Measurements and Modeling of Noise in Advanced MOSFETs

MOS-AK Meeting
20. April, 2007

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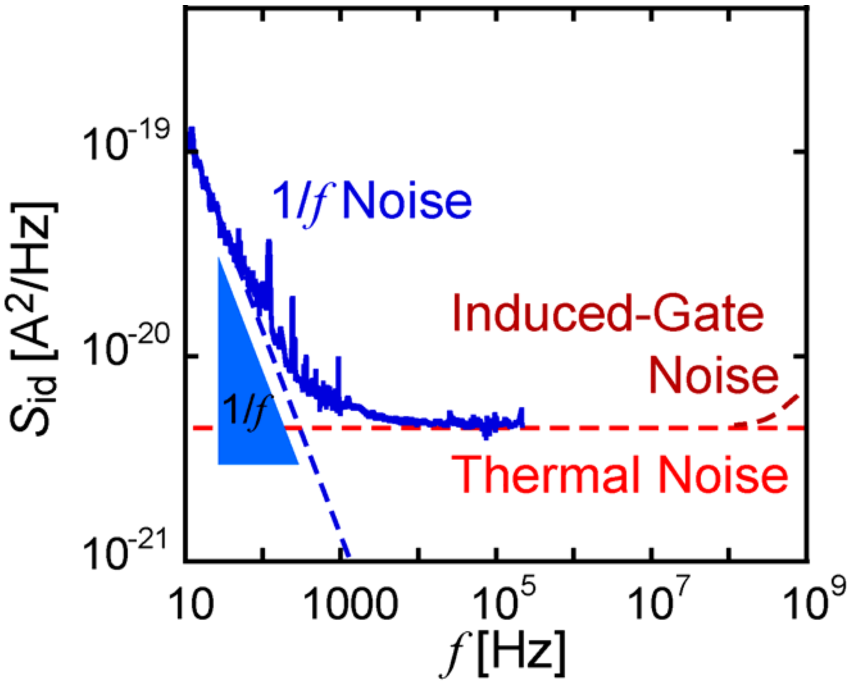
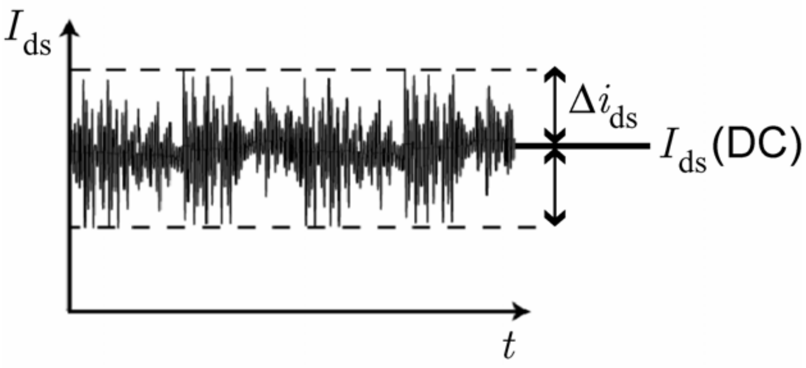
Noise Features in MOSFETs

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

- **Shot Noise**
- **Junction Noise**





Noise Spectral Intensity

$$S_{i_d} = \frac{\overline{\Delta i_{ds}{}^2}}{f}$$

Contents

- MOSFET Modeling
- 1/f Noise
- Thermal Noise
- Induced Gate Noise
  + Cross-Correlation Noise

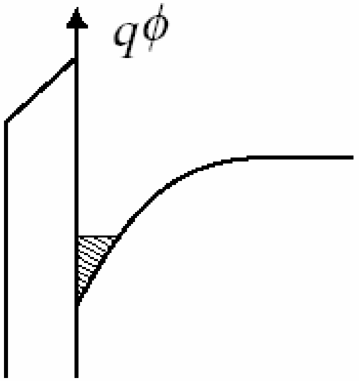
Basic Equations

-Poisson:

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

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

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



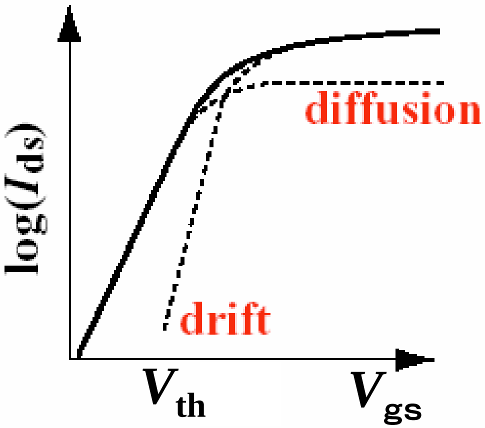
-Current Density:

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

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

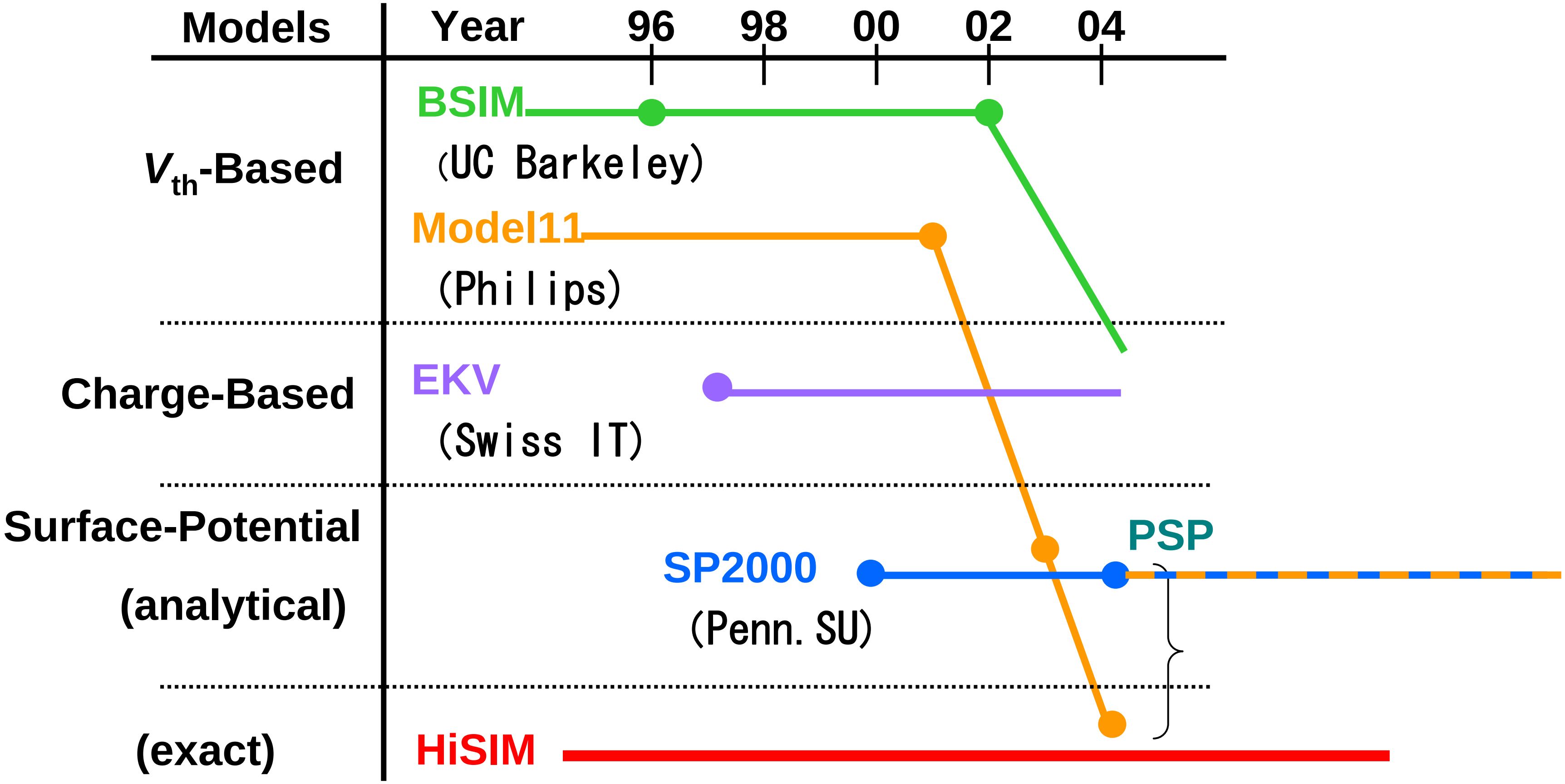
-Continuity: $I(\mathrm{t}) = I_0(\mathrm{t}) + \frac{\mathrm{d}Q}{\mathrm{d}t}$

(solved by circuit simulator)



Available Models in Commercial SPICEs

CMC Standardization Process



Models

Year

96 98 00 02 04

V_{th}-Based

BSIM

(UC Barkeley)

Model11

(Philips)

Charge-Based

EKV

(Swiss IT)

Surface-Potential

(analytical)

SP2000

(Penn. SU)

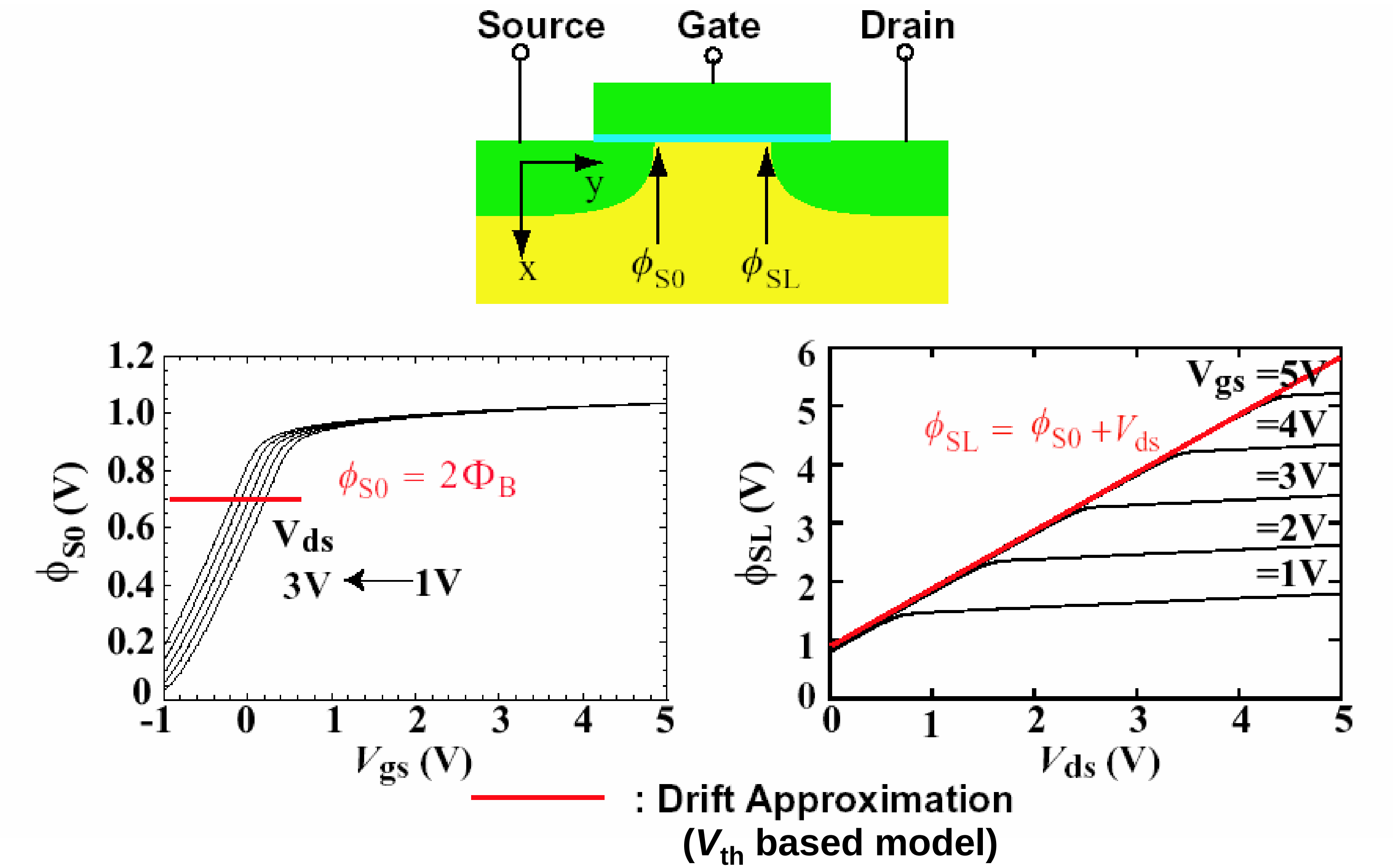
PSP

(exact)

HiSIM

HiSIM solves the Poisson equation iteratively.

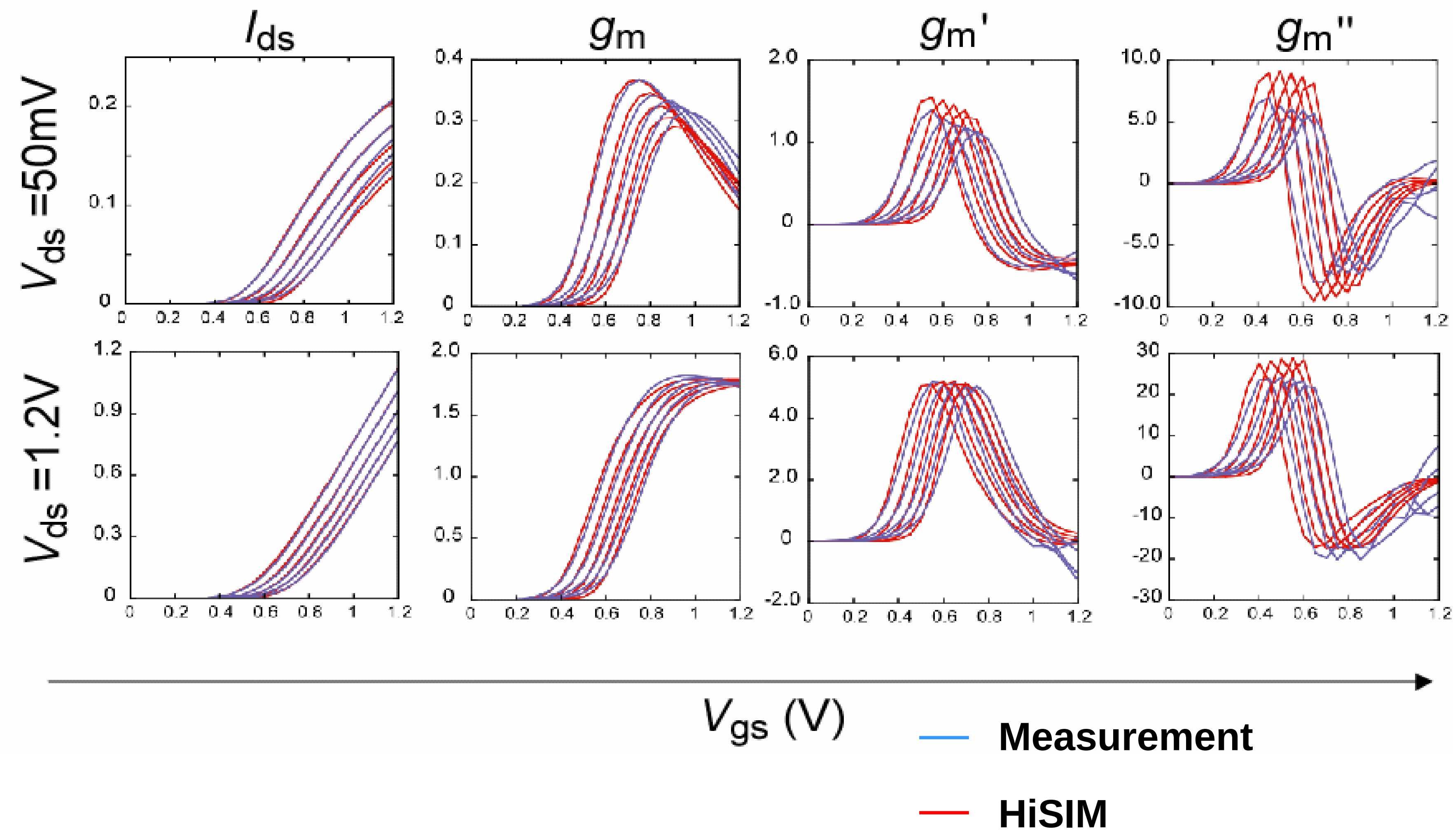
Surface Potentials: HiSIM Results



Short-channel effects are included in potential calculations.

