Modeling and Characterization of RF / Analog and Noise Using HiSIM2

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- Concept of HiSIM

- Modeling of HiSIM2

- Extension to High-Voltage Transistors : HiSIM-HV

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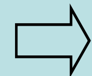
Development History

Date	Event	Version	Materials
2001 Oct.	release to vendors	HiSIM1.0.0	source code, 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, 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	
2008 April	"	HiSIM2.4.1	
2008 August	"	HiSIM2.4.2	
2008 September		HiSIM2.4.3	

Fundamental Modeling Approach

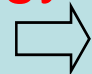
✱ Model Core:

Complete Surface-Potential-Based Modeling (I)



Surface potentials are origin for all device characteristics, and are obtained by solving the Poisson equation iteratively.

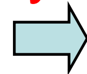
Technology-Based Modeling (II)



The impurity profile determines the surface-potential values.

✱ Phenomena Modeling:

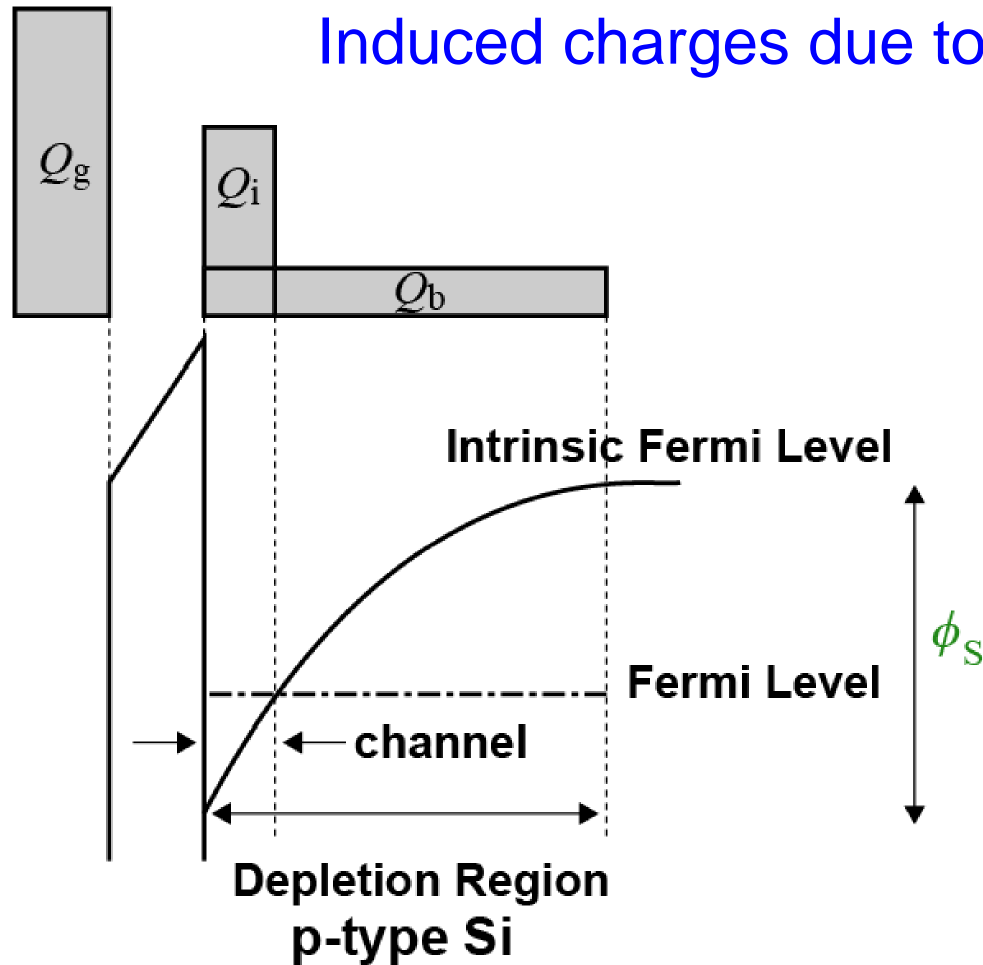
Device-Physics-Based Modeling (III)



Number of fitting parameters are reduced.

Surface-Potential-Based Model

Induced charges due to the applied voltage.



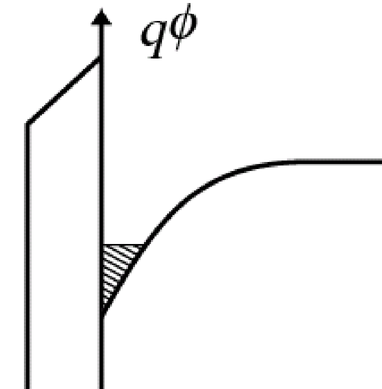
Basic Equations Solved in HiSIM

-Poisson:

$$\nabla^2\phi = -\frac{q}{\varepsilon_{\mathrm{Si}}}(N_{\mathrm{D}} - N_{\mathrm{A}} + p - n)$$

$$n = n_{\mathrm{i}} \exp \frac{q(\phi - \phi_{\mathrm{n}})}{kT}$$

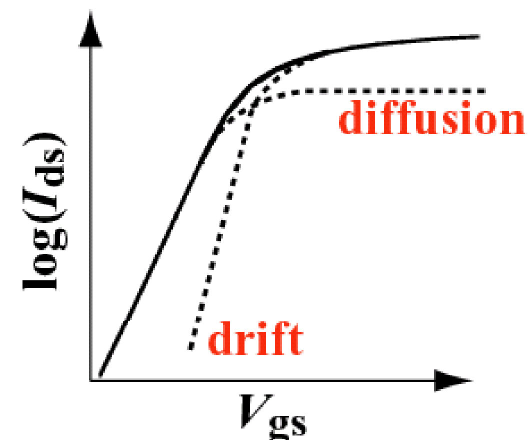
$$p = n_{\mathrm{i}} \exp \frac{q(\phi_{\mathrm{p}} - \phi)}{kT}$$



-Current Density:

$$j_{\mathrm{n}} = q\mu_{\mathrm{n}} n \frac{\phi}{y} + qD_{\mathrm{n}}\nabla n$$

$$j_{\mathrm{p}} = q\mu_{\mathrm{p}} p \frac{\phi}{y} - qD_{\mathrm{p}}\nabla p$$



-Continuity: $I(\mathrm{t}) = I_0(\mathrm{t}) + \frac{\mathrm{d}Q}{\mathrm{d}t}$

(solved by circuit simulator)

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  - Physics-Based Modeling

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Complete Surface-Potential-Based Model

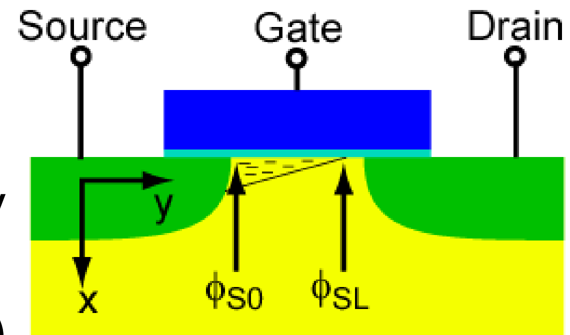
- Charge-Sheet Approximation
- Quasi-2D Approximation

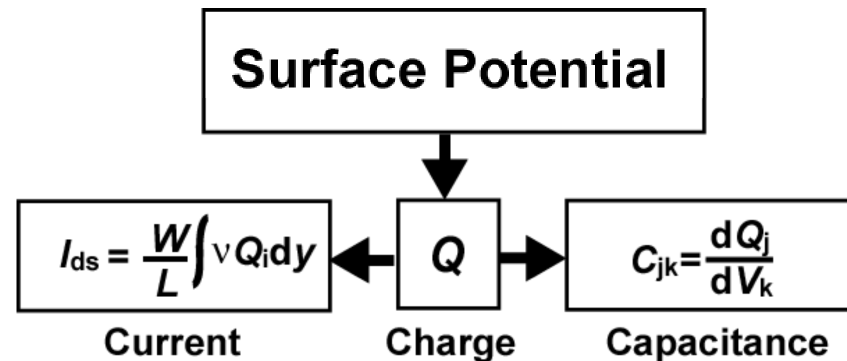
ϕ_S : Solution of the 1D Poisson Equation

Solved Iteratively

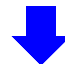
: Dependent on Device Parameters

(e.g. T_{ox}, N_{sub}, …)





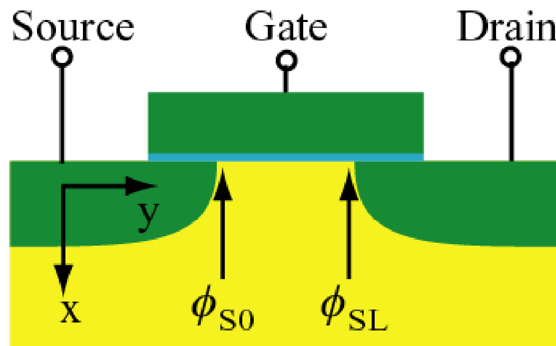
All device characteristics are described as a function of ϕ_{S0} and ϕ_{SL}.



All outputs derived from surface potential are consistent.

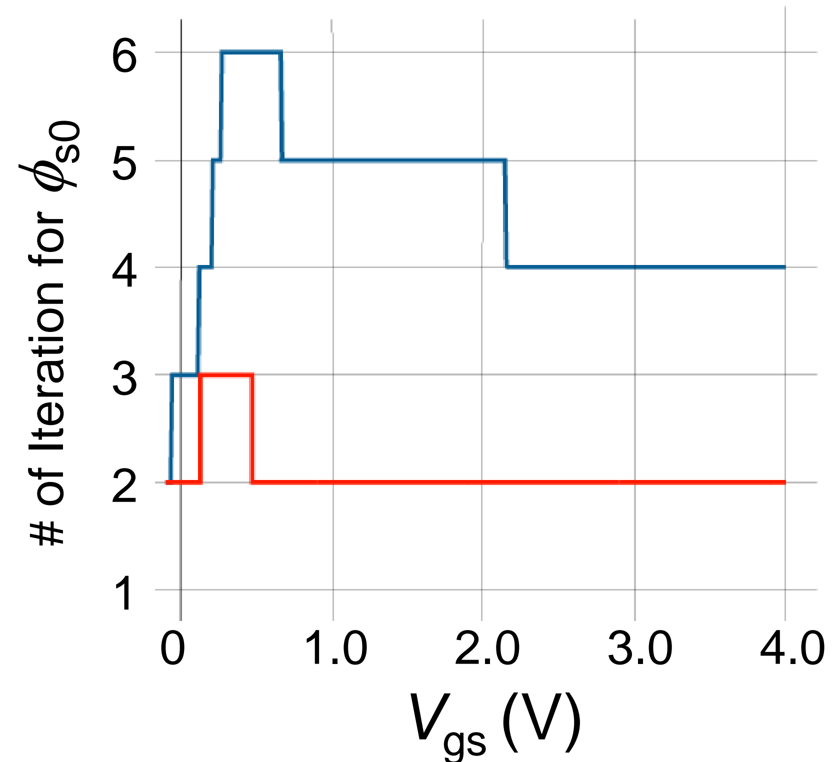
Calculation Costs for Iterative Solutions

✱ Iterations for ϕ_{SO} and ϕ_{SL}



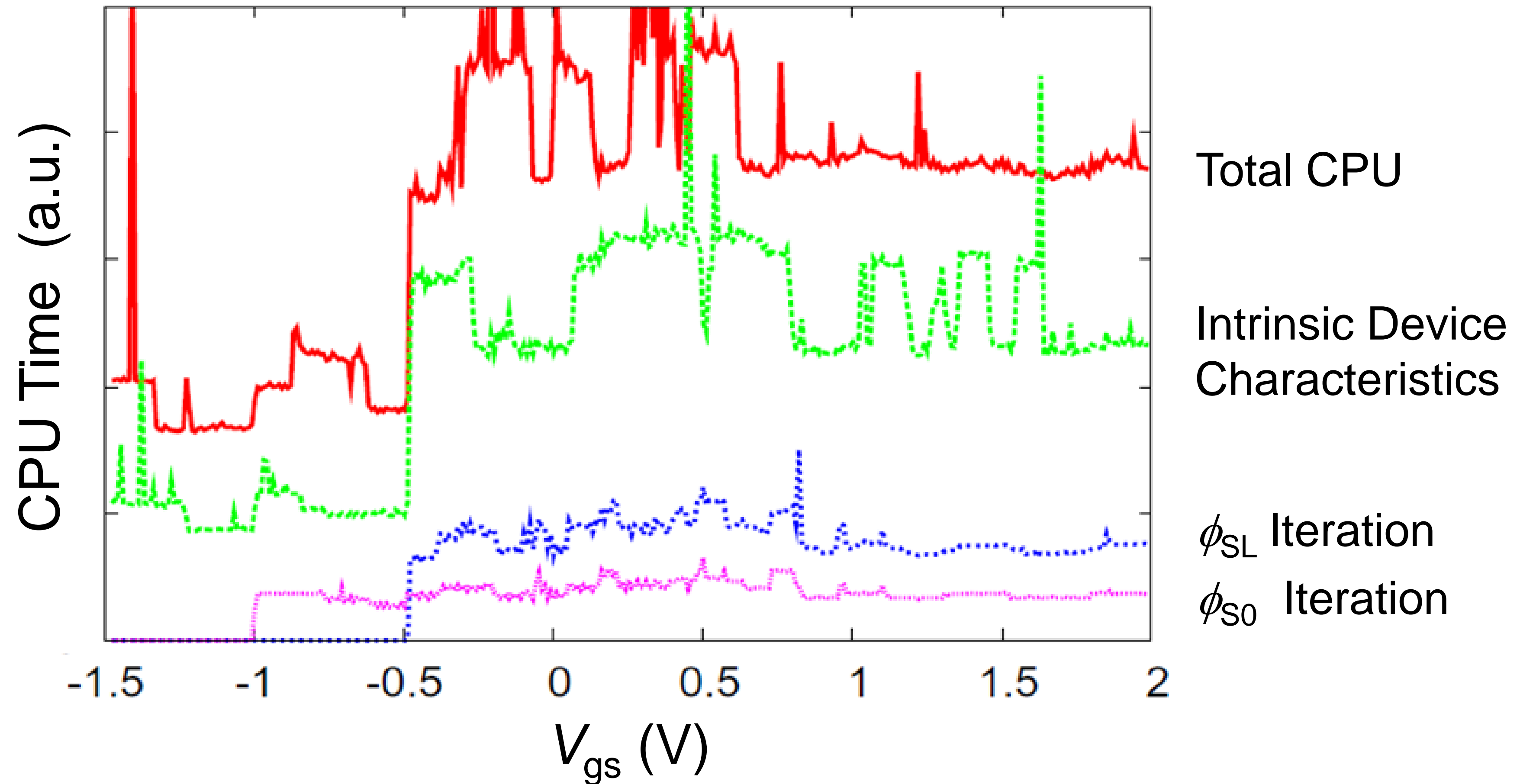
✱ Criterion for Convergence
- 1×10^{-11} V in accuracy

➡ Good initial guess is required.



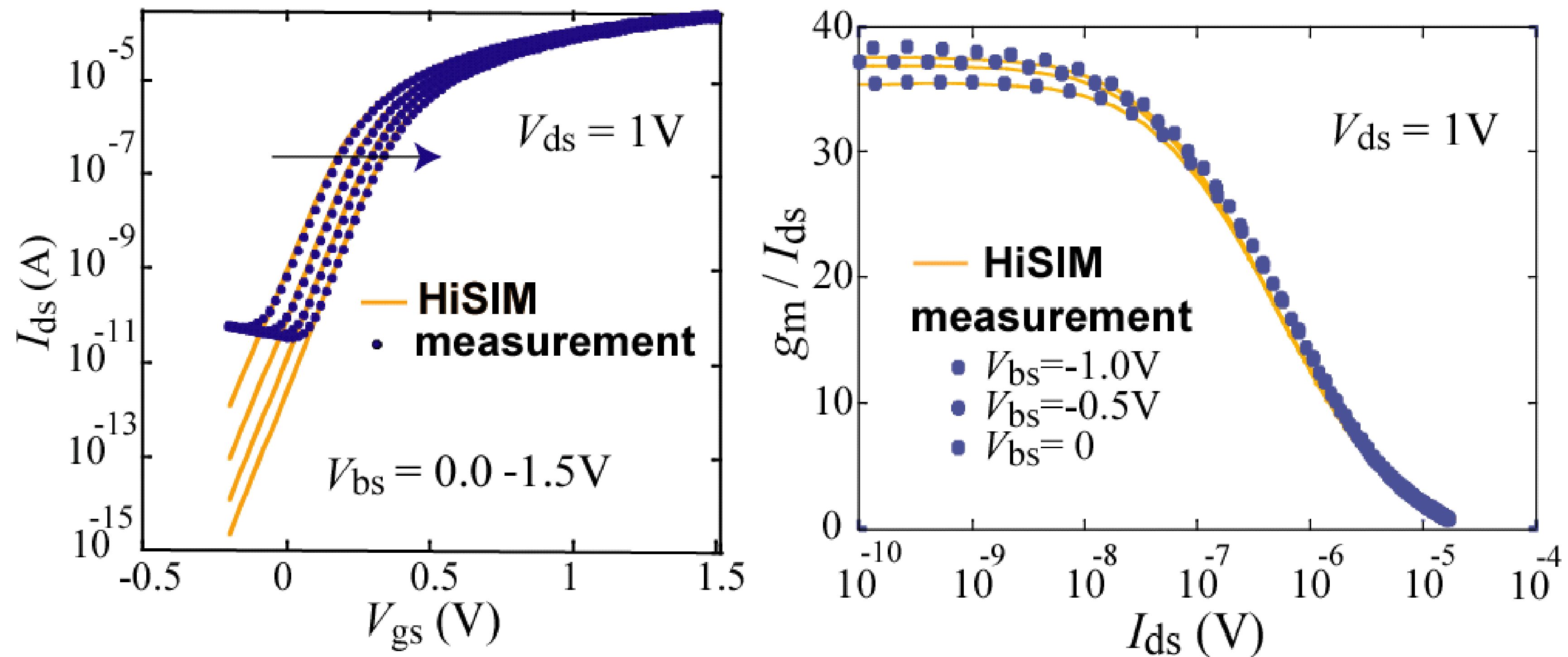
M. Miura-Mattausch et al., IEEE T. CAD/ICAS, vol. 15, pp. 1, 1996.

CPU Time Comparison



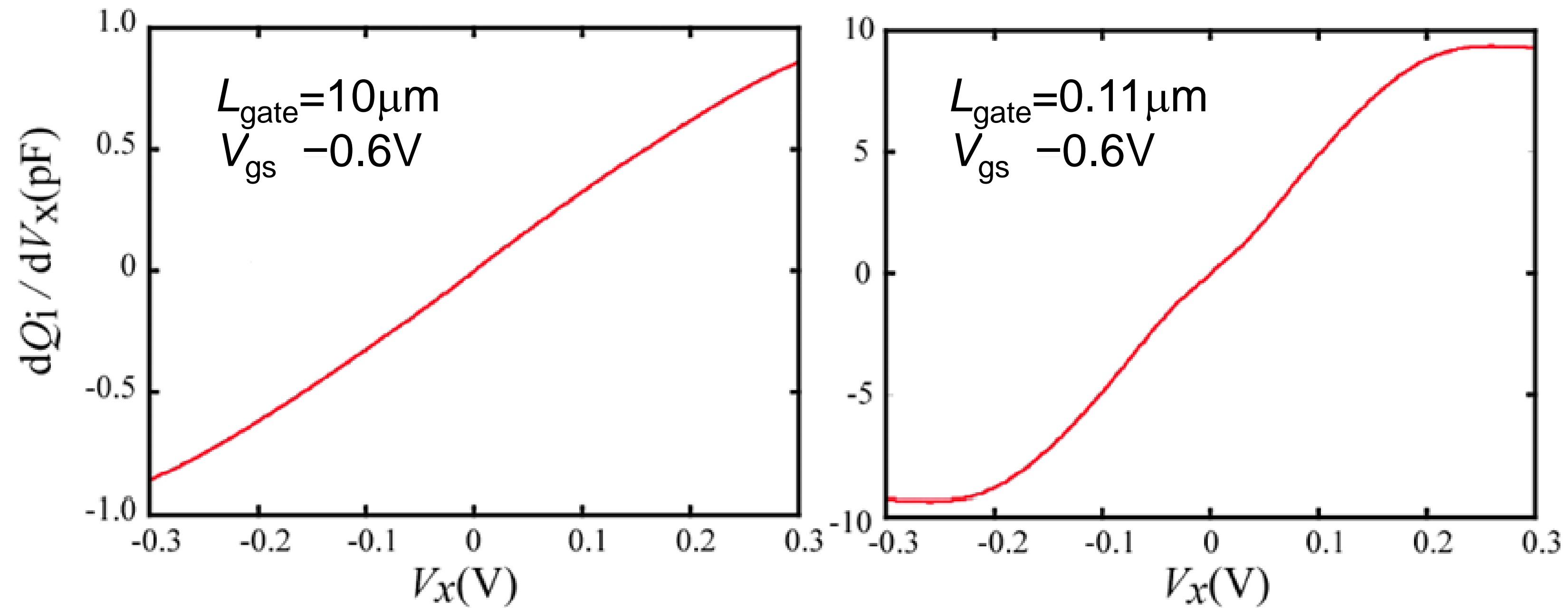
Solving Poisson's eqs. with iteration is applicable for compact model.

