MOSFET Modeling for RF-CMOS Design

COE Workshop, 30. Jan. 2004

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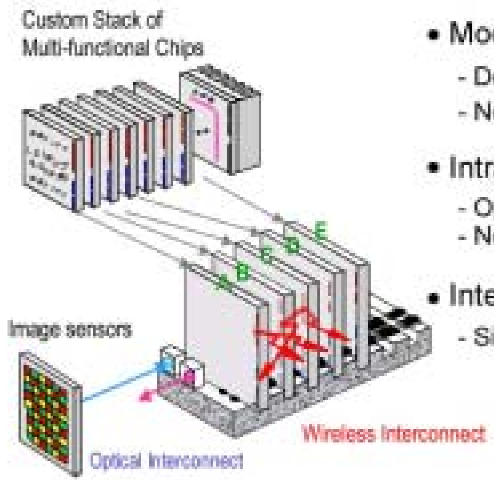
Towards 3D Integration System



- Modeling of Optical Response
  - Delay Analysis
  - Noise Analysis
- Intra-Deivce Coupling Effect
  - Optical Leakage
  - Noise Coupling
- Inter-Chip Coupling Effect
  - Signal Integrity

HiSIM: Surface-Potential-Based Model

Connection to Technology

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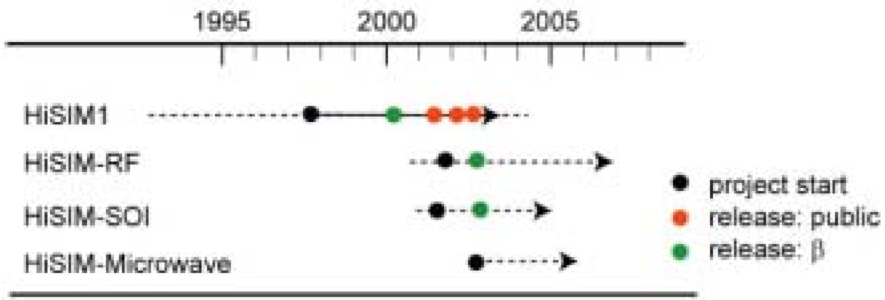
Prediction of Circuit Performance
Device Optimization

HiSIM Generations



MOSFET Modeling for RF-CMOS Design

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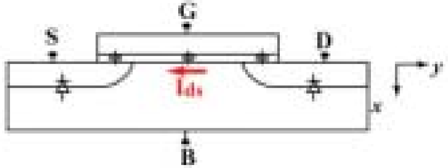
Circuit Simulation Model

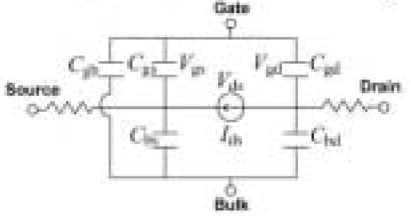


$$I_{ds} = f(V)$$

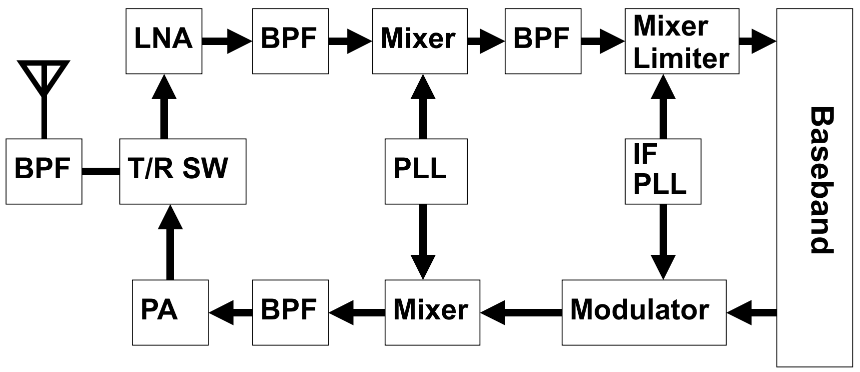
$$I_{ds} = \mu \frac{W}{L} C_{ox}\, nE$$

The Meyer Model

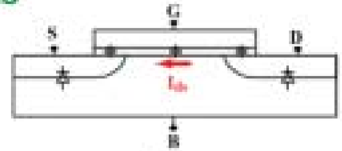
$$I_{ds} = \mu \frac{W}{L} C_{ox} \left[(V_{gs} - V_{th}) V_{ds} - \frac{1}{2} V_{ds}^{2} \right]$$



RF-Circuit

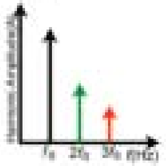


Requirements

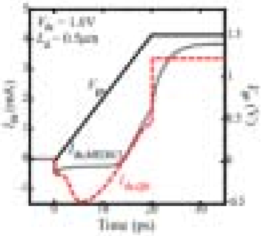


Device Modeling

- **DC Characteristics:** *I-V* Charactersitcs
- **AC Characteristics:** Capacitances



