

HiSIM2.4.0: Advanced MOSFET Model for 45nm Technology Node and Beyond

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M. Miura-Mattausch, N. Sadachika, M. Miyake, D. Navarro, T. Ezaki, H. J. Mattausch
*T. Ohguro, *T. Iizuka, *M. Taguchi, *S. Miyamoto, *R. Inagaki, *Y. Furui
*N. Fudanuki, **T. Yoshida

Hiroshima University, Hiroshima

*STARC, Yokohama

**NIS, Kawasaki

HiSIM: Hiroshima-university STARC IGFET Model

| | | |
|-------------------|-----------------------|---|
| 1990 JJAP | Sub-1 μ m MOSFETs | short-channel effect model |
| 1991 SISPAD | “ | 1 st 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 | |

Basic Device Equations

-Poisson:

$$\nabla^2 \phi = -\frac{q}{\epsilon_{Si}} (N_D - N_A + p - n)$$

$$n = n_i \exp \frac{q(\phi - \phi_n)}{kT}$$

$$p = n_i \exp \frac{q(\phi_p - \phi)}{kT}$$

-Current Density:

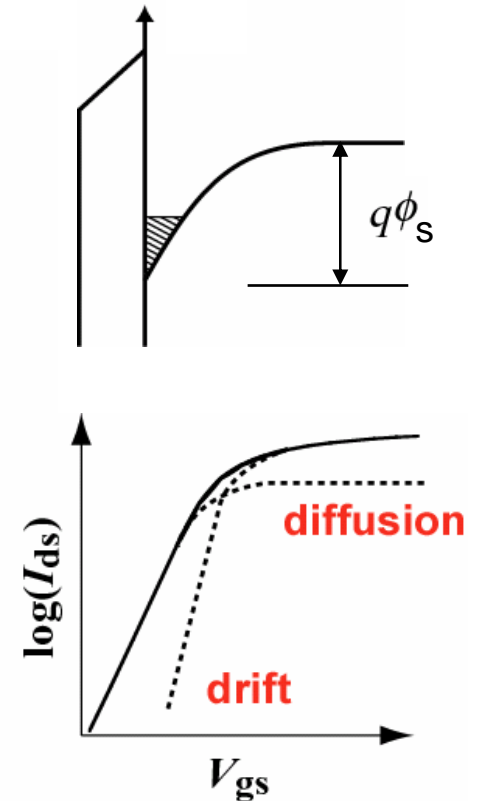
$$j_n = q\mu_n n \frac{\phi}{y} + qD_n \nabla n$$

$$j_p = q\mu_p p \frac{\phi}{y} - qD_p \nabla p$$

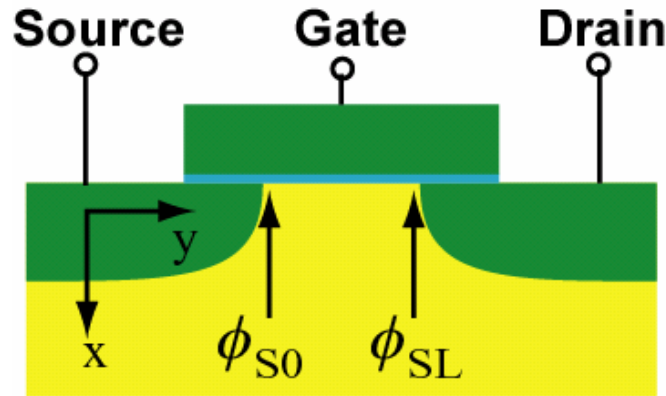
-Continuity:

$$I(t) = I_0(t) + \frac{dQ}{dt}$$

(solved by SPICE)

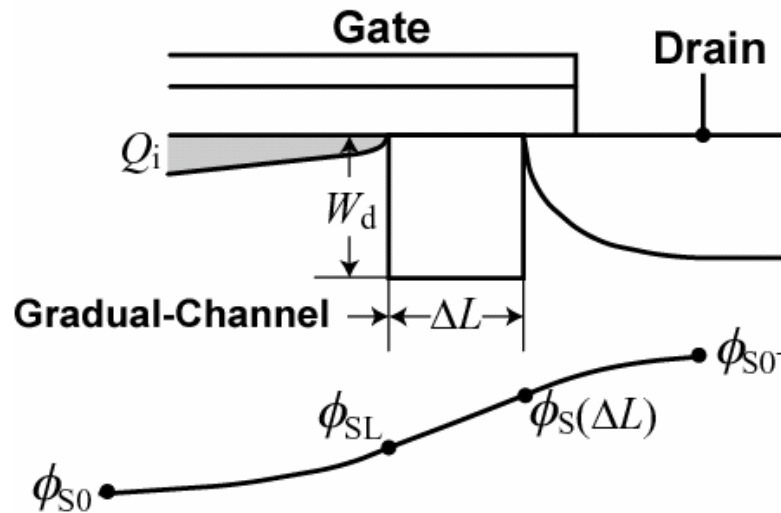


Surface Potentials



ϕ_{S0} : at source side
 ϕ_{SL} : at drain side
 (end of the gradual-channel approx.)

beyond the gradual-channel approximation



Channel-Length Modulation
 Overlap Capacitance

Surface Potentials \Rightarrow Measure for All Device Features

Model Extension

HiSIM Family: Based on Complete Surface-Potential Description

HiSIM2: Bulk MOSFET (**Analog, RF Applications**)

HiSIM-LDMOS

HiSIM-SOI: Dynamic Fully \Leftrightarrow Partially Depleted

HiSIM-TFT (March'08)

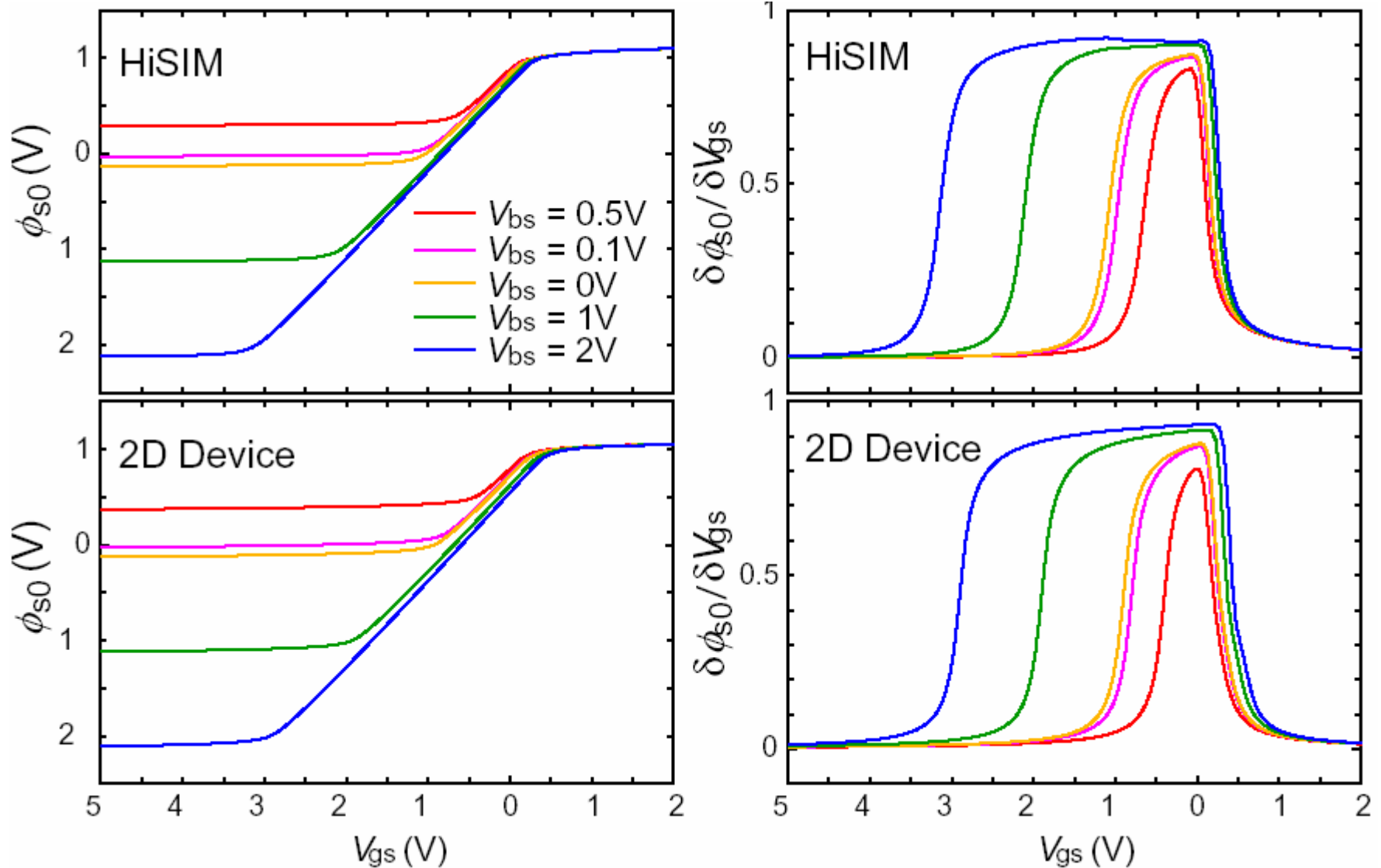
HiSIM-IGBT (March'08)

HiSIM-PD (Photodiode; IEDM'06)