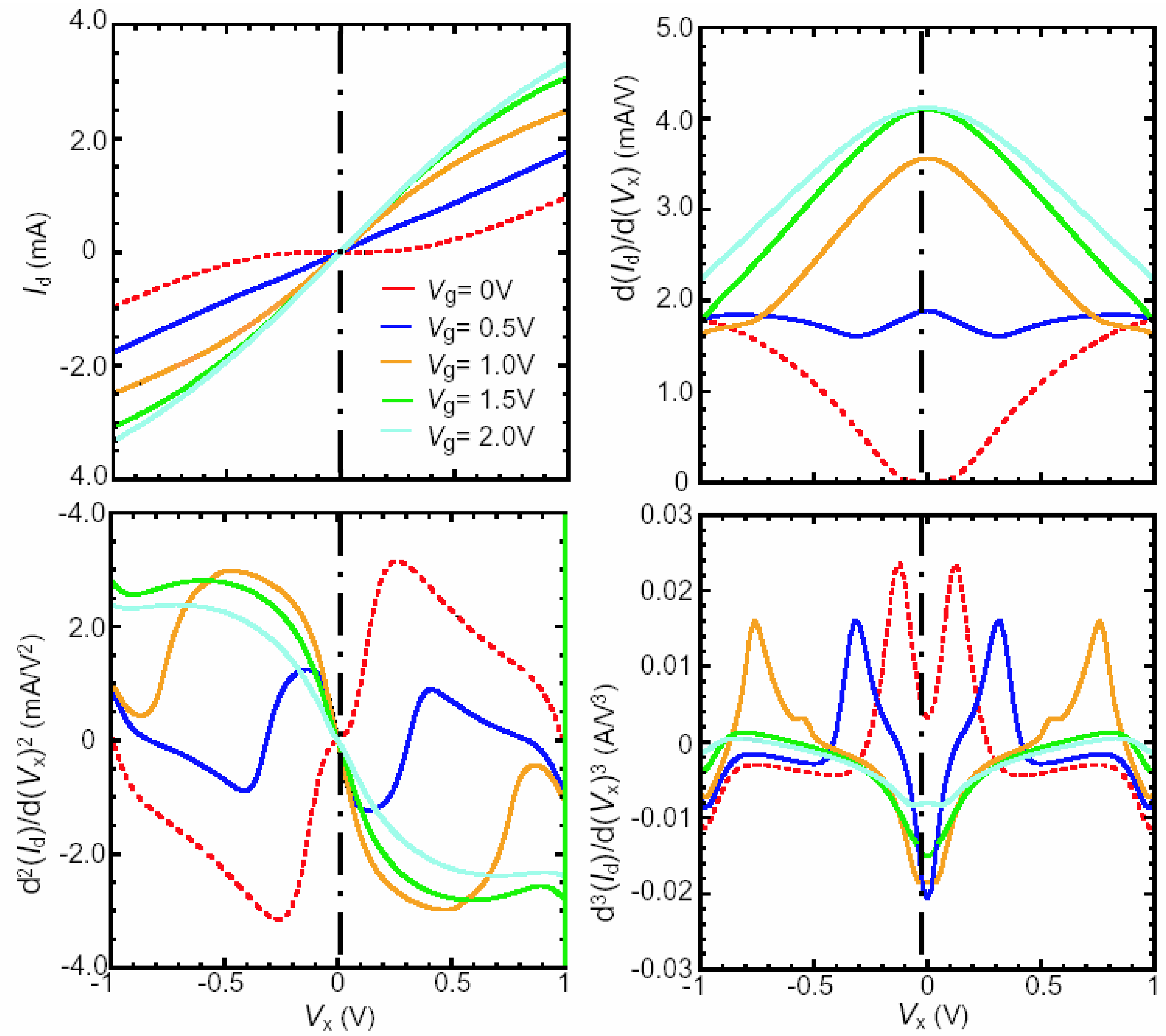
Derivatives of Drain Current

W_g/L_g=2μm/40nm

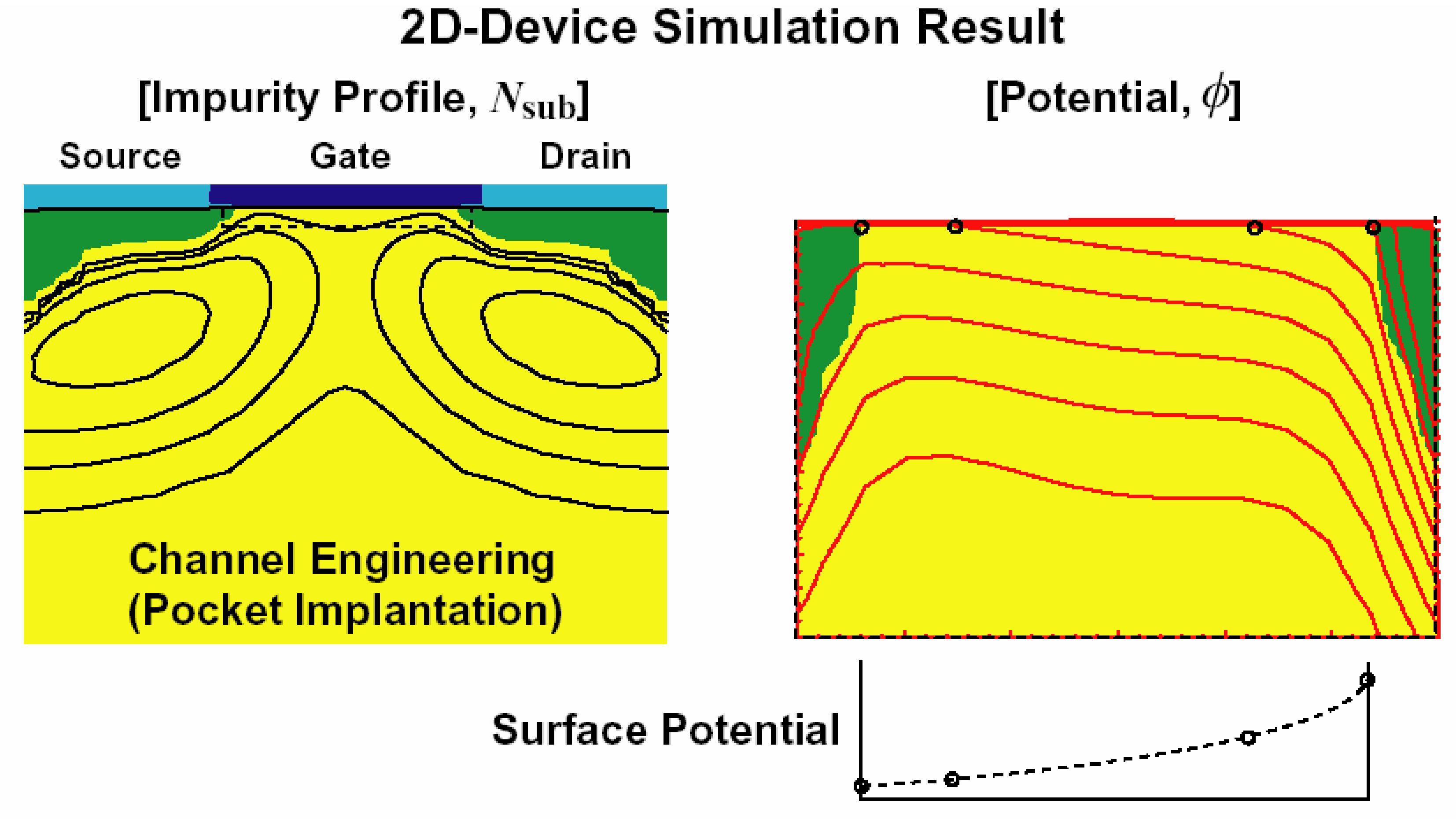


H. J. Mattausch et al., IEEE Circuit & Devices Magazine, vol. 22, no. 5, p. 29, 2006.

Gummel Symmetry Test

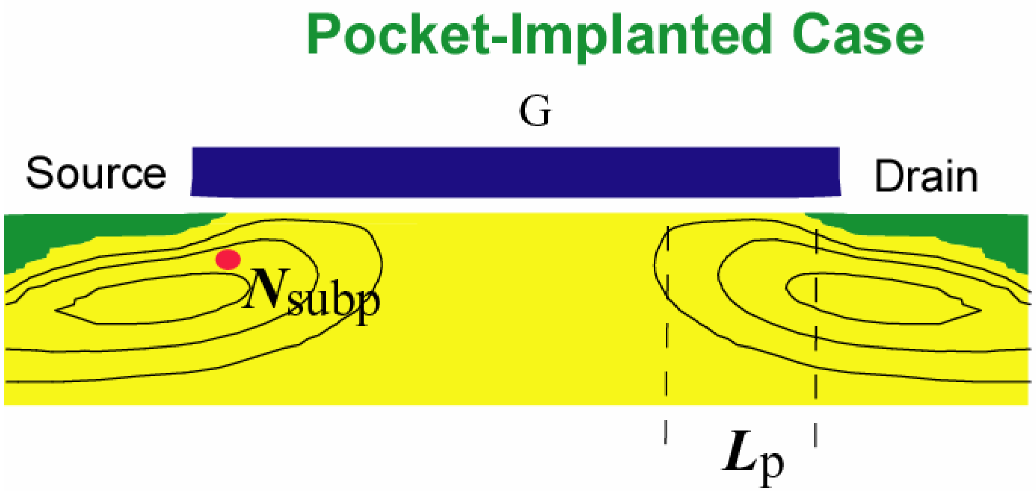


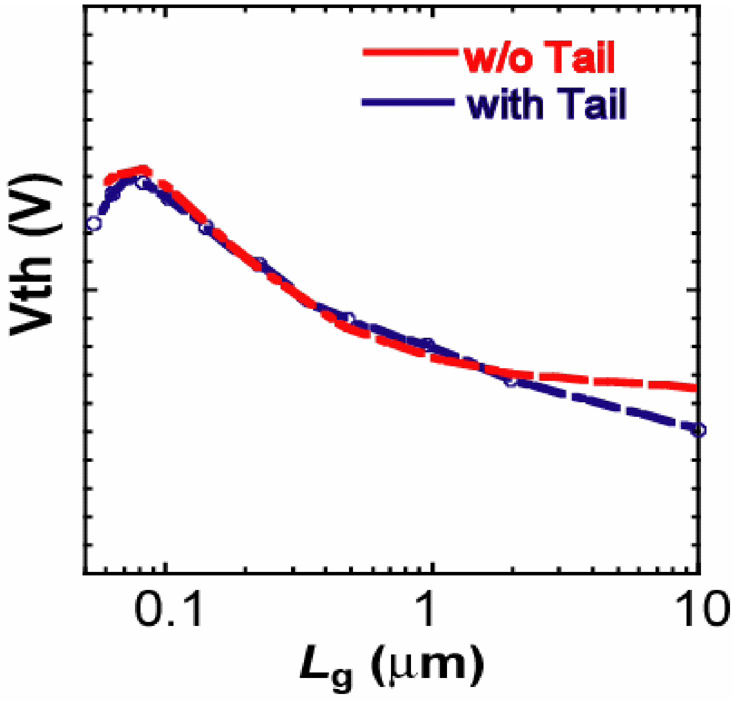
Technology-Based Modeling

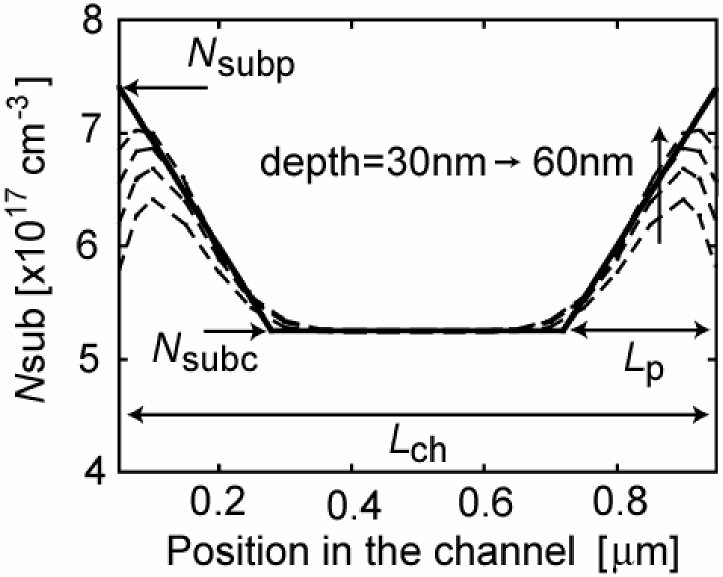


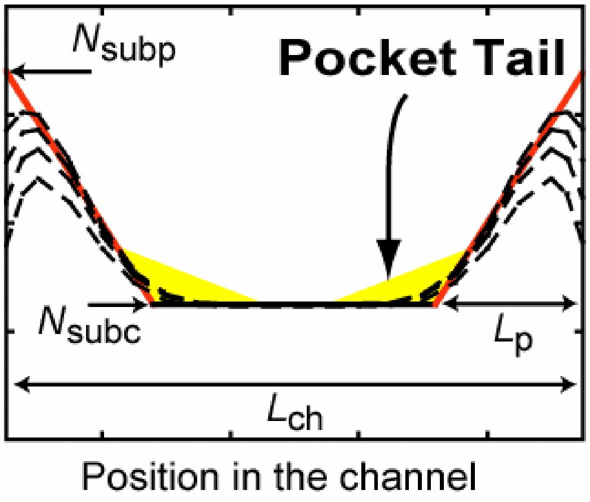
require accurate impurity-profile extraction

