Accuracy and Speed Performance of HiSIM Versions 231 and 240

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Outline

- **Overview of Compact-Modeling Approaches**
- **Accuracy Aspects of HiSIM2.3.1 and 2.4.0**
- **Speed Versus Accuracy Trade-Off and Position of Leading Compact Models**
- **Conclusion**

Basic Compact Model Approaches for the MOSFET

Threshold-Voltage-Based Models (e. g. BSIM3, BSIM4)

- currents expressed as functions of applied voltages
- different equations for:
  - sub-threshold region
  - linear region
  - saturation region

$$I_{ds} = \mu C_{ox}\frac{W}{L}\{(V_{gs} - V_{th})V_{ds} - (\frac{1}{2} + \frac{\sqrt{2\epsilon_{Si} q N_{sub}}}{4C_{ox}}\sqrt{2\Phi_B})V_{ds}^2\}$$

New Generation of Surface-Potential-Based Models

$$C_{\mathrm{ox}}(V_G' - \phi_{\mathrm{S}}(y)) = \sqrt{\frac{2\epsilon_{\mathrm{Si}} q N_{\mathrm{sub}}}{\beta}}\left[\exp\{-\beta(\phi_{\mathrm{S}}(y) - V_{\mathrm{bs}})\} + \beta(\phi_{\mathrm{S}}(y) - V_{\mathrm{bs}}) - 1 + \frac{n_{\mathrm{p0}}}{p_{\mathrm{p0}}}\left\{\exp\left(\beta(\phi_{\mathrm{S}}(y) - \phi_{\mathrm{f}}(y))\right) - \exp\left(\beta(V_{\mathrm{bs}} - \phi_{\mathrm{f}}(y))\right)\right\}\right]^{\frac{1}{2}}$$

- implicit equation for surface potential
- currents determined from drift and diffusion term of current density equation
- developed calculation methods for the surface potential:
  - iterative solution with the exact surface-potential equation ⇒HiSIM
  - approximate explicit solution by 1st & 2nd order perturbation theory, after prior conditioning of the surface-potential equation ⇒PSP

New Generation of Inversion-Charge-Based Models

- additional approximation to solve for inversion charge
  ⇒ EKV, BSIM5, AMC

HiSIM Development History

1990 JJAP	Sub-1μm MOSFETs	short-channel effect model
1991 SISPAD	“	1st surface-potential-based model
		parameter extraction strategy
1994 ICCAD	“	simulation time & stability verification
1995 Siemens	Flash-EEPROM	concurrent device/circuit development
1998 STARC	100-nm MOSFET	collaboration start

Release Activity

2001 Oct.	release to vendors	HiSIM1.0.0	source code and manual
2002 Jan.	release to public	“	“
June	“	HiSIM1.1.0	“
Oct.	“	HiSIM1.1.1	“
2003 Oct.	Test release to STARC clients	HiSIM2.0.0	source code and manual
2005 May	release to CMC members	HiSIM2.0.0	“
July	“		+ Verilog-A code
Oct.	“	HiSIM2.2.0	“
2006 Jan.	release to vendors	HiSIM2.3.0	“
2006 Dec.	“	HiSIM2.3.1	
2007 March		HiSIM2.4.0	

Modeled Phenomena in HiSIM2.4.0

[Phenomena]	[Subjects]
Short Channel:	
Reverse-short Channel:	impurity pile-up pocket implant
Poly-Depletion:	
Quantum-Mechanical:	
Channel-Length Modulation:	
Narrow-Channel:	
Temperature Dependency:	thermal voltage bandgap n_i phonon scattering maximum velocity
Mobility Models:	universal high Field
Shallow-Trench Isolation:	threshold voltage mobility leakage current
Capacitances:	intrinsic overlap lateral-field induced fringing

[Phenomena]	[Subjects]
Non-Quasi-Static:	transient time-domain AC frequency-domain
Noise:	1/f thermal induced gate cross-correlation
Leakage Currents:	substrate current gate current GIDL current
Source/Drain Resistances:	
Junction Diode:	currents capacitances

Binning Option

DFM Option

HiSIM Availability in Commercial EDA Software

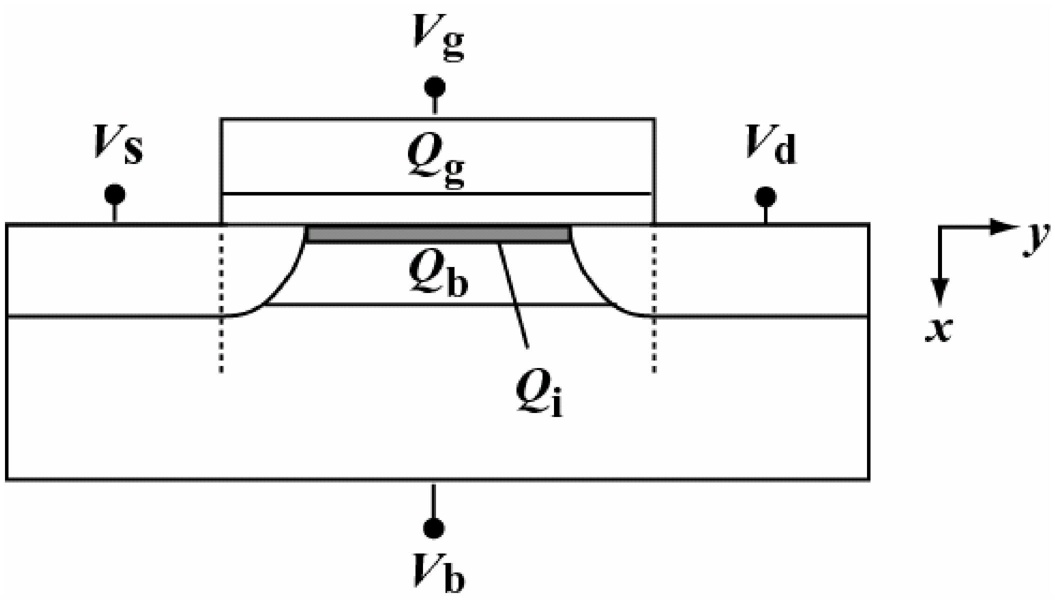
Type of EDA Software	HiSIM2.3.1	HiSIM2.4.0
Model Parameter Extraction	Accelicon-MBP, BSIM ProPlus, EXPARA, ICCAP (Nov 07), UTMOST4	EXPARA, UTMOST4
Circuit Simulation	ADS, Eldo, FineSime, Hspice, HSIM, Nexxim, SmartSpice, Spectre, Ultrasim	Eldo, FineSim, Hspice, HSIM, Nexxim, SmartSpice, Spectre (Dec 07), Ultrasim (Dec 07)

HiSIM versions 231 and 240 are available in many commercial EDA tools for circuit analysis.

Outline

- Overview of Compact-Modeling Approaches
- **Accuracy Aspects of HiSIM2.3.1 and 2.4.0**
  - Model Consistency Aspects
  - Surface-Potential Accuracy
  - Derivatives
  - Predictability, Variation Estimate
  - Inter-Modulation, Noise
- Speed Versus Accuracy Trade-Off and Position of Leading Compact Models
- Conclusion

Consistency Property of Surface-Potential Model



$$I_{ds} = q\frac{W}{L}\int vQ_i dy$$

$$Q(\phi)$$

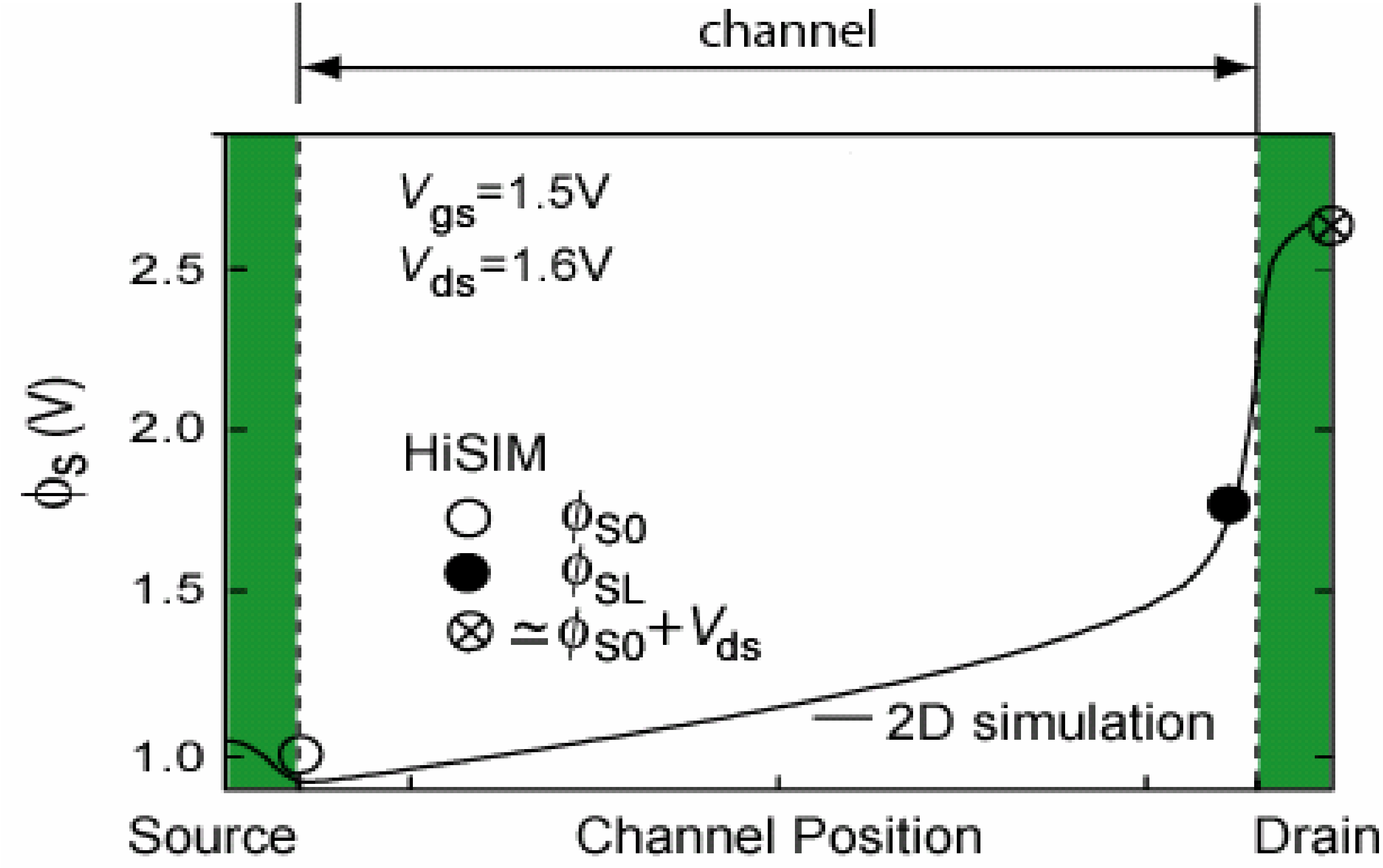
$$C_{jk} = \frac{dQ_j}{dV_k}$$

$v = \mu E$: velocity

$$\frac{1}{\mu_0} = \frac{1}{\mu_{CB}} + \frac{1}{\mu_{PH}} + \frac{1}{\mu_{SR}}$$: mobility

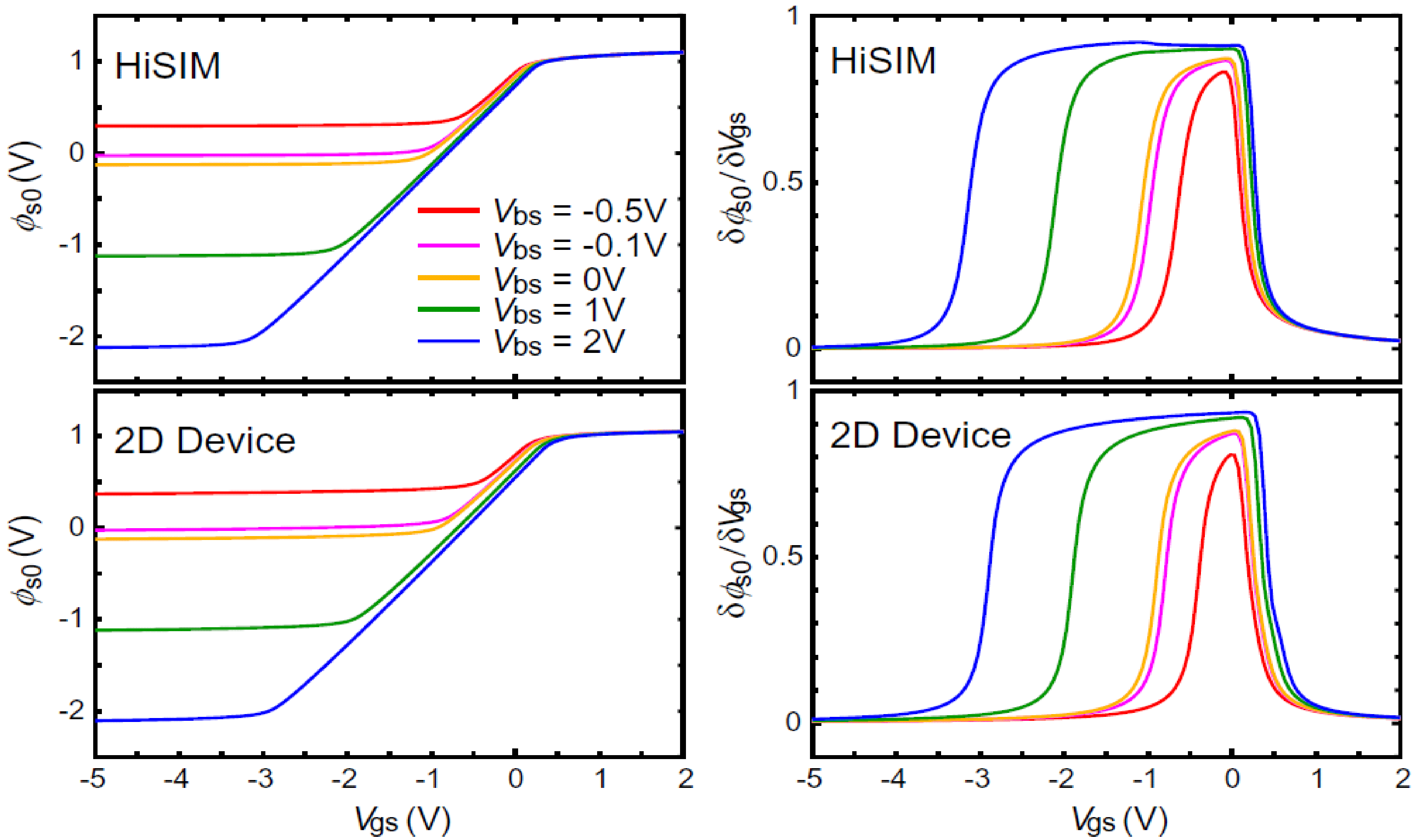
The surface potential consistently determines charges, capacitances and currents under all operating conditions.

