Submicron Circuit Design with BSIM3 or BSIM4

Mansun Chan

E-mail: mchan@eecs.berkeley.edu

Department of Electrical Engineering & Computer Science
University of California at Berkeley

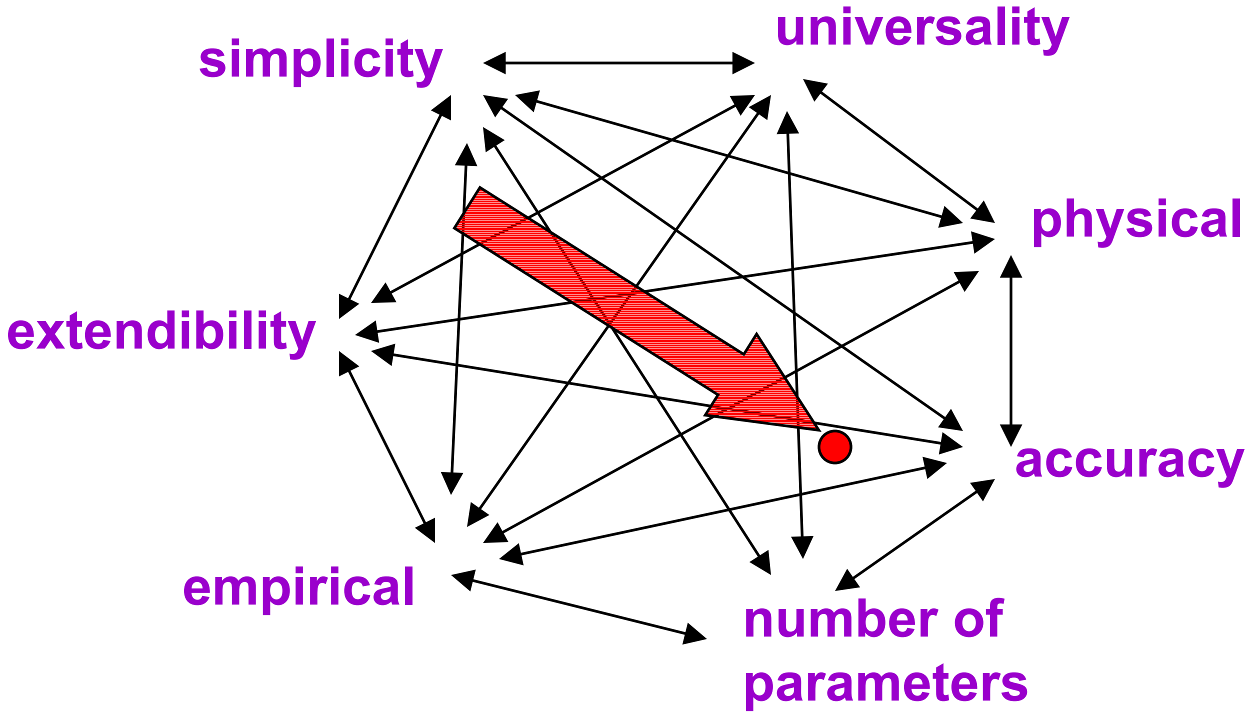
Department of Electrical & Electronic Engineering
Hong Kong University of Science & Technology

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



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

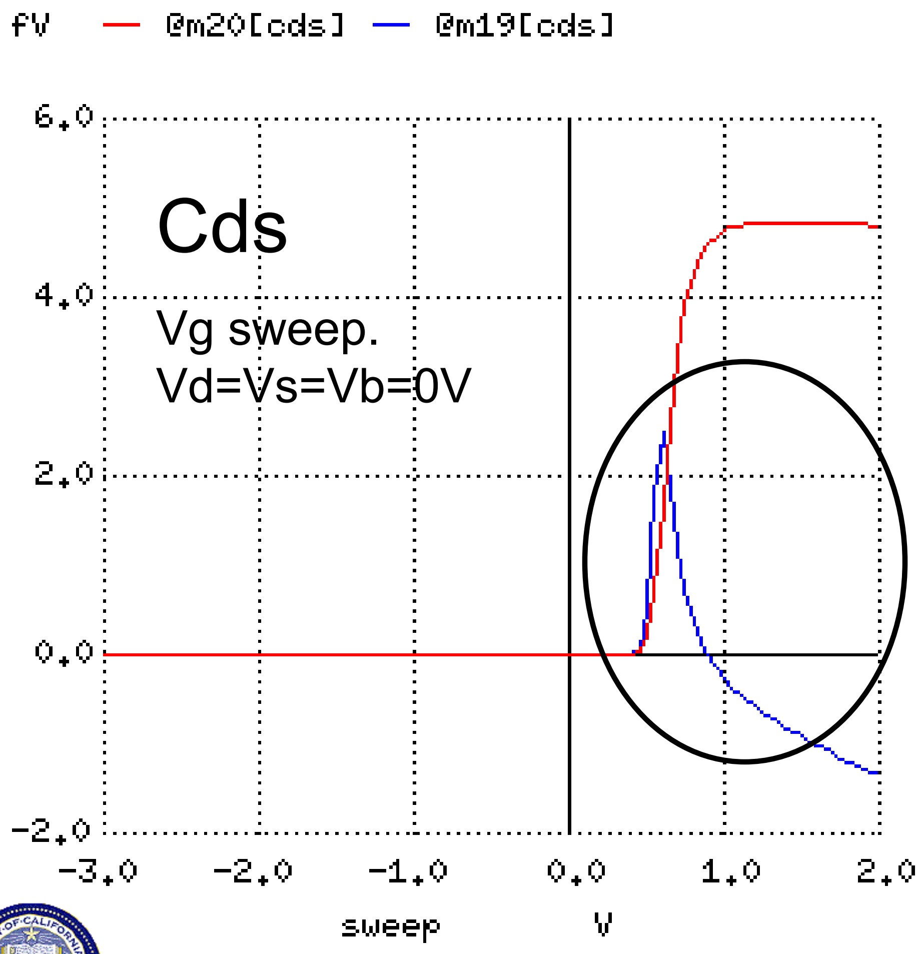
- Starts out as a simple physical model with a small number of parameters
- Closely follow process development with lots of advanced features such as
  - Super steep retrograde well
  - Pocket implant
  - Gate current model
  - GIDL/GISL
- Allow early adoptions of new process modules
- Under the guideline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

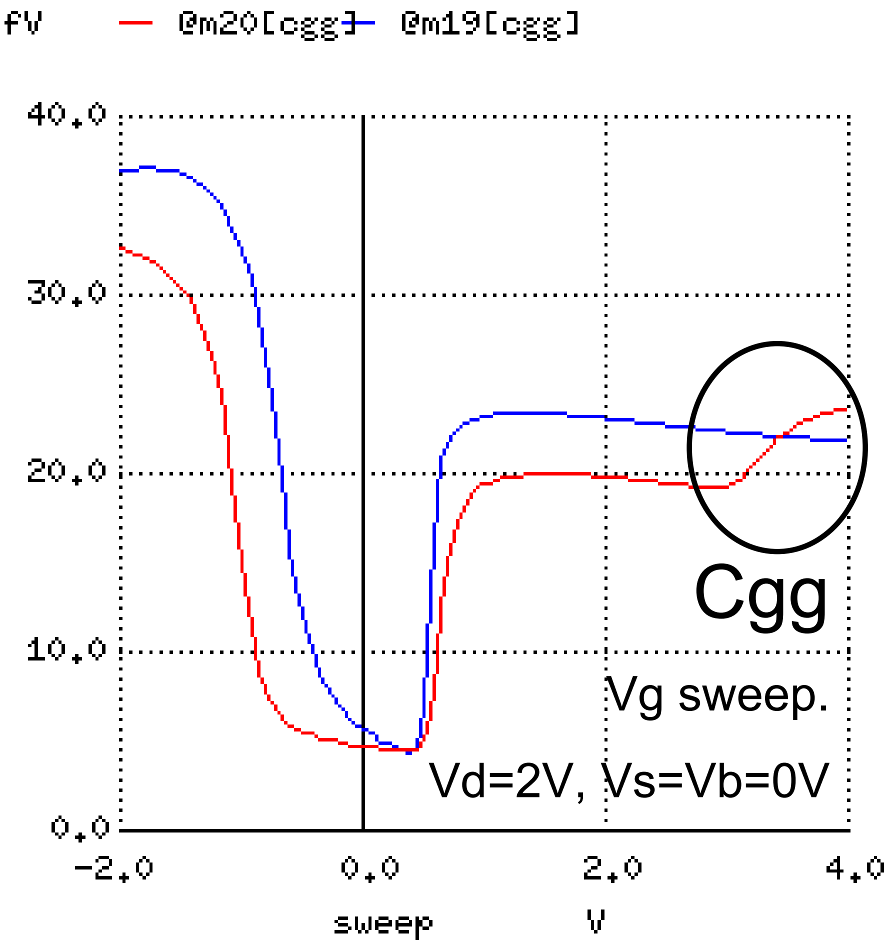
Preliminary solutions to Charge model

- 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)





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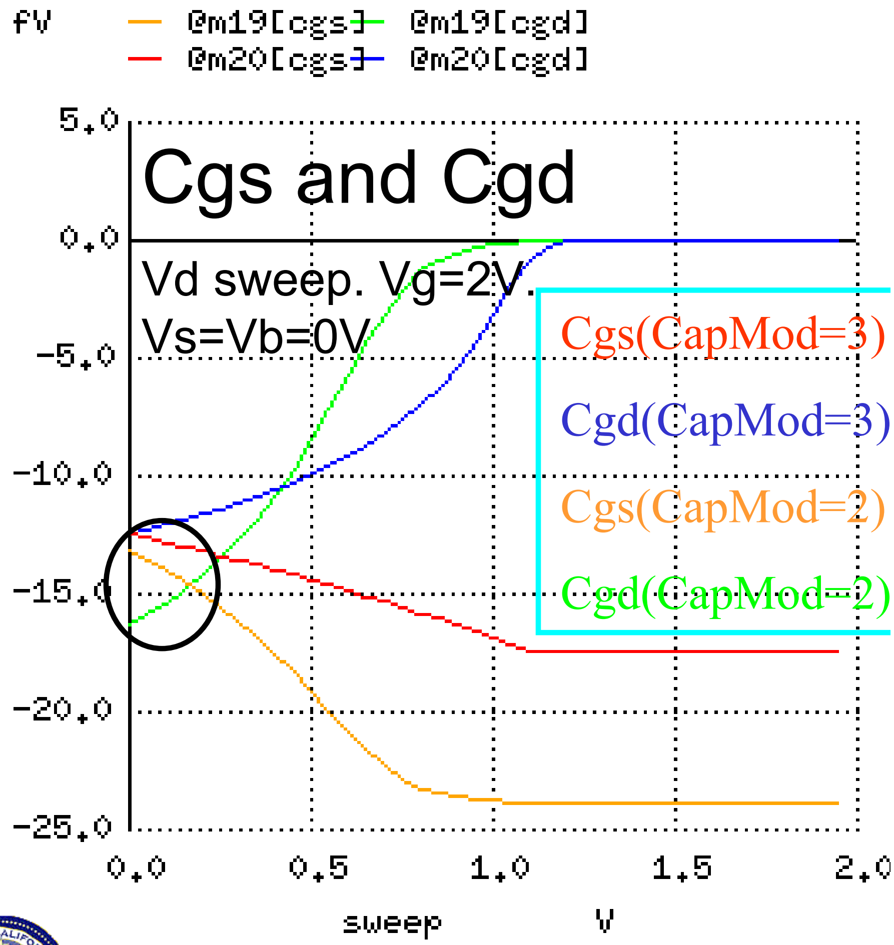
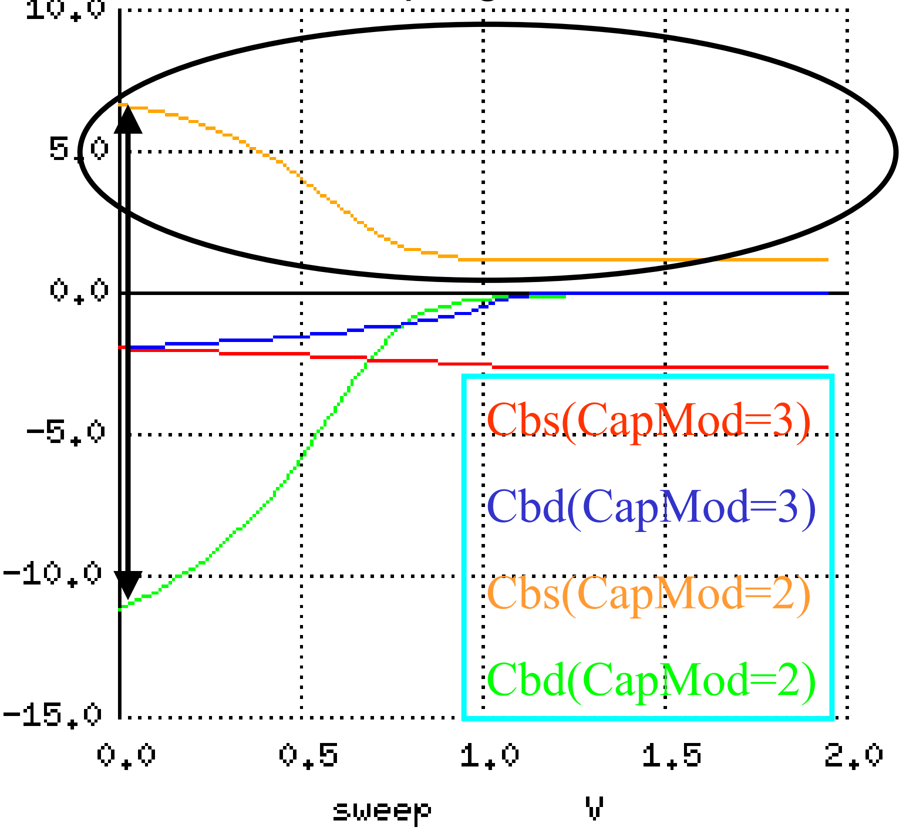