Advantage of Surface-Potential-Based Modeling 1



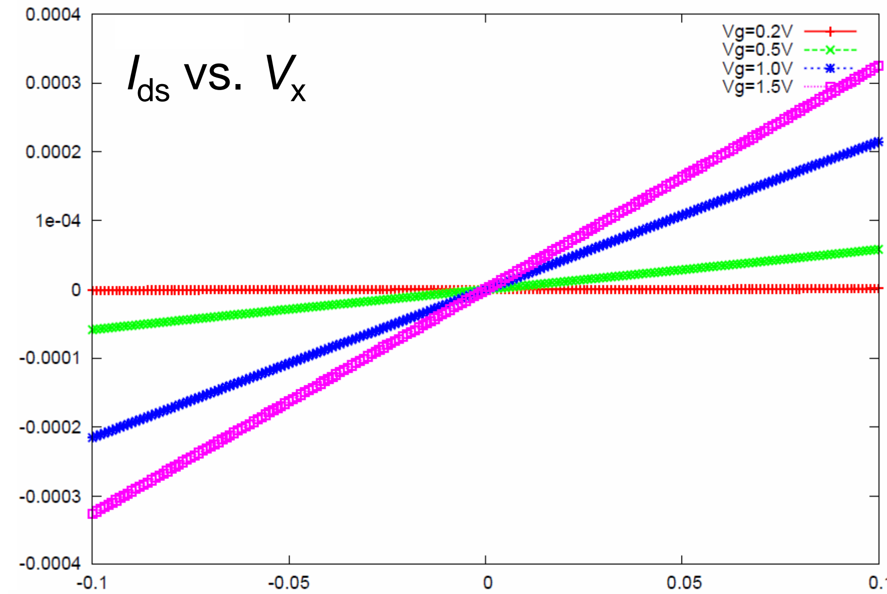
Automatically preserved smoothness
High accuracy suitable for analog applications

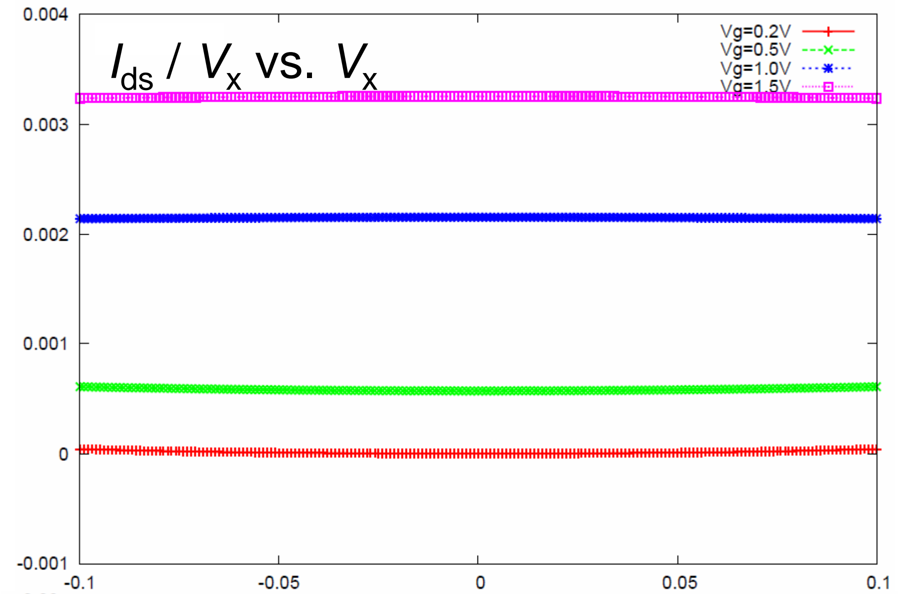
Advantage of Surface-Potential-Based Modeling 2

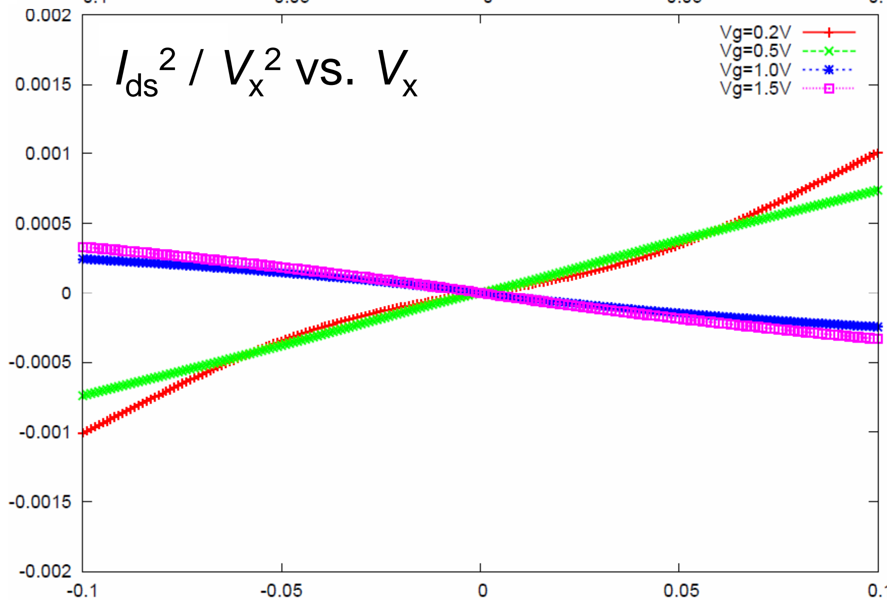


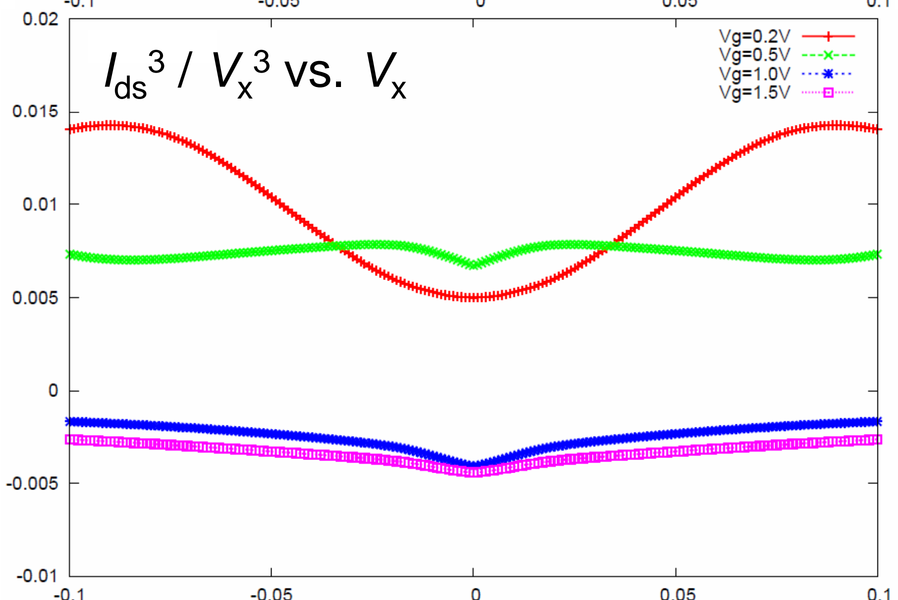
Symmetry at V_{ds}=0 is preserved.

Further Symmetry Test with HiSIM241









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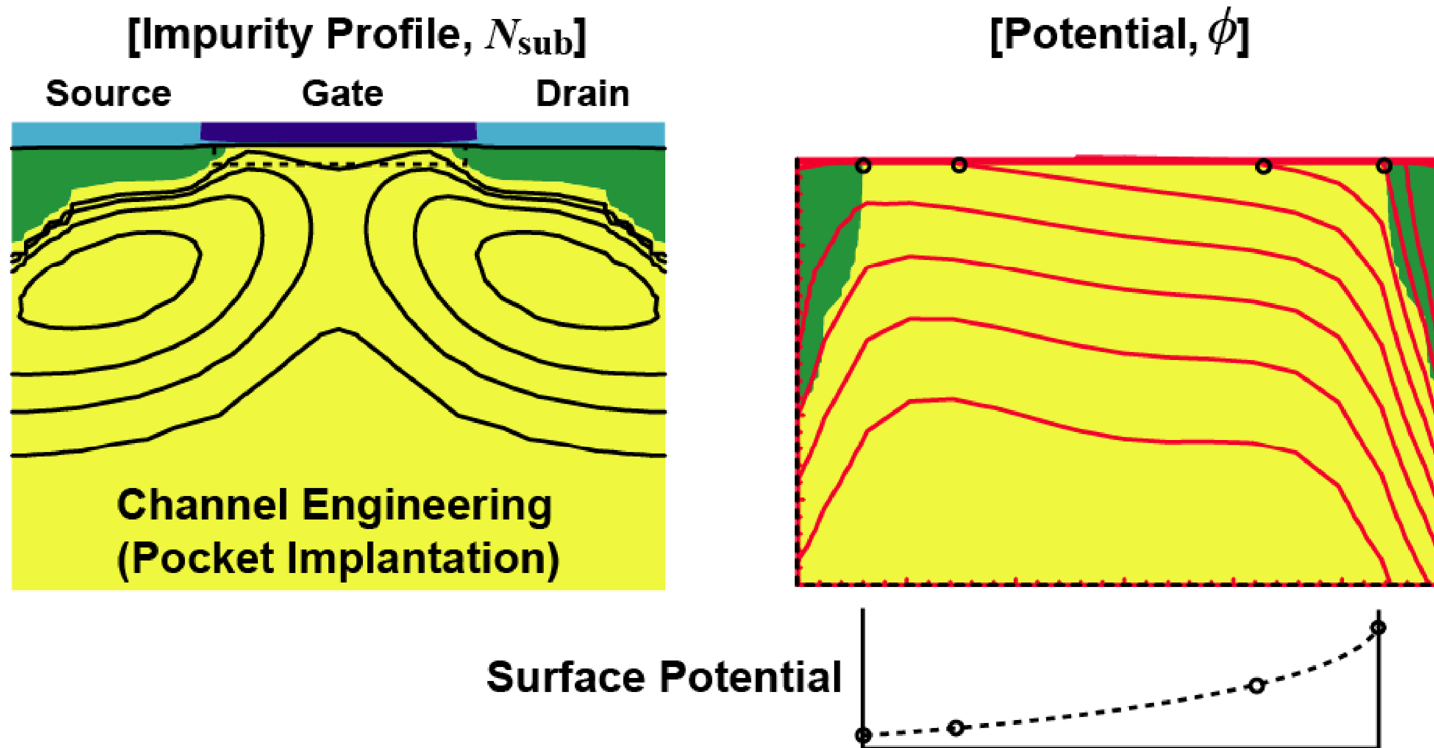
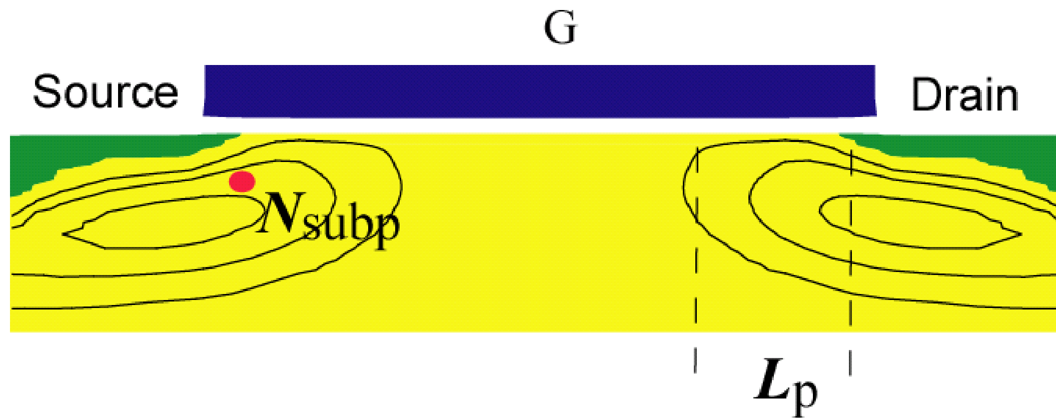
Technology-Based Modeling

- Impurity profile determines device characteristics.

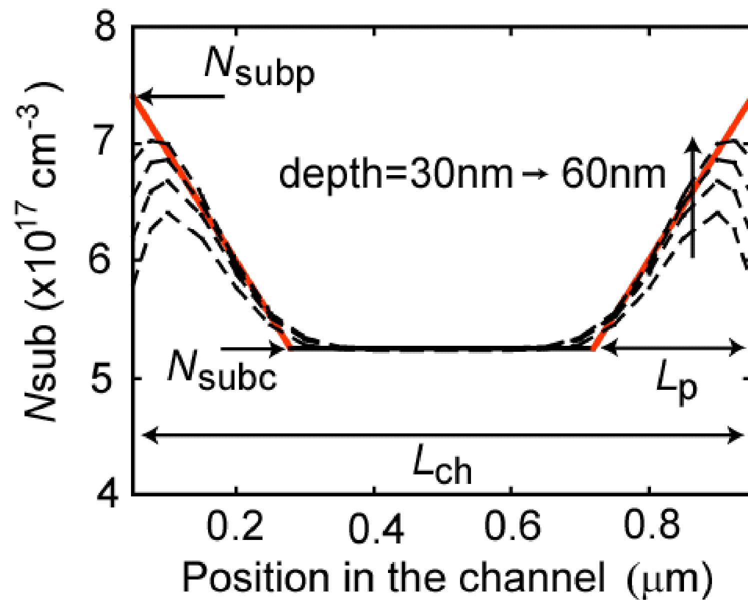


Accurate impurity-profile extraction is a core of modeling.

Example: Pocket-Implanted Case



Lateral Profile



Simplified Pocket Profile

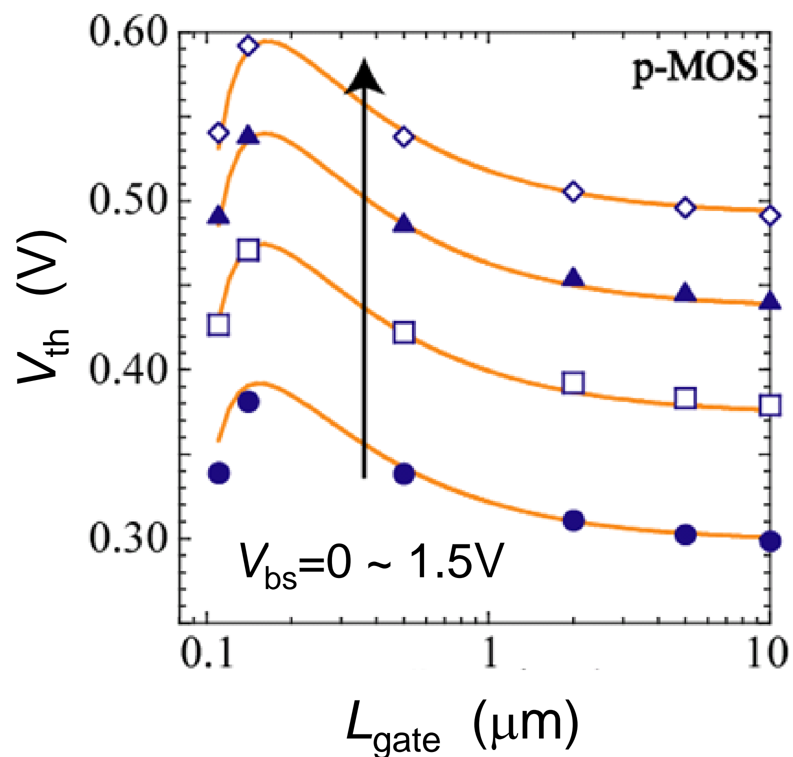
Model Parameters:

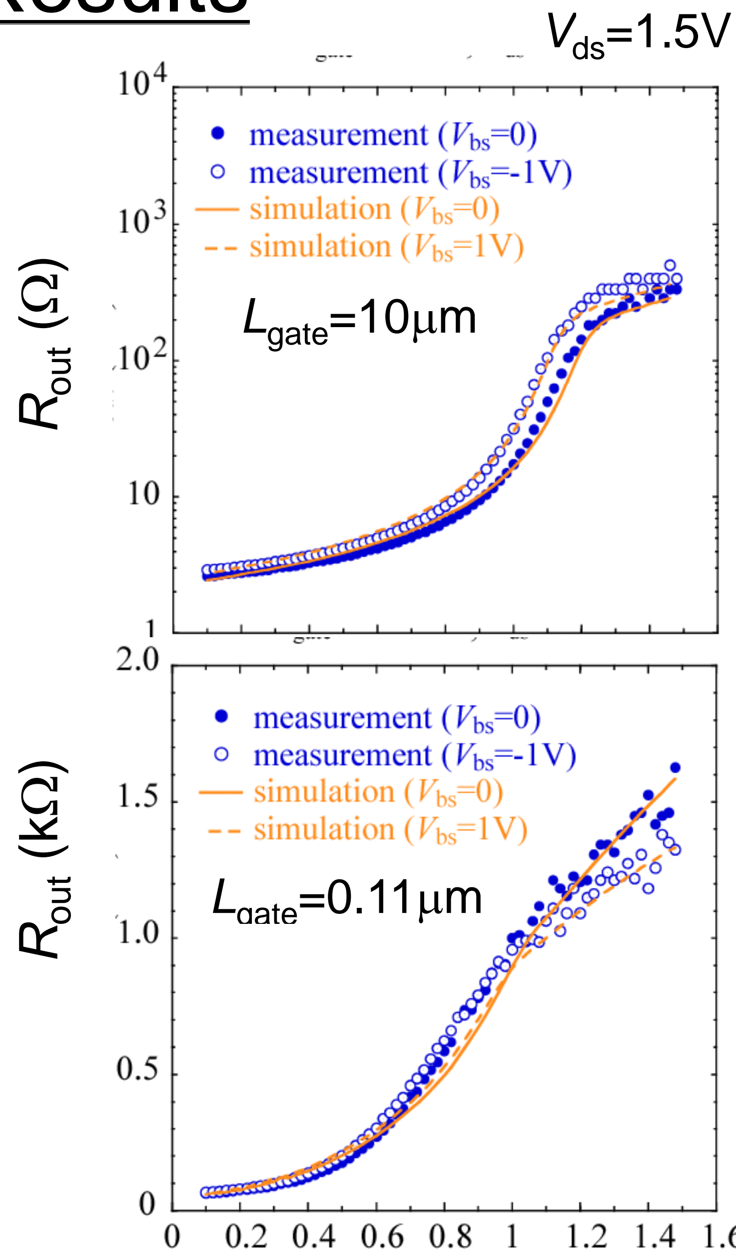
N_{subp}: Maximum Pocket Concentration

L_p: Pocket Extension Length

D. Kitamaru et al., Proc. SISPAD, pp. 392, 2001.

Calculation Results





H. Ueno et al., IEEE T. ED, vol. 49, pp. 1783, 2002.

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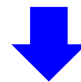
Physics-Based Modeling

Example:

- Carrier Mobility
- Temperature Dependence
- Channel-Length Modulation

Consistent through surface potential



- Reduction of model parameters has been achieved.