Modeling of Pocket Implant


Pocket-Implanted Case

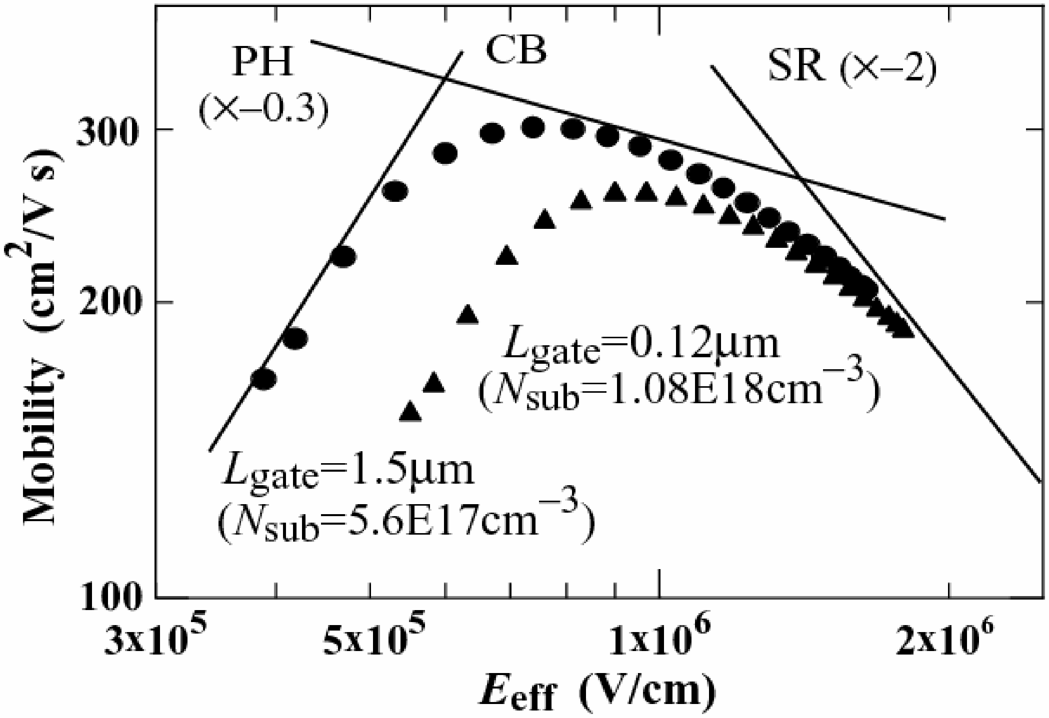





Pocket Tail

Universal Mobility

V_{ds}=0.1V



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

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

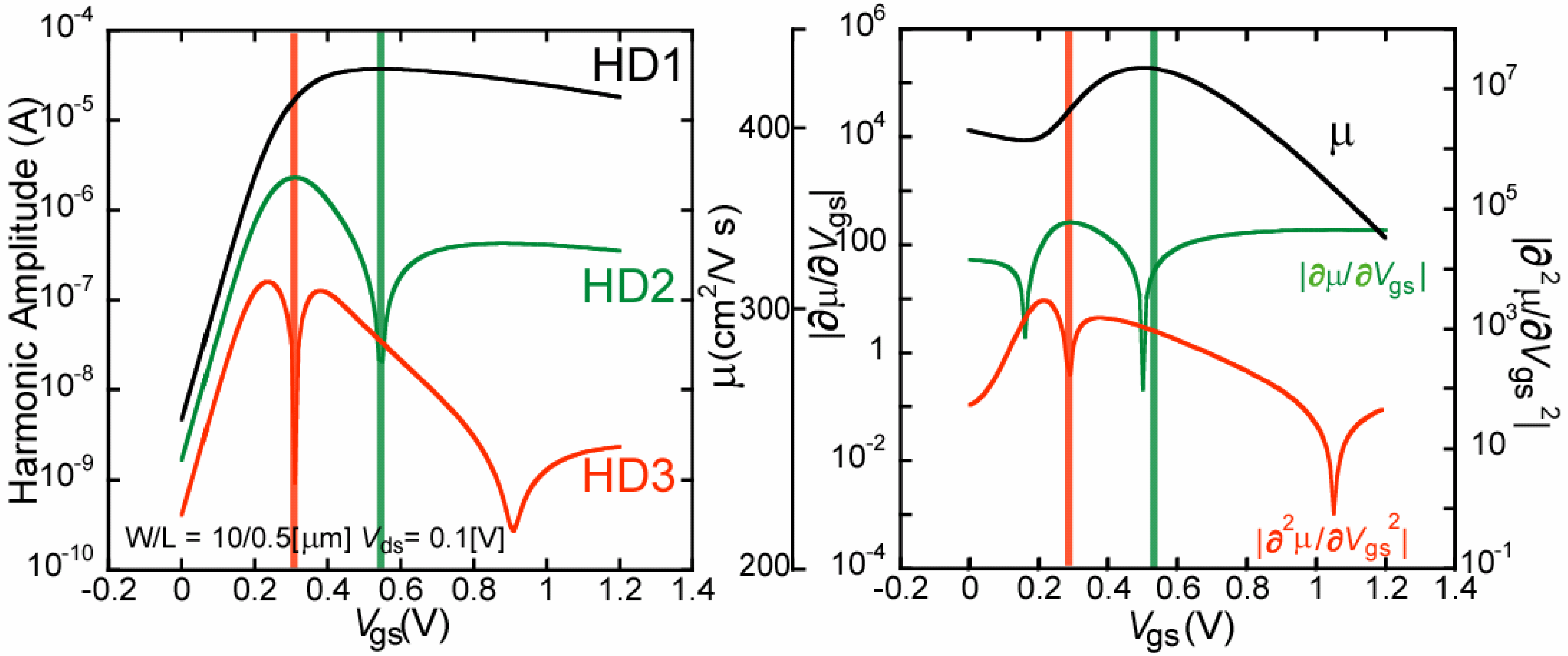
- $\mu_{CB} = CB0 + CB1 \dfrac{Q_i}{q \times 10^{11}}$
- $\mu_{PH} = \dfrac{PH0}{(T/300\mathrm{K})^{PHTMP} \times E_{eff}{}^{PH1}}$
- $\mu_{SR} = \dfrac{SR0}{E_{eff}{}^{SR1}}$

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

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

Harmonic Distortion vs. Mobility

V_{ds}=0.1V

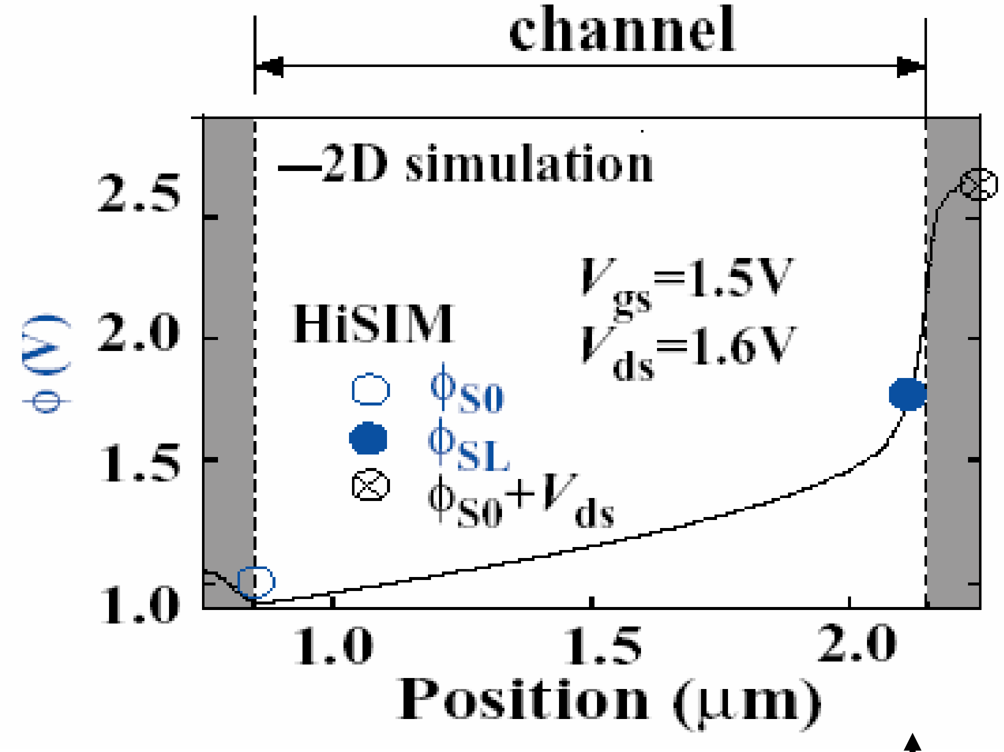


$$\mathrm{HD1} \approx \left| V_P \frac{\partial I_{ds}}{\partial V_{gs}} \right| \qquad \mathrm{HD2} \approx \left| -\frac{1}{4} V_P^2 \frac{\partial^2 I_{ds}}{\partial V_{gs}^2} \right| \qquad \mathrm{HD3} \approx \left| -\frac{1}{24} V_P^3 \frac{\partial^3 I_{ds}}{\partial V_{gs}^3} \right|$$

Mobility determines the harmonic distortion characteristics.

D. Navarro et al., IEEE Trans. ED, vol. 53, p. 2025, 2006.

Under Saturation Condition



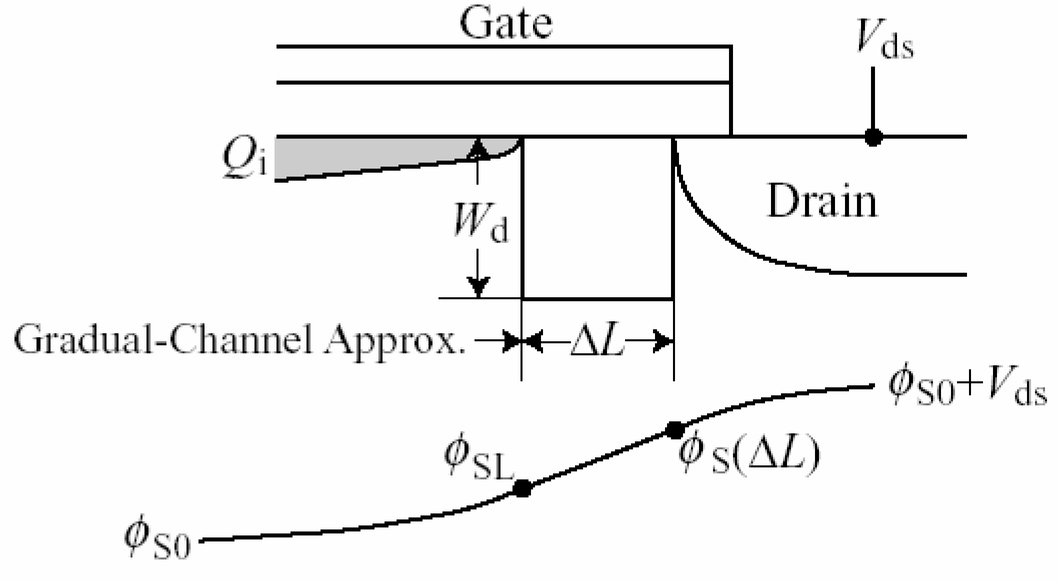
Pinch-off region
steep potential increase

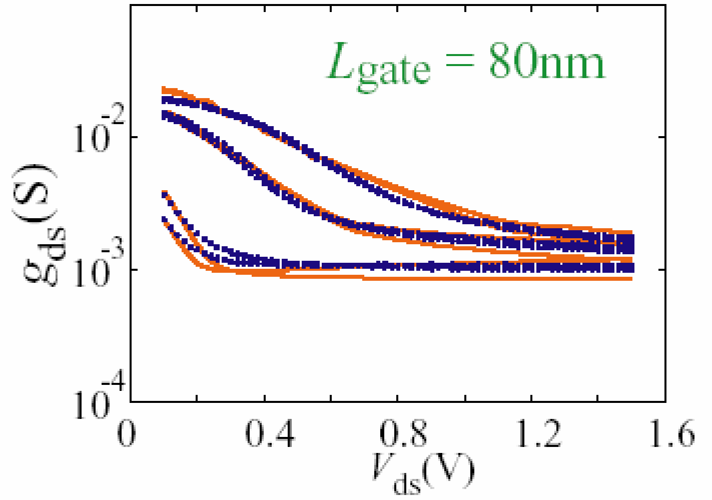
Beyond Pinch-off Point

Approximations Applied for Modeling

- **Inversion-Layer Thickness ~ 0**
- **Gradual-Channel Approximation**

➡ **Valid for long channel**





modeling further potential increase

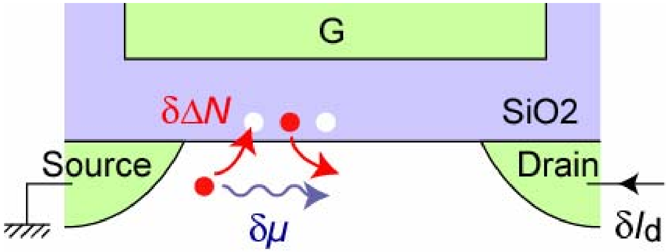
Contents

- MOSFET Modeling
- 1/f Noise
- Thermal Noise
- Induced Gate Noise

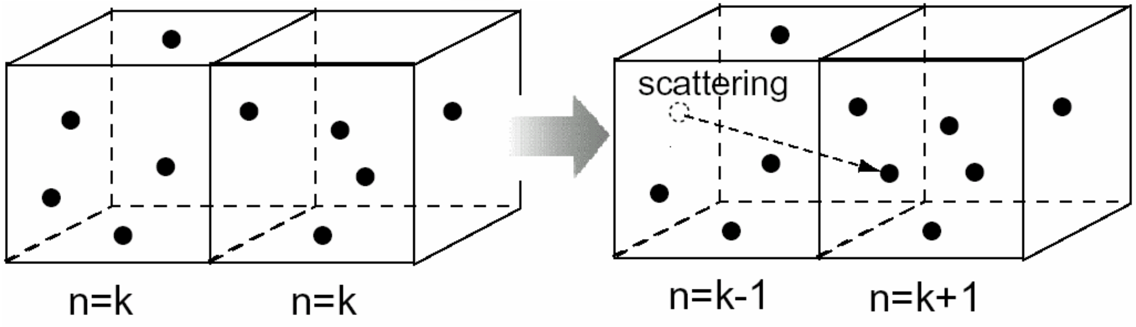
  + Cross-Correlation Noise

Noise Sources

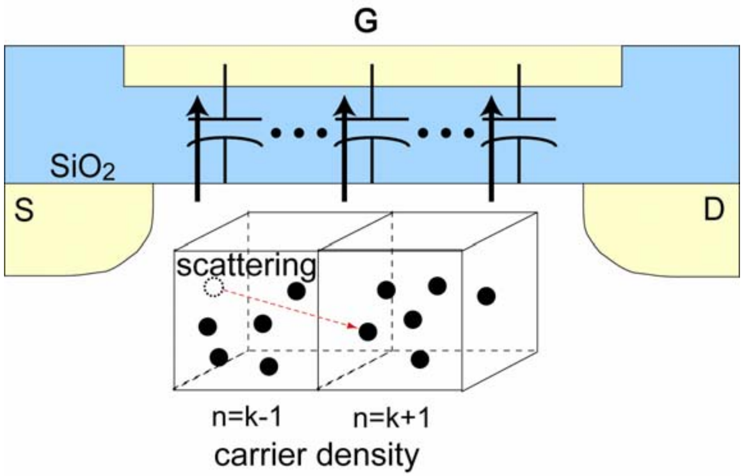
1/*f* Noise:



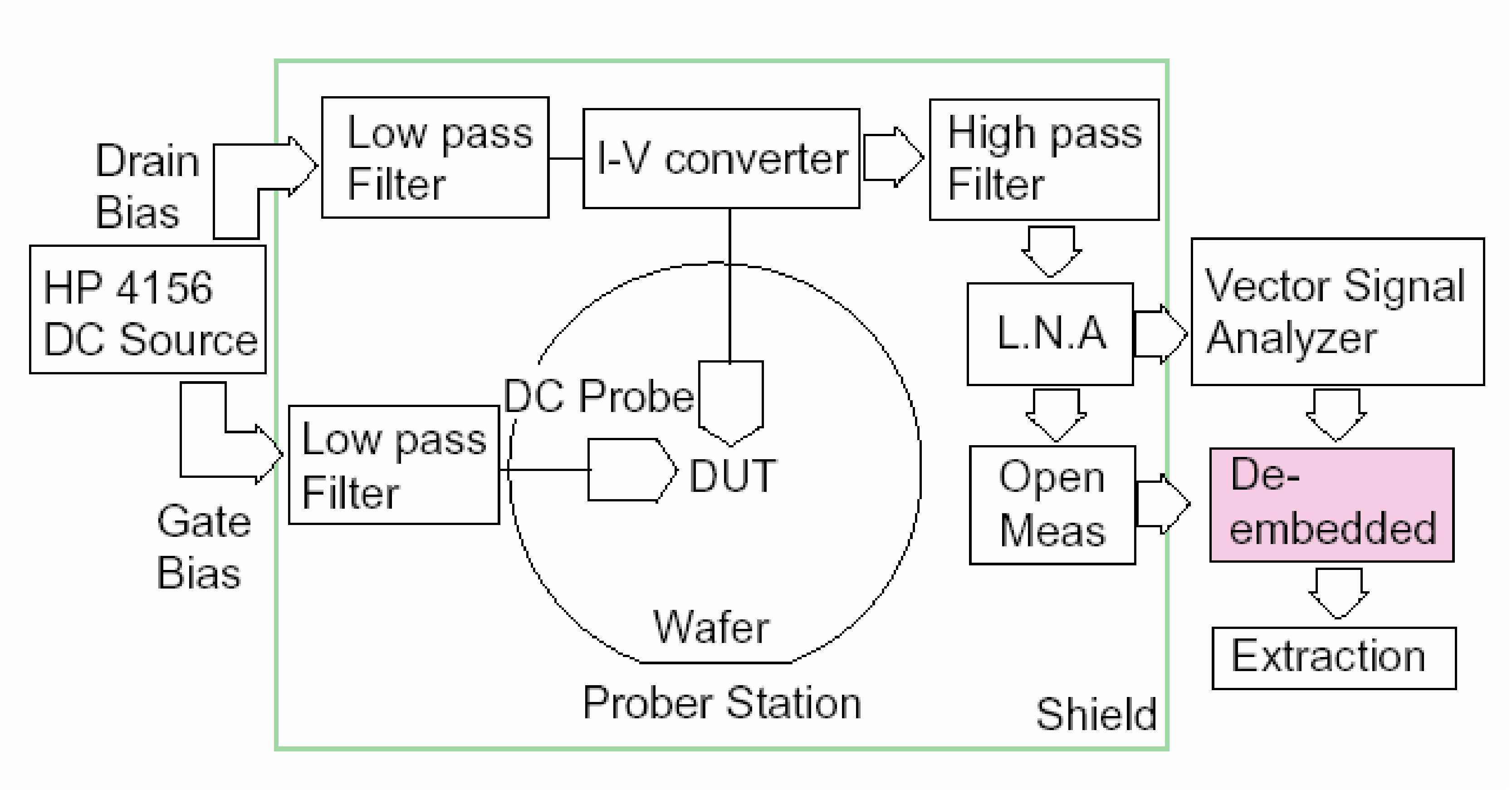
Thermal Noise:



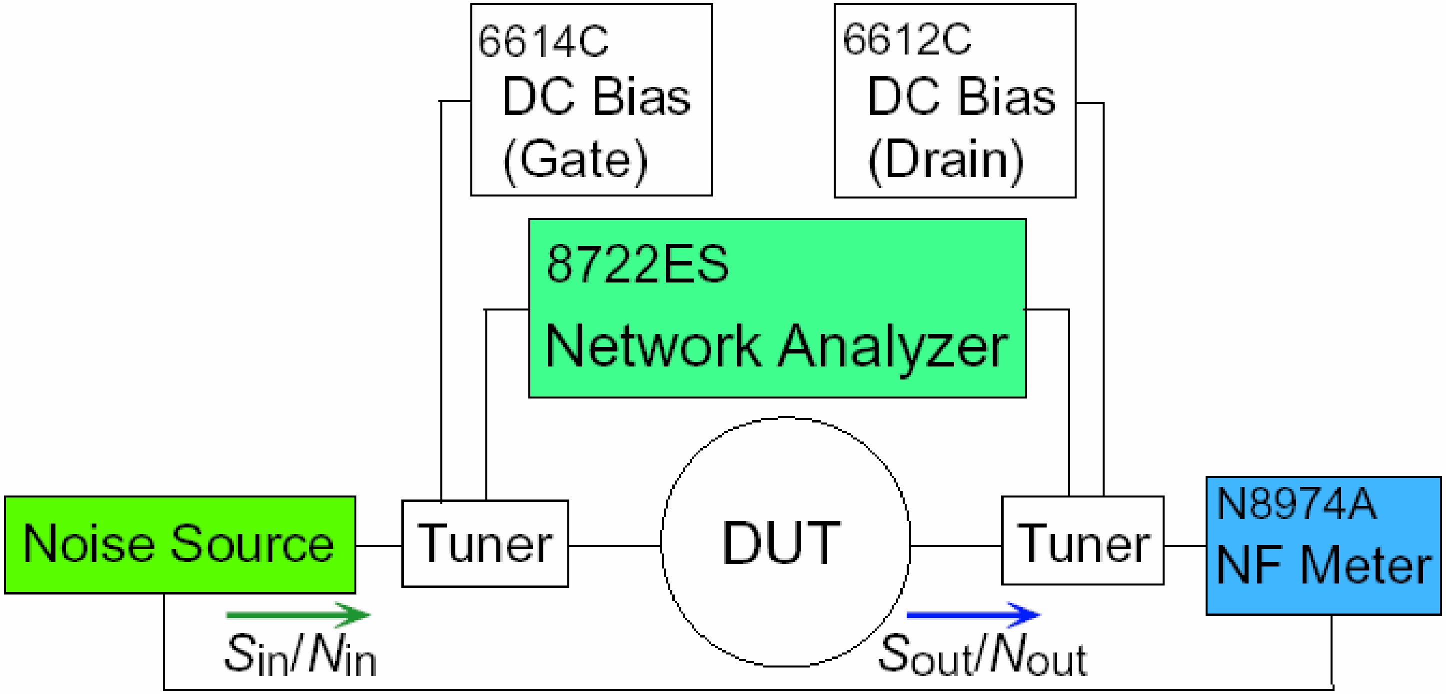
Induced Gate Noise +
Cross-Correlation Noise:



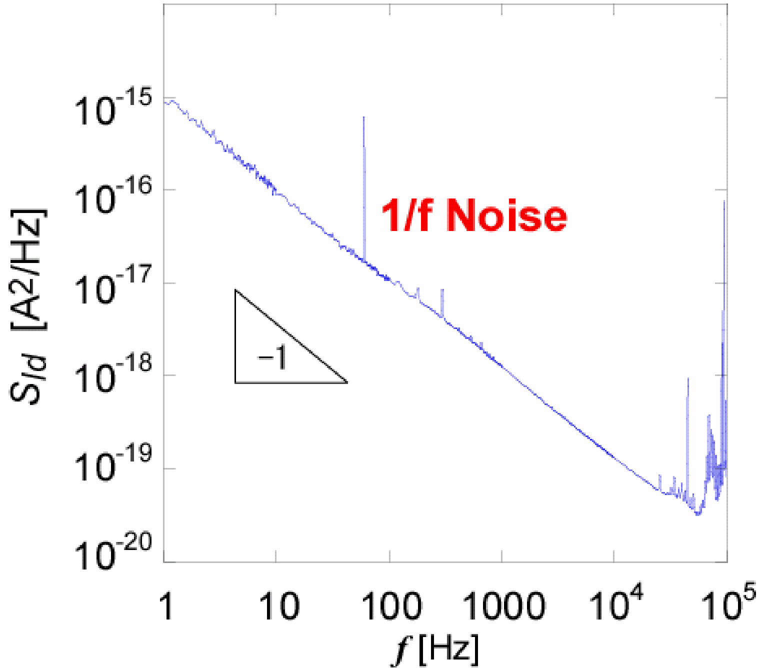
Measurement Setup for 1/f Noise

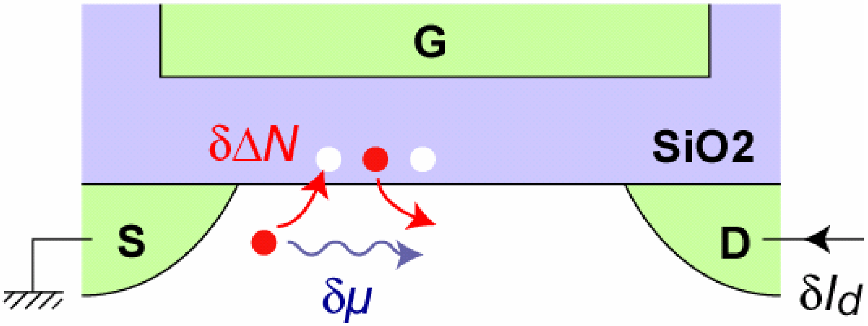


Noise Figure Measurement



Origin of 1/*f* Noise





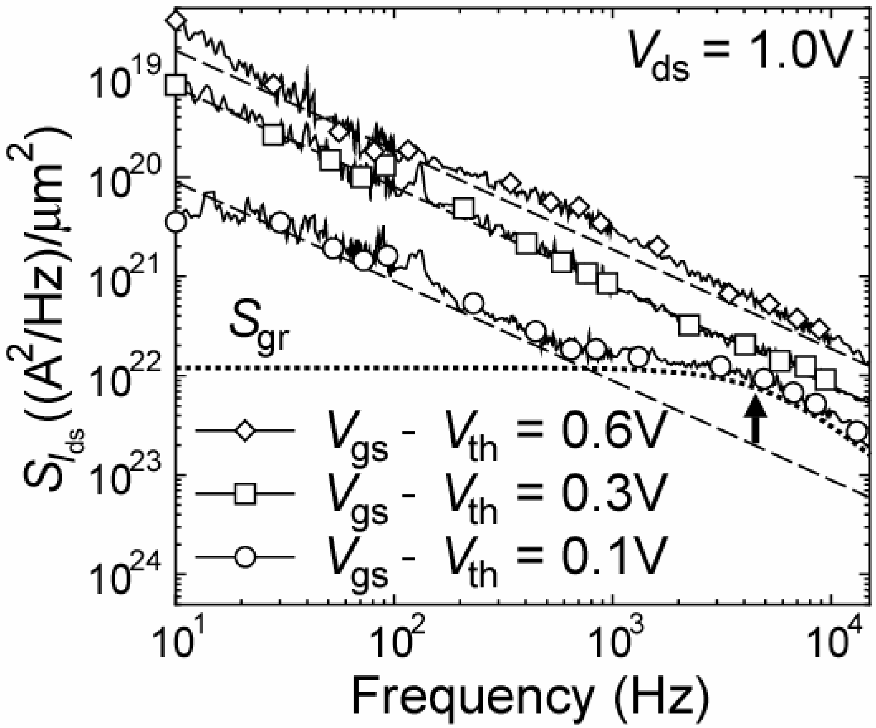
Origin: $\delta\Delta N$

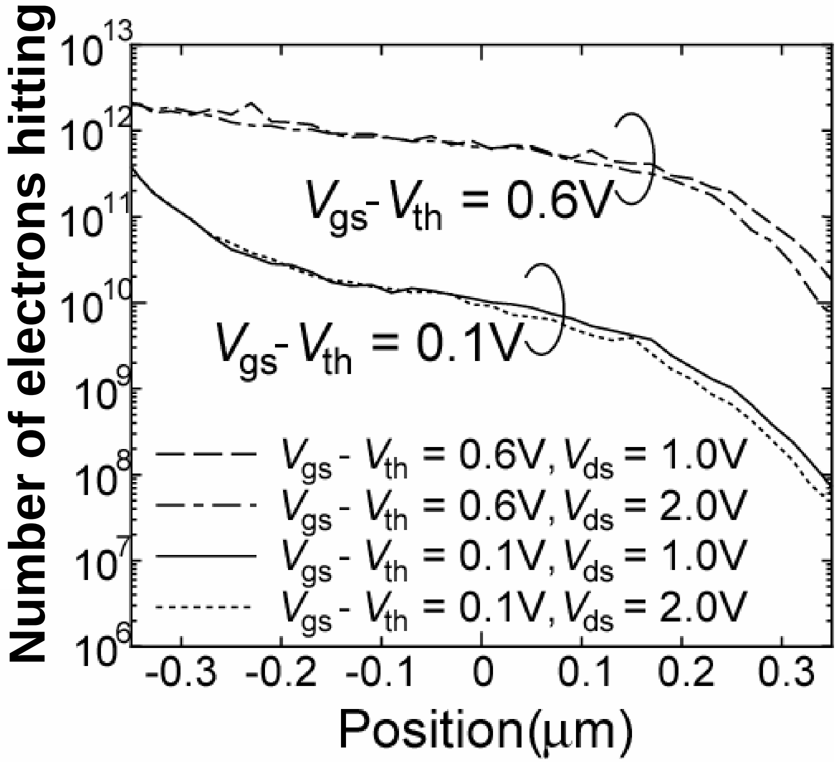
$+$

$\delta\mu$

K. K. Huang et al., IEEE Trans. ED, 37, p. 1323, 1990.

Monte Carlo Simulation

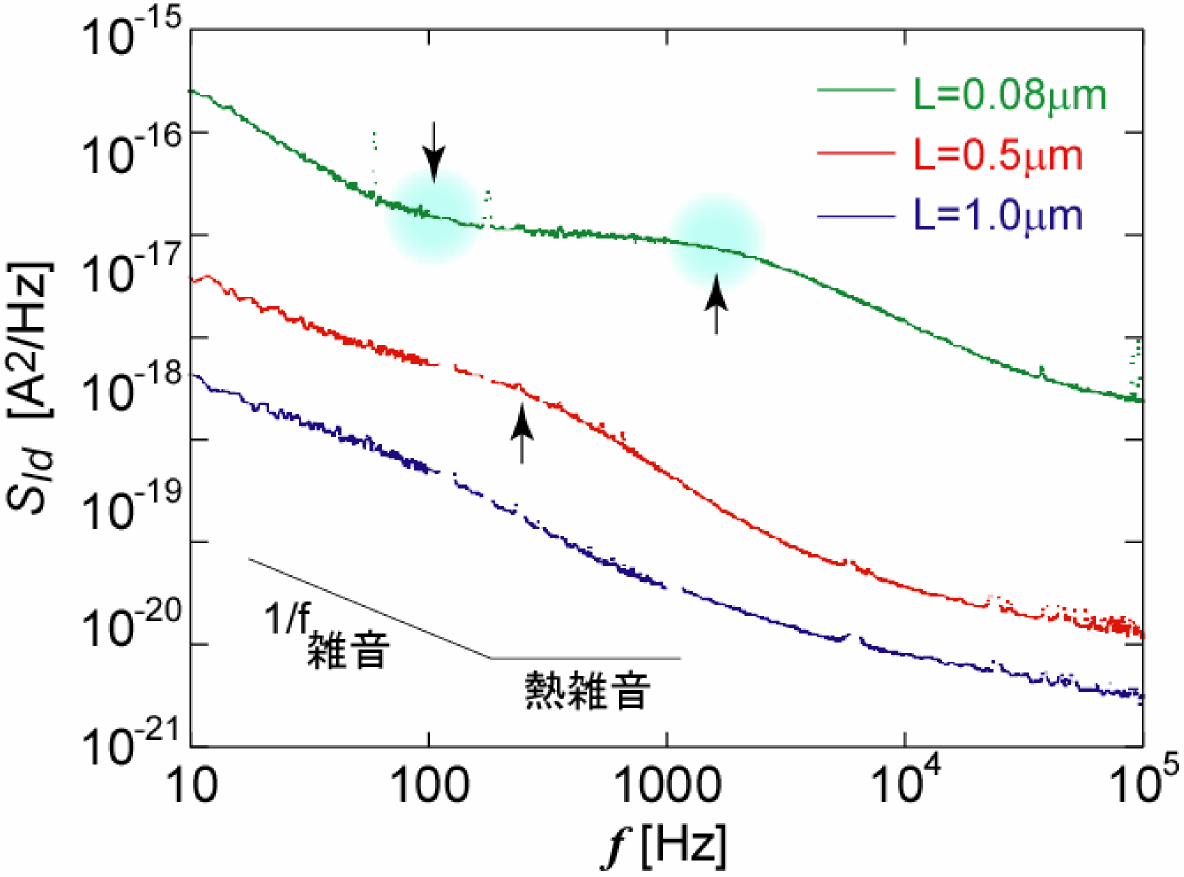




H. Ueno et al., Appl. Phys. Let., vol. 78, p. 380, 2001.

Noise Intensity ⇦ Number of electrons hitting SiO_2 surface

Measured 1/*f* Noise

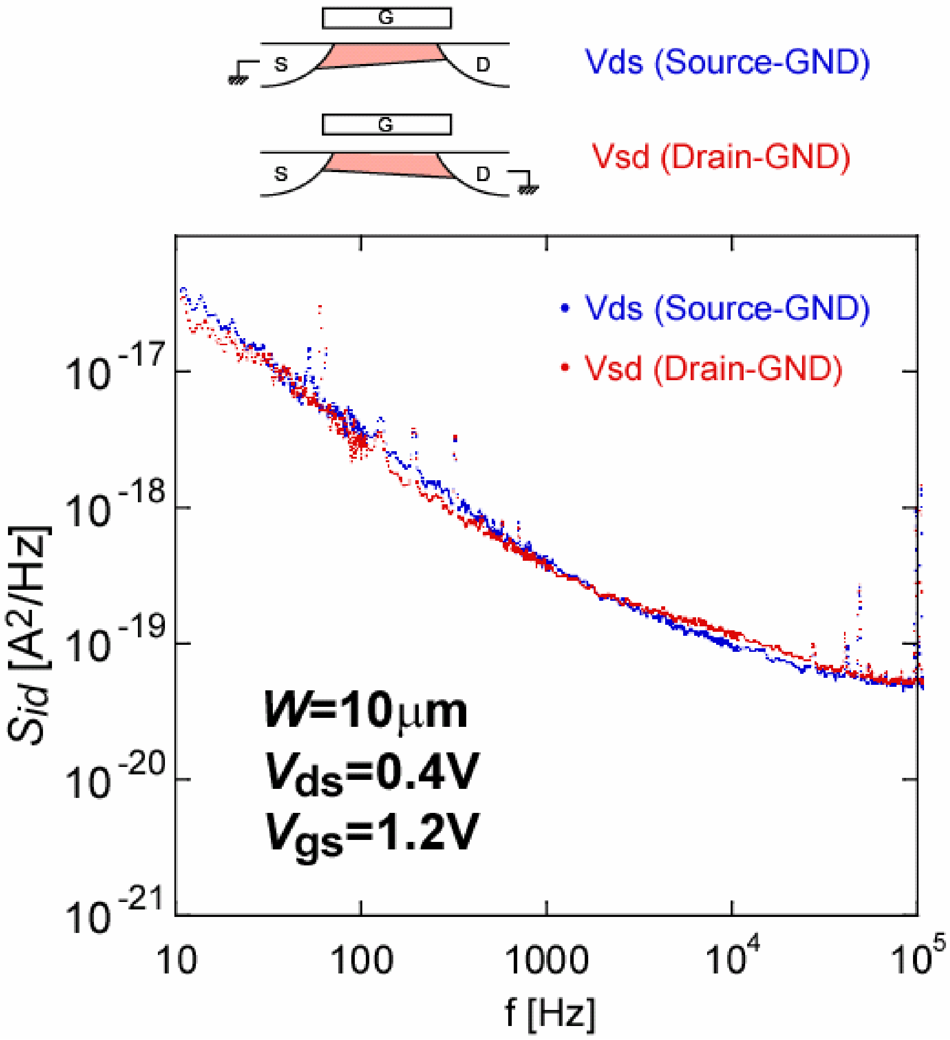


nMOSFET
W=10µm
V_{gs}=1.2V
V_{ds}=0.4V

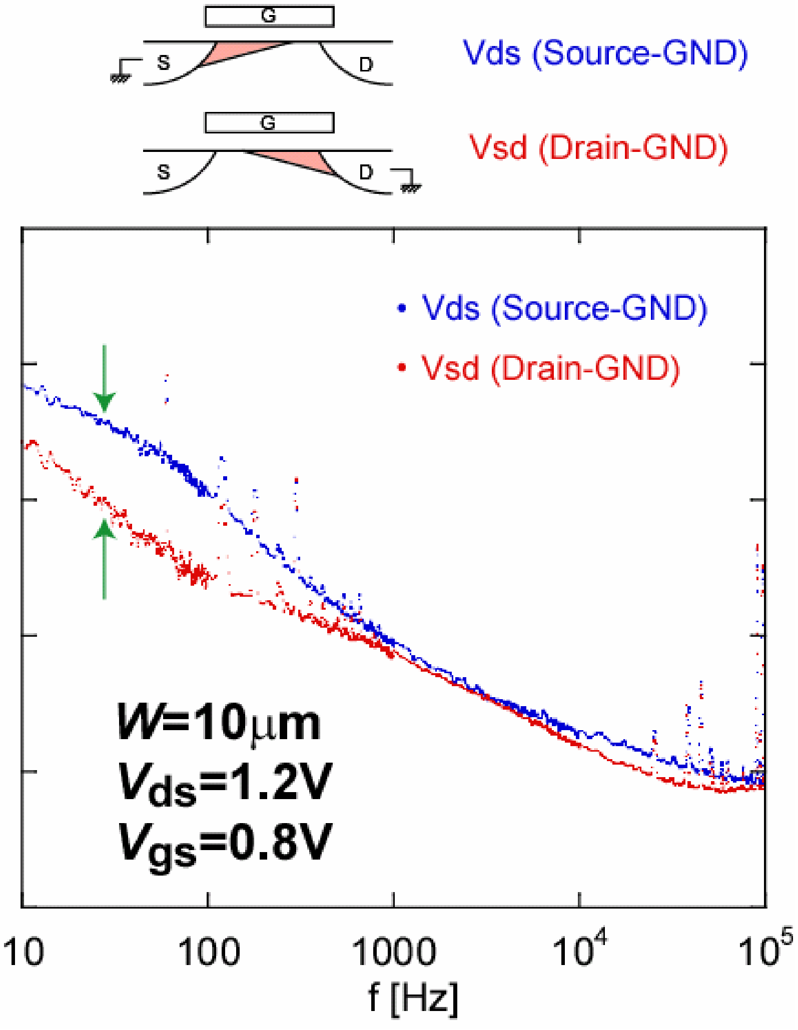
S. Matsumoto et al., IEIEC T E, E88-C, p. 247, 2005.

L_g=1μm (nMOSFET)

Linear Condition

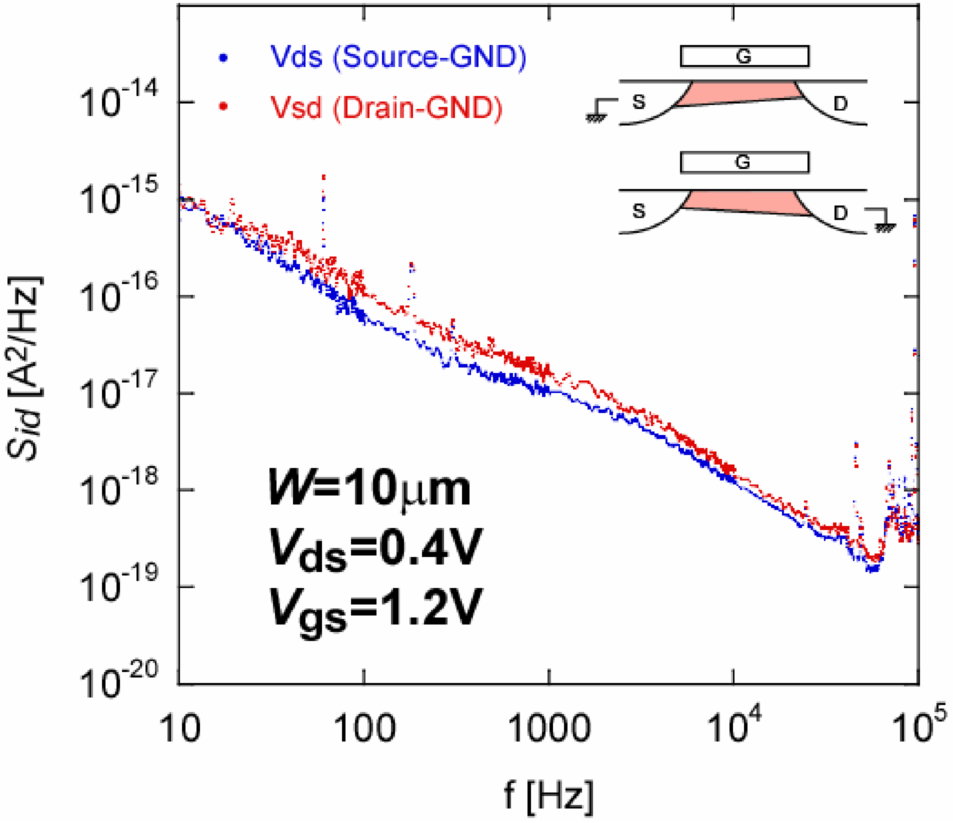


Saturation Condition

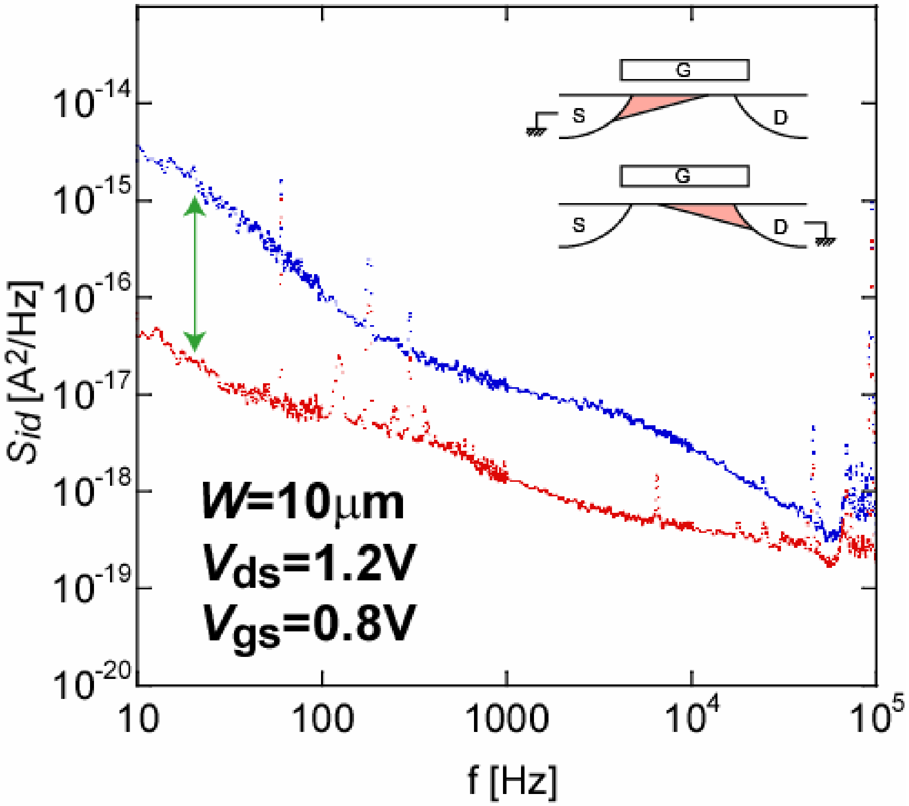


L_g=0.13μm (nMOSFET)

Linear Condition

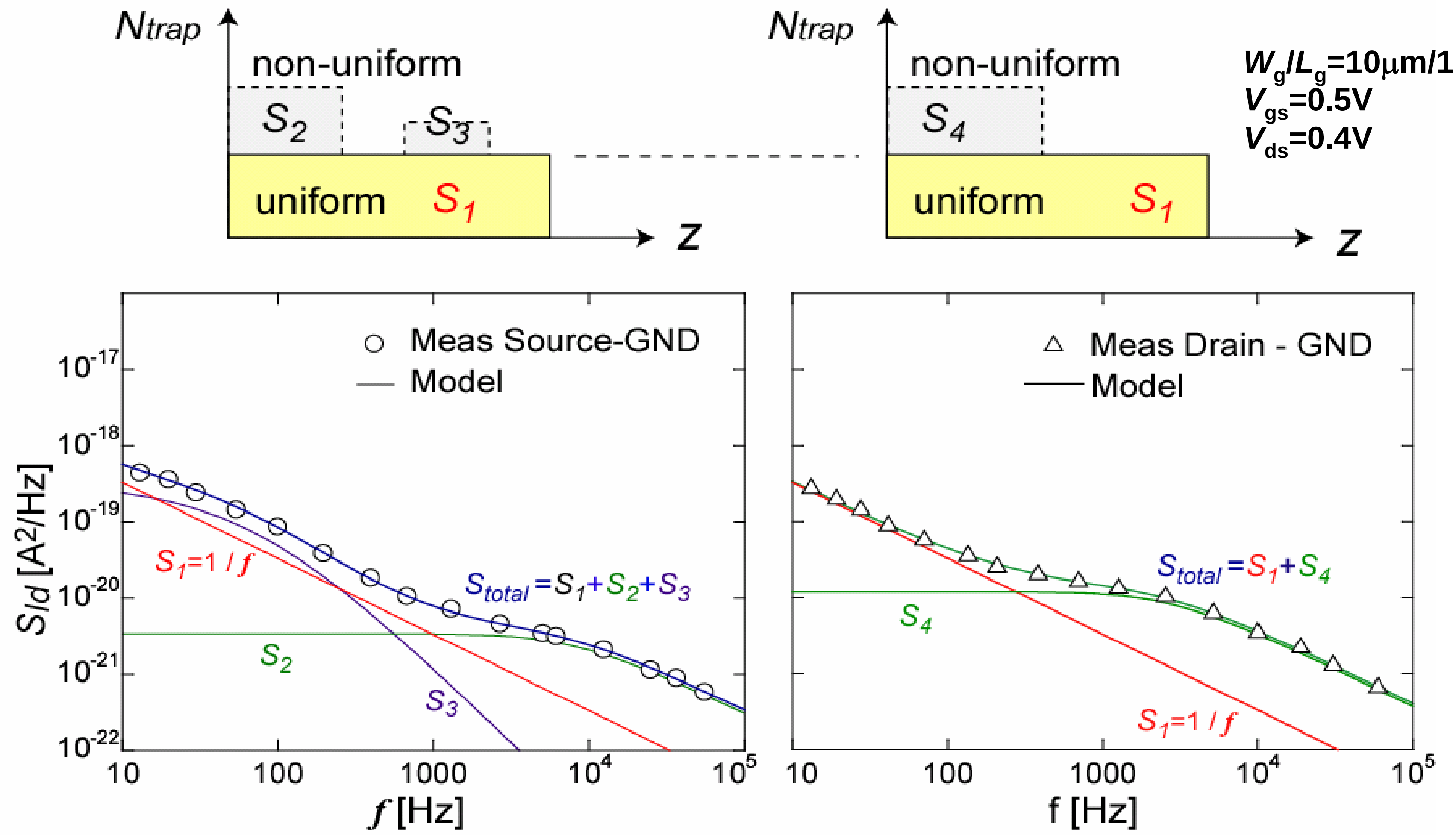


Saturation Condition



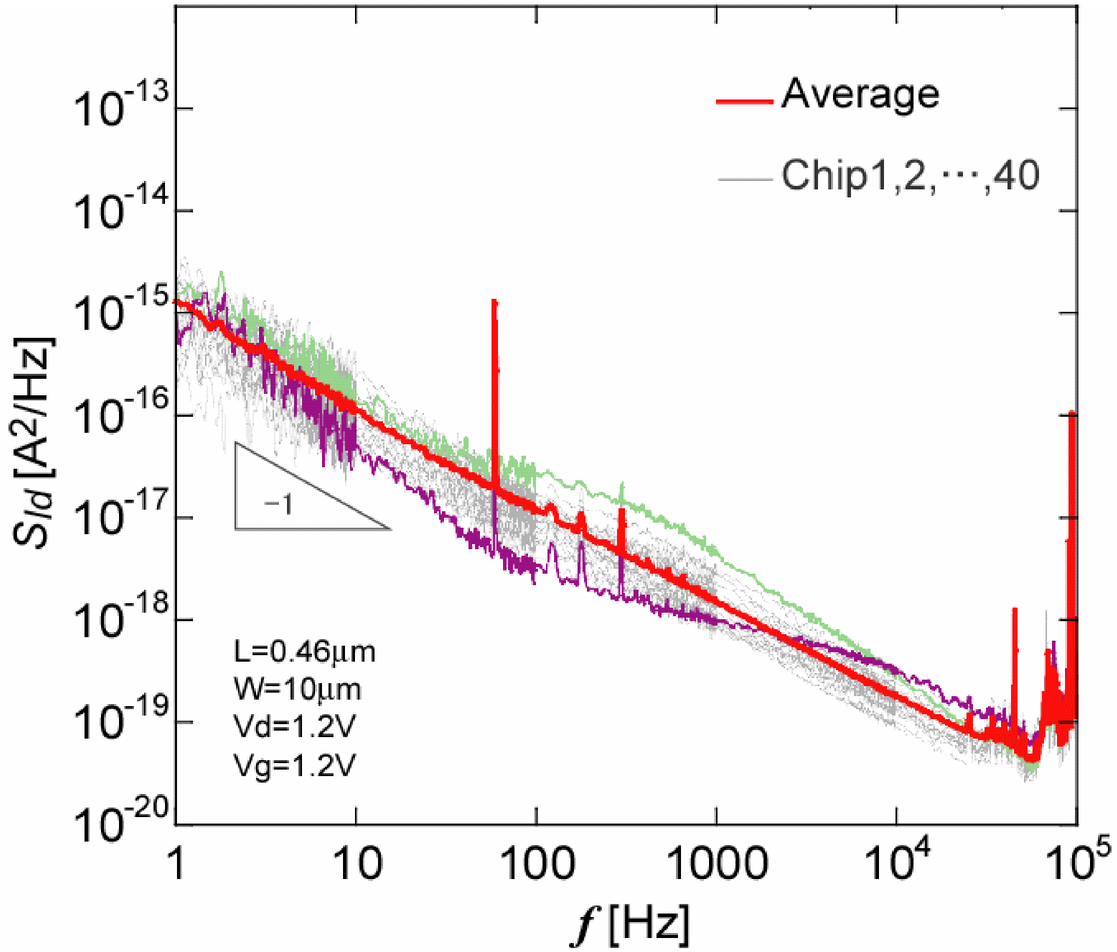
Explanation

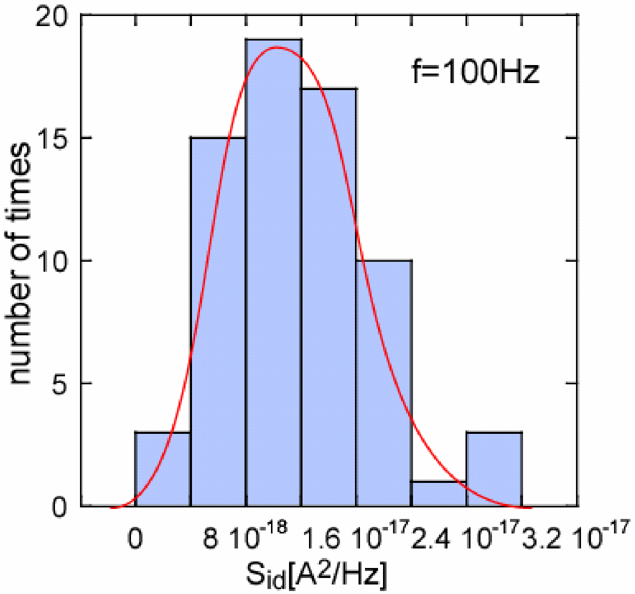
Inhomogeneous trap density distribution



W_g/L_g=10μm/1μm
V_{gs}=0.5V
V_{ds}=0.4V

Statistics on a Wafer

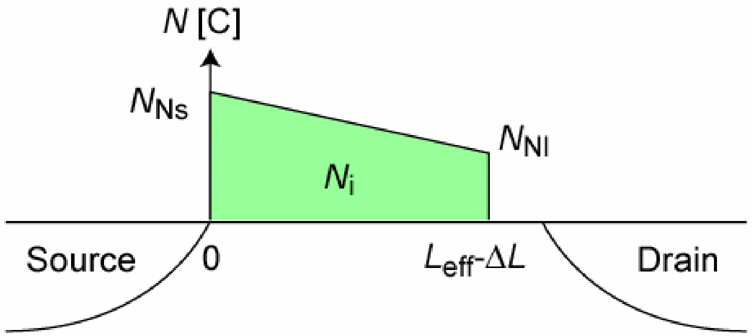




Homogeneous Distribution on a Wafer

Model Equations

$$S_{I_{ds}}(f) = \frac{W_g N_t}{q L_g^2 \eta f} kT \int_0^{L-\Delta L} \left(\frac{I_{ds}}{W_g}\right)^2 \left(\frac{1}{N(x)} \pm \alpha\mu\right)^2 dx$$