Cgs and Cgd

Vd sweep. Vg=2V. Vs=Vb=0V

Cbs and Cbd

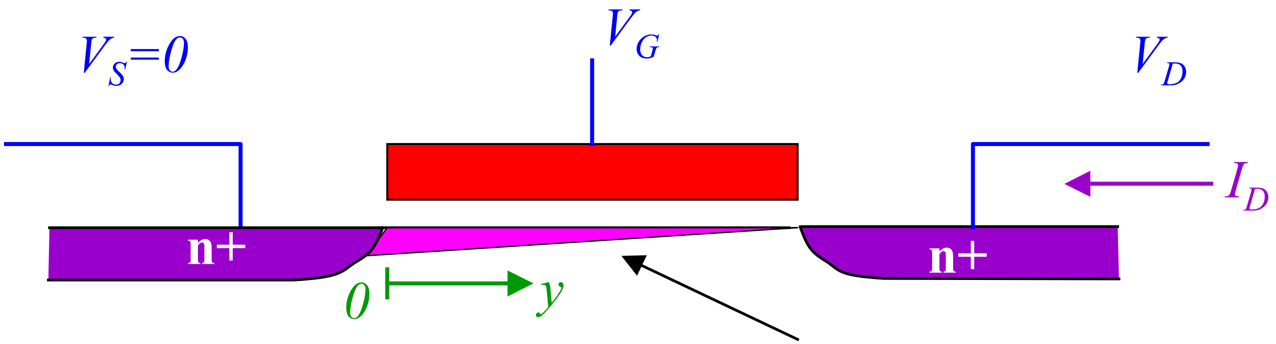
Vd sweep.Vg=2V,Vs=Vb=0V.



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 wide spread 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]



anywhere along the conducting channel:

$$I(y) = I_D = WQ_n(y)v(y) \quad \text{..............................} \quad (1)$$

free carrier (inversion charge) density

velocity of carriers

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

$$v(y) \approx \mu\vec{E} = \mu\frac{dV(y)}{dy}$$

The Basic of the Meyer's Model [2]

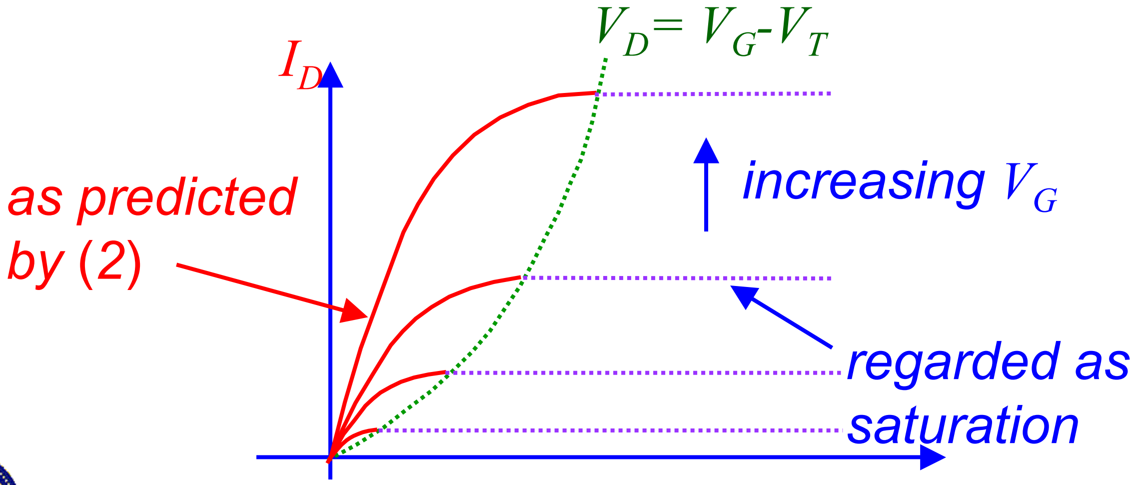
$$\int_0^L I_D dy = \mu W C_{ox} \int_0^{V_{DS}} \left(V_G - V_T - V(y)\right) dV \quad \cdots\cdots\cdots\cdots \quad (2)$$

$$\Rightarrow \quad I_D = \underbrace{WC_{ox}\left[\left(V_G - V_T\right) - \frac{V_{DS}}{2}\right]}\underbrace{\mu \frac{V_{DS}}{L}}$$

for $V_{DS} < V_G\text{-}V_T$

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

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



as predicted by (2)

increasing V_G

regarded as saturation

$$I_{Dsat} \approx \frac{\mu W C_{ox}}{2L}\left(V_G - V_T\right)^2$$

for $V_{DS} > V_G\text{-}V_T$

Most important Addition in BSIM [1]

Mobility degradation in BSIM

- mobMod = 1

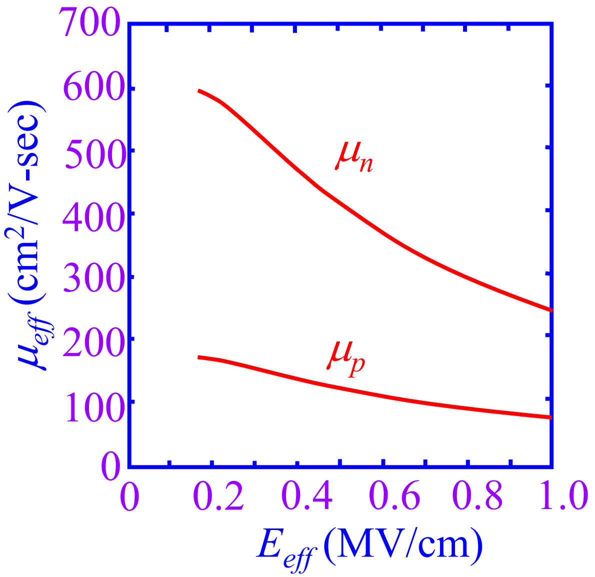
$$\mu_{eff} = \frac{\mu_0}{1+\left(U_A + U_C V_{BS}\right)\left(\frac{V_G+V_T}{t_{ox}}\right)+U_B\left(\frac{V_G+V_T}{t_{ox}}\right)^2}$$

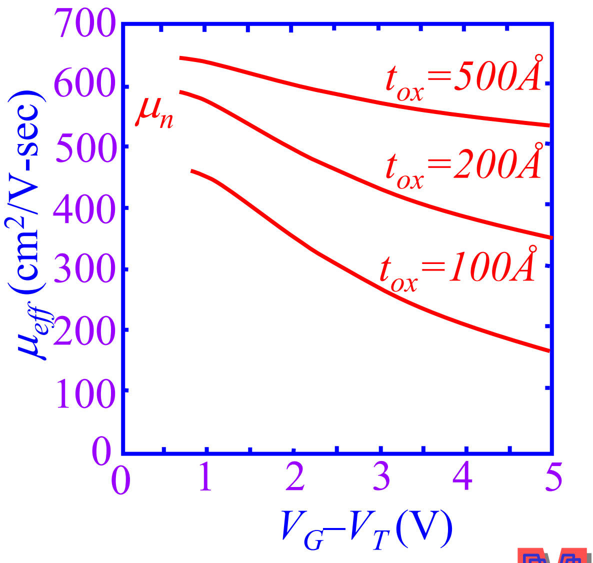
- mobMod = 2

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

- mobMod = 3

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





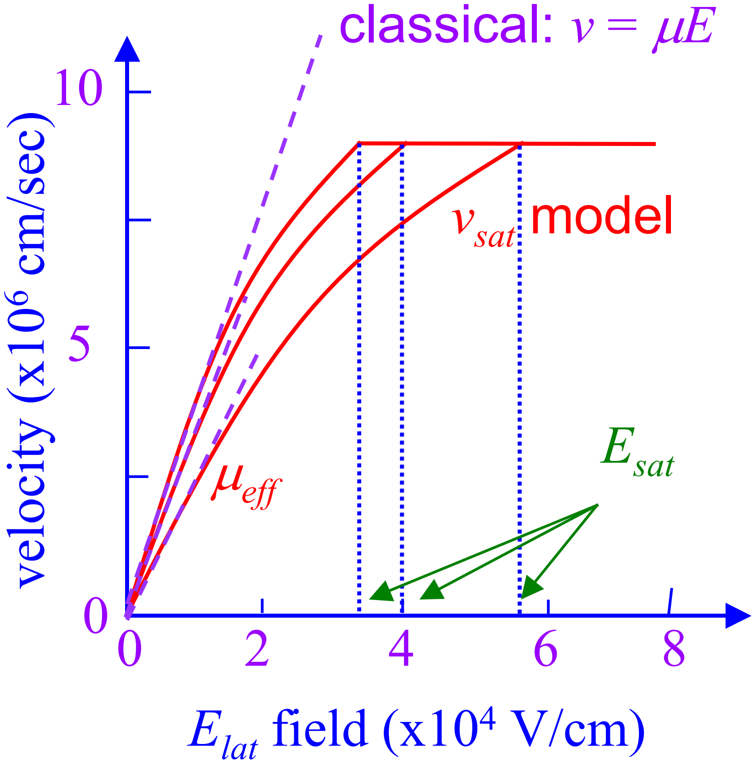
Most important Addition in BSIM [2]

Carrier velocity saturation

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

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

where $E_{sat} = \dfrac{2v_{sat}}{\mu_{eff}}$



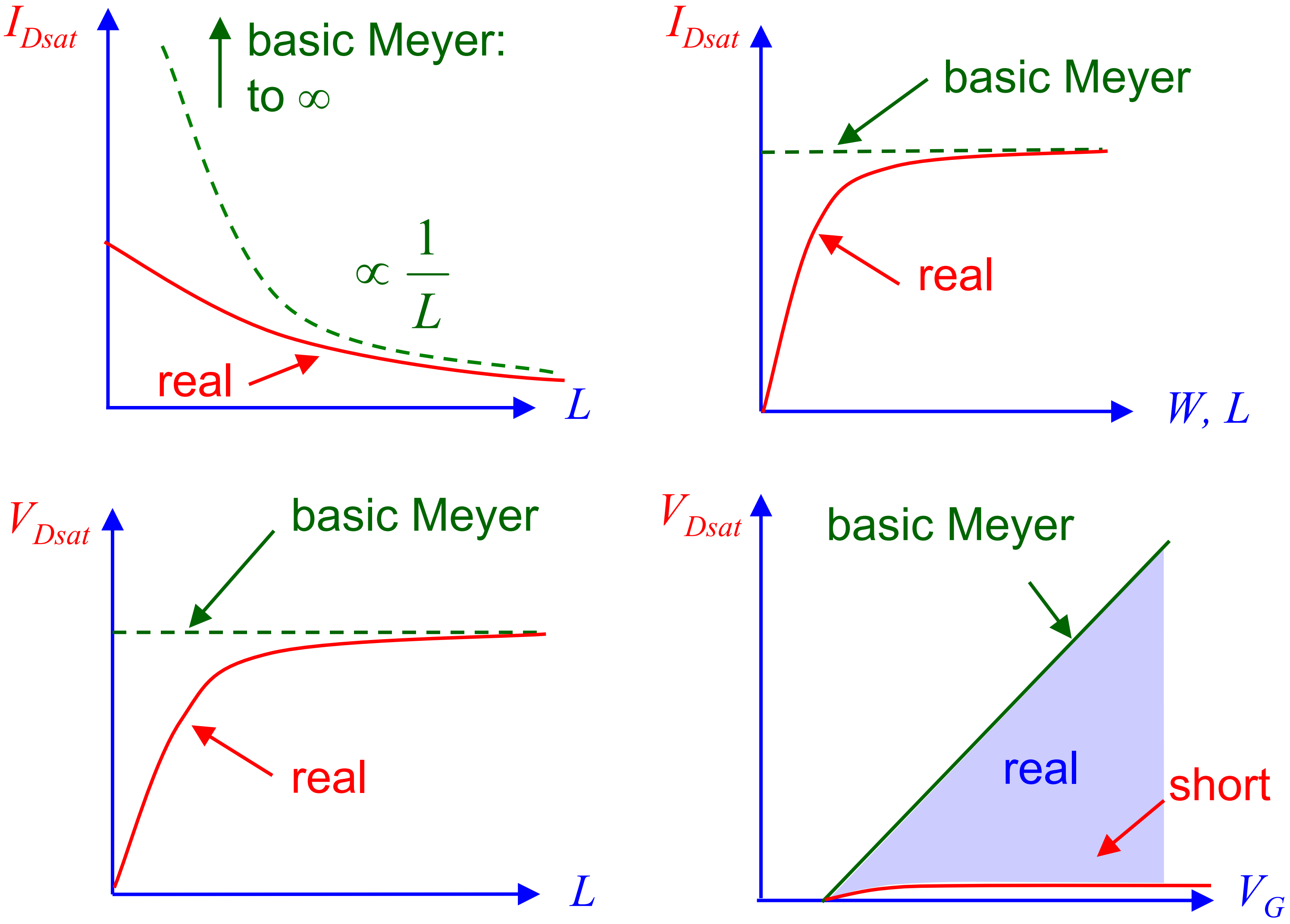
New set of equations

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

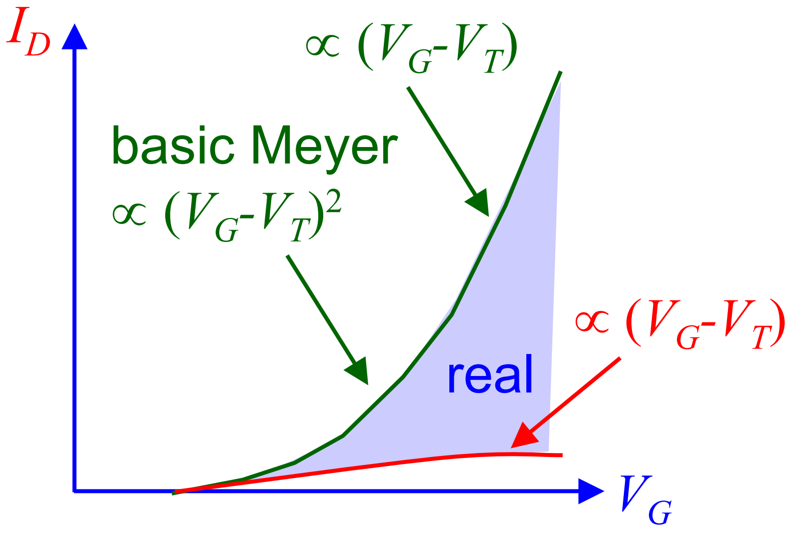
$$I_{Dsat} = W C_{ox} \left(V_G - V_T - V_{Dsat} \right) v_{sat}$$