HiSIM Surface Potential at Source and Drain



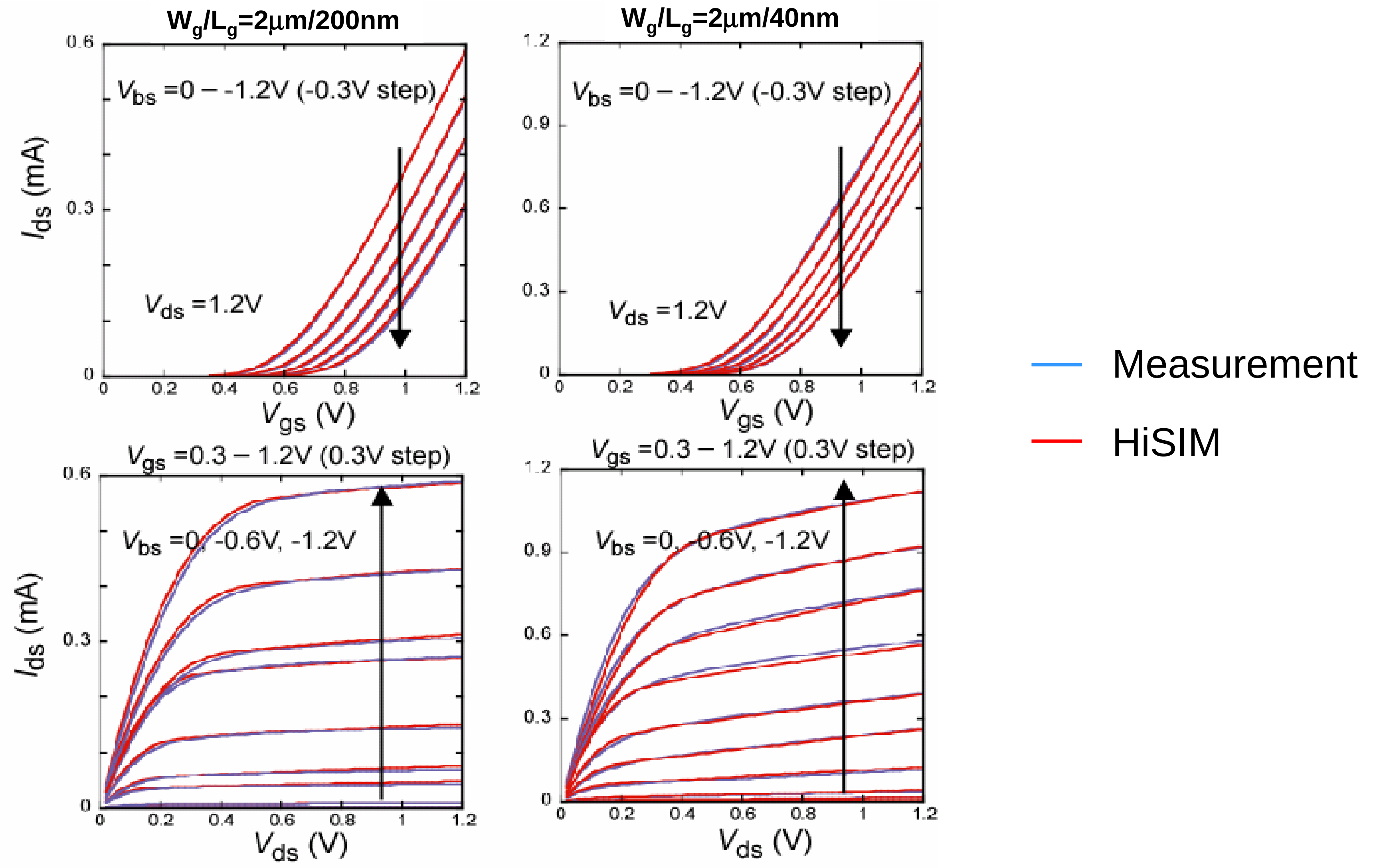
The absolute values of the HiSIM surface potential compare well with 2D simulation.

Bias Dependence & Derivatives of Surface Potential



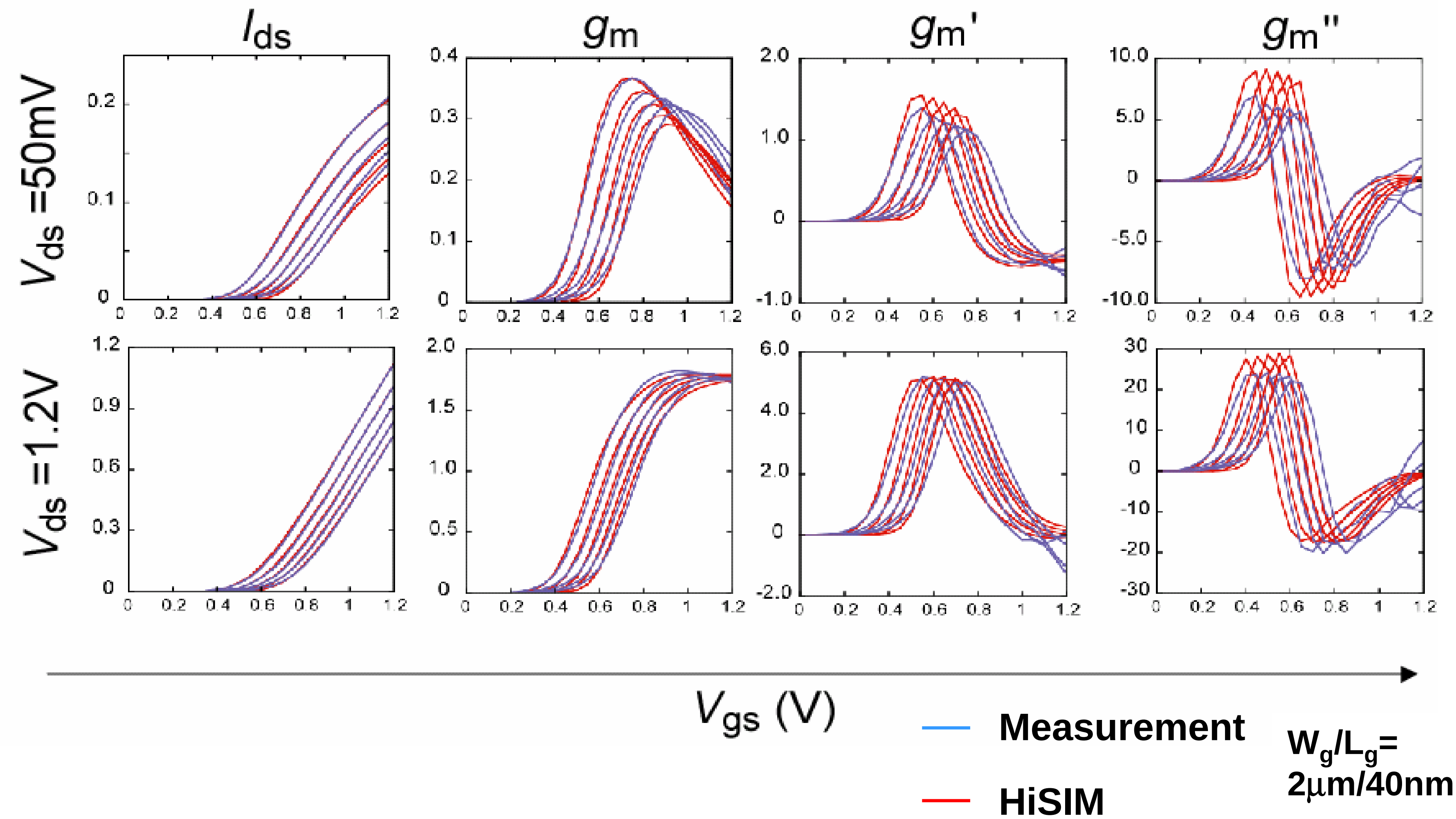
HiSIM accurately reproduces even the bias dependence of the surface-potential derivatives.

Model Extraction for Advanced 45nm Technology



HiSIM can model even advanced 45nm technology very accurately without the necessity of binning.

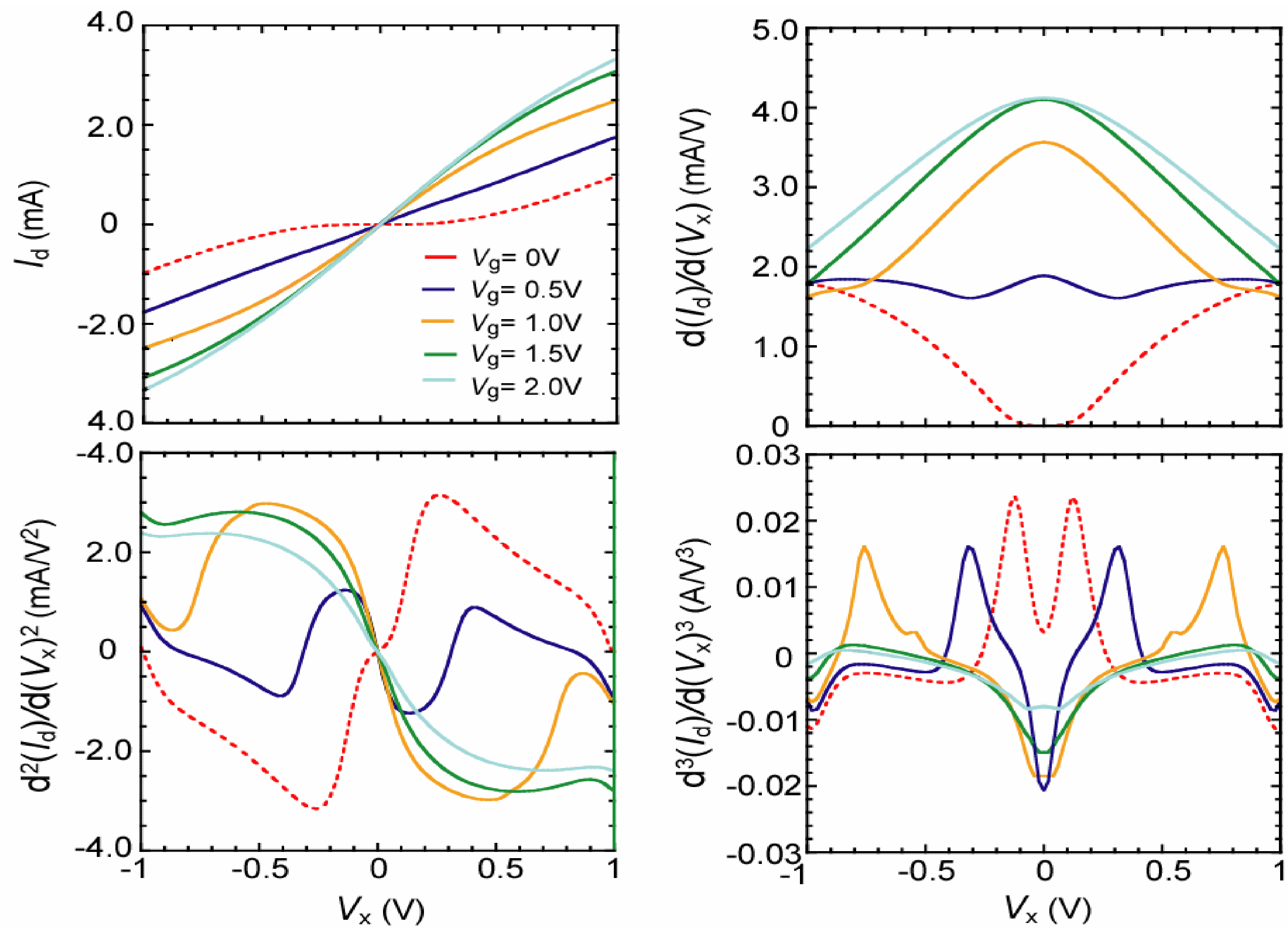
Current Derivatives for Advanced 45nm Technology



W_g/L_g= 2μm/40nm

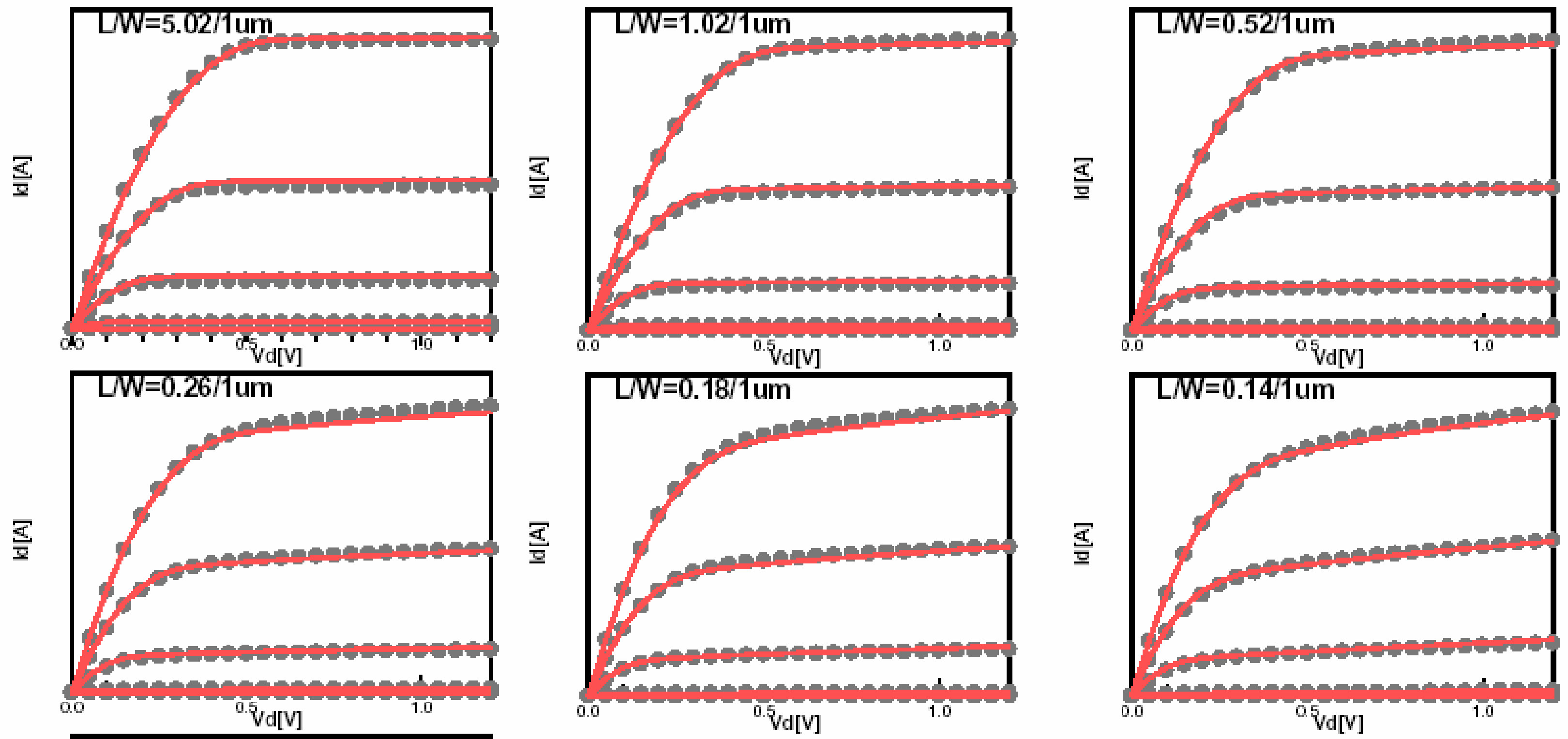
The current derivatives of a 45nm technology can likewise be well reproduced with HiSIM.

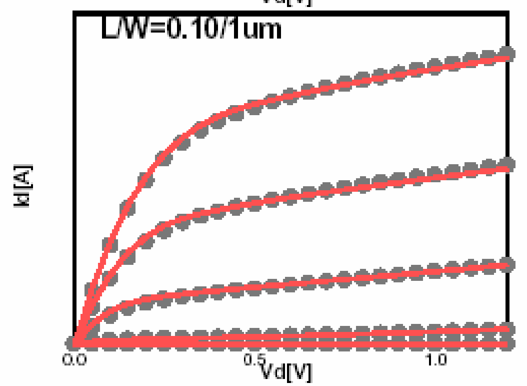
Gummel-Symmetry Properties



HiSIM preserves Gummel symmetry under drain and source exchange up to 3rd derivatives.

