Noise Modeling with HiSIM Based on Self-Consistent Surface-Potential Description

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Noise Measurement in MOSFETs

Outline

• MOSFET Model
• Flicker Noise
• Thermal Noise
• Summary
MOSFET Model

Basic Equations

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

  \[ n = n_i \exp \left( \frac{q(\phi - \phi_n)}{kT} \right) \]

  \[ p = n_i \exp \left( \frac{q(\phi_p - \phi)}{kT} \right) \]

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

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

  \[ I(t) = I_0(t) + \frac{dQ}{dt} : \text{Quasi-Static Approximation} \]

Solved by Circuit Simulator
Technology-Based Modeling

Impurity Profile $\rightarrow$ Device Performances

2D-Device Simulator: MEDICI

[Impurity Profile, $N_{\text{sub}}$] $\rightarrow$ [Potential, $\phi$]

Source $\rightarrow$ Gate $\rightarrow$ Drain

Channel Engineering (Pocket Implantation)

Surface Potential
Pocket-Implanted Case

Source  G  Drain

$N_{\text{subp}}$

$L_p$

$L_{\text{ch}}$

$N_{\text{subp}}$

depth = 30nm → 60nm

$L_p$

$L_{\text{ch}}$

Position in the channel [μm]

$L_{\text{ch}}$
Modeling of Reverse-Short-Channel Effect

![Graph showing the relationship between $V_{gs}$ and ln(carrier conc: $n$) with different scenarios: w/o pocket, with pocket (denoted as $n_c$), and pocket implant (denoted as $n_p$). There is also a notation for $n_{th}$, which represents the threshold carrier concentration.]

\[ n_{av} = \frac{L_{ch}}{n_c} \left( \frac{L_{ch}}{n_c} - 2L_p \right) + \frac{2L_p}{n_p} = n_{th} \]

$n_c$: with $N_{subc}$ (non-pocket region)

$n_{poc}$: pocket implant

$n_p$: with $N_{subp}$ (pocket maximum)

Low-Field Mobility: Universality

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

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

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

- \( PH1 = 0.3 \)
- \( SR1 = 2.0 \)
- \( NDEP = 1.0 \)
- \( NINV = 0.5 \)

Comparison with Measurements

- $I_{ds}$ vs $V_{gs}$
  - HiSIM
  - Measurement
  - $V_{bs} = 0.0 \rightarrow -1.5V$

- $I_{ds}$ (x10^-4A) vs $V_{ds}$
  - HiSIM
  - Measurement

- $g_m$ (x10^-3S) vs $V_{gs}$
  - $V_{ds} = 1.0V$
  - $V_{bs} = 0.0 \rightarrow -1.5V$

- $g_{ds}$ (S) vs $V_{ds}$
Origin of the 1/f Noise

\[ S_{id} \text{ [A}^2/\text{Hz}] \]

\[ 1/f \text{ Noise} \]

\[ f \text{ [Hz]} \]

\[ 1.0 \times 10^{-15} \]

\[ 1.0 \times 10^{-16} \]

\[ 1.0 \times 10^{-17} \]

\[ 1.0 \times 10^{-18} \]

\[ 1.0 \times 10^{-19} \]

\[ 1.0 \times 10^{-20} \]

\[ 1 \]

\[ 10 \]

\[ 100 \]

\[ 1.0 \times 10^{4} \]

\[ 1.0 \times 10^{5} \]

Origin: \( \delta \Delta N \) + \( \delta \mu \)

Monte Carlo Simulation

Measured $1/f$ Noise

- $L=0.08\mu m$
- $L=0.5\mu m$
- $L=1.0\mu m$

- nMOSFET
  - $W=10\mu m$
  - $V_{gs}=1.2V$
  - $V_{ds}=0.4V$

$S_{ld}$ [A²/Hz]

$f$ [Hz]
$L_g=1\mu m$ (nMOSFET)

Linear Condition

Saturation Condition

- $V_{ds}$ (Source-GND)
- $V_{sd}$ (Drain-GND)

$W=10\mu m$
$V_{ds}=0.4V$
$V_{gs}=1.2V$

$W=10\mu m$
$V_{ds}=1.2V$
$V_{gs}=0.8V$
$L_g=0.13\,\mu m \ (nMOSFET)$

**Linear Condition**

- $V_{ds}$ (Source-GND)
- $V_{sd}$ (Drain-GND)

$W=10\,\mu m$
$V_{ds}=0.4V$
$V_{gs}=1.2V$

**Saturation Condition**

$W=10\,\mu m$
$V_{ds}=1.2V$
$V_{gs}=0.8V$
$L_g = 1\mu m$ (nMOSFET)

Saturation Condition: $W_g = 10\mu m$
$V_{ds} = 0.4V$
$V_{gs} = 0.5V$

![Graph showing $N_{trap}$ vs. $Z$ with uniform and non-uniform sections with $S_1$, $S_2$, $S_3$, and $S_4$.]

![Graph showing $S_{id}/A^2/Hz$ vs. $f$ [Hz] with measured Source-GND and modeled data, including $S_1 = 1/f$, $S_{total} = S_1 + S_2 + S_3$, $S_2$, $S_3$, $S_4$, and $S_{total} = S_1 + S_4$.]

![Graph showing Measured Drain-GND with $S_{total} = S_1 + S_4$ and modeled data, including $S_1 = 1/f$, $S_4$, and $S_{total}$.]
Measured Result of a Wafer

\[ S_{id}[A^2/Hz] \]

- Average
- Chip1,2,\ldots,40

\[ f \text{ [Hz]} \]

- \( L=0.46\text{mm} \)
- \( W=10\text{mm} \)
- \( V_d=1.2\text{V} \)
- \( V_g=1.2\text{V} \)

\[ f=100\text{Hz} \]

S. Matsumoto et al., submitted for publication
Modeling with HiSIM

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

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

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

Model Parameters

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

Scattering Coeff.: \( \alpha \) \[ Vs \]

\[ \alpha = CIT \approx 0 \]
Comparison of 1/f noise
Nyquist's Theorem:

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

\[ = 4kT g_{ds0} \gamma \]

- \( g_{ds}(y) \): Channel Conductance
- \( g_{ds0} \): at \( V_{ds} = 0 \)
- \( \gamma \): Noise Coefficient
- Knoblinger et al. (2001): Hot Electron Contribution
- Jamal Deen et al. (2002): Channel Length Modulation
- Scholten et al. (2002): Velocity Saturation
\( \gamma \) for Short-Channel MOSFET

\begin{itemize}
  \item \( \mu \): Position Dependent
  \item \( \mu \): Constant
\end{itemize}

Origin of \( \gamma \) Increase \( \Rightarrow \) Mobility Reduction along Channel (No additional model parameter)

\( \gamma \) Increase \( \Rightarrow \) Potential Increase

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

Solid Lines: Simulation (HiSIM)
Symbols: Measurements

Model parameter values: extracted with measured $I-V$ characteristics
Comparison of Different Technologies

- first $\gamma$ reduction and increase in the saturation region
- no drastic increase of $\gamma$
- $\gamma$ minimum larger than 2/3

Lines: Simulation (HiSIM)
Symbols: Measurements
Obtained Result from the HiSIM Simulation

- 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.

- These results conclude that the noise is still governed by the equilibrium carrier dynamics for MOSFETs down to the 100nm channel length regime.
Summary

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 for Model

Noise Characteristics