

Advanced Compact MOSFET Model HiSIM2 Based on Surface Potentials with a Minimum Number of Approximations

WCM, May 2006, Boston

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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
1994 ICCAD	“	parameter extraction strategy
1995 Siemens	Flash-EEPROM	simulation time & stability verification
1998 STARC	100-nm MOSFET	concurrent device/circuit development
		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	“

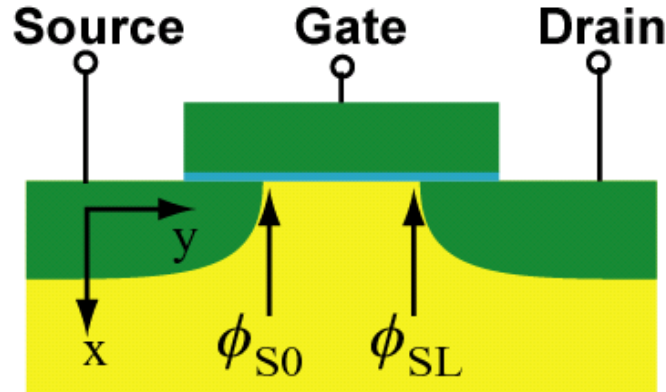
Outline

- **Modeled Phenomena**
- **Surface Potentials**
- **Harmonic Distortions**
- **Model Consistency**
- **Non-Quasi-Static Effect**
- **Noise Features**

Modeled Phenomena

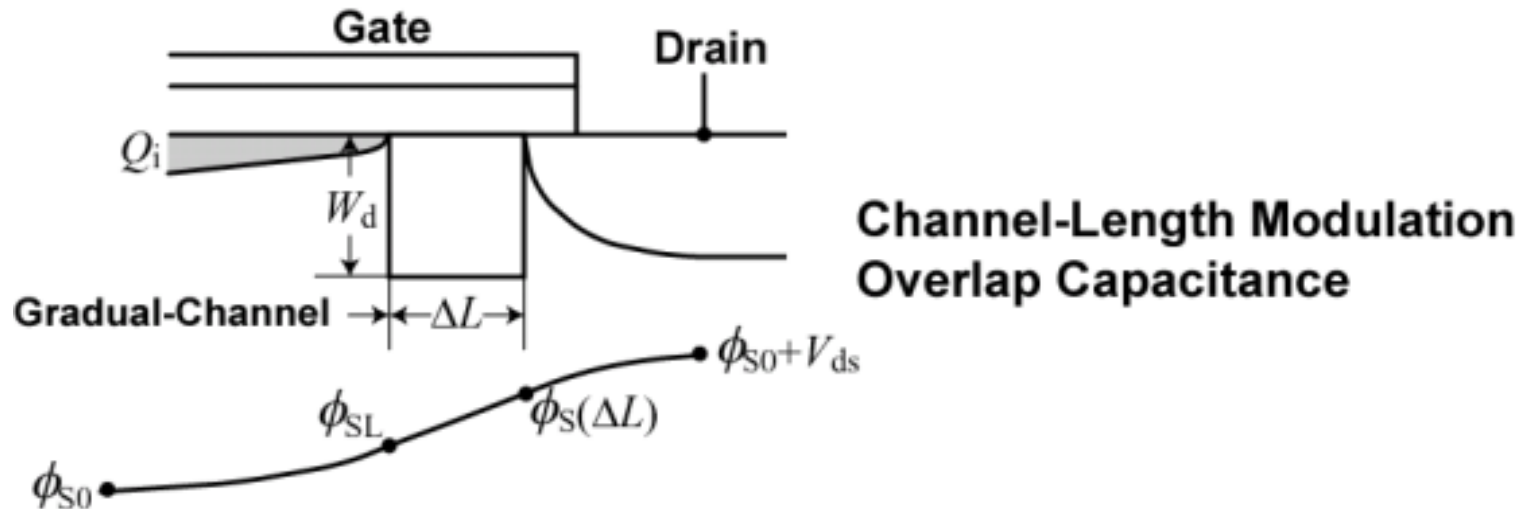
[Phenomena]	[Subjects]	[Phenomena]	[Subjects]
Short Channel:		Non-Quasi-Static:	transient time-domain AC frequency-domain
Reverse-short Channel:	impurity pile-up pocket implant	Noise:	1/f thermal induced gate cross-correlation
Poly-Depletion:		Leakage Currents:	substrate current gate current GIDL current
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		

Surface Potentials



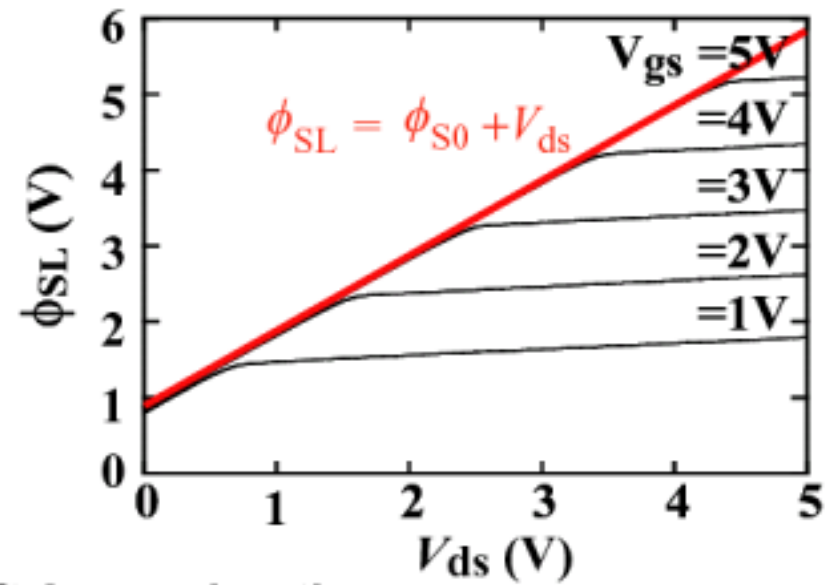
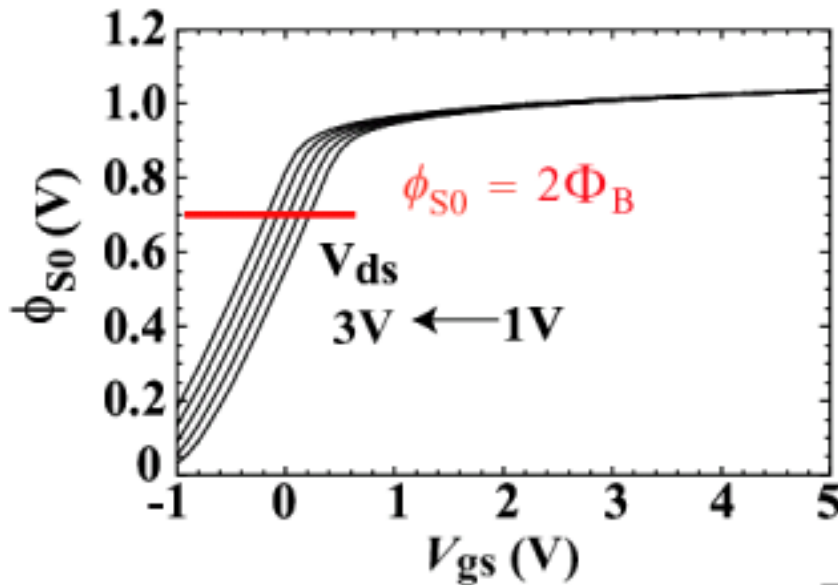
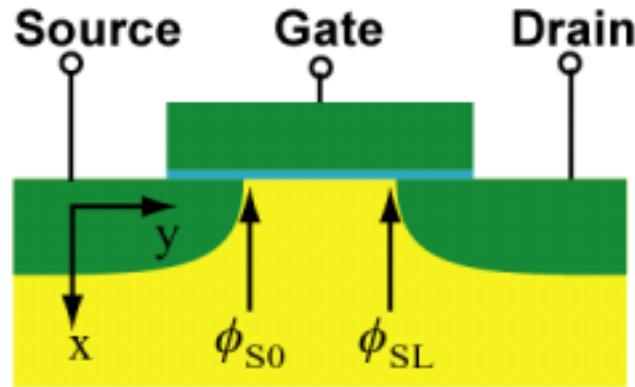
ϕ_{S0} : at source side
 ϕ_{SL} : at drain side
 (end of the gradual-channel approx.)

beyond the gradual-channel approximation



Surface Potentials \Rightarrow Measure for All Device Features

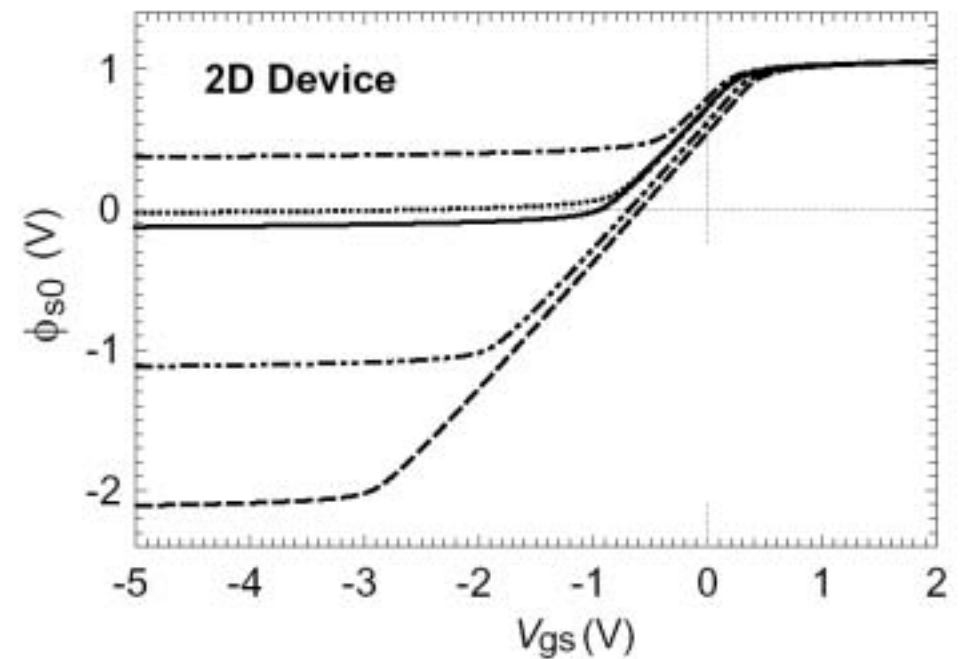
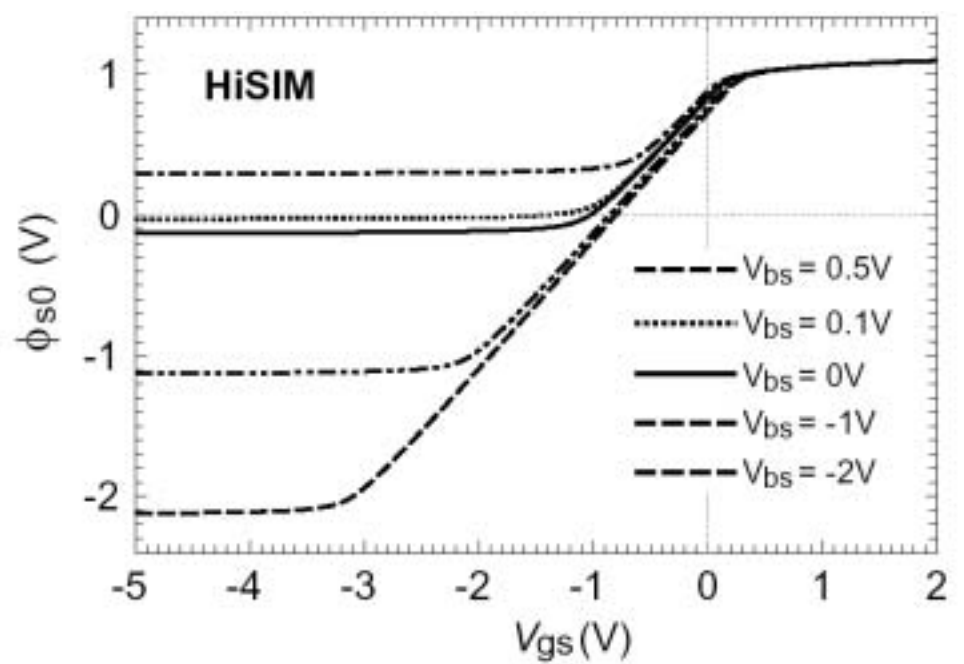
Calculated Surface Potentials



