Chapter 9: Noise Modeling

The following noise sources in MOSFETs are modeled in BSIM4 for SPICE noise ananlysis: flicker noise (also known as 1/f noise), channel thermal noise and induced gate noise and their correlation, thermal noise due to physical resistances such as the source/drain, gate electrode, and substrate resistances, and shot noise due to the gate dielectric tunneling current. A complete list of the noise model parameters and explanations are given in Appendix A.

9.1 Flicker Noise Models

9.1.1 General Description

BSIM4 provides two flicker noise models. When the model selector ***fnoiMod*** is set to 0, a simple flicker noise model which is convenient for hand calculations is invoked. A unified physical flicker noise model, which is the default model, will be used if ***fnoiMod*** = 1. These two modes come from BSIM3v3, but the unified model has many improvements. For instance, it is now smooth over all bias regions and considers the bulk charge effect.

9.1.2 Equations

- ***fnoiMod* = 0 (simple model)**

The noise density is

$$S_{id}(f) = \frac{KF \cdot I_{ds}^{AF}}{C_{oxe} L_{eff}^{2} f^{EF}} \tag{9.1.1}$$

where f is device operating frequency.

- ***fnoiMod* = 1 (unified model)**

The physical mechanism for the flicker noise is trapping/detrapping-related charge fluctuation in oxide traps, which results in fluctuations of both mobile carrier numbers and mobilities in the channel. The unified flicker noise model captures this physical process.

In the inversion region, the noise density is expressed as [14]

$$S_{id,inv}(f) = \frac{k_B T q^2 m_{eff} I_{ds}}{C_{oxe} L_{eff}^{2} A_{bulk} f^{ef} \cdot 10^{10}} \left(NOIA \log\left(\frac{N_0 + N^*}{N_l + N^*}\right) + NOIB (N_0 - N_l) + \frac{NOIC}{2}\left(N_0^2 - N_l^2\right) \right) + \frac{k_B T I_{ds}^{2} \Delta L_{clm}}{W_{eff} \cdot L_{eff}^{2} f^{ef} \cdot 10^{10}} \cdot \frac{NOIA + NOIB\, N_l + NOIC\, N_l^2}{\left(N_l + N^*\right)^2} \tag{9.1.2}$$

where m_{eff} is the effective mobility at the given bias condition, and L_{eff} and W_{eff} are the effective channel length and width, respectively. The parameter N_0 is the charge density at the source side given by

(9.1.3)

$$N_0 = C_{oxe} \cdot V_{gsteff} / q$$

The parameter N_l is the charge density at the drain end given by

(9.1.4)

$$N_l = C_{oxe} \cdot V_{gsteff} \cdot \left(1 - \frac{A_{bulk} V_{dseff}}{V_{gsteff} + 2n_t}\right) \Big/ q$$

N^* is given by

(9.1.5)

$$N^* = k_B T \cdot \left(C_{oxe} + C_d + CIT\right) \Big/ q^2$$

where CIT is a model parameter from DC IV and C_d is the depletion capacitance.

DL_{clm} is the channel length reduction due to channel length modulation and given by

(9.1.6)

$$\Delta L_{\mathrm{clm}} = Litl \cdot \log\left(\frac{\dfrac{V_{ds} - V_{dseff}}{Litl} + EM}{E_{sat}}\right)$$

$$E_{sat} = \frac{2VSAT}{\mu_{eff}}$$

In the subthreshold region, the noise density is written as

(9.1.7)

$$S_{id,subVt}(f) = \frac{NOIA \cdot k_B T \cdot I_{ds}^{\ 2}}{W_{eff} L_{eff} f^{EF} N^{*2} \cdot 10^{10}}$$

The total flicker noise density is

(9.1.8)

$$S_{id}(f) = \frac{S_{id,inv}(f) \times S_{id,subvt}(f)}{S_{id,subvt}(f) + S_{id,inv}(f)}$$

9.2 Channel Thermal Noise

There are two channel thermal noise models in BSIM4. One is a charge-based model (default model) similar to that used in BSIM3v3.2. The other is the holistic model. These two models can be selected through the model selector ***tnoiMod***.

