Submicron Circuit Design with BSIM3 or BSIM4

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Outline

- Modeling Tradeoffs and BSIM approaches
- The Meyer’s model and its deficiency
- Formulation of the basic BSIM model
- Simplified BSIM3 model for hand calculation
- Additional Features in BSIM4
- Summary
Modeling Tradeoff

- **Ultimate goal of model:** Accurate and Simple

- **Modeling tradeoff polygon**

![Diagram showing the tradeoff between simplicity, universality, physical, empirical, extendibility, accuracy, and number of parameters.](image)
Various Modeling Approaches

Charge based model
- terminal charges are associated to terminal voltages
- most compatible with the conventional design methodology
- simple, flexible but maybe more empirical

Surface potential based model
- more physically and ensure smooth transition between operation regions
- usually more complex and less flexible

Conductance based model
- good for circuit design with simple and predictable behavior
- need to improve on accuracy
- still a bit primitive for predictive purpose
Positioning of BSIM Models

- **Physical based**
  - basic derivation is from physical device parameters
  - important for predictive property

- **Traditional design compatibility**
  - most popular model among circuit designer is still the level 1 (basic Meyer) model
  - BSIM was first intended to be compatible with the level 1 model

- **Flexibility to fit most existing technology**
  - modular approach for flexible addition of new and complex technology modules quickly
  - capability to fit a wide range of technologies (good or bad)
  - by using some empirical fitting and tuning parameters
Some facts in BSIM development

- Starts out as a simple physical model with a small number of parameters
- Closely follow process development with lots of advanced features such as
  - Super steep retrograde well
  - Pocket implant
  - Gate current model
  - GIDL/GISL
- Allow early adoptions of new process modules
- Under the guideline of industrial partners in the direction of development
Preliminary solutions to Charge model

A new capacitor model (BSIM4 CapMod=3) has been formulated with the following features:

- No asymmetry or negative resistance problem
- About 1,200 lines of code
- About 50% slower than CapMod=2) for single transistor voltage sweep
- Share most parameters with other parts of BSIM model, but used very few internal results from other part of BSIM
- Quantum effects
- Embedded surface potential
- Polysilicon depletion effects
- 2 new parameters for retrograde doping
- Built-in infrastructure for possible expansion into I-V and parasitic model
Preliminary result from CapMod 3

CapMod=3 (red) vs. CapMod=2 (blue)

Cds
Vg sweep.
Vd=Vs=Vb=0V

Cgg
Vg sweep.
Vd=2V, Vs=Vb=0V
Preliminary result from CapMod 3

CapMod=3 (red) vs. CapMod=2 (blue)

Cgs and Cgd
Vd sweep. Vg=2V, Vs=Vb=0V.

Cbs and Cbd
Vd sweep. Vg=2V, Vs=Vb=0V.
The Meyer’s Model

- Still the most widely used model in among circuit designers
- Simplicity of the model for hand calculations is the most important factor for its widespread usage
- Still being use even for submicron devices with modified parameter extraction technique with calculated design margins
- Provide an entry point to understand the BSIM models
The Basic of the Meyer’s Model [1]

\[ V_s = 0 \]
\[ V_G \]
\[ V_D \]
\[ I_D \]
\[ n^+ \]
\[ n^+ \]
\[ 0 \rightarrow y \]

anywhere along the conducting channel:

\[ I(y) = I_D = WQ_n(y)\nu(y) \quad \text{(1)} \]

Free carrier (inversion charge) density

\[ Q_n \approx C_{ox} \left( V_G - V_T - V(y) \right) \]

Velocity of carriers

\[ \nu(y) \approx \mu \tilde{E} = \mu \frac{dV(y)}{dy} \]
The Basic of the Meyer's Model [2]

\[ \int_0^L I_D dy = \mu W C_{ox} \int_0^{V_{DS}} (V_G - V_T - V(y))dV \] 

\[ \Rightarrow I_D = W C_{ox} \left[ (V_G - V_T) - \frac{V_{DS}}{2} \right] \mu \frac{V_{DS}}{L} \] 

for \( V_{DS} < V_G - V_T \)

average free carrier density in the mid-potential point of the channel

velocity of carriers with average \( E \)-field proportional to \( V_{DS} \)

