RF MOSFET Noise Parameter Extraction and Modeling

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RF Performance of MOSFETs

- DUTs are fabricated in 0.18 μm CMOS technology and measured at $V_{DS} = 1.0 \text{ V}$.
- Maximum $f_T$ is around 50 GHz and the best $NF_{\text{min}}$ is about 0.5 dB at 2GHz.
Measurement System Setup

- HP8970B Noise Figure Meter
- HP8971C Noise Parameter Test Set
- HP8341B Frequency Synthesizer
- HP8510B Vector Network Analyzer
- NP5B Controller
- HP8514A S-Parameter Test Set
- Power Supply
- MNS-5
- RRM-5
- Switch Box
- PC Controller
- Printer
- RF Cable
- Bias Cable
- Control Cable
- GPIB Cable

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Effect of $R_n$

$$NF = NF_{\text{min}} + \frac{4R_n|\Gamma_S - \Gamma_{S, OPT}|^2}{(1 - |\Gamma_S|^2) \cdot |1 + \Gamma_{S, OPT}|^2};$$

$$\Gamma_S = \frac{R_S + jX_S - Z_o}{R_S + jX_S + Z_o}$$

$NF_{\text{min}} = 2 \text{ dB}$

$R_n = 110 \Omega$

$R_n = 55 \Omega$

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Noise Parameter De-embedding

AC Noise Model of MOSFETs

Internal Part

\[ y_m = g_m \times (1 - j\omega\tau) \]
Noise Parameter Extraction

RF & Noise Parameter Measurements

De-embedding of Pads and Interconnections

Intrinsic S-Parameters

Parameter Extraction & Verification

Y-Parameter Calculation at two-port (33'-44')

Intrinsic Noise Parameters

Noise Parameter Deembedding to ports 11' and 22'

Extracting $i_g^2$, $i_d^2$ and $i_g i_d^*$

Noise Parameter Verification

$y_m = g_m \times (1 - j \omega \tau)$
Results of Y- Parameter Fitting

Noise Source Extraction

\[
Y_{\text{cor}} = \frac{NF_{\text{min}} - 1}{2R_n} - Y_{\text{opt}}
\]

\[
\frac{i_d^2}{\Delta f} = 4kT_o R_n \left| Y_{21,\text{int}} \right|^2
\]

\[
\frac{i_g^2}{\Delta f} = 4kT_o R_n \left| Y_{\text{opt}} \right|^2
\]

\[- \left| Y_{11,\text{int}} \right|^2 + 2\Re[(Y_{11,\text{int}} - Y_{\text{cor}})Y_{11,\text{int}}^*]
\]

\[
\frac{i_g i_d^*}{\Delta f} = 4kT_o (Y_{11,\text{int}} - Y_{\text{cor}})R_n Y_{21,\text{int}}^*
\]

Noise Sources vs. Frequency

- The noise sources are directly extracted from intrinsic noise parameters.
- $i_d^2$ is frequency independent and $i_g^2$ is proportional to $f^2$. 
Noise Sources vs. $V_{GS}$ Bias

- $i_d^2$ mainly comes from the gradual channel region.
- $i_g^2$ mainly depends on the gate-to-source capacitance $C_{GS}$.
• $i_g i_d^* \propto f \ (i_g i_d^* = \varepsilon_{sat} \cdot j 4kT \omega C_{GS})$.

• $i_g i_d^*$ mainly depends on the gate-to-source capacitance $C_{GS}$. 

\[ \text{Correlation vs. Frequency & Bias} \]
Channel Noise vs. $V_{DS}$ Bias

- $i_{d}^2$ contributed from the saturation region in the channel is not important for short-channel devices.
• The channel noise equations $\overline{i_d^2} = \frac{8kTg_m}{3}$ and $\overline{i_d^2} = \frac{8kTg_{do}}{3}$ suggested for the long channel devices predict lower equivalent noise resistance $R_n$. 
- The extracted noise sources are fed into the a.c. noise model for noise source verification.

- The induced gate noise has a great influence on the $\text{NF}_{\text{min}}$ of long channel devices but does not affect the equivalent noise resistance.
• All extracted a.c. parameters and extracted noise $\bar{i}_d^2$, $\bar{i}_g^2$ and $\bar{i}_g \bar{i}_d^*$ are used in the calculation of the four noise parameters.