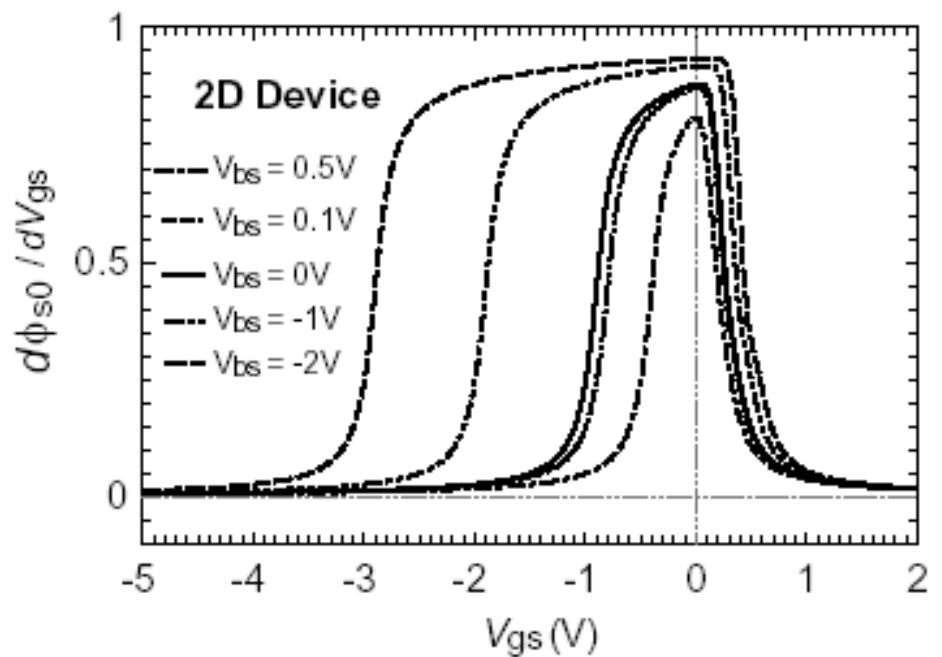
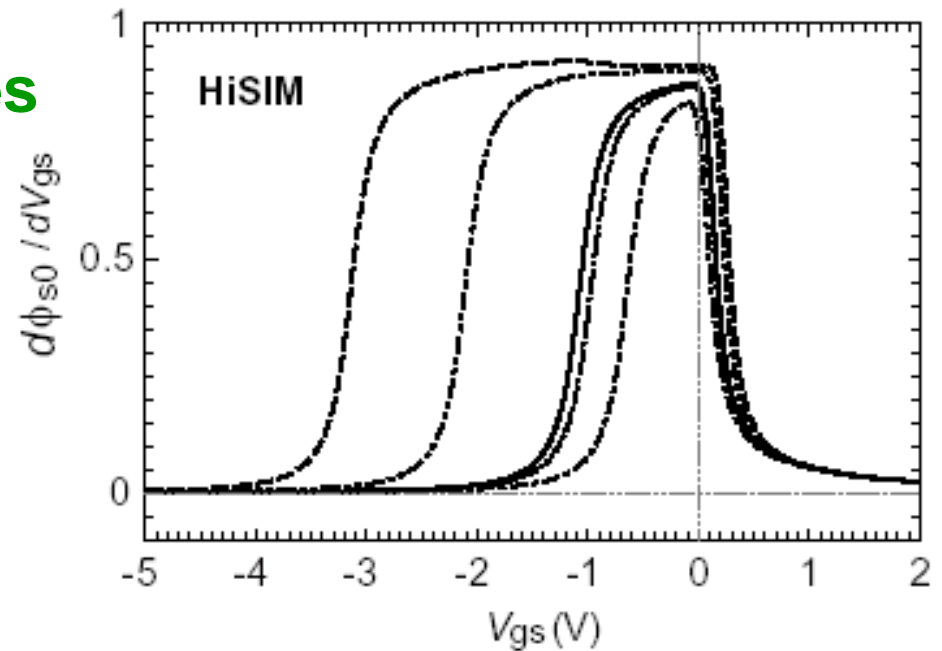
— : Drift Approximation

Short-channel effect is included in the ϕ_s calculation.

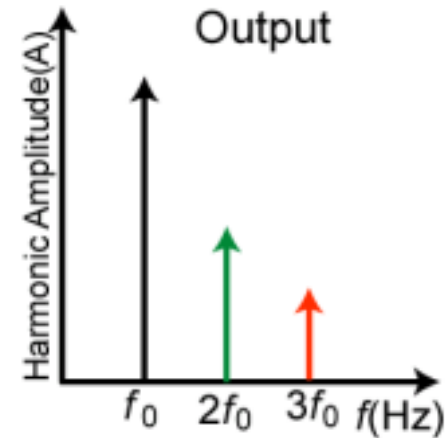
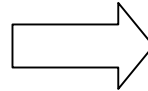
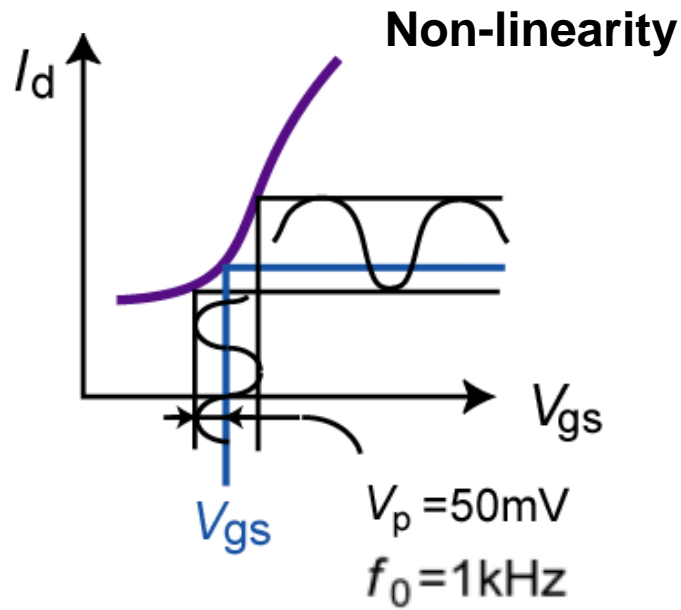
Comparison of ϕ_{s0} Values



Comparison of ϕ_S Derivatives

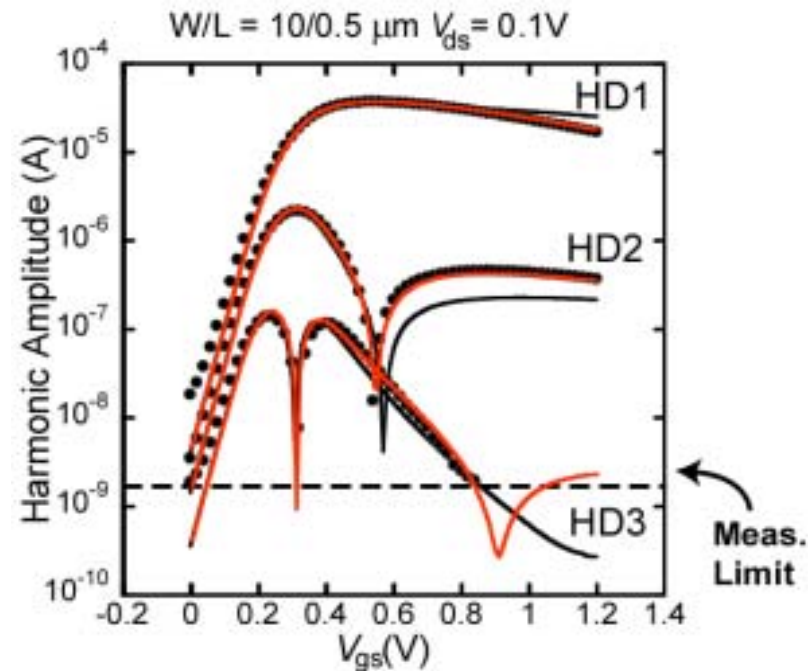
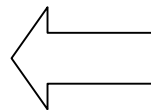


Harmonic Distortions

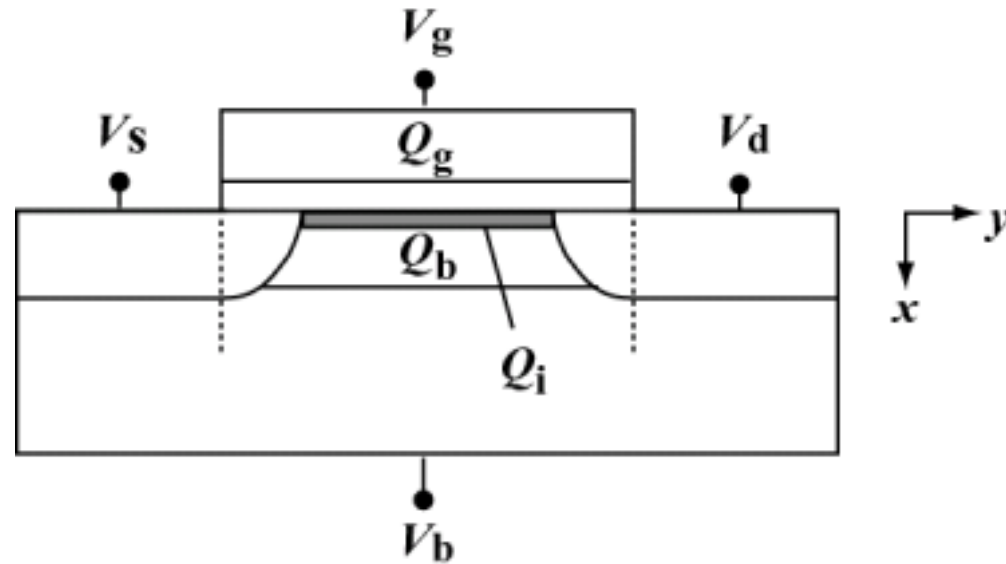


$$V(t) = V_{gs} + V_p \sin(2\pi f_0 t)$$

Higher-order derivatives of I - V characteristics are important.