\( V_D = V_G - V_T \)

\( I_{D_{sat}} \approx \frac{\mu W C_{ox}}{2L} (V_G - V_T)^2 \) 

for \( V_{DS} > V_G - V_T \)

as predicted by (2)

increasing \( V_G \)

regarded as saturation
**Most important Addition in BSIM [1]**

**Mobility degradation in BSIM**

- **mobMod = 1**
  \[
  \mu_{\text{eff}} = \frac{\mu_0}{1 + \left(U_A + U_C V_{BS} \right) \left( \frac{V_G + V_T}{t_{ox}} \right) + U_B \left( \frac{V_G + V_T}{t_{ox}} \right)^2}
  \]

- **mobMod = 2**
  \[
  \mu_{\text{eff}} = \frac{\mu_0}{1 + \left(U_A + U_C V_{BS} \right) \left( \frac{V_G - V_T}{t_{ox}} \right) + U_B \left( \frac{V_G - V_T}{t_{ox}} \right)^2}
  \]

- **mobMod = 3**
  \[
  \mu_{\text{eff}} = \frac{\mu_0}{1 + \left[U_A \left( \frac{V_G + V_T}{t_{ox}} \right) + U_B \left( \frac{V_G + V_T}{t_{ox}} \right)^2 \right] \left(1 + U_C V_{BS}\right)}
  \]
Most important Addition in BSIM [2]

**Carrier velocity saturation**

\[
v = \frac{\mu_{\text{eff}} E}{1 + E / E_{\text{sat}}} \quad \text{for } E < E_{\text{sat}}
\]

\[= v_{\text{sat}} \quad \text{for } E > E_{\text{sat}}\]

where

\[E_{\text{sat}} = \frac{2v_{\text{sat}}}{\mu_{\text{eff}}}\]

**New set of equations**

\[I_{\text{Dlin}} = C_{\text{ox}} \frac{W}{L} \left(V_G - V_T - \frac{V_{\text{DS}}}{2}\right)V_{\text{DS}} \frac{\mu_{\text{eff}}}{1 + V_{\text{DS}} / E_{\text{sat}} L}\]

\[I_{\text{Dsat}} = WC_{\text{ox}} \left(V_G - V_T - V_{\text{Dsat}}\right)v_{\text{sat}}\]

where

\[V_{\text{Dsat}} = \frac{(V_G - V_T) E_{\text{sat}} L}{V_G - V_T + E_{\text{sat}} L}\]
Correction to the basic Meyer Model [1]

basic Meyer: 
\[ I_{Dsat} \propto \frac{1}{L} \]

real

$L$

basic Meyer

real

$L$

basic Meyer

real

$V_{Dsat}$

real

$V_{Dsat}$

short
Correction to the basic Meyer Model [2]

\[ f_T = \frac{g_m}{2\pi C_{in}} \]
\[ = \frac{\mu}{2\pi L_{eff}^2} (V_G - V_T) \]  basic Meyer
\[ f_T = \frac{v_{sat}}{L_{eff}} \left( 1 - \frac{\partial V_{Ds}}{\partial V_G} \right) \] corrected model
Basic Set of Parameters

- **Threshold voltage**
  - $V_{th0}$: long channel $V_T$ at $V_{BS}=0V$
  - $K1$: first order body effect $\gamma$
  - $K2$: second order body effect
  - $K3$, $K3B$: body effect in narrow width devices
  - $D_{VT0W}$, $D_{VT1W}$, $D_{VT2W}$, $D_{VT0}$, $D_{VT1}$, $D_{VT2}$: narrow-width and short channel non-ideality effect

- **mobility degradation**
  - $\mu_0$: low field mobility
  - $UA$: 1st order mobility degradation coefficient
  - $UB$: 2nd order $\mu$ degradation coefficient
  - $UC$: body factor on $\mu$ degradation