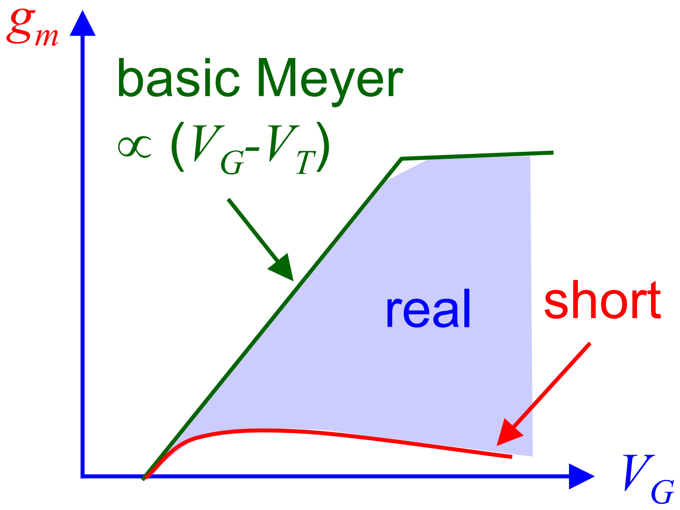
where $V_{Dsat} = \dfrac{(V_G - V_T) E_{sat} L}{V_G - V_T + E_{sat} L}$

Correction to the basic Meyer Model [1]



Correction to the basic Meyer Model [2]

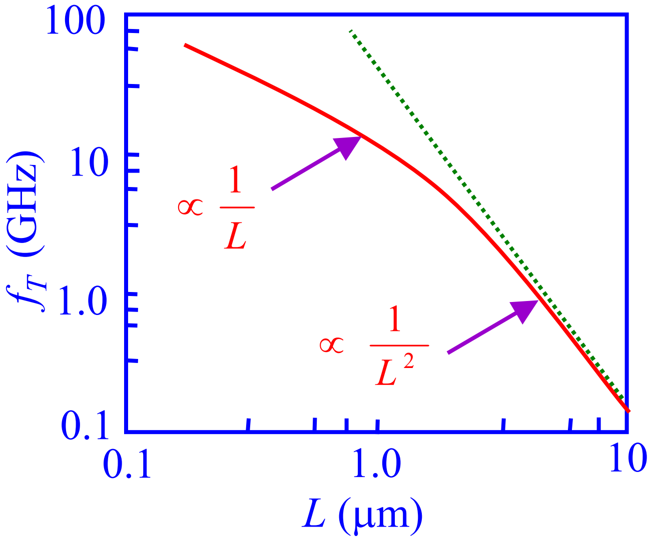




$$f_T = \frac{g_m}{2\pi C_{in}}$$

$$= \frac{\mu}{2\pi L_{eff}^2}(V_G - V_T) \quad \text{basic Meyer}$$

$$f_T = \frac{v_{sat}}{L_{eff}}\left(1 - \frac{\partial V_{Dsat}}{\partial V_G}\right) \quad \text{corrected model}$$



Basic Set of Parameters

Threshold voltage

V_{th0}: long channel V_T at $V_{BS}=0V$

$K1$: first order body effect γ

$K2$: 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

μ_0: low field mobility

UA: 1st order mobility degradation coefficient

UB: 2nd order μ degradation coefficient

UC: body factor on μ degradation

velocity saturation model

v_{sat}: saturation velocity

$A1$: first non-saturation parameter

$A2$: second non-saturation parameter

Example Calculation

Given data

t_{ox}=200Å, W=50μm, L=0.5μm, V_G=3V, V_T=0.7V, V_D=1.5V

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

using $U0$=670 cm^2/V-sec, UA= 2.25x10^{-9}m/V and UB=5.87x10^{-19}(m/V)^2

from v_{sat}=8x10^{4}m/sec $$E_{sat} = \frac{2v_{sat}}{\mu_{eff}} \approx 3.43 \times 10^4\,\mathrm{Vcm}^{-1}$$

$$V_{Dsat} = \frac{(V_G - V_T)E_{sat}L}{V_G - V_T + E_{sat}L} = 0.98V$$

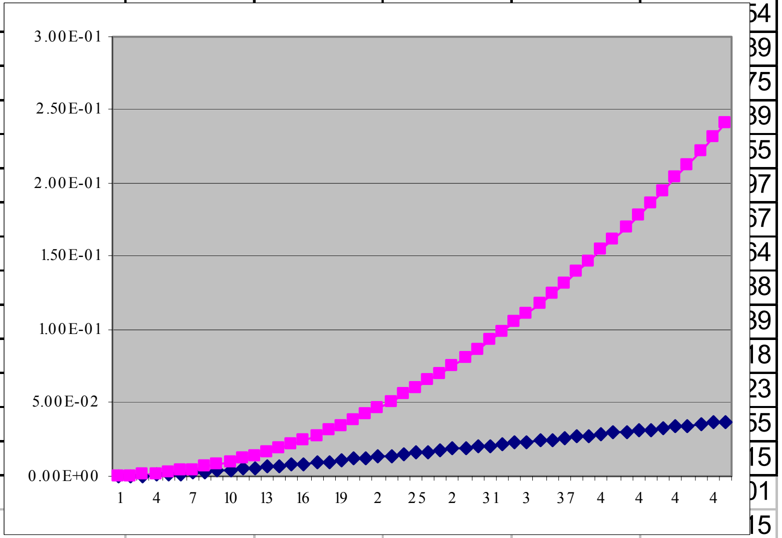
$$V_D = 1.5V > V_{Dsat} \Rightarrow I_D = WC_{ox}v_{sat}\left(V_G - V_T - V_{Dsat}\right) = 9mA$$

- note: if $V_D < V_{Dsat}$, use linear region equation

$$I_D = C_{ox}\frac{W}{L}\left(V_G - V_T - \frac{V_{DS}}{2}\right)V_{DS}\frac{\mu_{eff}}{1 + V_{DS}/E_{sat}L}$$

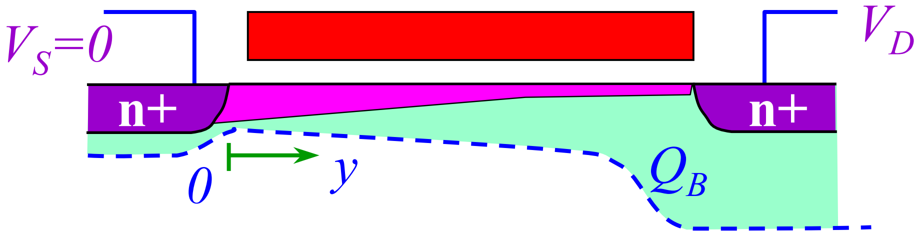
Example calculation with EXCEL

L (cm)	W (cm)	Tox (cm)	Cox(F)	VT (V)	u0 (cm2/V	VG (V)	VD (V)	mobility (	Esat(V/cm	EsatL (V)	Vdsat	Idsat(S)	Idsat (L)
6.00E-05	6.00E-03	1.20E-06	2.88E-07	0.7	6.70E+02	0.8	5	4.97E+02	3.22E+04	1.93E+00	9.51E-02	6.79E-05	9.635E-05
6.00E-05	6.00E-03	1.20E-06	2.88E-07	0.7	6.70E+02	0.9	5	4.88E+02	3.28E+04	1.97E+00	1.82E-01	2.55E-04	0.0003854
6.00E-05	6.00E-03	1.20E-06	2.88E-07	0.7	6.70E+02	1	5	4.80E+02	3.33E+04	2.00E+00	2.61E-01	5.40E-04	0.0008672
6.00E-05	6.00E-03	1.20E-06	2.88E-07	0.7	6.70E+02	1.1	5	4.72E+02	3.39E+04	2.03E+00	3.34E-01	9.08E-04	0.0015417
6.00E-05	6.00E-03	1.20E-06	2.88E-07	0.7	6.70E+02	1.2	5	4.64E+02	3.45E+04	2.07E+00	4.03E-01	1.34E-03	0.0024089
6.00E-05	6.00E-03	1.20E-06	2.88E-07	0.7	6.70E+02	1.3	5	4.57E+02	3.50E+04	2.10E+00	4.67E-01	1.84E-03	0.0034688
6.00E-05	6.00E-03	1.20E-06	2.88E-07	0.7	6.70E+02	1.4	5	4.49E+02	3.57E+04	2.14E+00	5.27E-01	2.38E-03	0.0047214
6.00E-05	6.00E-03	1.20E-06	2.88E-07	0.7	6.70E+02	1.5	5	4.41E+02	3.63E+04	2.18E+00	5.85E-01	2.97E-03	0.0061667
6.00E-05	6.00E-03	1.20E-06	2.88E-07	0.7	6.70E+02	1.6	5	4.34E+02	3.69E+04	2.21E+00	6.40E-01	3.59E-03	0.0078047
6.00E-05	6.00E-03	1.20E-06	2.88E-07	0.7	6.70E+02	1.7	5						54
6.00E-05	6.00E-03	1.20E-06	2.88E-07	0.7	6.70E+02	1.8	5						39
6.00E-05	6.00E-03	1.20E-06	2.88E-07	0.7	6.70E+02	1.9	5						75
6.00E-05	6.00E-03	1.20E-06	2.88E-07	0.7	6.70E+02	2	5						39
6.00E-05	6.00E-03	1.20E-06	2.88E-07	0.7	6.70E+02	2.1	5						55
6.00E-05	6.00E-03	1.20E-06	2.88E-07	0.7	6.70E+02	2.2	5						97
6.00E-05	6.00E-03	1.20E-06	2.88E-07	0.7	6.70E+02	2.3	5						67
6.00E-05	6.00E-03	1.20E-06	2.88E-07	0.7	6.70E+02	2.4	5						64
6.00E-05	6.00E-03	1.20E-06	2.88E-07	0.7	6.70E+02	2.5	5						38
6.00E-05	6.00E-03	1.20E-06	2.88E-07	0.7	6.70E+02	2.6	5						39
6.00E-05	6.00E-03	1.20E-06	2.88E-07	0.7	6.70E+02	2.7	5						18
6.00E-05	6.00E-03	1.20E-06	2.88E-07	0.7	6.70E+02	2.8	5						23
6.00E-05	6.00E-03	1.20E-06	2.88E-07	0.7	6.70E+02	2.9	5						55
6.00E-05	6.00E-03	1.20E-06	2.88E-07	0.7	6.70E+02	3	5						15
6.00E-05	6.00E-03	1.20E-06	2.88E-07	0.7	6.70E+02	3.1	5						01
6.00E-05	6.00E-03	1.20E-06	2.88E-07	0.7	6.70E+02	3.2	5						15
6.00E-05	6.00E-03	1.20E-06	2.88E-07	0.7	6.70E+02	3.3	5	3.25E+02	4.92E+04	2.95E+00	1.38E+00	1.68E-02	0.0651356



Bulk Charge Effects [1]

- Non-uniform substrate charge



$$Q_n = C_{ox}\left(V_{GS} - V_T(y) - V(y)\right)$$

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

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

$$V_{Dsat} = \frac{(V_G - V_T)E_{sat}L}{V_G - V_T + A_{bulk}E_{sat}L}$$

$$I_{Dsat} = WC_{ox}v_{sat}\left(V_G - V_T - A_{bulk}V_{Dsat}\right)v_{sat}$$

Bulk Charge Effects [2]

