Accurate Channel Thermal Noise Modeling in BSIM4

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1. Introduction

Low noise circuit design is one of the key issues in the overall RFIC performance, especially in the front-end receiver. Thus, it is very important to predict the high-frequency noise of RF MOSFETs [1]. The channel thermal noise is most dominant noise source at high frequency [2]. BSIM model adopted the channel thermal noise equation derived from the long-channel theory. To account for the excess channel thermal noise in short-channel MOSFETs, the latest BSIM version provides NTNOI parameter. In this paper, we present NTNOI value of nanoscale MOSFETs and NTNOI equation for circuit designers to accurately simulate channel thermal noise. By using the developed NTNOI equation, circuit designers can calculate NTNOI from DC measurements and BSIM parameters.

2. Accurate Channel Thermal Noise Modeling in BSIM4

To simulate the channel thermal noise, BSIM model up to BSIM3v3.3 offers following equation.

\[ S_{th} = \frac{4kT}{R_{DS} + \frac{L_{eff}}{\mu_{eff} |Q_{inv}|}} \]  
(1)

where \( Q_{inv} \) is total inversion charge in the channel and \( L_{eff} \) is the effective channel length. Eq. (1) is based on the long-channel theory without short-channel effects [3, 4]. Note that \( R_{DS} \) is used to model the source and drain resistances in absorbed-resistance approach (RDSW is nonzero). If lumped-resistance approach is used, \( R_{DS} \) is zero and eq. (1) will be changed accordingly. The channel thermal noise of short-channel device is much higher than the predicted value by long-channel model because of various short-channel effects [2]. To correct this shortcoming, BSIM4 adopted the excess noise parameter, NTNOI, as

\[ S_{th} = \frac{4kT}{R_{DS} + \frac{L_{eff}}{\mu_{eff} |Q_{inv}|}} \times NTNOI \]  
(2)

Since NTNOI is set to a constant value in BSIM model, precise prediction cannot be performed. Thus, we need to obtain the NTNOI value at different bias points and device sizes. To provide bias dependent NTNOI value of short-channel MOSFETs we need to derive the channel thermal noise equation taking into account various short-channel effects. In [2], we derived channel thermal noise as an integral form. For simplification of the model, we assume that \( E(x) \approx V_{DS}/L_c \) in the channel, which is reasonable approximation as shown in [5]. Then, the PSD of the channel thermal noise is

\[ S_d = 4kT \cdot \frac{Q_{inv}}{|L_c^2|} \]  
(3)

where \( L_c \) is the electrical channel length (= \( L_{eff} - \Delta L \)). By using short-channel current equation, eq. (3) can be expressed as

\[ S_d = 4kT \cdot I_{DS} \cdot \left( \left( 1 + E_{L_c} \right) \right) \]  
(4)

Eq. (3) and (4) are valid at both linear and saturation regions. Figs. 1. (a), (b) show that the modeled data with eq. (4) predicts measured noise as a function of gate and drain voltage from long-channel to nanoscale MOSFETs. In Fig. 1, we also observe that BSIM equation underestimates the channel thermal noise. The excess channel thermal noise factor, NTNOI, can be calculated from the ratio of short-channel model, eq. (3) to the long-channel BSIM model, eq. (1). To investigate the channel thermal noise only, we use the lumped-resistance approach \( R_{DS} = 0 \). Then, excess noise factor NTNOI is expressed as

\[ NTNOI = \left( \frac{L_{eff}}{L_c} \right) \]  

This result is in accordance with the result of [6], which showed that the channel-length modulation is critical short-channel effect to explain excess channel thermal noise in short-channel MOSFET. \( L_c \) can be obtained from the result of [7, eq. (8)]. To calculate \( L_c \), the effective mobility is extracted using the methodology of [8]. Figs. 2 (a), (b) show the extracted effective mobility and velocity saturation region in nanoscale MOSFET of \( L_{poly} = 51 \) nm and \( L_{eff} = 36 \) nm. In Fig. 3, the NTNOI values from long-channel to nanoscale MOSFETs as a function of gate and drain voltage are plotted. As channel length decreases, NTNOI value increases because the channel-length modulation effect becomes more prominent. NTNOI value is obtained with BSIM parameters as

\[ \left[ \frac{I_{DS}^{lin}}{\mu_{eff} Q_{inv}} \right]_{BSIM} \times \left( \frac{1}{V_{DS}} + \frac{1}{E_{L_c}} \right) \]  

for linear region

\[ \left[ \frac{I_{DS}^{sat}}{\mu_{eff} Q_{inv}} \right]_{BSIM} \times \left( \frac{V_{GS}-V_T}{m} \right) \]  

for saturation region

where \( V_{GT} = V_{GS} - V_{TH} \) (\( V_{GS} \) is intrinsic gate bias) and \( V_c = I_{DS}/WC \). From eq. (5) we can obtain NTNOI with BSIM parameter and DC measurements for accurate noise simulation.
3. Conclusions
In this work, we extracted excess noise factor, $NTNOI$, to predict channel thermal noise using BSIM4 model. $NTNOI$ value is obtained from proposed short-channel thermal noise model and it is ascertained that $NTNOI$ is strongly dependent on the channel-length modulation effect. In addition, we propose $NTNOI$ equation which can be obtained from provided BSIM parameter and DC measurements. Through this approach, circuit designers using BSIM4 model can simulate accurate channel thermal noise in nanoscale MOSFETs.

Acknowledgements
This work was supported by Inter-university Semiconductor Research Center (ISRC) and Samsung Electronics Ltd.

References

Fig. 1 (a), (b) Measured and modeled channel thermal noise as a function of $V_{GS}$ and $V_{DS}$ using eq. (4).

Fig. 2 (a) Extracted effective mobility and (b) velocity saturation region from measurements.

Fig. 3 Calculated NTNOI values of (a) $L_{poly}=491$ nm, (b) $L_{poly}=171$ nm, and (c) $L_{poly}=51$ nm devices.