Flicker Noise Extraction for Scalable MOS Simulation Models

Dr. Thomas Gneiting
AdMOS GmbH
thomas.gneiting@admos.de
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- Flicker noise equations in modern MOS models
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The most MOS simulation models provide the following 2 principal degrees of freedom to adjust the flicker noise behavior.
NOIMOD = 1, 4, 5

BSIM3 Flicker Noise

\[ S_{id}(f) = \frac{(KF) \cdot I_{DS}}{C_{OX} \cdot L_{eff}^{2} \cdot f^{2 \cdot EF}} \]

“classic” SPICE model

NOIMOD = 2, 3, 6

BSIM3 model

\[ V_{gs} > V_{th} + 0.1: \]

\[ S_{id}(f) = \frac{k_{B} \cdot T \cdot q^{2} \cdot \mu_{eff} \cdot I_{DS}}{C_{oxe} \cdot (L_{eff} - 2 \cdot LINTNOI_{w}) \cdot A_{bulk} \cdot f^{2 \cdot EF} \cdot 10^{8}} \cdot \left( \text{NOIA} \cdot \log \left( \frac{N_{O} + 2 \cdot 10^{14}}{N_{I} + 2 \cdot 10^{14}} \right) + \text{NOIB} \cdot (N_{O} - N_{I}) + \frac{\text{NOIC}}{2} \cdot \left( N_{O}^{2} - N_{I}^{2} \right) \right) \]

\[ + \frac{k_{B} \cdot T \cdot I_{DS}^{2} \cdot \Delta L_{CLM}}{W_{eff} \cdot (L_{eff} - 2 \cdot LINTNOI_{w}) \cdot f^{2 \cdot EF} \cdot 10^{8}} \cdot \frac{\text{NOIA} \cdot \text{NOIB} \cdot N_{I} + \text{NOIC} \cdot N_{I}^{2}}{N_{I} + N^{*}} \]

\[ V_{gs} < V_{th} + 0.1: \]

\[ S_{id}(f) = \frac{S_{llimit} \cdot S_{wi}}{S_{llimit} + S_{wi}}, \quad S_{wi}(f) = \frac{\text{NOIA} \cdot V_{im} \cdot I_{DS}^{2}}{W_{eff} \cdot L_{eff} \cdot f^{2 \cdot EF} \cdot 4 \cdot 10^{36}} \]
BSIM4 Flicker Noise

\[ S_{id} = \frac{K_F \cdot I_{DS}^{AF}}{C_{OX} \cdot L_{eff}^{2} \cdot f^{EF}} \]  

“classic” SPICE model

\[ S_{id,inv}(f) = \frac{k_B \cdot T \cdot q^2 \cdot \mu_{eff} \cdot I_{DS}}{C_{oxe} \left( L_{eff} - 2 \ast LINTNOI \right)^2 \cdot A_{bulk} \cdot f^{EF} \cdot 10^{10} \cdot \left( \frac{N_o + N^*}{N_i + N^*} \right) + NOIB(N_o - N_i) + \frac{NOIC}{2} \left( N_o^2 - N_i^2 \right)} \]

Inversion:

\[ S_{id}(f) = \frac{S_{id,inv}(f) \cdot S_{id,subVt}(f)}{S_{id,inv}(f) + S_{id,subVt}(f)}, \quad S_{id,subVt}(f) = \frac{NOIA \cdot k_B \cdot T \cdot I_{DS}^{2}}{W_{eff} \cdot L_{eff} \cdot f^{EF} \cdot N^*^2 \cdot 10^{10}} \]

SubVth:
**PSP Flicker Noise**

**Local model:**

\[
S_f(f) = \frac{\Phi_e}{f \cdot G_{ox} \cdot G_{vsat} \cdot N^*} \left( \frac{(NFA + NFB \cdot N^* + NFC \cdot N^*)^2}{N_m^* + \Delta N / 2} \right) \ln \left( \frac{N_m^* + \Delta N / 2}{N_m^* - \Delta N / 2} \right) 
+ (NFB + NFC) \left( N_m^* - 2 \cdot N^* \right) \Delta N
\]

**Scaling equation:**

\[
\begin{align*}
NFA &= \frac{NFALW}{W_e \cdot L_e} \cdot \frac{W_{EN} \cdot L_{EN}}{W_e \cdot L_e} \\
NFB &= \frac{NFBW}{W_e \cdot L_e} \cdot \frac{W_{EN} \cdot L_{EN}}{W_e \cdot L_e} \\
NVC &= \frac{NFCLW}{W_e \cdot L_e} \cdot \frac{W_{EN} \cdot L_{EN}}{W_e \cdot L_e}
\end{align*}
\]