- Applicable for RF/ noise characterization without additional parameter fitting

Carrier Mobility at Low Field

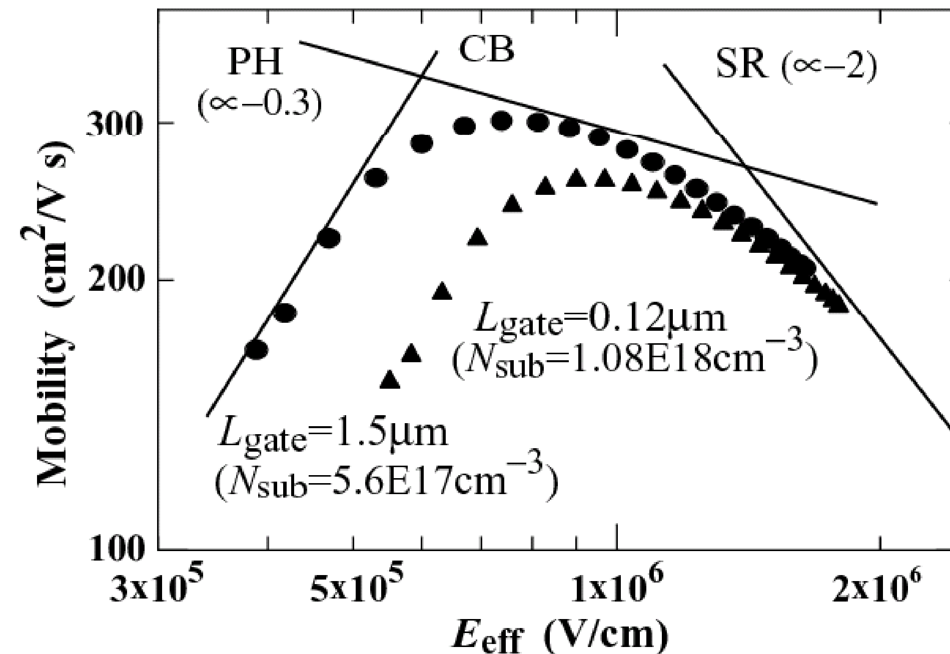
$$\frac{1}{\mu_0} = \frac{1}{\mu_{CB}} + \frac{1}{\mu_{PH}} + \frac{1}{\mu_{SR}}$$

- $\mu_{CB} = CB0 + CB1 \frac{Q_i}{q \times 10^{11}}$
- $\mu_{PH} = \frac{PH0}{(T/300K)^{PHTMP} \times E_{eff}^{PH1}}$
- $\mu_{SR} = \frac{SR0}{E_{eff}^{SR1}}$

$$E_{eff} = \frac{1}{\varepsilon_{Si}}(NDEP \times Q_b + NINV \times Q_i)$$

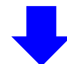
Universality:

$PH1 = 0.3$
$SR1 = 2.0$
$NDEP = 1.0$
$NINV = 0.5$



S. Matsumoto et al., J. Appl. Phys., vol. 92, pp. 5228, 2002.

Mobility is determined by charges.



Consistent charge calculation is important.

Temperature Dependence

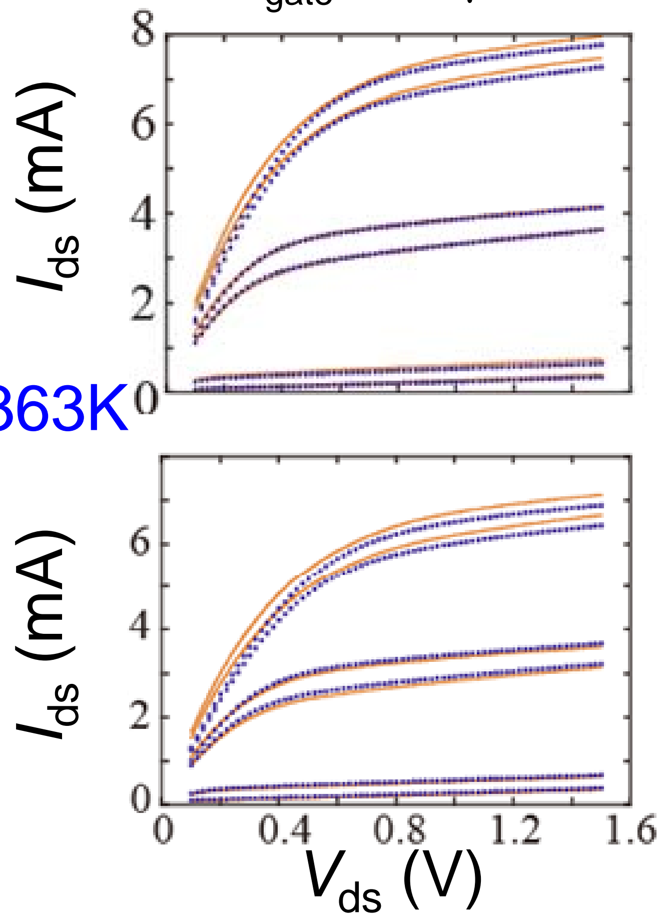
- Band Gap
- Phonon Scattering
- Saturation Velocity

Measured
HiSIM2

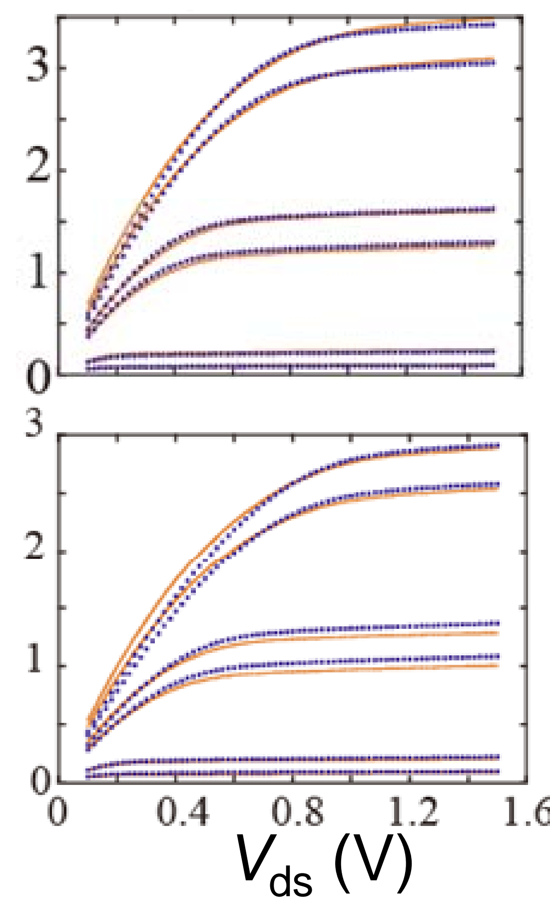
V_{gs} =0.5, 1.0, 1.5V
V_{bs} =0, -1.0V

300K

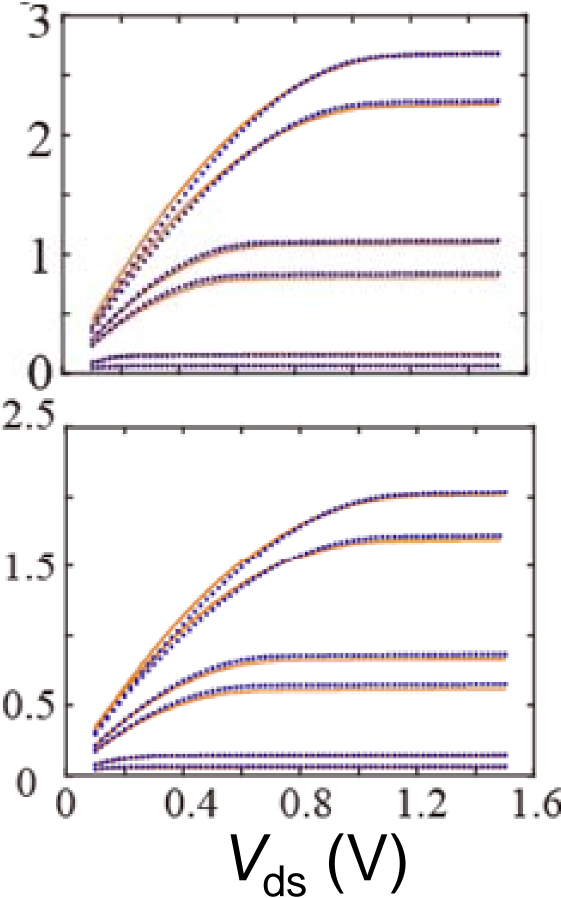
L_{gate}=0.11μm



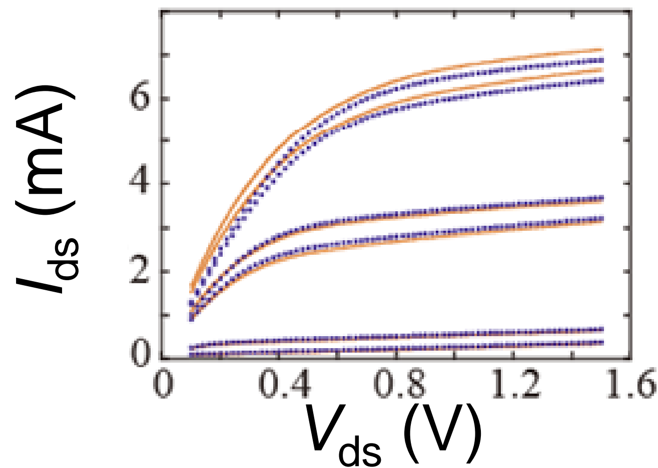
L_{gate}=0.5μm

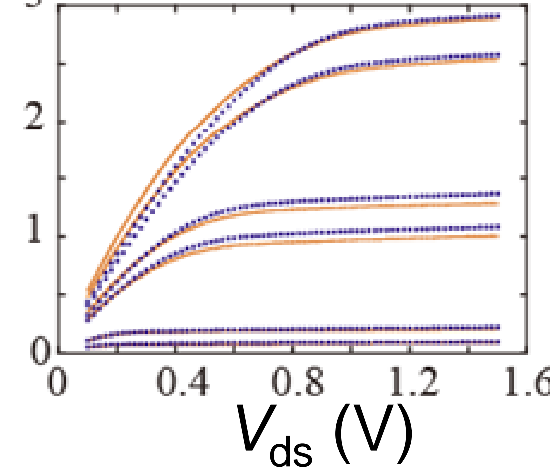


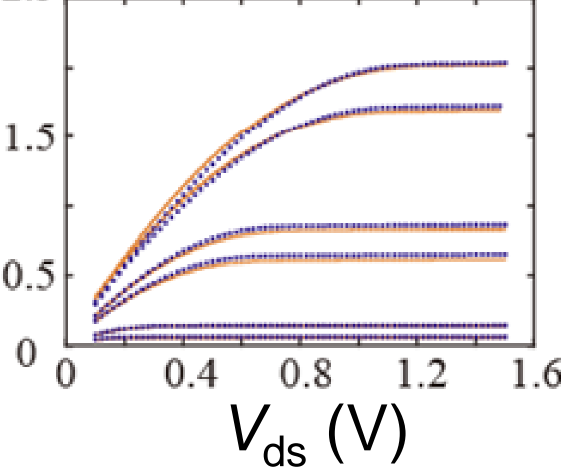
L_{gate}=10μm



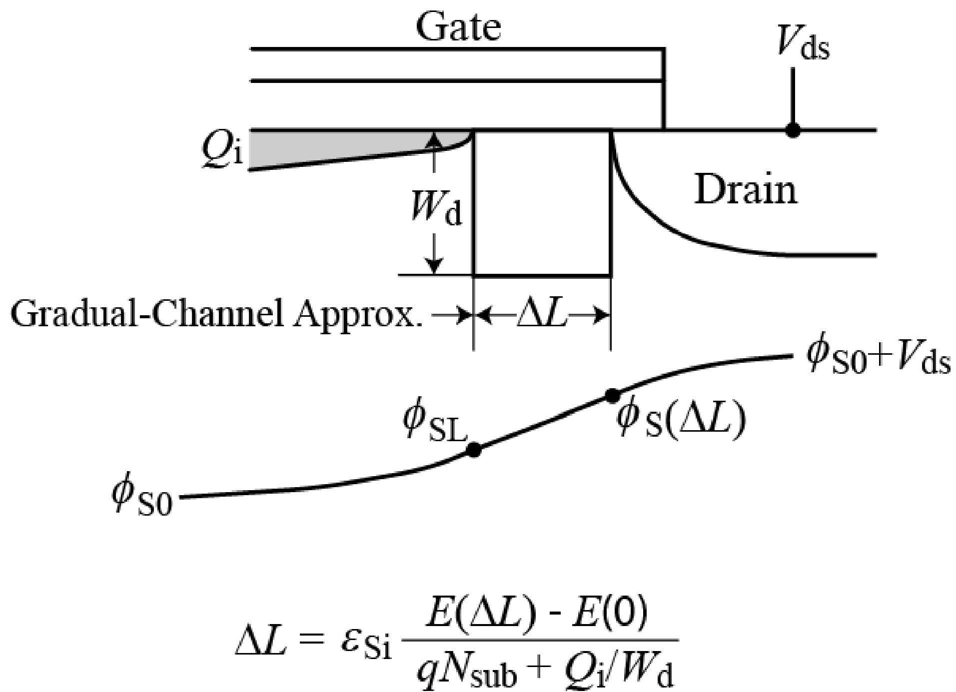
363K

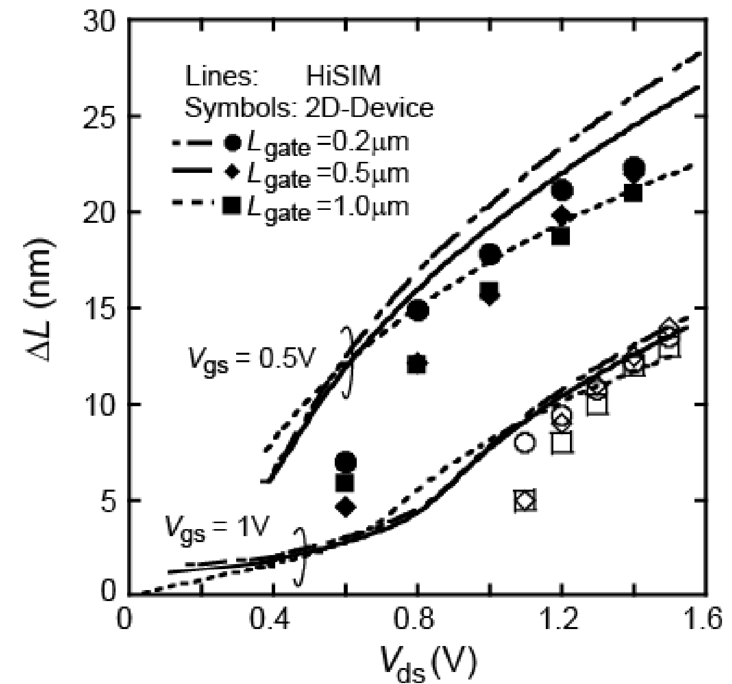






Channel-Length Modulation



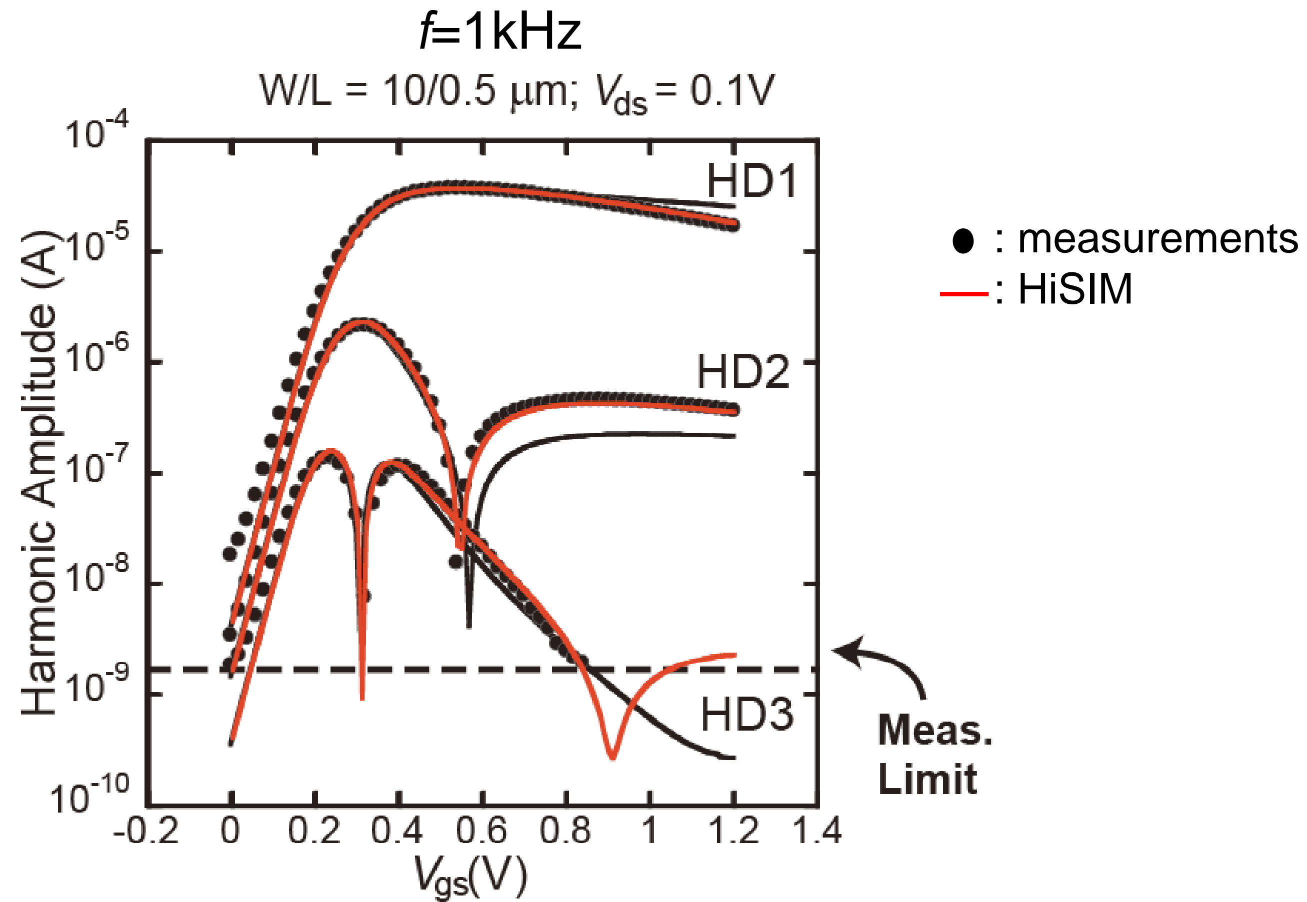


$$\Delta L = \varepsilon_{Si} \frac{E(\Delta L) - E(0)}{qN_{sub} + Q_i/W_d}$$

$$\phi_S(\Delta L) = CLM1\,(\phi_{S0} + V_{ds}) + (1 - CLM1)\,\phi_{SL}$$

CLM1, dependent on the junction profile, determines the CLM effect.