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

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

Universal Mobility

$$\bullet \mu_{CB} = MUECB0 + MUECB1 \frac{Q_i}{q \times 10^{11}}$$

$$\bullet \mu_{PH} = \frac{MUEPH0}{(T/300K)^{MUETMP} \times E_{eff}^{MUEPH1}}$$

$$\bullet \mu_{SR} = \frac{MUESR0}{E_{eff}^{MUESR1}}$$

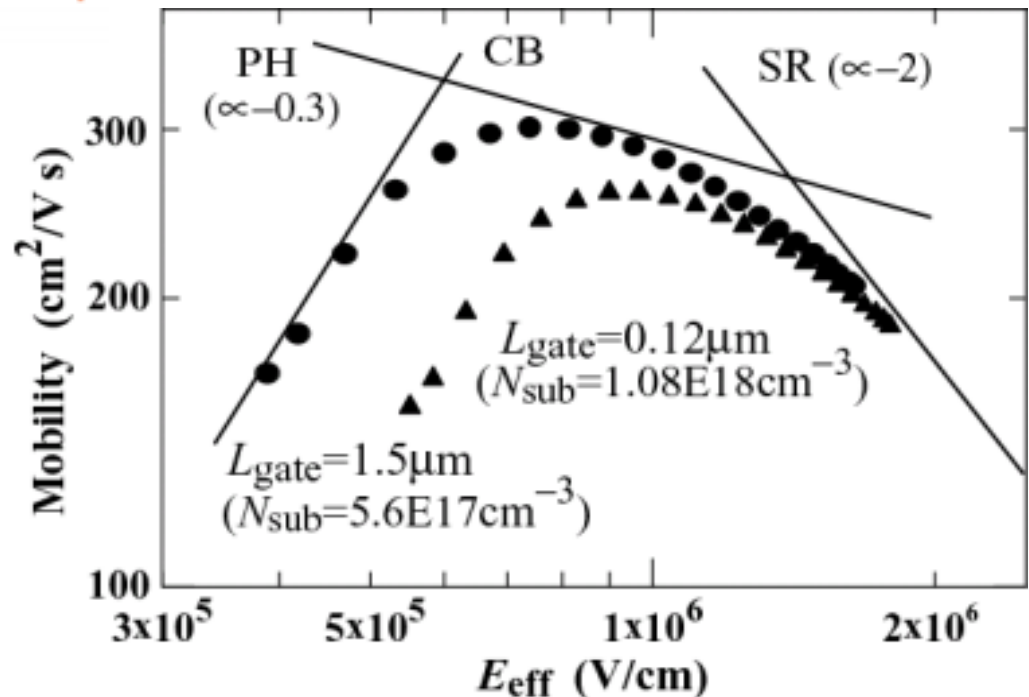
$$E_{eff} = \frac{1}{\epsilon_{Si}} (NDEP \times Q_b + NINV \times Q_i)$$

$$MUEPH1 = 0.3$$

$$MUESR1 = 2$$

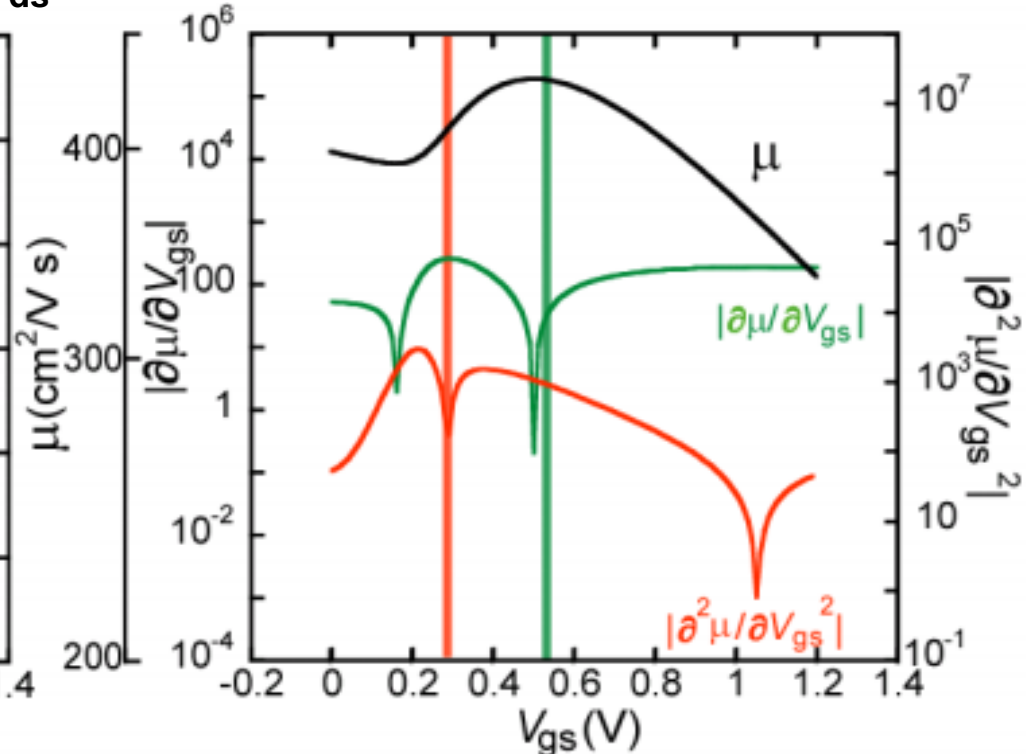
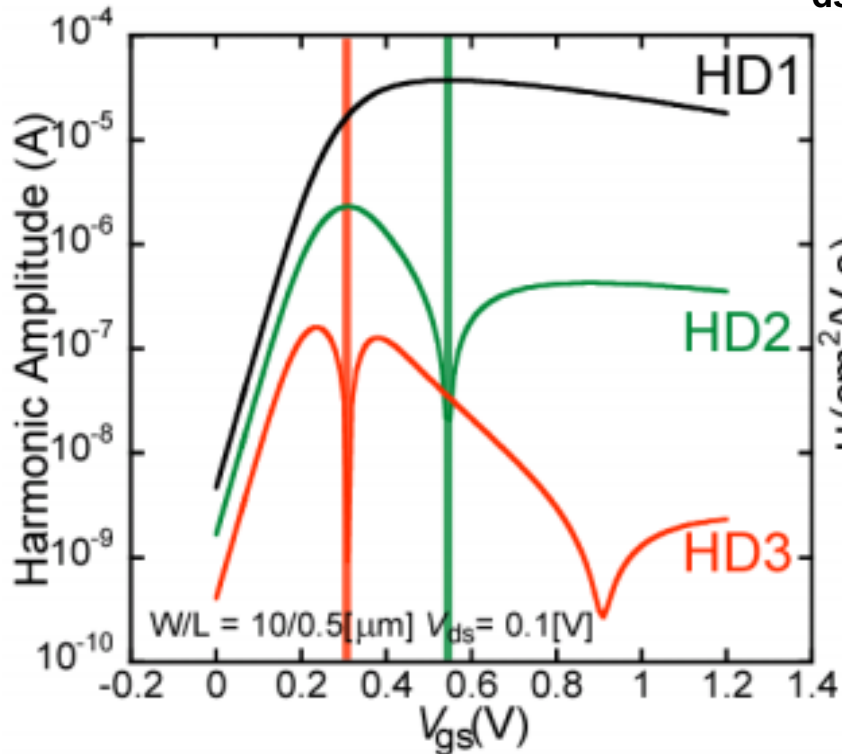
$$NDEP = 1$$

$$NINV = 0.5$$



Harmonic Distortion vs. Mobility

$V_{ds}=0.1V$



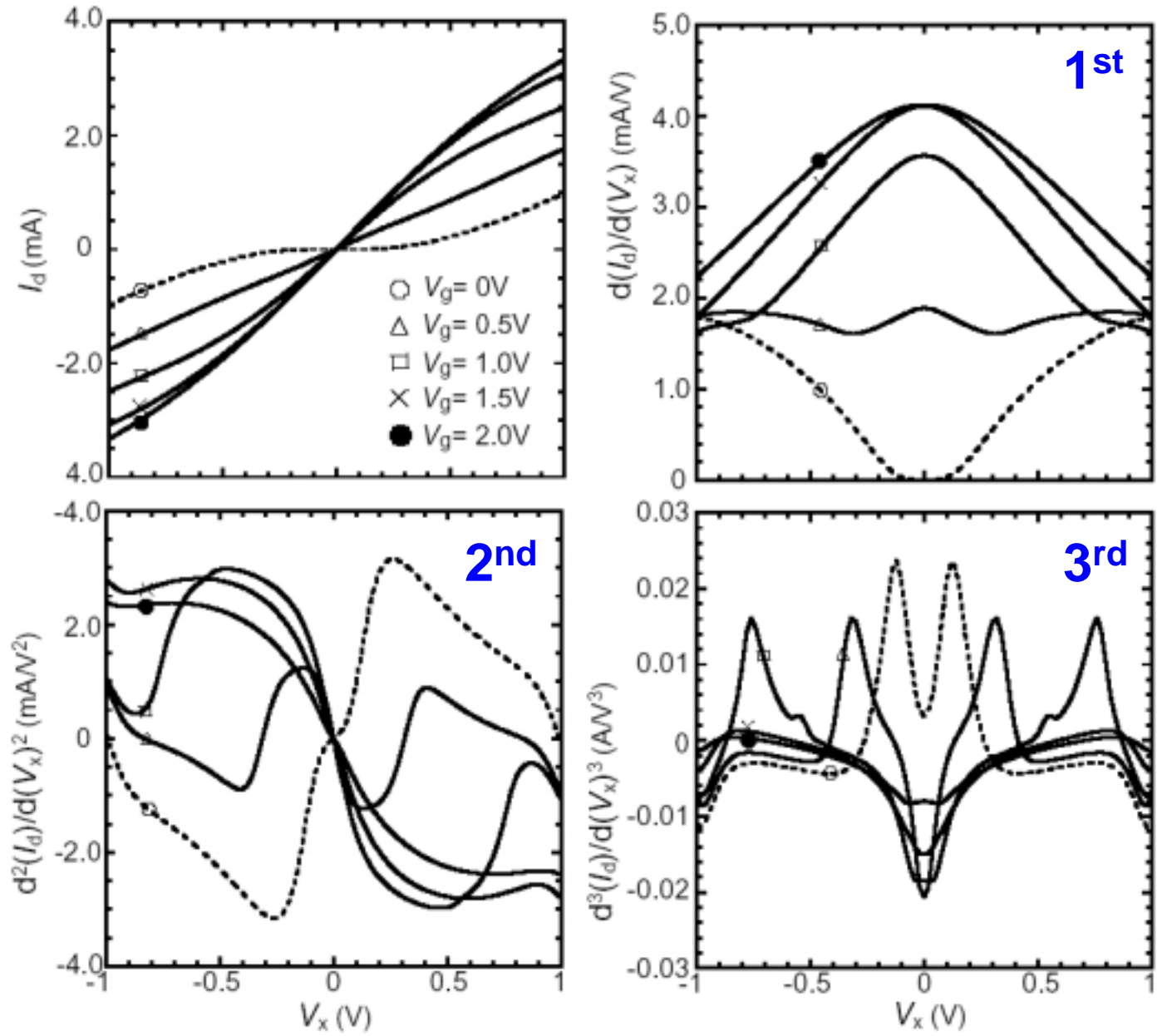
$$\text{HD1} \approx \left| V_P \frac{\partial I_{ds}}{\partial V_{gs}} \right|$$