Typical Extraction Result for 90nm CMOS (NMOS)





Source:
Fujitsu
(HiSIM231)

$$Error = 3.5\,[\%]$$

$$@Vg \geq Vth + 0.1\,[\mathrm{V}]$$

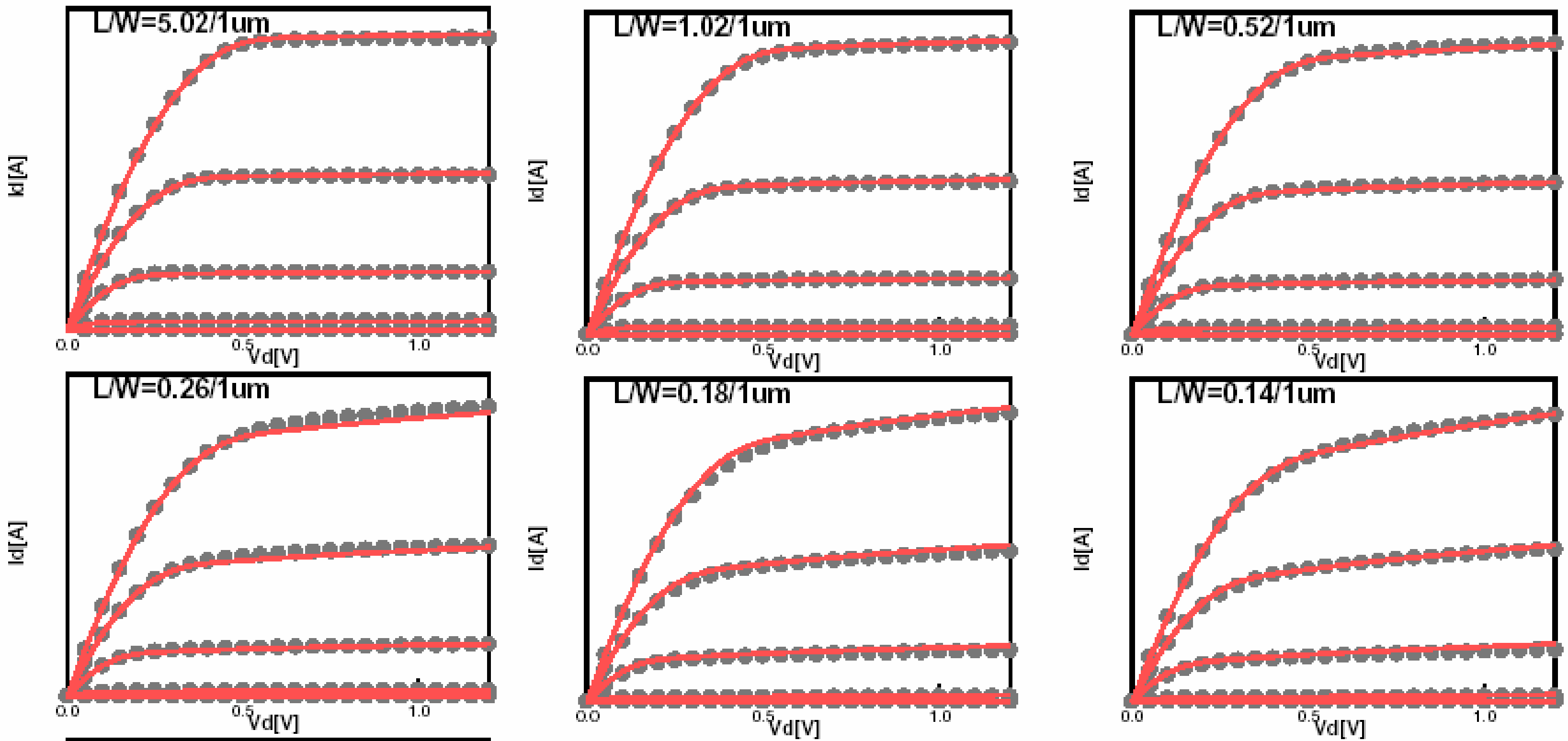
$$L\ :\ 0.1 \Leftrightarrow 5.02\ [um]$$

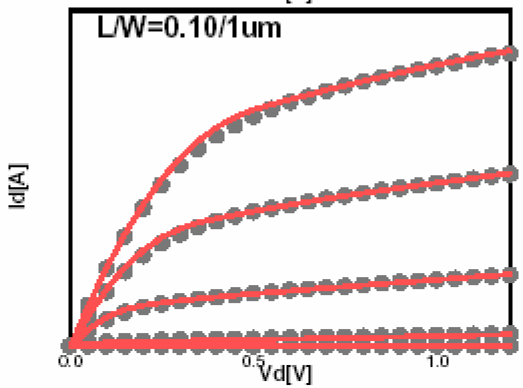
$$Error = \sqrt{\frac{\sum_{i=1}^{n} Err(i)^2}{n}}$$

$$Err(i) = \frac{(Sim_i - Meas_i)}{Meas_i}$$

Small-error fitting is normally achieved without binning

Typical Extraction Result for 90nm CMOS (PMOS)





Source: Fujitsu (HiSIM231)

$$Error = 2.7\,[\%]$$

$$@Vg \geq Vth + 0.1\,[\mathrm{V}]$$

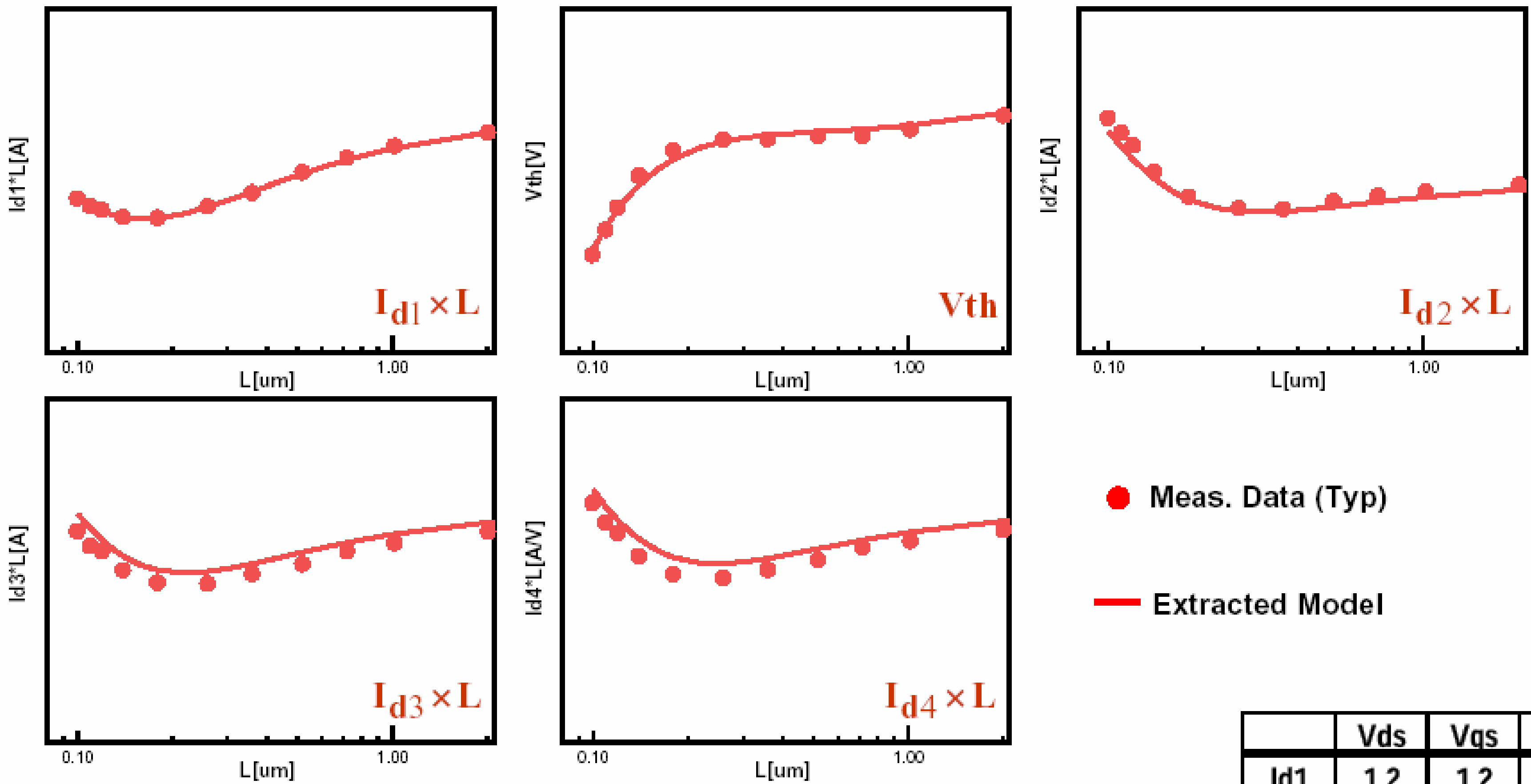
$$L \;:\; 0.1 \Leftrightarrow 5.02\;\;[um]$$

$$Error = \sqrt{\frac{\sum_{i=1}^{n} Err(i)^2}{n}}$$

$$Err(i) = \frac{(Sim_i - Meas_i)}{Meas_i}$$

PMOS,NMOS fitting approximately with equal quality

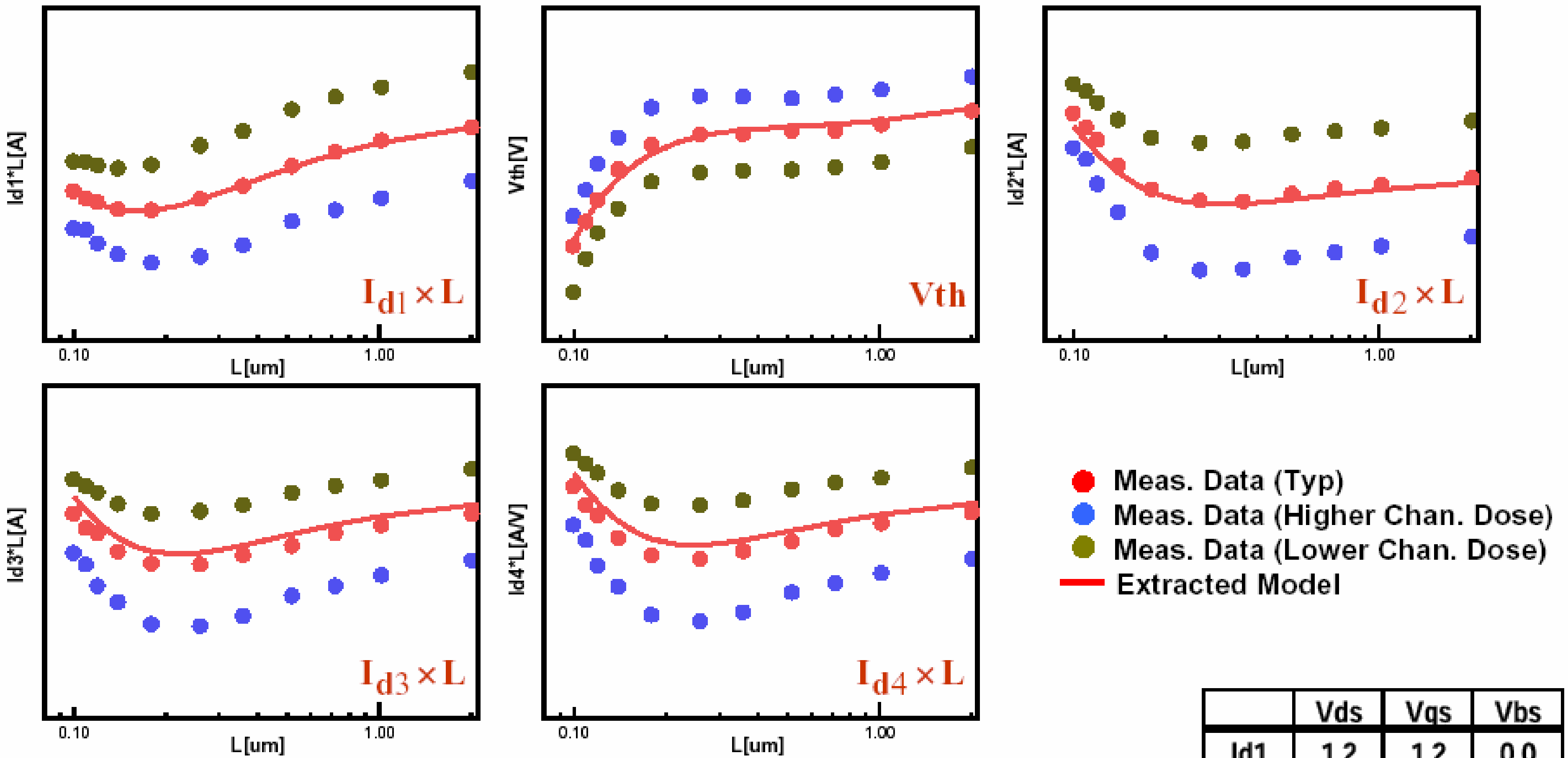
Predictability Test: Nominal Extraction



Source: Fujitsu (HiSIM231)

	Vds	Vgs	Vbs
Id1	1.2	1.2	0.0
Id2	1.2	1.2	-1.2
Id3	0.8	0.8	0.0
Id4	1.2	0.8	0.0

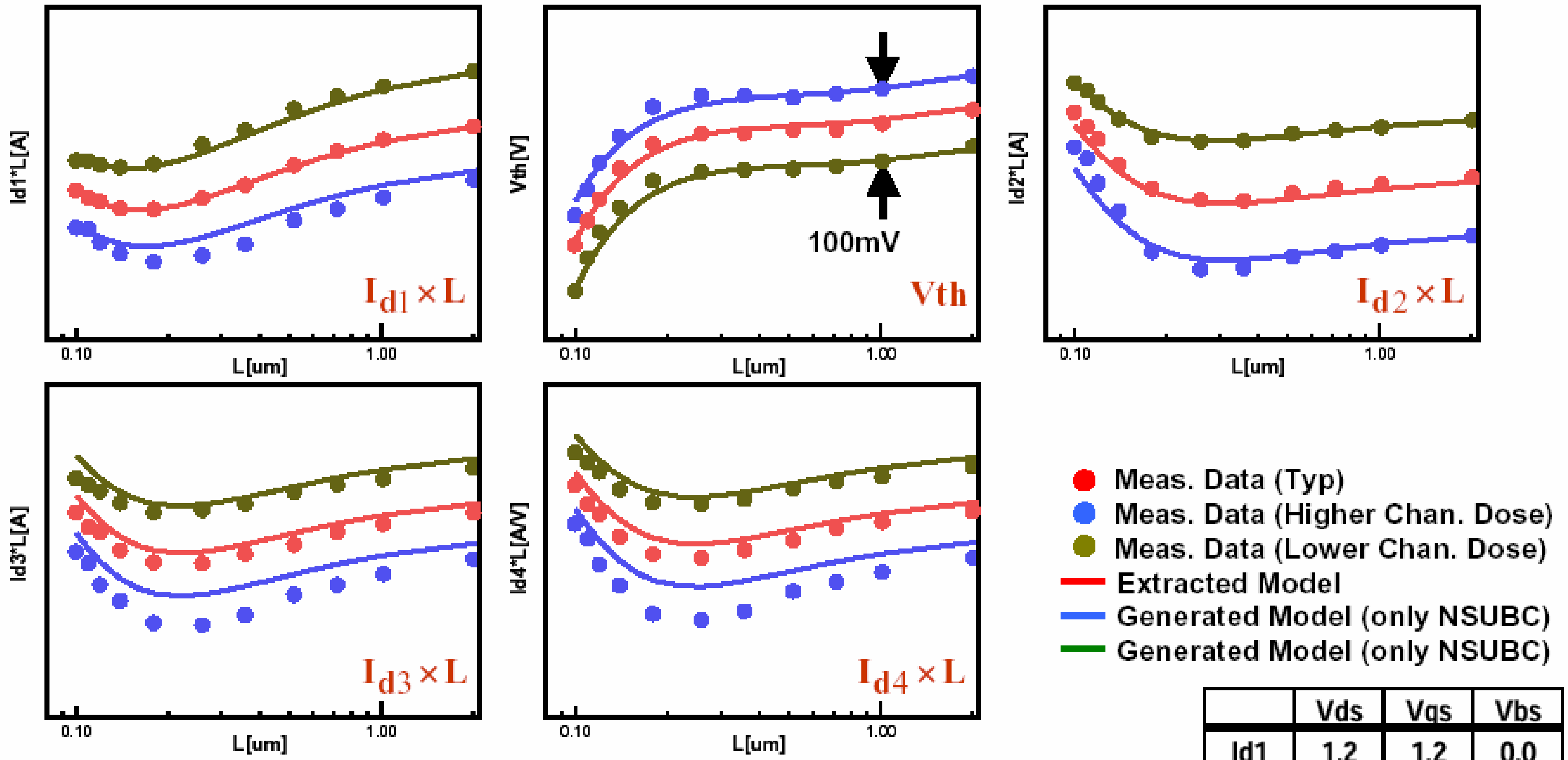
Predictability Test: Changed Channel Dose



