Investigation of the Thermal Noise of MOS Transistors under Analog and RF Operating Conditions

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Purpose of the Work

• The thermal noise magnitude is an important design parameter for high performance analog and RF-CMOS circuits
  (which are strongly needed in many SoC designs)

• There is a lot of controversial discussion on the validity of the classical noise models in modern short channel MOS devices

➤ In this work we will present experimental noise data for modern devices and a simple physics based and analytical model to explain these data
Content

• Measurement Set-up
• New Model for the Thermal Noise
• Comparison to ‘Classical’ Theory
• Comparison to Experimental Data
• Conclusions
Measurement Set-up I

- To remove noise components arising from the set-up, three different noise measurements of the DUT are taken.
- They give information about the total noise (including the device noise) and the noise of the set-up.
- From these data, the device’s noise is calculated.
The accuracy of the set-up is better than 10% especially in the impedance range between $40\Omega$ and $400\Omega$. 
Classical Model versus Experiment

The noise is slightly higher than expected from classical theory.

- Drain current noise [A/√Hz]
  - Experimental data
  - Classical model

- Frequency [Hz]
  - $10^5$ to $10^8$

- Drain current noise values:
  - $10^{-10}$
  - $10^{-11}$
  - $10^{-12}$

- Parameters:
  - $V_{gs,\text{eff}}$: 0.20V;
  - $V_{ds}$: 0.65V;
  - $g_{ds}$: 0.63mS;
  - $g_m$: 6.50mS;
  - $g_{mb}$: 1.26mS;

- Device: n-MOS 200µm / 0.5µm
Theory of Thermal Noise

Thermal noise arises from the random thermal motion of the carriers in addition to its drift in the field.

The contribution of a carrier to the total noise at a certain location in the device is proportional to the conductance in that region:

$$\frac{\overline{i^2}}{\Delta f} = 4kT \cdot g(x)$$
Classical Theory of Thermal Noise of MOSFETs

The thermal noise of a MOSFET is given by:

\[
\frac{i_d^2}{\Delta f} = 4kT \cdot \frac{W}{L} \cdot \frac{\int_0^{V_{d0}} \mu^2(V) \cdot Q^2(V) dV}{\int_0^{V_{d0}} \mu(V) \cdot Q(V) dV}
\]

(after Klaasen/Prins)

This formula is often simplified by using a constant mobility \( \mu_0 \):

\[
\frac{i_{d,\text{classical}}^2}{\Delta f} = 4kT \cdot \frac{W}{L} \cdot \mu_0 \cdot \frac{\int_0^{V_{d0}} Q^2(V) dV}{\int_0^{V_{d0}} Q(V) dV} = f(V_{gs}, V_{ds}) \cdot kT \cdot g_{m,\text{max}}
\]
Local Channel Approach for the Noise of MOSFETs

For the new model we use the following formula for \( \mu(V) \) instead:

\[
\mu(V) = \frac{\mu_0}{1 + \Theta \cdot (V_{gs,eff} - V)} \cdot \frac{1}{1 + \frac{V}{L \cdot E_c}}
\]

Together with an approximation for the noise arising in the region beyond the pinch-off point the following formula results:

\[
\frac{i_{d,\text{new}}^2}{\Delta f} = \frac{4kT}{I_{ds}} \cdot \left( \frac{W}{L} \right)^2 \cdot \int_0^{V_{d0}} \mu(V)^2 \cdot Q^2(V) dV + I_{ds} \cdot \frac{4kT}{WL \cdot E_c^2} \cdot (V_{ds} - V_{d0})
\]

(the remaining integral is analytically solvable)
• With increasing effective gate voltage the new theory gives higher noise values compared to the ‘classical’ theory.
• The new model does not use any additional fit parameters and can be easily included into a circuits simulation model.
Good agreement between new model and experiment
Agreement better than compared to ‘classical’ model
Gate Voltage Dependence p-MOS

Good agreement between new model and experiment
Agreement better than compared to ‘classical’ model
Drain Voltage Dependence n-MOS

Good agreement between new model and experiment
Agreement better than compared to ‘classical’ model
Drain Voltage Dependence p-MOS

Good agreement between new model and experiment
Agreement better than compared to ‘classical’ model
Length Dependence p-MOS

Especially for short gate lengths the new model gives much better results
Conclusion

• A new analytical model for the thermal noise of short channel MOSFETs is presented.
• The model is in excellent agreement with experimental data from a 0.25µm analog CMOS technology.
• It can easily be implemented for circuit simulation without fitting parameters.
• The observed noise enhancements compared to the classical model are less severe than proposed by several other groups (≤40% for analog/RF relevant operating conditions).