$$\Big\downarrow$$

$$S_{I_d}(f) = \frac{(L-\Delta L)}{L^2}\frac{I_{ds}^2}{W}\frac{N_t(E_f)}{q\eta f} kT \left\{ \frac{1}{(N_s+N^*)(N_1+N^*)} + \frac{2\alpha\mu}{N_1-N_s}\log\left(\frac{N_1+N^*}{N_s+N^*}\right) + (\alpha\mu)^2 \right\}$$

$$N^* = \frac{C_{ox}+C_{dep}+CIT}{q\beta}$$

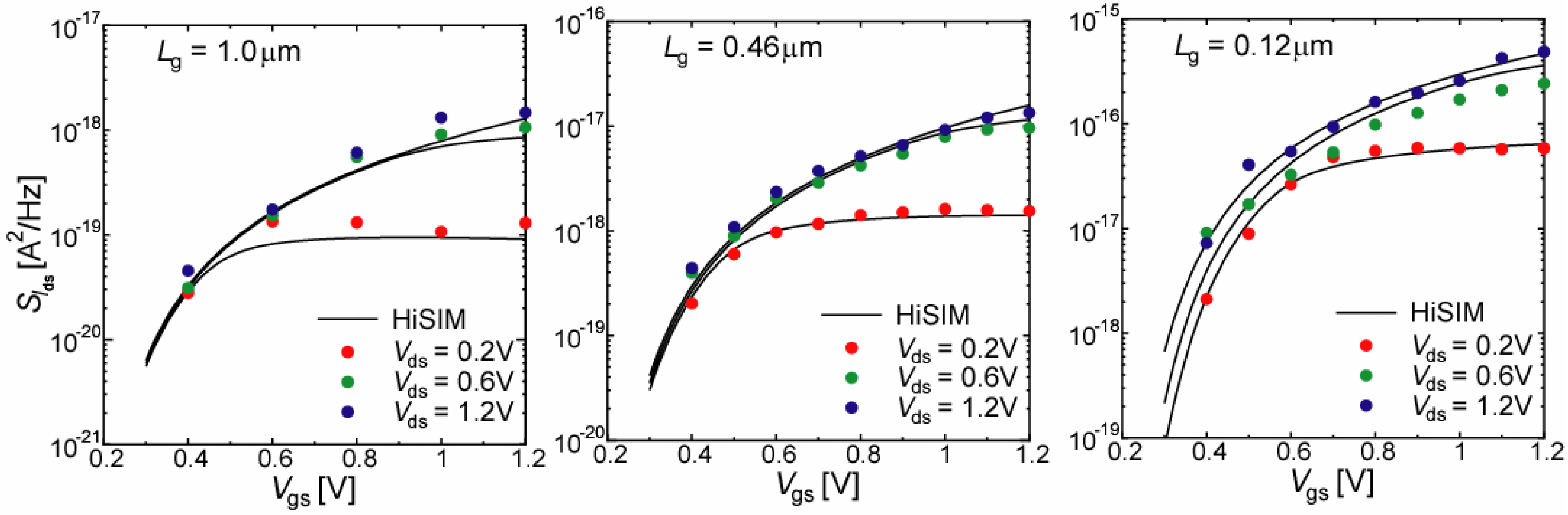
Model Parameters

Trap Density: $N_{trap} = N_t(E_f)/\eta \quad [eV^{-1}cm^{-3}][cm] = [eV^{-1}cm^{-2}]$

Scattering Coeff.: $\alpha \quad [Vs]$

Capacitance Change: $CIT \simeq 0$

Comparison with Measurements

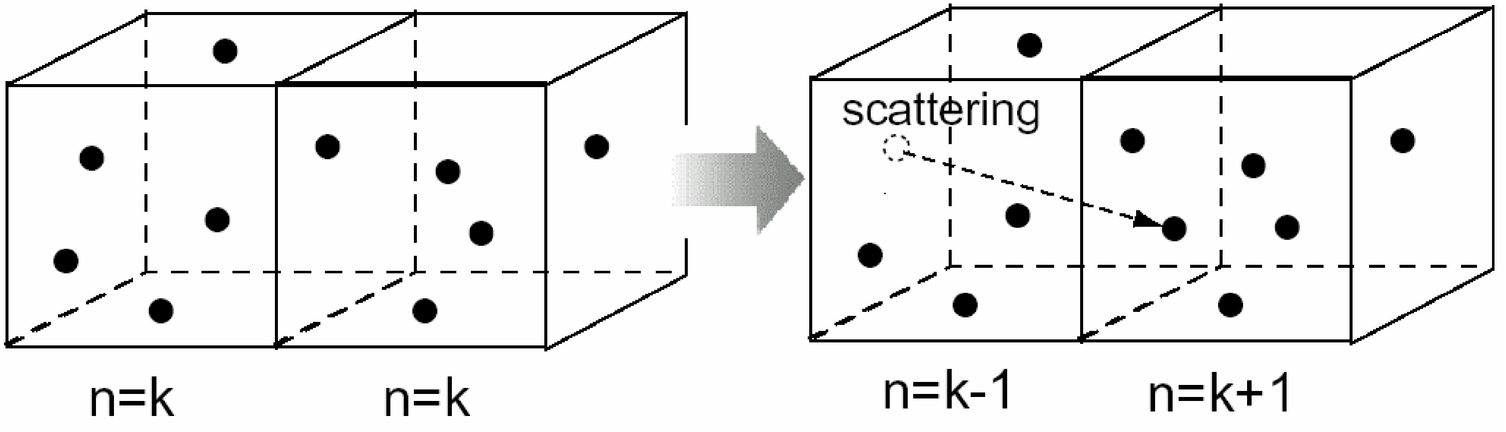


- **N_{trap} is fitted to measurements.**
- **If technology is mature, N_{trap} is nearly universal.**

- ***I-V* characteristics determine 1/*f* noise characteristics.**
- **1/*f* noise is predictable.**

S. Matsumoto et al., IEIEC T E, E88-C, p. 247, 2005.

Origin of Thermal Noise



van der Ziel Equation based on Nyquist Theorem:

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

$$= 4kTg_{\mathrm{ds0}}\gamma$$

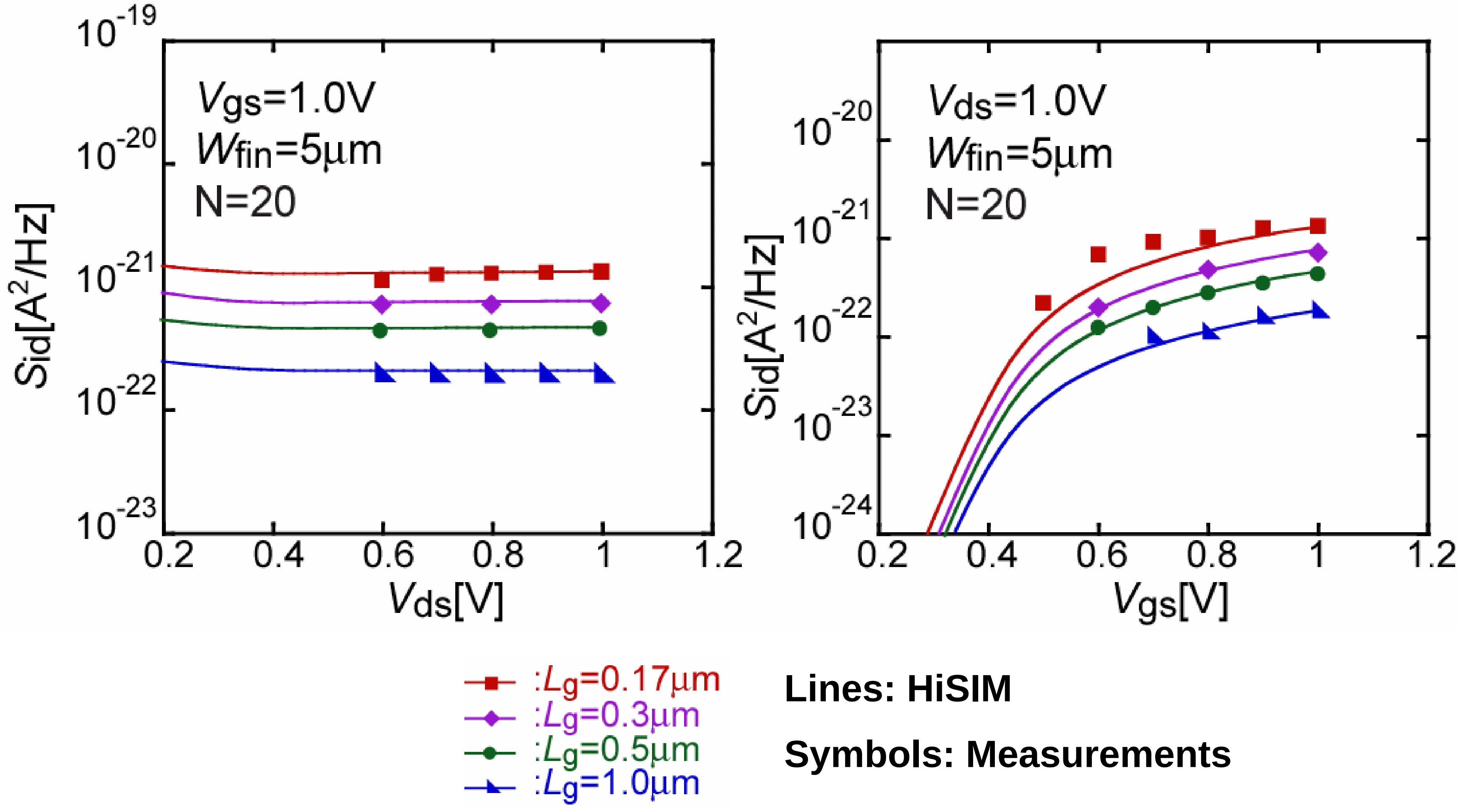
g_{ds}(y): Channel Conductance

g_{ds0}: at V_{ds}=0

γ : Noise Coefficient

No Additional Model Parameters

Comparison with Measurements

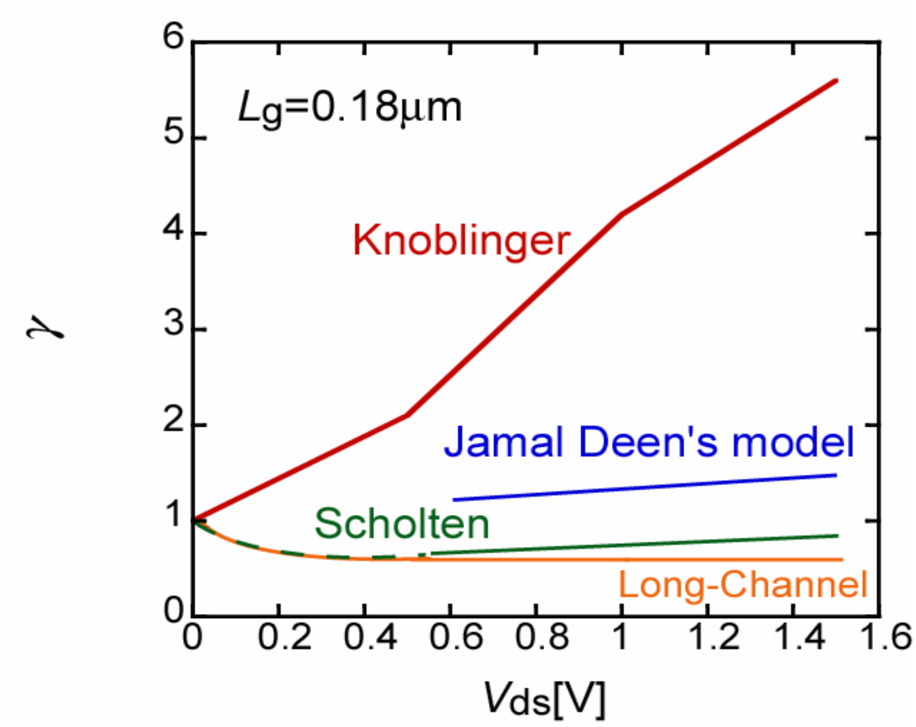


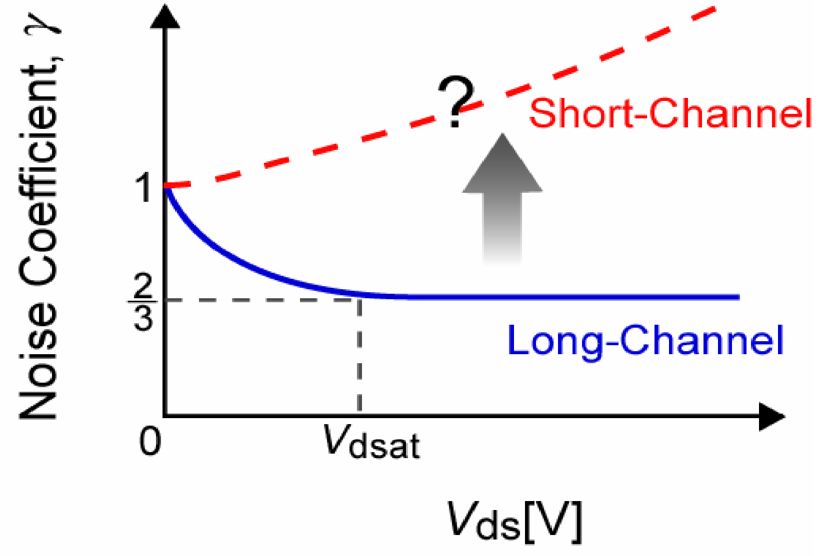
Lines: HiSIM

Symbols: Measurements

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

Noise Coefficient (γ) in Short-Channel MOSFETs



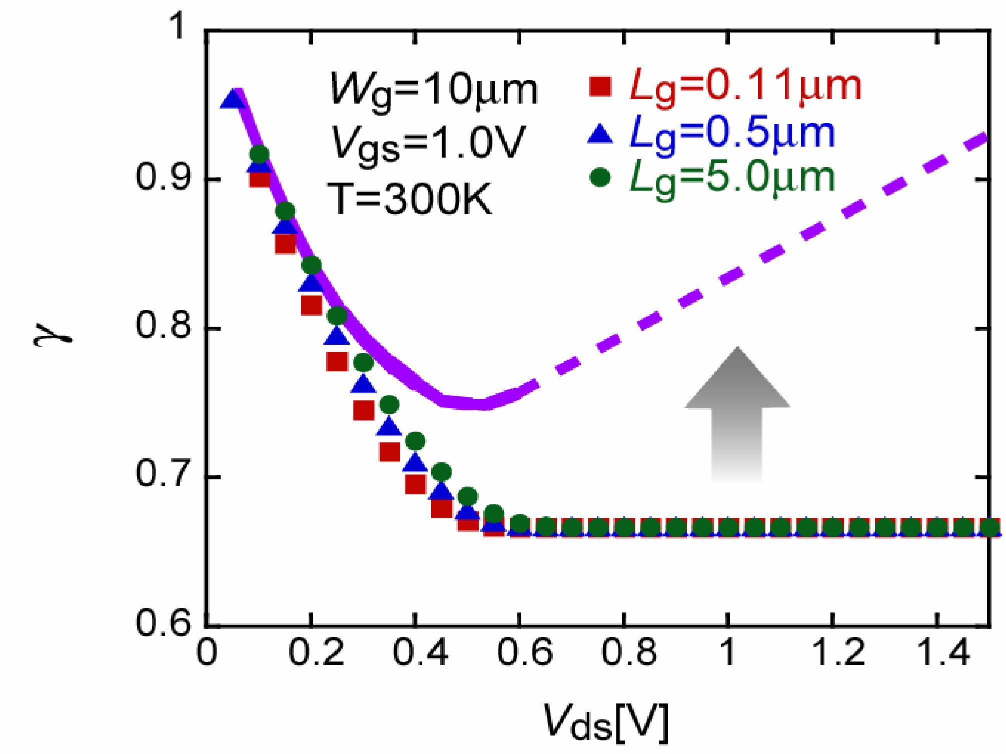


Different Explanations

- **Knoblinger et al. (2001): Hot Electron Contribution**
- **Jamal Deen et al. (2002): Channel Length Modulation**
- **Scholten et al. (2002): Velocity Saturation**