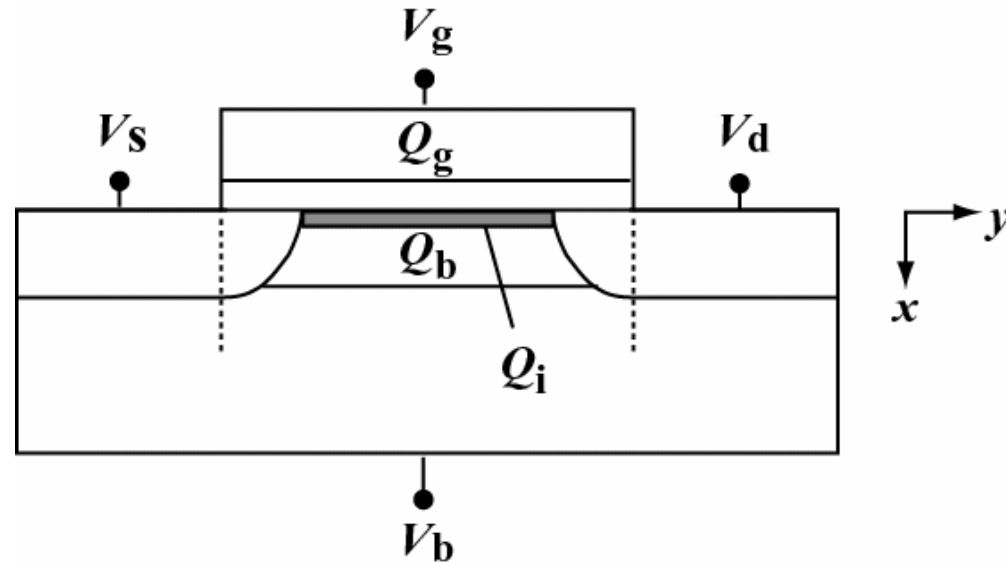
HiSIM-Varactor (SSDM'06)

HiSIM-DG (testing)

Comparison of ϕ_{s0} Values and Their Derivatives



Model Consistency



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



$$Q$$

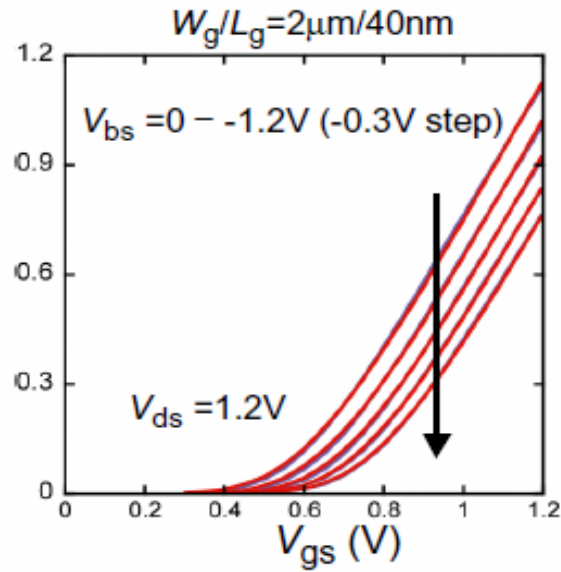
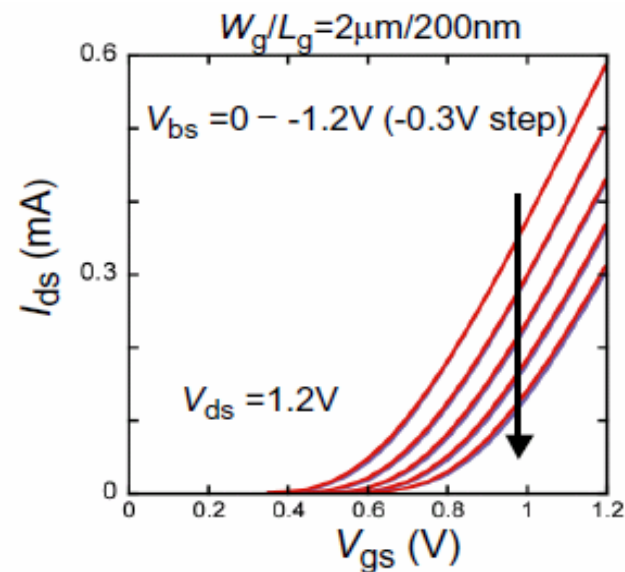


$$C_{jk} \frac{dQ_j}{dV_k}$$

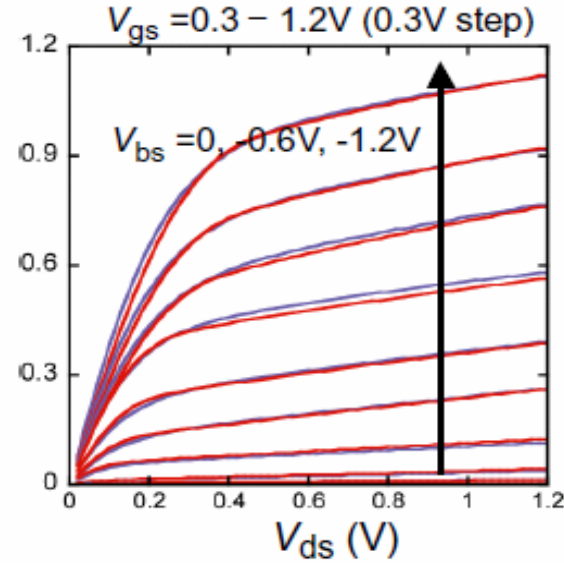
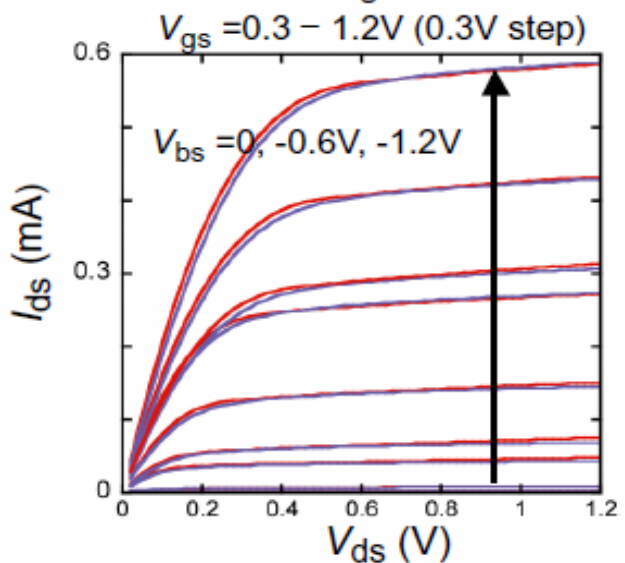
$V = \mu E$: velocity