- **velocity saturation model**
  - $v_{sat}$: saturation velocity
  - $A1$: first non-saturation parameter
  - $A2$: second non-satisfaction parameter
Example Calculation

**Given data**

\[ t_{ox}=200\text{Å}, \ W=50\mu\text{m}, \ L=0.5\mu\text{m}, \ V_G=3\text{V}, \ V_T=0.7\text{V}, \ V_D=1.5\text{V} \]

\[
\mu_{\text{eff}} = \frac{\mu_0}{1 + U_A \left( \frac{V_G + V_T}{t_{ox}} \right) + U_B \left( \frac{V_G + V_T}{t_{ox}} \right)^2} = 466\text{cm}^2/\text{V} - \text{sec}
\]

using \( U0=670 \text{ cm}^2/\text{V} - \text{sec} \), \( U_A= 2.25\times10^{-9}\text{m/V} \) and \( U_B=5.87\times10^{-19}(\text{m/V})^2 \)

from \( v_{sat}=8\times10^4\text{m/sec} \)

\[
E_{\text{sat}} = \frac{2v_{sat}}{\mu_{\text{eff}}} \approx 3.43 \times 10^4 \text{ Vcm}^{-1}
\]

\[
V_{D_{\text{sat}}} = \frac{(V_G - V_T)E_{\text{sat}}L}{V_G - V_T + E_{\text{sat}}L} = 0.98\text{V}
\]

\[
V_D = 1.5\text{V} > V_{D_{\text{sat}}} \Rightarrow I_D = W C_{ox} v_{sat} (V_G - V_T - V_{D_{\text{sat}}}) = 9\text{mA}
\]

- note: if \( V_D < V_{D_{\text{sat}}} \), use linear region equation

\[
I_D = C_{ox} \frac{W}{L} \left( V_G - V_T - \frac{V_{DS}}{2} \right) V_{DS} \frac{\mu_{\text{eff}}}{1 + V_{DS}/E_{\text{sat}}L}
\]
### Example calculation with EXCEL

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<th>W (cm)</th>
<th>Tox (cm)</th>
<th>Cox(F)</th>
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<th>u₀ (cm²/V)</th>
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![Graph](image-url)
Bulk Charge Effects [1]

Non-uniform substrate charge

To avoid complex mathematical formulation, a fitting approach is used by introducing an $A_{bulk}$ parameter

\[
I_D = C_{ox} \frac{W}{L} \left( V_G - V_T - \frac{A_{bulk} V_{DS}}{2} \right) V_{DS} \frac{\mu_{eff}}{1 + V_{DS} / \varepsilon_{sat} L}
\]

\[
V_{Dsat} = \frac{(V_G - V_T) \varepsilon_{sat} L}{V_G - V_T + A_{bulk} \varepsilon_{sat} L}
\]

\[
I_{Dsat} = WC_{ox} v_{sat} (V_G - V_T - A_{bulk} V_{Dsat}) v_{sat}
\]
Bulk Charge Effects [2]

**$A_{bulk}$ expression**

$$A_{bulk} = \left\{ 1 + \frac{K1}{2\sqrt{\phi_s - V_{BS}}} \left[ \frac{A_0 L}{L + 2\sqrt{x_j X_{dep}}} \left( 1 - A_{GS} (V_G - V_T) \left( \frac{L}{L + 2\sqrt{x_j X_{dep}}} \right)^2 + \frac{B_0}{W + B_1} \right) \right] \right\} \frac{1}{1 + K_{ETA} V_{BS}}$$

**parameters:** $A_0, A_{GS}, B_0, B_1, K_{ETA}$

**why empirical approach?**

- device is never ideal due to edge effects and non-uniform lateral doping
- flexibility is required to fit a wide range of technologies

**for near ideal device**

$A_{GS} = 0, B_0 = 0$ and $B_1 = 0$

$$A_{bulk} = \left\{ 1 + \frac{K1}{2\sqrt{\phi_s - V_{BS}}} \left[ \frac{A_0 L}{L + 2\sqrt{x_j X_{dep}}} \right] \right\} \frac{1}{1 + K_{ETA} V_{BS}}$$
Output resistance model [1]