- **Non-Linear Phenomena:** Harmonic Distortion
- **Non-Quasi-Static Phenomena:** Transient Delay
- **Parastic Effects:** Overlap Capacitance
  Gate Capacitance
- **Noise Features**



Accurate Parameter Extraction

System-Level Simulation

Technology Based Modeling

Outline

I. Modeling of Basic MOSFET Characteristics

1. *I-V* characteristics
2. Intrinsic & Extrinsic Capacitances
3. Harmonic Distortion
4. Noise Characteristics

II. Large-Signal Analysis

III. Small-Signal Analysis

IV. Challenges

V. Summary

Basic Equations

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

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

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

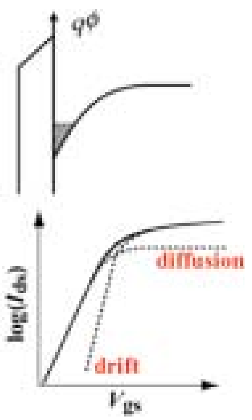
-Current Density: $j_n = q\mu_n n\frac{\phi}{y} + qD_n\nabla n$

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

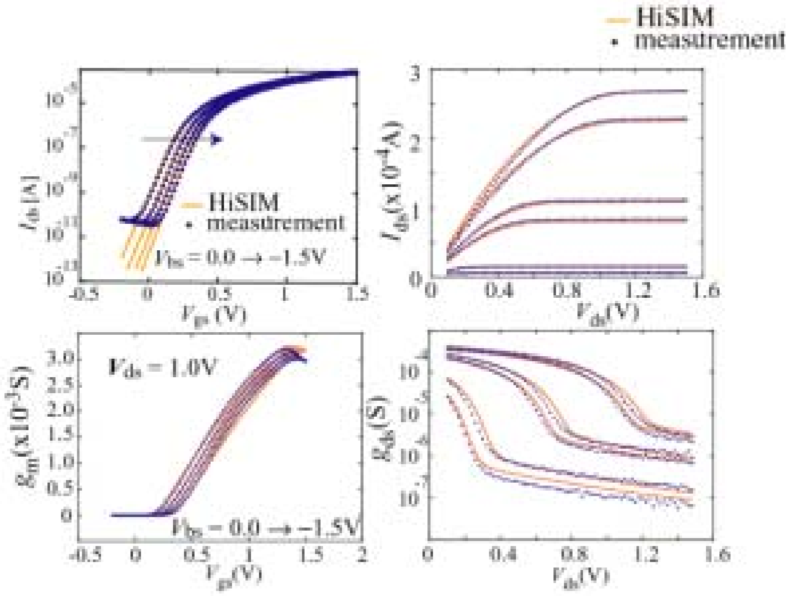
-Continuity: $\frac{\partial n}{\partial t} = G_n - R_n + \frac{1}{q}\nabla j_n$

$$\frac{\partial p}{\partial t} = G_p - R_p + \frac{1}{q}\nabla j_p$$

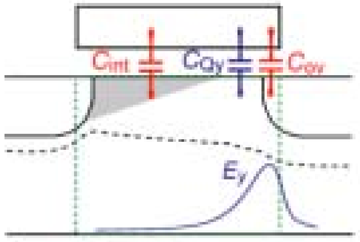
$$I(t) = I_0(t) + \frac{dQ}{dt}$$: Quasi-Static Approximation Solved by Circuit Simulator

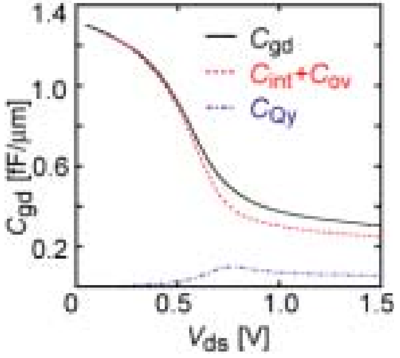


Comparison with Measurements



2. Intrinsic & Extrinsic Capacitances
Field-Induced Capacitance





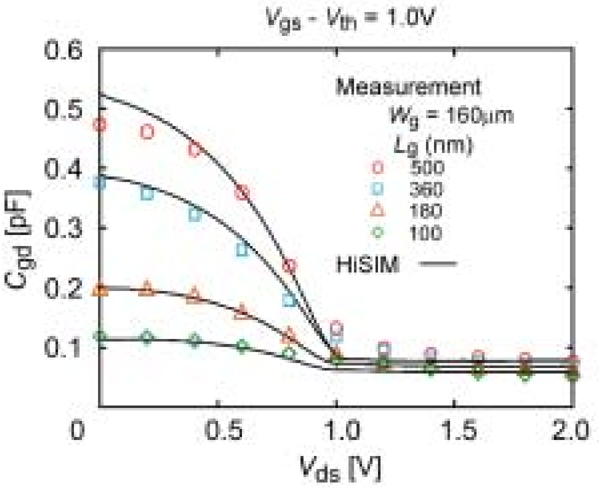
nMOS L_g = 180nm
$V_g - V_{th}$ = 1 V

2D charge integration:

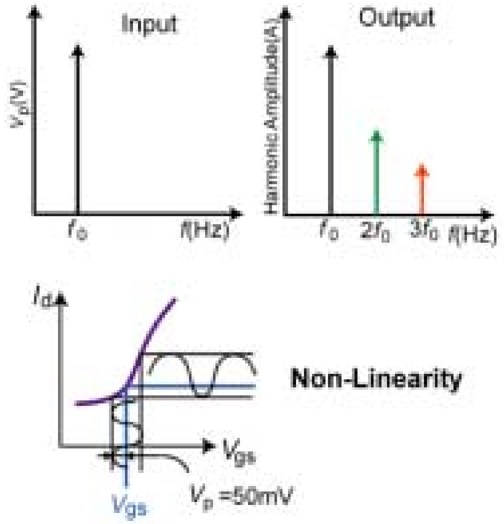
$$Q_Y = \varepsilon_{Si}\int x_d(y)\frac{dE_Y}{dy}dy$$

D. Navarro et al., IEICE Tran. Elecron., vol. E86, pp. 474, 2003

Comparison of Calculated C_{gd} with Measurements



3. Harmonic Distortion

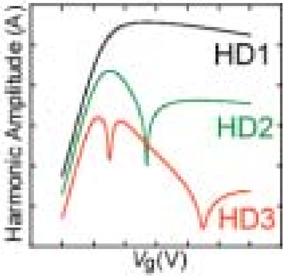


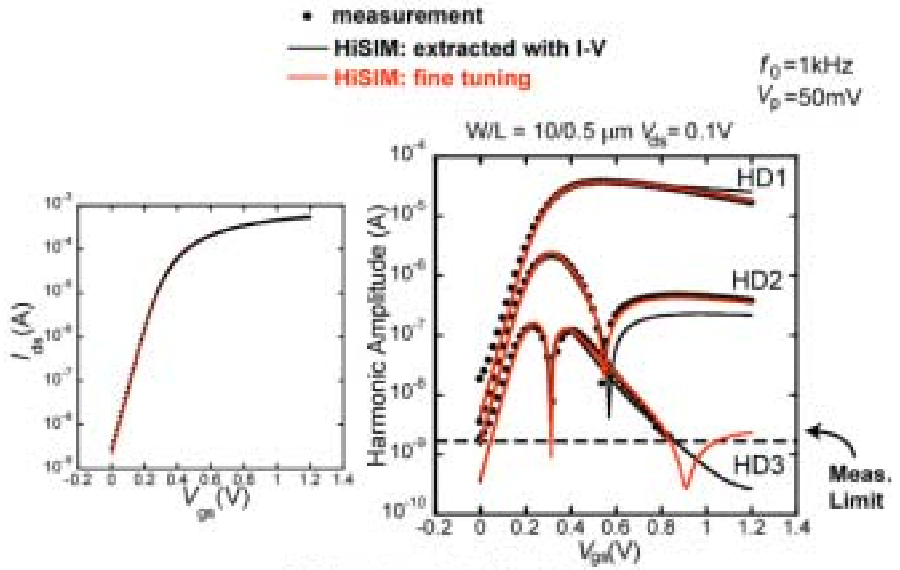
Non-Linearity

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

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

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





S. Chiba, to be submitted for publication

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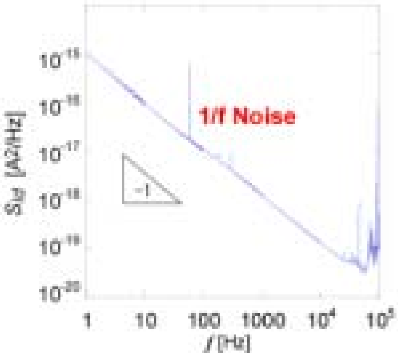
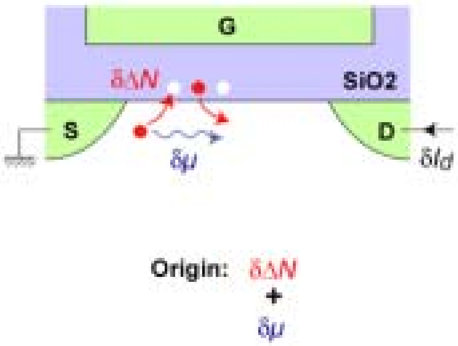
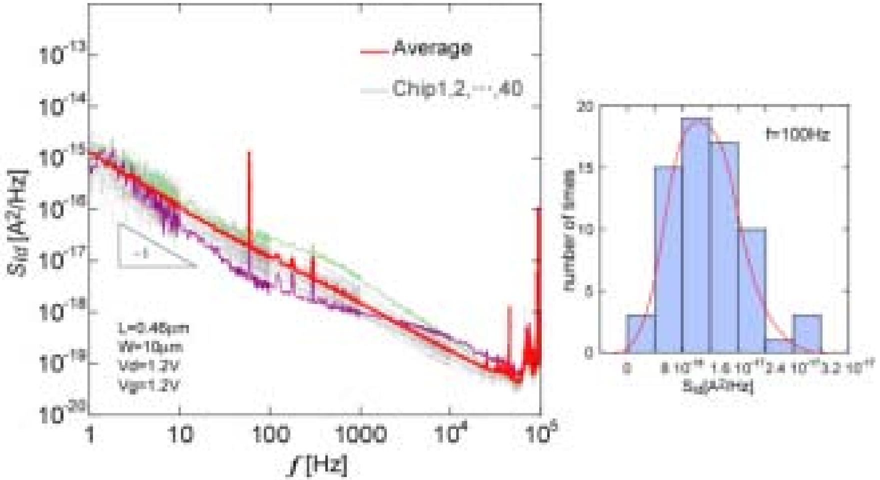
4. Noise Characteristics: 1/f Noise