	Vds	Vgs	Vbs
Id1	1.2	1.2	0.0
Id2	1.2	1.2	-1.2
Id3	0.8	0.8	0.0
Id4	1.2	0.8	0.0

Source: Fujitsu (HiSIM231)

Predictability Test: Adjustment of Substrate Doping



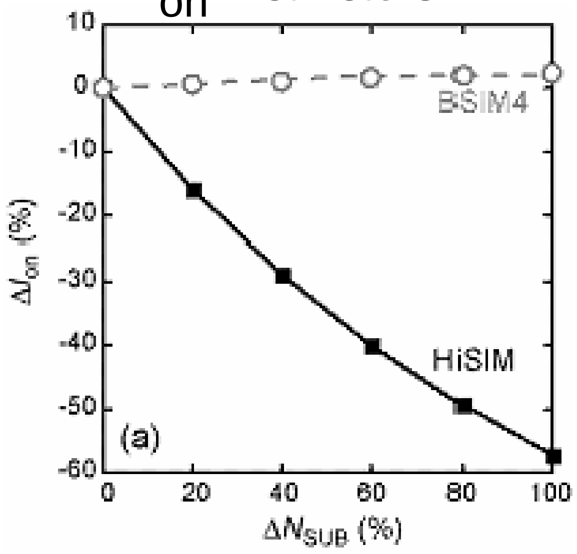
	Vds	Vgs	Vbs
Id1	1.2	1.2	0.0
Id2	1.2	1.2	-1.2
Id3	0.8	0.8	0.0
Id4	1.2	0.8	0.0

Source: Fujitsu (HiSIM231)

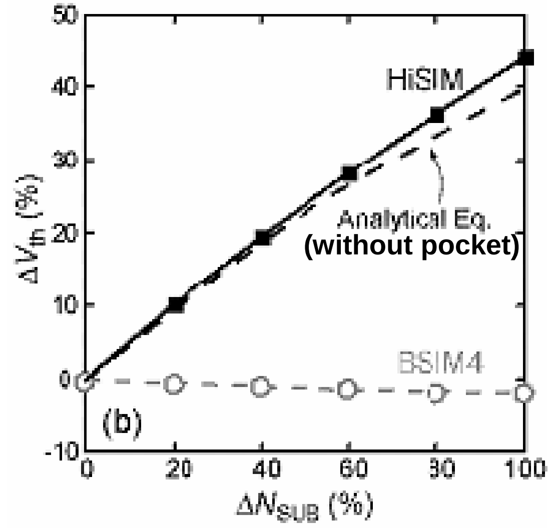
Substrate-doping parameter correlates well with physical substrate doping value

Variation Prediction

I_{on} variation

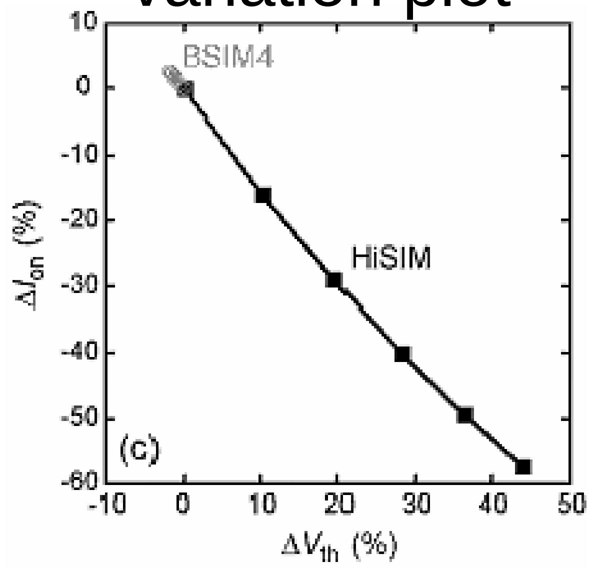


V_{th} variation



Data:
HiSIM231

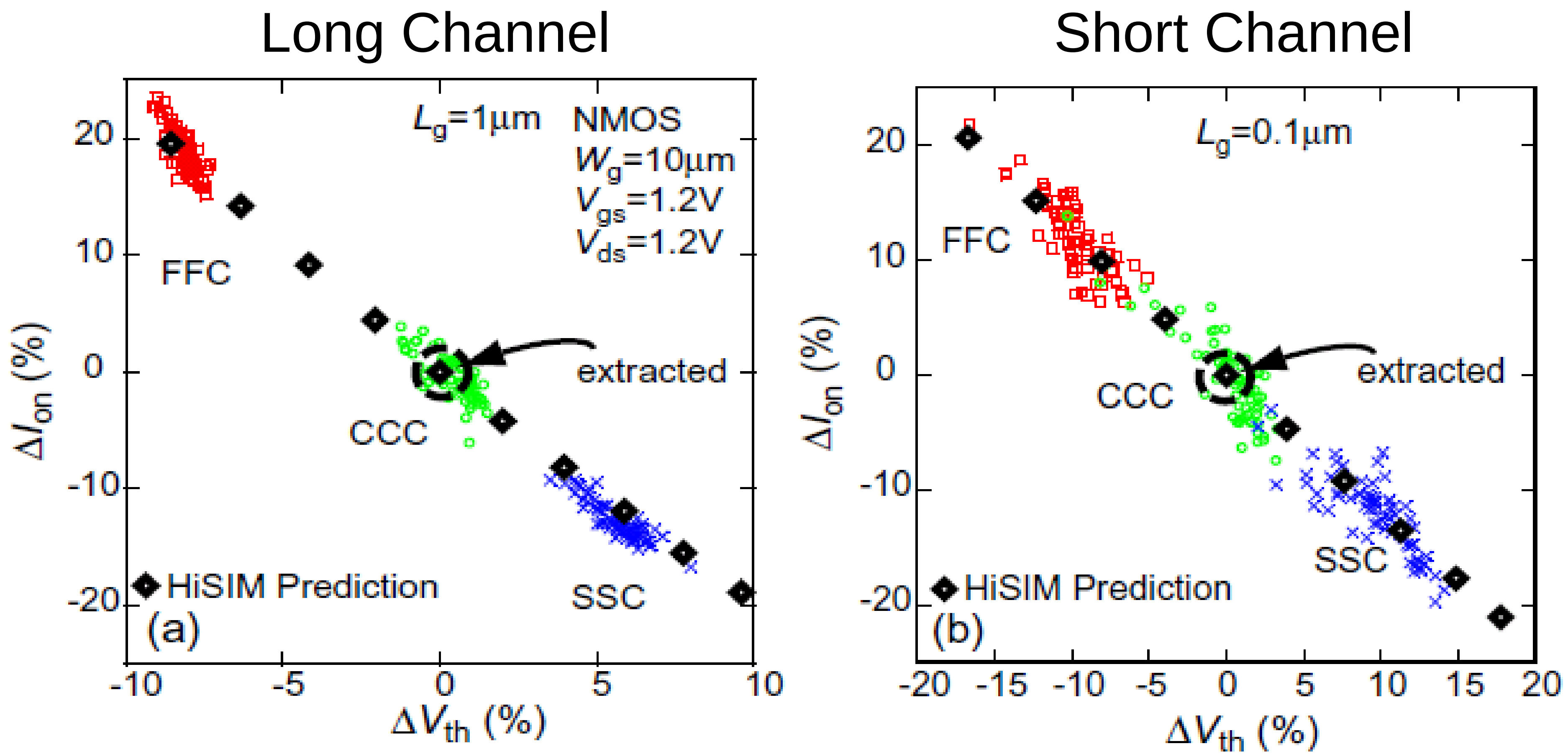
Combined I_{on}, V_{th} variation plot



Correct correlation between device and process parameters is required.

Surface-potential models like HiSIM are needed.

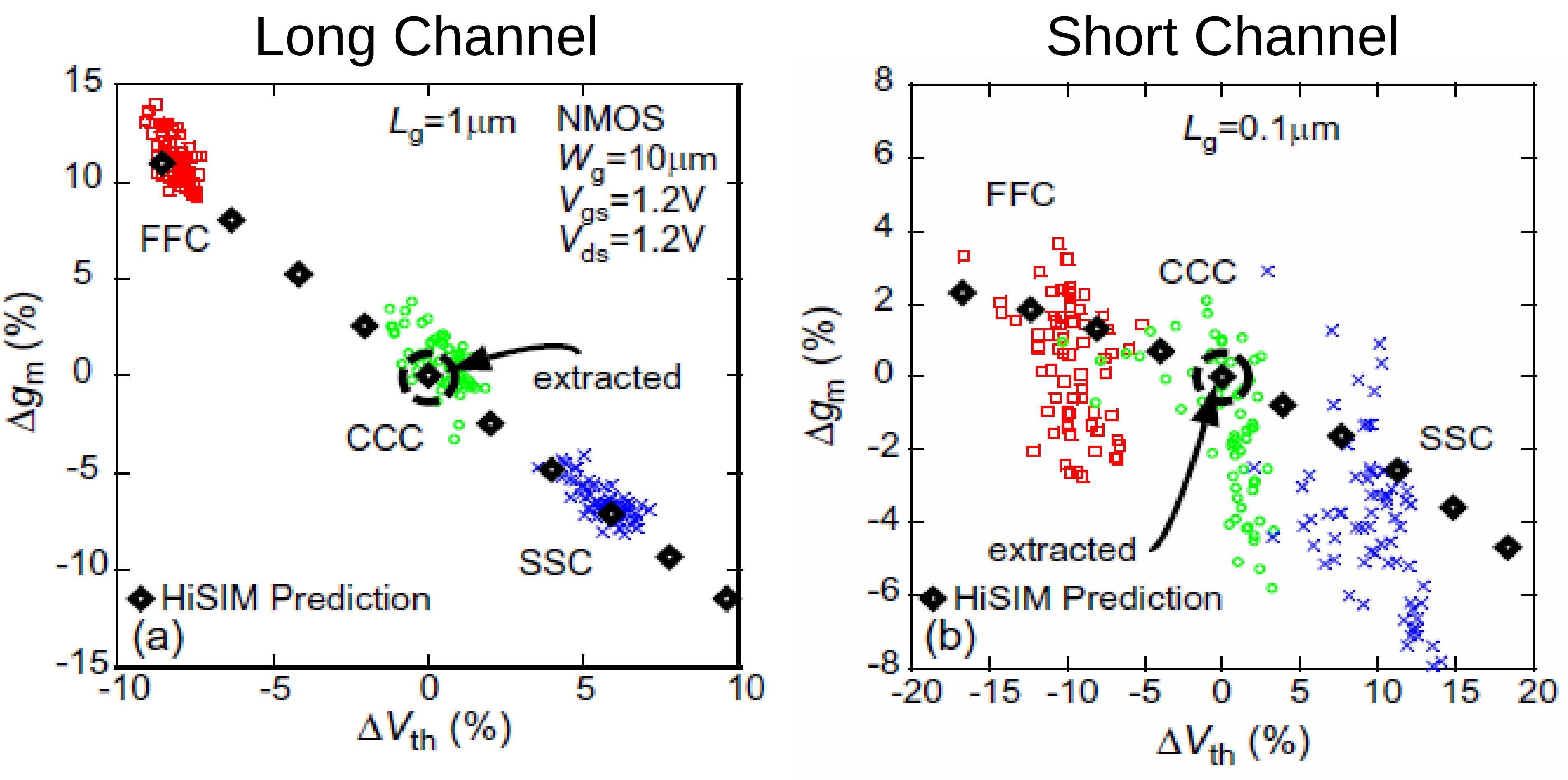
Inter-Wafer Variation Prediction



Data: HiSIM231

Prediction of inter-wafer variation for Ion, Vth possible

Inter-Wafer Variation Prediction: g_m

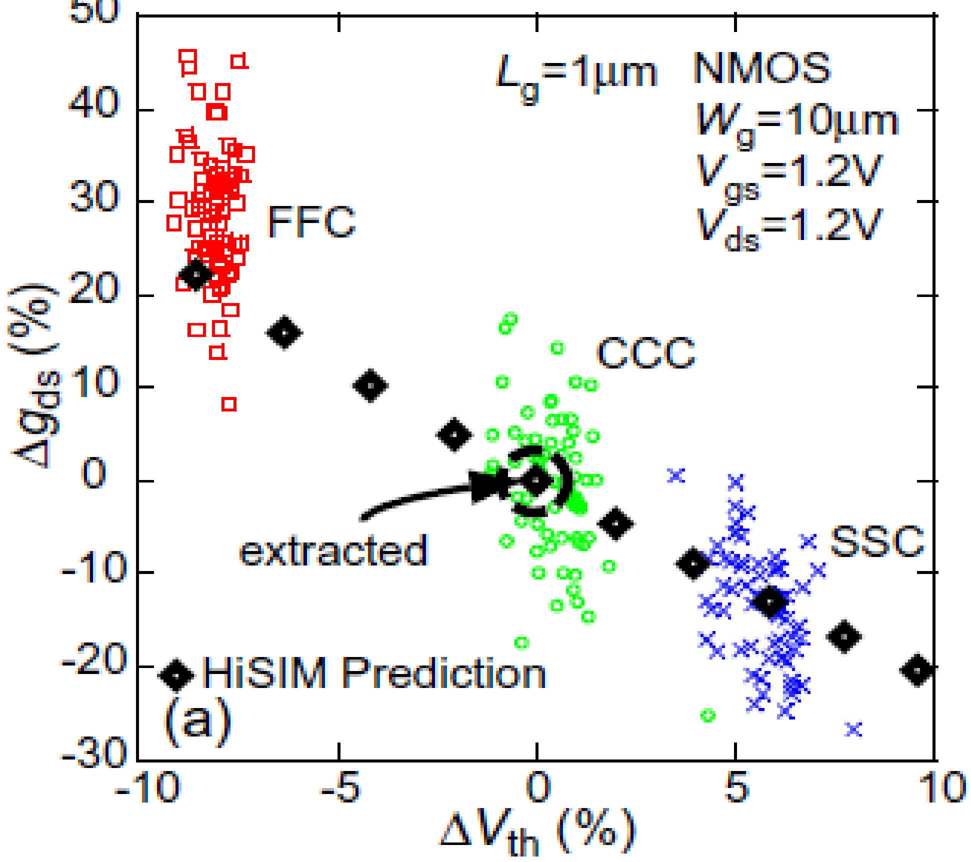


Data: HiSIM231

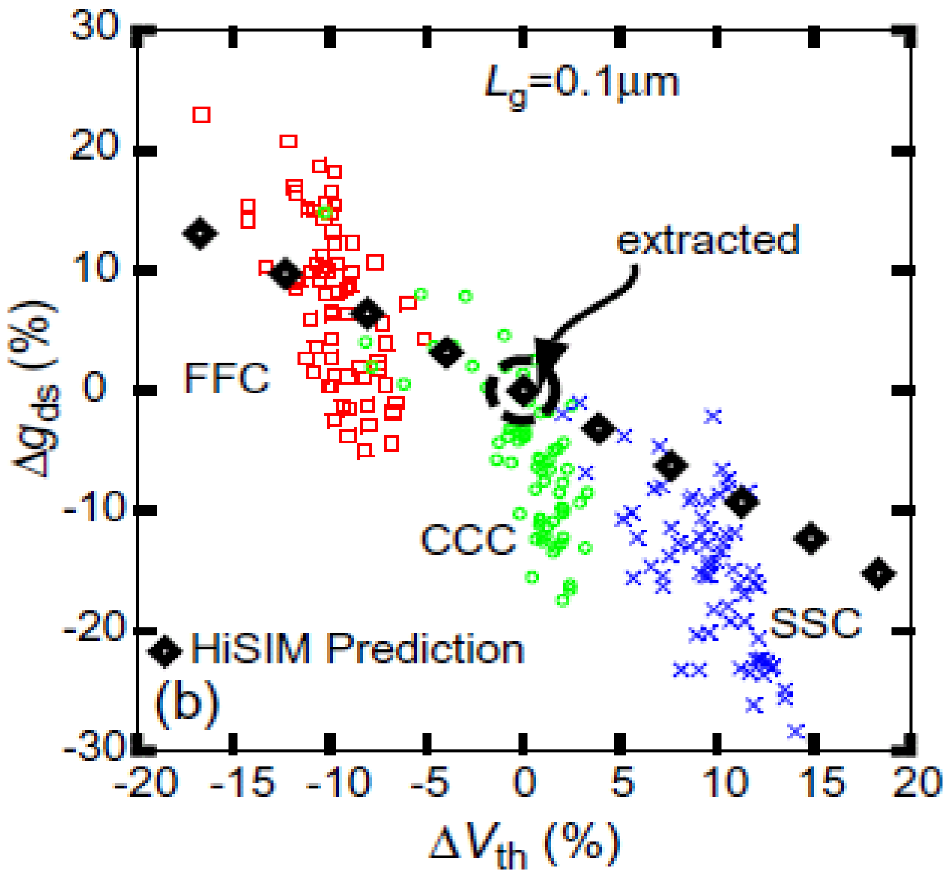
Variation predictability is good even for derivatives