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

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

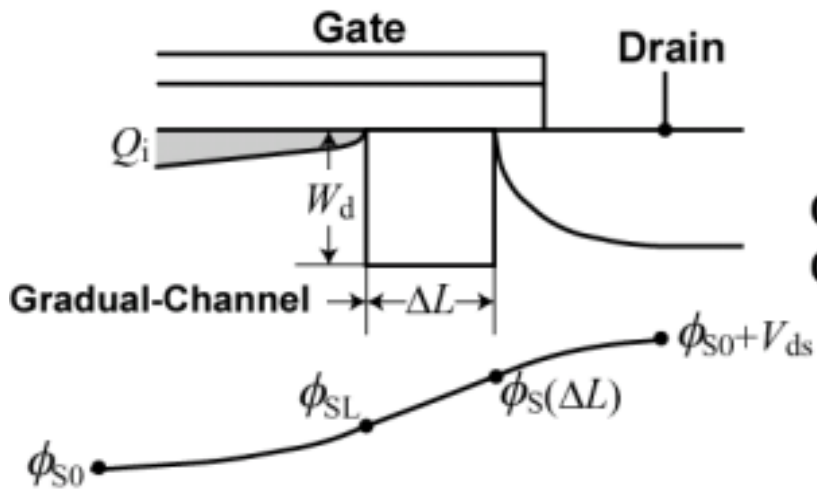
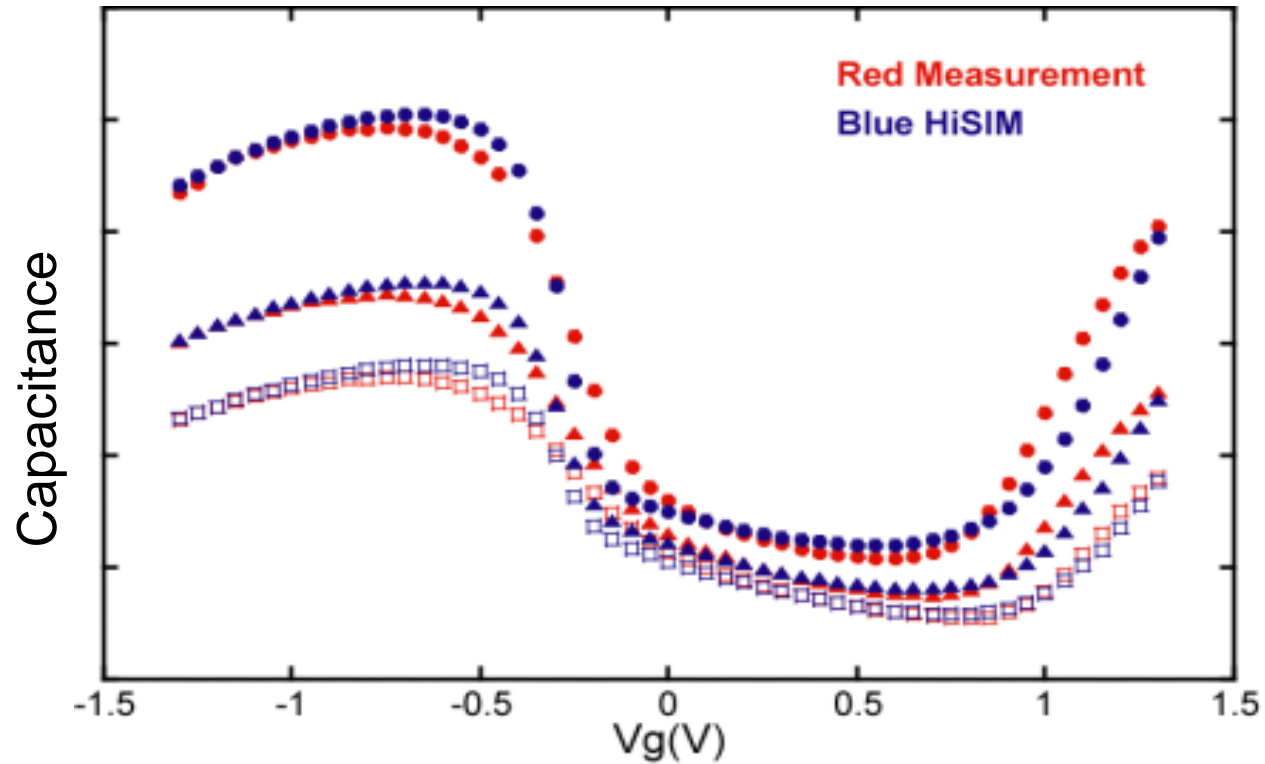
Mobility determines the harmonic distortion characteristics.

I_d Symmetry at $V_{ds} \rightarrow 0$



Capacitances

wide/short

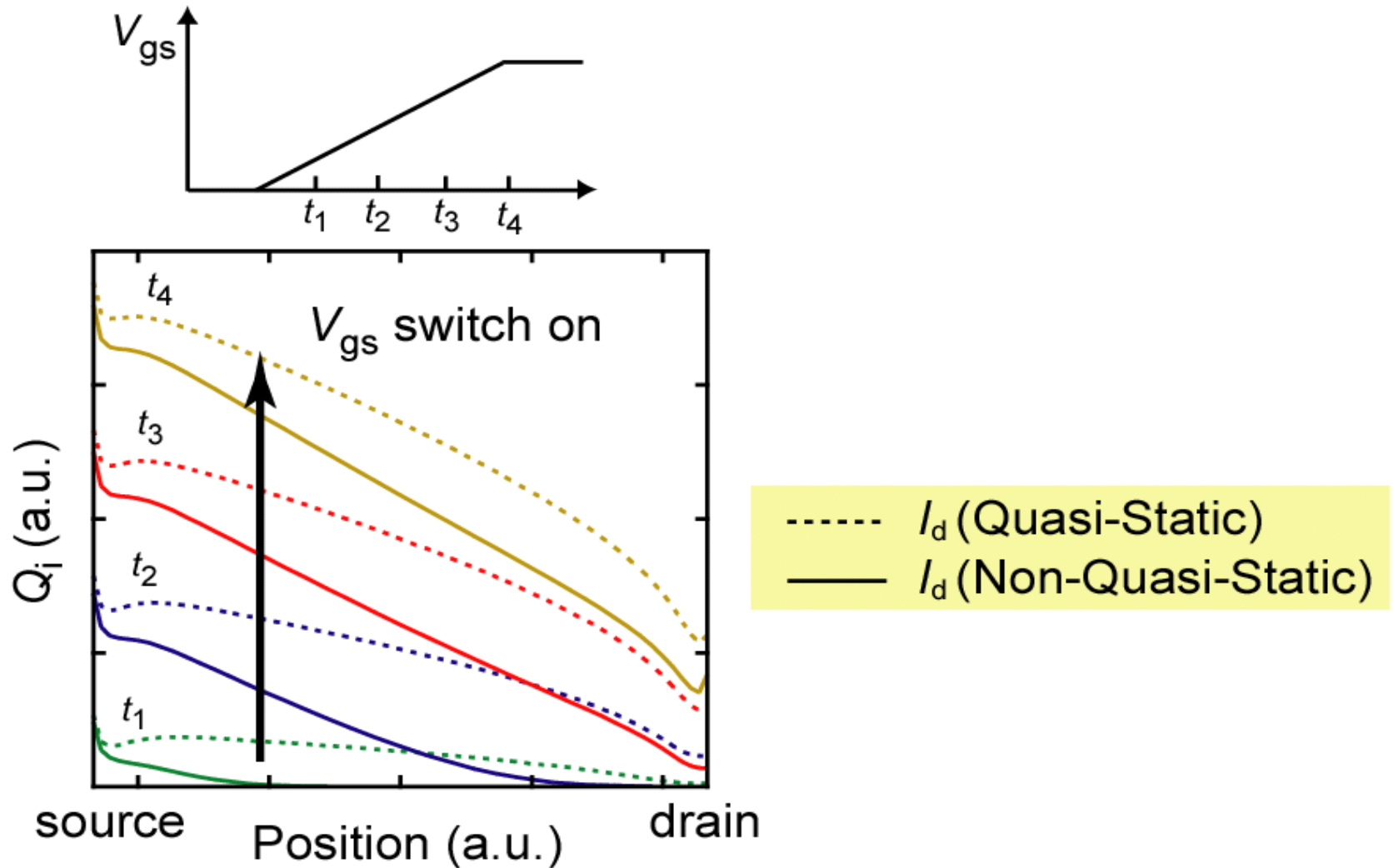


Channel-Length Modulation
Overlap Capacitance

Outline

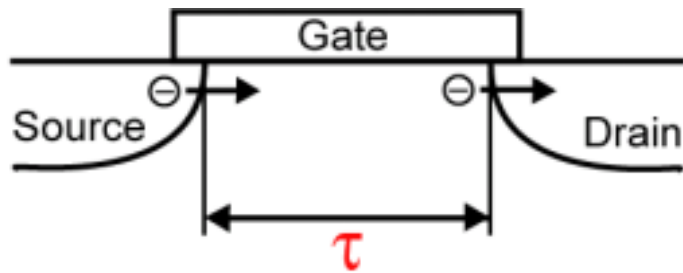
- Modeled Phenomena
- Surface Potentials
- Harmonic Distortions
- Model Consistency
- **Non-Quasi-Static Effect**
- **Noise Features**