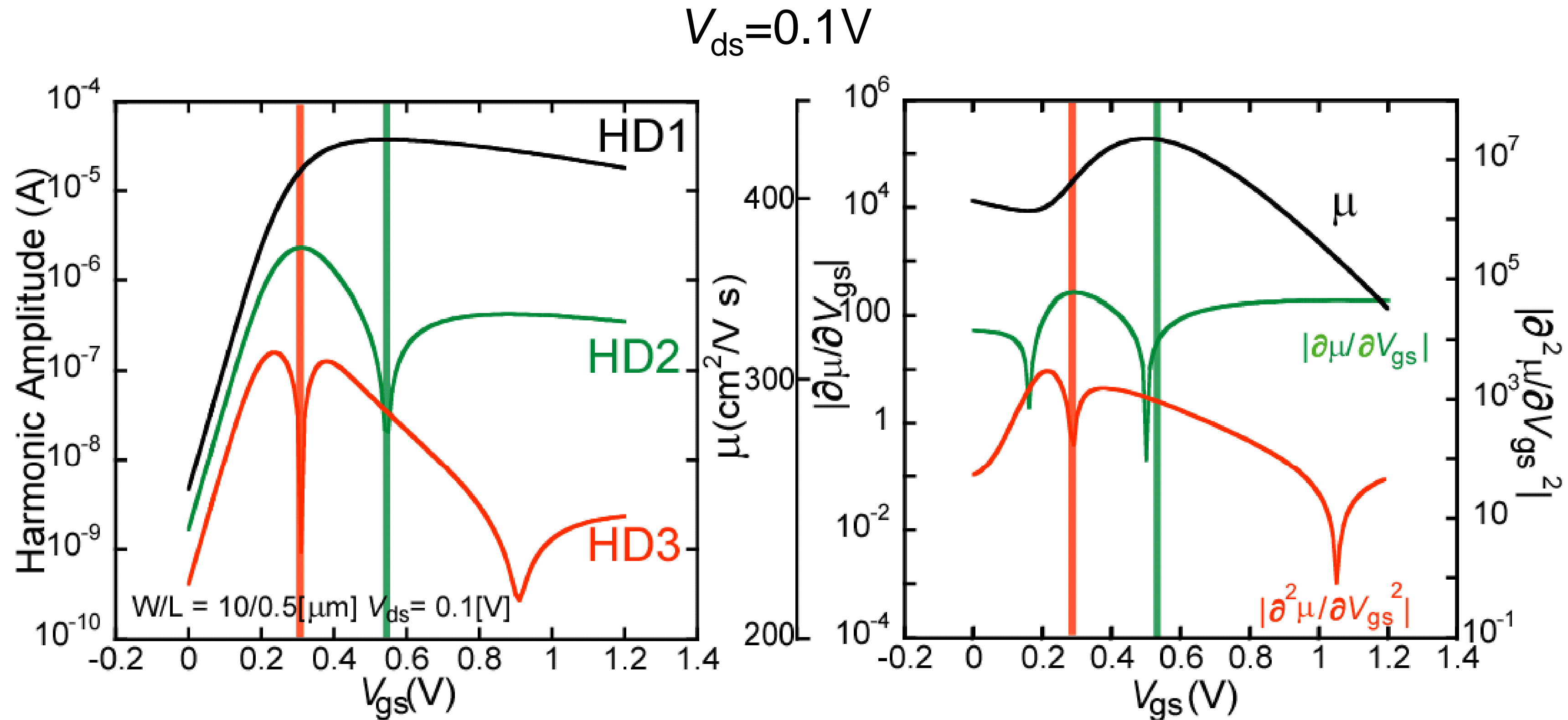
Harmonic Distortion



HD characteristics are acquired automatically.

S. Chiba et a., Oyo Butsuri Spring Meeting, 28p-ZL-4, 2003.

Harmonic Distortion vs. Mobility

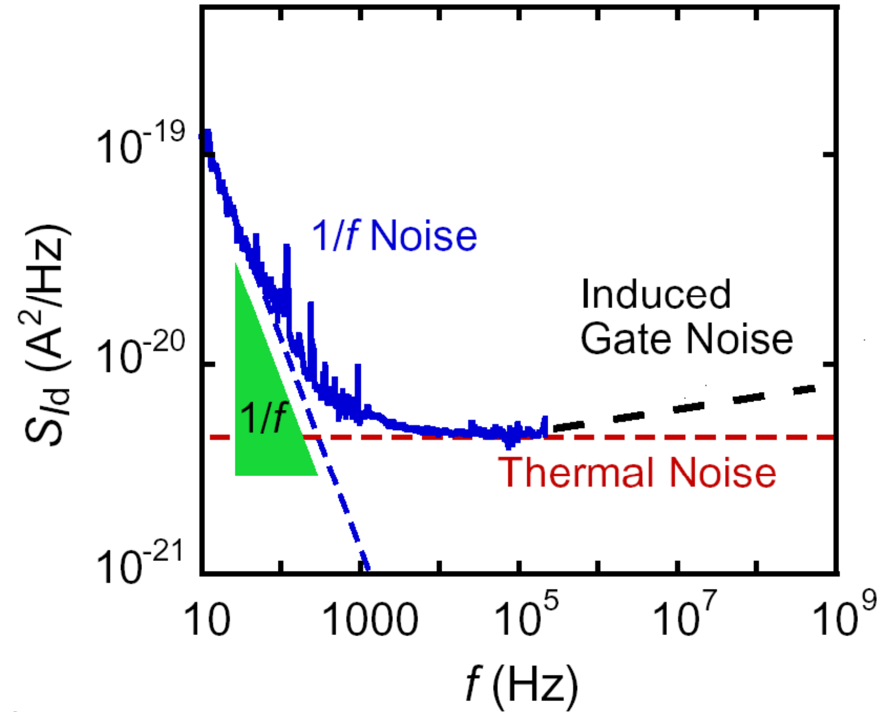


$$\mathrm{HD1} \approx \left| V_P \frac{\partial I_{ds}}{\partial V_{gs}} \right| \qquad \mathrm{HD2} \approx \left| -\frac{1}{4} V_P^2 \frac{\partial^2 I_{ds}}{\partial V_{gs}^2} \right| \qquad \mathrm{HD3} \approx \left| -\frac{1}{24} V_P^3 \frac{\partial^3 I_{ds}}{\partial V_{gs}^3} \right|$$

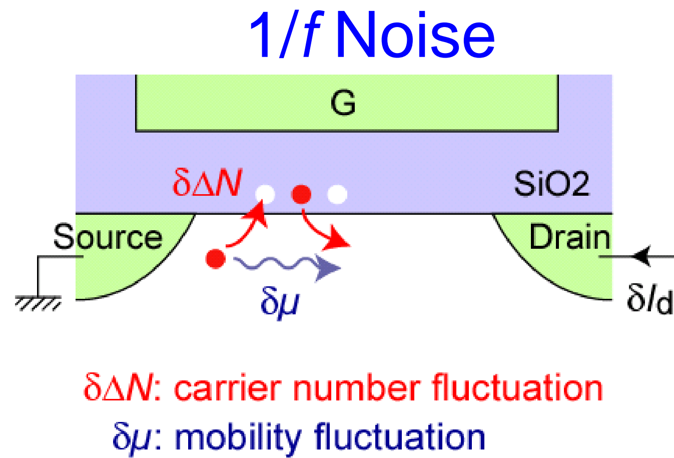
D. Navarro et al., IEEE T. ED, p. 2025, 2006.

Mobility determines the harmonic distortion characteristics.

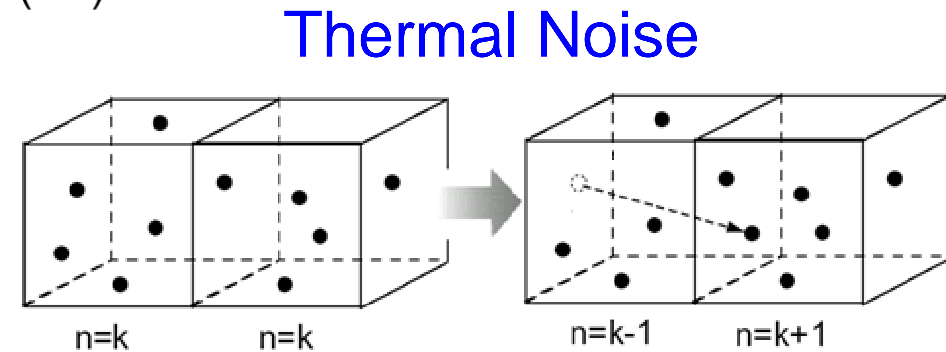
Noise Characteristics



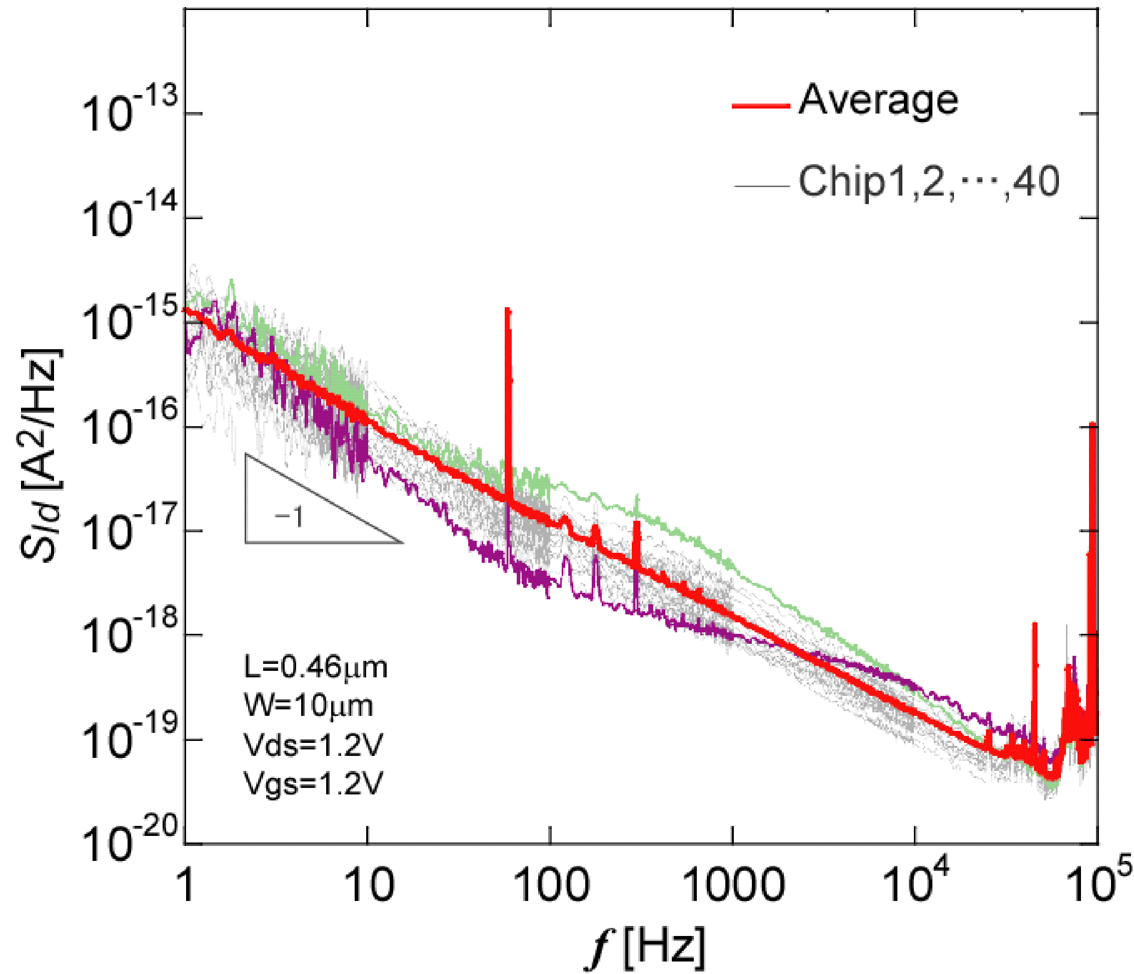
1/*f* Noise

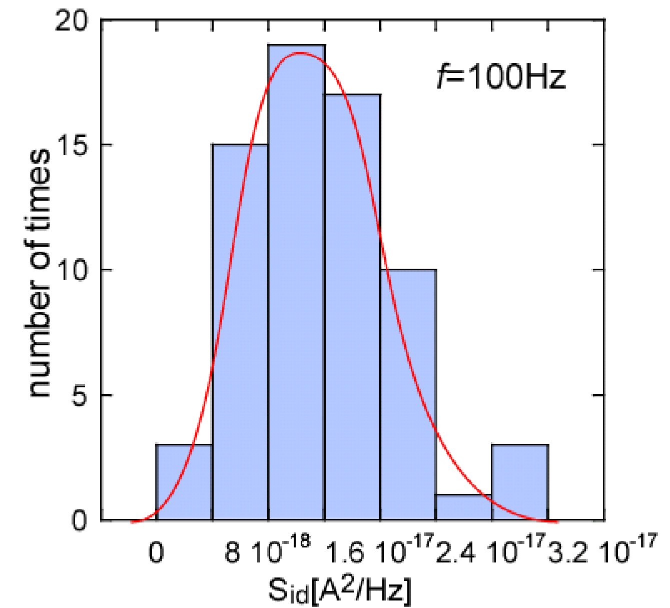


Thermal Noise



1/*f* Noise Measurements

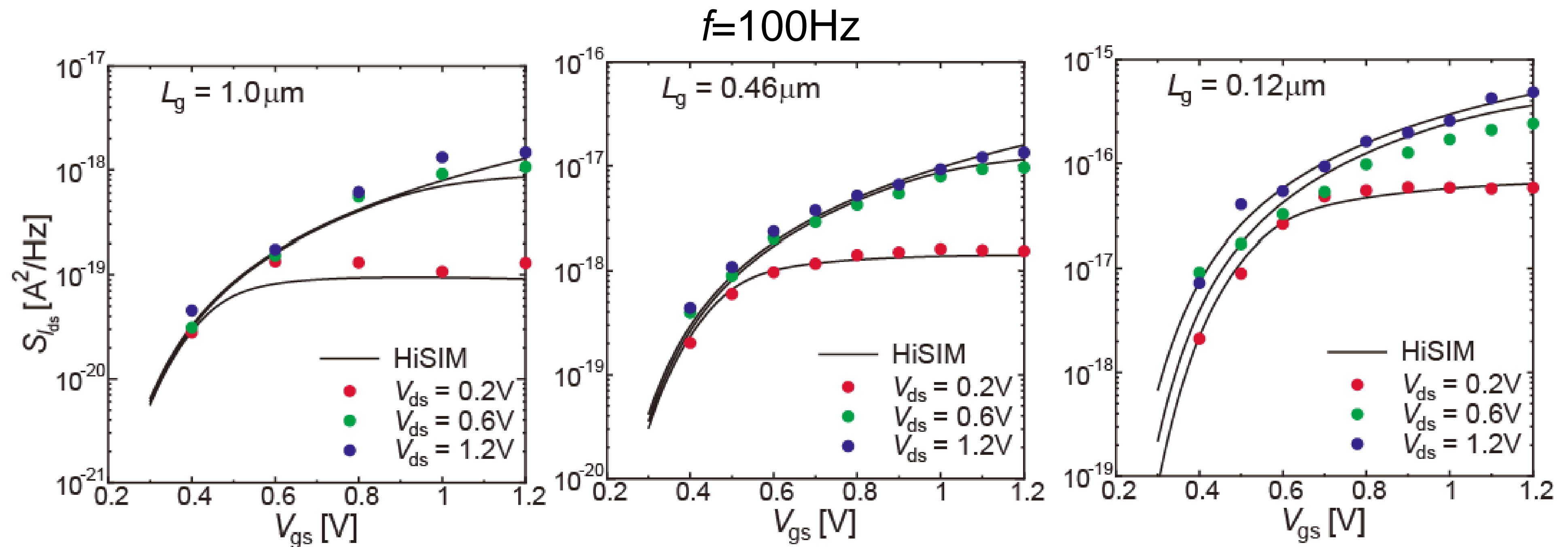




Averaged noise preserves the 1/f characteristic.

Comparison with Measured Noise

Modeled with carrier distribution along the channel



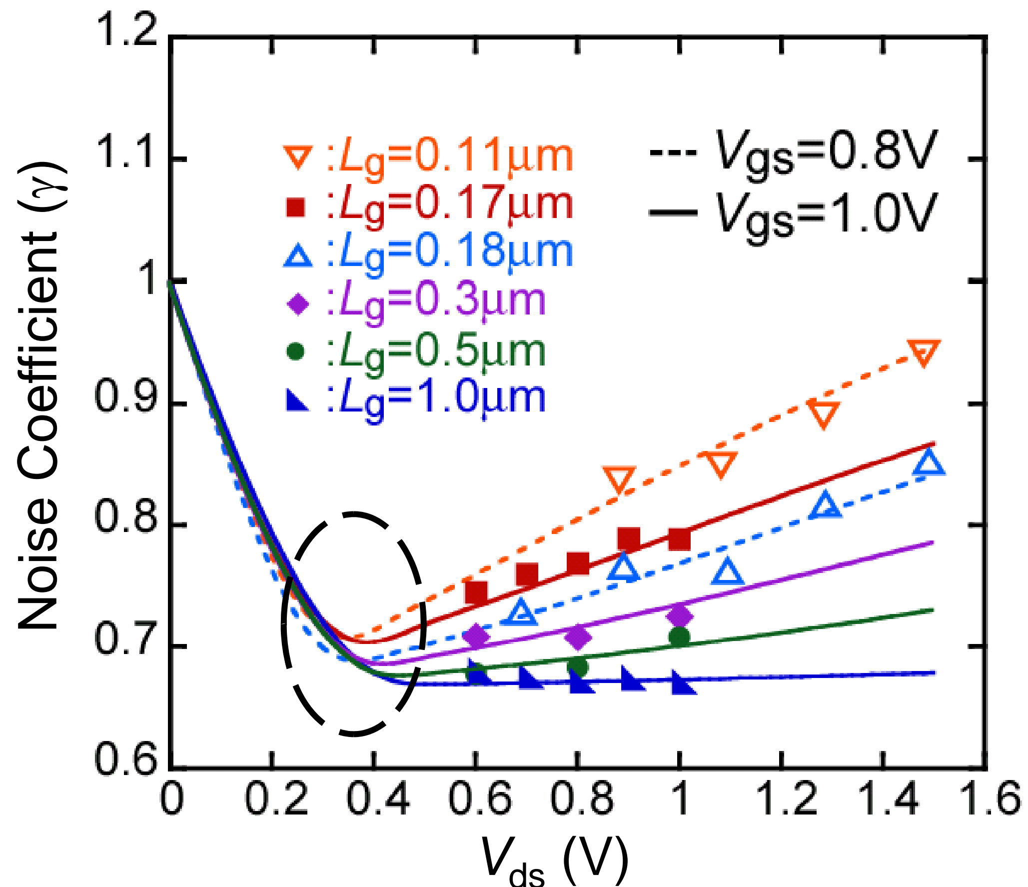
2 model parameters trap density & scattering coefficient

S. Matsumoto, Master Thesis, Hiroshima University, 2002.
S. Matsumoto et al., IEICE TE, vol. E88-C, pp. 247, 2005.

Thermal Noise

γ: Noise Coefficient;

$$S_{id} = 4kTg_{ds0}\gamma$$

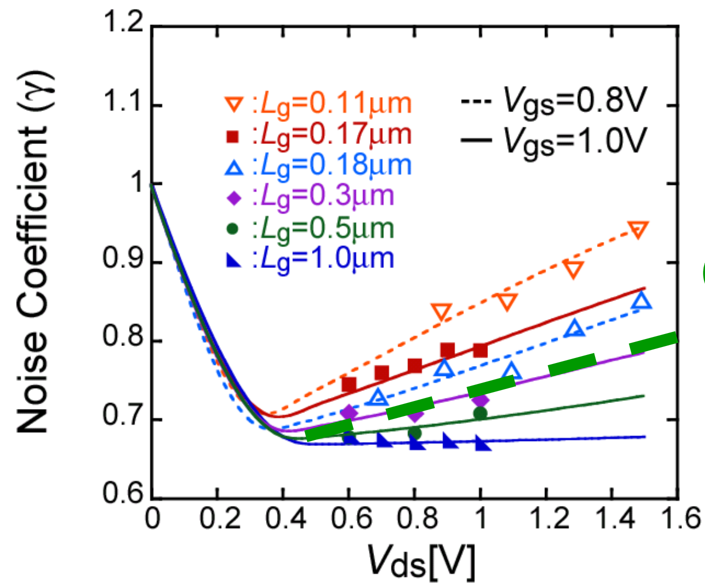


lines: HiSIM
symbols: measurements

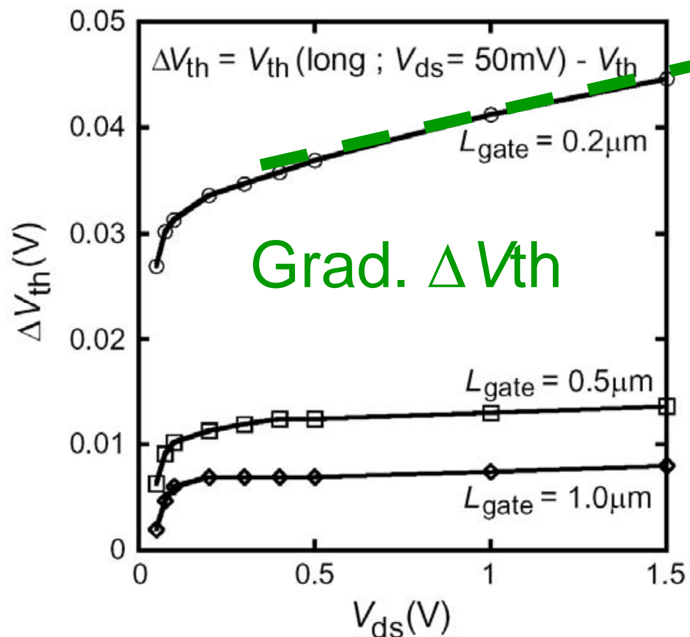
Potential distribution along the channel determines thermal noise characteristics.