A_{bulk} expression

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

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

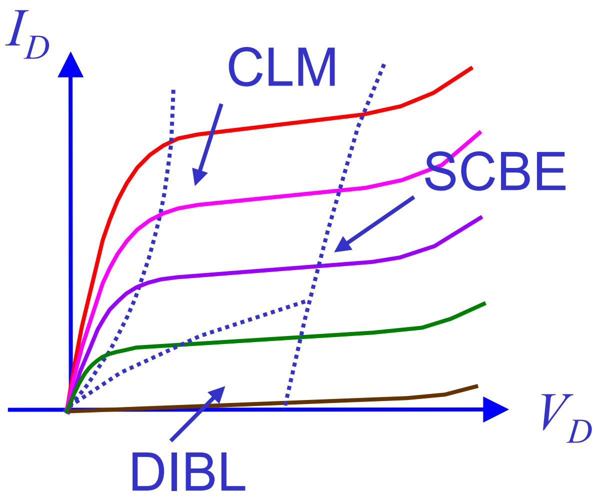
$A_{GS}=0$, $B_0=0$ and $B_1=0$

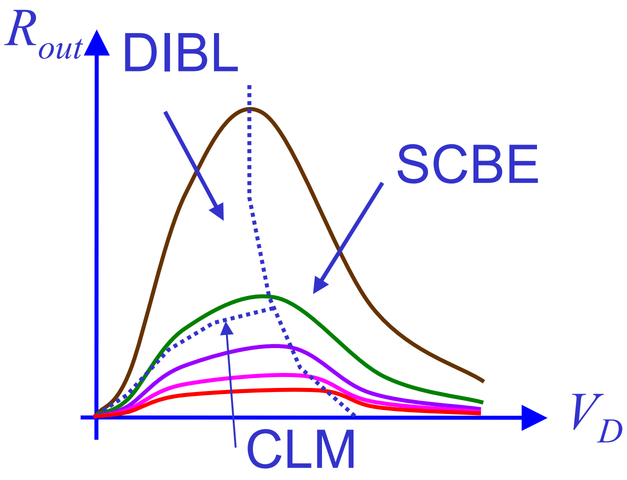
$$A_{bulk} = \left\{ 1 + \frac{K1}{2\sqrt{\phi_S - V_{BS}}} \left[\frac{A_0 L}{L + 2\sqrt{x_j X_{dep}}} \right] \right\} \frac{1}{1 + K_{ETA} V_{BS}}$$

Output resistance model [1]

3 Effects to account for

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

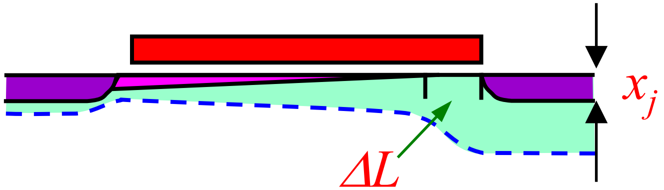




CLM is the dominating effect

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 = $0.22 t_{ox}^{1/3} x_j^{1/2}$

- **R_{out} as a result of CLM**

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

- **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]

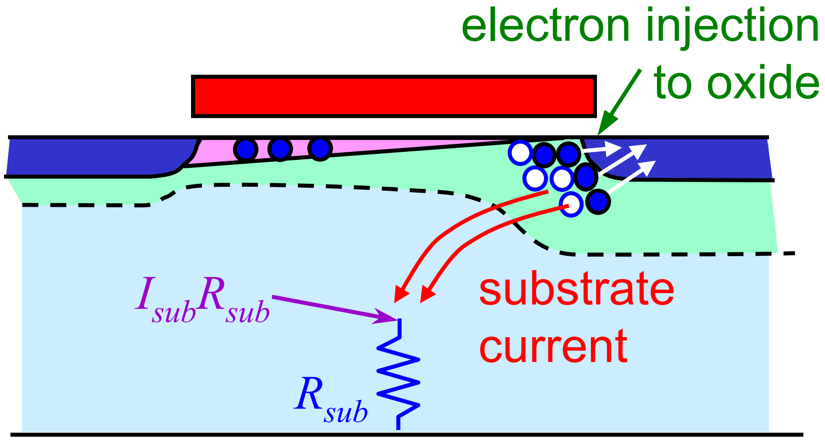
DIBL

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

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

where l_2 is another fitting parameter = $\sqrt{\dfrac{\varepsilon_{Si} t_{ox} x_{D\max}}{\varepsilon_{ox}}}$

SCBE



$$I_{sub} = \frac{A}{B}(V_D - V_{Dsat})I_D e^{\frac{-Bl_1}{V_D - V_{Dsat}}}$$

where

	NMOS	PMOS
B (Vcm^{-1})	1.7x10^6	3.7x10^6
A/B (V^{-1})	1.2	2.2

and $l_1 = 0.22 t_{ox}^{1/3} x_j^{1/2}$

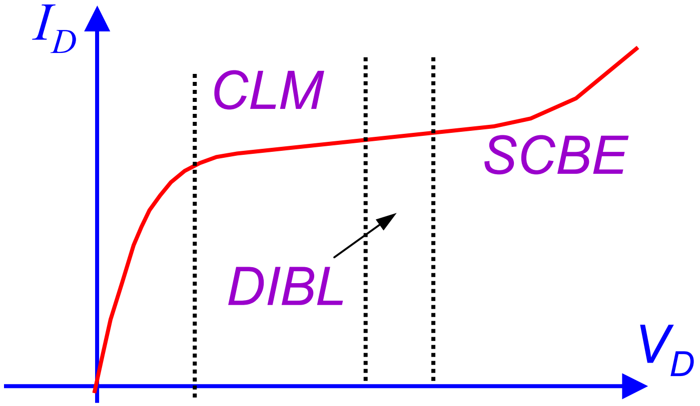
Output resistance model [4]

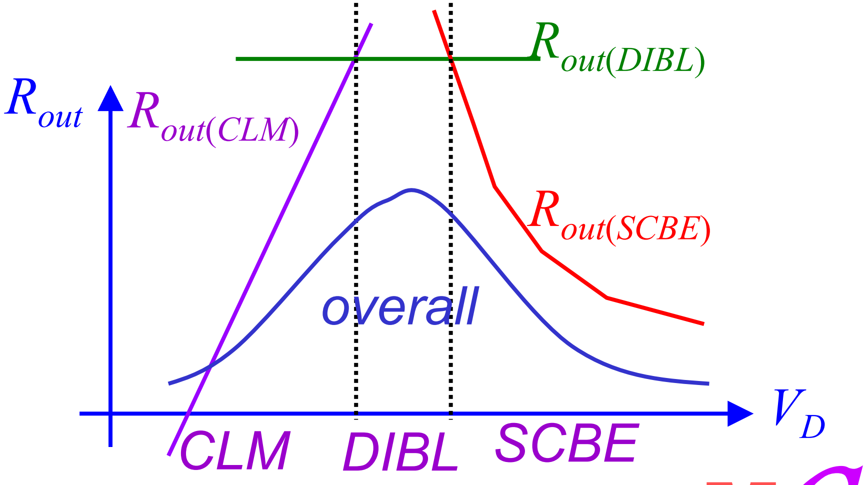
$$\frac{1}{R_{out}} = \frac{dI_{Dsat}}{dV_T}\frac{dV_T}{dV_{BS}}\frac{dV_{BS}}{dI_{sub}}\frac{dI_{sub}}{dV_D}$$

$$\Rightarrow \quad R_{out} \approx \left[I_D \frac{A}{B}\left(1 + g_m \frac{K1 R_{sub}}{2\sqrt{2\phi_B - V_{BS}}}\left(1 + \frac{Bl_1}{V_D - V_{Dsat}}\right)\right)\exp\left(-\frac{Bl_1}{V_D - V_{Dsat}}\right)\right]^{-1}$$

Overall R_{out} model

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





Smoothing Functions [1]

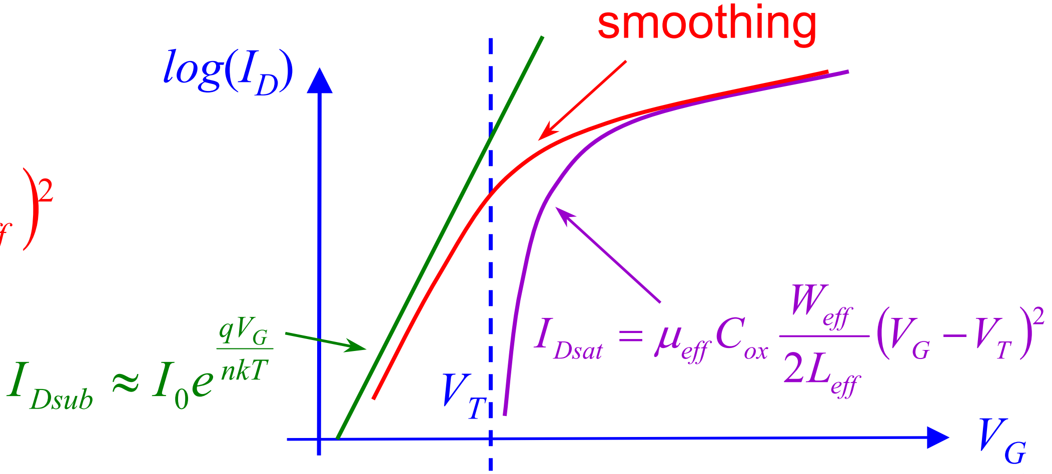
- **Ensure fast convergent by having all current and derivatives continuous**
- **Smoothing function in V_{GS} domain (V_{GSeff})**

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

V_{off}: required for non ideal device effects

and

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



$$I_{Dsub} \approx I_0 e^{\frac{qV_G}{nkT}}$$

$$I_{Dsat} = \mu_{eff}C_{ox}\frac{W_{eff}}{2L_{eff}}\left(V_G-V_T\right)^2$$

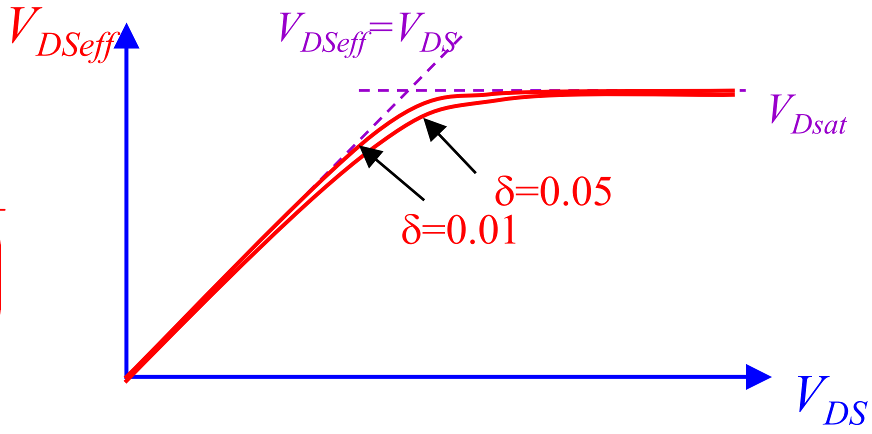
Smoothing Functions [2]

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

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

- **Where δ is a fitting parameter to adjust the abruptness of the transition**

$$I_{DS} \approx W C_{ox}\left(V_{GSeff} - \frac{\alpha}{2} V_{DSeff}\right)\frac{\mu V_{DSeff}}{L\left(1 + \frac{V_{DSeff}}{E_{sat} L}\right)}$$



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

$$V_{BSeff} = V_{BC} + \frac{1}{2}\left(V_{BS} - V_{BC} - \delta_1 + \sqrt{\left(V_{BS} - V_{BC} - \delta\right)^2 - 4\delta_1 V_{BC}}\right)$$ with $\delta_1 = 0.001$

Simplified Strong Inversion Equations [1]

Define:

$u_d = \frac{UA}{t_{ox}}$ mobility degradation coefficient

$u_d \approx 0.5\mathrm{V}^{-1}$ for $t_{ox}=10\mathrm{nm}$

$E_C = \frac{2v_{sat}}{U0}$ critical E-field for velocity saturation

$E_C \approx 2\times10^4\,\mathrm{V/cm}$ (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**

$$V_{Dsat} = \left(V_G - V_T\right)\left[\frac{1 + u_d\left(V_G - V_T\right)}{1 + \left(u_d + {}^{1}\!/\!{}_{E_c L}\right)\left(V_G - V_T\right)}\right]$$

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

$$I_{Dsat} = \mu_0 C_{ox}\frac{W}{2L}\left[\frac{\left(V_G - V_T\right)^2}{1 + \left(u_d + {}^{1}\!/\!{}_{E_C L}\right)\left(V_G - V_T\right)}\right] = I_{Dsat(long)}\left[\frac{1}{1 + \left(u_d + {}^{1}\!/\!{}_{E_C L}\right)\left(V_G - V_T\right)}\right]$$

Simplified Strong Inversion Equations [3]

Equations of derivatives

$$g_{msat}=\frac{I_{Dsat}}{\left(V_G-V_T\right)}\left[1+\frac{I_{Dsat}}{I_{Dsat(long)}}\right]=\frac{I_{Dsat}}{\left(V_G-V_T\right)}\left[1+\frac{1}{1+\left(u_d+{}^{1}\!/_{E_C L}\right)\left(V_G-V_T\right)}\right]$$

$$r_{out}=\frac{2\left\{\left(V_D-V_{Dsat}\right)+\left[1+u_d\left(V_G-V_T\right)\right]\left(V_G-V_T\right)\right\}L^2}{\mu_0 C_{ox} W l P_{CLM}\left[1+u_d\left(V_G-V_T\right)\right]\left(V_G-V_T\right)^2}=\frac{\left\{\left(V_D-V_{Dsat}\right)+\left[1+u_d\left(V_G-V_T\right)\right]\left(V_G-V_T\right)\right\}L}{I_{Dsat(long)}\, l P_{CLM}\left[1+u_d\left(V_G-V_T\right)\right]}$$