3 Effects to account for

- Channel Length Modulation (CLM)
- Drain Induced Barrier Lowering (DIBL)
- Substrate Current induced Body Effect (SCBE)

CLM is the dominating effect
Output resistance model [2]

Channel Length Modulation

\[ \Delta L = l_1 \ln \left[ \frac{V_D - V_{Dsat}}{E_{sat}l_1} \right] \]

where \( l_1 \) is a fitting parameter = \( 0.22t_{ox}^{1/3}x_j^{1/2} \)

\[ R_{out} \] as a result of CLM

\[ \frac{1}{R_{out}} = \frac{dI_{Dsat}}{d\Delta L} \frac{d\Delta L}{dV_D} \Rightarrow R_{out} = \frac{V_D - V_{Dsat0}}{P_{CLM}l_1} \left( L + \frac{V_G - V_T}{E_{sat}} \right) \]

Incorporate into current equation

\[ I_{Dsat}(V_D) = I_{Dsat0} \left[ 1 + \frac{(V_D - V_{Dsat0})}{V_{ACLM}} \right] \]

where \( V_{ACLM} = R_{out(CLM)}I_{Dsat0} \)
Output resistance model [3]

**DIBL**

\[
\frac{1}{R_{\text{out}}} = \frac{dI_{\text{Ds}}}{dV_T} \frac{dV_T}{dV_D} \Rightarrow R_{\text{out(DIBL)}} = \frac{(V_G - V_T)}{\theta_{\text{rout}}(1 + P_{\text{DIBLCB}}V_{BS})} \left[ 1 + \frac{V_{\text{Ds}}}{(V_{\text{Ds}} + V_G - V_T)} \right]
\]

with \( \theta_{\text{rout}} = P_{\text{DIBLC1}} \left( e^{-l_2/2} + 2e^{-l_2/l_2} \right) + P_{\text{DIBLC2}} \)

where \( l_2 \) is another fitting parameter = \( \sqrt{\frac{\varepsilon_{\text{Si}} t_{\text{ox}} x_{D_{\text{max}}}}{\varepsilon_{\text{ox}}}} \)

**SCBE**

\[
I_{\text{sub}} = \frac{A}{B} (V_D - V_{\text{Ds}}) I_{D} e^{-\frac{B l_1}{V_D - V_{\text{Ds}}}}
\]

where

<table>
<thead>
<tr>
<th></th>
<th>NMOS</th>
<th>PMOS</th>
</tr>
</thead>
<tbody>
<tr>
<td>( B )</td>
<td>1.7x10^6</td>
<td>3.7x10^6</td>
</tr>
<tr>
<td>( A/B )</td>
<td>1.2</td>
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</table>

and \( l_1 = 0.22 t_{\text{ox}}^{1/3} x_j^{1/2} \)
Output resistance model [4]

\[
\frac{1}{R_{\text{out}}} = \frac{dI_{\text{sat}}}{dV_T} \frac{dV_T}{dV_{BS}} \frac{dV_{BS}}{dI_{\text{sub}}} \frac{dI_{\text{sub}}}{dV_D}
\]

\[
\Rightarrow \quad R_{\text{out}} \approx I_D \frac{A}{B} \left( 1 + g_m \frac{K1R_{\text{sub}}}{2\sqrt{2}\phi_B - V_{BS}} \left( 1 + \frac{Bl_1}{V_D - V_{\text{sat}}} \right) \right) \exp \left( -\frac{Bl_1}{V_D - V_{\text{sat}}} \right) \right)^{-1}
\]

**Overall** \(R_{\text{out}}\) **model**

\[
I_{\text{sat}}(V_D) = I_{\text{sat0}} \left[ 1 + \left( \frac{V_D - V_{\text{sat0}}}{V_{ACL\text{M}}} \right) \right] \left[ 1 + \left( \frac{V_D - V_{\text{sat0}}}{V_{ACL\text{M}}} \right) \right] \left[ 1 + \left( \frac{V_D - V_{\text{sat0}}}{V_{AS\text{CBE}}} \right) \right]
\]
Smoothing Functions [1]