- ***tnoiMod* = 0 (charge based)**

The noise current is given by

(9.2.1)

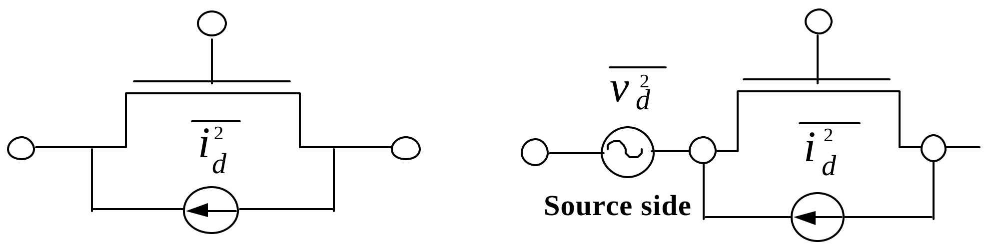
$$\overline{i_d^2} = \frac{4 k_B T \Delta f}{R_{ds}(V) + \frac{L_{eff}^{\ 2}}{m_{eff} |Q_{inv}|}} \cdot NTNOI$$

where $R_{ds}(V)$ is the bias-dependent LDD source/drain resistance, and the parameter *NTNOI* is introduced for more accurate fitting of short-channel devices. Q_{inv} is modeled by

(9.2.2)

$$Q_{inv} = W_{active} L_{active} C_{oxeff} \cdot NF \cdot \left[V_{gsteff} - \frac{A_{bulk} V_{dseff}}{2} + \frac{A_{bulk}{}^2 V_{dseff}{}^2}{12 \cdot \left(V_{gsteff} - \frac{A_{bulk} V_{dseff}}{2} \right)} \right]$$

Figure 9-1a shows the noise source connection for ***tnoiMod*** = 0.



(a) ***tnoiMod*** = 0 (b) ***tnoiMod*** = 1

Figure 9-1. Schematic for BSIM4 channel thermal noise modeling.

- ***tnoiMod*** **= 1 (holistic)**

In this thermal noise model, all the short-channel effects and velocity saturation effect incorporated in the IV model are automatically included, hency the name “holistic thermal noise model”. In addition, the amplification of the channel thermal noise through G_m and G_{mbs} as well as the induced-gate noise with partial correlation to the channel thermal noise are all captured in the new “noise partition” model. Figure 9-1b shows schematically that part of the channel thermal noise source is partitioned to the source side.

The noise voltage source partitioned to the source side is given by

(9.2.3)

$$\overline{v_d^{\ 2}} = 4k_B T \cdot q_{tnoi}^{\ 2} \cdot \frac{V_{dseff}\Delta f}{I_{ds}}$$

and the noise current source put in the channel region with gate and body amplication is given by

(9.2.4)

$$\overline{i_d^{\ 2}} = 4k_B T \frac{V_{dseff}\Delta f}{I_{ds}}\left[G_{ds} + b_{tnoi}\cdot\left(G_m + G_{mbs}\right)\right]^2 - \overline{v_d^{\ 2}}\cdot\left(G_m + G_{ds} + G_{mbs}\right)^2$$

where

(9.2.5)

$$q_{tnoi} = 0.37\cdot\left[1 + TNOIB\cdot L_{eff}\cdot\left(\frac{V_{gsteff}}{E_{sat}L_{eff}}\right)^2\right]$$

and

(9.2.6)

$$b_{tnoi} = 0.577\cdot\left[1 + TNOIA\cdot L_{eff}\cdot\left(\frac{V_{gsteff}}{E_{sat}L_{eff}}\right)^2\right]$$

9.3 Other Noise Sources Modeled

BSIM4 also models the thermal noise due to the substrate, electrode gate, and source/drain resistances. Shot noise due to various gate tunneling components as shown in Figure 3-1 is modeled as well.