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Spatial Distribution of Channel Thermal Noise in Short-Channel MOSFETs

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1. Introduction

Due to the continuous downscaling of MOS transistor, CMOS become a viable technology in RF circuit design[1]. Low noise circuit design is one of the key issues in the overall RFIC performance, especially in the front-end receiver. Thus, it is important to understand the physical origin of the high-frequency noise in RF MOSFETs[2]. In this paper, we analyzed the origin of the channel thermal noise in RF MOSFETs taking into account various short-channel effects since the channel thermal noise has been known to be the most dominant noise source in deep sub-micron MOSFETs[3]. Firstly, we presented physics-based analytical channel thermal noise model and then we investigated the physical origin of the channel thermal noise by comparing MOSFETs with different channel lengths.

2. Analysis of the Channel Thermal Noise Origin

Commonly used noise models[3-5] results in significant under-estimation of channel thermal noise because they neglected short-channel effects. The current noise source and propagation equation which take into account the channel length modulation, velocity saturation and carrier heating effect are needed to investigate the channel thermal noise of short-channel MOSFETs.

When a short-channel MOSFET is biased in the saturation region, the channel of the MOSFET is divided into two regions. One is the so called gradual channel region of length L_c (region I) and the other is the velocity saturation region of length $\triangle L$ (region II) as shown in Fig. 1. Since the contribution of the carriers in the velocity saturation region to the channel thermal noise is negligible[6], we will focus on the formulation of the channel thermal noise in the gradual channel region. The noise characterization involves derivation of the current noise source, $S_{in}(x)$, and propagation equation from local fluctuations to the output port, $A(x)$. Then the current noise power at the drain electrode can be expressed as

$$S_{id}(x) = |A(x)|^2 \cdot S_{in}(x) \qquad (1)$$

The total channel thermal noise is obtained by integrating (1) over all channel region I. The current noise source can be derived as

$$S_{in}(x) = 4 \cdot q \cdot D_n \cdot (-Q_I'(x)) \cdot \frac{W}{\Delta x} = 4kT_c \cdot \frac{(-Q_I'(x)) \cdot W \cdot \mu_n'(x)}{\Delta x} \qquad (2)$$

where D_n is the noise diffusion coefficient, W is the width of the channel, q is the electronic charge, $Q_I'(x)$ is the inversion charge per unit area, T_c is carrier temperature, and $\mu_n'(x)$ is ac mobility. Note that noise source where velocity saturation effect plays a role should be derived by using ac mobility concept[7,8]. Transfer equation including velocity saturation effect is calculated as following.

$$A(x) = \frac{\Delta i_{dn}}{\Delta i_n} = -\frac{\Delta x}{L + V_{DS}/E_c} \cdot \left(1 + E(x)/E_c\right) \qquad (3)$$

where $E(x)$ is the electric field along the channel, and E_c is the critical electric field. The total channel thermal noise is acquired by using eqs. (1)-(3) and the result is compared with measured data in Fig. 2. The predicted channel thermal noise shows excellent agreement with measurements from long channel to short channel MOSFET, which verifies the validity of the model.

Fig. 3 shows the spatial distribution of $S_{in}(x)$, $A(x)$, and $S_{id}(x)$ of a short-channel MOSFET and the great part of the channel thermal noise originates close to the source junction. This phenomenon represents that the effect of spatial distribution of noise source which is dependent on the inversion charge, $Q_I'(x)$, is more dominant than the effect of spatial distribution of propagation which is dependent on the electric field, $E(x)$.

Fig. 4 shows the spatial distribution of $S_{id}(x)$ of MOSFETs with different channel lengths. Higher $S_{id}(x)$ level of shorter channel devices can be explained as $A(x)$ is much stronger in shorter channel devices due to higher $E(x)$ although all devices have a similar magnitude of $S_{in}(x)$ as shown in Fig. 5.

Fig. 5 shows the normalized spatial distribution of $S_{in}(x)$, $A(x)$, and $S_{id}(x)$ with various channel lengths. As the channel length becomes longer, the channel thermal noise near the source junction is greater as shown in Fig. 5. The lateral position dependency of the propagation, $A(x)$, becomes weaker in long-channel device since the smaller $E(x)$ in the longer channel devices makes $E(x)/E_c \approx 0$ in eq. (3). Simultaneously, current noise source is more localized near the source junction in a long-channel device.

3. Conclusions

In this work, the spatial distribution of channel thermal noise is analyzed by using equations for current noise source and its propagation which take into account short channel effects such as velocity saturation and carrier heating effect. The channel thermal noise is dominated by the source-side contributions in the gradual channel region. We compared characteristics of the channel thermal noise with different channel length MOSFETs.

