Complete analysis of BSIM3 noise models for the optimum design of a low noise preamplifier

T Noulis, M Drakaki and S Siskos
Aristotle University of Thessaloniki, Physics Department, Electronics Laboratory, Thessaloniki, Greece
E-mail: tnoul@physics.auth.gr, drakaki@el.teithe.gr, siskos@physics.auth.gr

Abstract. An analysis of a preamplifier noise performance, of a low-energy X-rays strip detector for space applications, is examined in relation to BSIM3V3 thermal and flicker noise models. These noise models (BSIM3 and Spice2) are studied and analytically presented in the frequency and voltage domain. A differentiation of the total preamplifier output noise associated with simulator noise models is demonstrated. Analysis is supported by simulation results in 0.35µm AMS process, which confirm that the selection of the simulator noise model combination and specifically the usage of BSIM3 flicker noise model, instead of Spice2, for a given shaper, results to a different preamplifier noise response.

1. Introduction
Noise performance is a crucial part of microelectronic systems reliability and becomes extremely important in readout amplification stages. A low noise charge sensitive preamplifier (CSA) is used at the front-end basically due to its low noise configuration (figure 1). The generated signal is fed to a bandpass filter, where the pulse shaping is performed to optimize the signal to noise ratio. The noise performance of a detector readout system is generally expressed as the equivalent noise charge (enc). In order to minimize the thermal and flicker amplification stage noise, and therefore the total noise of the system, it is important to select the optimum type (n- or p-type) and gatewidth of the preamplifier input MOS [1], [2]. Shot noise is determined by the characteristics of pulse shaper and detector and does not affect the design of CSA. In all noise optimization techniques thermal and flicker noise models are commonly oversimplified empirical models and they are not in agreement with simulator noise models. In order to achieve accuracy and agreement between the theoretical analysis and the simulation results in detector applications, the Spice simulator noise models are analytically examined.

2. Analysis of BSIM3v3 noise models
BSIM3v3 develops two distinct models (Spice2 and BSIM3) to calculate the $1/f$ noise and the respective two models to calculate the channel thermal noise. The two models of a MOSFET device thermal noise phenomenon are given below [3], [4]:

\[
\frac{\overline{I_d^2}}{\Delta f} = \frac{1}{2} kT \left| g_m + g_d + g_{mb} \right| 
\]  \hspace{1cm} (1)

\[
\frac{\overline{I_d^2}}{\Delta f} = \frac{4kT}{R_{ds} + L_{eff} / (\mu_{eff} Q_m)} 
\]  \hspace{1cm} (2)
Figure 1. Front-end readout system block diagram with an analytical schema of preamplifier circuit.

where \( k \) is the Boltzmann constant, \( T \) is the temperature, \( g_m, g_d \) and \( g_{mb} \) are the mutual, drain and bulk transconductance respectively, \( Q_{inv} \) (in coulombs) is the inversion charge in the channel, \( L_{eff} \) is the effective channel length and \( R_{DS} \) is the drain–source resistance.

The Spice2 thermal noise model isn’t accurate in all MOS operating regions. When MOS transistor is at the linear region, \( g_m = g_{mb} = 0 \) since \( V_{ds} \to 0 \), and (1) gives for the Spice2 thermal noise model

\[
\overline{i_d^2} = 4kT\Delta f \cdot (2/3)g_d
\]

whereas the theoretically calculated thermal noise current is given by:

\[
\overline{i_d^2} = 4kT\Delta f \cdot g_d
\]

This suggests that equation (1) isn’t correct in all operation regions. Therefore, BSIM3 thermal noise model is preferred. On the other hand, BSIM3 thermal noise model can at times exhibit a kink behavior at the transition between subthreshold and inversion regions. Both models are derived with the long channel approximation but underestimate thermal noise in short channel transistors [5].

Spice2 and BSIM3 flicker noise models are given in equations (5) and (6) and state the average value of the square of the flicker noise drain current at a particular frequency [3], [4].

Flicker – Spice2 model

\[
\overline{i_d^2} / \Delta f = KF \left| \frac{I_{DS}}{C_{ox}L_{eff}^2} \right| f^{\frac{1}{2}}
\]

Flicker – BSIM3 model

\[
\overline{i_d^2} / \Delta f = \begin{cases} \frac{S_{inversion}}{S_{subthreshold}} & \text{if} \ V_{gs} > V_{th} + 0.1 \\ \text{otherwise} & \end{cases}
\]

\[
S_{inversion} = \frac{g^2 T \mu_{ox} 5}{C_{ox} L_{eff}^2 f^{\frac{1}{2}}} 10^8 \left[ \text{NOIA} \ln \left( \frac{N_0 + 2 \cdot 10^{14}}{N_1 + 2 \cdot 10^{14}} \right) + \text{NOIB}(N_0 - N_1) + \frac{\text{NOIC}}{2}(N_0^2 - N_1^2) \right] + \frac{kT q I_{DS}^2 \Delta L_{clm}}{W_{eff} L_{eff}^2 f^{\frac{1}{2}}} \frac{\text{NOIA} + \text{NOIB} \cdot N_1 + \text{NOIC} \cdot N_1^2}{(N_1 + 2 \times 10^{14})^2}
\]

\[
S_{subthreshold} = \frac{S_{inversion}}{S_{inversion} + S_{weak-inversion}}
\]

where \( S_{limit} = S_{inversion} \) evaluated at \( V_{gs} = V_{th} + 0.1 \)

\[
S_{weak-inversion} = \frac{\text{NOIA} \cdot kT q I_{DS}^2}{W_{eff} L_{eff}^2 f^{\frac{1}{2}}} 4 \cdot 10^{36}
\]
KF is the flicker noise coefficient, which is the proportional factor and depends critically on processing, AF (flicker exponent) and EF (flicker frequency exponent) characterize the power dependence of the measured $i_f^2$ on $I_{DS}$ and frequency respectively, $C_{ox}$ is the gate capacitance per unit area, $W_{off}$ is the effective channel width, NOIA, NOIB and NOIC are noise fitting parameters, $N_0$ and $N_l$ are the charge density at the source and drain respectively, $q$ is the electron charge and $\Delta L'_{clm}$ refers to channel length reduction due to channel modulation and depends on the model parameter EM [4].