γ for Short-Channel MOSFET

Analytical Investigation



μ: Position Dependent

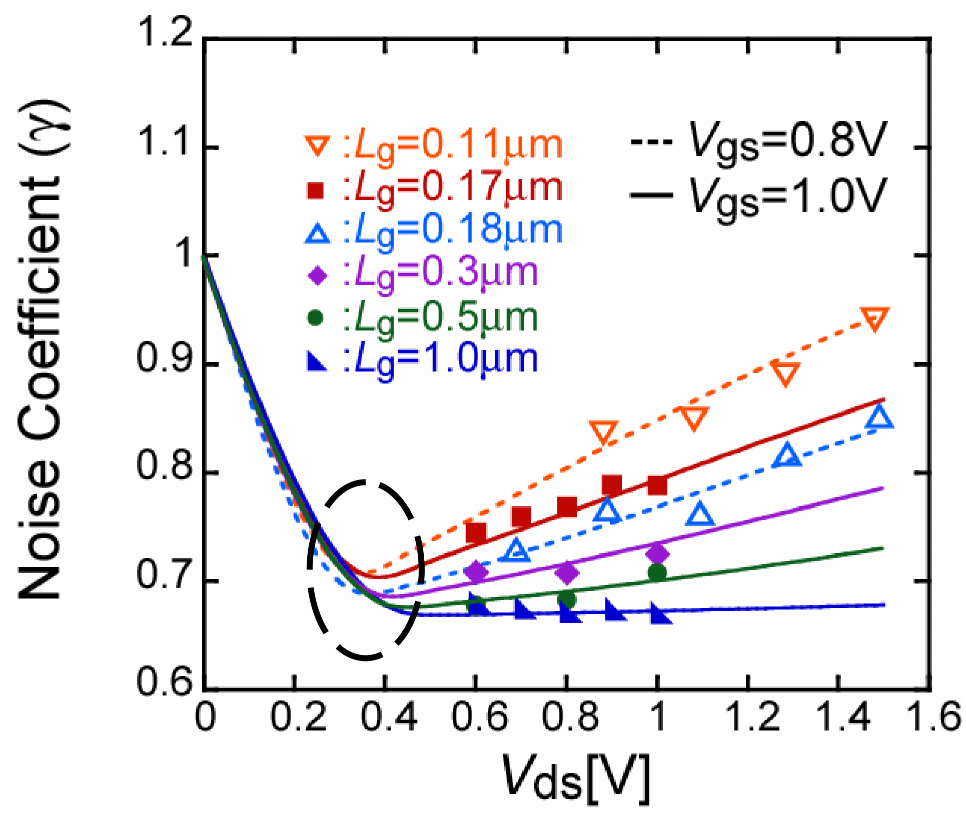
μ: Constant

Origin of γ Increase → **Mobility Reduction along Channel**
(No additional model parameter)

γ Increase → **Potential Increase**

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

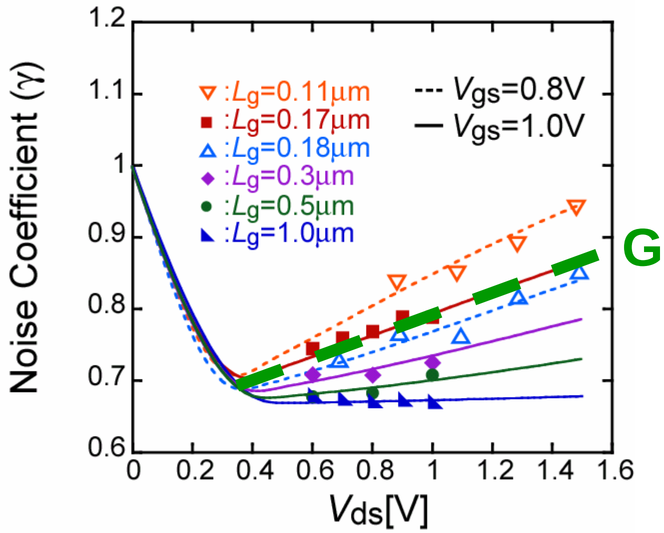
Comparison with Measurements: Excess Noise



Lines: Simulation (HiSIM)
Symbols: Measurements

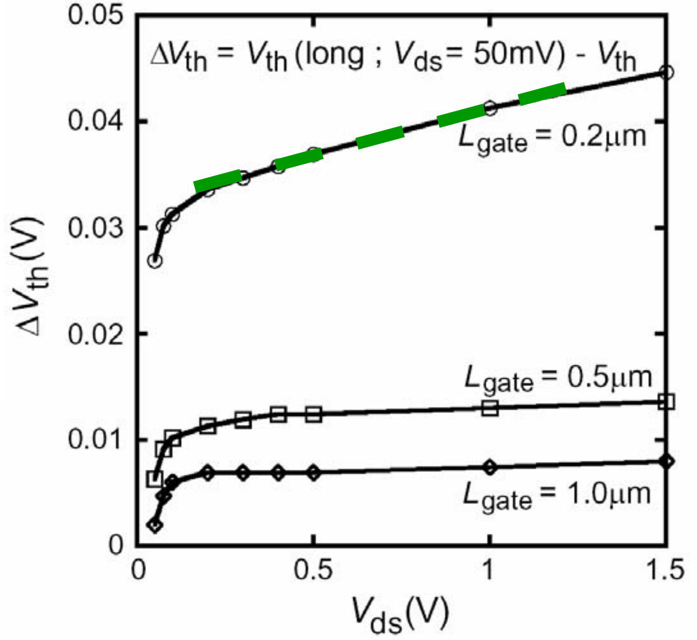
- ➢**First γ Reduction and Increase in the Saturation Region**
- ➢**No Drastic Increase of γ**
- ➢ **γ Minimum Increase from 2/3**

Comparison with V_{th} Shift

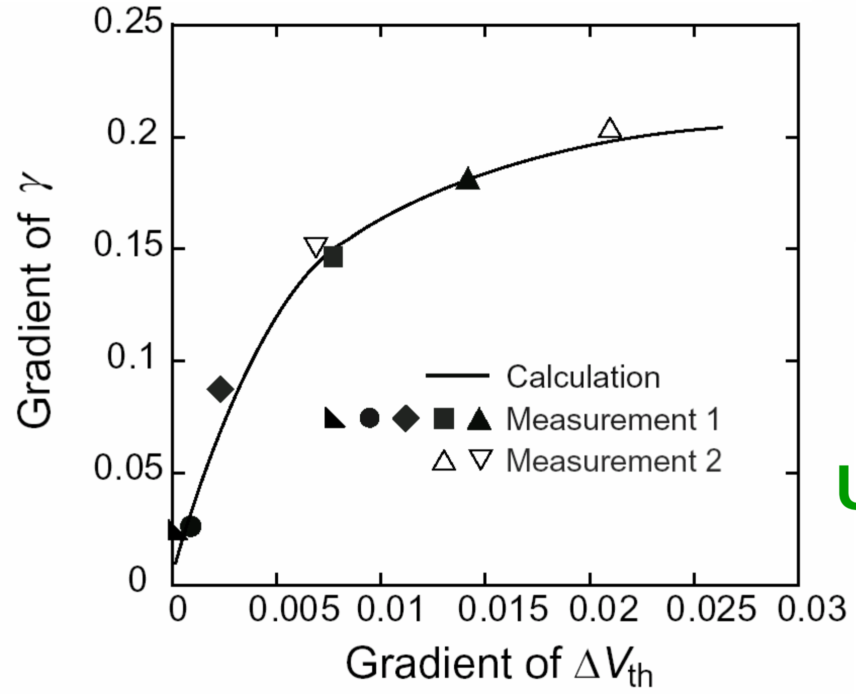


Grad. γ

Grad. ΔV_{th}

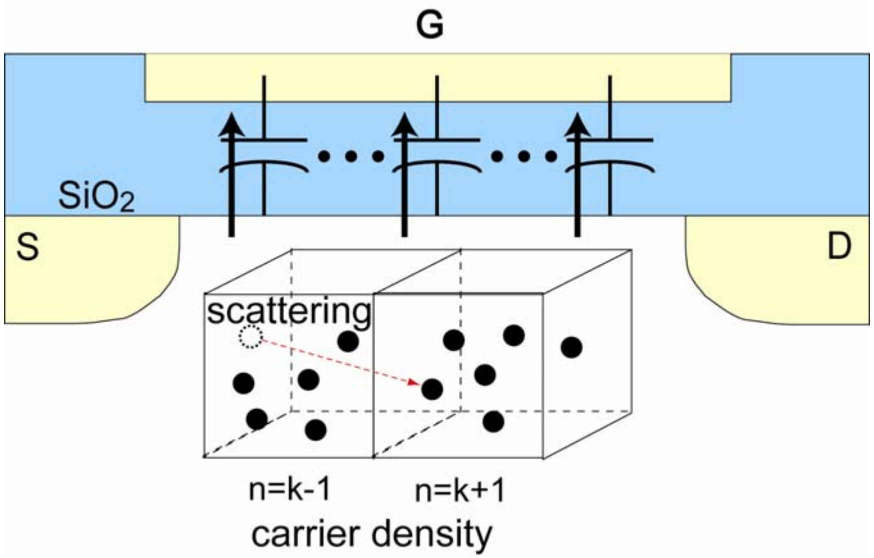


ΔV_{th}=V_{th}(long)-V_{th}(short)



Universal Relationship

Induced Gate Noise & Cross-Correlation Noise



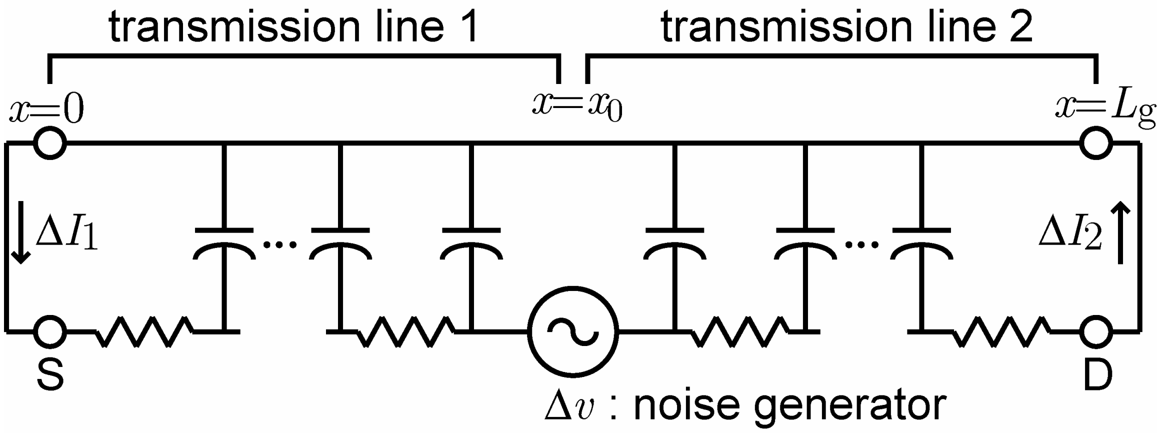
$$S_{\mathrm{ig}} = \int \left|\Delta i_{\mathrm{g}}\right|^2 dx = \int \left(\Delta I_1{}' + \Delta I_2{}'\right)^2 \Delta v^2 dx$$: induced gate

$$S_{\mathrm{i_g i_d}} = \int \Delta i_{\mathrm{g}}{}^{*} \Delta i_{\mathrm{d}} dx = \int \left(\Delta I_1{}' + \Delta I_2{}'\right)^{*} \left(\Delta I_2{}'\right) \Delta v^2 dx$$: cross - correlation

T. Warabino et al., Proc. SISPAD, p. 158, 2006.

$$S_{\mathrm{i_g}} = \int \left|\Delta i_{\mathrm{g}}\right|^2 dx = \int \left(\Delta I_1{}' + \Delta I_2{}'\right)^2 \Delta v^2 dx$$

$$S_{\mathrm{i_g i_d}} = \int \Delta i_{\mathrm{g}}{}^{*} \Delta i_{\mathrm{d}} dx = \int \left(\Delta I_1{}' + \Delta I_2{}'\right)^{*} \left(\Delta I_2{}'\right) \Delta v^2 dx$$



M. Shoji, IEEE TED, pp. 520-524, 1966.

Continuity eq.

$$\frac{\partial\{i(x)\}}{\partial x} = -j\omega \frac{\varepsilon W}{d} v(x)$$

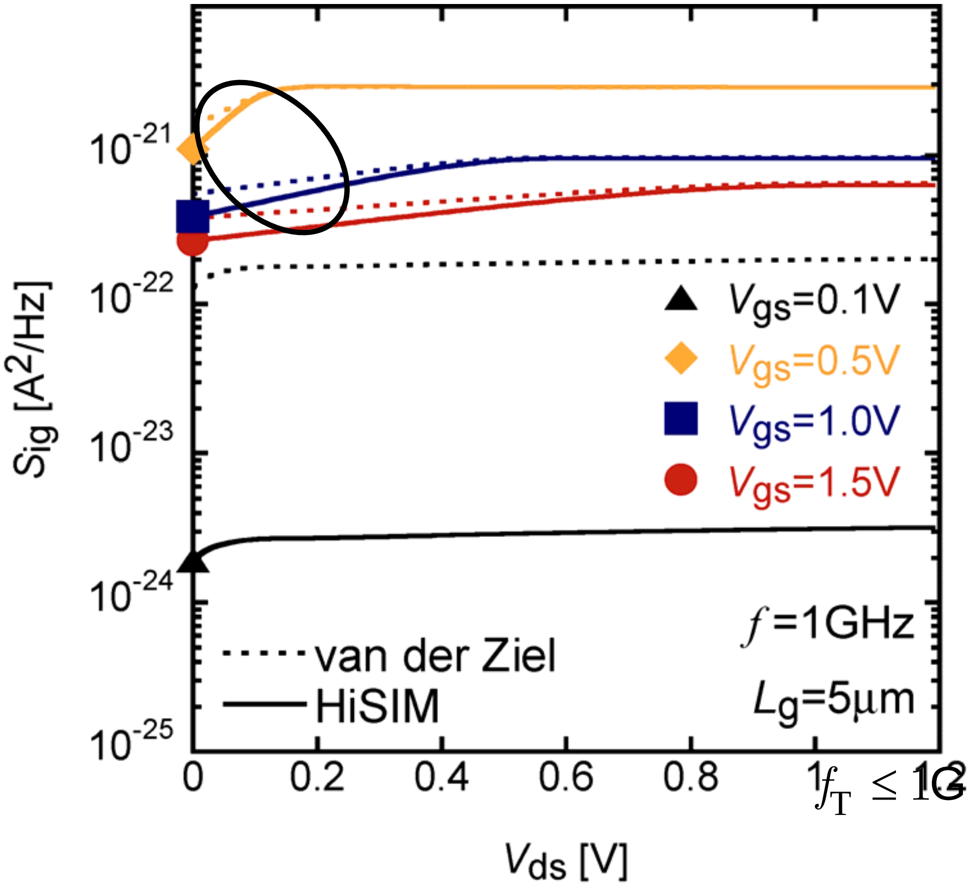
Current Density eq.

