g}{12 \cdot W_g \cdot M} \right)
\]
Poly Gate Resistance Model

- Includes salicide to bulk poly contact resistance – vertical component
  - Dominant component of Rgate at narrower widths, short lengths
- Accurate modeling of Rg scaling

\[ R_{gsal} = \frac{\rho_{sal} \cdot W_g}{L_g \cdot 3 \cdot N_{cnts}^2} \]

\[ R_{gpv} = \frac{\rho_{pv}}{W_g \cdot L_g} \]

Horizontal Salicide resistance

Vertical Salicide to poly interface contact resistance

Cox
MOS Varactor Layout and Metal Connection Considerations

- Metal R and L ~ NS/NF (segments)
- High metal resistance (thin M1)
- Low metal capacitance (M1-M1)

- Metal R and L ~ NF/NS (fingers)
- Low metal resistance (wide M2)
- High metal capacitance (M2-M1)
Physical Parameter Extraction:
Scalable MOS Capacitance

- Regression fitting of $C_{\text{max}}$ and $C_{\text{min}}$ on $W_g$ and $L_g$ yields $D_L$, $D_W$, $C_{\text{frw}}$
- $T_{\text{ox}}$, $N_b$ (well doping), QM, and PD parameters extracted from large plate capacitor

\[
C_{\text{max}} = \left( C_{\text{ox}} \cdot (L_g - D_L) \cdot (W_g - D_W) + 2C_{\text{frw}} \cdot (W_g - D_W) \right) \cdot (N_s \cdot N_f) \\
C_{\text{min}} = \left( \frac{C_{\text{ox}} \cdot C_{\text{dep}}}{C_{\text{ox}} + C_{\text{dep}}} \cdot (L_g - D_L) \cdot (W_g - D_W) + 2C_{\text{frw}} \cdot (W_g - D_W) \right) \cdot (N_s \cdot N_f)
\]
Scalable Nwell Resistance Model Extraction

\[ R_{\text{nwell}} = \frac{R_{\text{end}}}{W_g} + \frac{R_{\text{SHS}} \cdot L_g}{W_g \cdot 12} \]

- Physical extraction through regression vs. Lg
- Plot vs. 1/(Wg) verifies model accuracy

Slope yields \( R_{\text{SHS}} \)

Lg=0 intercept yields \( R_{\text{end}} \)

\[ \text{slope} = \frac{R_{\text{end}}}{W_g} + \frac{R_{\text{SHS}} \cdot L_g}{12} \]

Rnw=0 @ intercept
MOS Varactor Model Results: Varying Lg

\[ Q = \frac{|\text{Im}(\gamma_{11})|}{\text{Re}(\gamma_{11})} \]

\[ C_{max}/C_{min} \uparrow \]

\[ Q \downarrow \]

\[ R_{nw} \uparrow \]
MOS Varactor Model Results: Varying Wg

- $C_{\text{max}}/C_{\text{min}}$ increases
- $Q$ decreases
- $R_{\text{poly}}$ increases

Graphs showing $C_{gb}$ and $Q$ at $3\text{GHz}$ for different values of $W_g$. The graphs illustrate how $C_{gb}$ and $Q$ change with varying $W_g$.
MOS Varactor Model Results: Varying NsxNf

- $C_{\text{max}} / C_{\text{min}}$
- $Q \downarrow$
- $R_{m1} \uparrow$
- $L_g/L_s \uparrow$
N⁺ vs. P⁺ Poly MOS Varactors

- **N⁺ poly on Nwell by self-alignment allows for shortest Lg**
  - Highest Q
  - Typical VCO biasing requires DC shift of tank voltage to allow for full tuning
  - Easy integration
- **P⁺ poly on Nwell provides entire tuning range on +V_{GB} axis**
  - N⁺ contact to Nwell pulled back to prevent counter doping of poly
  - Lg > Lmin to allow to avoid design rule violations in implanting poly with P⁺
  - Decreases Q minimally
  - Tricky integration but doable
Gate Current