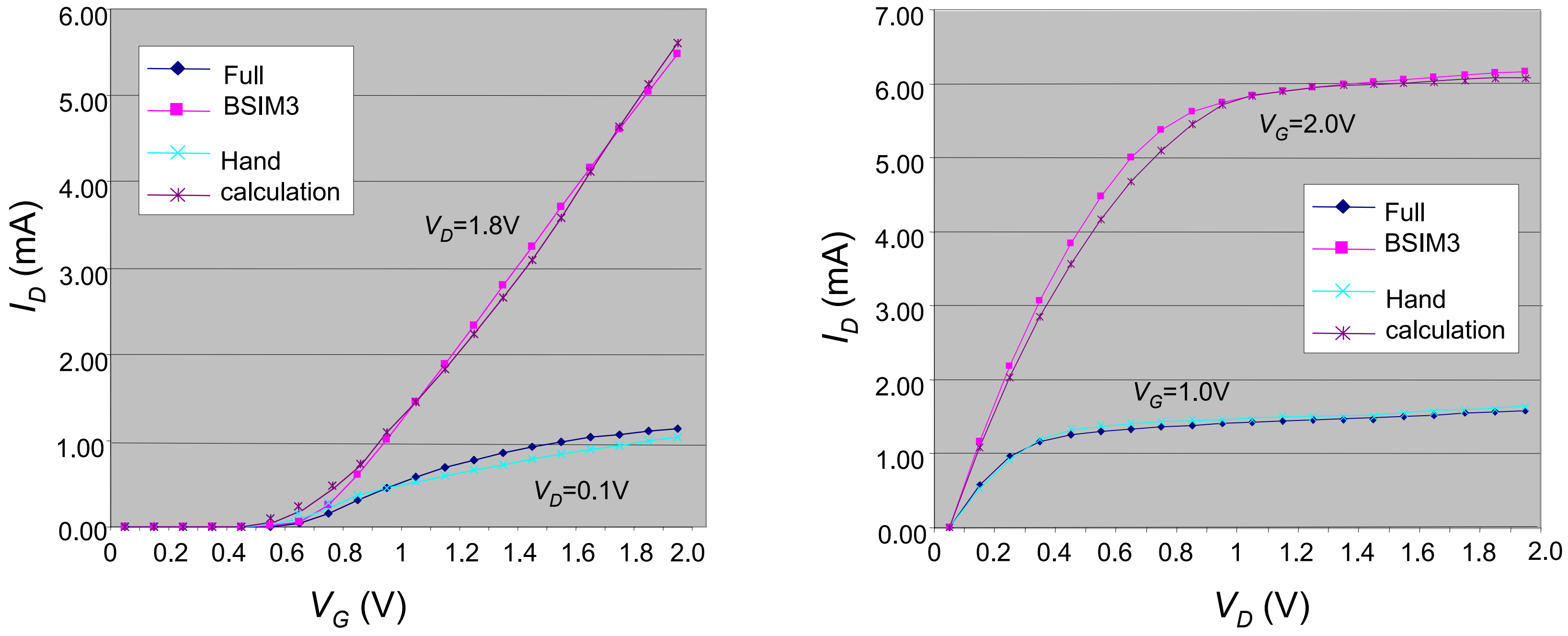
with $l=\sqrt{3t_{ox}x_j}$

Parameters used:

W, L, TOX, U0, UA, VSAT, VTH0, PCLM, XJ

Simplified Strong Inversion Equations [4]

- **Comparison between full and simplified model**

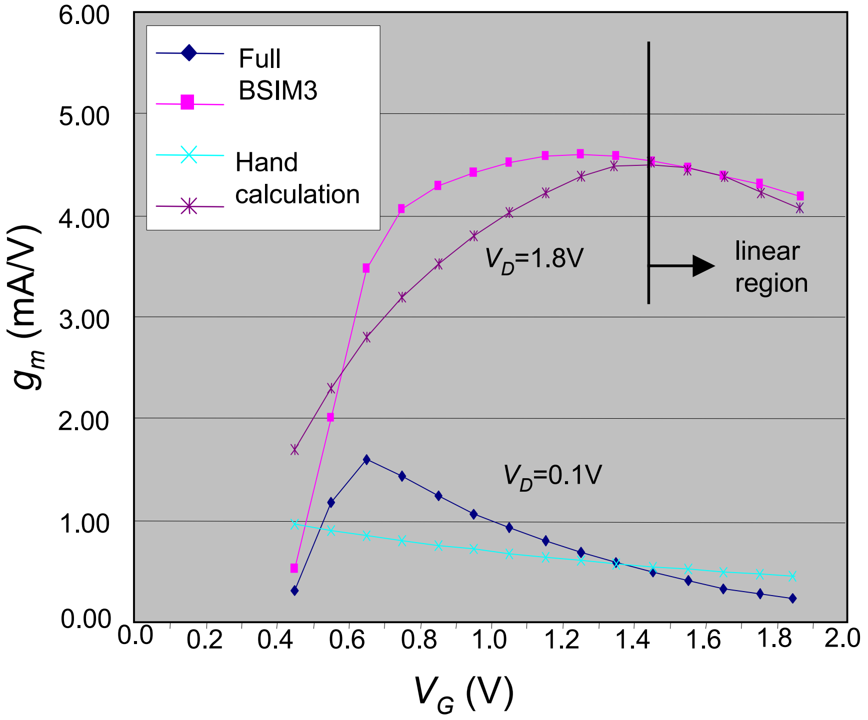


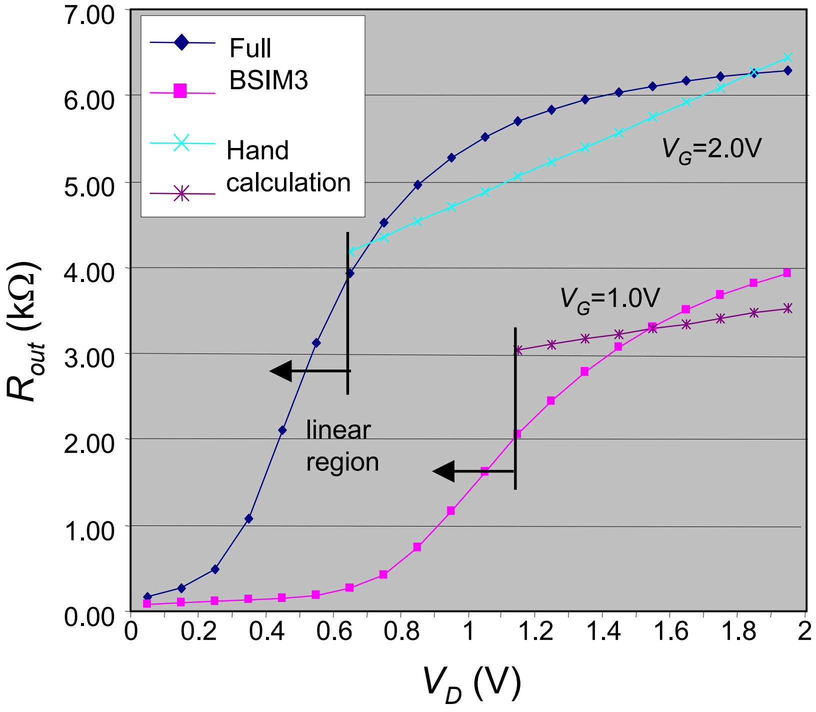
- **Parameter detail:** TSMC 0.18μm process

t_{ox}: 4.1nm, W=10μm, V_{T0}=0.39V

Simplified Strong Inversion Equations [5]

Comparison of first derivative simplification





Other features included in BSIM3v3

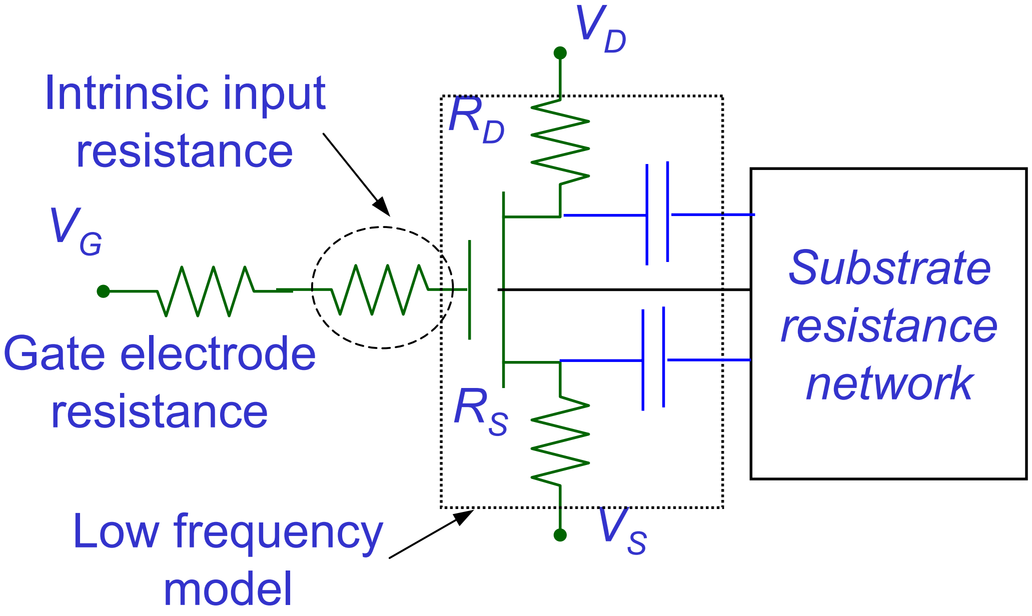
- Short/Narrow Channel Effects on Threshold Voltage
- Non-Uniform Vertical Doping Effects
- Non-Uniform Lateral Doping Effects
- Quantum Mechanic Charge Thickness Model
- Unified Flicker Noise Model
- Polysilicon Depletion Effects
- Non-quasitic Effects

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

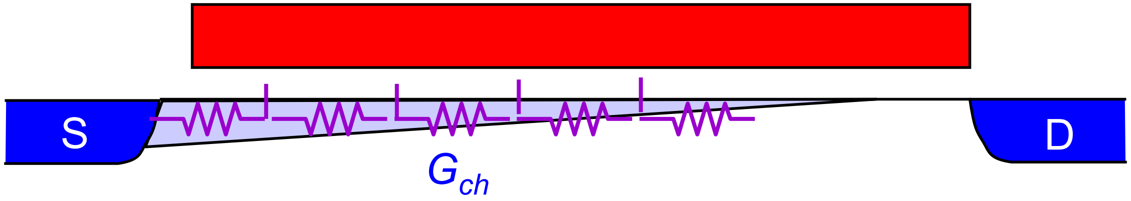
RF Model in BSIM4

- **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

$\eta \approx 14$ as determined by 2-D simulation

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

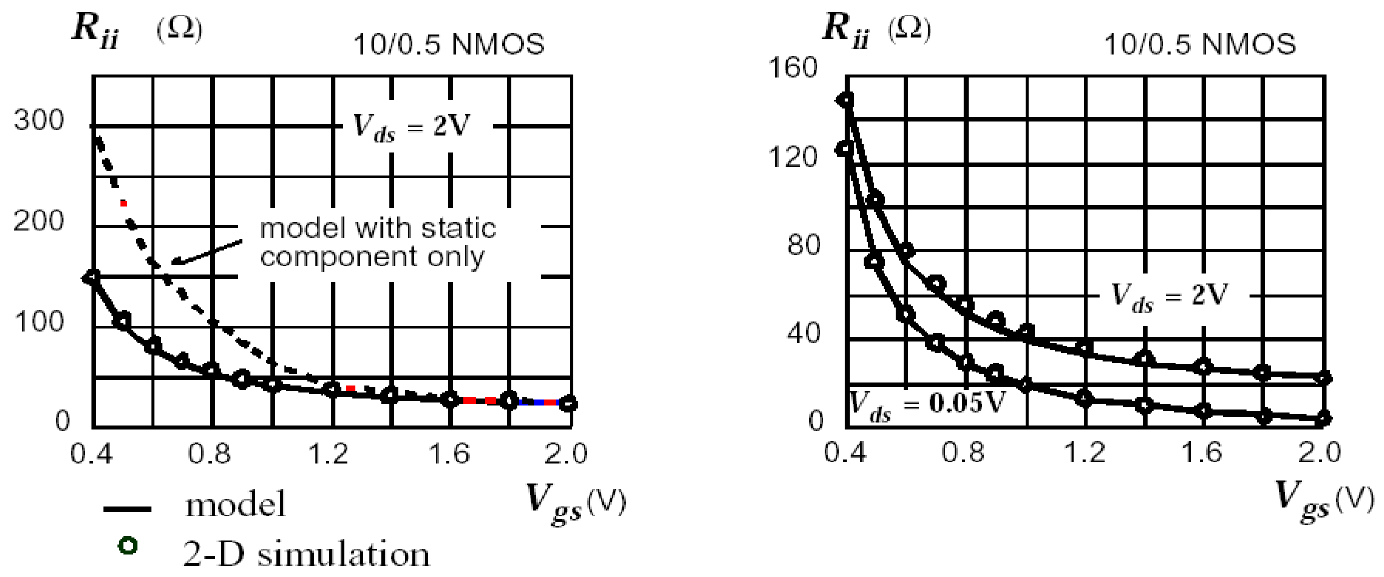
in subthreshold

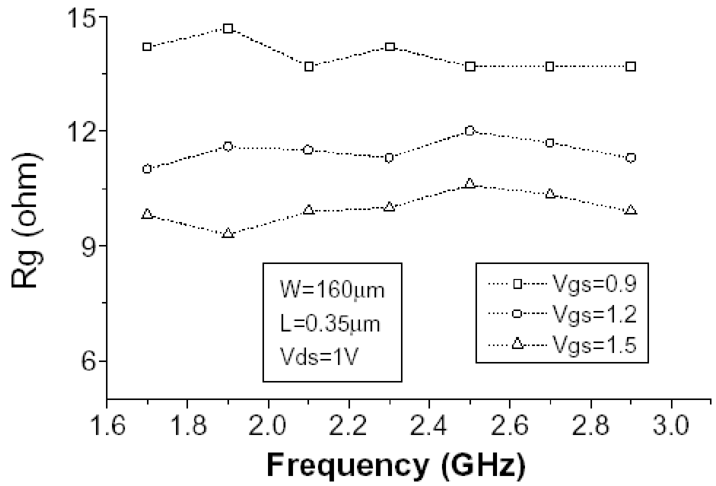
$$R_{ii}(sub) = \left(\frac{kT}{q} \mu_{eff} C_{ox} \frac{W_{eff}}{L_{eff}} \right)^{-1}$$

