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

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STARC, Yokohama
HiSIM: Hiroshima-university STARC IGFET Model

1990 JJAP        Sub-1 µm MOSFETs  short-channel effect model
1991 SISPAD      “                        1st 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
            June                           HiSIM1.1.0                        “
            Oct.                           HiSIM1.1.1                        “
2003. Oct.       Test release to STARC clients
2005. May       release to CMC members  HiSIM2.0.0 source code and manual
            July                           HiSIM2.0.0                        “
            Oct.                           HiSIM2.2.0 + Verilog-A code
2006 Jan.       release to vendors     HiSIM2.3.0                        “
Outline

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

\[ \phi_{S0}, \phi_{S0} + V_{ds}, \phi_{SL}, \phi_{S(\Delta L)} \]

: at source side

: at drain side

(end of the gradual-channel approx.)

beyond the gradual-channel approximation

Surface Potentials \[\rightleftharpoons\] Measure for All Device Features
Calculated Surface Potentials

\[ \phi_{S0} = 2\Phi_B \]

\[ \phi_{SL} = \phi_{S0} + V_{ds} \]

Short-channel effect is included in the \( \phi_s \) calculation.
Comparison of $\phi_s$ Values

![Graph comparing $\phi_s$ values for HiSIM and 2D Device under different $V_{bg}$ conditions.](image-url)
Comparison of $\phi_S$ 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

\[ V = \mu E: \text{velocity} \]

\[ \frac{1}{\mu_0} = \frac{1}{\mu_{CB}} + \frac{1}{\mu_{PH}} + \frac{1}{\mu_{SR}}: \text{mobility} \]
Universal Mobility

\[ \mu_{CB} = MUECB_0 + MUECB_1 \frac{Q_i}{q \times 10^{11}} \]

\[ \mu_{PH} = \frac{MUEPH_0}{(T/300K) \times MUETMP \times E_{eff}^{MUEPH_1}} \]

\[ \mu_{SR} = \frac{MUESR_0}{E_{eff}^{MUESR_1}} \]

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

- \( MUEPH_1 = 0.3 \)
- \( MUESR_1 = 2 \)
- \( NDEP = 1 \)
- \( NINV = 0.5 \)
Harmonic Distortion vs. Mobility

\[ V_{ds} = 0.1V \]

Mobility determines the harmonic distortion characteristics.

\begin{align*}
\text{HD1} & \approx V_P \left| \frac{\partial I_{ds}}{\partial V_{gs}} \right| \\
\text{HD2} & \approx -\frac{1}{4} V_P^2 \left| \frac{\partial^2 I_{ds}}{\partial V_{gs}^2} \right| \\
\text{HD3} & \approx -\frac{1}{24} V_P^3 \left| \frac{\partial^3 I_{ds}}{\partial V_{gs}^3} \right|
\end{align*}
$I_d$ 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

\[ Q_i (\text{a.u.}) \]

\[ V_{gs} \text{ switch on} \]

- \[ I_d (\text{Quasi-Static}) \]
- \[ I_d (\text{Non-Quasi-Static}) \]
Transient Time-Domain Analysis: Response Delay

\[ \tau: \text{Carrier Transit Delay} \]
(function of surface potentials)

Harmonic Distortion under High Frequency

Time-Domain Analysis ↔ Frequency Domain Analysis
Fourier Transformation

Carrier transit delay dominates the HD characteristics.

IP3 Prediction

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

\[ f_0 = 5 \text{GHz} \]
\[ L_{gate} = 1 \mu\text{m} \]
\[ V_{gs} = 0.6 \text{V} \]
\[ V_{ds} = 0.1 \text{V} \]

Y. Takeda et al., CICC, p. 827, 2005.
Y-parameters: Frequency-Domain Analysis

The same model as for the Time-Domain Analysis: modeled with $\tau$
K. Machida et al., SiRF, p. 73, 2006.
Non-Quasi-Static Effects

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

Noise Features

- 1/f Noise
- Thermal Noise
- Induced Gate Noise
- Cross-Correlation Noise
- Shot Noise
- Junction Noise
Different Origins

1/f Noise:

Thermal Noise:

Induced Gate Noise:

Cross-Correlation Noise:
Carrier distribution along the channel determines the characteristics.

Model Parameters:
- Trap density
- Mobility fluctuation

Thermal Noise

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

Universal Relationship

$\gamma$ vs. Short-Channel Effect
Induced Gate Noise

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

T. Warabino et al., SISPAD, 2006.
# Important Model Parameters

<table>
<thead>
<tr>
<th>Device</th>
<th>Description</th>
<th>Short Channel</th>
<th>Mobility</th>
</tr>
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<tr>
<td>TOX</td>
<td>Oxidation thickness</td>
<td>PARL2 depletion width</td>
<td>Coulomb scattering</td>
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<tr>
<td>XLD</td>
<td>Gate-overlap length</td>
<td>SC1 short-channel coefficient 1</td>
<td>MUECB0 Coulomb scattering</td>
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<tr>
<td>XWD</td>
<td>Gate-overlap width</td>
<td>SC2 short-channel coefficient 2</td>
<td>MUECB1 Coulomb scattering</td>
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<tr>
<td>XPOLYD</td>
<td>Gate-poly overlap</td>
<td>SC3 short-channel coefficient 3</td>
<td>MUEPH0 phonon scattering ***0.3</td>
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<tr>
<td>TPOLY</td>
<td>Height of the gate poly-Si</td>
<td>SCP1 pocket short-channel coefficient 1</td>
<td>MUEPH1 phonon scattering</td>
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<td>RS</td>
<td>Source-contact resistance</td>
<td>SCP2 pocket short-channel coefficient 2</td>
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<td>RD</td>
<td>Drain-contact resistance</td>
<td>SCP3 pocket short-channel coefficient 3</td>
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<tr>
<td>NSUBC</td>
<td>Substrate-impurity concentration</td>
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<td>MUESTMP temperature dependence</td>
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<tr>
<td>NSUBP</td>
<td>Maximum pocket concentration</td>
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<td>MUESR0 surface-roughness scattering*** 2.0</td>
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<td>VFBC</td>
<td>Flat-band voltage</td>
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<td>MUESR1 surface-roughness scattering</td>
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<td>LP</td>
<td>Pocket penetration length</td>
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<td>NDEP effective-electric field *** 1.0</td>
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<td>BGTMP1</td>
<td>Bandgap narrowing 1</td>
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<td>NINV effective-electric field *** 0.5</td>
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<td>BGTMP2</td>
<td>Bandgap narrowing 2</td>
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<td>NINV modification of NINV</td>
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<td>QME1</td>
<td>Quantum mechanical effect 1</td>
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<td>BB high-field mobility *** 2.0</td>
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<td>Quantum mechanical effect 2</td>
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<td>VMAX saturation velocity</td>
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<td>QME3</td>
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<tr>
<td>PGD1</td>
<td>Strength of poly depletion</td>
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<td>VOVERP velocity overshoot</td>
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<td>PGD2</td>
<td>Threshold of poly depletion</td>
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<td>RPOCK1 pocket resistance</td>
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<td>PGD3</td>
<td>$V_{ds}$ dependence of poly depletion</td>
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<td>RPOCK2 pocket resistance</td>
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<td>Channel length modulation 1</td>
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<td>CML2</td>
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<tr>
<td>CLM3</td>
<td>Channel length modulation 3</td>
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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