S. Hosokawa et al., Ext. Abs. SSDM, pp. 20, 2003.

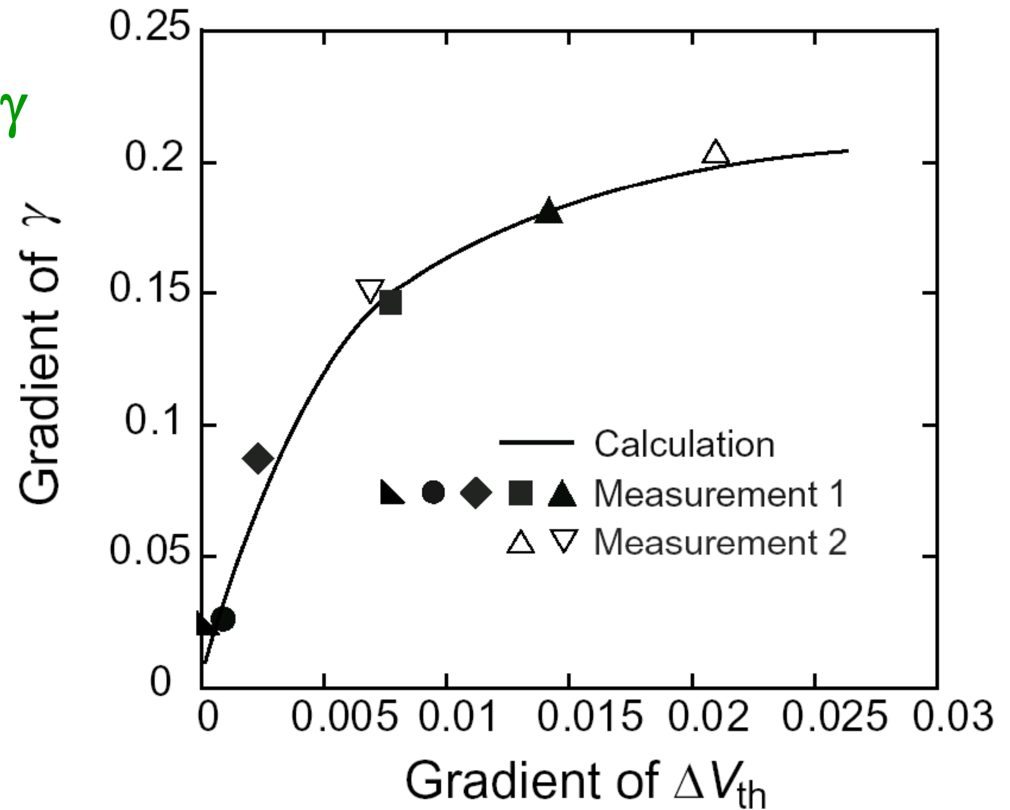
Thermal Noise vs. V_{th} Shift



Grad. γ



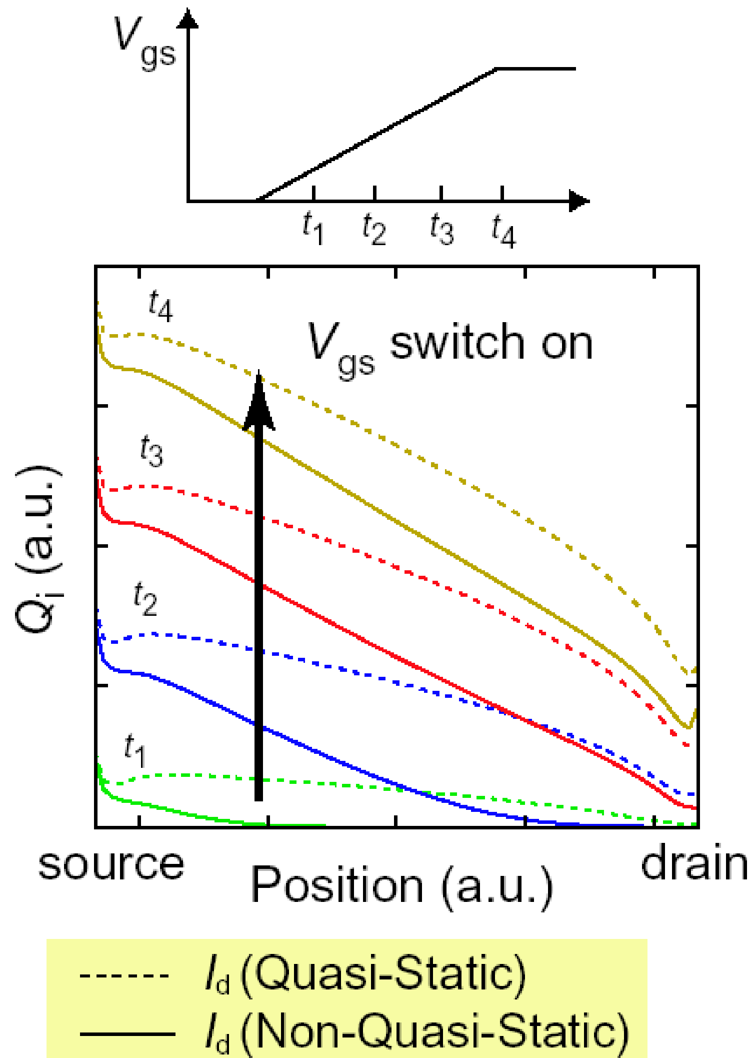
Grad. Δ Vth



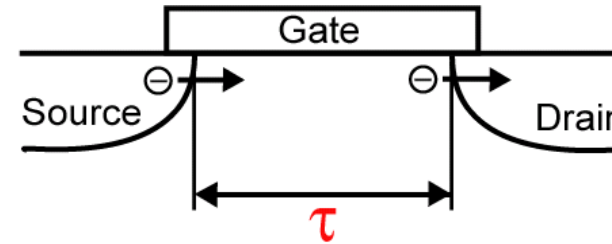
Universal relationship is observed.

S. Hosokawa et al., Appl. Phys. Lett., vol. 87, pp. 092104, 2005.

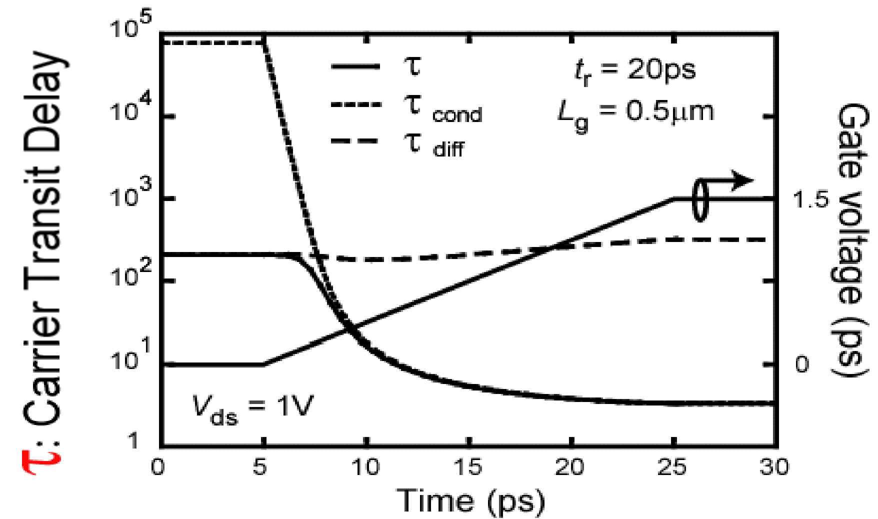
NQS Model



NQS: carrier transit delay



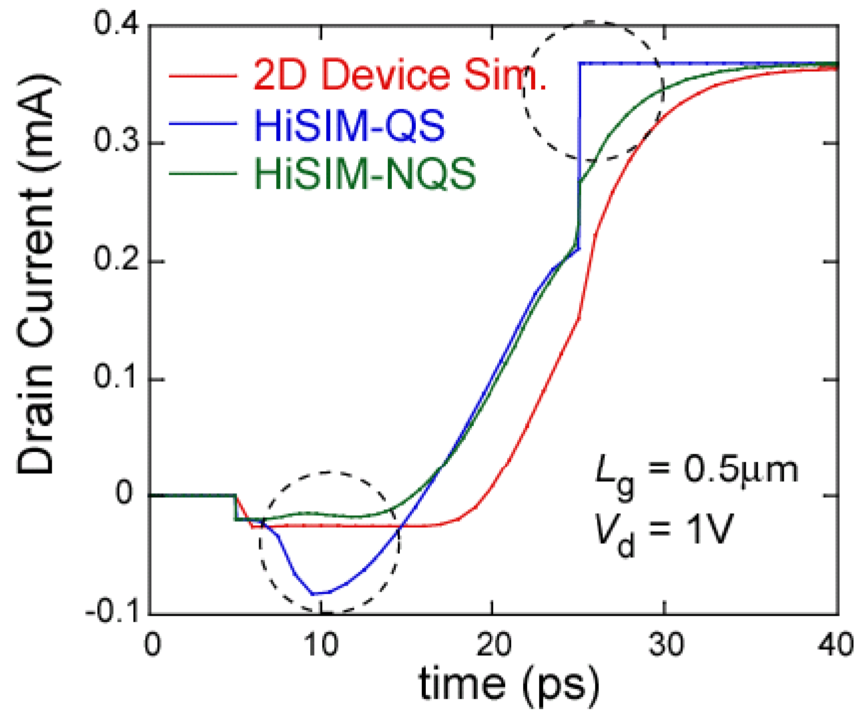
τ: Carrier Transit Delay
(function of surface potentials)

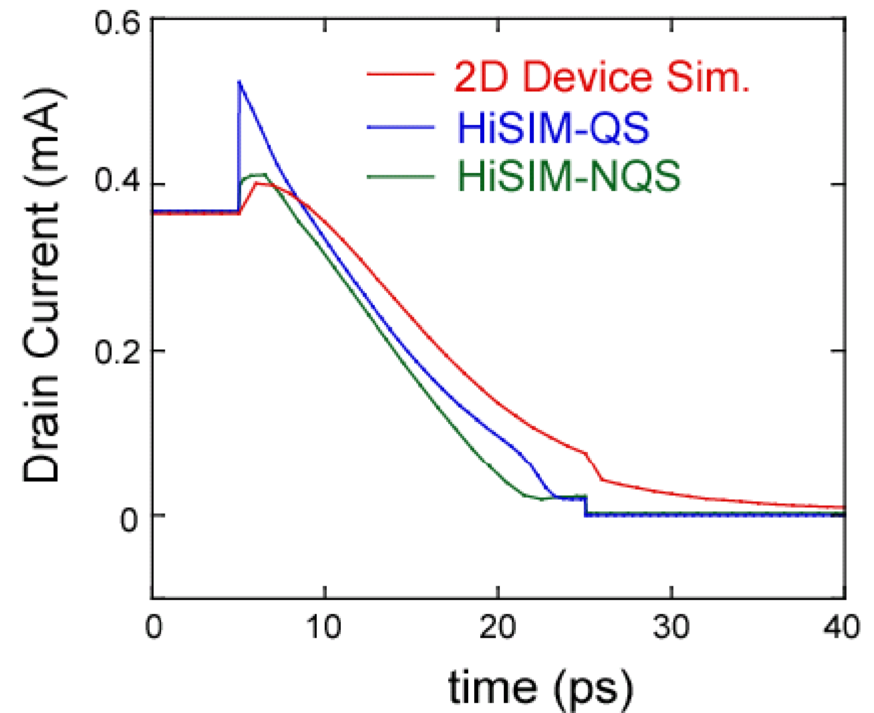


N. Nakayama et al., Ext. Abs. SSDM, p. 408, 2002.

Simulation Results

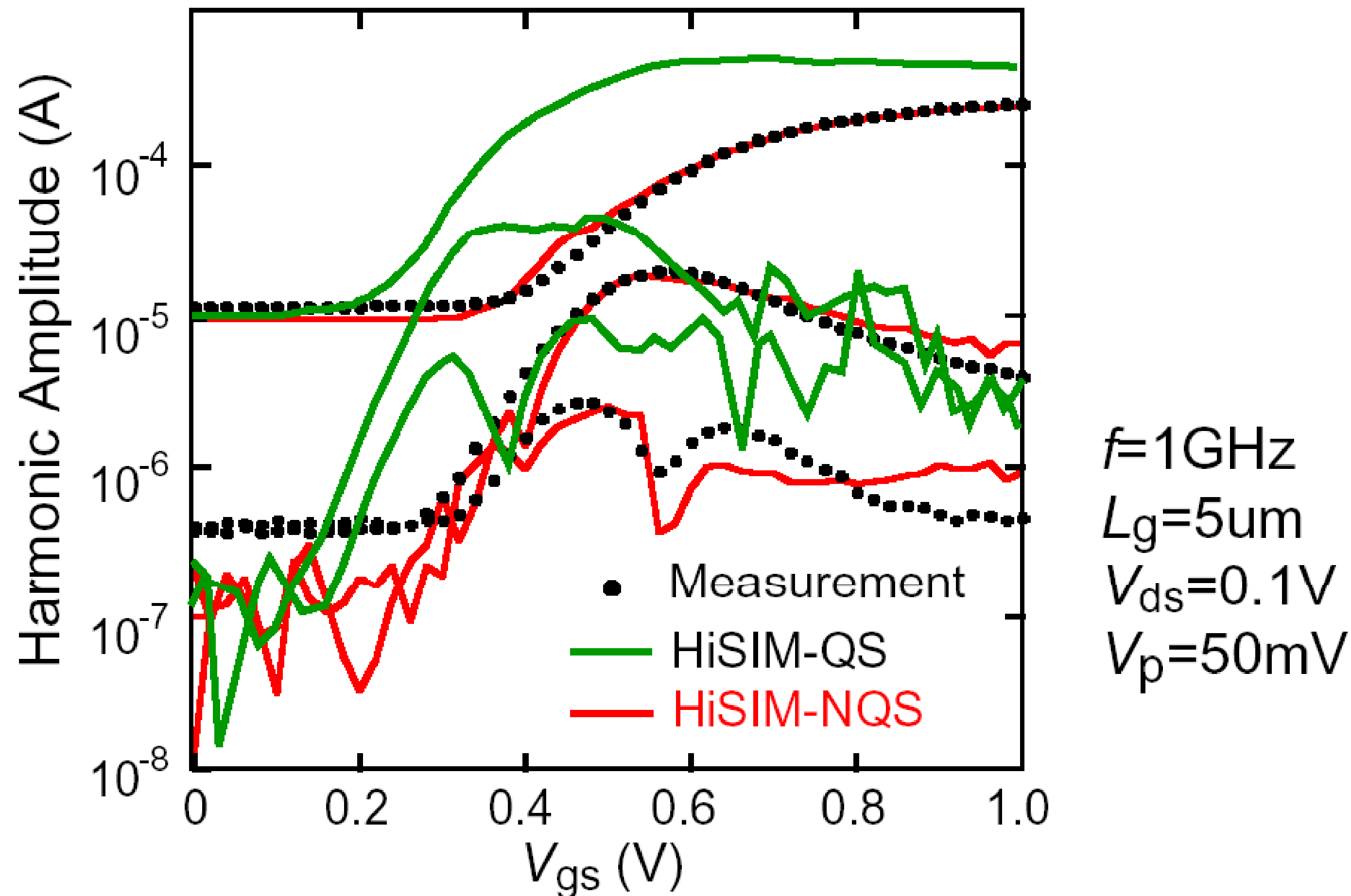
V_{gs}=1.5V   Rise / Fall Time = 20ps





D. Navarro et al., IEEE T. ED, p. 2025, 2006.

Comparison with Measurements

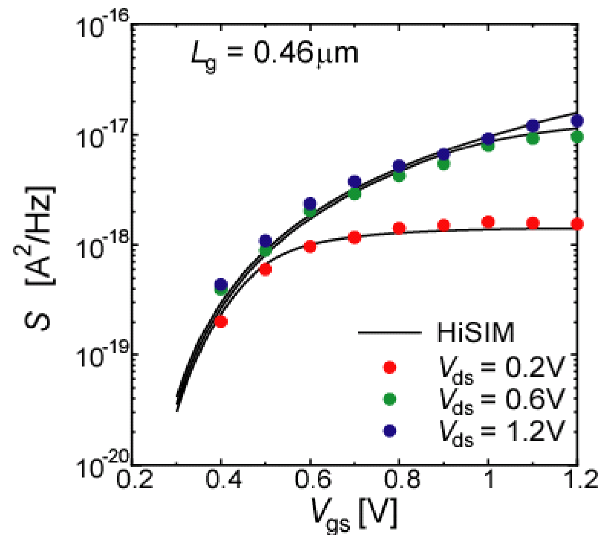


f=1GHz
L_g=5um
V_{ds}=0.1V
V_p=50mV

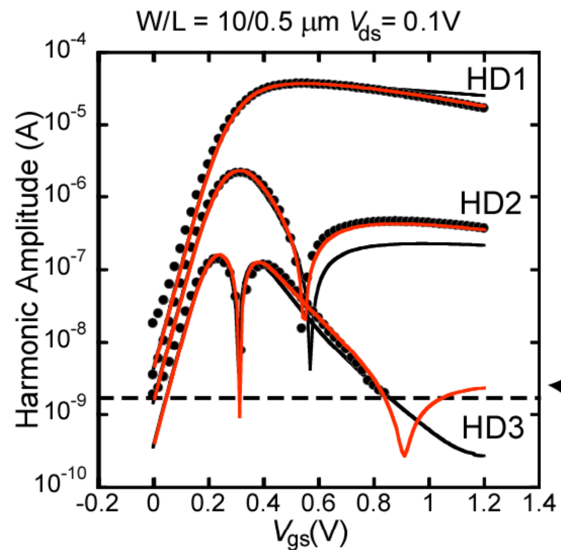
Y. Takeda et al., Proc. CICC, p. 827, 2005.

Observations

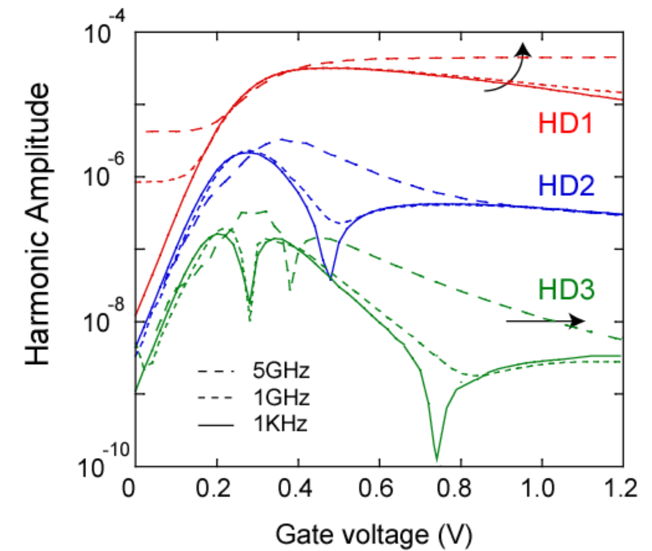
Noise



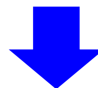
Harmonic Distortion



Non-Quasi-Static



✱ No additional model parameters are required for RF modeling.