Non-Quasi-Static Effect

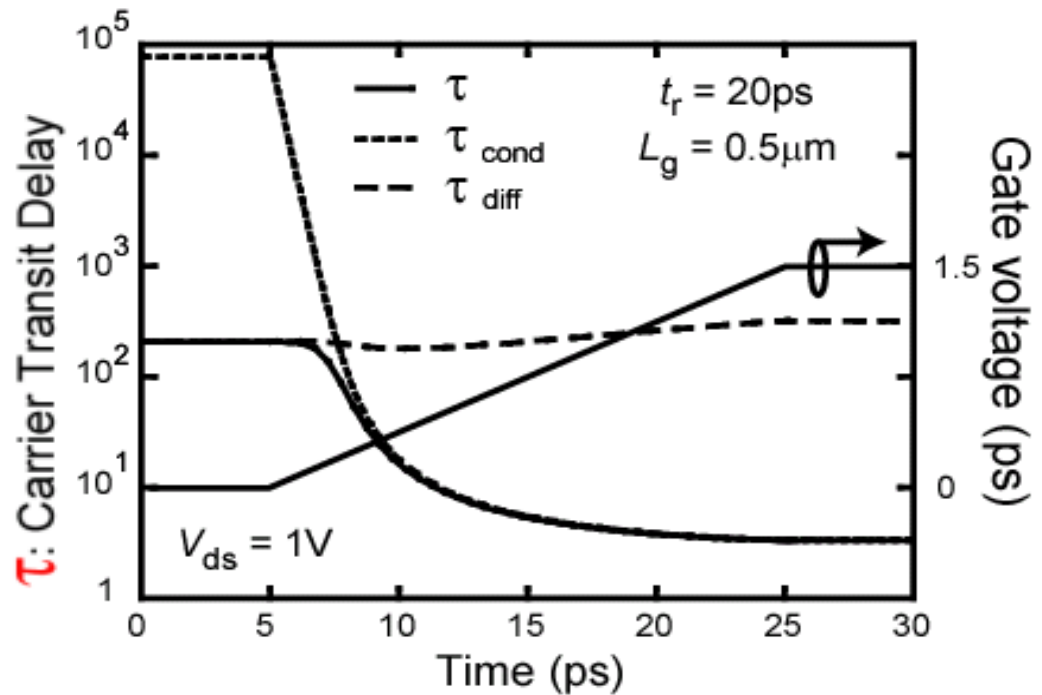


Carrier Deficit in the Channel

Transient Time-Domain Analysis: Response Delay



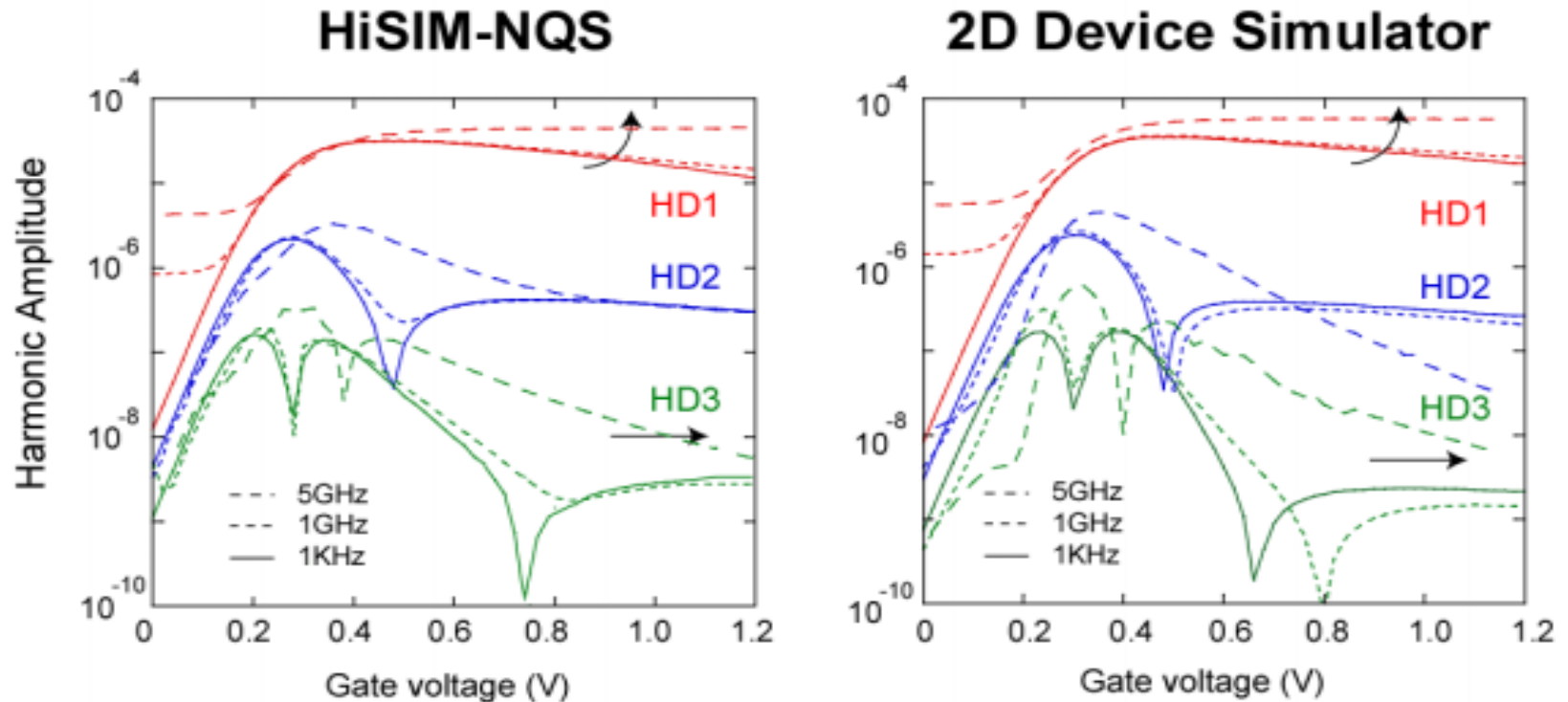
τ : Carrier Transit Delay
(function of surface potentials)



N. Nakayama et al., Electron. Lett., 40, p. 276, 2004.

Harmonic Distortion under High Frequency

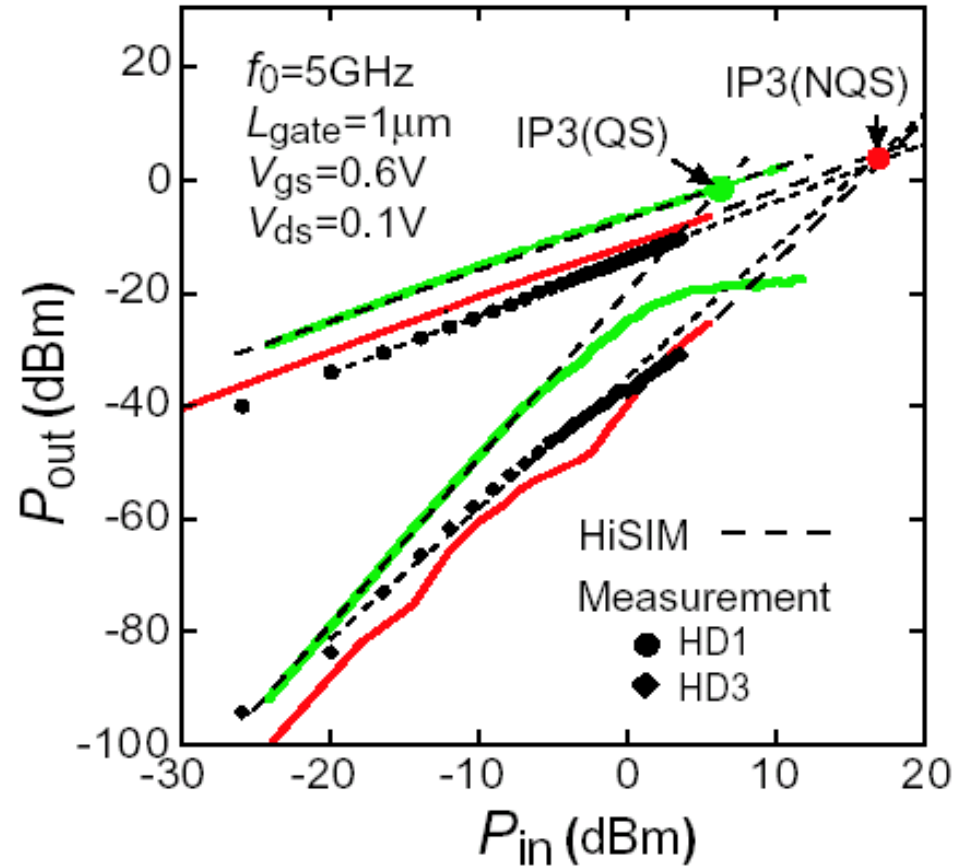
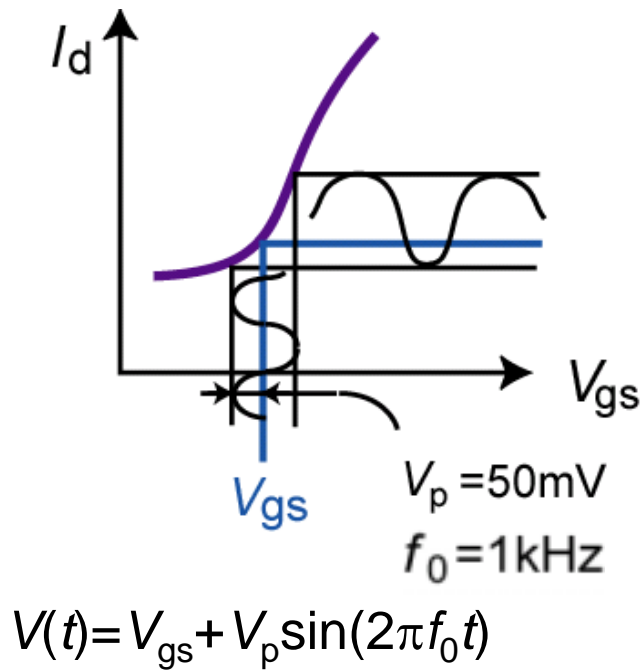
Time-Domain Analysis \Rightarrow Frequency Domain Analysis
Fourier Transformation



Carrier transit delay dominates the HD characteristics.

D. Navarro et al., SISPAD, p. 259, 2004.

IP3 Prediction



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

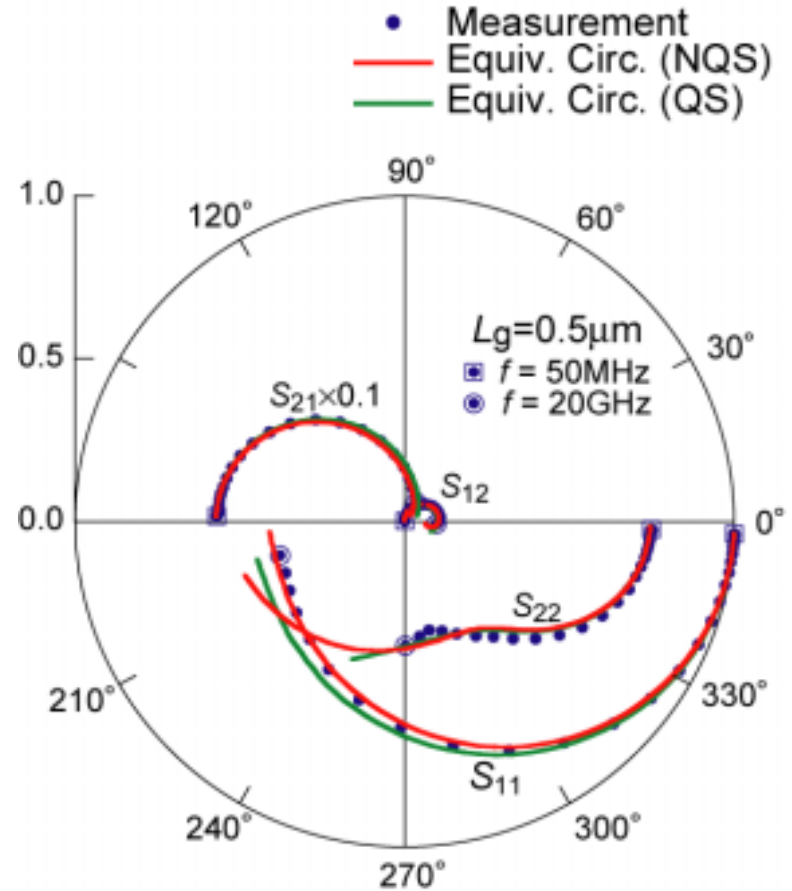
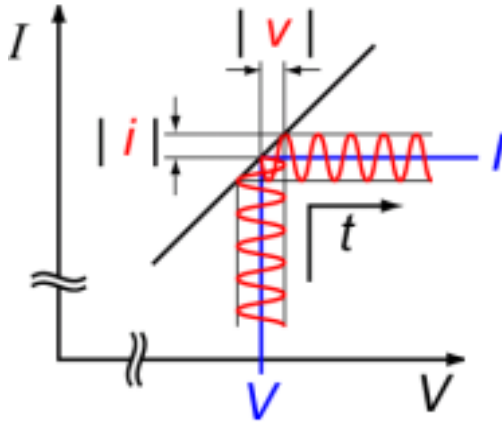
D. Navarro et al., IEEE MWC Lett., p. 125, 2006.