Inter-Wafer Variation Prediction: g_{ds}

Long Channel



Short Channel

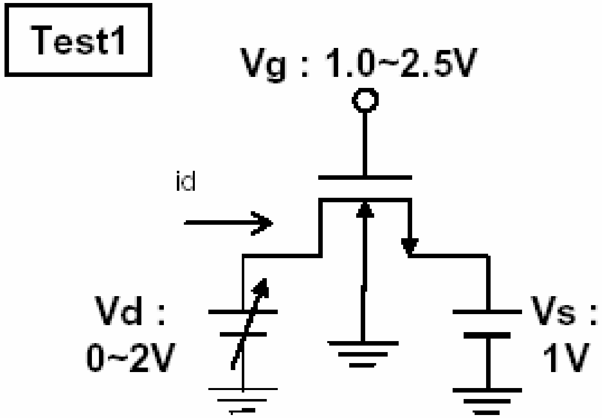


Data: HiSIM231

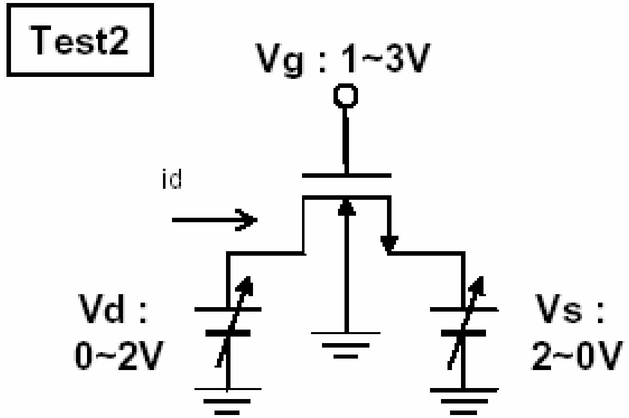
Variation predictability is good even for derivatives

Evaluation of Derivative Characteristics

- Model : BSIM3v3, HiSIM2.3.1
- Device : 0.25um NMOS(Low Vth) W/L = 8um / 4um
- Condition :
  - Test1
    vd=0~2V(0.02V step), vg=1.0~2.5V(0.25V step), vs=1V, vb=0V
  - Test2
    vd=0~2V(0.02V step),vg=1~3V(0.5V step),vs=2~0V(vd synchronous),vb=0V



Vd=0~1V : Source
Vd=1~2V : Drain



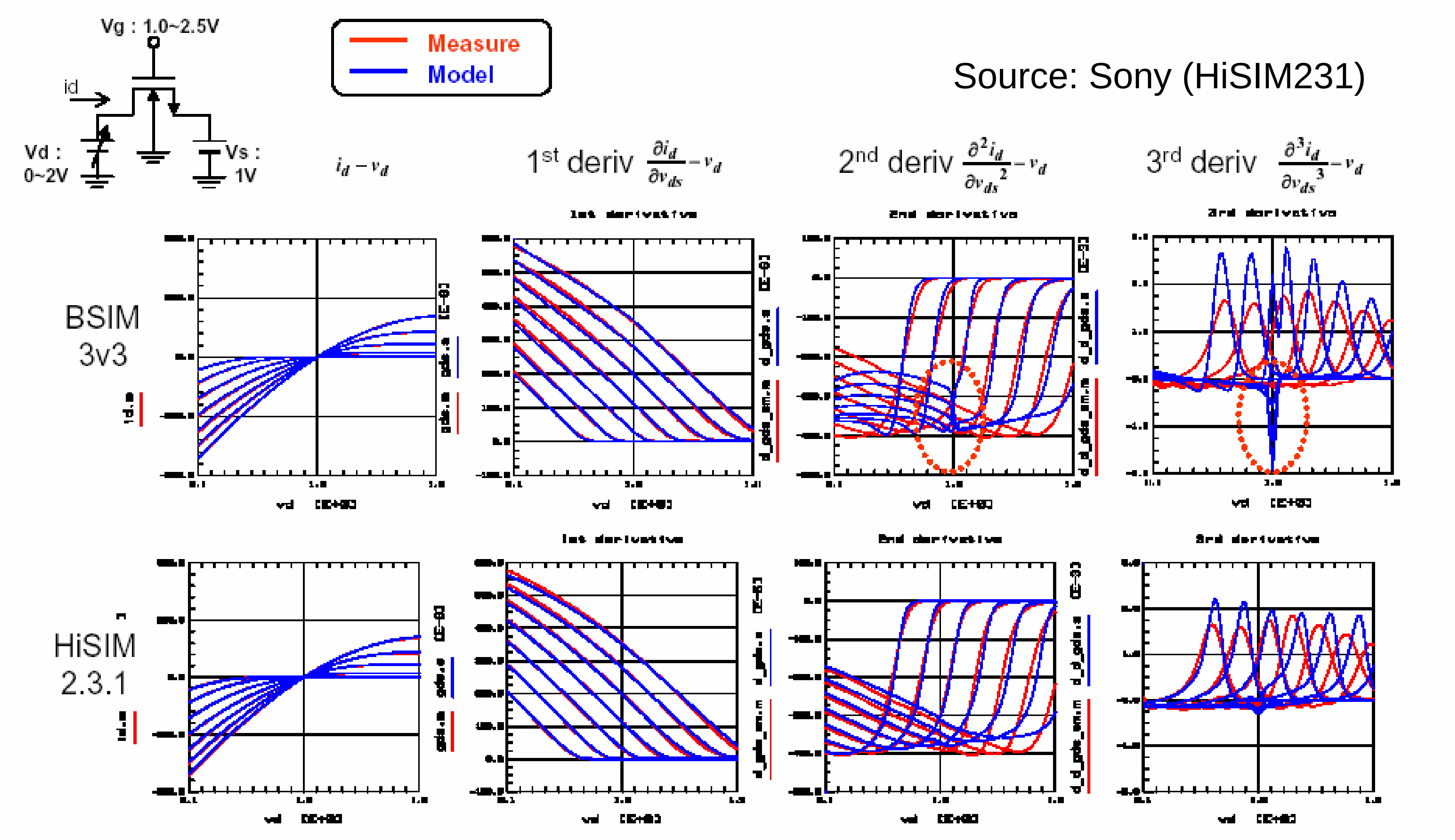
Vd=0~1V : Source
Vd=1~2V : Drain

Vs=2~1V : Drain
Vs=1~0V : Source

Source: Sony (HiSIM231)

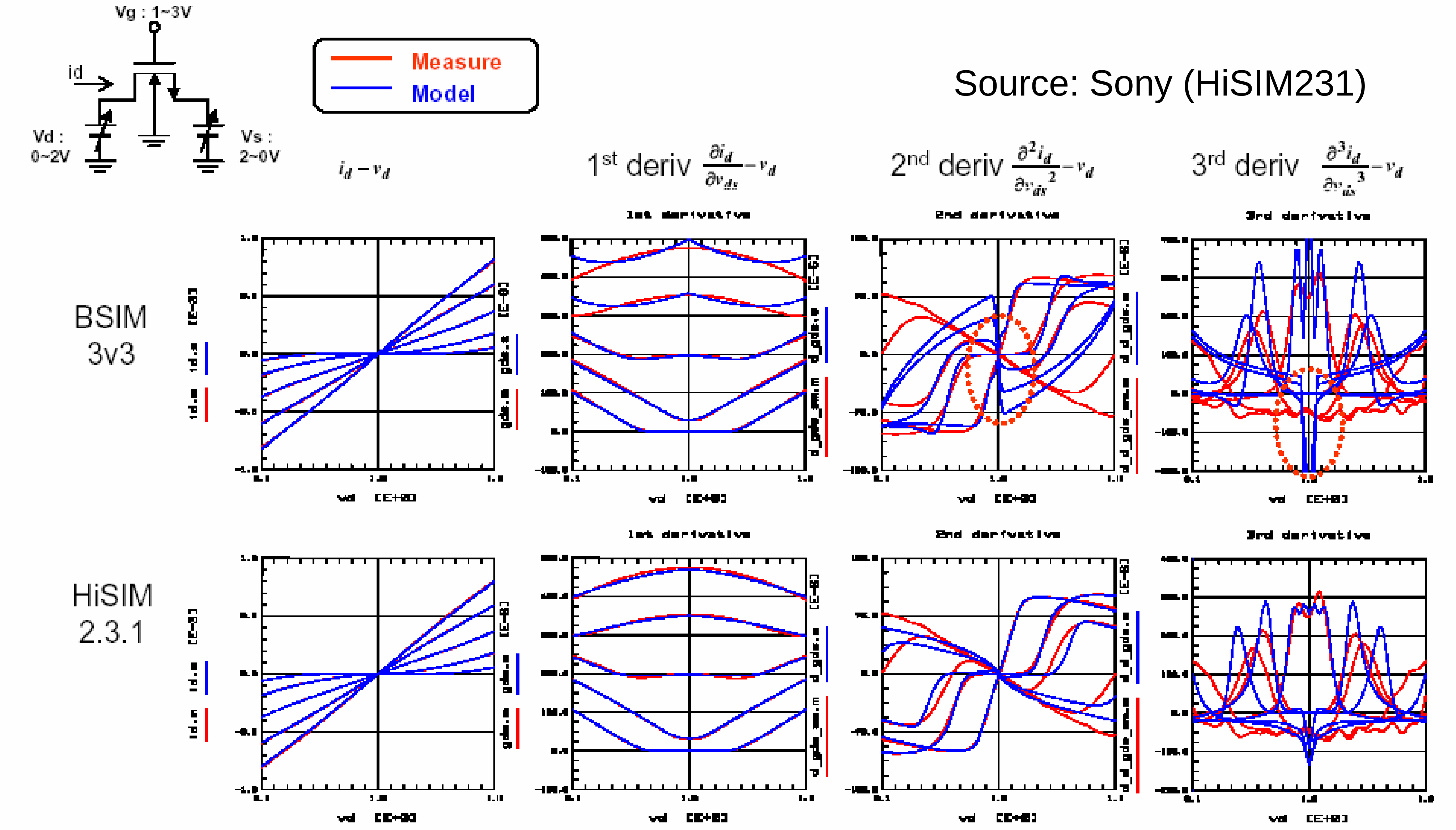
Derivatives at Elevated Bias

Source: Sony (HiSIM231)



HiSIM2.3.1 is in excellent agreement with measurement

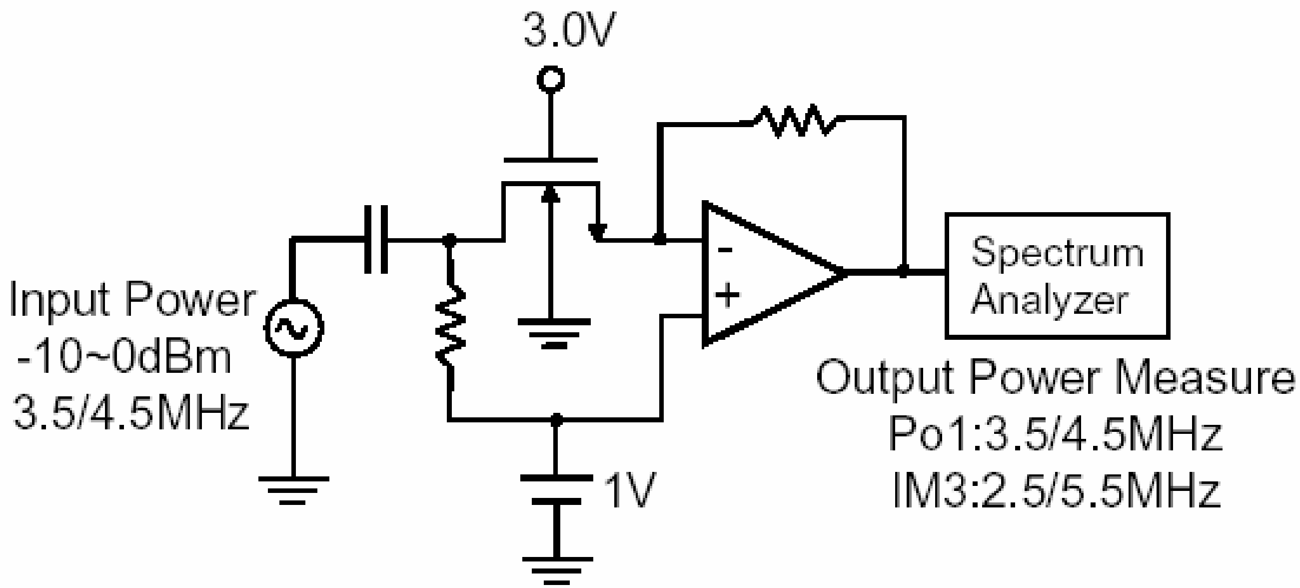
Derivatives for Source-Drain Interchange at 0V



HiSIM2.3.1 is in excellent agreement with measurement

Evaluation of IM3 Characteristics (250nm CMOS)

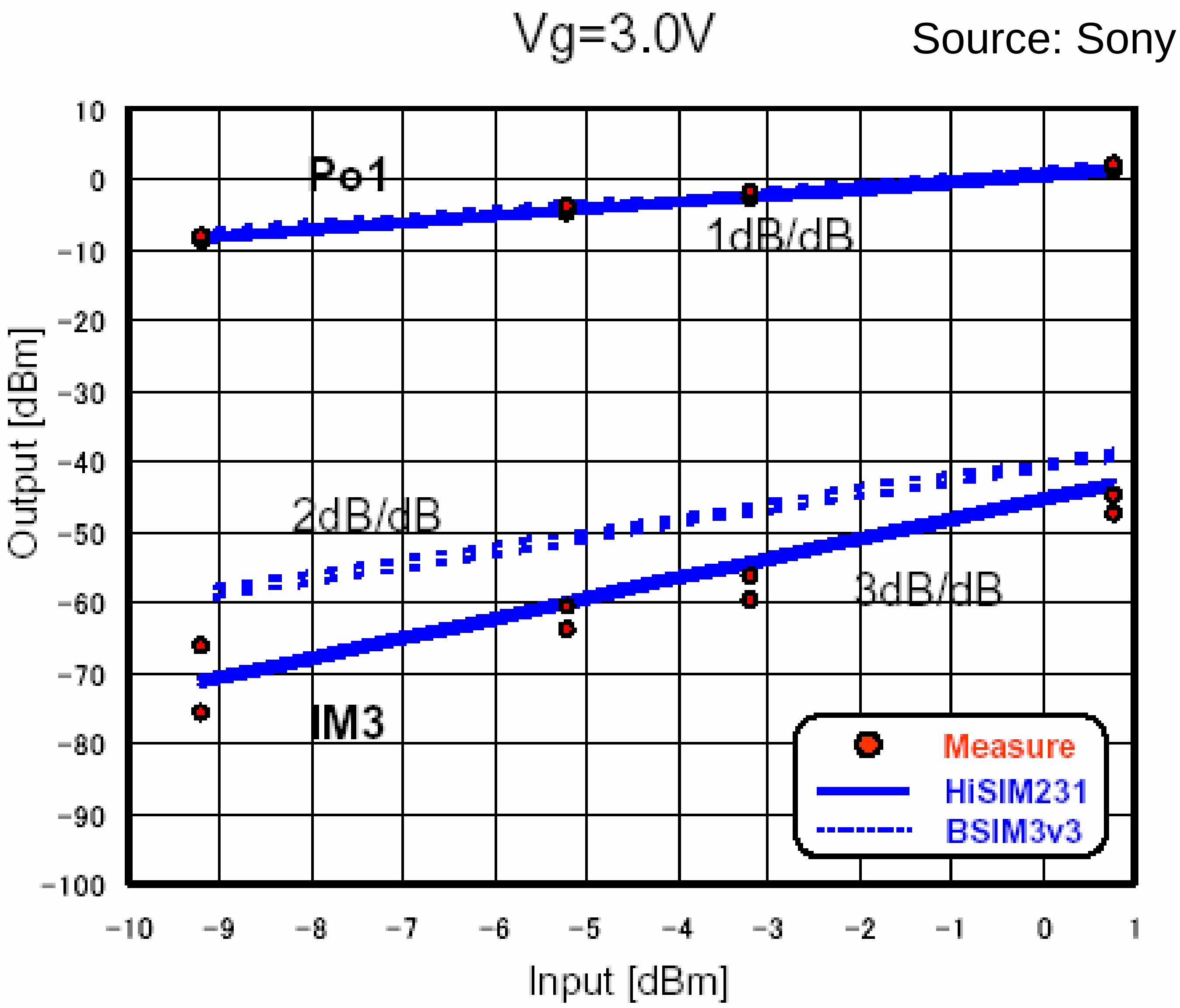
- Model : BSIM3v3, HiSIM2.3.1
- Device : 0.25um NMOS(Low Vth)   W/L = 8um / 4um
- Conditions :
  - Input : 3.5/4.5MHz 2-tone, Output : Po1 3.5/4.5MHz, IM3 : 2.5/5.5MHz
  - Simulation : Spectre-RF PSS Analysis