Potential distribution determines device features.
Modeling based on the surface potential is the essence.

Contents

- Concept of HiSIM

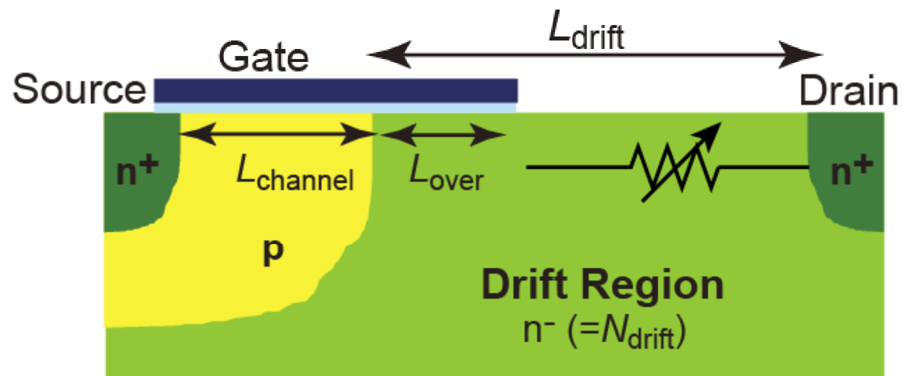
- Modeling of HiSIM2

- Extension to High-Voltage Transistors : HiSIM-HV

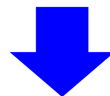
High-Voltage MOSFET Features

HV MOSFETs

Device Structure : Extension of Conventional MOSFETs



1. High Resistive Drift Region
2. Lateral Impurity Profile



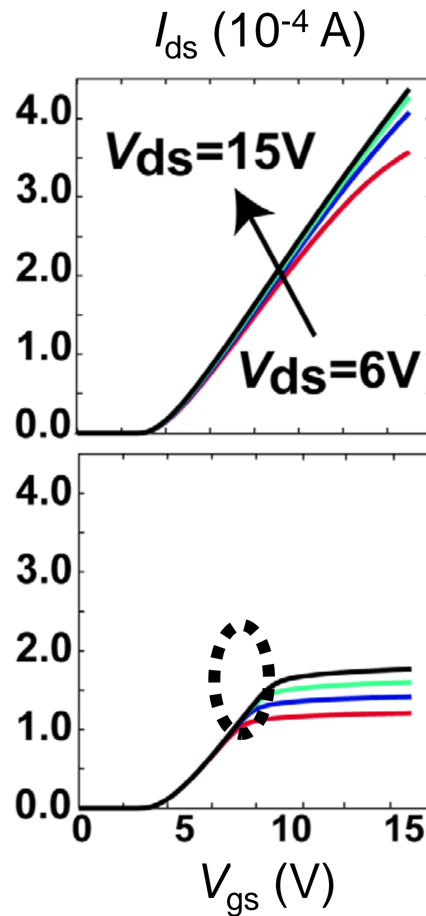
Application Range : a few volts ~ a few hundred volts

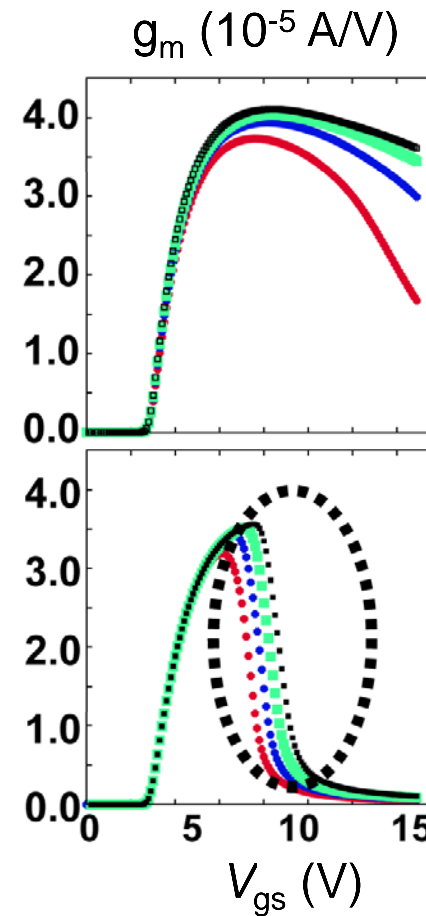
High-Voltage MOSFET Characteristics

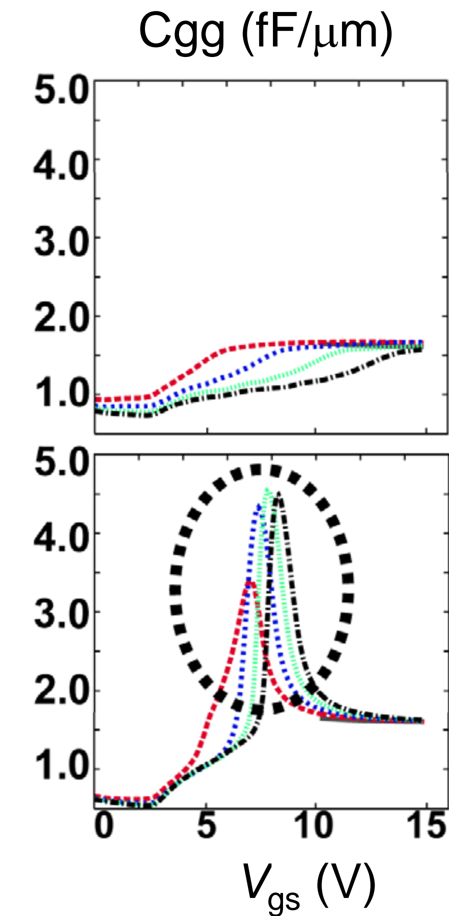
2D-Device Simulation

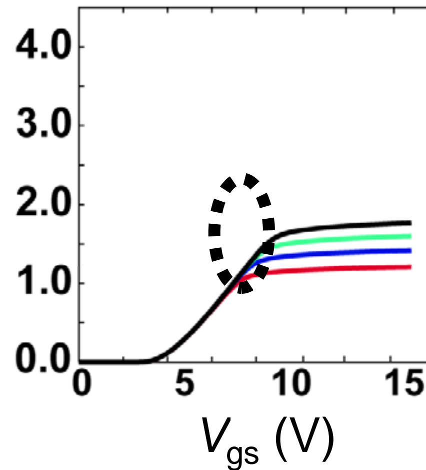
With
Lower Resistive
Drift region

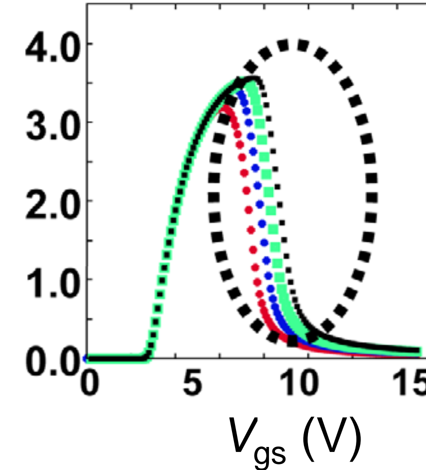
With
Higher Resistive
Drift region

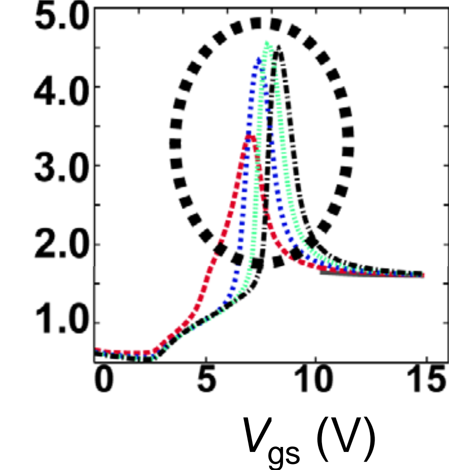






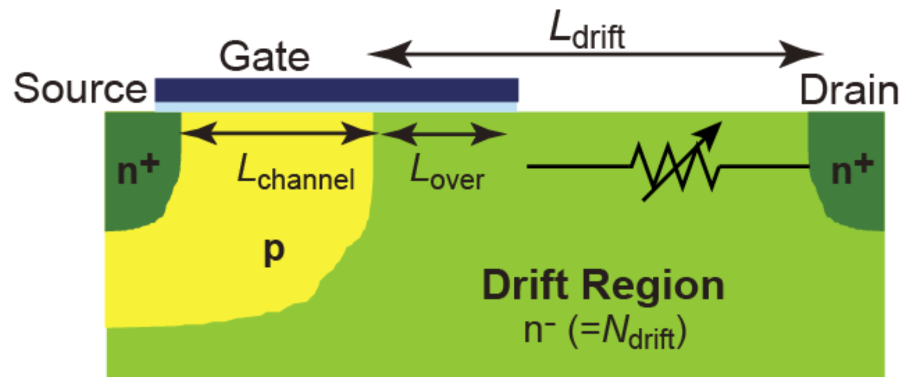






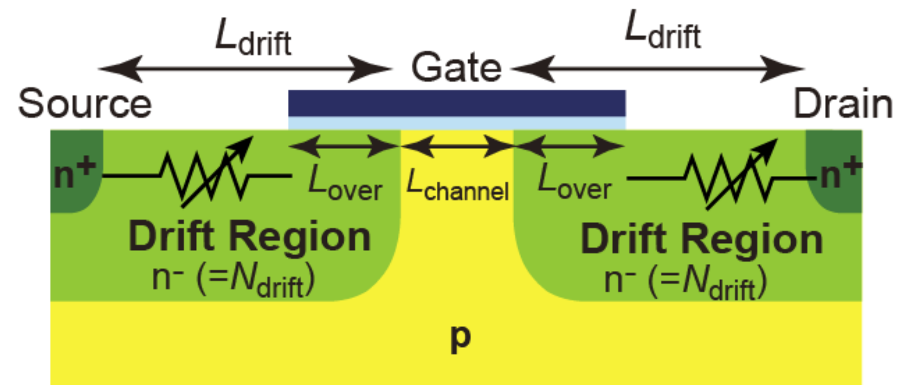
Modeling HV MOSFETs

Laterally-Diffused MOS



Asymmetrical

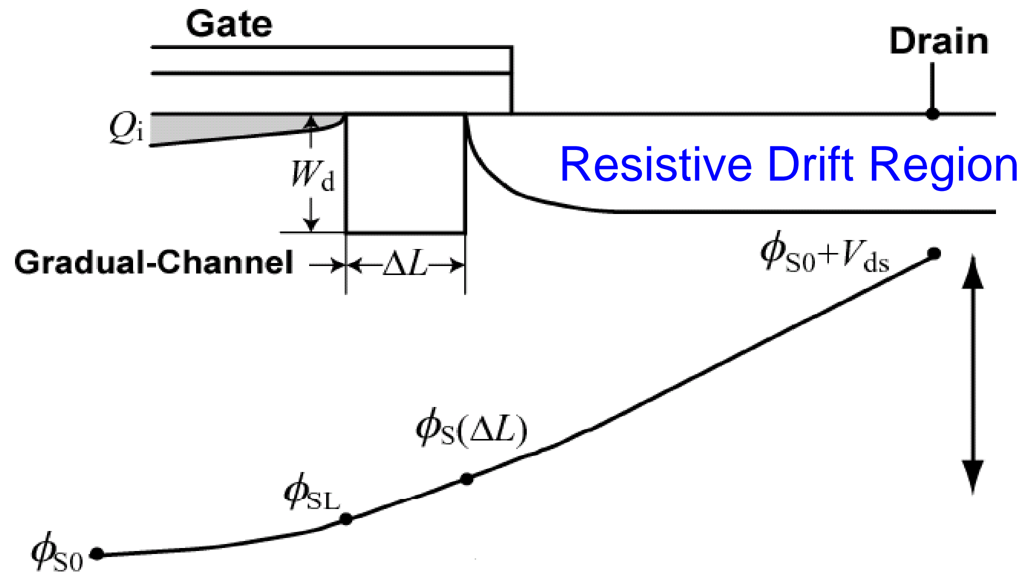
High-Voltage MOS



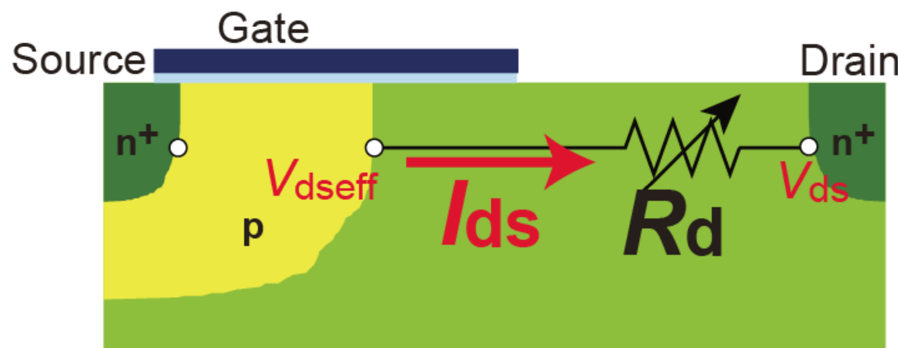
Symmetrical

Task: modeling effects caused by high resistive drift region

HiSIM-HV: Complete Surface-Potential-Based Model



Potential drop in the drift region

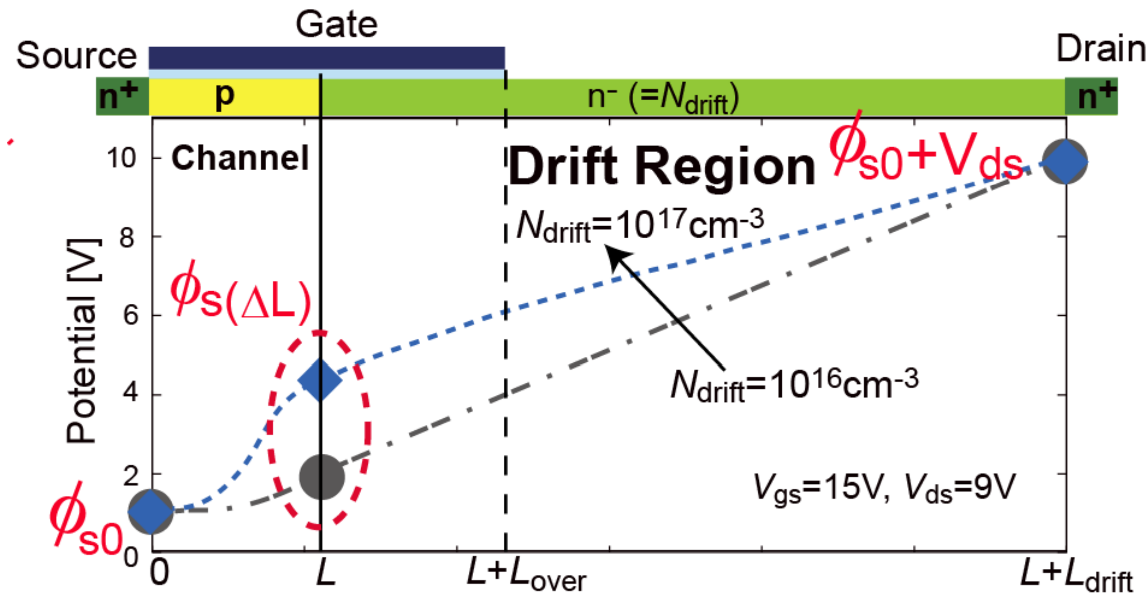


$$V_{dseff} = V_{ds} - R_d \times I_{ds}$$

: solved iteratively

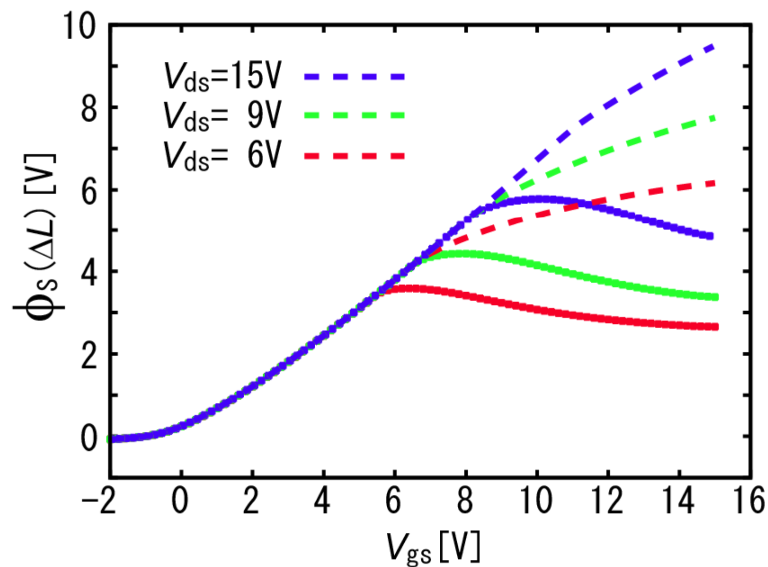
Potential distribution along the device is considered.