Origin: δΔN + δμ



S. Matsumoto et al., submitted for publication

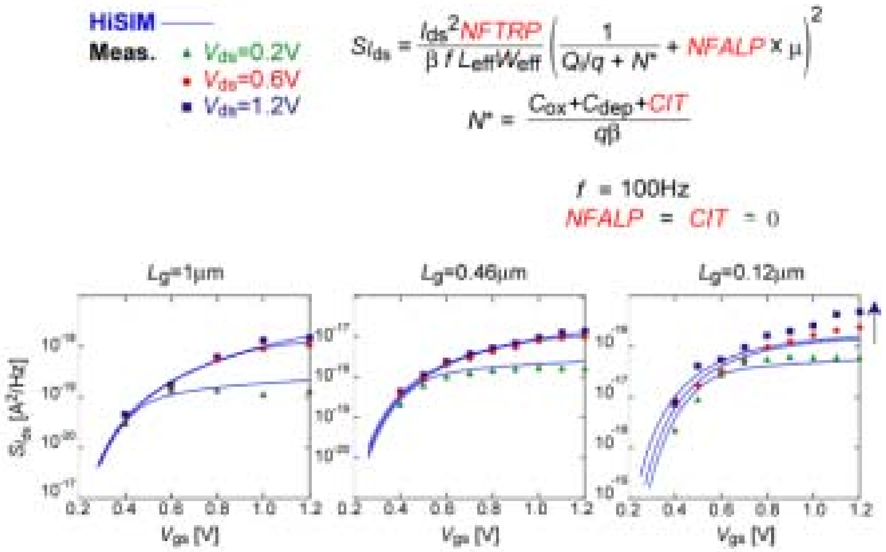
1/f-Noise Model

$$S_{I_{ds}} = \frac{I_{ds}^2 \, NFTRP}{\beta \, f \, L_{eff} W_{eff}} \left(\frac{1}{Q_i/q + N^*} + NFALP \times \mu \right)^2$$

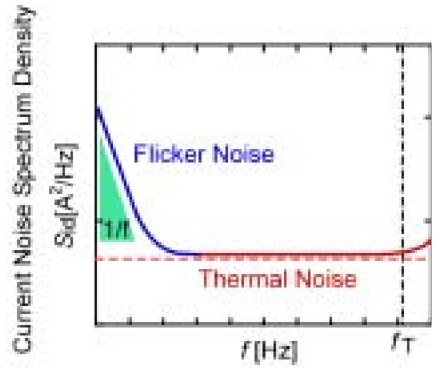
$$N^* = \frac{C_{ox} + C_{dep} + CIT}{q\beta}$$

f = 100Hz

$NFALP$ = CIT = 0



Thermal-Noise Model



f_T: **Cut off Frequency**

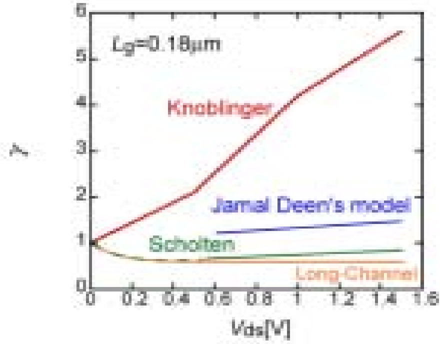
- Nyquist's Theorem for Thermal Noise

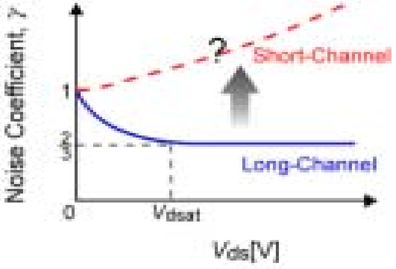
$$S_{id} = \frac{4kT}{L_{eff}^2 I_{ds}} \int g_{ds}^2(y)dy$$
$$= 4kTg_{ds0}\gamma$$