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

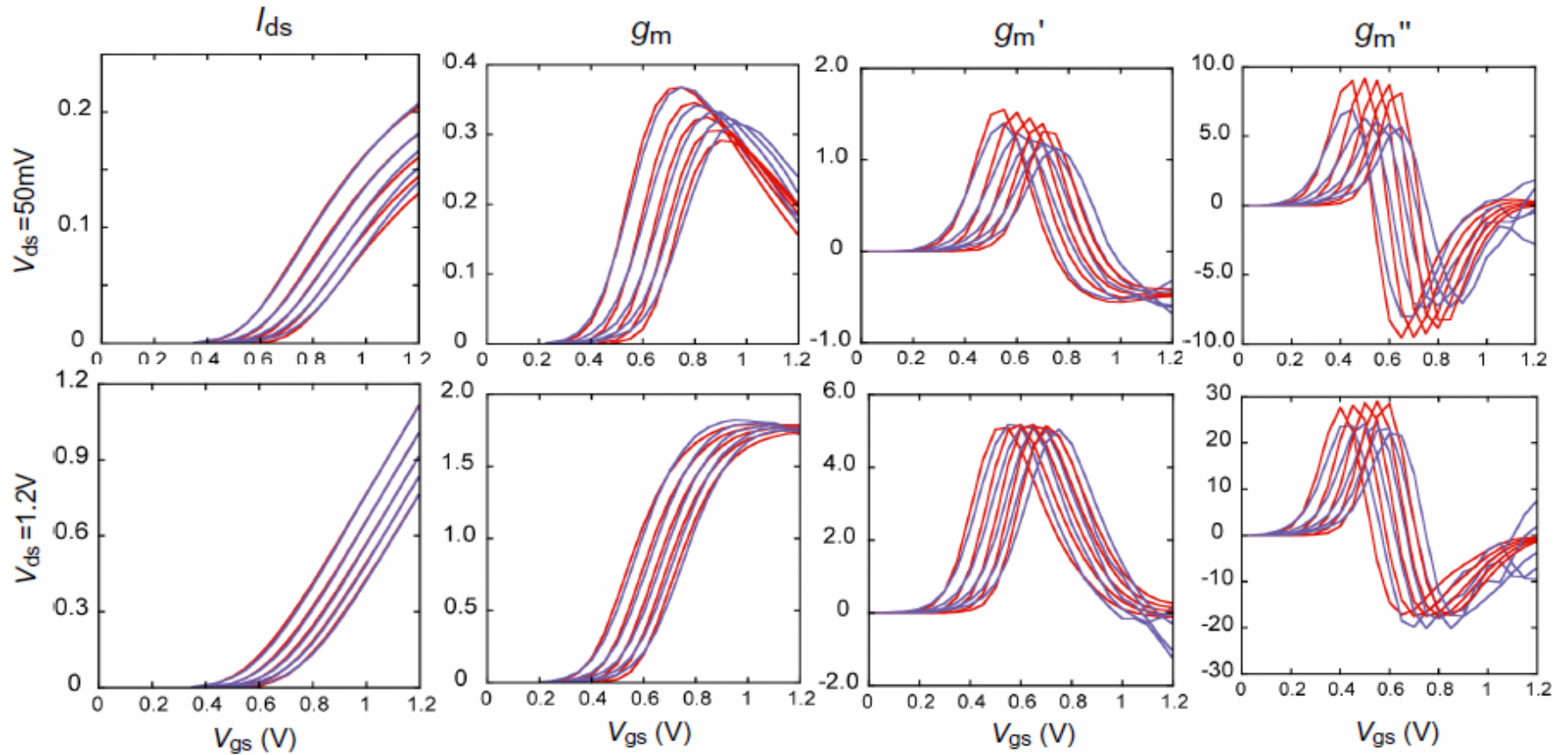
I-V Characteristics



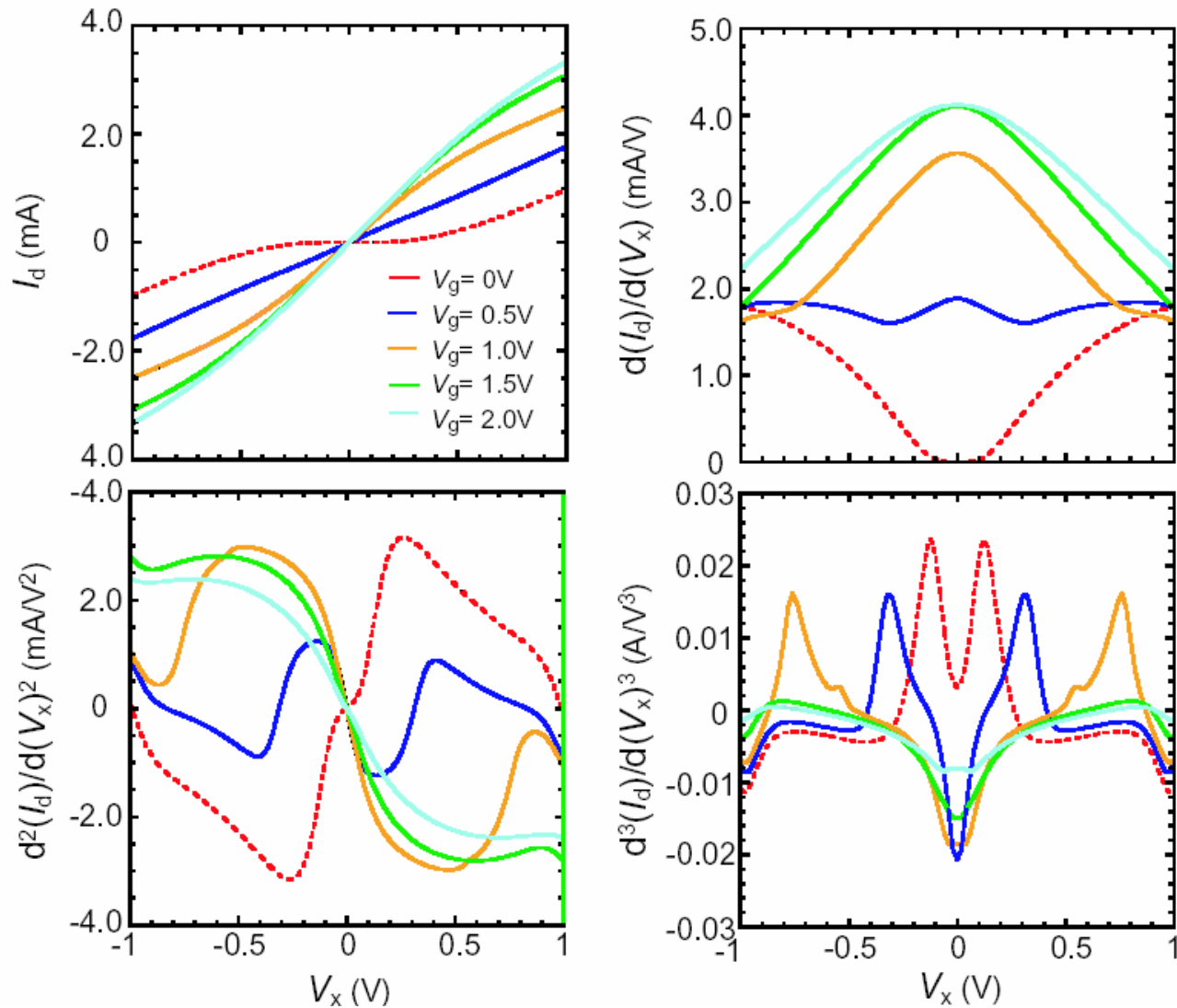
— HiSIM
— Measure.



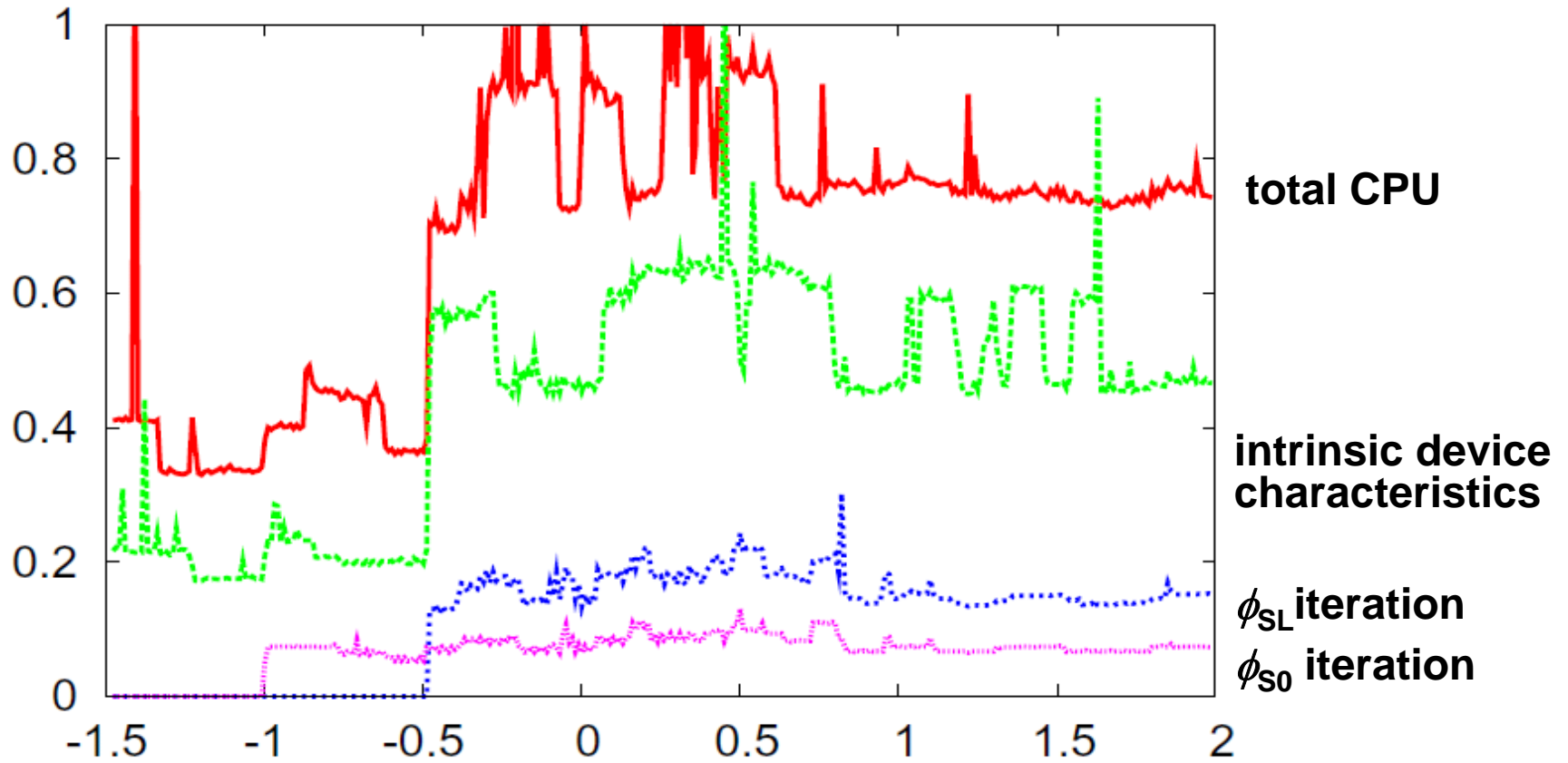
Derivatives



Gummel Symmetry Test



CPU Time Comparison



**How to solve Poisson's Equation:
good initial guess**

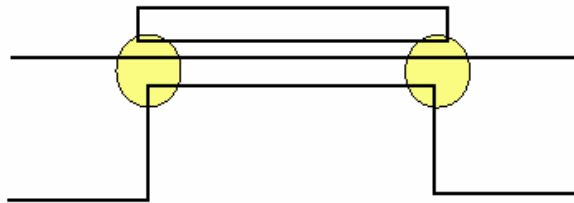
$$\nabla^2 \phi = -\frac{q}{\epsilon_S} (N_D - N_A + p - n)$$