Source: Sony (HiSIM231)

IM3 Simulation in Comparison to Measurement

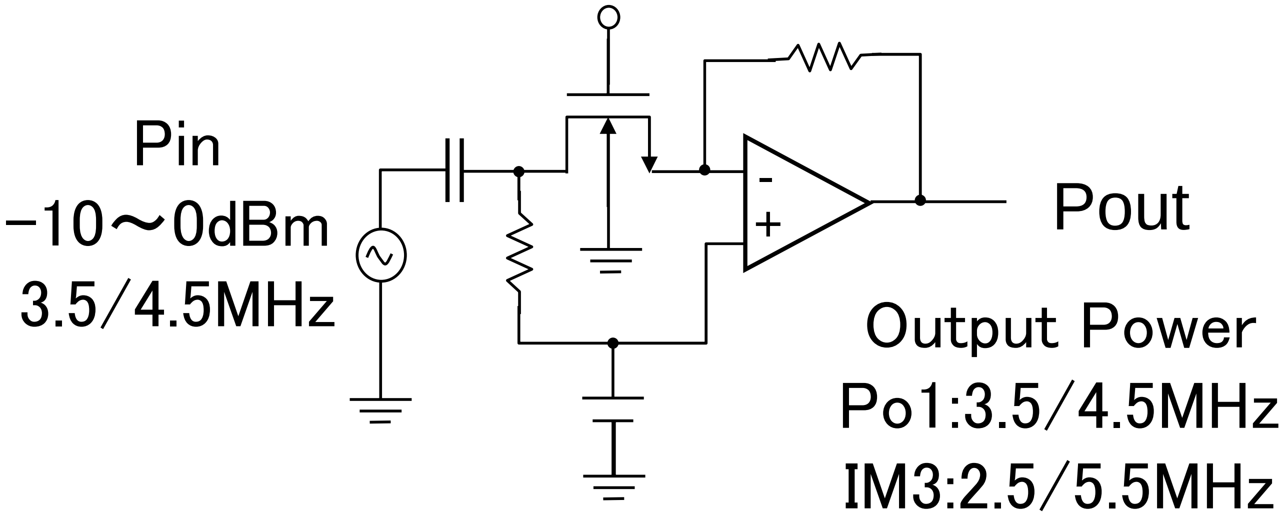
Source: Sony (HiSIM231)

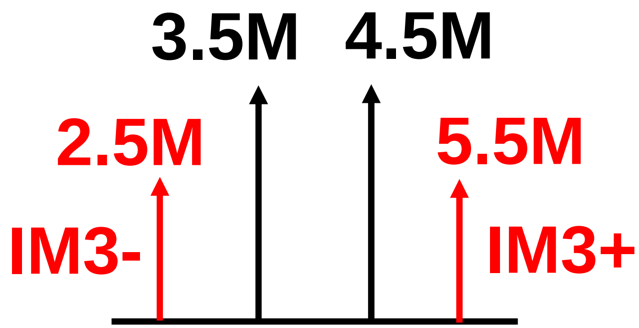


Accurate reproduction of IM3 measurements with HiSIM

Evaluation of IM3 Characteristics (90nm CMOS)

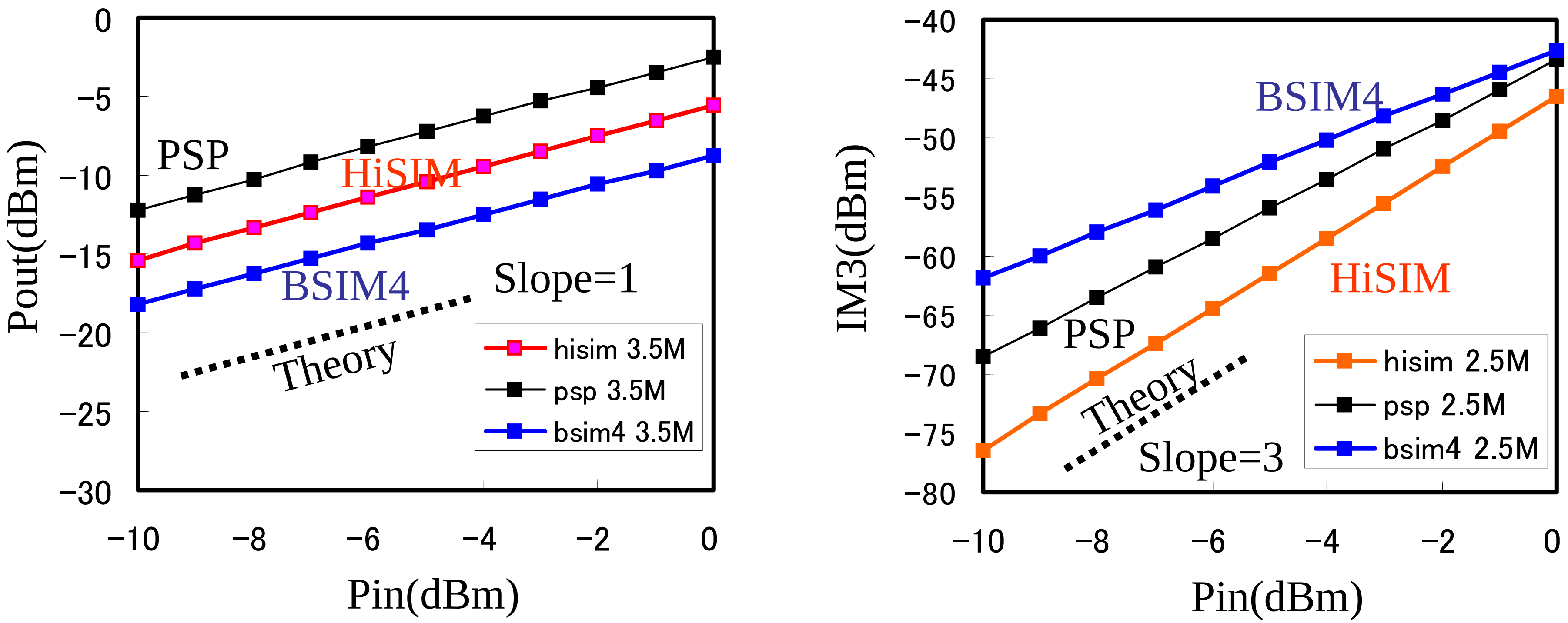
- Model：BSIM4, HiSIM2.3.1, PSP102
- Device：90nm technology, NMOS transistor, W/L = 8um / 4um
- Simulation condition
  - Input：3.5/4.5MHz 2-tone, Output：Po1 3.5/4.5MHz, IM3：2.5/5.5MHz
  - Simulation： PSS analysis of Spectre-RF





Source: Toshiba

IM3 Results for BSIM4, PSP102 and HiSIM2.3.1



Slope in IM3 Analysis (90nm CMOS)

BSIM4 : 2.0 (in large disagreement with theory)

PSP102 : 2.7 (in improved agreement with the theory)

HiSIM2.3 : 3 (in perfect agreement with the theory)

Source: Toshiba

1/f-Noise Evaluation

1/f noise model of BSIM model

$$FN = \frac{q^2 V_{tm} I_{ds}}{C_{ox} L_{eff}^2 f^{EF} \times 10^8} \left\{ Noia \times \log\left(\frac{N_0 + 2\times 10^{14}}{N_l + 2\times 10^{14}} \right) + Noib (N_0 - N_l) + \frac{Noic}{2} (N_0^2 - N_l^2) \right\}$$

$$+ \frac{V_{tm} I_{ds} \Delta L_{clm}}{W_{eff} L_{eff}^2 f^{EF} \times 10^8} \times \frac{Noia + Noib \times N_l + Noic \times N_l^2}{(N_l + 2\times 10^{14})^2}$$

1/f noise model of HiSIM model

Very simple equation and high accuracy

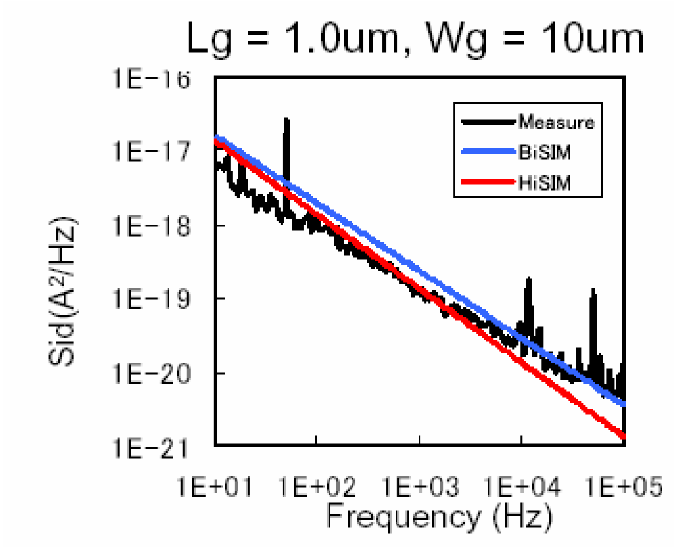
Mobility fluctuation

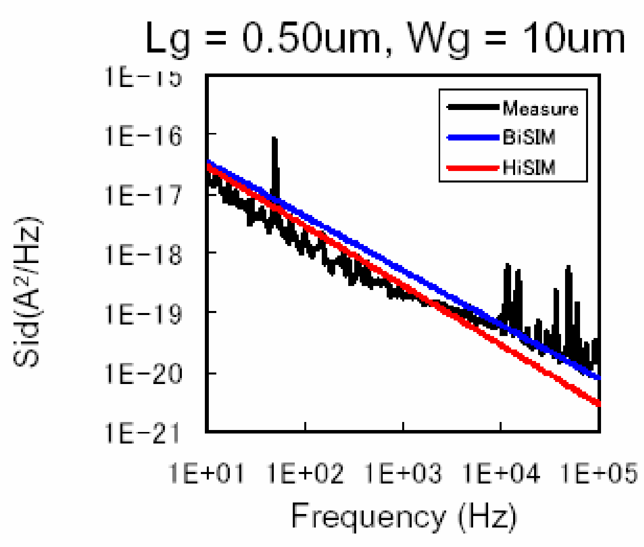
Trap density

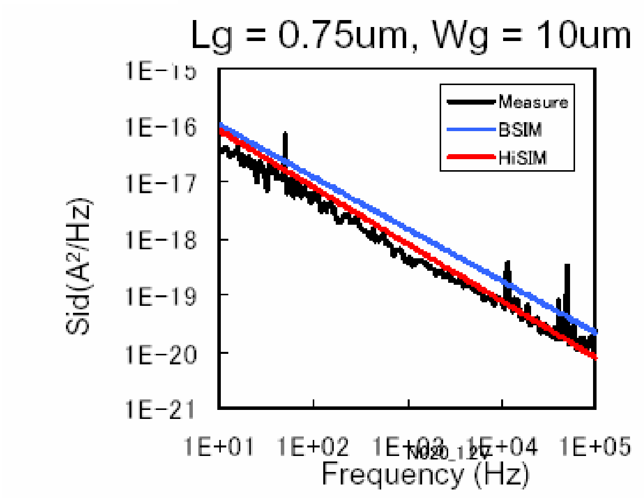
$$S_{I_{ds}} = \frac{I_{ds}^2 NFTRP}{\beta f (L_{eff} - \Delta L) W_{eff}} \left[\frac{1}{(N_0 + N^*)(N_L + N^*)} + \frac{2\mu E\, NFALP}{N_L - N_0} \ln\left(\frac{N_L + N^*}{N_0 + N^*}\right) + (\mu E\, NFALP)^2 \right]$$

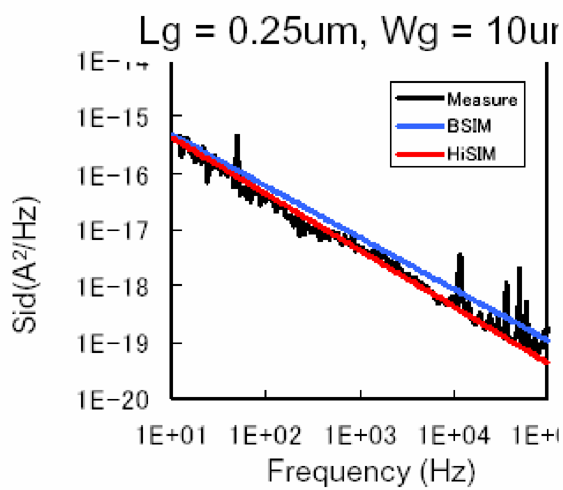
Source: Toshiba

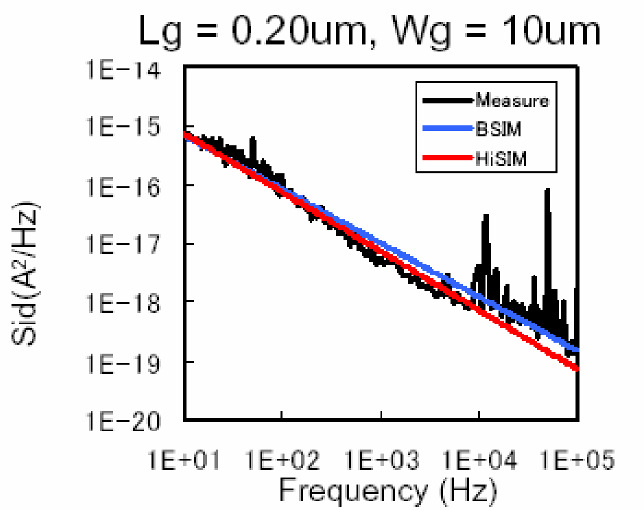
Simulation Results Compared with Measurements











Source: Toshiba (HiSIM2.3.1)