g_{ds}(y): Channel Conductance

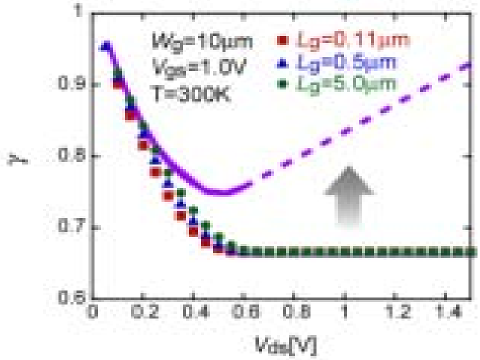
g_{ds0}: at V_{ds}=0

γ : Noise Coefficient





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



μ: Position Dependent

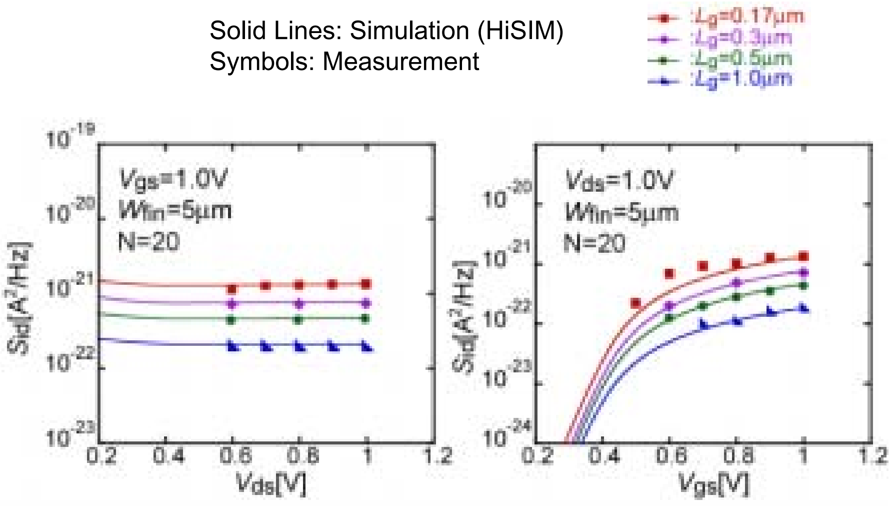
μ: Constant

Origin of γ Increase → Mobility Reduction along Channel

γ Increase → Potential Increase

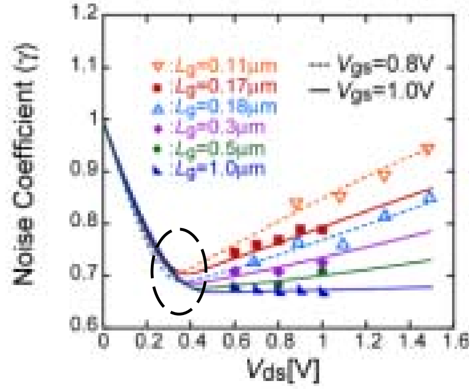
S. Hosokawa et al., Ext. Abs. SSDM, pp. 20, 2003

Solid Lines: Simulation (HiSIM)
Symbols: Measurement



With model parameter values extracted by *I-V* characteristics, good agreement can be achieved.

Solid Lines: Calulation (HiSIM)
Symbols: Measurement



- γ reduces first and increases under the saturation region.
- The increase is not drastic.
- The γ minimum becomes larger than 2/3.

MOSFET Model

***I-V* characteristics**
- **Short-Channel & Reverse-Short-Channel Effect**
- **Mobility Model**
- **Quantum & Poly-Depletion Effect**

