Excessive High-Frequency Drain and Gate Current Noise in Short-Channel MOSFETs

Gleb V. Klimovitch

Thomas H. Lee, Yoshihisa Yamamoto

Electrical Engineering Department

Stanford University

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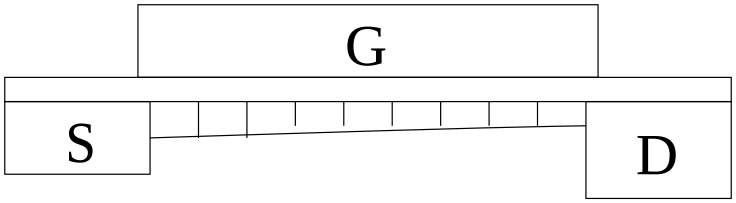
Outline

- How to calculate HF noise in a MOSFET
- Noise properties of long-channel devices
- Noise properties of short-channel devices
- Conclusions

How to Calculate HF Noise in a MOSFET



- Divide the channel into physically infinitesimal *independent* voltage noise sources
- Find the contribution of each noise source to drain and gate noise currents
- Integrate these contributions over the channel length

Noise Calculations in Long vs. Short-Channel Devices

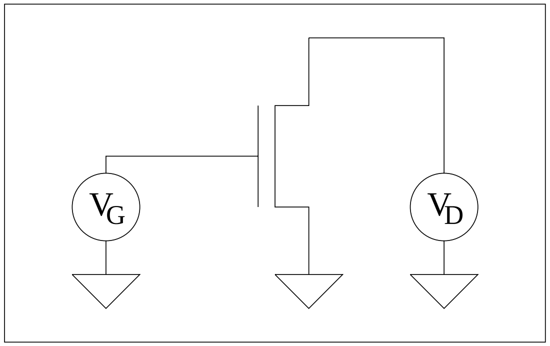
Long channels:

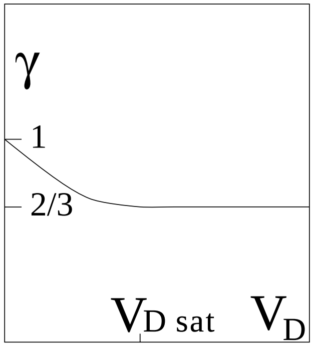
- Gradual Channel Approximation (GCA) applies
- Low-field regime → Nyquist-Johnson theorem for voltage noise density may be used: $\Delta\overline{v_n^2} = 4k_B T_0 \Delta r \Delta f$

Short-channel devices in saturation:

- Velocity saturation occurs in a significant fraction of the channel, where GCA does not apply
- Nyquist-Johnson theorem does not hold

Results for HF Drain Current Noise in Long-Channel MOSFETs





For short-circuited gate and drain, the drain current noise is:
$\overline{i_d^2} = \gamma 4 k_B T g_{d0} \Delta f$.

The noise factor γ is close to $2/3$ in saturation.

Reflected as a gate voltage noise, it is: $\overline{v_g^2} \equiv \overline{i_d^2}/g_m^2 \sim 1/\sqrt{I_D}$,

a decreasing function of the drain current I_D.

Results for HF Gate Current Noise in Long-Channel MOSFETs

For short-circuited gate and drain, the gate current noise is:

$$\overline{i_g^2} = \delta 4k_B T \frac{\omega^2 C_{gs}^2}{5g_{d0}} \Delta f \ .$$

The noise factor δ is close to $4/3$ in saturation.

The correlation coefficient c between gate and drain current noise is:

$$c \equiv \frac{\overline{i_g i_d}}{\sqrt{\overline{i_d^2}\,\overline{i_g^2}}} \approx 0.395j \ .$$

Voltage Noise Temperature

Definition of T_n: $\Delta\overline{v_n^2} = 4k_B T_n \Delta r \Delta f$,

$T_n(E) \neq T_0$ starting from fields $E \sim E_c$.

T_n strongly depends on the differential mobility:

$$T_n(E) = T_0 \frac{D_{\|}(E)\mu_0^2}{D_0 \mu_d(E)^2} \; .$$

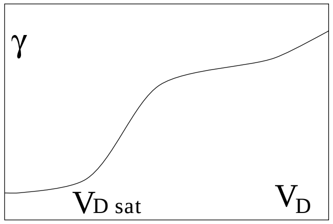
T_n rises sharply when velocity saturation occurs and, in general, continues to increase as field is increasing.