$$V(x) \frac{\partial}{\partial x} V(x) = -\frac{d}{W\varepsilon\mu} I(x)$$

$$\begin{cases} V(x) = V_0(x) - \Delta v(x) \\ I(x) = I_0 - \Delta I(x) \end{cases}$$

$$V_0(x) = V_{\mathrm{g}} - V_{\mathrm{ch}}(x) - V_{\mathrm{th}}$$

S_{ig} for Long-Channel Case



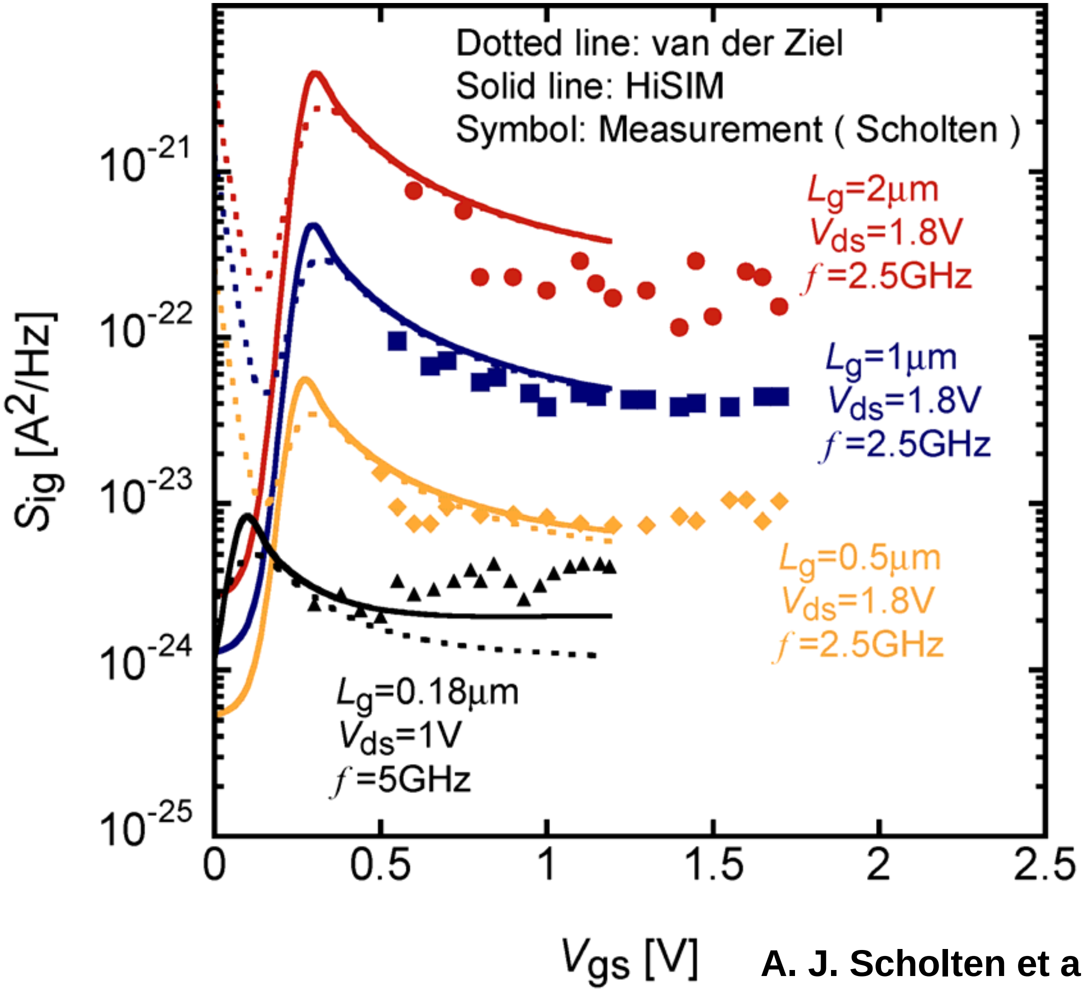
$f_T \leq 1$GHz

van der Ziel's model

$$S_{ig} = 4kT\frac{(\omega C_{gs})^2}{5g_{ds0}}\beta$$

The van der Ziel model is valid only in the saturation region.

Comparison with Measurements

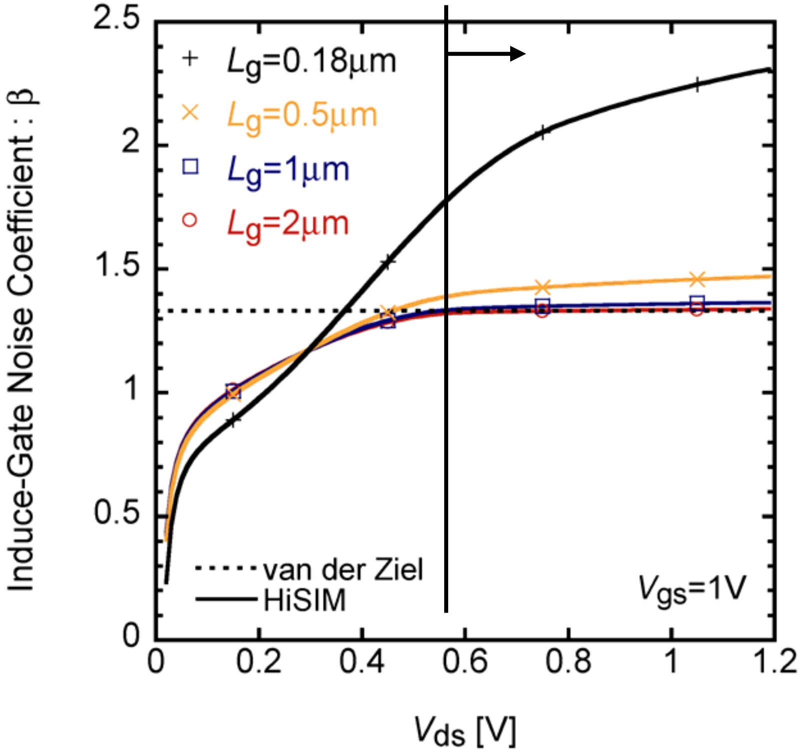


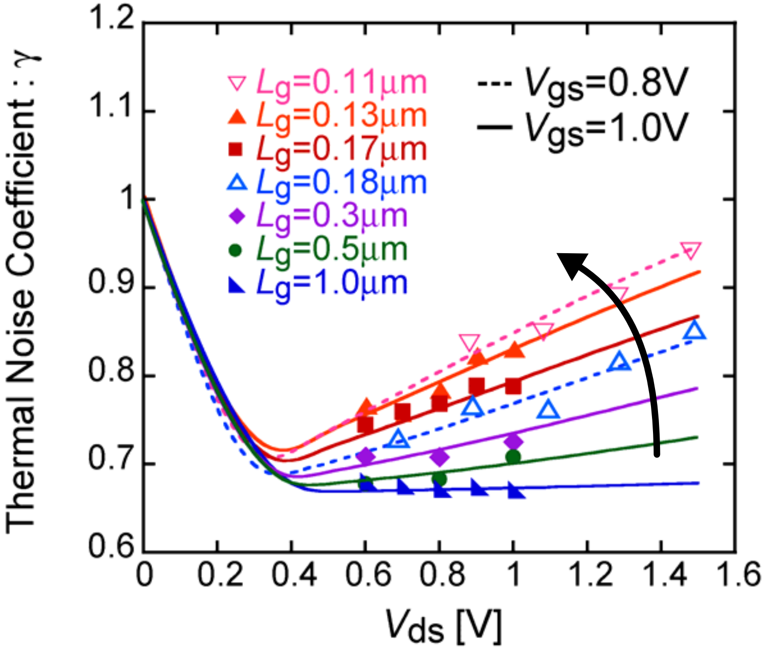
A. J. Scholten et al., Tech. Dig. IEDM, p. 867, 2003.

The excess noise for short-channel devices is due to the potential increase along the channel.

Excess Noise in Short-Channel MOSFETs

$$S_{\mathrm{ig}} = 4kT\frac{\left(\omega C_{\mathrm{gs}}\right)^2}{5g_{\mathrm{ds0}}}\beta$$

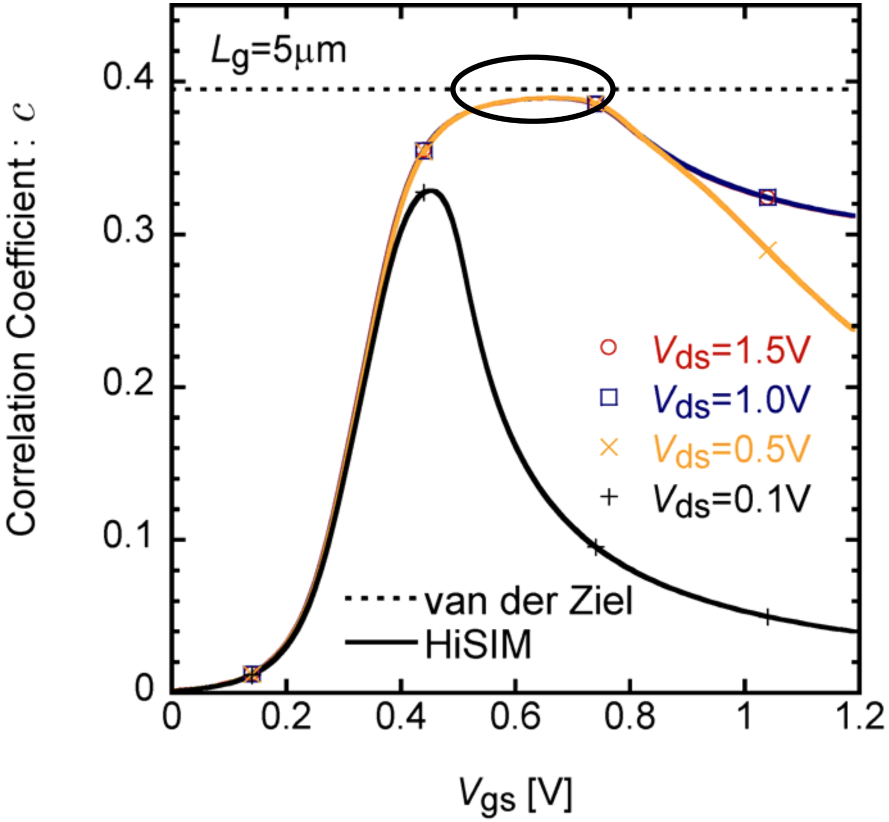


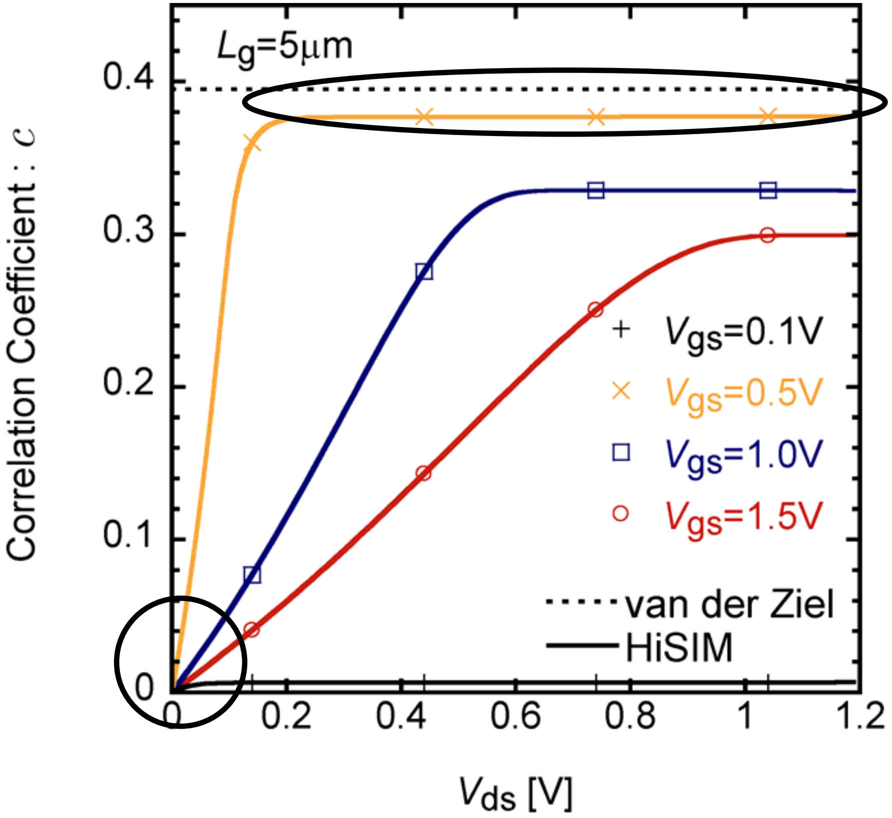


Excess noise starts to saturate for further V_{ds} increase.

Correlation Coefficient (*c*)

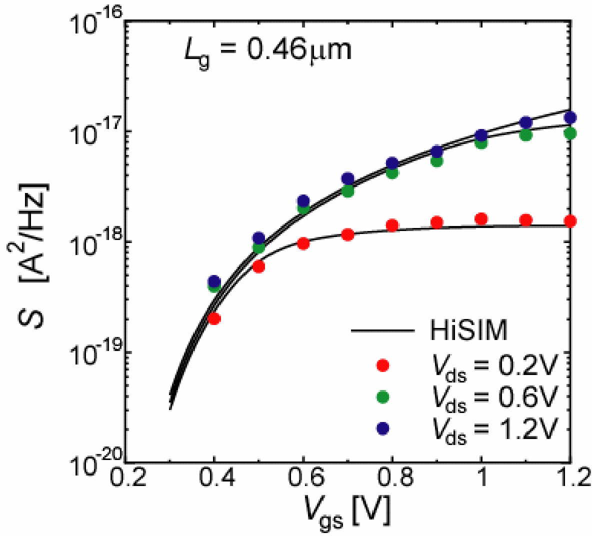
Correlation Coefficient : $$c = \frac{S_{\mathrm{i_g i_d}}}{\sqrt{S_{\mathrm{i_g}} S_{\mathrm{i_d}}}}$$



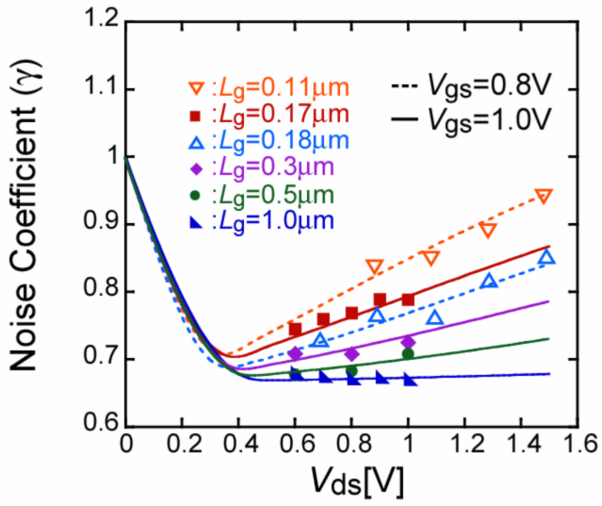


Phenomena Important for RF Applications

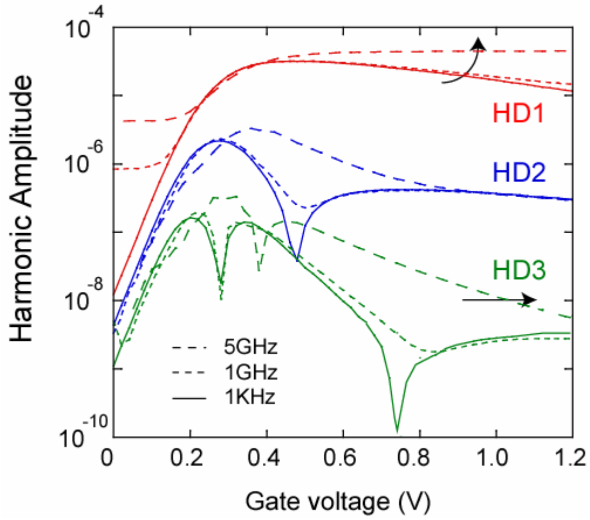
1/*f* Noise



Thermal Noise



Harmonic Distortion



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

Electrostatic effect is still dominating.

Surface potential is important.

Summaries

- ✓ **The 1/f noise is mostly governed by the carrier fluctuation due to the trap/detrap process.**
- ✓ **The thermal noise is governed by the potential distribution along the channel.**
- ✓ **The induced gate noise and the cross-correlation noise are governed by the same mechanism as the thermal noise.**
- ✓ **These results conclude that the noise is still governed by the equilibrium carrier dynamics for MOSFETs down to the sub-100nm channel length regime.**
- ✓ **The surface-potential-based model HiSIM is capable for predicting noise characteristics.**