Intrinsic & Extrinsic Capacitances

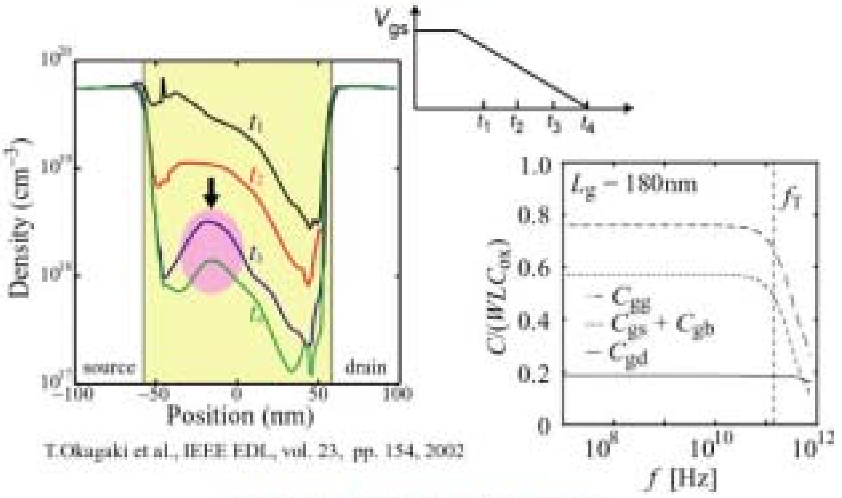
Derivatives of *I-V* Characteristics

Reliability Test and Fine Tuning of Model Parameters

Harmonic Distortion

Noise Characteristics

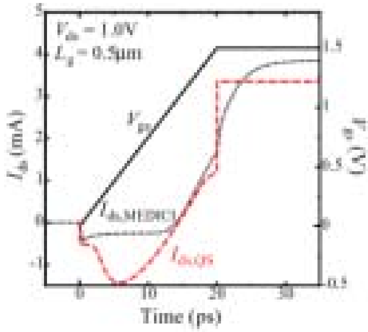
Carrier Dynamics



T.Okagaki et al., IEEE EDL, vol. 23, pp. 154, 2002

II. Large-Signal Analysis
III. Small-Signal Analysis

II. Large-Signal Analysis



MEDICI: 2D-Device Simulator

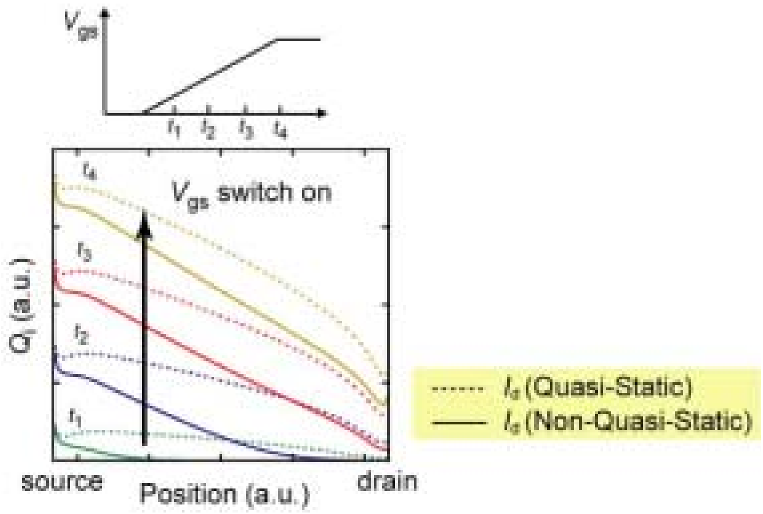
- **Quasi-Static Model :** $I(t) = I_0(t) + \frac{dQ}{dV}\frac{dV}{dt}$

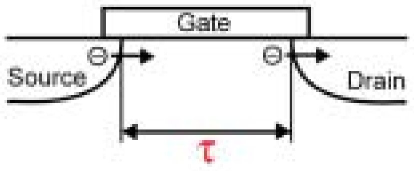
  simultaneous potential response
  neglection of carrier transit delay ➡ $Q = Q(V(t))$

- **Non-Quasi-Static Model :** $\omega > \omega(f_T) / 10$

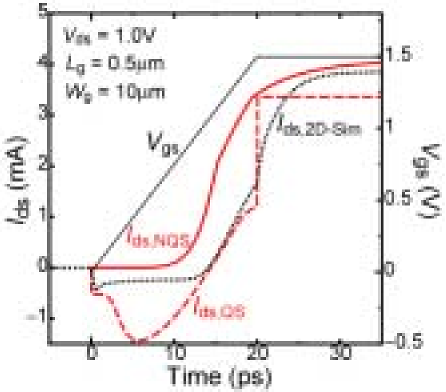
  $\omega(f_T) \propto \frac{\mu(V_{gs}-V_{th})}{L^2}$ **:cut-off frequeny**

Non-Quasistatic Model:Transit Delay of Carriers





τ: Carrier Transit Delay
(function of surface potentials)



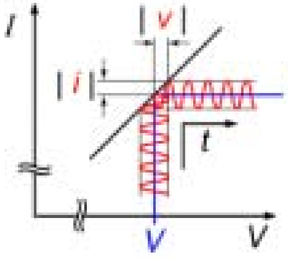
Non-Quasistatic Model (HiSIM2.0β)
Output Capacitance=0

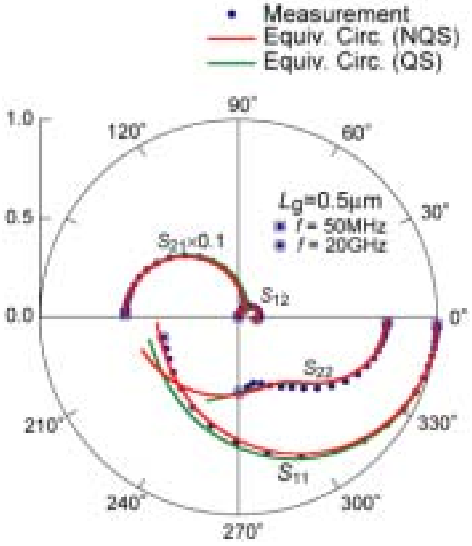
N. Nakayama et al., Japn. J. Appl. Phys., vol. 42, pp. 2132, 2003