$$n = n_i \exp \frac{q(\phi - \phi_n)}{kT}$$

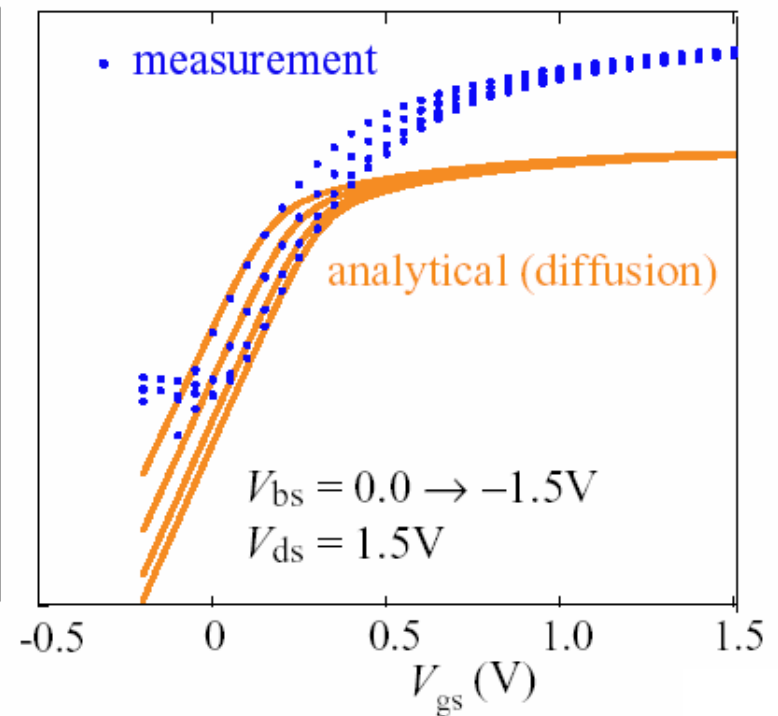
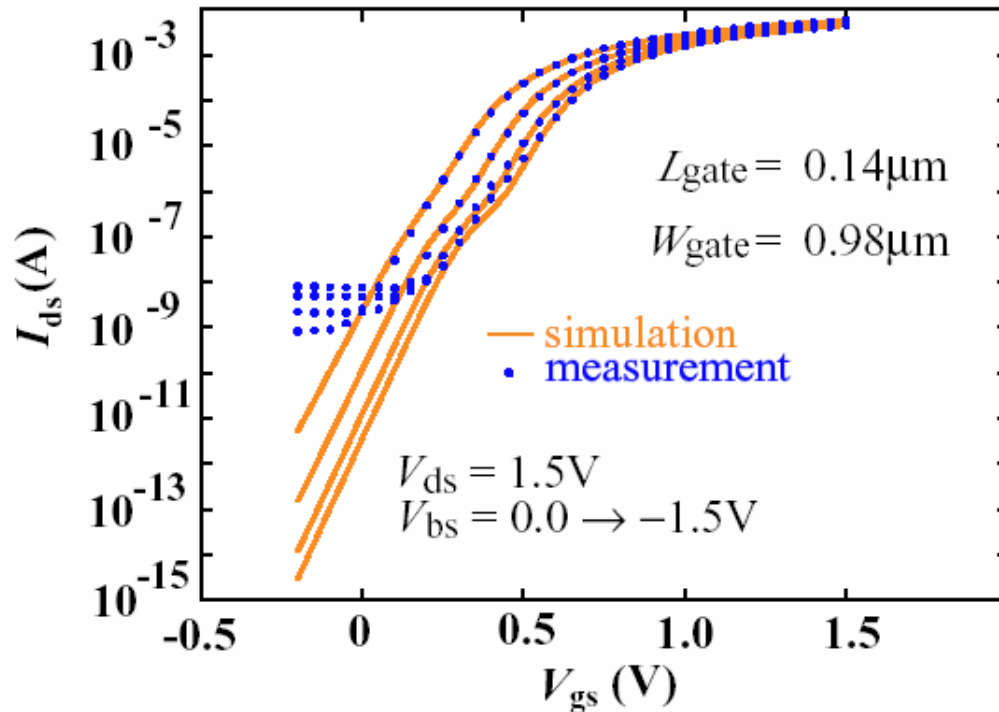
$$p = n_i \exp \frac{q(\phi_p - \phi)}{kT}$$

Shallow-Trench-Isolation Modeling

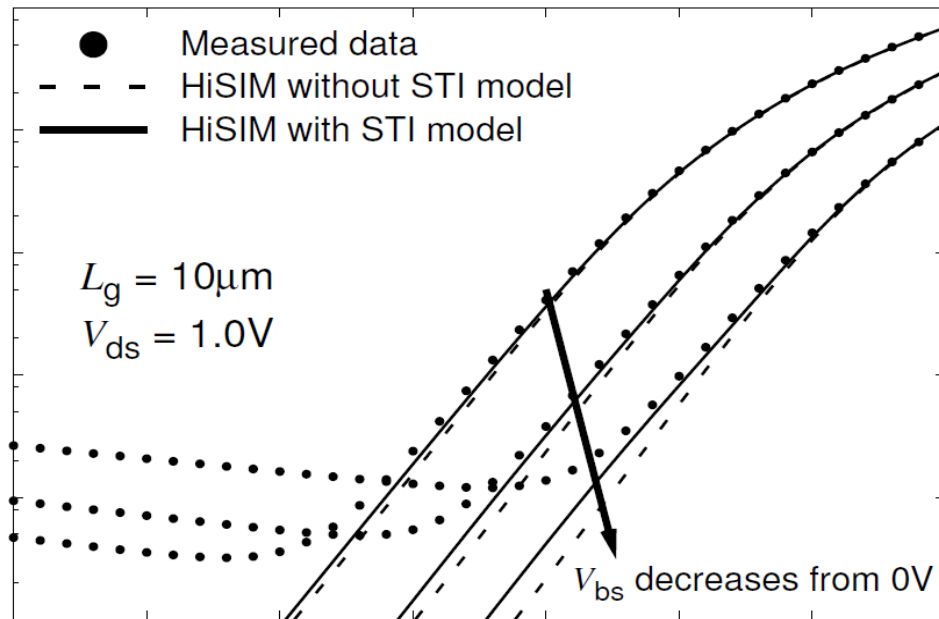
Simplification of Poisson's Equation



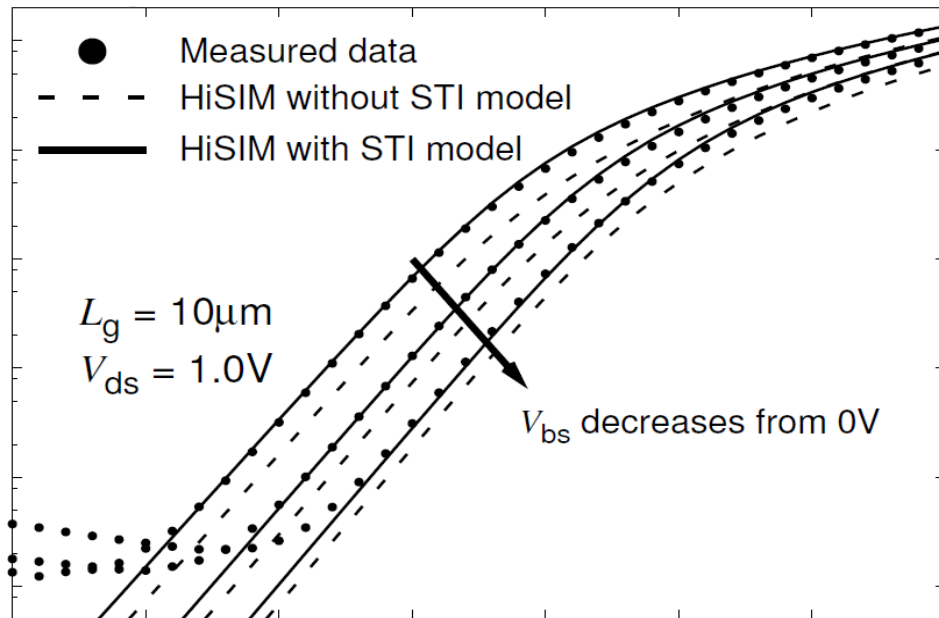
$$\nabla^2 \phi = -\frac{q}{\epsilon_S} (N_D - N_A + p - n)$$
$$n = n_i \exp \frac{q(\phi - \phi_n)}{kT}$$
$$p = n_i \exp \frac{q(\phi_p - \phi)}{kT}$$



$W_g = 10\mu\text{m}$



$W_g = 0.11\mu\text{m}$

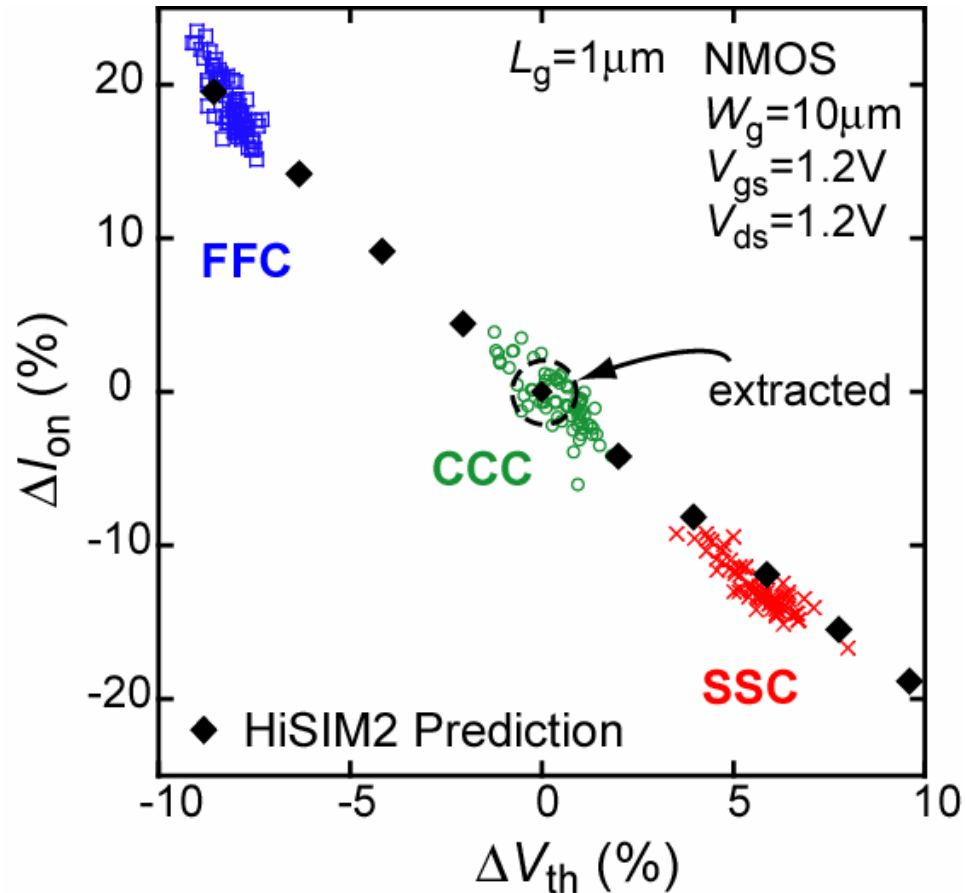


Modeled Phenomena in HiSIM2.4.0

| [Phenomena] | [Subjects] | [Phenomena] | [Subjects] |
|----------------------------|--|---------------------------|---|
| Short Channel: | | Non-Quasi-Static: | transient time-domain AC frequency-domain |
| Reverse-short Channel: | impurity pile-up pocket implant | Noise: | 1/f thermal induced gate cross-correlation |
| Poly-Depletion: | | Leakage Currents: | substrate current gate current GIDL current |
| Quantum-Mechanical: | | Source/Drain Resistances: | |
| Channel-Length Modulation: | | Junction Diode: | currents capacitances |
| 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 | | |