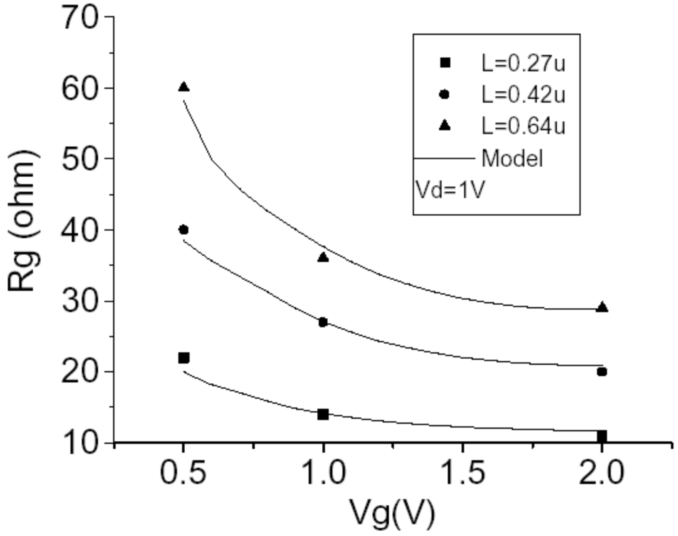
combine:

$$R_{ii} = R_{ii}(inv) // R_{ii}(sub)$$

Intrinsic gate resistance verification

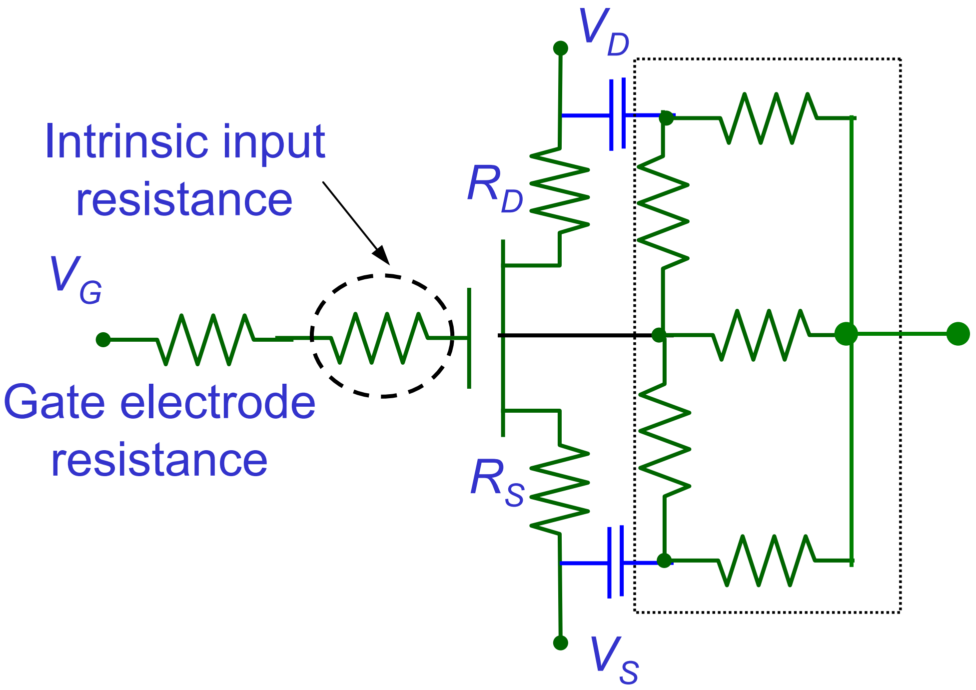






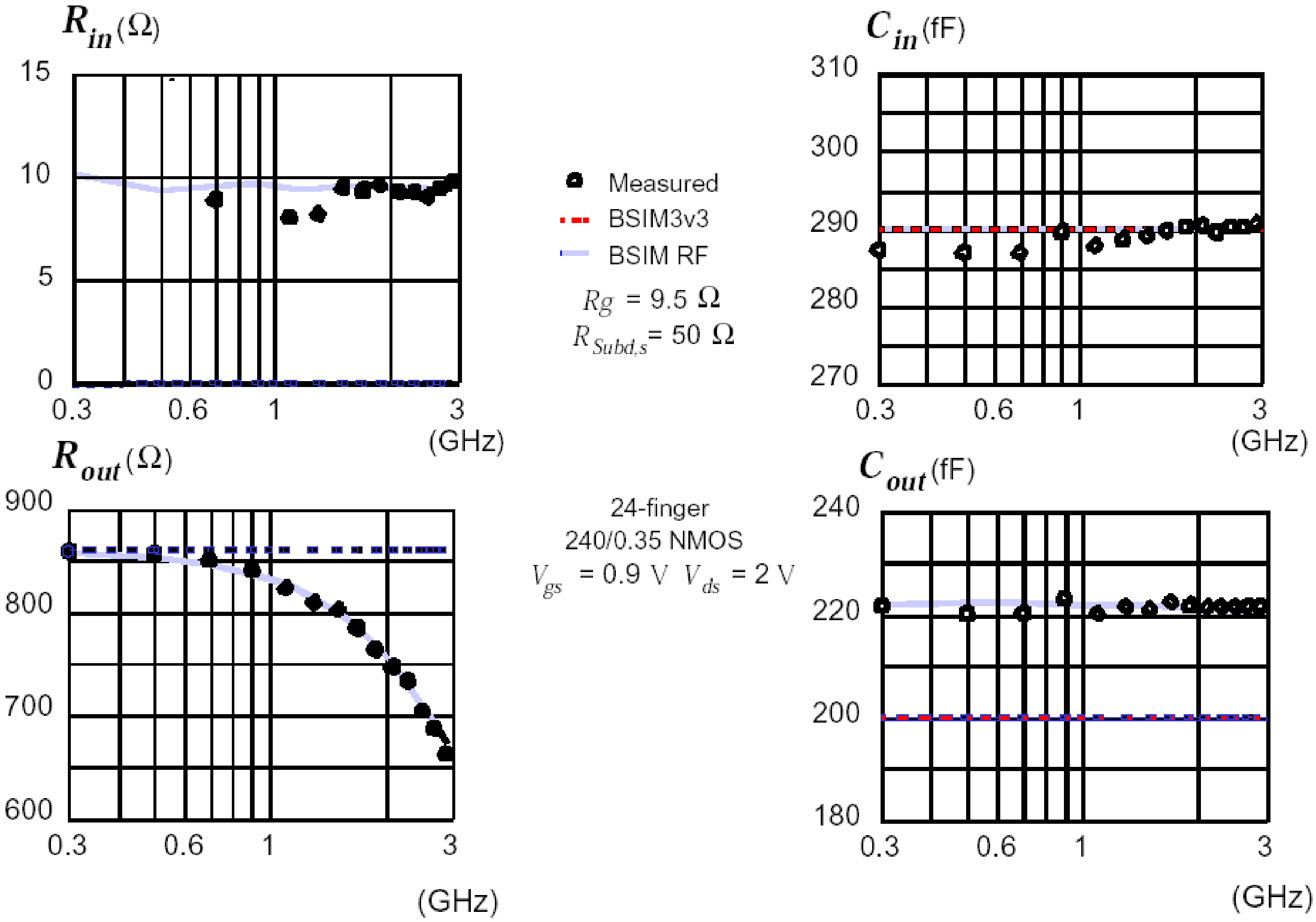
Substrate Network

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



- **In practice, 2-3 resistors are sufficient for accurate modeling**

Verification of Substrate Network



$Rg = 9.5\ \Omega$

$R_{Subd,s} = 50\ \Omega$

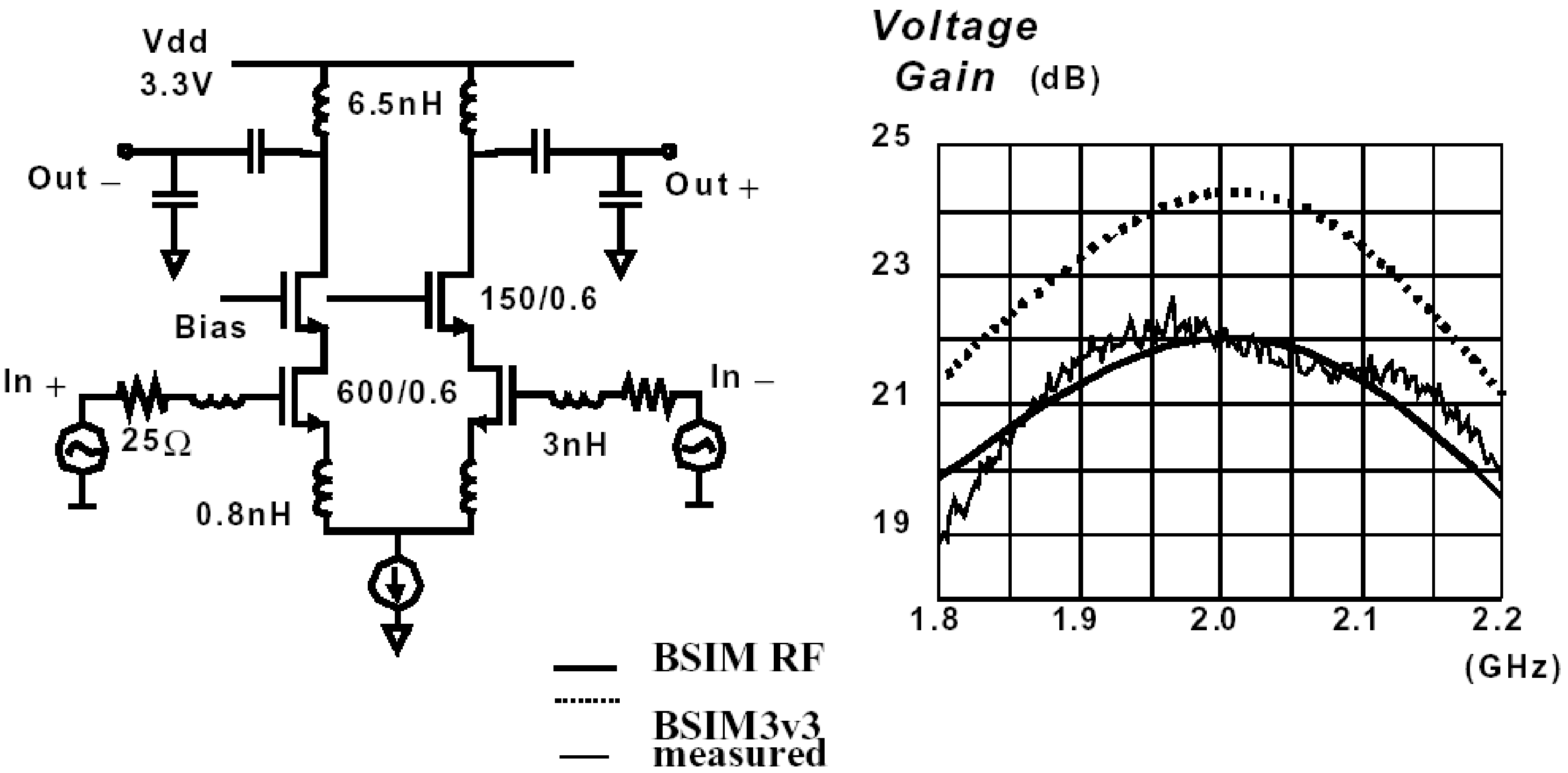
24-finger

240/0.35 NMOS

$V_{gs} = 0.9$ V $V_{ds} = 2$ V

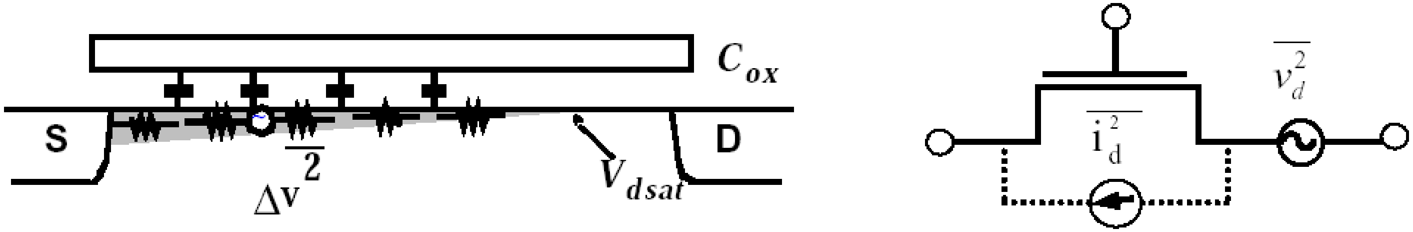
Circuit Level Verification of RF Model

- **LNA design with 0.6μm CMOS technology**



Holistic Thermal Noise Model [1]