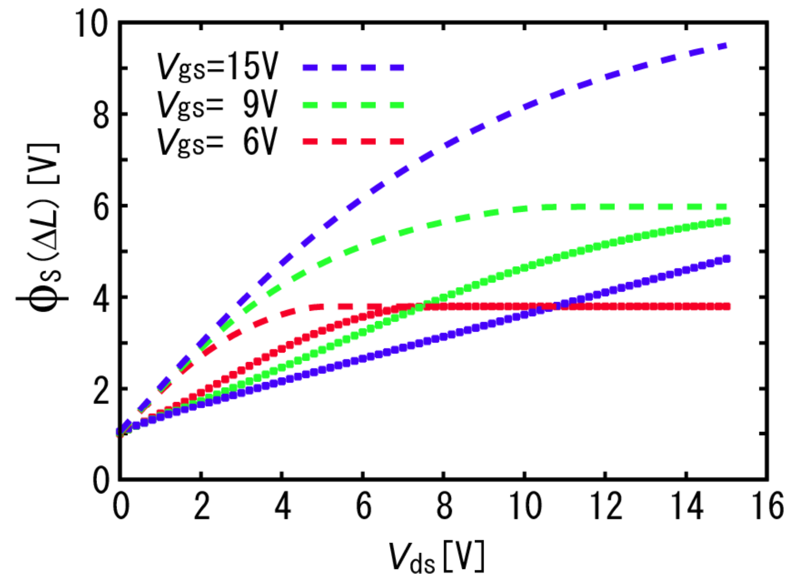
Calculated Potential Distribution



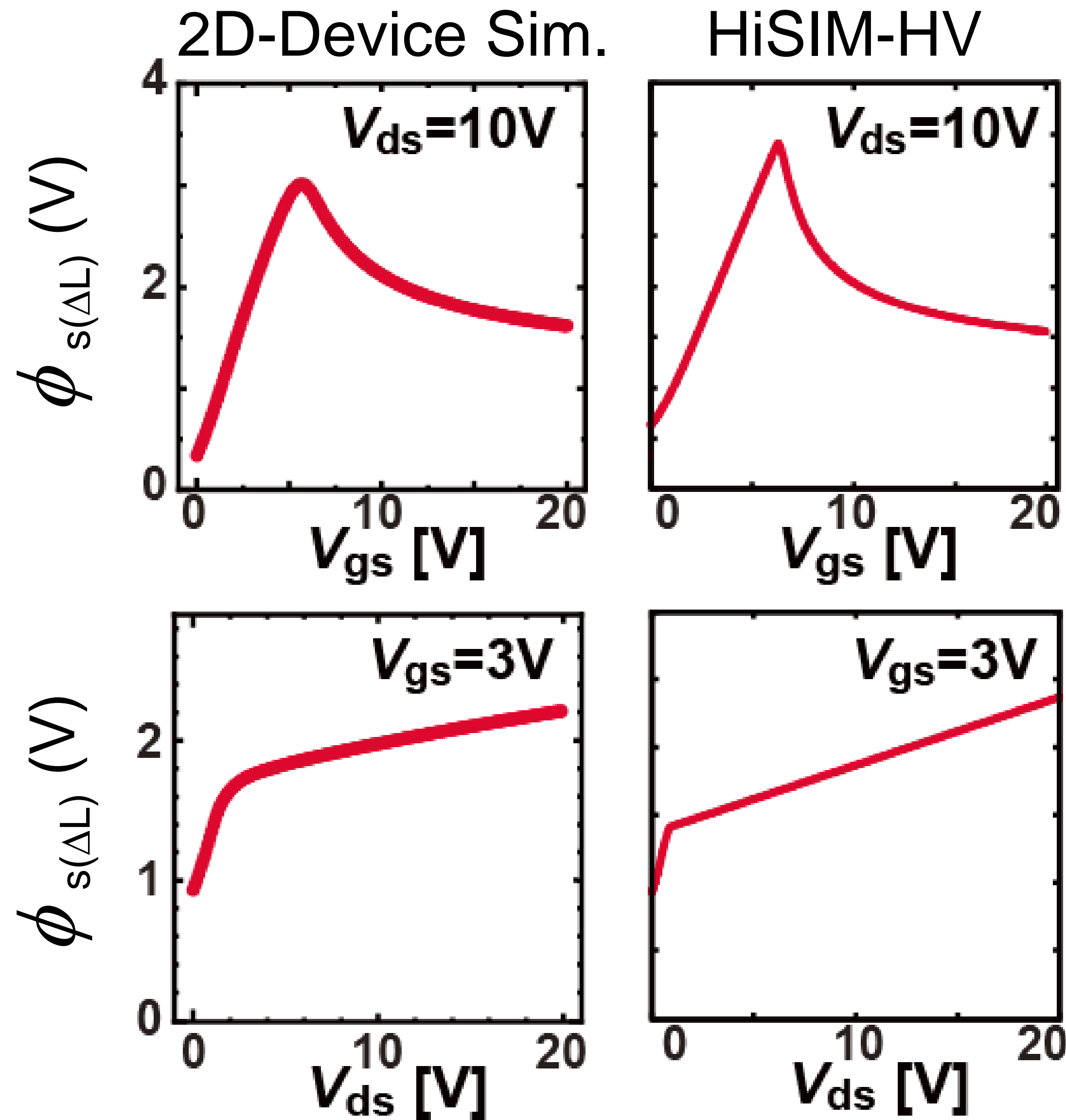
Symbol: HiSIM-HV
Line : 2D-Device

Solid Line: W/ Resistance
Dashed Line: W/O Resistance



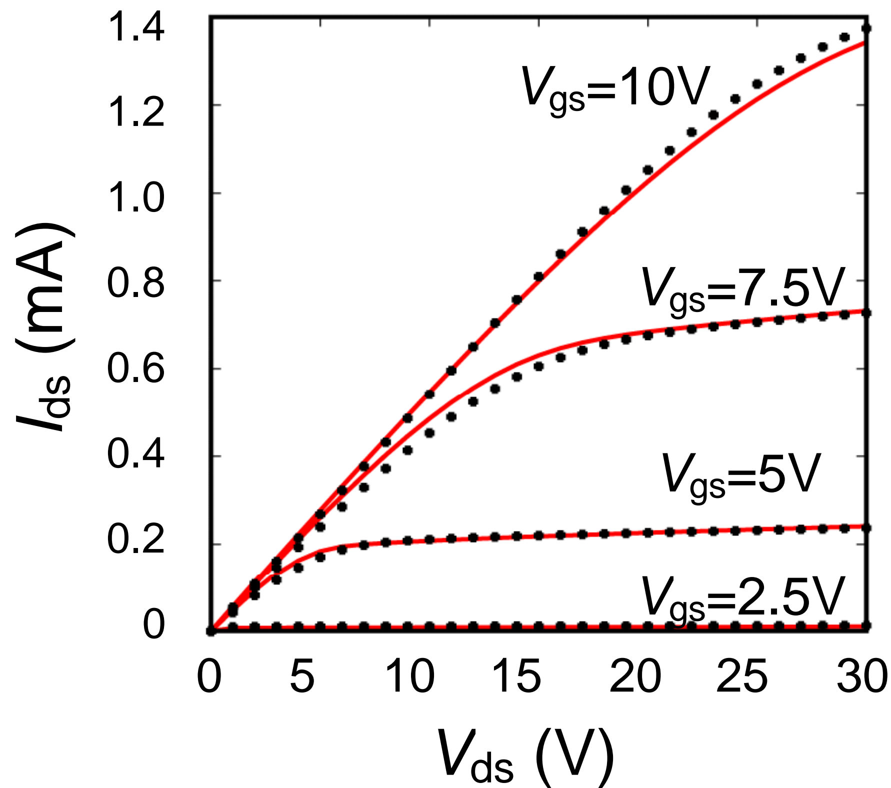


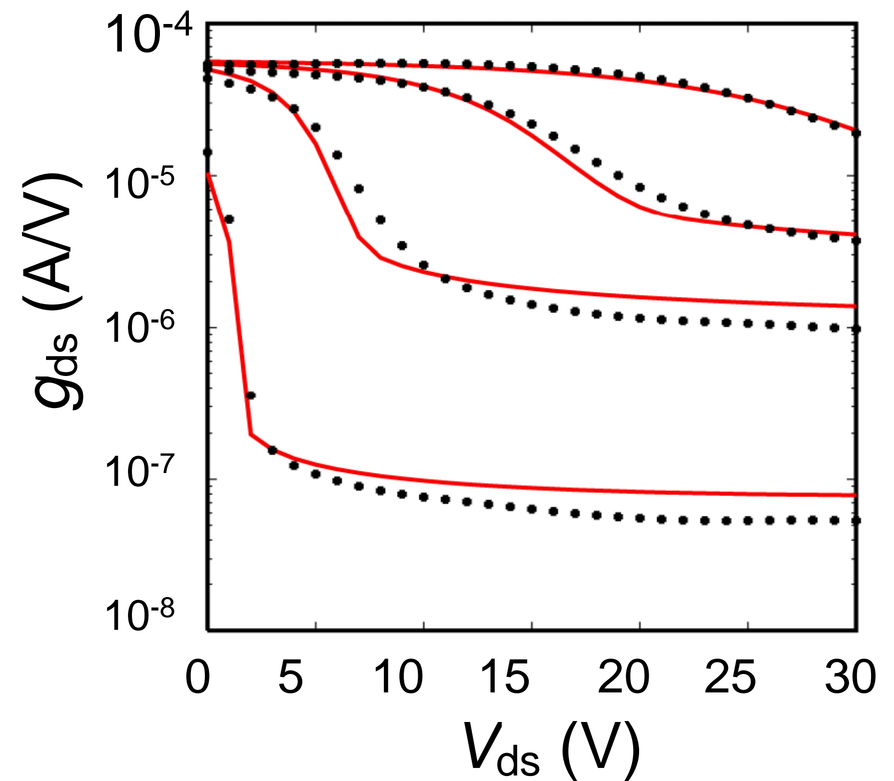
Accuracy of Potential Characteristics



Comparison of I_{ds}-V_{ds}

● : 2D-Device Simulation Results
— : HiSIM-HV Results

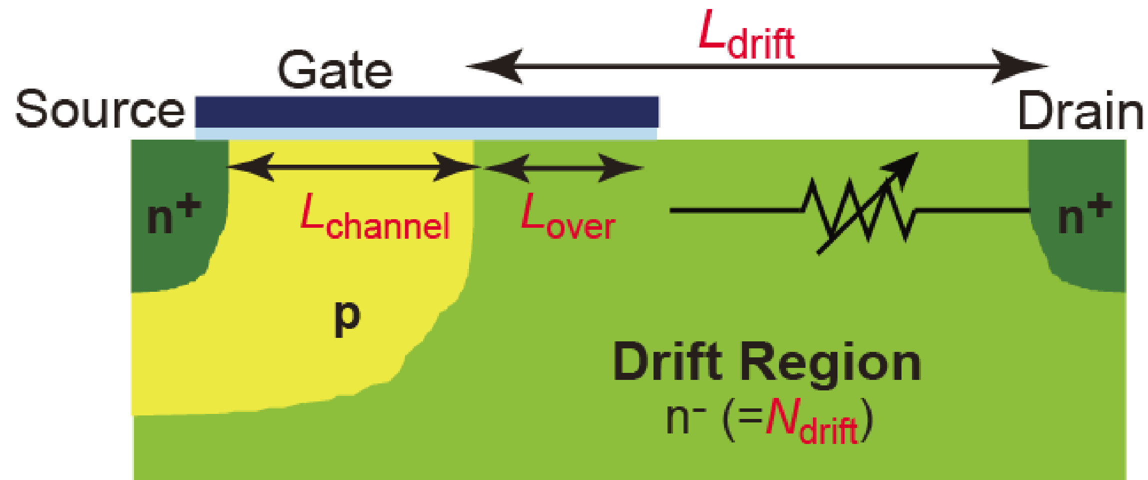




Device Optimization

For *Voltage Endurance* and *Drive Current* control

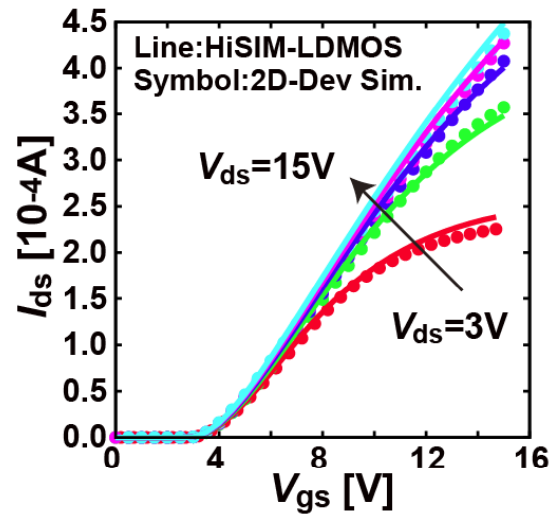
Possible device parameters for device optimization

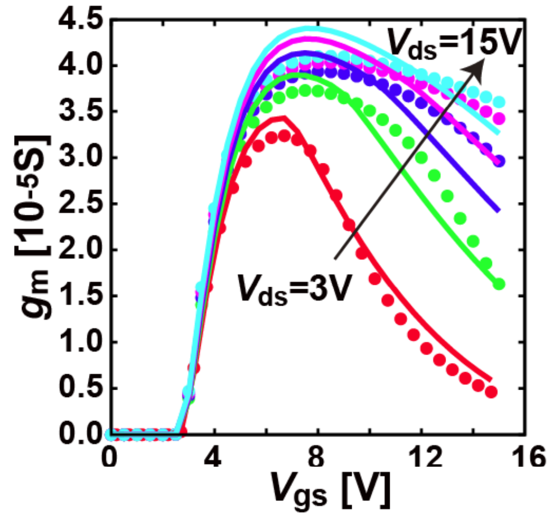


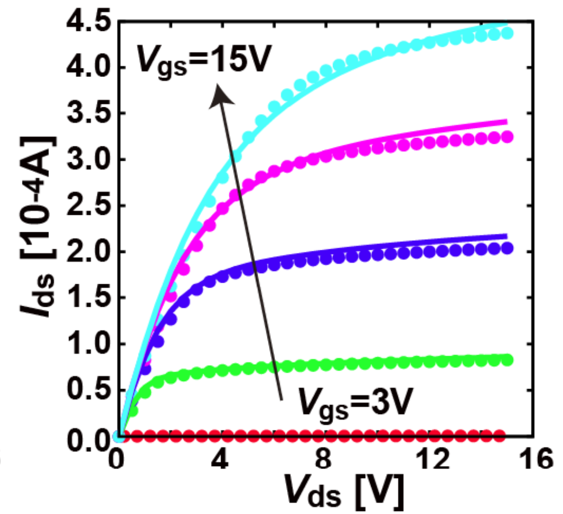
➡ L_{drift}, N_{drift} } are major device parameters.