Binning Option
DFM Option

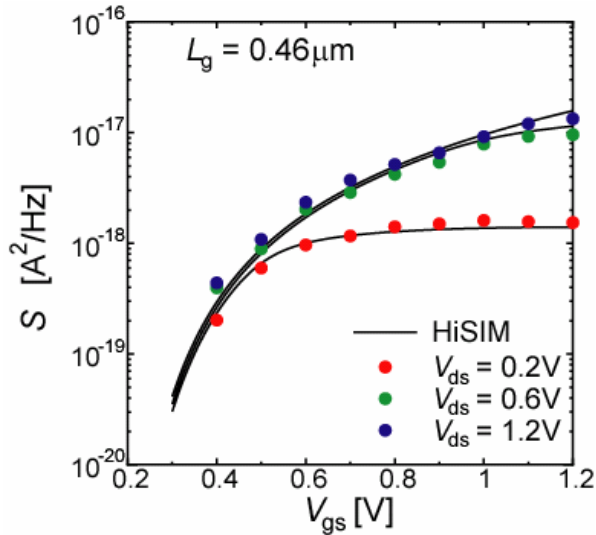
Design for Manufacturability



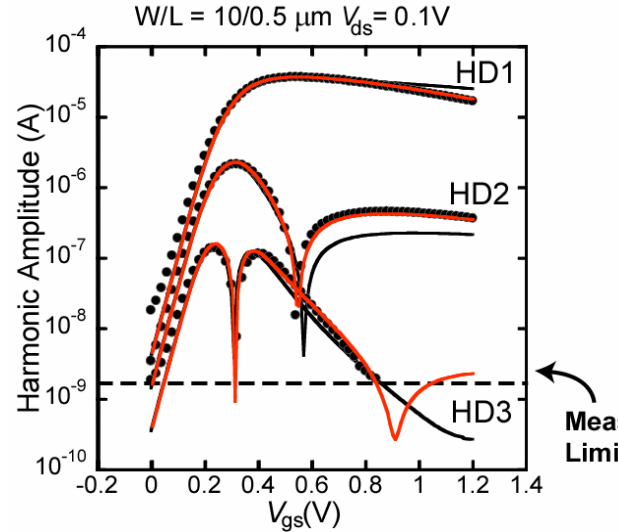
The surface-potential-based modeling has its strength in predictability and scalability.

Important Features

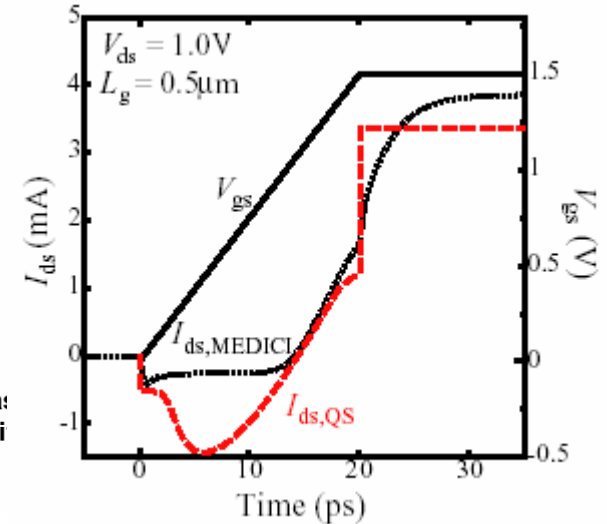
Noise



Harmonic Distortion



Non-Quasi-Static

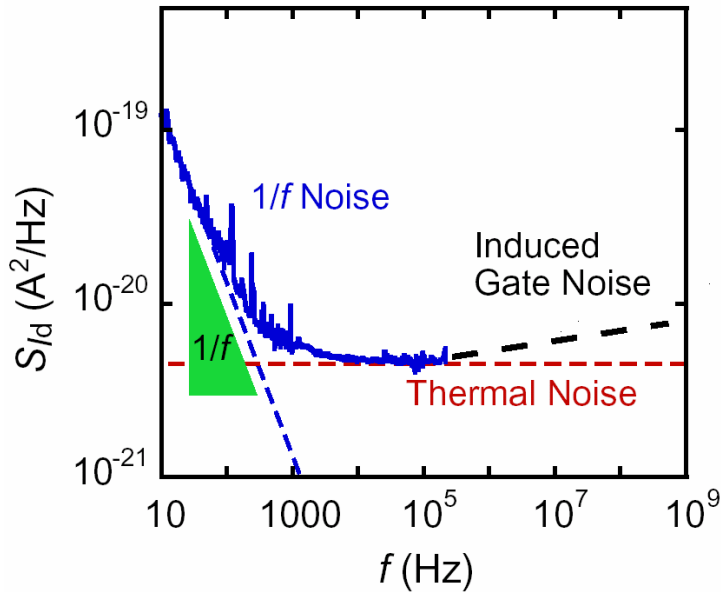


- No model parameter fittings are required.
- Features are determined only by I - V characteristics.

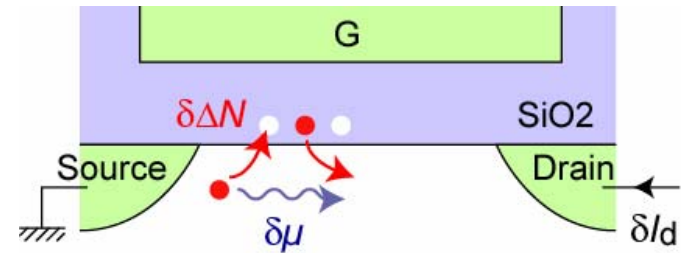


Accurate parameter extraction for I - V characteristics is the key for accurate prediction of circuit performances.

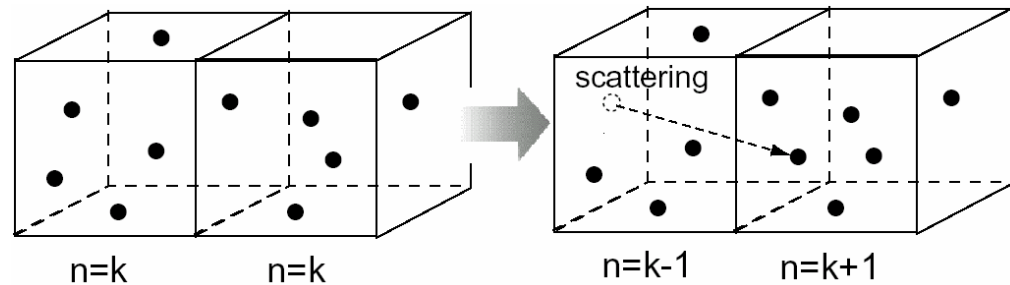
Different Noise Mechanisms



1/f Noise:

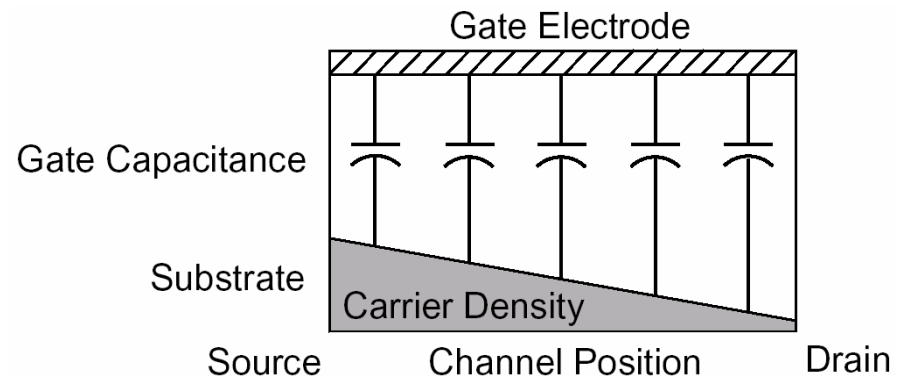


$\delta\Delta N$: carrier number fluctuation
 $\delta\mu$: mobility fluctuation



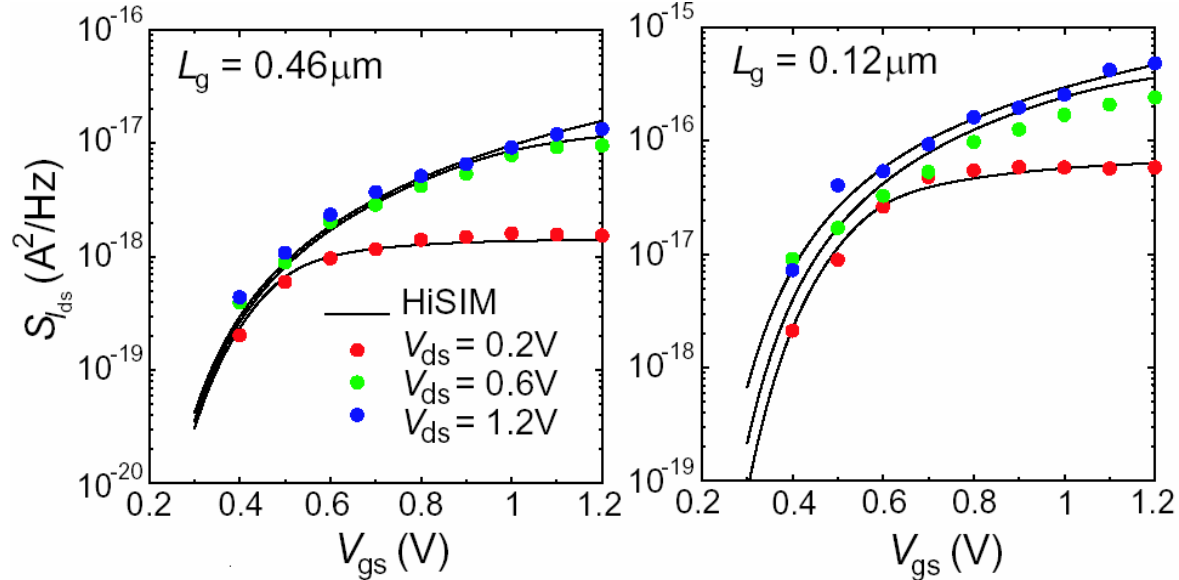
Thermal Noise:

Induced Gate Noise:
Cross-Correlation Noise:

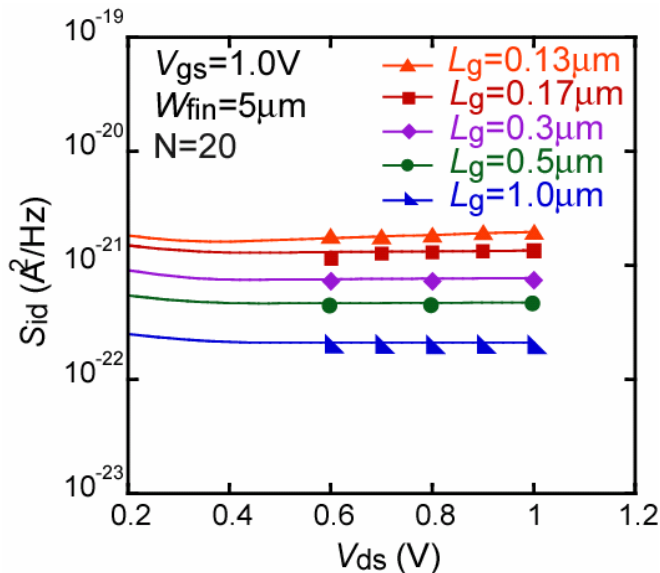


Short-Channel Effect in Noises

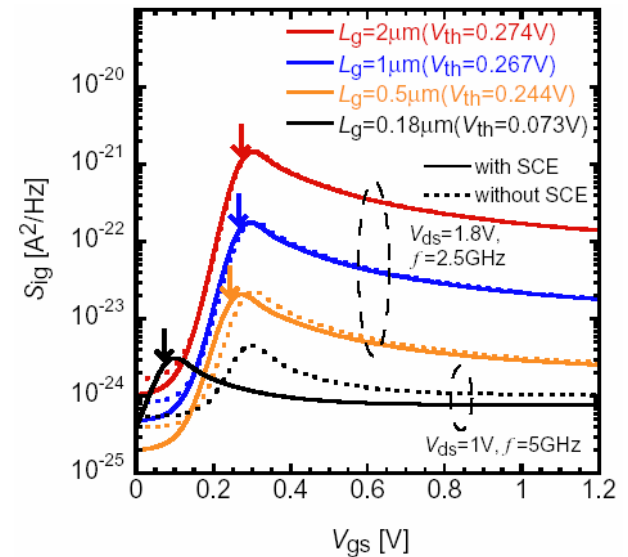
1/f Noise:



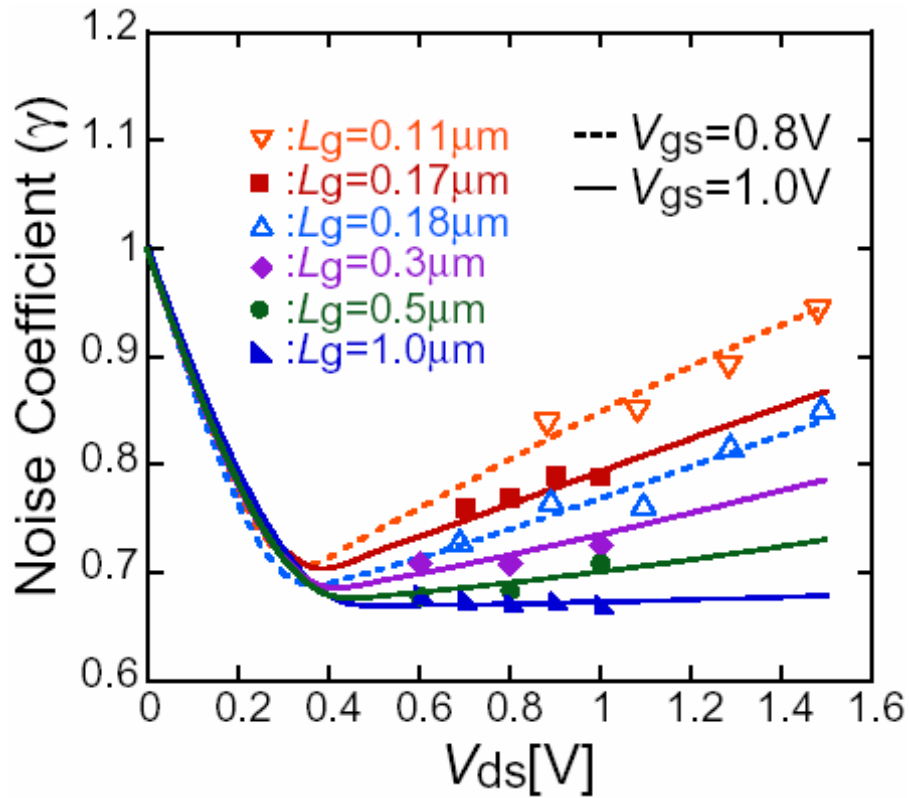
Thermal Noise:



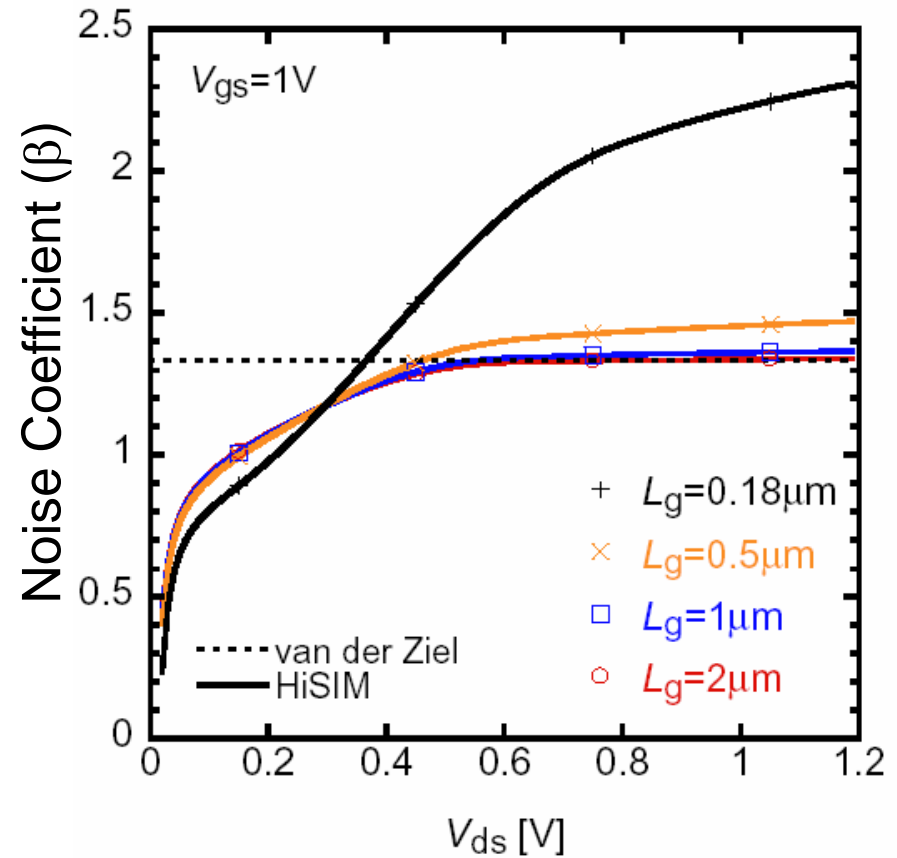
Induced Gate Noise:



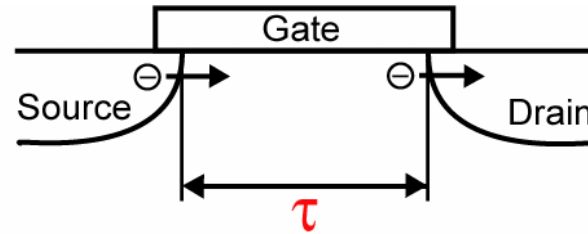
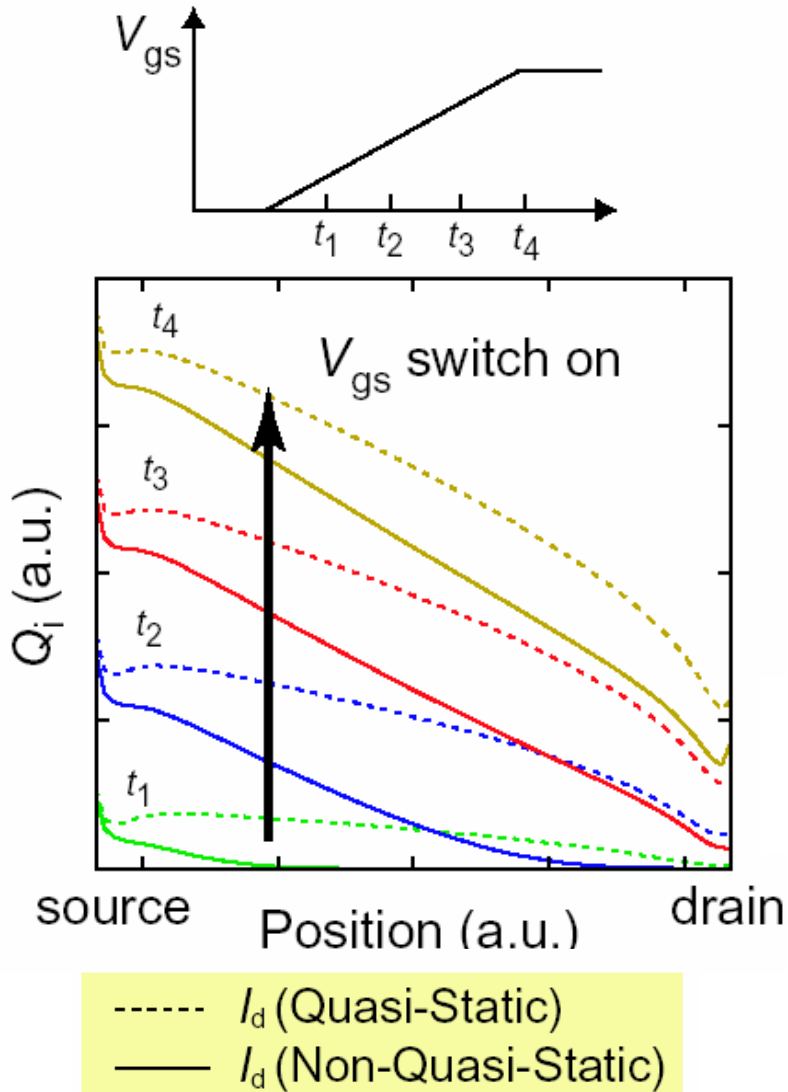
Thermal Noise Coefficient