Y-parameters: Frequency-Domain Analysis

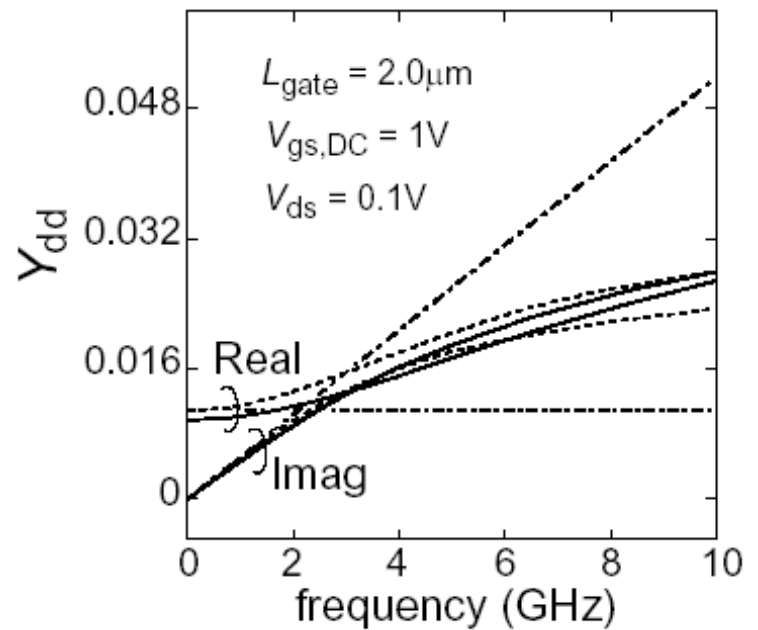
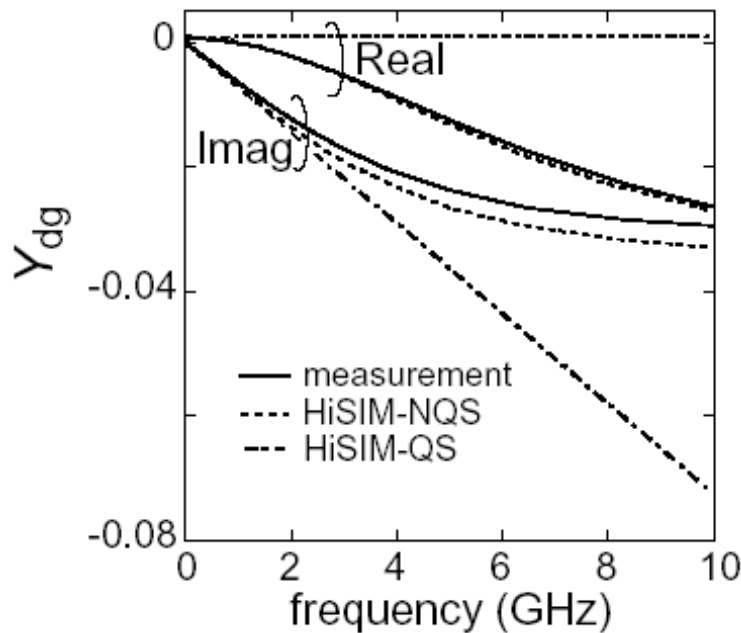
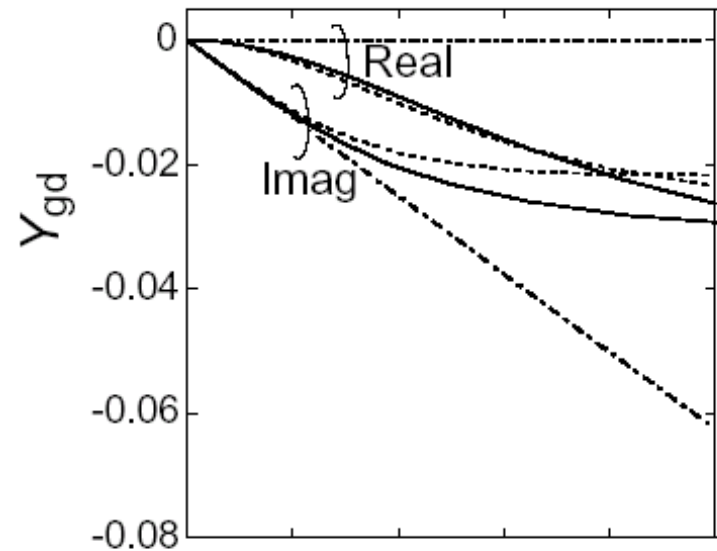
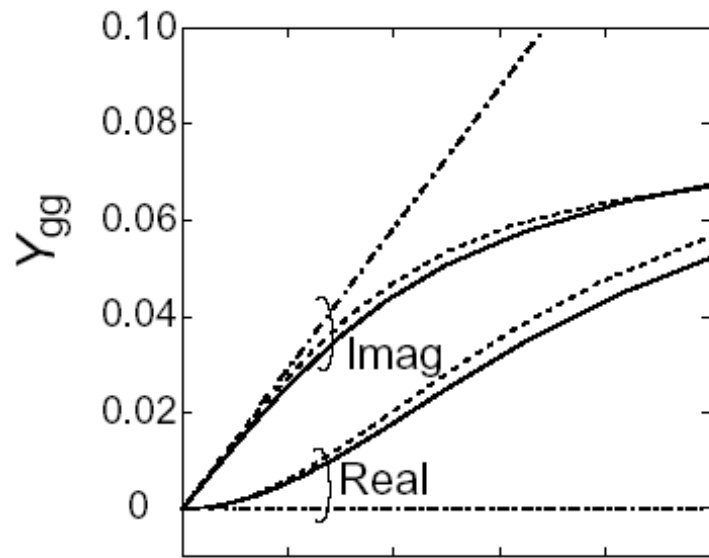
Small Signal

$$v = |v| \exp(j\omega t)$$

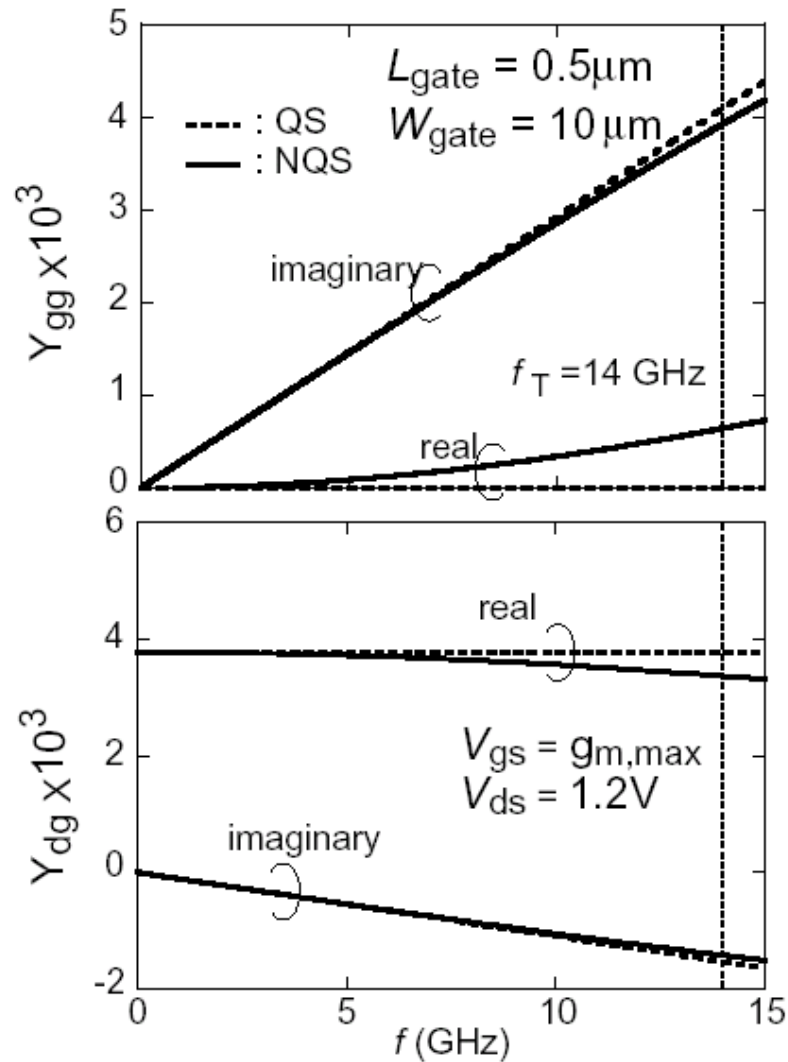
$$i = |i| \exp(j\omega t)$$



The same model as for the Time-Domain Analysis: modeled with τ



Non-Quasi-Static Effects



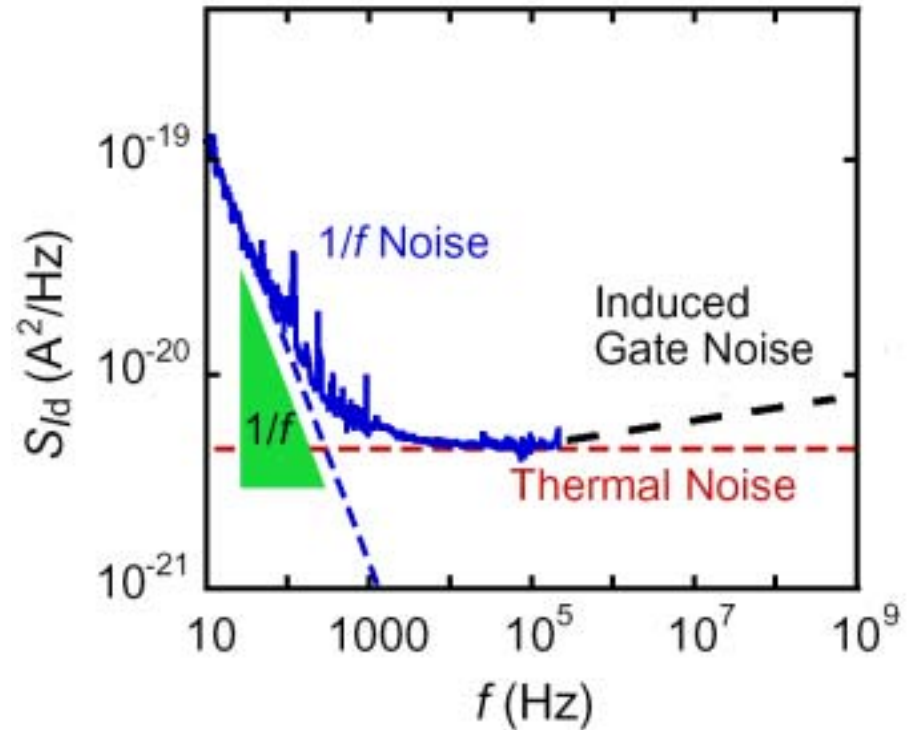
NQS Effect: occurs beyond 1/3 of the cut-off frequency, f_T

H. Ueno et al., SISPAD, p. 71, 2002.

Noise Features

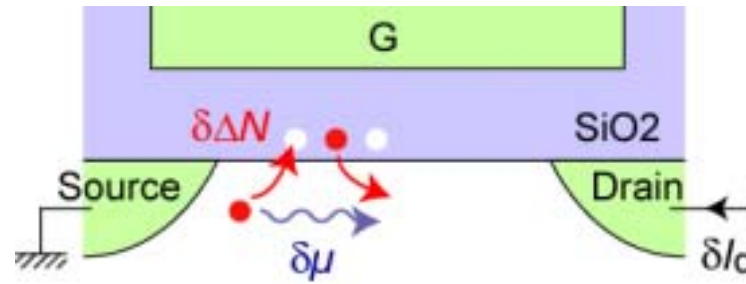
- $1/f$ Noise
- Thermal Noise
- Induced Gate Noise
- Cross-Correlation Noise

