Issues in High Frequency Noise Simulation for Deep Submicron MOSFETs

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Outline

• Introduction
• Classical Noise Optimization
• New Noise Optimization for CMOS RF
• Bias Dependent Intrinsic Noise Performance
• Direct Tunneling Current
• Conclusions and Open Questions
• Acknowledgments
Introduction (RF CMOS)

- Rapid $f_t$ increase of MOSFETs, driven by the microprocessor industry, attracts RF designers.
- Promise of realizing single chip system solution.
- Noise behavior in short channel MOSFETs is not well understood yet, especially for state-of-art MOSFETs technologies.
- Substantial gate leakage current in ultrathin oxides.
Introduction (Continue)
(MOSFET Noise)

• Flicker ($1/f$) Noise
  ✧ Dominant up to few MHz range

• Shot Noise
  ✧ Dominant in the subthreshold region
  ✧ Important in MOSFETs with ultrathin oxides below 4nm

• Thermal Noise (Velocity Fluctuation Noise)
  ✧ Dominant in high frequencies
Classical Noise Optimization

• In general,

\[ F = F_{min} + \frac{R_n}{G_s} [(G_s - G_{opt})^2 + (B_s - B_{opt})^2] \]

• Minimum noise is

\[ F_{min} = 1 + 2R_n(G_{opt} + G_c) \]

when

\[ G_{opt} = \sqrt{\frac{G_u}{R_n} + G_c^2} \approx \sqrt{\frac{G_u}{R_n}} \]
\[ B_{opt} = -B_c \]
Classical Noise Optimization (Continue)

- No relation between the optimum noise match source admittance ($Y_{opt}$) and the optimum power gain condition.
  ✧ Possible to minimize the noise figure with little or no gain.
  ✧ Possible to the minimize the noise figure with a poor impedance match.

- Does not consider power consumption directly.
- Device is given with fixed characteristics.
New Noise Optimization for CMOS

• Permitting selection of device geometries.
  ✧ Gain-constrained noise optimization.
  ✧ Power-constrained noise optimization.

• More freedom in bias point selection.
  ✧ Excess drain noise in short-channel MOSFETs.
  ✧ Induced gate noise in GHz range (partially correlated to drain noise).
  ✧ Exhaustive noise information for the entire operating conditions is needed.
Simulation Method
( Hybrid Approach)

TSUPREM4 ↔ MEDICI → MONO
Simulation Method (Continue)

(Hybrid Approach)

- TSUPREM4 (2D process simulator)
  - Accurate structure and doping for complex processing
- MEDICI (2D device simulator)
  - Hydrodynamic model captures the physics required in short channel MOSFETs
- MONO (1D MOsfet NOise simulator)
  - Non-uniform active transmission line + IFM
  - Fast noise calculation
Simulation Method (Continue)
(Interface between 2D and 1D)

\[ \Delta C_{gs} + \Delta C_{gd} = \frac{\Delta Q_{inv}}{\Delta V_{gs,local}} \]
\[ \Delta r_o = \frac{\Delta V_{ds,local}}{\Delta I_{DS}} \]
\[ g_m = \frac{\Delta I_{DS}}{\Delta V_{gs,local}} \]
\[ \Delta S_{in} = 4kT_n \frac{I_{DS}}{V_{ds,local}} \]
Simulation Method (Continue)
(Open Questions)

- Applicability of the Langevin stochastic source
  ✧ Hydrodynamic transport formulation shows promise down to 0.25µm
  ✧ Nonstationary effects?
  ✧ Space correlations?

- Applicability of conventional IFM
  ✧ Extendable beyond 0.25µm? (Especially $L_g < 0.1µm$)
Bias Dependent Intrinsic Noise Performance

5μm nMOSFET

Noise Parameters

Drain to Source Voltage [V]

0.25μm nMOSFET

Noise Parameters

Drain to Source Voltage [V]

\[ \begin{align*}
\gamma &= \frac{v^2}{4 kT \Delta f g_{d0}} \\
\delta &= \frac{v^2 q}{4 kT \Delta f \Re[Y_{GS}]} \\
c &= \frac{q}{\sqrt{g^2 + r^2}}
\end{align*} \]
Bias Dependent Intrinsic Noise Performance (Continue)

\[ \gamma \]

\[ \delta \]

\[ Im[c] \]

\[ g_m \]

Bias Dependent Intrinsic Noise Performance (Continue)
Direct Tunneling
(Tunneling Mechanism)

Fowler-Nordheim Tunneling

Direct Tunneling

$V_{ox} > \Phi_b$

$V_{ox} < \Phi_b$
Direct Tunneling (Continue)

(Characteristics)

Fowler-Nordheim Tunneling

Direct Tunneling

Gate Current [A/cm²] vs. Gate Voltage [V]

Gate Current [A/cm²] vs. Gate Voltage [V]
Direct Tunneling (Continue)

(Impact on Noise Calculation)

- Additional conductances
  ✧ Smaller than $\omega C_{gs}$ and $\omega C_{gd}$ from MHz range

- Extra noise sources
  ✧ Introduce gate shot noise
  ✧ Subsequently introduce drain shot noise as well
  ✧ Uncorrelated with channel noise sources
Direct Tunneling (Continue)
(Open Questions)

- Drain shot noise becomes comparable to the drain thermal noise in oxides below 2nm.
- Rigorous modeling of the tunneling current is prerequisite.
  - Involves multi-dimensional Schrödinger equation (Unsolved problem to date).
  - Need to take into account various process conditions for ongoing dielectric related researches (e.g. oxinitride)
Conclusions and Open Questions

• Bias dependent noise modeling
  ✧ Must be exhaustive for the entire operating condition as CMOS RF design permits selection of device geometry.
  ✧ Extendability of the conventional IFM approach beyond 0.25μm (Especially below 0.1μm) is open to question.

• Direct tunneling current
  ✧ Oxides below 4nm introduces substantially large leakage and subsequently shot noise.
  ✧ Multi-dimensional Schrödinger equation : unsolved to date
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