Drain Current Noise due to Hot Electrons as a Function of Drain Voltage

The hot-electron drain current noise is: $\overline{i_d^2} \sim \frac{I_D}{L_{eff}^2} \int_{L_c}^{L_{tot}} \frac{T_n(E)}{E^2} dy.$

As device enters saturation, the noise current increases fast until the length of the saturation region $L_{tot} - L_c$ is comparable with the field length scale: $L_{tot} - L_c \sim l_E$.

At higher drain voltages, noise current grows slower due to noise of hot electrons near drain and channel length modulation.



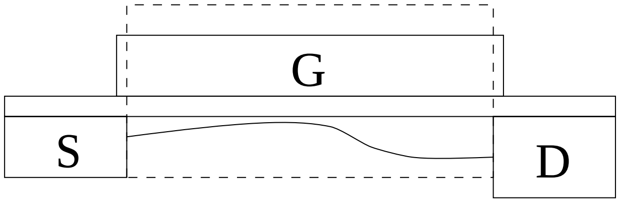
Input-Reflected Drain Current Noise due to Hot Electrons may be an *increasing* Function of Drain Current

In strong saturation, for a constant channel field distribution, the input-referred hot electron drain current noise is: $\overline{v_g^2}_{he} \sim I_D/g_m^2$.

In the best case, $g_m \sim \sqrt{I_D}$, so that $\overline{v_g^2}_{he}$ is independent of the drain current.

Otherwise, $\overline{v_g^2}_{he}$ is an increasing function of I_D (e.g., if velocity saturation effects are important). ¡

Gate Current Noise due to Hot Electrons



By Poisson theorem, the gate charge depends on both channel charge and drain field: $\Delta q_G \approx -\Delta q_{ch} - \epsilon_{si} W t_{ch} \Delta E_D$.

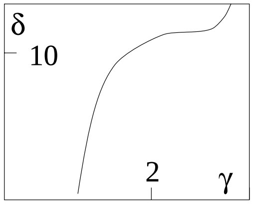
Neglecting drain field fluctuations, hot electron gate current noise would be completely correlated with drain current noise: $q_g = \tau_{ch} i_d$, where $\tau_{ch} \equiv \partial q_{ch} / \partial I_D \approx L_{tot}/u_{sat} - \tau_{tr1}$.

Gate vs Drain Current Noise due to Hot Electrons

Weak saturation: $\Delta_1\delta_{he} \approx 10[V_{GT}/V_{D\ sat}]^2\Delta\gamma_{he} \gg \Delta\gamma_{he}$.

Starting from moderate saturation, hot electron gate current noise is a superlinear function of hot electron drain current noise due to drain field fluctuations:

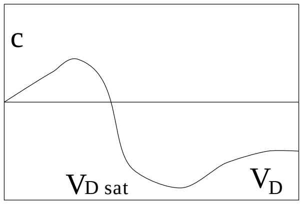
$$\Delta_2\delta_{he} \sim \Delta_1\delta_{he}\left[\frac{l_E}{L-l_E}\frac{\epsilon_{si}}{\epsilon_{ox}}\frac{E_D}{E_c}\right]^2 \sim 10\Delta\gamma_{he}\frac{E_D^2}{E_c^2}\ .$$



(Imaginary) Correlation Coefficient between the Gate and Drain Current Noise

Originates from three sources:

- Cold electron noise (gives positive contribution)
- Hot electron channel charge noise (sign depends on sign of τ_{ch}: negative in weak/moderate saturation)
- Hot electron drain field noise (gives negative contribution)



Comparison with Experiment from [4]

Very simplified noise temperature $T_n(E > E_c) \approx 10T_0$ is used.

V_{GT}	4.5	4.5	3.5	2.5	1.5	3.5	2.5
V_D	5	4	4	4	4	3	3
γ_{exp}	3.42	2.55	2.68	3.31	4.78	2.38	2.96
γ_{cald}	2.72	2.39	2.97	3.78	4.69	2.44	2.77
%	-20	-6	11	14	-2	3	-6

Conclusions

- Techniques to calculate drain current noise, gate current noise, and their correlation coefficient are outlined, results independent on a particular functional dependence of the noise temperature on field are given
- Input-referred hot electron noise is not a decreasing function of drain current in strong saturation
- Gate current noise factor grows much faster than drain current noise factor
- To keep drain and gate noise factors low, the drain voltage V_D should not exceed the saturation voltage V_{Dsat} by more than a few $l_E E_c$, or roughly one volt