HiSIM2.3.1 accurately reproduces 1/f measurements

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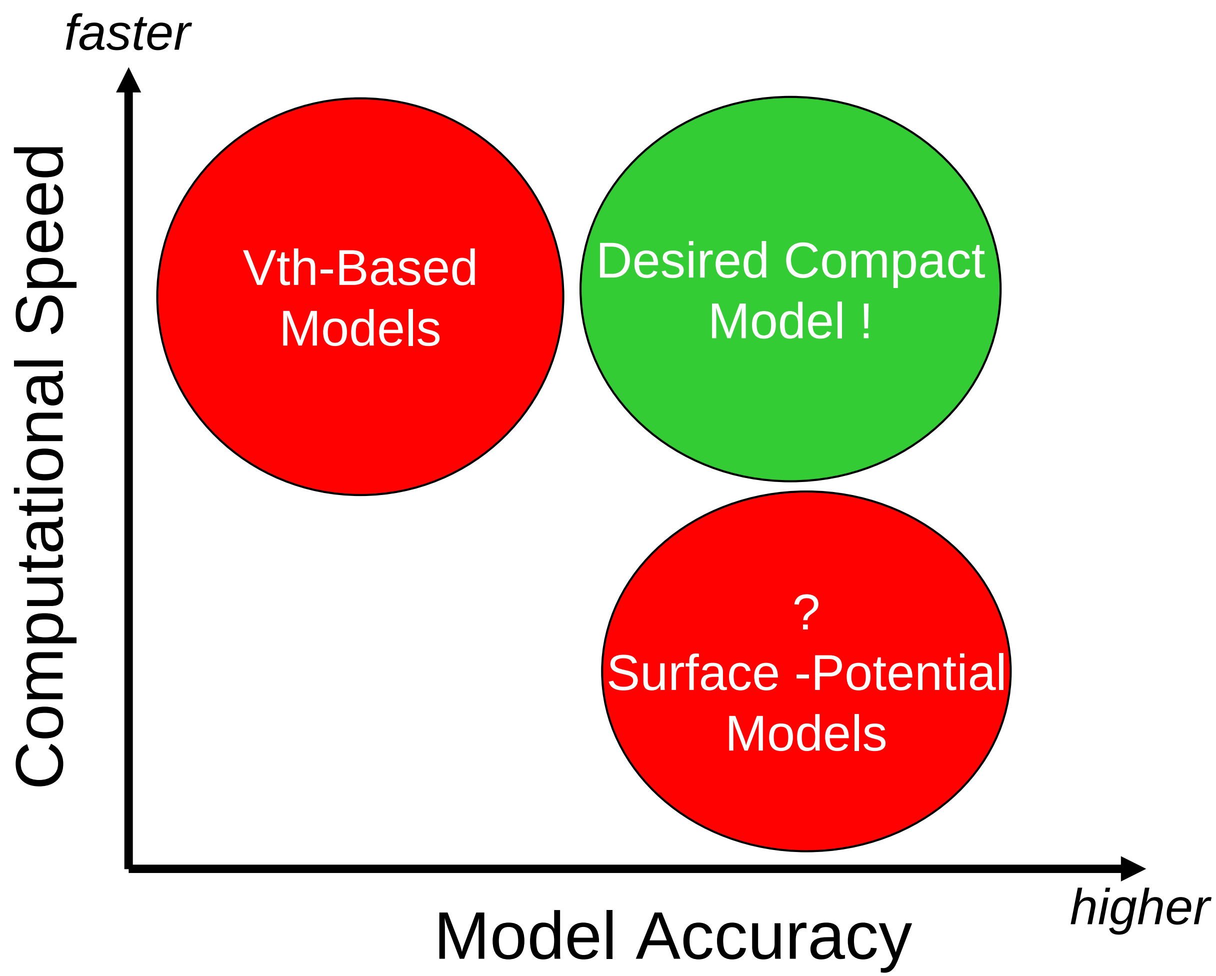
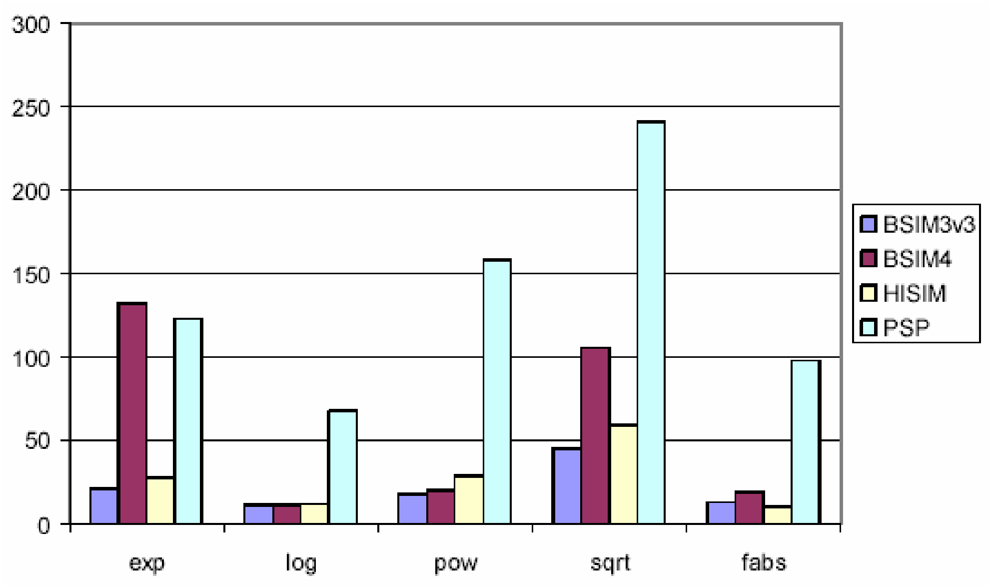
Speed versus Accuracy Trade-Off

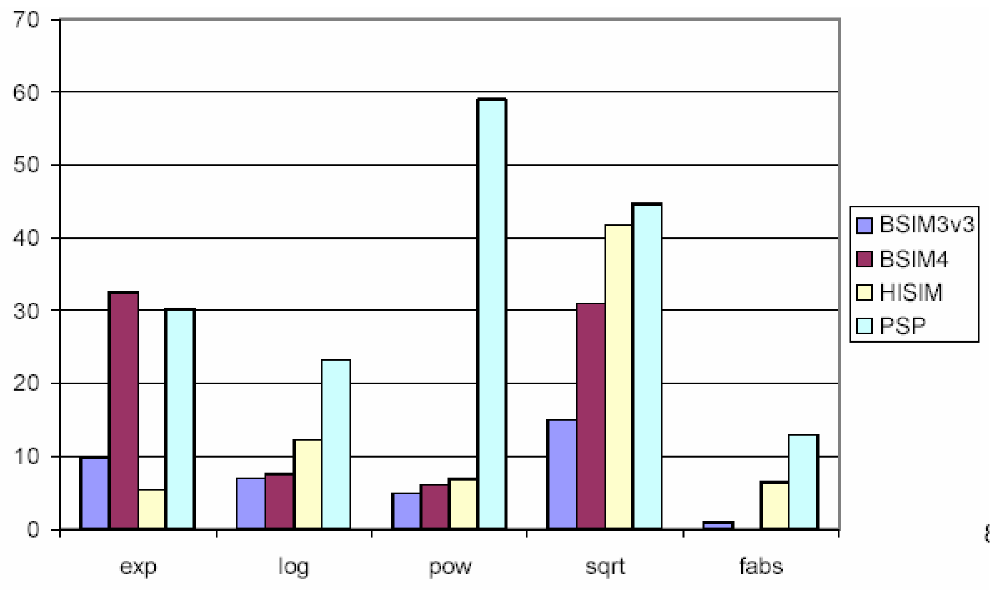


Is it possible to combine high speed and high accuracy to obtain an “ideal” MOSFET model ?

High Cost Functions in the Source Code



Static Count of High Cost Functions
(Complete Source Code)

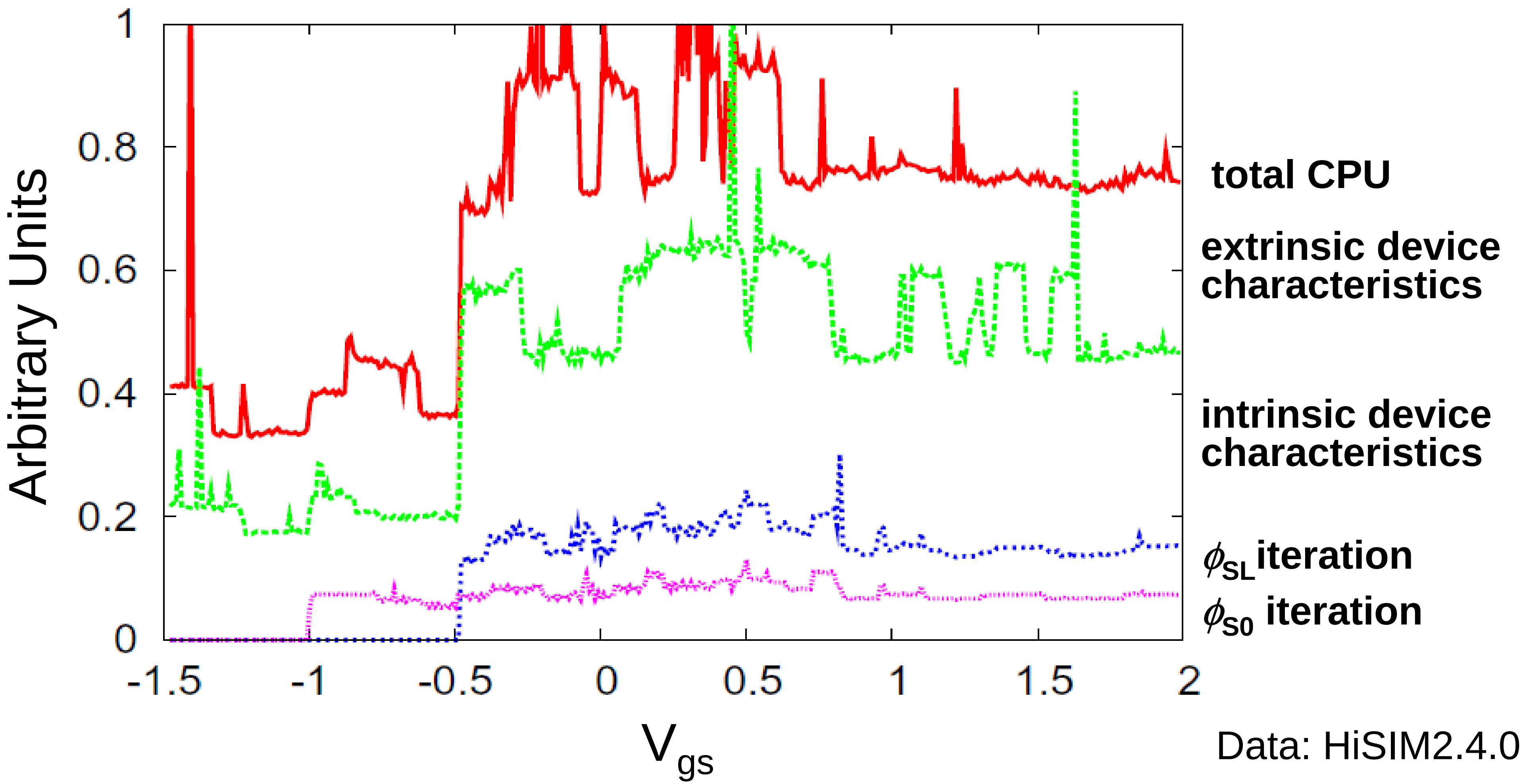


Dynamic Count of High Cost Functions
(average of 9 different bias conditions)

Data Source: Silvaco, Oct. 2005

The number of high-cost functions in the HiSIM2 source code is not larger than for advanced Vth-based models.

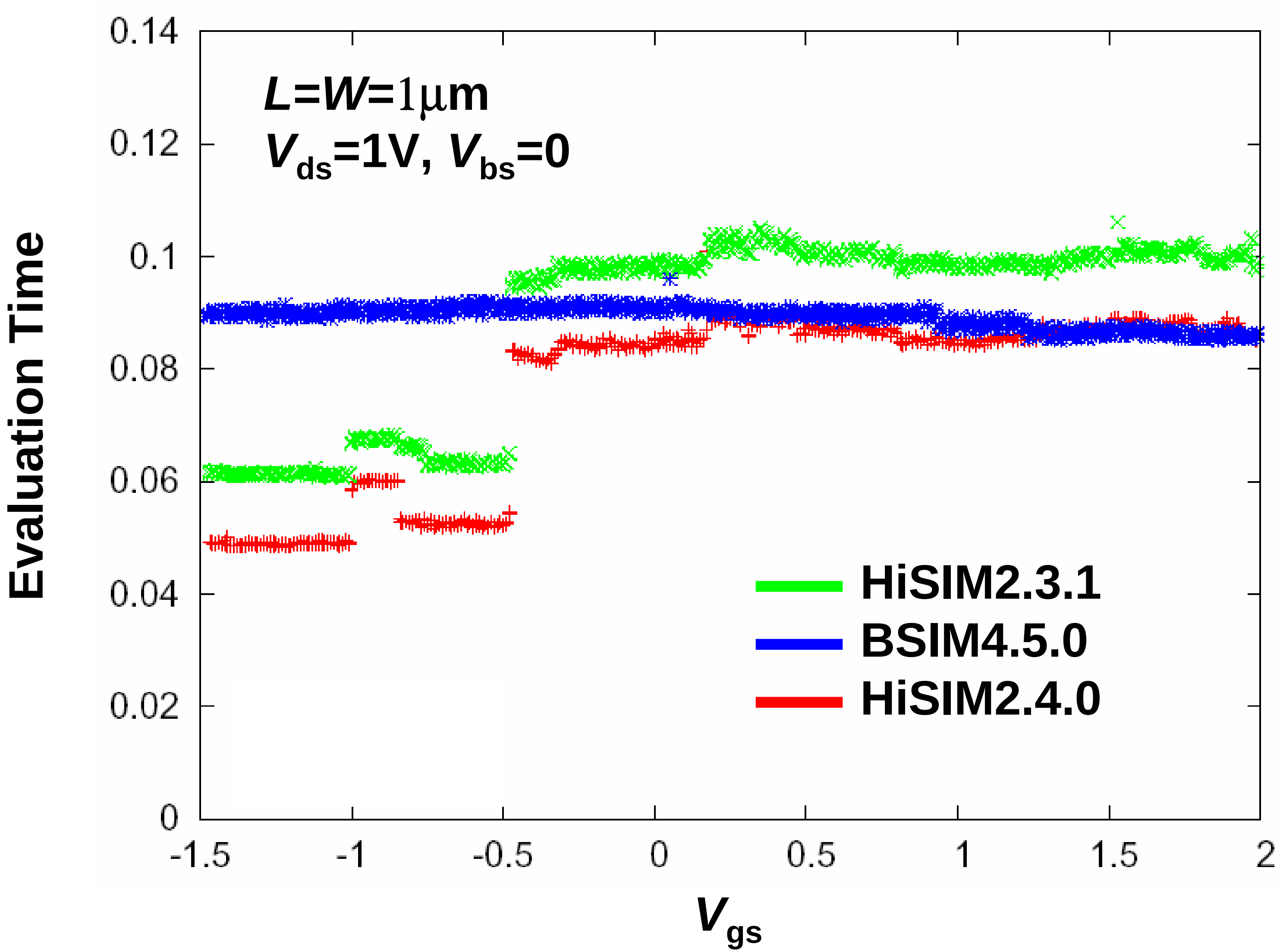
Breakdown of HiSIM's Model Evaluation Time



Data: HiSIM2.4.0

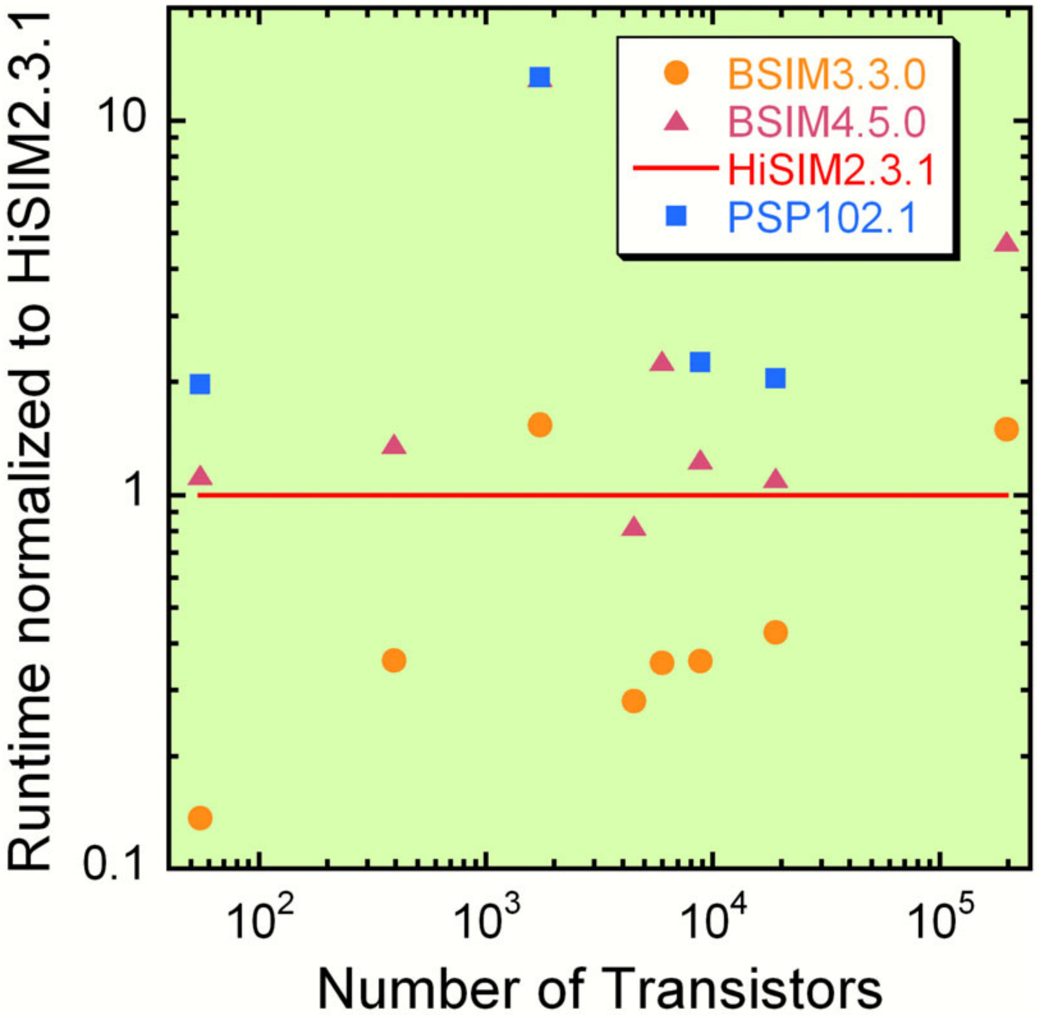
Iteration for surface-potential determination requires only a small fraction of the total model evaluation time.