• No fitting is used in the calculation of the four noise parameters.
Coefficients vs. Channel Lengths

- $\gamma_{sat}$, $\delta_{sat}$ and $\varepsilon_{sat}$ are 
  
  $$\gamma_{sat} = \frac{i_d^2}{4kTg_{do}}, \quad \delta_{sat} = \frac{i_g^2}{4kT\omega^2 C_{GS}^2} \quad \text{and} \quad \varepsilon_{sat} = \frac{i_g i_d^*}{j4kT\omega C_{GS}}.$$
Choosing Device Sizes - Channel L

- Channel length of devices reduced => (1) $g_m$ increased and (2) the peak value of $g_m$ happens at lower $V_{GS}$ value.
- The faster increase in $g_m$ makes (1) the $NF_{min}$ reduced and (2) the lowest $NF_{min}$ shifted to the lower $V_{GS}$ region.
Choosing DC Bias Conditions

- Higher $V_{DS}$ bias will increase $g_m$ at the higher $V_{GS}$ region.
- Higher $g_m$ will decrease $NF_{min}$ at higher $V_{GS}$ region.
- Decreased $NF_{min}$ at higher $V_{GS}$ region makes the lowest $NF_{min}$ less sensitive to $V_{GS}$ bias.
Device Geometry and Layout

**NMOSFETs**

- **L** = 0.8 µm
- **f** = 4 GHz
- **V_{DS}** = 3.0 V

- **W** = 1 x 60 µm
- **W** = 6 x 10 µm

**Distributed effects**

\[
R_G = \frac{1}{3} \times R_{gsh} \times \frac{W}{L}
\]

**Distributed effects**

\[
R_G = \frac{1}{3} \times R_{gsh} \times \frac{W/2}{L} \times \frac{1}{2} = \frac{1}{3} \times 4 \times R_{gsh} \times \frac{W}{L}
\]

**Distributed effects**

\[
R_G = \frac{1}{3} \times R_{gsh} \times \left(\frac{W}{n} \times \frac{1}{n}\right) = \frac{R_{gsh} \cdot W}{3n^2 L}
\]

- two resistors connected in parallel
- each signal travels half of the distance **W**

**Distributed effects**

\[
R_G = \frac{1}{3} \times R_{gsh} \times \frac{W}{n} \times \frac{1}{n} = \frac{R_{gsh} \cdot W}{3n^2 L}
\]
Cross Section of MOSFET Channel

- $V_{DS}$
- $V_{DS_{sat}}$
- $L_{elec}$
- $\Delta L$
- $L_{eff}$
- $E_{crit}$
- $v_{sat}$
- $x$

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Channel Noise in Linear Region

• Noise current from the gradual channel region:

\[
S_{id}^2 = \frac{4kT_0}{L_{eff}^2} \mu_{eff}(-Q_{inv}) + \delta \frac{4kT_0 I_D}{L_{eff}^2 E_{crit}^2} V_{DS}
\]

\[
Q_{inv} = -W_{eff} L_{eff} C_{ox} \cdot \left( V_{gteff} - \frac{A_b V_{dseff}}{2} + \frac{A_b^2 V_{dseff}^2}{12 \cdot \left(V_{gteff} - \frac{A_b V_{dseff}}{2}\right)} \right)
\]

- \(\delta\) is used to model the hot electron effect.
- \(V_{DS}\) becomes \(V_{DS_{sat}}\) in the saturation mode.
- Using \(L_{elec}\) instead of \(L_{eff}\) in the saturation mode.
Channel Noise in Saturation Region

- Noise current from velocity saturation is zero [1]:

  -> Thermal noise theory (4kTR) cannot be applied in the velocity saturation region.

  -> Physical noise mechanism in the velocity saturation region is unknown - though a drifting dipole layer model [2] and a diffusion noise model [3] were proposed for the thermal noise modeling of FETs.

  -> For a given voltage fluctuation, it generates zero noise fluctuation because of the local $g_{DS}(x_0) = 0$.

Channel Noise vs. $V_{GS}$ and $V_{DS}$

- Hot electron is not important in the channel noise modeling.
- No noise current from velocity saturation is found.
- Using $L_{elec}$ to catch the increasing trend in the channel noise vs. $V_{DS}$ characteristics.
- Simulated $\gamma$ for long channel devices $L = 10 \, \mu m$ is 0.68 at $V_{GS} = 1.8V$ which is close to the theoretical value $2/3$.

- The $\gamma$ value increases from 0.68 to 1.2 or 1.8 (depending on the $V_{GS}$ bias) when the channel length is decreased because of CLM effect.
Conclusions

- Direct extraction of $i_d^2$, $i_g^2$ and $i_g i_d^*$ from RF noise measurements.

- The channel noise $i_d^2$, in general, is frequency independent.

- The $i_g^2$ and $i_g i_d^*$ are proportional to $f^2$ and $f$, respectively.

- $i_d^2$ increases because of the higher $g_{DS}$ at the same bias condition.

- $i_g^2$ and $i_g i_d^*$ decrease because of the decrease of $C_{GS}$.

- CLM effect - $i_d^2$ modeling of deep submicron MOSFETs down to 0.18 µm.

- Noise current from $v_{sat}$ region is negligible because of zero $g_{DS}$.

- Hot electron effect seems negligible in the RF noise modeling of MOSFETs.