Acknowledgements

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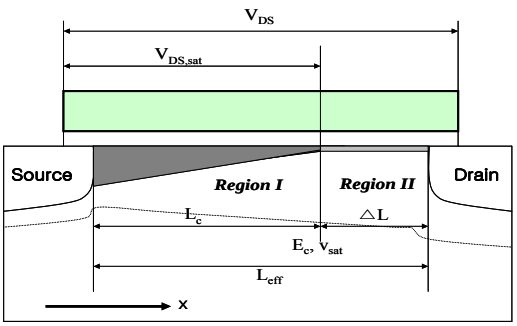


Fig. 1. The channel region of MOSFET in saturation mode.

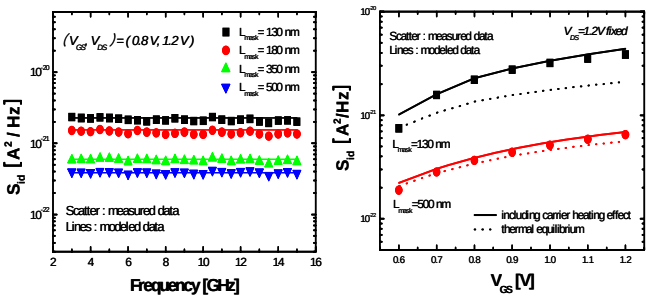
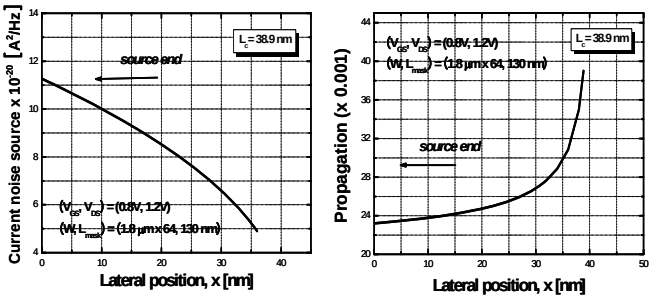


Fig. 2. Measured and modeled channel thermal noise. These show the validity of derived equations, (2) and (3).



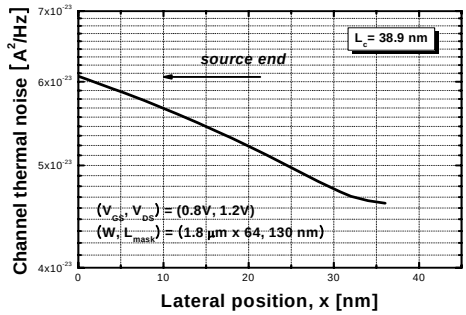


Fig. 3. Spatial distribution of $S_{in}(x)$, $A(x)$, and $S_{id}(x)$ for 130nm channel length MOS transistor.

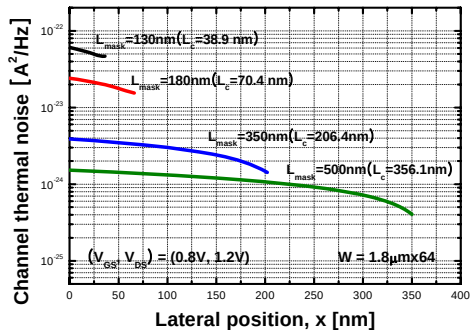


Fig. 4. Spatial distribution of channel thermal noise, $S_{id}(x)$, for MOSFETs with different channel lengths.

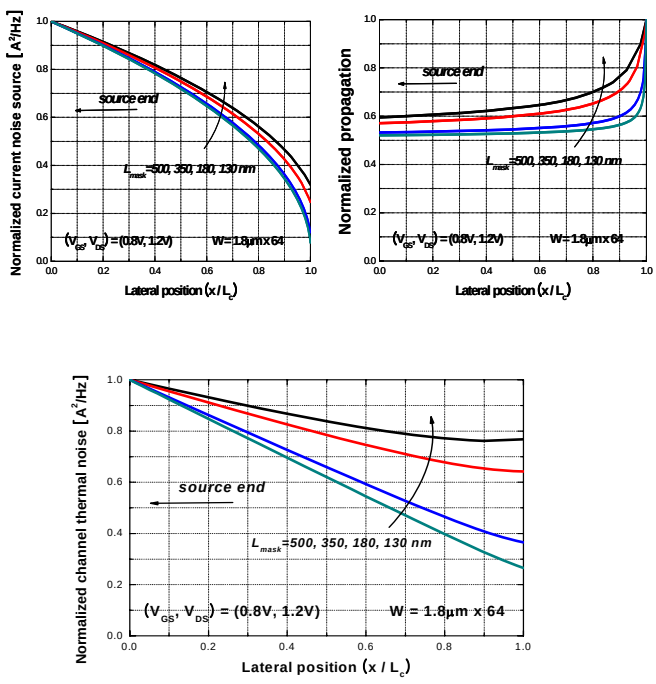


Fig. 5. Normalized spatial distribution of $S_{in}(x)$, $A(x)$, and $S_{id}(x)$ for MOS transistors with different gate lengths.