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Origin of Enhanced Thermal Noise for 100nm-MOSFETs

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1. Introduction

The thermal noise (TN) increases in importance as RF application of MOSFETs is becoming realistic. However, to achieve accurate measurement is still a serious task, and thus to realize its accurate modeling is an urgent task for accurate simulation of RF-circuits. Our aim is to determine the origin of observed TN enhancement, and to develop a reliable model based on this origin, which can be even used for testing and supplementing measurements.

The thermal noise is independent of applied frequency. Thus the Nyquist theorem describes the spectral intensity of the TN current ($S_{\rm id}$) of a MOSFET at temperature T [1, 2] by

$$S_{\rm id} = 4kT \int g_{\rm ds}(y)dy = 4kTg_{\rm ds0}\gamma \qquad (1)$$

where k, $g_{\rm ds}(y)$, $g_{\rm ds0}$, γ are Boltzmann's constant, position dependent channel conductance, channel conductance at $V_{\rm ds}$=0, and noise coefficient, respectively. Origin of TN is attributed to the carrier fluctuation in a time interval. The Nyquist theorem predicts that γ varies from 1 to 2/3 as a function of $V_{\rm ds}$ for long-channel transistors as shown in Fig. 1 schematically. This prediction has been proved experimentally for long-channel transistors. For short-channel transistors, Knoblinger et al. measured much larger γ than 2/3, even more than 3 in the saturation region [3], and explained this result by hot electrons [4]. Jamal Deen et al. have measured smaller values than Knoblinger, and modeled $S_{\rm id}$ only with the effective channel length ($L_{\rm eff}$) considering the channel length modulation as shown in Fig. 2 [5]. Their result shows a monotonically increasing γ characteristics as a function of $V_{\rm ds}$ for the gate length ($L_{\rm g}$) of 0.18μm, similar to the Knoblinger result. Recently, Scholten et al. measured that γ for $L_{\rm g}$=0.18μm is about 1 in the saturation region [6]. They explained the enhanced γ by the velocity saturation. However, detailed description of the model is not given.

2. Theoretical Investigation

We followed the Nyquist theory given in Eq. (1). For the $g_{\rm ds}$ description we applied HiSIM, a circuit simulation model based on the drift-diffusion approximation [7], which makes the $g_{\rm ds}$ description valid for any bias conditions. The final TN description is verified by calculated γ, which should give an universal relationship without varying from technology to technology. Fig. 3 shows the calculation result including both previously proposed explanation, the velocity saturation [6] and the channel-length modulation but with a constant mobility [5] by symbols. Calculated γ characteristics are nearly the same for all gate lengths, and expected γ increase is not obtained. From this fact a conclusion is derived that the previous explanations are not sufficient and the origin of the enhanced TN is missing in the modeling.

We have extended the TN description including the channel-position dependence of all physical quantities such as mobility and carrier concentration. The final equation is a function of surface potentials at source & drain sides and their derivatives. Calculated γ with this model is also depicted in Fig. 3 and shows the expected behavior. Thus the reason of the γ increase for short-channel MOSFETs is attributed to the position dependence of physical device quantities, which can be reduced to the surface potential distribution along the channel. The basis of the Nyquist theorem is the carrier fluctuation by scattering, and this is enhanced by the potential increase along the channel. HiSIM distinguishes potential values at source & drain sides, which allows to include the potential gradient in a consistent way, and thus to model the enhanced TN of short-channel MOSFETs correctly.

3. Calculation Results

Calculated TN characteristics are compared with the Scholten measurements in Fig. 4. Required model parameters for the calculation were extracted from measured current-voltage characteristics with a normal parameter extraction. Without any fitting parameter good agreement can be achieved for any channel length and any bias conditions. This concludes that the TN characteristics are determined only by the carrier transport in the channel, and the origin of the carrier transport is the potential difference along the channel. The difference between TN and other device characteristics such as the drain current is that the gradient itself, namely $g_{\rm ds}$, determines the TN characteristics. Fig. 5 shows the γ characteristics as a function of $V_{\rm ds}$. By reducing $L_{\rm g}$, γ increases, but not so drastic as reported previously [3]. It is also seen that γ for short $L_{\rm g}$ length reduces in the liner region, and starts to increase as $V_{\rm ds}$ enters the saturation condition, causing steep potential increase in the channel. The minimum of γ becomes larger than 2/3 as reduction of $L_{\rm g}$ is further continued.

4. Conclusion

We found that the enhancement of TN for short-channel MOSFETs is caused by the potential gradient in the channel. A model developed on the basis of this concept reproduces measured noise characteristics without any fitting parameter. This provides the possibility to even predict noise characteristics for accurate circuit simulation.