Model Evaluation Time Comparison



Model evaluation time of HiSIM2.4.0 is 20% improved and shorter than BSIM4.5.0.

Runtime Comparison of Compact Models



<u>Simulated Circuit Types:</u>

(90nm CMOS, productively used circuits)
ADC, Active Driver, PLL, I/O Module, VCO, DLL, Parity Checker, MUX Buffer

<u>Simulator:</u>

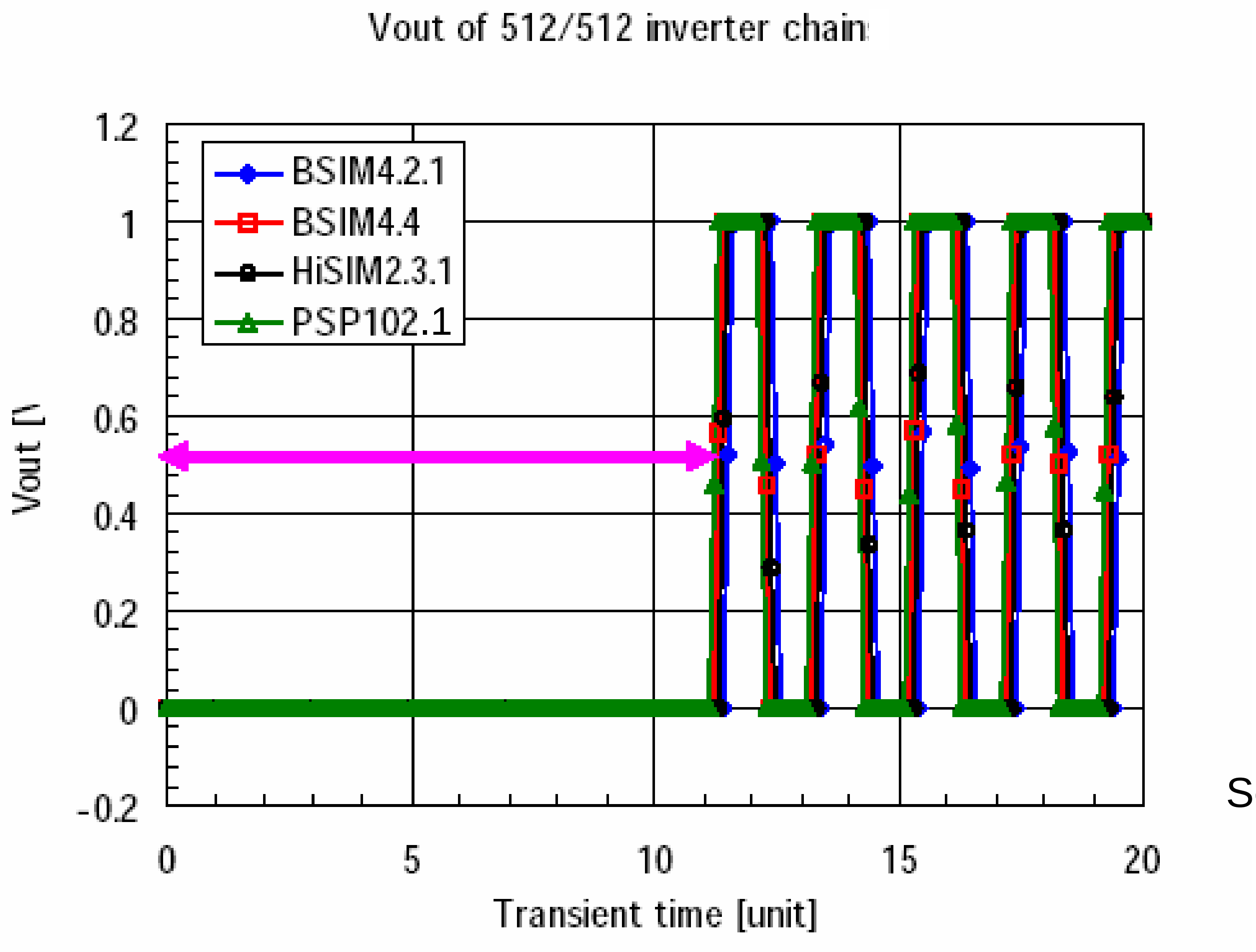
SmartSpice 64bit, Version 3.3.0B

<u>Data Source:</u>

Simucad, Dec. 2006

HiSIM2 executes faster than non-iterative surface-potential models as well as the latest Vth-based models.

Runtime of Inverter Chains with Different Length

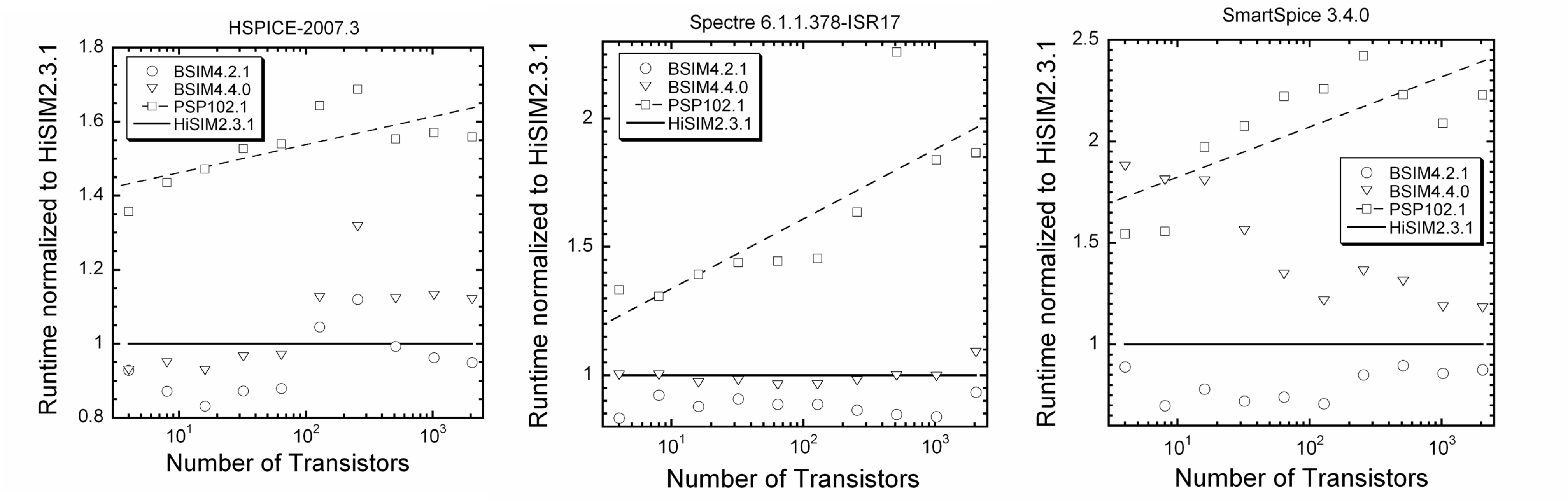


Source: NEC

Propagation delay times are equalized for all models.

Runtime Comparison in 3 Different Simulators

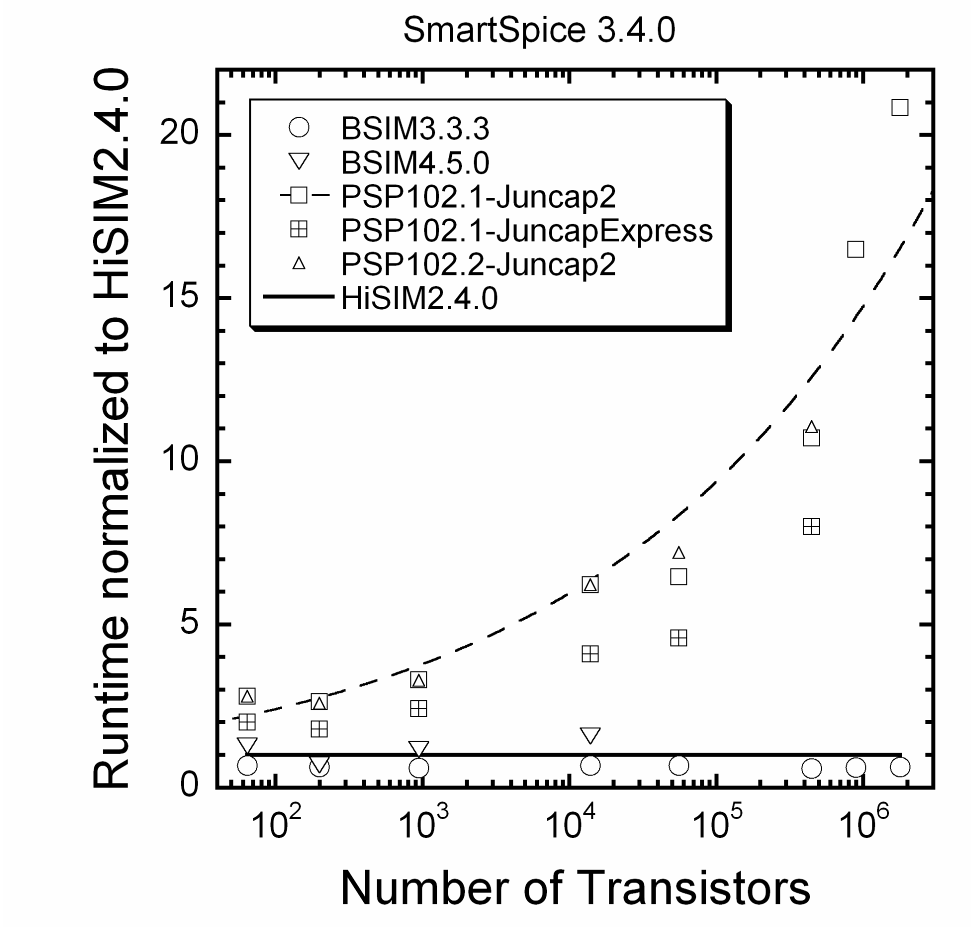
Inverter chains with up to 2024 transistors

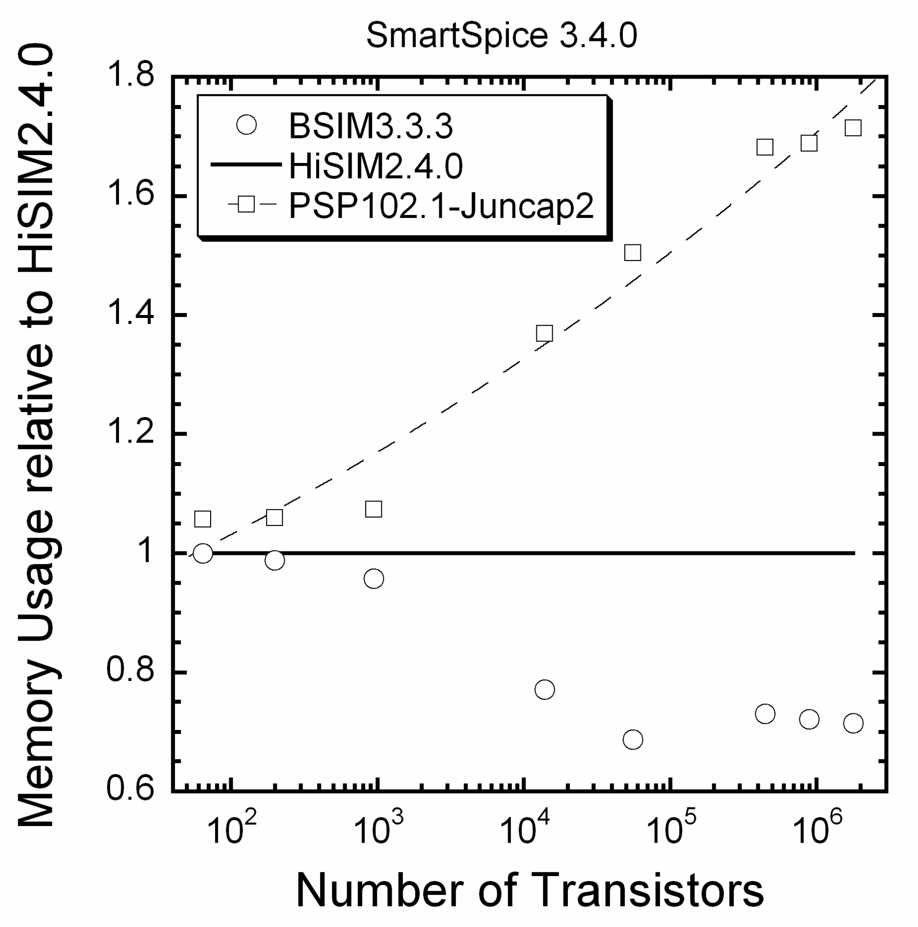


Source: NEC

HiSIM2.3.1 computational runtimes are comparable to BSIM4. The relative runtimes of PSP102.1 consistently increase as a function of the transistor number.

Computational Performance for Large Circuits





Source: Simucad

HiSIM2.4.0 is faster than BSIM4.5.0 and has comparable memory consumption. PSP runtimes increase strongly above 50K transistors.

Large RF Circuit Simulation Performance

- Ran on Opteron with 8 2.8GHz CPU and RH.4 OS
- FineSim Spice v2007.03.01

GHz PLL Pre-Layout
MOSFET – 3k
Resistor – 0.05k
Capacitor – 0.7k
Vsource - 0.02k
Fvco=M/N X Fref=GHz
Tran: 100us,
TYP 1.0v, 25C

MOS Model	Relative Runtime Pre-Layout
BSIM 4.21	**1.28**
HiSIM 231	**1**

GHz PLL Post-Layout
MOSFET - 4k
Resistor - 150k
Capacitor – 60k
Vsource - 0.02k
Fvco=M/N X Fref=GHz
Tran: 100us,
TYP 1.0v, 25C

MOS Model	Relative Runtime Post-Layout
BSIM 4.21	**1.66**
HiSIM 231	**1**

Source: Magma

Conclusion

- HiSIM2.3.1 and 2.4.0 are a highly accurate MOSFET model based on the full iterative surface-potential concept.
- HiSIM2.3.1 and 2.4.0 have no runtime disadvantage in comparison to surface-potential models using a non-iterative approximation, but rather an advantage.
- HiSIM2.3.1 and 2.4.0 have even shorter computer runtime than the most advanced Vth-based models.

HiSIM2 (Versions 231 and 240) is a compact MOSFET model concept with optimized accuracy/speed trade-off