Fixed frequency exponent of 1!
define noise_circ (D G OUT)
Flicker_Noise:MAIN D1 G 0 0 \ L=10u W=10u Mult=1
;
; sense the noise current
R:Rdummy D D1 R=1m Noise=no
;
; convert noise current into an identical voltage
Z_Port:v D1 D OUT 0 Z[2,1]=1
R:Raux OUT 0 R=1k Noise=no
;
end noise_circ
Noise in Spice, HSPICE

.subckt noise_circ 1 2 5 7
MAIN 9 6 0 0 Flicker_Noise
+ L=10u W=10u NF=1
L2 6 2 1000000
C2 5 6 1000000
H1 8 0 V1 1
R1 7 8 1e-4
V1 1 9 0
.ends
- Flicker noise equations in modern MOS models
- Noise simulation in different simulators
- Steps in parameter extraction using a PSP example
  - Measurement (see paper from IHP, Falk Korndörfer)
  - Determination of the frequency exponent
  - Determination of bias dependency
  - Extraction of parameters for scalable noise models shown with an example using the PSP model
- Problems to be solved
- Summary

*) Based on the work of Knoblinger, Grabinski, Sischka
If the model provides a frequency exponent, it can be derived from the slope of the measured curves in logarithmic representation:
(Example for SPICE model, the other models behave similar)

\[
S_{id}(f) = \frac{K_F \cdot I_{DS}^{AF}}{C_{OX} \cdot L_{eff}^2 \cdot f^{EF}}
\]

\[
S_{id}(f) = \text{con} \cdot f^{-EF}
\]

\[
\log(S_{id}(f)) = \log(\text{con}) - \text{EF} \cdot \log(f)
\]

\[
y = c + m \cdot x
\]
In the real world:

- EF must fit several devices with diff. L, W simultaneously.
- Take into account only parts of the curves due to measurement restrictions.
Once the slope is given, the noise values at 1Hz can be determined by extrapolating the measured curve to 1Hz.

(Example for SPICE model, the other models behave similar)

\[ S_{id}(f) = \frac{K_F \cdot I_{DS}^{AF}}{C_{OX} \cdot L_{eff}^2 \cdot f^{EF}} \]

\[ = 1 \text{ at } 1 \text{Hz} \]
DC Bias dependency (2)

3 Steps:

- Select range of curves to determine slope
- Make curves slopeless
- Apply linear fitting to the selected range of the curve and determine cross-point at 1Hz
DC Bias dependency (2)

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Parameter Extraction – PSP (1)

\[ S_{id}(f=1\text{Hz}) \]
@ diff Vg, Vd, L, W

Iterative Solution using a modified Levenberg-Marquardt algorithm

Solver
\[ S_{fl}(1\text{Hz}) = f(\text{Parameter, Dimensions, DC Bias}) \]

Noise parameters

PSP: PSP1020 Par. L, W, MULT VG, VD

PSP: NFALW, NFBLW, NFCLW
Parameter Extraction – PSP (2)

Example parameter extraction process:

1. Simulation with default values of NFALW, NFBLW, NFCLW

2. Perform extraction in ca. 1s and repeat simulation
Parameter Extraction – PSP (2)

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Parameter Extraction – PSP (2)

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1. Simulation with default values of NFALW, NFBLW, NFCLW

2. Perform extraction in ca. 1s and repeat simulation
Parameter Extraction – PSP (3)

Final result for 4 different transistor dimensions.
Problems to be solved

The scalability of the simulation models is still not good enough.

The PSP scaling equation:

\[
\begin{align*}
NFA &= \frac{W_{EN} \cdot L_{EN}}{W_L \cdot L_E} \\
NFB &= \frac{W_{EN} \cdot L_{EN}}{W_L \cdot L_E} \\
NVC &= \frac{W_{EN} \cdot L_{EN}}{W_L \cdot L_E}
\end{align*}
\]

does not allow to modify parameters independently for L and W. Actually, only the product L·W is taken into account.

Fitting for small device cannot be improved in this area without the distortion of the other devices.
Together with the measurement of flicker noise (presented by Falk Korndörfer, IHP), the shown extraction strategy is the basis of a complete noise modeling method.

The very effective simultaneous extraction of flicker noise parameters for different devices with different dimensions is the key improvement of this tool.

The shown methodology for PSP was implemented for common MOS models (BSIM3, BSIM4) and can be easily extended to other models like HiSIM2 etc.

The co-operation between IHP and AdMOS resulted in a commercial available Flicker Noise Modeling Tool. For details, please see: www.admos.de → Products → Flicker Noise System