- Ensure fast convergent by having all current and derivatives continuous

- Smoothing function in $V_{GS}$ domain ($V_{GSeff}$)

\[
V_{GSeff} = \frac{2nV_{th} \ln \left[ 1 + \exp \left( \frac{V_{GS} - V_T}{2nV_{th}} \right) \right]}{1 + 2nC_{ox} \frac{2\phi_s}{q\varepsilon_{Si}N_{CH}} \exp \left( - \frac{V_{GS} - V_T - 2V_{off}}{2nV_{th}} \right)}
\]

and

\[
I_{Dsat/sub} = \mu_{eff} C_{ox} \frac{W_{eff}}{2L_{eff}} \left( V_{GTeff} \right)^2
\]

$V_{off}$: required for non ideal device effects

$V_{Dsat} \approx I_0 e^{\frac{qV_G}{nkT}}$
Smoothing Functions [2]

**Smoothing function in $V_{DS}$ domain ($V_{DSeff}$)**

$$V_{DSeff} = V_{Dsat} - \frac{1}{2}(V_{Dsat} - V_{DS} - \delta + \sqrt{(V_{Dsat} - V_{DS} - \delta)^2 + 4\delta V_{Dsat}})$$

- Where $\delta$ is a fitting parameter to adjust the abruptness of the transition

**Similar approach in $V_{BS}$ domain ($V_{BSeff}$)**

$$V_{BSeff} = V_{BC} + \frac{1}{2}(V_{BS} - V_{BC} - \delta_1 + \sqrt{(V_{BS} - V_{BC} - \delta_1)^2 - 4\delta_1 V_{BC}}) \quad \text{with} \quad \delta_1 = 0.001$$
Simplified Strong Inversion Equations [1]

Define: \[ u_d = \frac{U A}{t_{ox}} \]

- mobility degradation coefficient

\[ u_d \approx 0.5 V^{-1} \quad \text{for } t_{ox} = 10 \text{nm} \]

\[ E_C = \frac{2 V_{sat}}{U 0} \]

- critical $E$-field for velocity saturation

\[ E_C \approx 2 \times 10^4 \text{V/cm} \quad (\text{typical value}) \]

Assumptions:

- $V_T$ is given from the process
- mobility model of mobmod = 2 is used
- bulk charge effect not significant in short channel devices
- Channel Length Modulation is the main contribution to $R_out$
Simplified Strong Inversion Equations [2]

Current Equations in strong inversion becomes

\[ V_{Dsat} = (V_G - V_T) \left[ \frac{1}{1+u_d(V_G - V_T)} \right] \]

\[ I_{Dlin} = \mu_0 C_{ox} \frac{W}{L} \left[ V_G - V_T - \frac{V_D}{2} \right] V_D \left[ \frac{1}{1+u_d(V_G - V_T)} + \frac{V_D}{E_CL} \right] = I_{Dlin(long)} \left[ \frac{1}{1+u_d(V_G - V_T)} + \frac{V_D}{E_CL} \right] \]

\[ I_{Dsat} = \mu_0 C_{ox} \frac{W}{2L} \left[ \frac{(V_G - V_T)^2}{1+u_d(V_G - V_T)} \right] = I_{Dsat(long)} \left[ \frac{1}{1+u_d(V_G - V_T)} \right] \]
Simplified Strong Inversion Equations [3]

Equations of derivatives

\[ g_{msat} = \frac{I_{Dsat}}{(V_G - V_T)} \left[ 1 + \frac{I_{Dsat}}{I_{Dsat(long)}} \right] = \frac{I_{Dsat}}{(V_G - V_T)} \left[ 1 + \frac{1}{1 + \left( u_d + \frac{1}{E_CL}(V_G - V_T) \right)} \right] \]

\[ r_{out} = \frac{2((V_D - V_{Dsat}) + [1 + u_d (V_G - V_T)](V_G - V_T))^2}{\mu_0 C_{ox} W I_{PCLM} [1 + u_d (V_G - V_T)]^2} = \frac{((V_D - V_{Dsat}) + [1 + u_d (V_G - V_T)](V_G - V_T))L}{I_{Dsat(long)} I_{PCLM} [1 + u_d (V_G - V_T)]} \]

with \( l = \sqrt{3t_{ox} x_j} \)