III. Small-Signal Analysis

Small Signal

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





S-Parameters : Power Measurement

Y-Parameters : Admittance

$$\begin{bmatrix} i_g \\ i_d \end{bmatrix} = \begin{bmatrix} Y_{11}(\omega) & Y_{12}(\omega) \\ Y_{21}(\omega) & Y_{22}(\omega) \end{bmatrix} \begin{bmatrix} v_g \\ v_d \end{bmatrix}$$

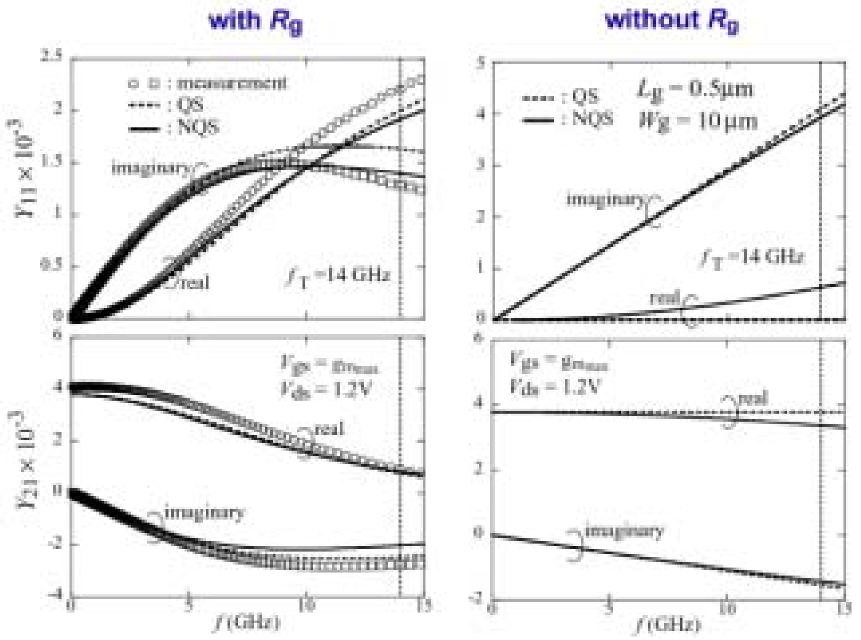
Admittance Matrix

$$Y_{\alpha\beta} = Re(Y_{\alpha\beta}) + Im(Y_{\alpha\beta})$$

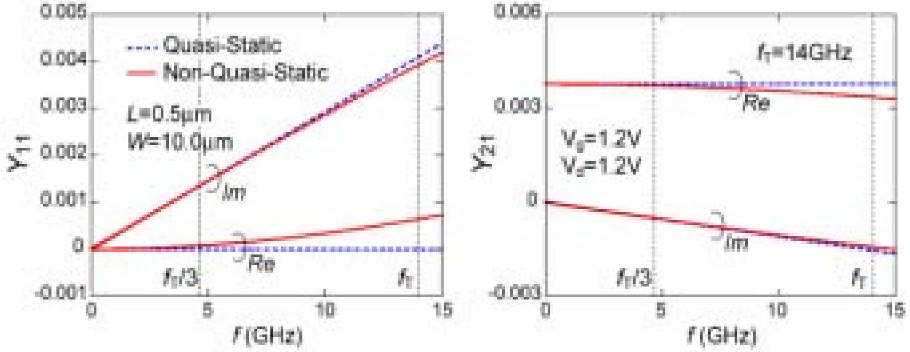
Analytical Description:

$$Y_{11}(\omega) = \omega^2 R_g C_{gg}{}^2 + j\omega C_{gg}$$

$$Y_{21}(\omega) = g_m - \omega^2 R_g C_{gg} (C_m + C_{gd})$$



NQS: solving the continuity equation analytically ⇨ HiSIM-SSA



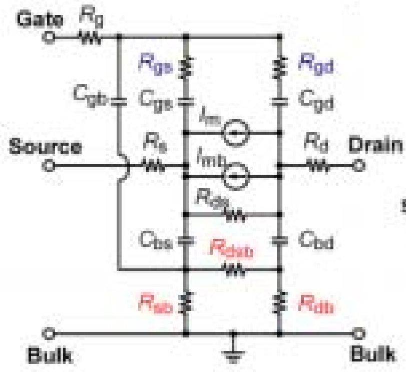
Literature ⇨ **This Result**
NQS: f_T/10 ⇨ $f > f_T/3$

