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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.

$$S_{id} = \frac{4k_B T}{R_{DS} + L_{eff}^2 / (\mu_{eff} \, |Q_{inv}|)} \tag{1}$$

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

$$S_{id} = \frac{4k_B T}{R_{DS} + L_{eff}^2 / (\mu_{eff} \, |Q_{inv}|)} \times NTNOI \tag{2}$$

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 $E(x) \approx V_{Dsat}/L_c$ in the channel, which is reasonable approximation as shown in [5]. Then, the PSD of the channel thermal noise is

$$S_{id} = 4k_B T \cdot \mu_{eff} \, |Q_{inv}| / L_c^2 \tag{3}$$

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

$$S_{id} = 4k_B T \cdot I_{DS} \cdot \left(1/V_{DS} + 1/E_c L_c\right) \tag{4}$$

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* = $(L_{eff}/L_c)^2$. 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

$$NTNOI = \left[\frac{L_{eff}^2}{\mu_{eff} Q_{inv}}\right]_{BSIM} \times \left[I_{DS} \cdot \left(\frac{1}{V_{DS}^{'}} + \frac{1}{E_c L_{eff}}\right)\right]_{measurement} \quad \text{for linear region} \tag{5a}$$

$$NTNOI = \left[\frac{L_{eff}^2}{\mu_{eff} Q_{inv}}\right]_{BSIM} \times \left[I_{DS} \cdot \frac{V_{GT} - V_o}{m} \cdot \left(1 + \frac{V_o}{V_{GT}}\right)\right]_{measurement} \quad \text{for saturation region} \tag{5b}$$

where $V_{GT}=V_{GS}^{'}-V_{TH}$ ($V_{GS}^{'}$ is intrinsic gate bias) and $V_o = I_{DS}/WC_{ox}v_{sat}$. 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

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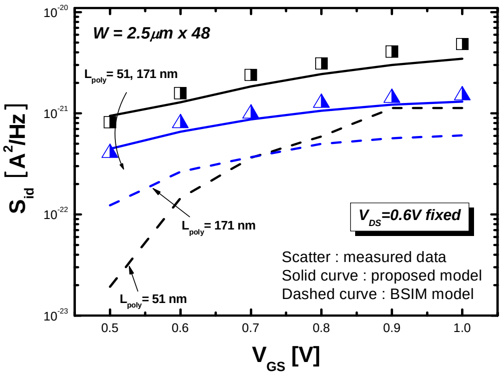
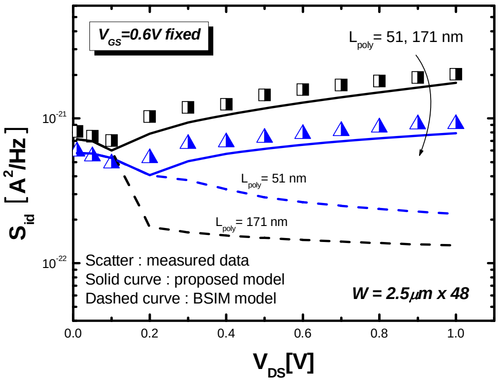
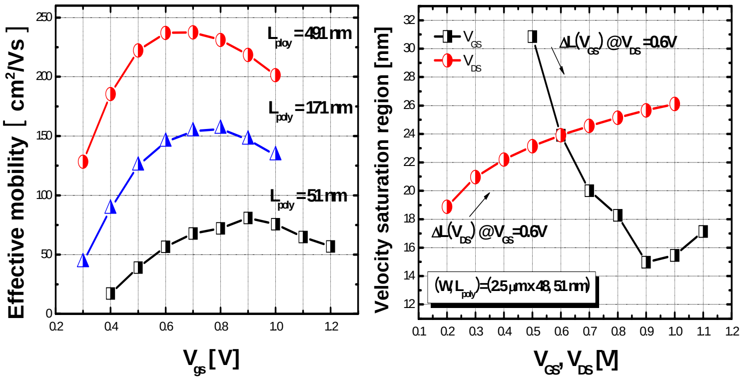


(a)



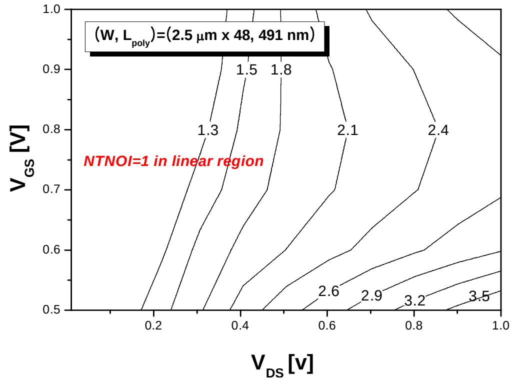
(b)

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

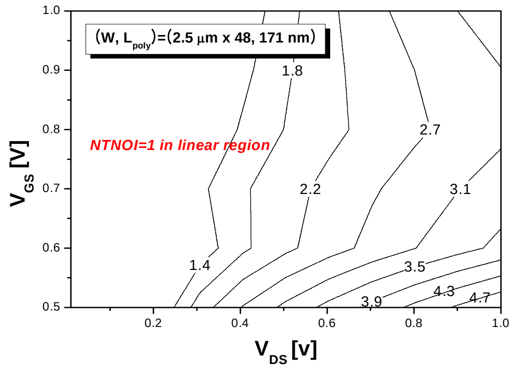


(a) (b)

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



(a)



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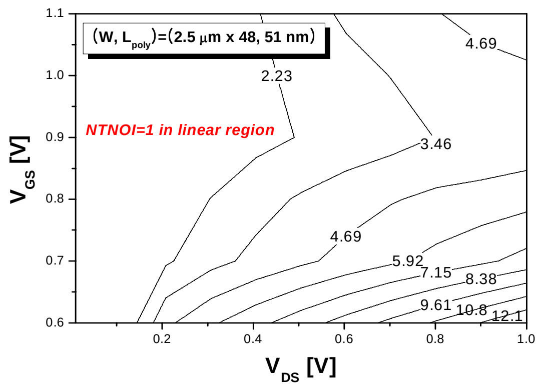

(c)

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