- Shot Noise
- Junction Noise



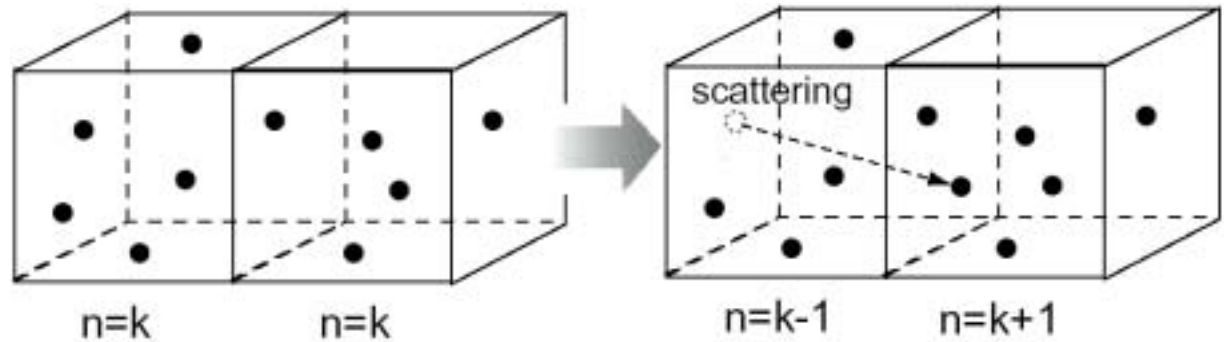
Different Origins

1/f Noise:

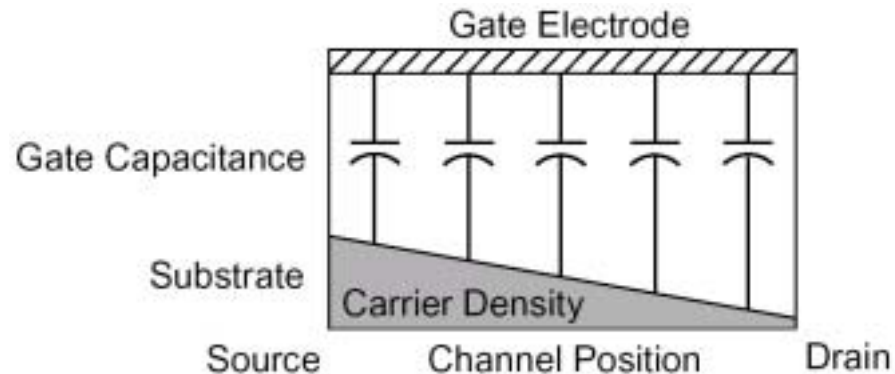


δN : carrier number fluctuation
 $\delta \mu$: mobility fluctuation

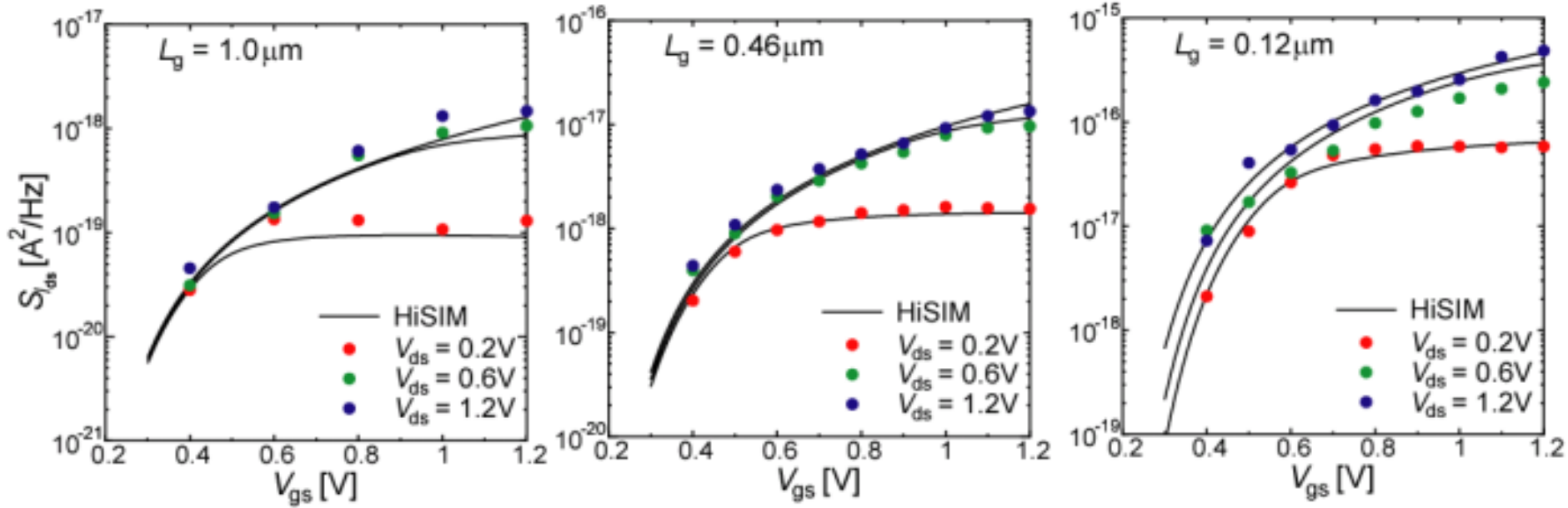
Thermal Noise:



**Induced Gate Noise:
 Cross-Correlation Noise:**



1/f Noise



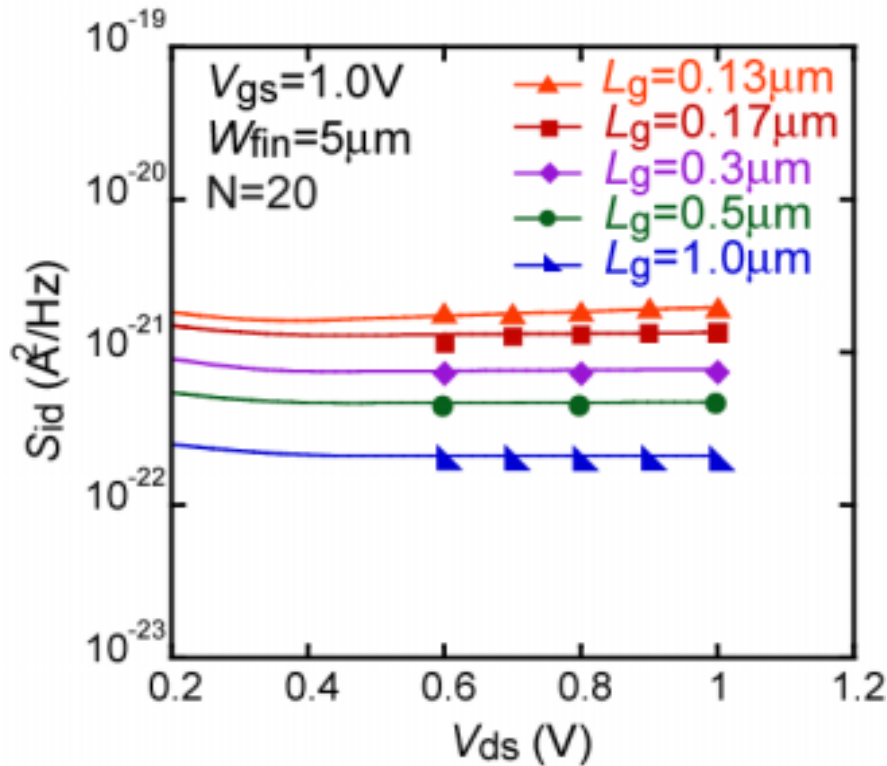
Carrier distribution along the channel determines the characteristics.

Model Parameters:

- Trap density
- Mobility fluctuation

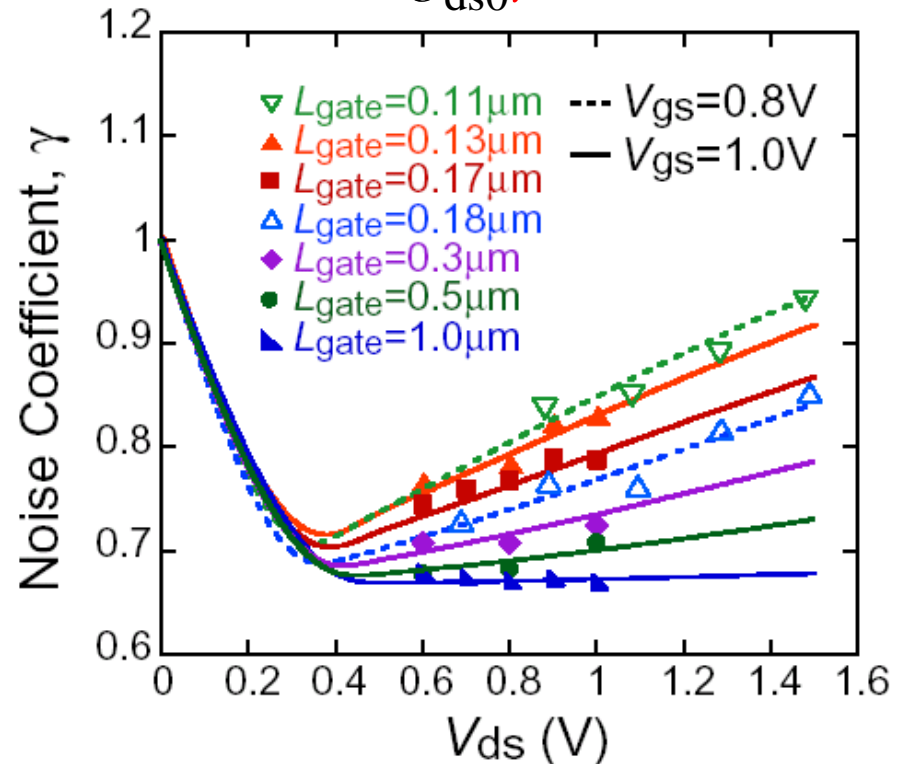
S. Matsumoto et al., IEICE Trans. Electron., vol. E88-C, p. 247, 2005.