N_{drift} Dependence

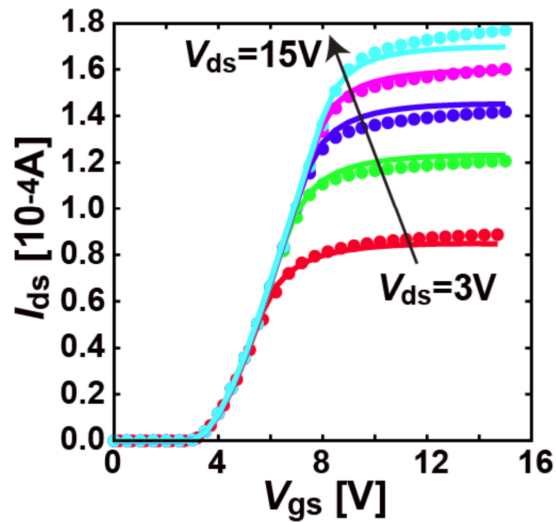
$N_{drift} = 10^{17}$ cm^{-3}

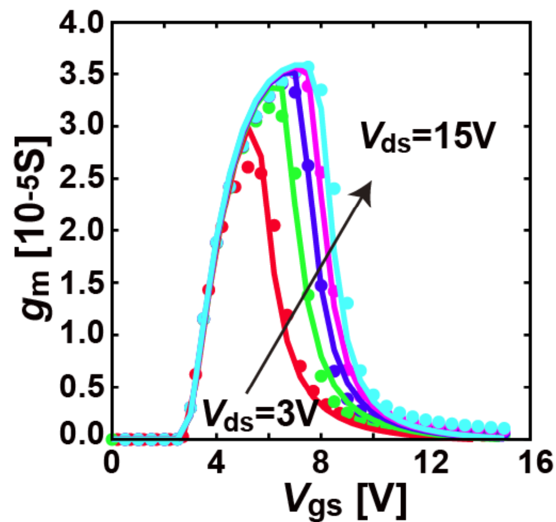


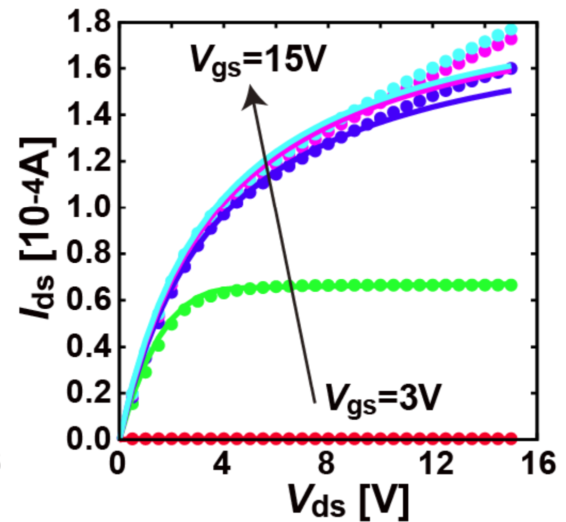




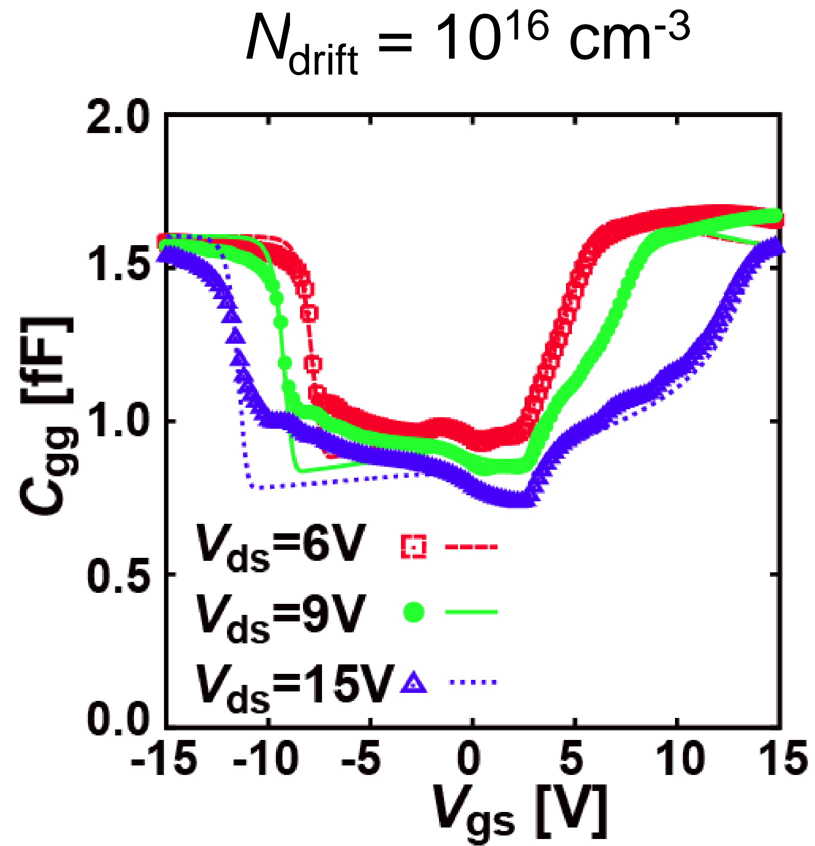
$N_{drift} = 10^{16}$ cm^{-3}

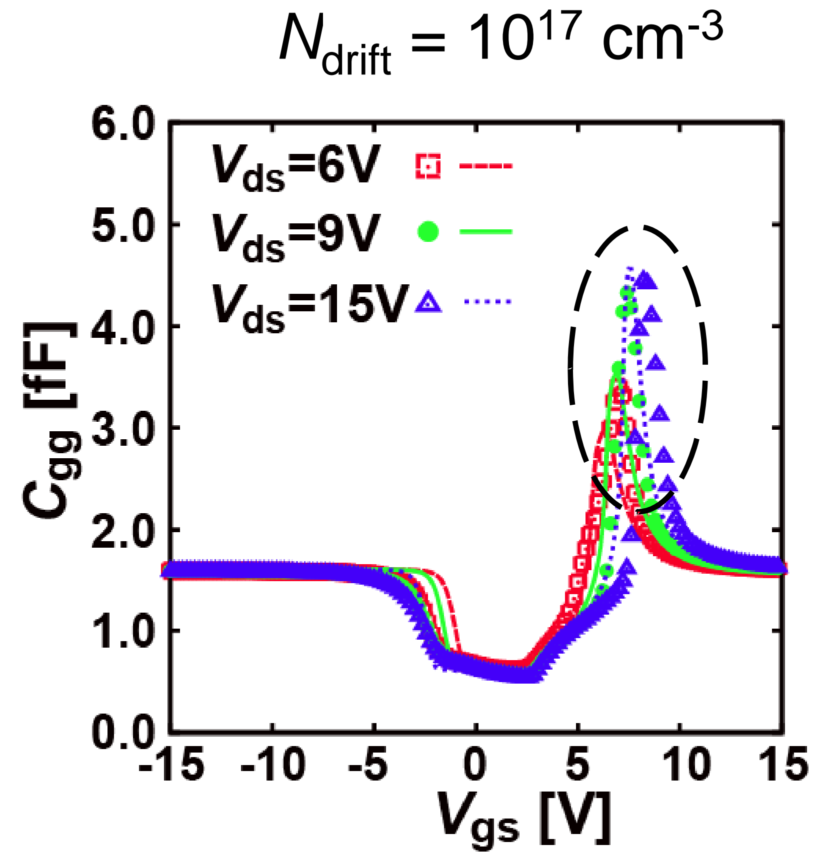




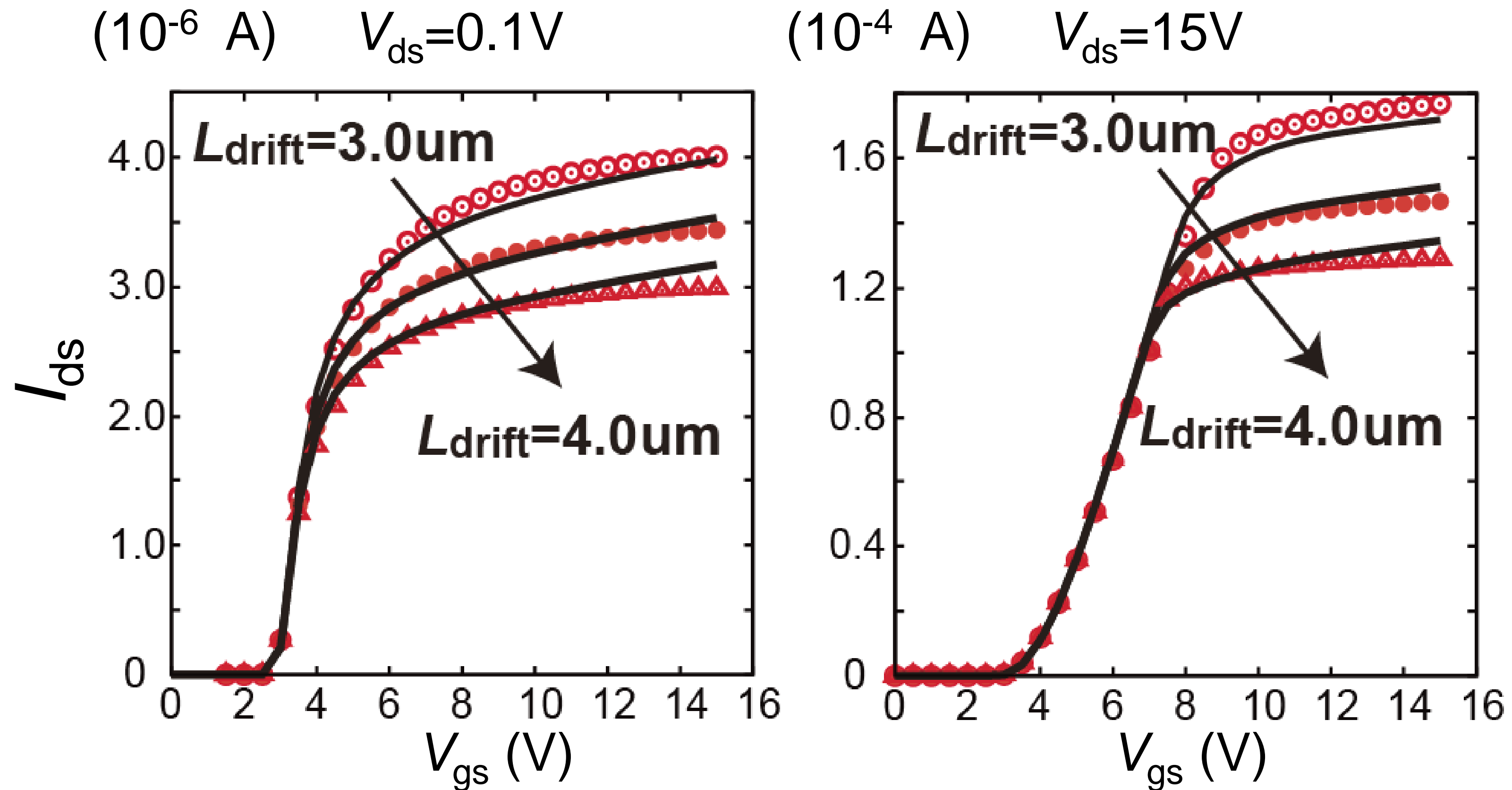


N_{drift} Dependence (Cont'd)



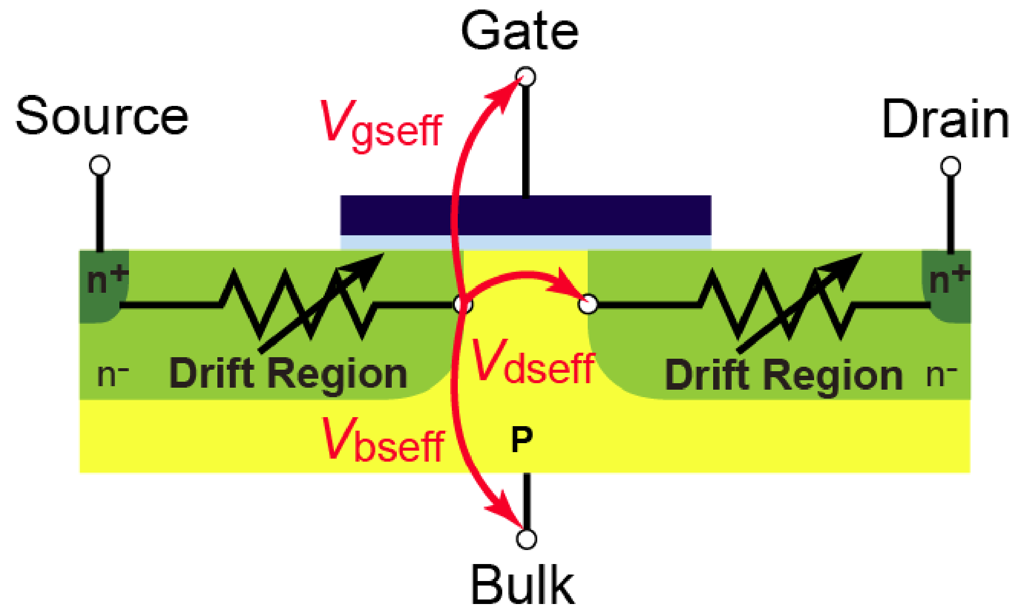


L_{drift} Dependence



HiSIM-HV is applicable for device optimization

Symmetrical HV-MOS

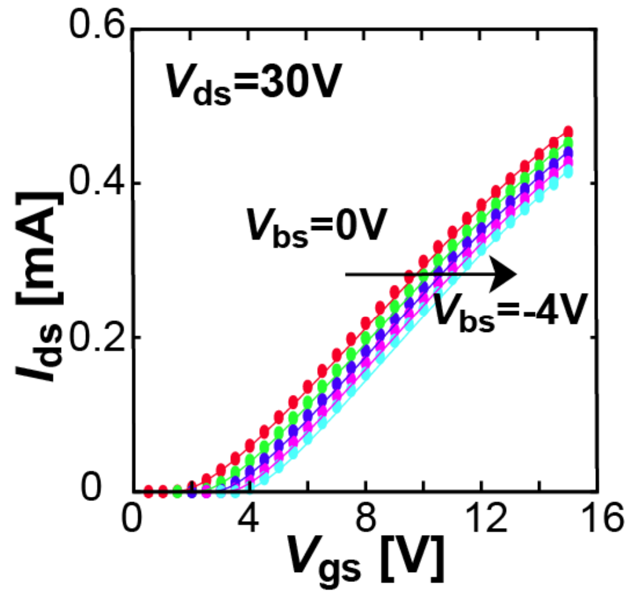


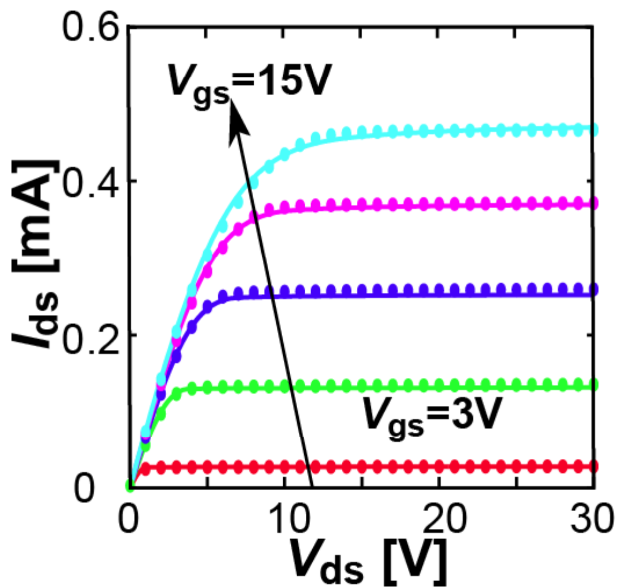
$$V_{gseff} = V_{gs} - R_s \times I_{ds}$$

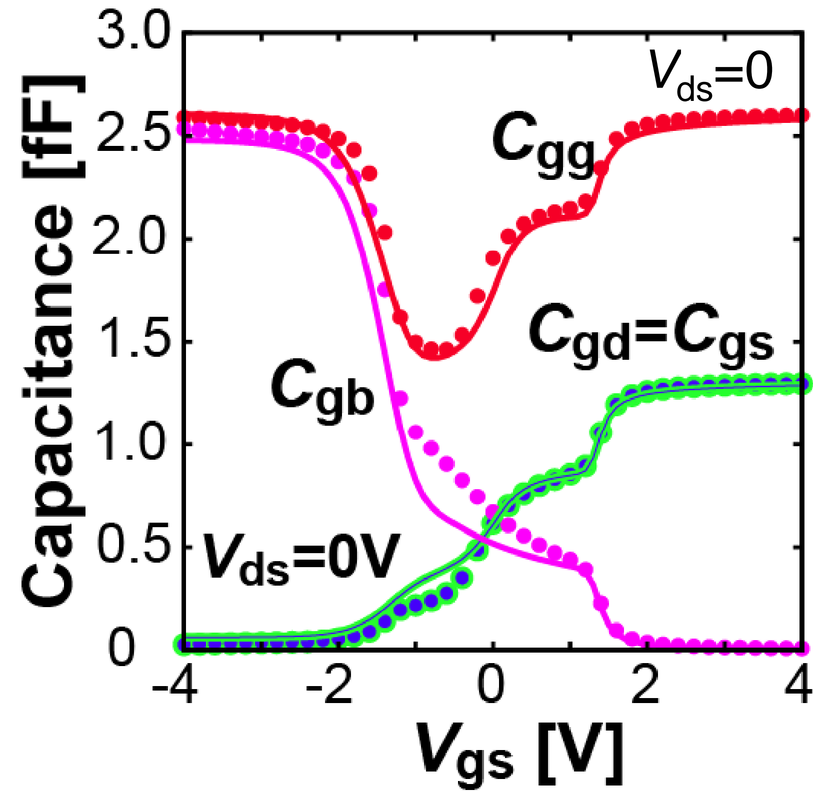
$$V_{dseff} = V_{ds} - (R_s + R_d) \times I_{ds}$$

$$V_{bseff} = V_{bs} - R_s \times I_{ds}$$

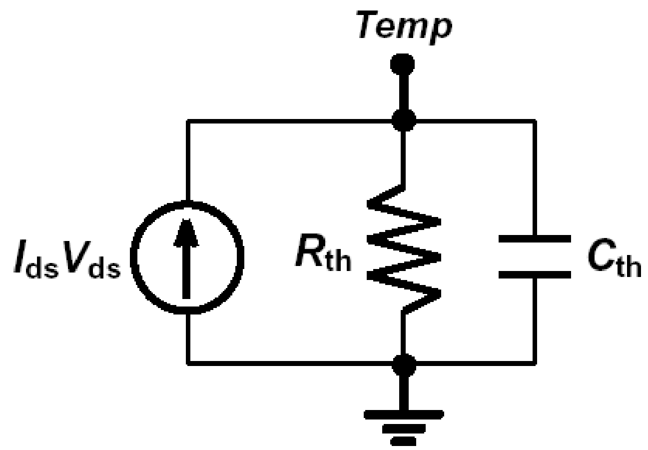
Device Characteristics



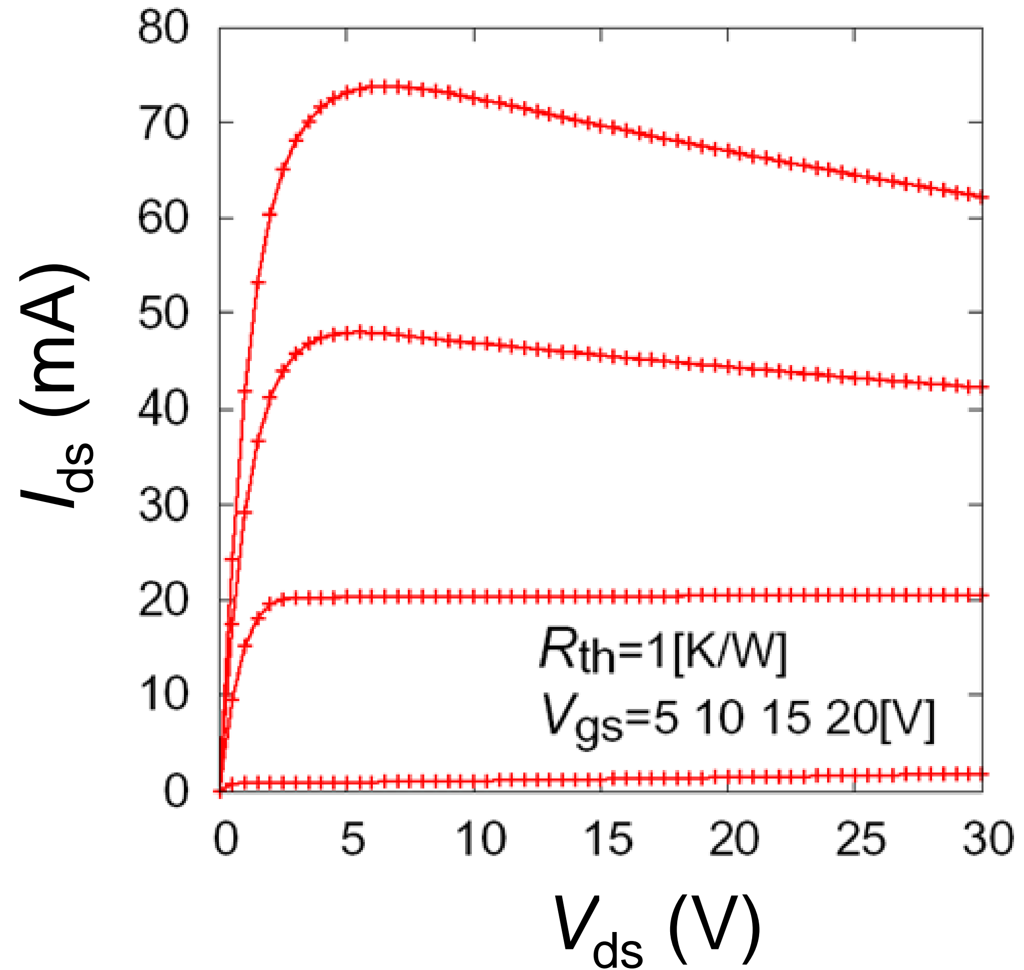




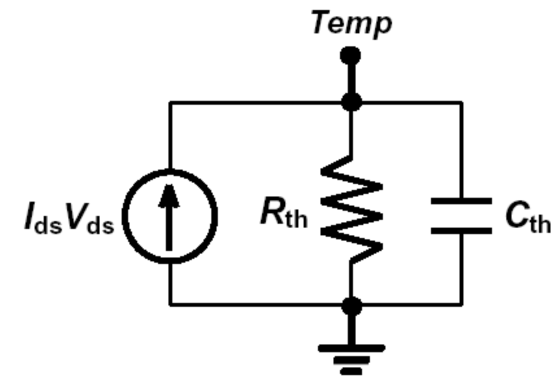
Self-Heating Effect for DC Analysis



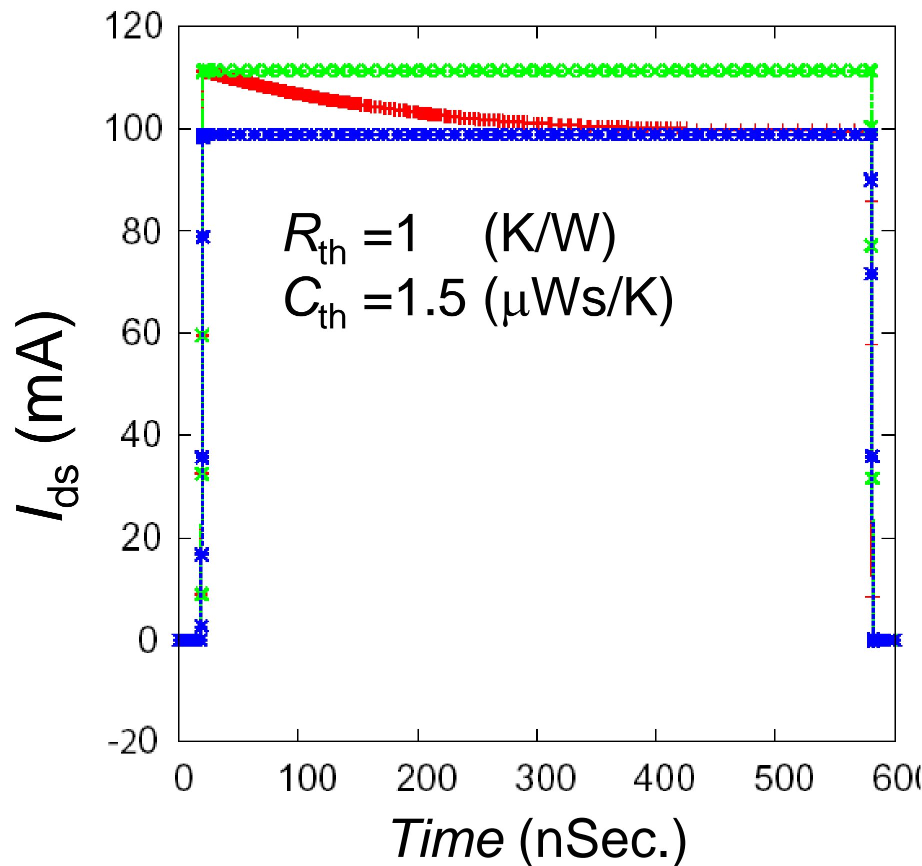
Thermal-Network

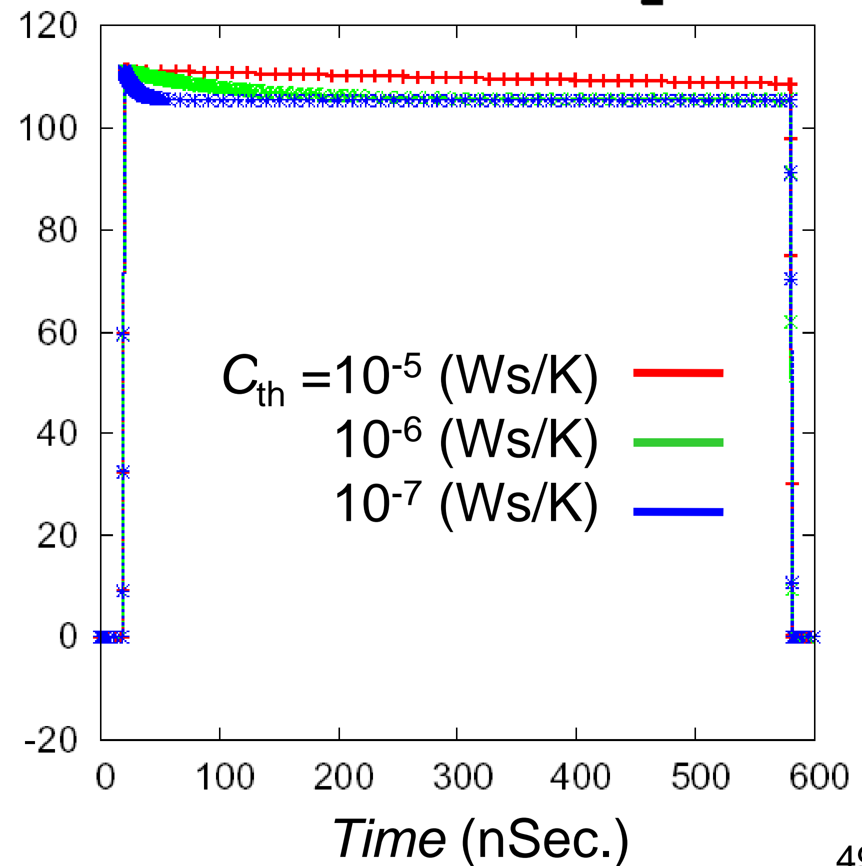


Self-Heating Effect for Transient Analysis



With Self Heating Model
Fixed Temperature @300K
@380K





Summary

✱ HiSIM is the 1st complete surface-potential-based model for advanced MOSFETs.

✱ Modeling of the impurity profile is the core for the modeling.

✱ The potential distribution along the channel determines higher-order phenomena such as noise characteristics.

✱ HiSIM-HV has been developed based on the complete surface-potential description and applicable for device optimizations.

Acknowledgment

This work was supported by STARC and NEDO.
We would like to express their sincere thanks for the supports.