Spice2 flicker noise model is a simple model with only one primary parameter (KF), which can vary the noise magnitude, contrary to BSIM3 model, which is considerably complicated. The physics of the thermal noise mechanism is well described by the BSIM3 model. If the model parameters are correctly extracted we expect better fit to the measurements with the BSIM3 model.

There are a total of four combinations depending on the particular 1/f noise and thermal noise model. The exact model used to calculate flicker and channel thermal noise depends on the value of BSIM3 model parameter NOIMOD (NOIse MODels), which takes on integer values between 1 and 4 [3], [4]. The selector parameter NOIMOD is the flag to choose a combination among the four noise models. All noise models combinations are listed in table 1 and shown in figure 2, in the frequency and voltage domain, for an NMOS transistor with dimensions (292/0.9). The default combination is NOIMOD=1, NOIMOD=4 is the preferred combination and NOIMOD=2 is the most accurate one.

| NOIMOD | Flicker noise model | Channel Thermal noise model |
|--------|---------------------|-----------------------------|
| 1      | Spice2              | Spice2                      |
| 2      | BSIM3               | BSIM3                       |
| 3      | BSIM3               | Spice2                      |
| 4      | Spice2              | BSIM3                       |

3. Design and simulation results of a space application preamplifier

In order to examine the noise issues described above, we use a practical CSA circuit and specifically, a charge sensitive preamplifier of a low energy X-rays silicon strip detector (Cd =0.5pF) for space applications. The CSA was designed in 0.35µm process by Austria Micro Systeme (AMS) and its input transistor was selected to be an NMOS with dimensions $\left(\frac{L}{W}\right)_1 = \left(\frac{292\mu m}{0.9\mu m}\right)$. This circuit is based on a folded cascode built of transistors M1, M2 and M3 and the CSA reset device is a MOS transistor biased in the triode region with an adaptive self-biased circuit [6].

The circuit was simulated using HSpice and specifically BSIM3V3.3 Berkley Spice MOS model. The preamplifier output voltage (figure 3) increases to a maximum value, when the charge of the feedback capacitance, $C_f$ ends. The $C_f$ charge time, the output node discharge time and the power consumption are 200nsec, 13.4µsec and 676µW respectively.

Figure 2. Noise current spectral density a) in the frequency and b) voltage domain.
The CSA noise behavior is examined in relation to the four different noise models combinations. The noise spectral density of the preamplifier output for all four cases in a frequency bandwidth that refers to a shaper with a peaking time of 10 µsec, is shown in figure 4.

A comparison of the four CSA output noise shows that using BSIM3 flicker noise model implies, in this application, less noise in low frequencies, and therefore a differentiation in the simulation curves. This is the reason why the curves corresponding to values 1 and 2 of NOIMOD flag are identical to these corresponding to 4 and 3 respectively. The effect of a different thermal noise model on the total noise response is negligible, due to shot noise presence in the same frequencies where thermal noise exists. However, the selection of a noise model combination using the NOIMOD parameter determines in general the circuit noise response in the simulations. This differentiation, in a front end system, implies different total equivalent noise charges at CSA output. The total enc was calculated 215e for NOIMOD 1 or 4 and 207e for NOIMOD 2 or 3. In all cases, shot noise enc due to detector leakage current, is constant and depends only on the characteristics of the pulse shaper and the detector.

4. Conclusions
In this paper, BSIM3v3 thermal and flicker noise models (BSIM3 and Spice2) are analytically studied and examined in relation to the noise performance of a read out system preamplifier, in the voltage and frequency domain. In particular, the exact model used to calculate the flicker and the channel thermal noise depends on the value of the BSIM3V3 model parameter NOIMOD, and CSA noise performance is differentiated in relation to the value of NOIMOD parameter. It is demonstrated by simulations that using BSIM3 flicker noise model, instead of Spice2, results to a different preamplifier noise response. In order to match the theoretical analysis and the simulations results in detector applications, we have to apply these noise models to the noise optimization theoretical techniques.

5. Acknowledgment
This work is financially supported by the program Platon 2003-2005, a scientific cooperation between GSRT – Greece and CNRS – France.

6. References
[1] Sansen W and Chang Z Y 1990 IEEE Trans. on Circuits and Syst. 11 1375-82
[2] Chang Z Y and Sansen W 1991 Nuclear Instrum. and Methods in Phys. Research 305 553-60
[3] Liu W 2001 MOSFET Models for SPICE Simulation (New York: Wiley–Interscience)
[4] 1995, 1996 BSIM3v3 Manual (final version) (Berkeley)
[5] Abidi A 1986 IEEE Trans. Electron Devices 33 1801-05
[6] Noulis T, Siskos S and Sarrabayrouse G 2004 Proc. IEEE Mediterranean Electrotechnical Conf. (Dubrovnik, Croatia, 12–15 May 2004) pp 51–54