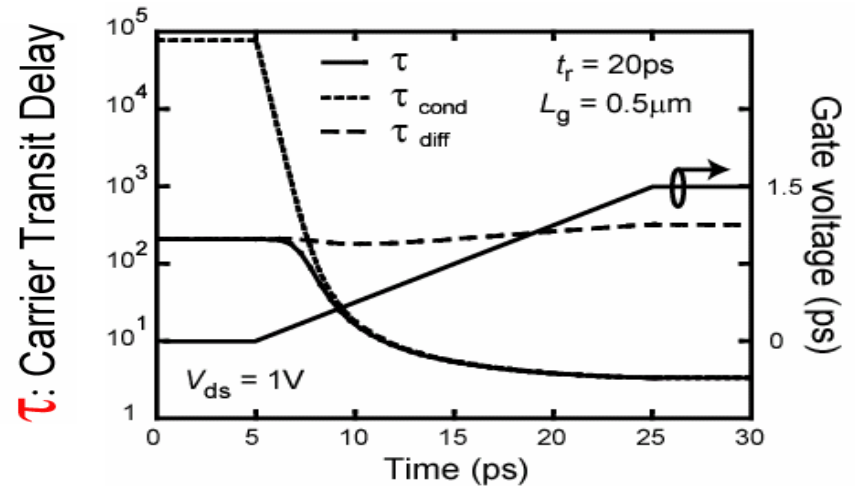
Induced Gate Noise Coefficient



Non-Quasi-Static Effect

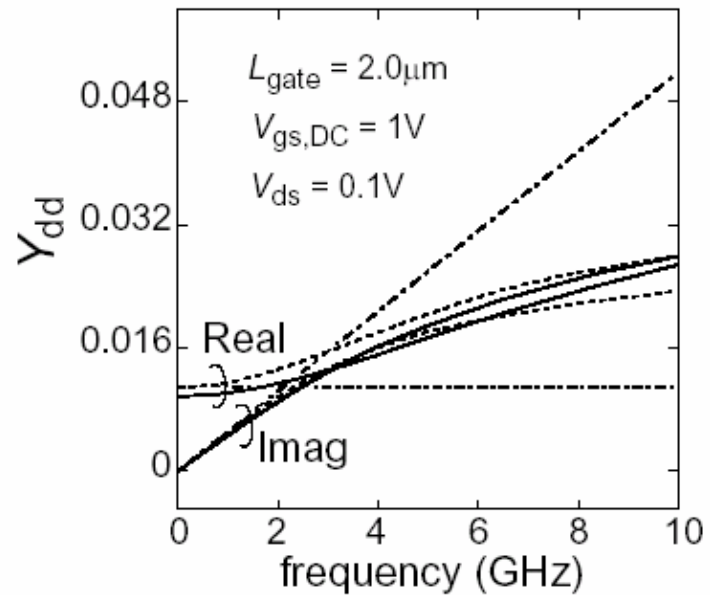
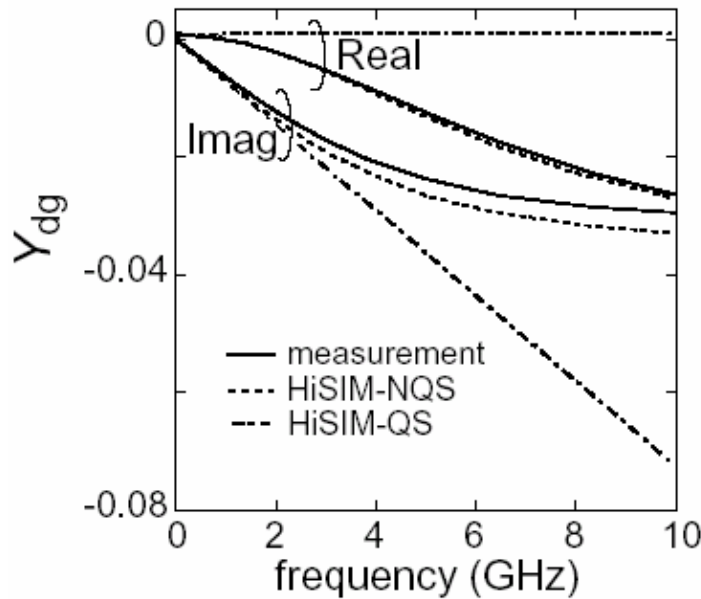
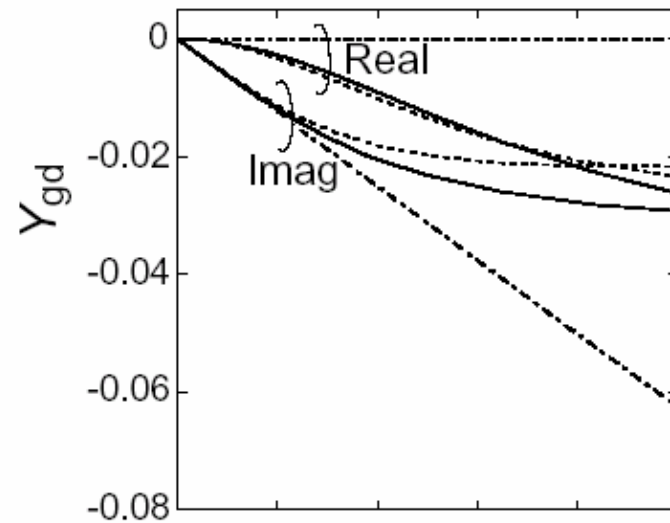
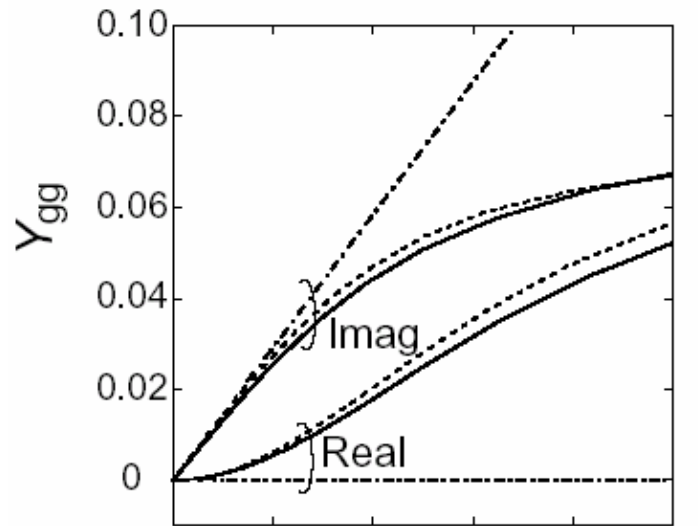


τ : Carrier Transit Delay
(function of surface potentials)