Parameters used:

\( W, L, TOX, U0, UA, VSAT, VTH0, PCLM, XJ \)
Simplified Strong Inversion Equations [4]

Comparison between full and simplified model

Parameter detail: TSMC 0.18μm process

\( t_{ox}: 4.1\text{nm}, \ W=10\text{μm}, \ V_{T0}=0.39\text{V} \)
Simplified Strong Inversion Equations [5]

Comparison of first derivative simplification

![Graph showing comparison of first derivative simplification for different voltages.](image)
Other features included in BSIM3v3

- Short/Narrow Channel Effects on Threshold Voltage
- Non-Uniform Vertical Doping Effects
- Non-Uniform Lateral Doping Effects
- Quantum Mechanic Charge Thickness Model
- Unified Flicker Noise Model
- Polysilicon Depletion Effects
- Non-quasitic Effects
Additional Features of BSIM4

- Bug-fixes of former BSIM3 model
- Intrinsic input resistance model
- Extrinsic gate resistance model
- New Non-Quasi-Static (NQS) model
- Holistic and noise-partition thermal noise model
- Substrate resistance network
- Improved Flicker noise model
- Geometry calculation (Layout-dependent parasitics) model
- Asymmetrical S/D junction diode model
- Gate-Induced Drain Leakage (GIDL) model
- Gate dielectric tunneling current model
RF Model in BSIM4

- Require low frequency, $R_G$ and $R_{sub}$ model

- Note that it is a RC effect more than NQS effects
Intrinsic gate resistance model

in strong inversion

\[ R_{ii}(inv) = \frac{R_{ch}}{\eta} = \frac{V_{DS}}{\eta I_{DS}} \] in triode region \quad \eta \approx 14 \quad \text{as determined by 2-D simulation}

\[ = \frac{V_{DSat}}{\eta I_{DS}} \] in saturation

in subthreshold \quad R_{ii}(sub) = \left( \frac{kT}{q} \mu_{eff} C_{ox} \frac{W_{eff}}{L_{eff}} \right)^{-1}

combine: \quad R_{ii} = R_{ii}(inv) \parallel R_{ii}(sub)
Intrinsic gate resistance verification
Substrate Network

- Responsible for $R_{out}$ roll-off at high frequency

In practice, 2-3 resistors are sufficient for accurate modeling.
Verification of Substrate Network

\[ R_{\text{in}}(\Omega) \]
\[ R_{\text{out}}(\Omega) \]
\[ C_{\text{in}}(\text{fF}) \]
\[ C_{\text{out}}(\text{fF}) \]

- Measured
- BSIM3v3
- BSIM RF

\[ R_g = 9.5 \ \Omega \]
\[ R_{\text{Subs}} = 50 \ \Omega \]

- 24-finger
- 240/0.35 NMOS
- \( V_{gs} = 0.9 \ \text{V} \)
- \( V_{ds} = 2 \ \text{V} \)
Circuit Level Verification of RF Model

LNA design with $0.6\mu m$ CMOS technology

![Circuit Diagram]

![Gain Graph]
Holistic Thermal Noise Model [1]

Combine channel thermal noise model and noise partition model to unifies the induced gate noise and channel noise.

\[
\overline{v_d^2} = \int \Delta v_d^2 = 4kTB \int dR
\]

\[
= 4kTB \frac{V_d}{I_d}
\]

\[
\overline{i_d^2} = \overline{v_d^2 g_{ds}^2}
\]

\[
= 4kTB \frac{V_d}{I_d} g_{ds}^2
\]

\[
\frac{V_d}{I_d} \equiv \frac{V_{dsat}}{I_{ds}} \quad \text{in saturation}
\]

\[
\frac{V_d}{I_d} \equiv \frac{V_{ds}}{I_{ds}} \quad \text{in triode}
\]
Holistic Thermal Noise Model [2]