References

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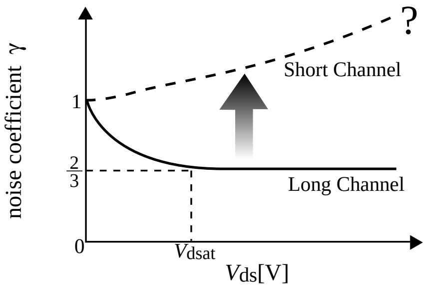

Figure 1: Schematic of noise coefficient γ as a function of $V_{\rm ds}$ for a long channel MOSFET. The dashed line showes that given in [4].

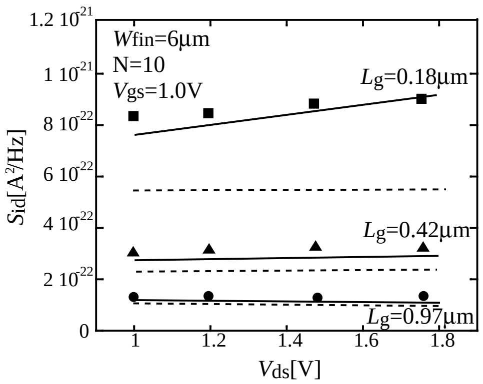

Figure 2: Comparison of measured thermal noise current (symbols) with calculated results as a function of $V_{\rm ds}$ given in [5] : with the channel length modulation (solid lines) and without the channel length modulation (dashed lines).

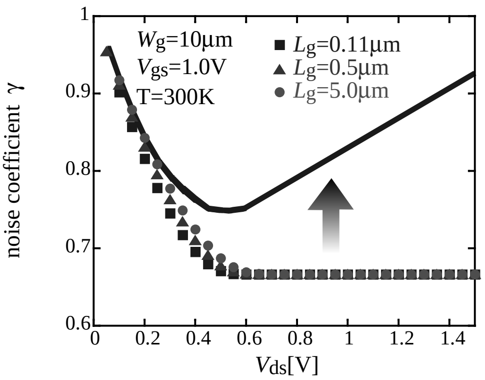

Figure 3: Calculated noise coefficient γ with a constant mobility μ (symbols) and that considering the channel-position dependence of μ and other device parameters (solid line) for a short channel.

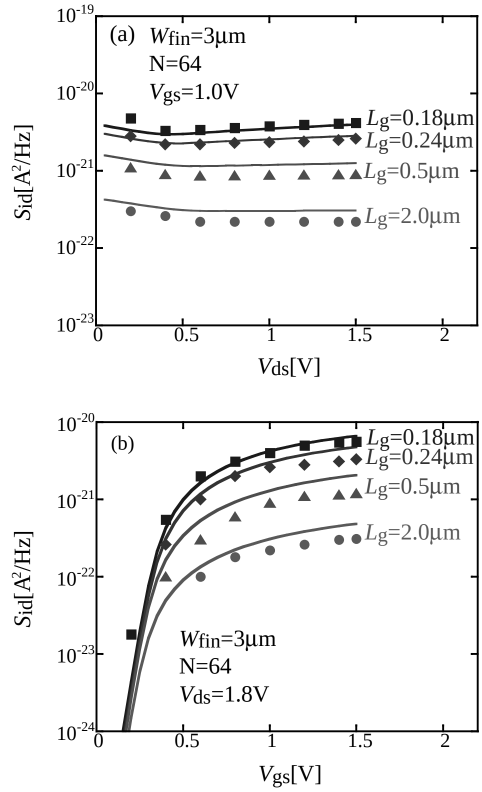

Figure 4: Calculated thermal noise current characteristics with the developed model (solid lines) compared with measurements (symbols) given in [6], (a) as a function of $V_{\rm ds}$ and (b) as a function $V_{\rm gs}$.

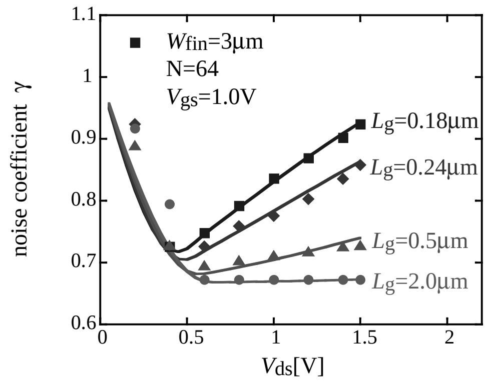

Figure 5: Calculated noise coefficient γ with the developed model as a function of $V_{\rm ds}$ (solid lines) compared with the transformed Scholten measurements into γ, where the $g_{\rm ds0}$ values are selected so that γ is unity at $V_{\rm ds}$=0.