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



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

$$= 4kTB \frac{V_d}{I_d}$$

$$\overline{i_d^2} = \overline{v_d^2} g_{ds}^2$$

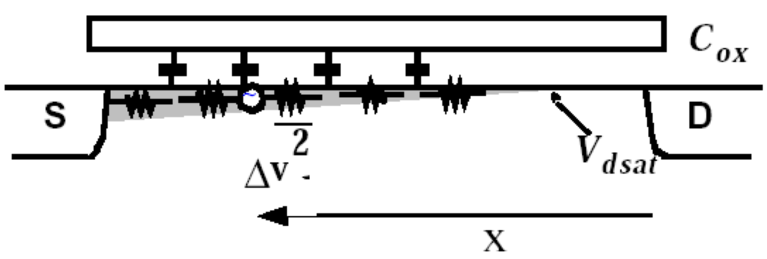
$$= 4kTB \frac{V_d}{I_d} g_{ds}^2$$

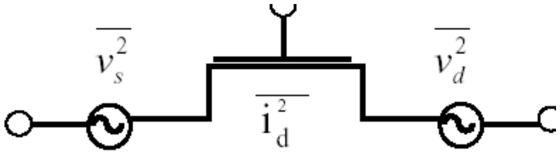
$$\frac{V_d}{I_d} \equiv \frac{V_{dsat}}{I_{ds}} \quad \text{in saturation}$$

$$\equiv \frac{V_{ds}}{I_{ds}} \quad \text{in triode}$$

Holistic Thermal Noise Model [2]

- **Channel noise amplification by front/back gate**





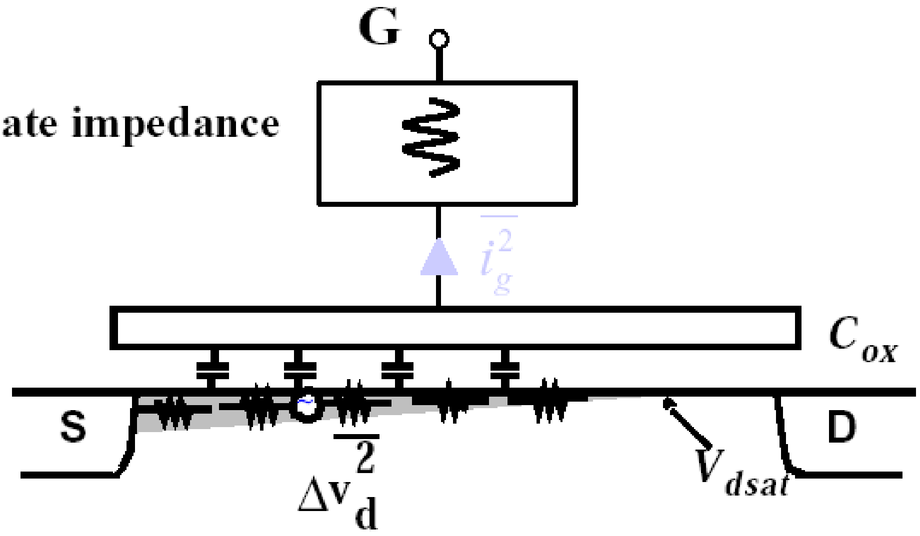
$$\Delta i_d = \Delta v(g_{ds} + g_{mx} + g_{mbx})$$

$$\overline{i_d^2} = \overline{v_d^2}(\beta g_m + \beta g_{mb} + g_{ds})^2$$

$$= 4kTB\frac{V_d}{I_d}(\beta g_m + \beta g_{mb} + g_{ds})^2$$

Holistic Thermal Noise Model [3]

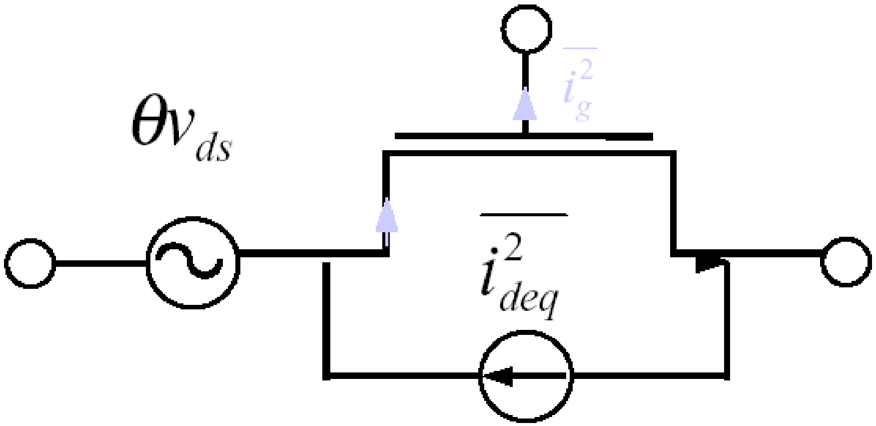
Unification of channel noise and induced gate noise



- 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

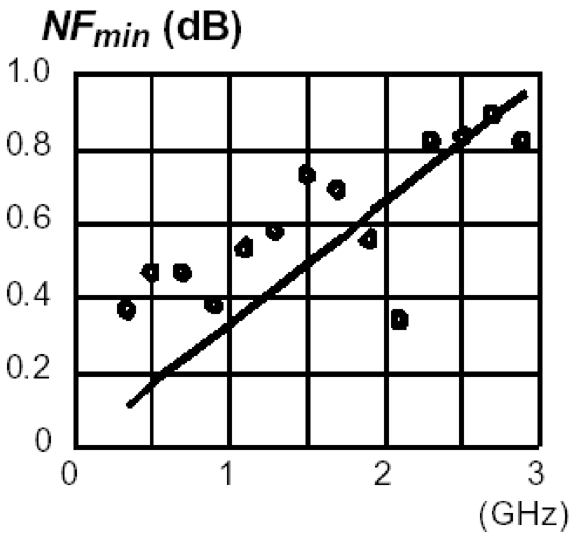


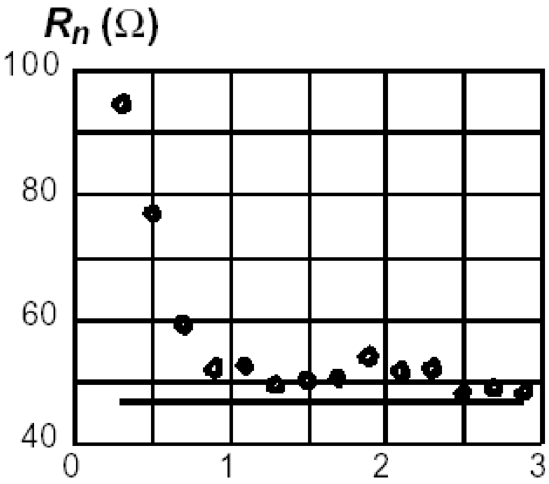
$$\overline{v_d^2} = 4kTB\frac{V_d}{I_d}$$

$$\overline{i_{d,new}^2} = \overline{i_d^2} - 4kTB\theta^2(g_m + g_{mb} + g_{ds})^2(\frac{V_d}{I_d})$$

The total noise can be partitioned into two parts to model induced gate noise

Verification of Holistic Noise Model [1]





○ measurement

— BSIM RF

Rg = 9.5 Ω

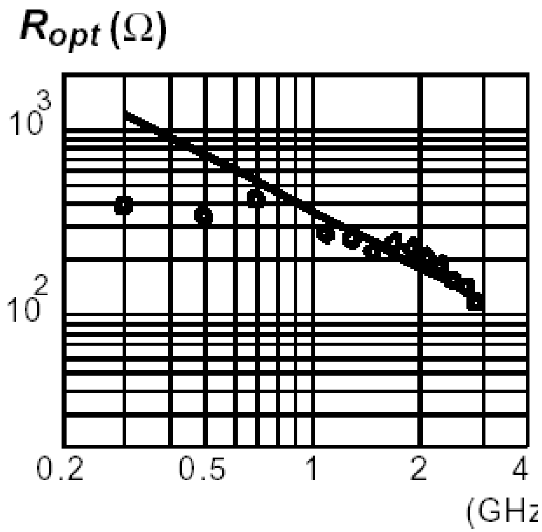
R_{subd} = 50 Ω

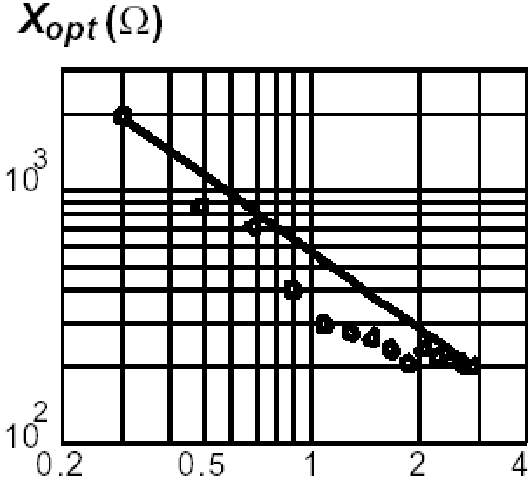
· ·

24-finger

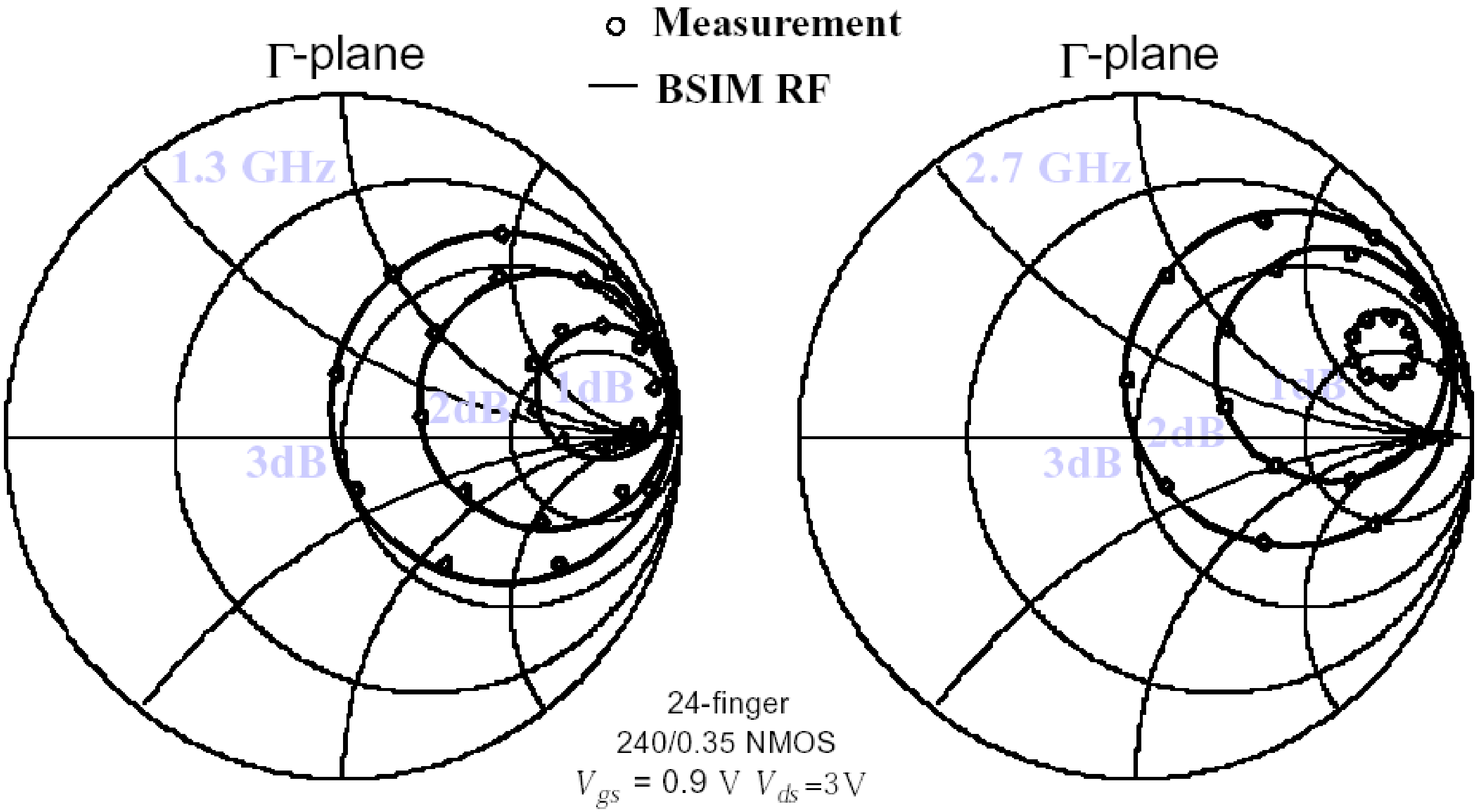
240/0.35 NMOS

V_{gs} = 0.9 V V_{ds} = 3 V





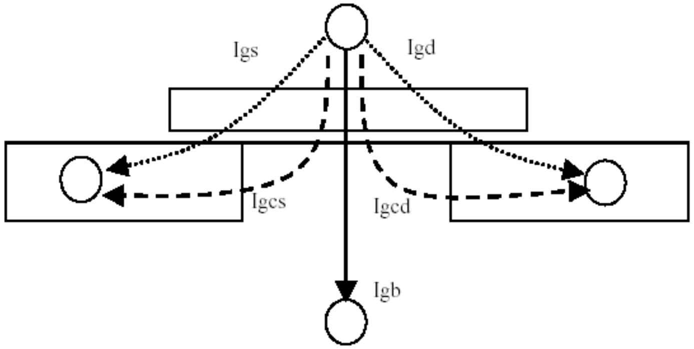
Verification of Holistic Noise Model [2]