S. Jinbou et al., Ext. Abs. SSDM, pp. 26, 2002

Equivalent Circuit

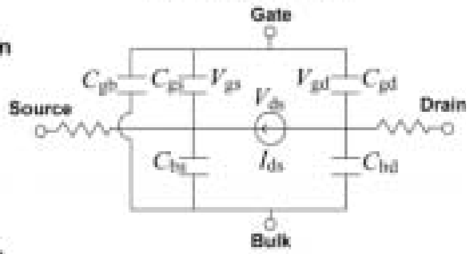
$$\Delta I = g_m \Delta V_{gs} + g_{mb} \Delta V_{bs} + g_{ds} \Delta V_{ds}$$

(Liniearization)



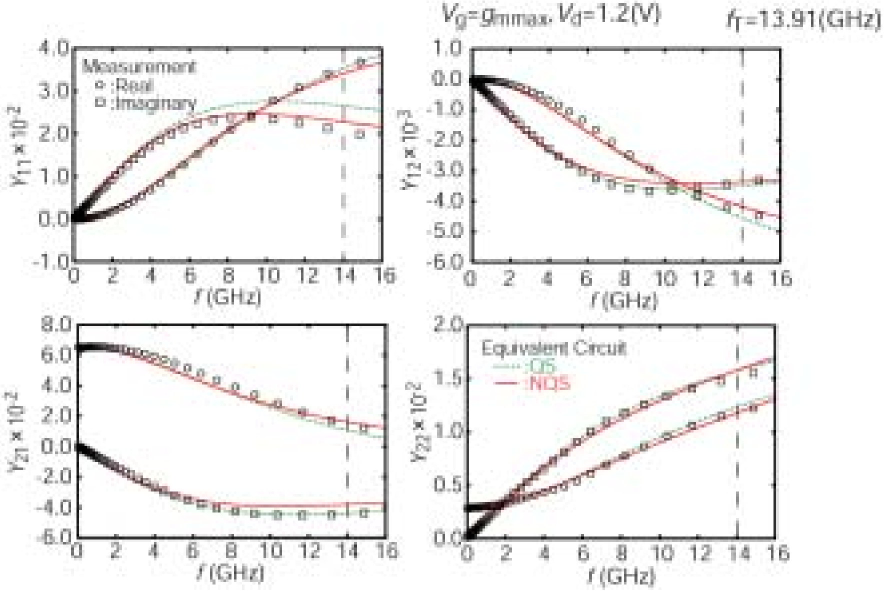
※$I_m = g_m + j\omega C_m$ $C_m = C_{dg} - C_{gd}$
$I_{mb} = g_{mb} + j\omega C_{mb}$ $C_{mb} = C_{db} - C_{bd}$
R_{gs}, R_{gd} :Elmore Resistances

The Meyer Model

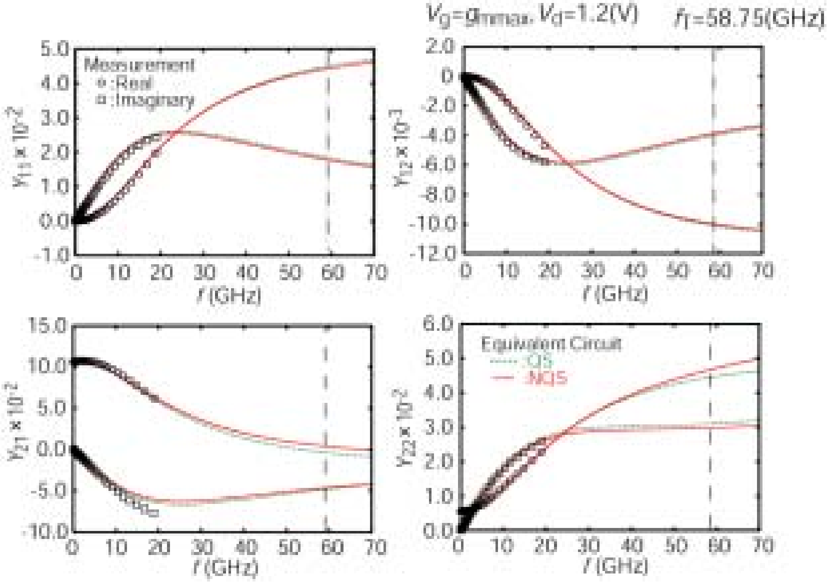


H. Kawano et al., Digest MS, pp. 2121, 2002

- L_g=0.5μm



- L_g=0.18μm



IV. Challenges

- **Accurate Harmonic-Balance Simulation**
- **Modeling for SOI-MOSFET**
- **Beyond the 50nm-MOSFET Era**
- **Fluctuation and Manufacturability**

V. Summary

Importance of Basic Device Performances

I-V characteristics
- •Short-Channel & Reverse-Short-Channel Effect
- •Mobility Model
- •Quantum & Poly-Depletion Effect (α; impurity concentration in poly-gate)

Intrinsic & Extrinsic Capacitances

Derivatives of *I-V* Characteristics (no parameter)

Harmonic Distortion (no parameter)

Noise Characteristics (1/f: trap density; thermal: no parameter)

Large-Signal Analysis (carrier transit delay)

Small-Signal Analysis (phenomenological equivalent circuit model)