Thermal Noise



$$S_{id} = \frac{4kT}{L_{eff}^2 I_{ds}} \int g_{ds}^2(y) dy$$

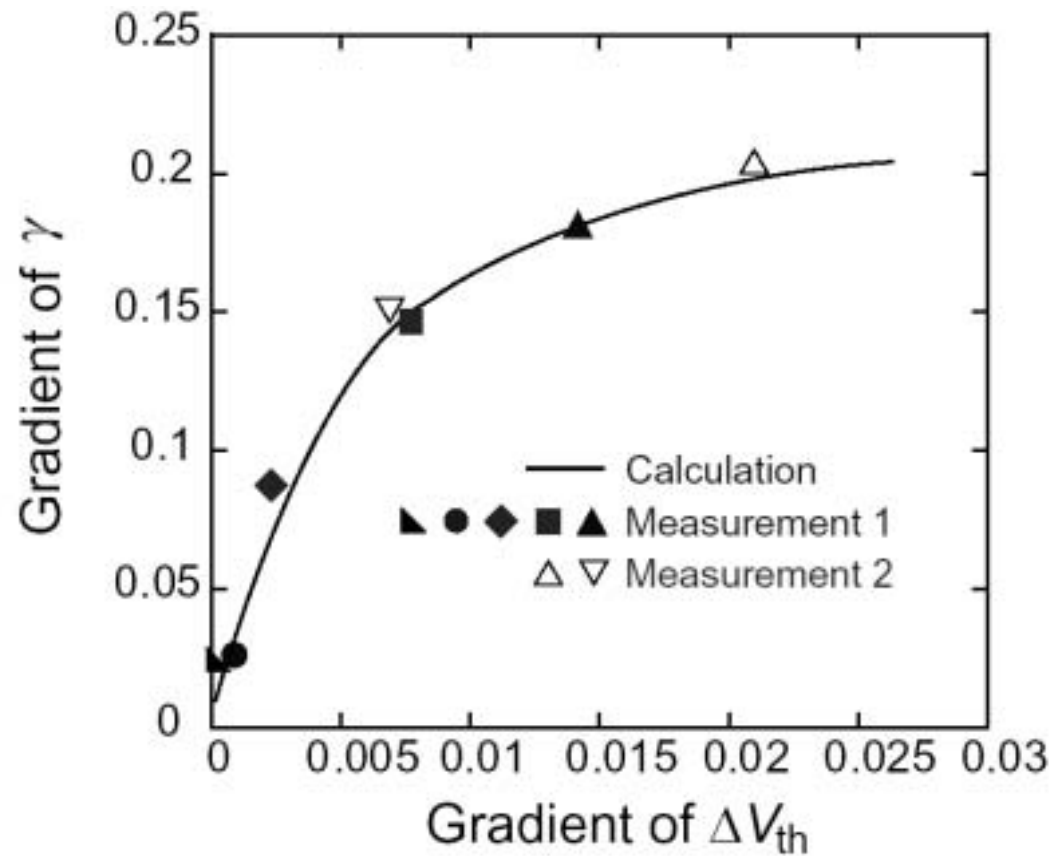
$$= 4kT g_{ds0} \gamma$$



**Potential distribution along the channel is responsible.
 No Additional Model Parameters**

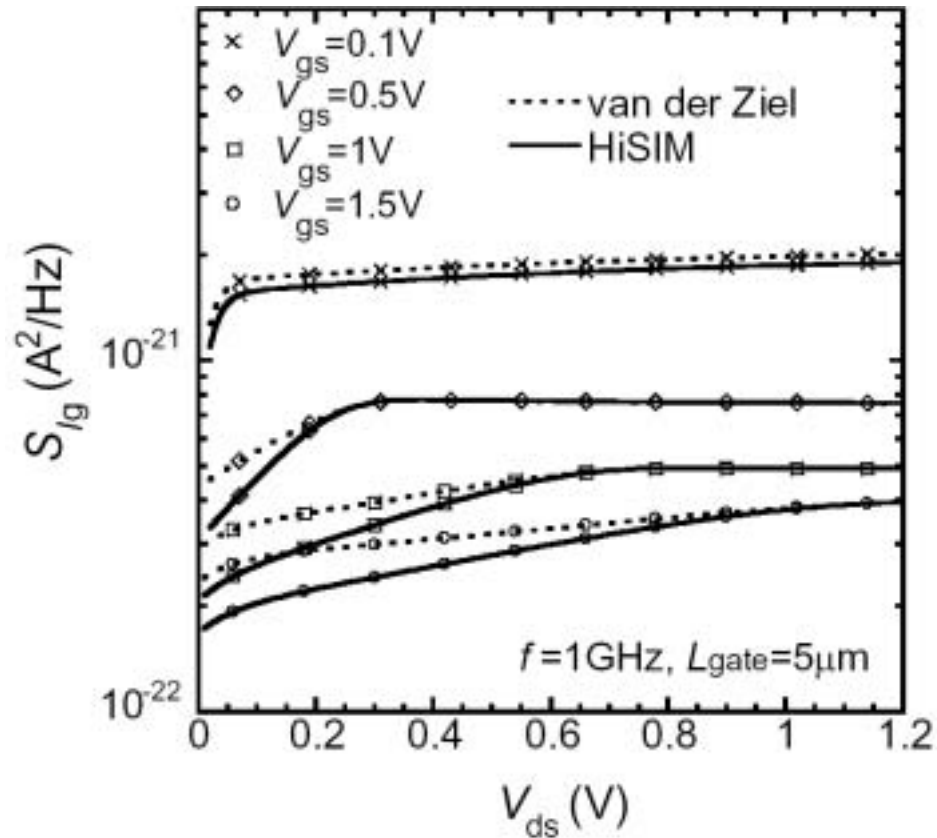
S. Hosokawa et al., Appl. Phys. Lett., vol. 87, p. 092104, 2005.

γ vs. Short-Channel Effect



Universal Relationship

Induced Gate Noise



**Potential distribution along the channel is responsible.
No Additional Model Parameters**

T. Warabino et al., SISPAD, 2006.

Important Model Parameters

Short Channel

Device	<i>TOX</i>	oxide thickness
	<i>XLD</i>	gate-overlap length
	<i>XWD</i>	gate-overlap width
	<i>XPOLYD</i>	gate-poly overlap
	<i>TPOLY</i>	height of the gate poly-Si
	<i>RS</i>	source-contact resistance
	<i>RD</i>	drain-contact resistance
	<i>NSUBC</i>	substrate-impurity concentration
	<i>NSUBP</i>	maximum pocket concentration
	<i>VFBC</i>	flat-band voltage
	<i>LP</i>	pocket penetration length

<i>PARL2</i>	depletion width: channel/contact
<i>SC1</i>	short-channel coefficient 1
<i>SC2</i>	short-channel coefficient 2
<i>SC3</i>	short-channel coefficient 3
<i>SCP1</i>	pocket short-channel coefficient 1
<i>SCP2</i>	pocket short-channel coefficient 2
<i>SCP3</i>	pocket short-channel coefficient 3

Temp	<i>BGTMP1</i>	bandgap narrowing 1
	<i>BGTMP2</i>	bandgap narrowing 2

Quant	<i>QME1</i>	quantum mechanical effect 1
	<i>QME2</i>	quantum mechanical effect 2
	<i>QME3</i>	quantum mechanical effect 3

Poly	<i>PGD1</i>	strength of poly depletion
	<i>PGD2</i>	threshold of poly depletion
	<i>PGD3</i>	V_{ds} dependence of poly depletion

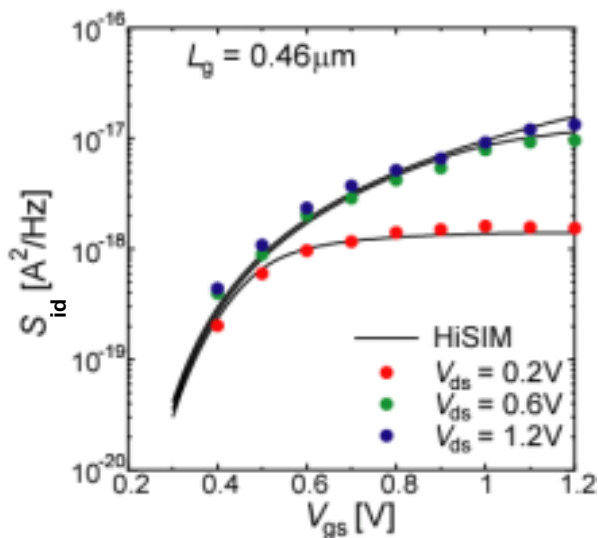
Channel	<i>CLM1</i>	channel length modulation 1
	<i>CML2</i>	channel length modulation 2
	<i>CLM3</i>	channel length modulation 3

Mobility

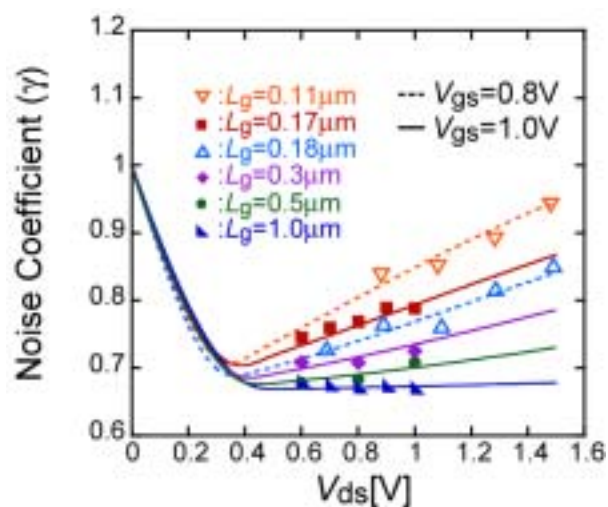
<i>MUECB0</i>	Coulomb scattering
<i>MUECB1</i>	Coulomb scattering
<i>MUEPH0</i>	phonon scattering ***0.3
<i>MUEPH1</i>	phonon scattering
<i>MUETMP</i>	temperature dependence
<i>MUESR0</i>	surface-roughness scattering *** 2.0
<i>MUESR1</i>	surface-roughness scattering
<i>NDEP</i>	effective-electric field *** 1.0
<i>NINV</i>	effective-electric field *** 0.5
<i>NINVD</i>	modification of NINV
<i>BB</i>	high-field mobility *** 2.0
<i>VMAX</i>	saturation velocity
<i>VO</i>	velocity overshoot
<i>VOVERP</i>	velocity overshoot
<i>RPOCK1</i>	pocket resistance
<i>RPOCK2</i>	pocket resistance

Features of Higher-Order Phenomena

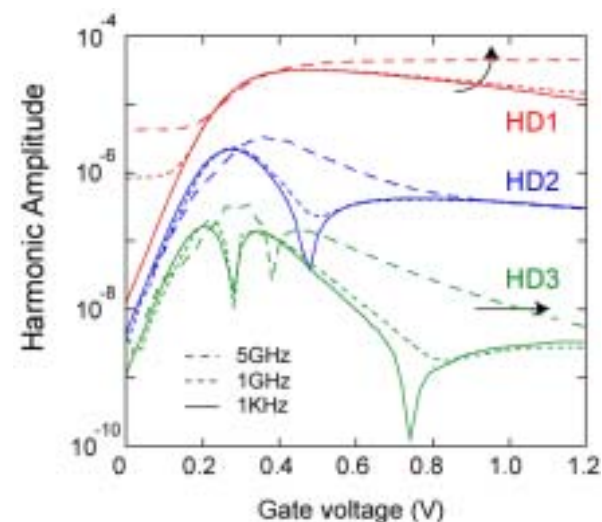
1/f Noise



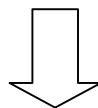
Thermal Noise



Harmonic Distortion



- No additional model parameters are required.
- Features are determined only by I - V characteristics.



Electrostatic effects still dominate device features.

Summary

- ***I-V* characteristics view carrier dynamics in detail.**
- **Electrostatic effects still dominate device characteristics in the sub-100nm era.**
- **The key for modeling are the surface potentials.**

**HiSIM2: Surface-Potential-Based MOSFET Model for Advanced Technologies
Including All Required Device Features
Stable Circuit Simulation with Shorter Simulation Time than BSIM4**

**Physics and Modeling of MOSFETs
--Surface-Potential Model HiSIM--
World Scientific**