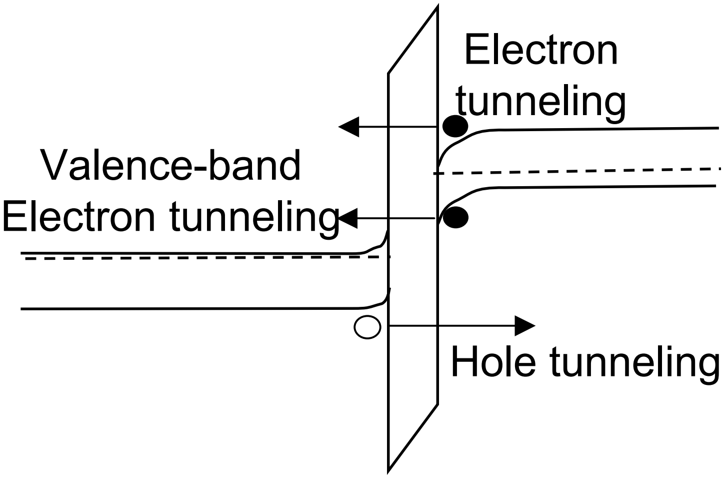


24-finger
240/0.35 NMOS
V_{gs} = 0.9 V V_{ds}=3V

Gate Tunneling Model

Gate current flow



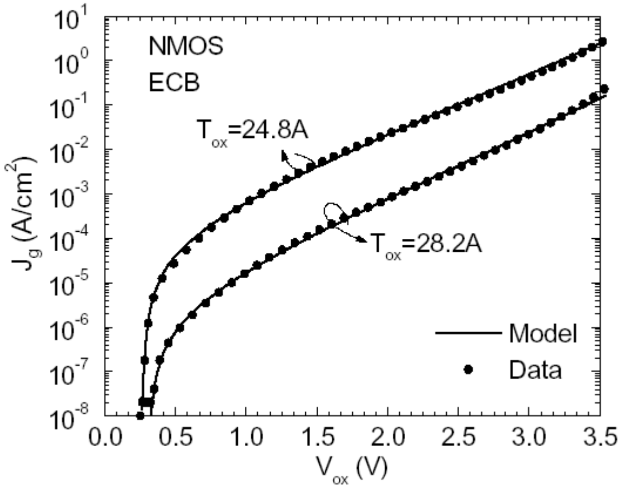


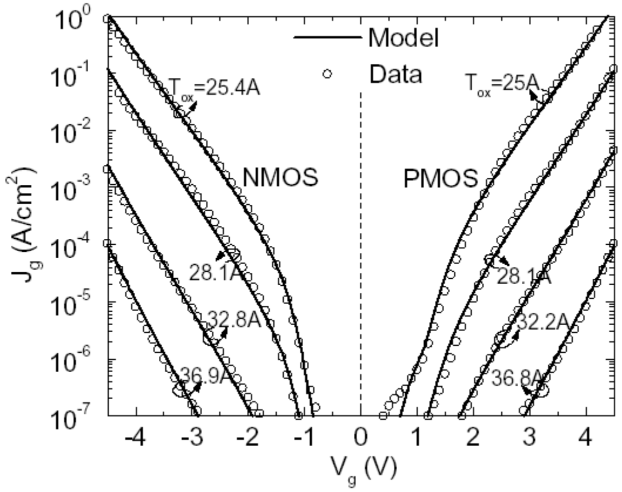
Electron tunneling

Valence-band Electron tunneling

Hole tunneling

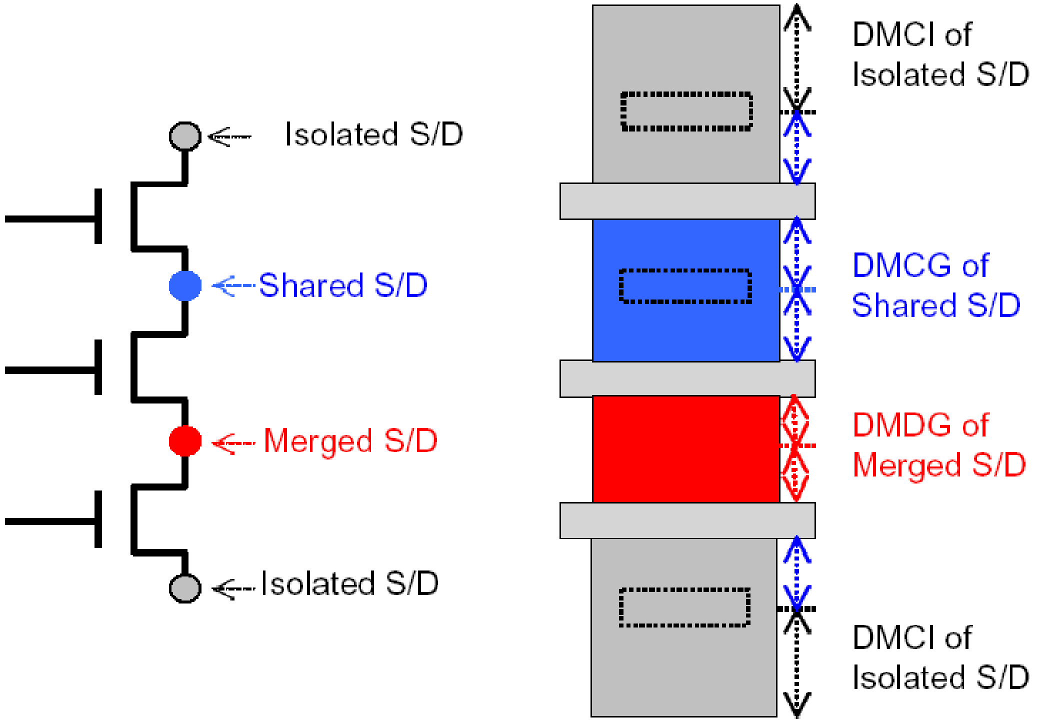
Verification





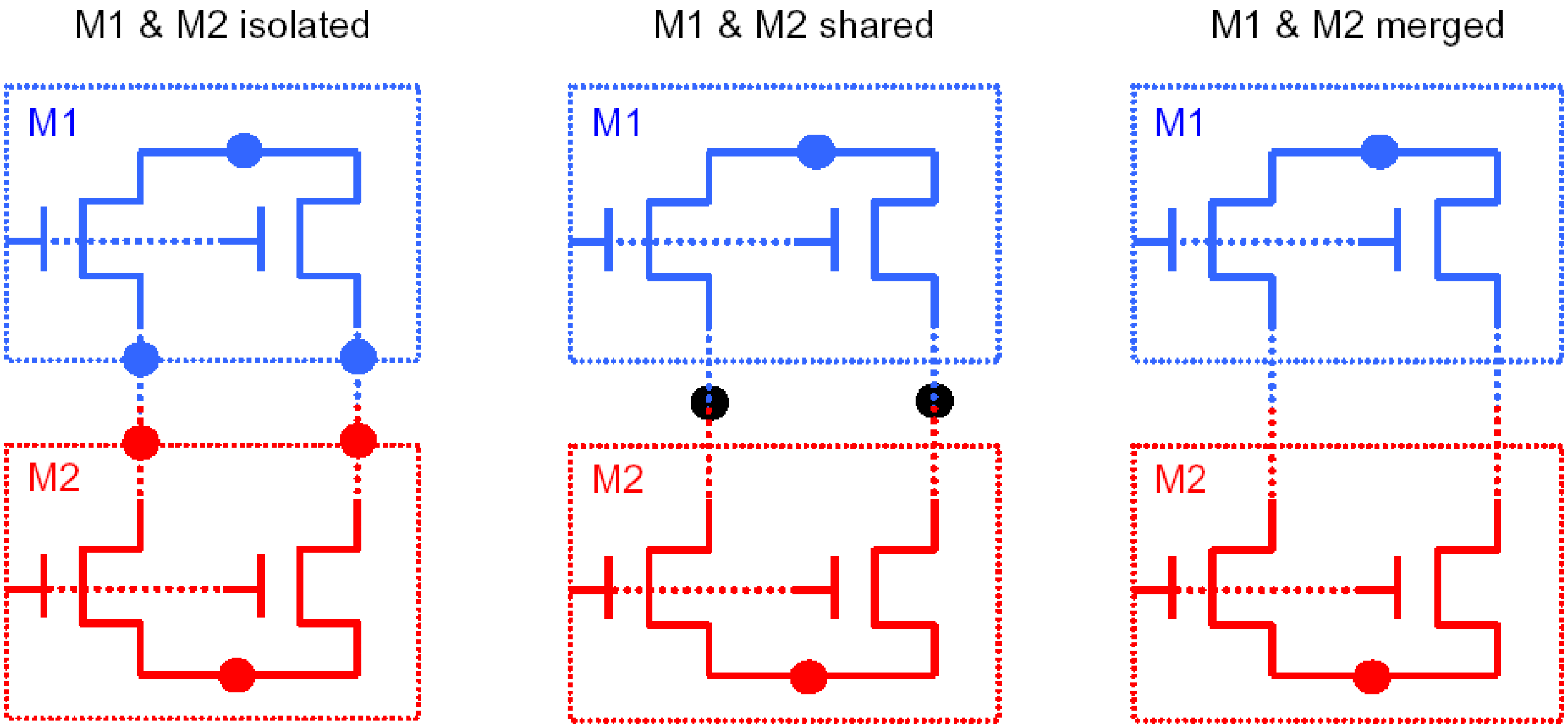
Layout dependent parasitic model [1]

- **Series/cascode connections: isolated, shared, and merged**



Layout dependent parasitic model [2]

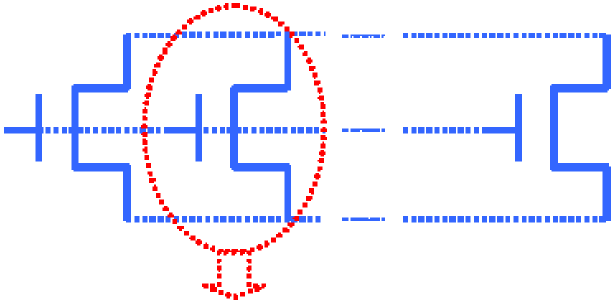
- **Example: Combination of Series/Parallel Connections**



Layout dependent parasitic model [3]

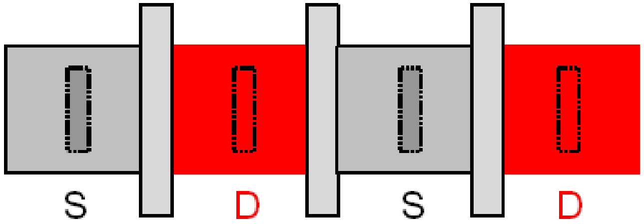
Multi-finger/parallel devices:

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

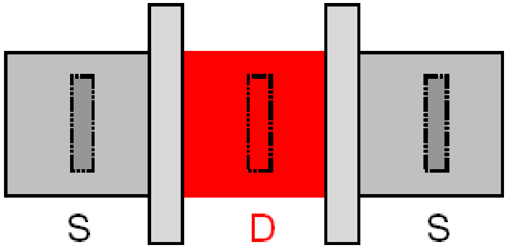


Per-finger device

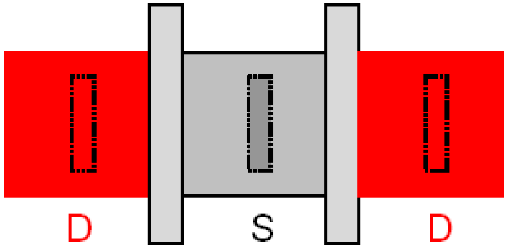
NF=Odd, MINSD is not needed



NF=Even, MINSD==0



NF=Even, MINSD==1

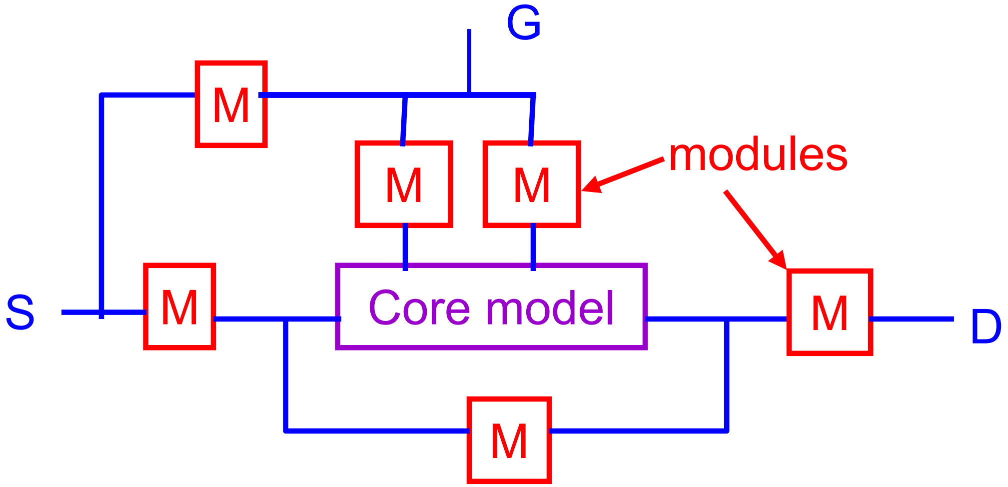


Future BSIM direction (some thoughts)

- 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 follows 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