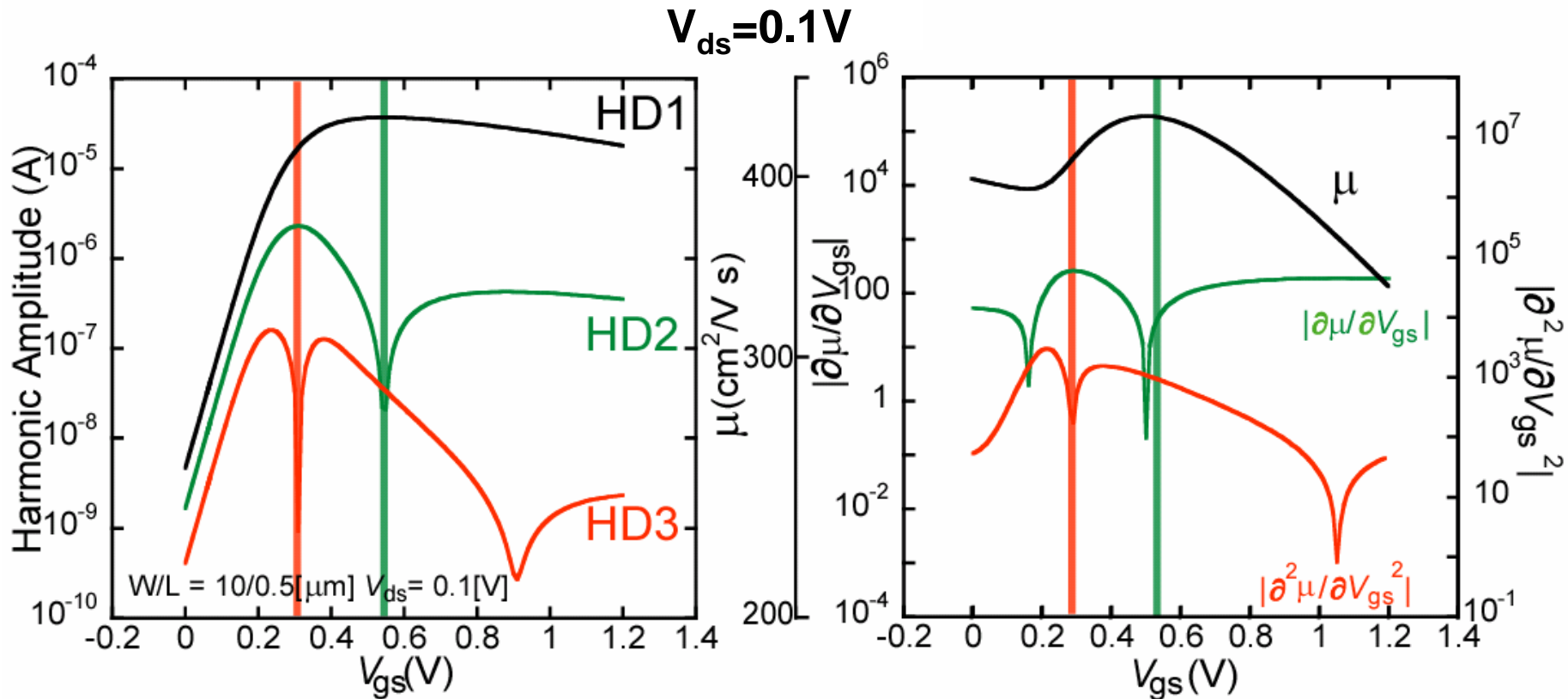


Carrier Deficit in the Channel

Y-Parameter Calculation



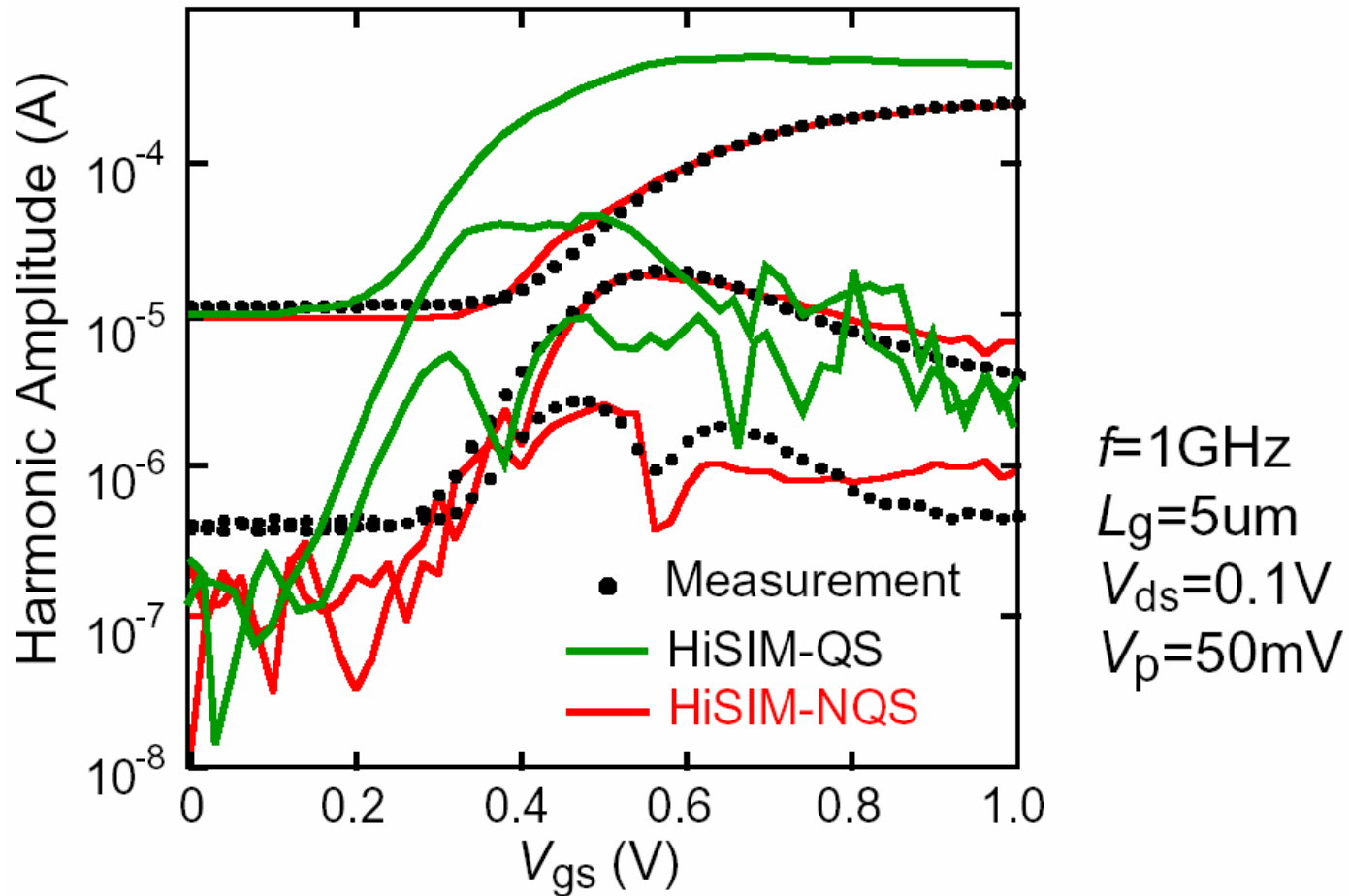
Harmonic Distortion vs. Mobility (low frequency)



$$\text{HD1} \approx \left| V_P \frac{\partial I_{ds}}{\partial V_{gs}} \right| \quad \text{HD2} \approx \left| -\frac{1}{4} V_P^2 \frac{\partial^2 I_{ds}}{\partial V_{gs}^2} \right| \quad \text{HD3} \approx \left| -\frac{1}{24} V_P^3 \frac{\partial^3 I_{ds}}{\partial V_{gs}^3} \right|$$

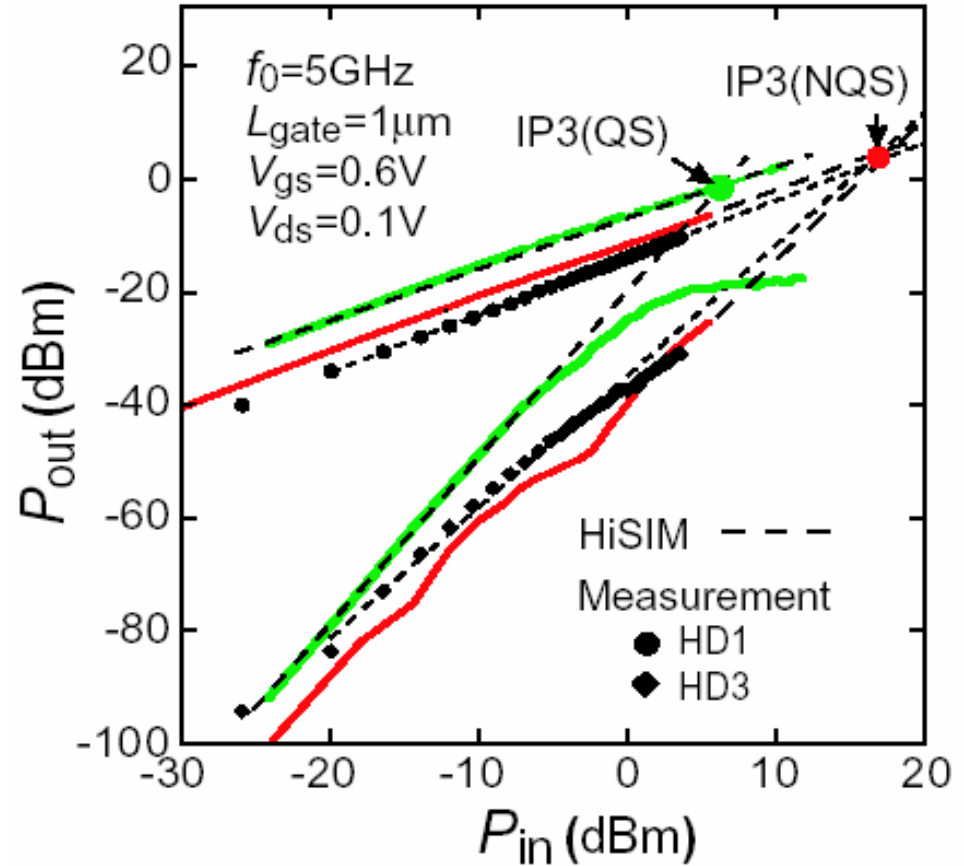
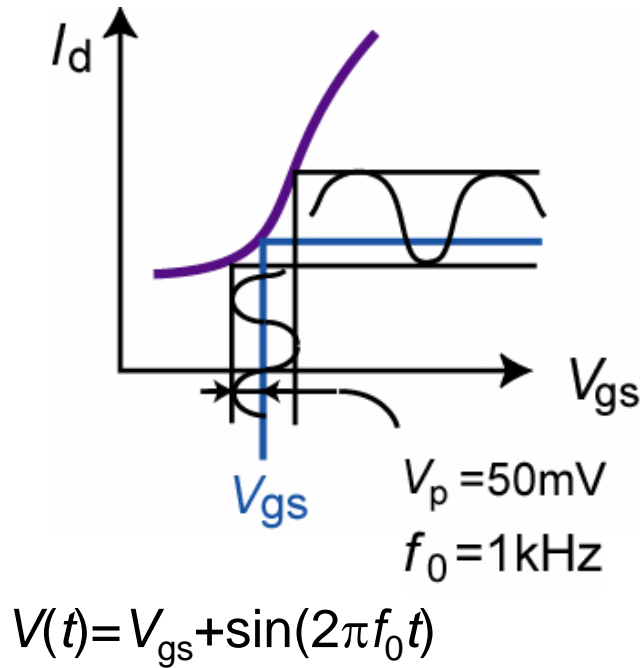
Mobility determines the low-frequency harmonic distortion characteristics.

Harmonic Distortion (high frequency)



Carrier transit delay determines the high-frequency harmonic distortion characteristics.

IP3 Prediction



Y. Takeda et al., CICC, p. 827, 2005.

D. Navarro et al., IEEE MWC Lett., p. 125, 2006.

Summary

- ***I-V* characteristics of HiSIM240 contain already the carrier dynamics in detail, even down to the sub-100nm era.**
- **In the HiSIM approach, the key for modeling accuracy, scalability and predictability are the surface potentials, which can be calculated by solving the Poisson equation directly.**
- **The total simulation time of HiSIM240 is equivalent to the advanced V_{th} -based models.**