- Accurate modeling of overlap and intrinsic gate current components specific to MOS Varactor structure
- 130nm and below, Ig represents non negligible loss mechanism

![Diagram of gate current components and numeric values](image)

- Lg=0.5
- Lg=3.0
MOS Varactor Effects on Voltage Controlled Oscillator (VCO)
VCO Principles

- Ideal Tank Circuit
  - Perfect transfer of energy between L&C

\[ \omega = \frac{1}{\sqrt{LC}} \]

- Lossy Tank Circuit
  - Energy dissipated in Rs

- VCO Tank Circuit
  - Energy dissipated in tank compensated by active transistors
MOS Varactor Purpose: Tune Frequency in VCO

RFCMOS VCO
M1/M2 presents -1/gm
MOS Varactor Purpose: Tune Frequency in VCO

RFCMOS VCO
M1/M2 presents -1/gm

![Diagram of RFCMOS VCO circuit]

\[ f \]

\[ C \text{ [pF]} \]

\[ V_{\text{gb}} \text{ [V]} \]

\[ -2.0 \quad -1.5 \quad -1.0 \quad -0.5 \quad 0 \quad 0.5 \quad 1.0 \quad 1.5 \quad 2.0 \]
MOS Varactor Purpose: Tune Frequency in VCO

RFCMOS VCO

M1/M2 presents -1/gm

\( V_{control} \)

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<th>( V_{gb} [\text{V}] )</th>
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Vcontrol

Min \( \rightarrow \) Max
Tank Q: MOS Varactor Influence

\[ Q_{\text{tank}} = \frac{Q_L \cdot Q_C}{Q_L + Q_C} = \frac{\omega L}{R_L + \omega^2 L C R_C} \]

- As frequency increases, varactor Q plays increased role
- Above 5G, MOS varactor Q starts to influence
- Above 10G, MOS varactor Q dominates
Phase Noise

- Phase noise (PN): random variation of phase error in a frequency synthesis system
- Noise (1/f and thermal/shot) injected by active transistors
- Higher $Q_{tank}$ sharpens the spectrum of the oscillator, reducing effect of injected noise
- Higher $Q_{tank}$ means lower $R_s$, lower $g_m$ needed to sustain oscillation → lower $g_m$ equates to less noise, lower power

Leeson’s PN Model

$$|H(j\Delta \omega)|^2 = \frac{1}{4(Q_{tank})^2} \left( \frac{\omega_0}{\Delta \omega} \right)^2$$
MOS Varactor Model Scaling
Critical for VCO Design

\[ KVCO = \frac{d\omega}{dV} = \frac{\omega}{2} \left( \frac{Lg}{C_i' \cdot Lg + C_{FRW}} \right) \cdot \frac{dC_i'}{dV} \]

\[ |H(j\Delta\omega)|^2 = \frac{1}{4Q_{tank}^2} \left( \frac{\omega_0}{\Delta\omega} \right)^2 \]
Summary MOS Varactor Model: Key Things to Get Right

• Physical CV equation dependent on process and geometry parameters
  – Cmax/Cmin, tuning range variation with geometry
  – Accurate dC/dV critical for VCO phase noise
  – Facilitates accurate statistical modeling

• Accurate models for device resistance over geometry
  – Provides designer ability to trade off tuning range for Q, effectively trading VCO gain vs. phase noise

• Gate Current – non-negligible at 130nm and below

• Proper dependence of metal parasitics on device layout
  – Poor layout can kill Q
Summary

• PSP Model
  – Key improvements for nanometer RF design

• Introducing MOSVAR Model

• Don’t settle: Demand PSP and MOSVAR models from your foundry!

• References for this material:


  http://pspmodel.asu.edu/
  http://www.eigroup.org/cmc/
Acknowledgments

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