Channel noise amplification by front/back gate

\[
\Delta i_d = \Delta v (g_{ds} + g_{mx} + g_{mbx})
\]

\[
\bar{i}_d^2 = \bar{v}_d^2 (\beta g_m + \beta g_{mb} + g_{ds})^2
\]

\[
= 4kTB \frac{V_d}{I_d} (\beta g_m + \beta g_{mb} + g_{ds})^2
\]
Holistic Thermal Noise Model [3]

- Unification of channel noise and induced gate noise

- At high frequencies, the elemental channel resistance noise source will generate significant noise current through the gate capacitance.

- The induced gate noise is correlated with the channel noise.
Holistic Thermal Noise Model [3]

**Noise Partition Model**

\[
\theta v_{ds} \quad \overset{\text{\underline{i}_{eq}}}{\rightarrow} \quad \frac{i_{eq}^2}{i_{eq}}
\]

\[
\bar{v}_d^2 = 4kTB \frac{V_d}{I_d}
\]

\[
\bar{i}_{d,\text{new}}^2 = \bar{i}_d^2 - 4kTB \theta^2 (g_m + g_{mb} + g_{ds})^2 \left( \frac{V_d}{I_d} \right)
\]

The total noise can be partitioned into two parts to model induced gate noise.
Verification of Holistic Noise Model [1]

\[ NF_{\text{min}} \text{ (dB)} \]

\[ NF_{\text{min}} \text{ vs. GHz} \]

- Measurement
- BSIM RF

\[ R_g = 9.5 \ \Omega \]
\[ R_{\text{subd}} = 50 \ \Omega \]

\[ 24\text{-finger} \]
\[ 240/0.35 \text{ NMOS} \]
\[ V_{gs} = 0.9 \ \text{V} \]
\[ V_{ds} = 3 \ \text{V} \]
Verification of Holistic Noise Model [2]

Measurement
- BSIM RF

$\Gamma$-plane

1.3 GHz
2dB
3dB

24-finger
240/0.35 NMOS
$V_{gs} = 0.9 \text{ V} \quad V_{ds} = 3 \text{ V}$

2.7 GHz
2dB
3dB

$\Gamma$-plane
Gate Tunneling Model

- **Gate current flow**

- **Verification**

![Diagram of gate tunneling model with symbols for electron and hole tunneling]

![Graphs showing NMOS and PMOS characteristics]
Layout dependent parasitic model [1]

Series/cascode connections: isolated, shared, and merged

[Diagram showing different types of connections: isolated, shared, and merged S/D connections.]
Layout dependent parasitic model [2]

Example: Combination of Series/Parallel Connections

M1 & M2 isolated

M1 & M2 shared

M1 & M2 merged
Layout dependent parasitic model [3]

**Multi-finger/parallel devices:**

- **NF** (number of fingers) per-finger devices in parallel

- **NF** = Odd, MINSD is not needed

- **NF** = Even, MINSD == 0

- **NF** = Even, MINSD == 1
Future BSIM direction (some thoughts)

- Have to catch up with the fast technology development
- More closely integrated to the CAD environment
- Development a fast model development platform
- Be the “Operating System” of the underlying hardware
- A more “open-source” like architecture
- Really address the issues of statistical modeling
Model Modularization

Model should be modularized

The core model should be simple and represent the ideal device with nice behavior

Not all modules are required in most simulation
Model Modularization

- Much easier to add new effects (like LDD) and adopt to new technology
- Much easier to debug and maintain
- Allow better team management
- Provide a sustainable modeling environment
- Trade-off: more internal nodes maybe created leading to slower simulation time (order of $n^{1.4}$)
Summary

- The BSIM models follow the basic Meyer model to allow design compatibility.
- BSIM4 provides a more unified solution to most device physics in current technology.
- There is no perfect model, but tradeoffs to address different needs.
- Modeling has been developed in an isolated fashion with the software engineering world.
- Probably it is time to re-think the position of compact modeling and how it fits to the big picture.