$1/f$ and Non-$1/f$ Low Frequency Noise Measurements and their Modeling with HiSIM

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1 Introduction

Shortcomings of existing $1/f$ noise models for circuit simulations are that they can hardly reproduce the strong gate length (L_g) dependence as well as the complicated bias dependence with a single model-parameter set. The measured $1/f$ noise was found to exhibit the large increase of noise by reducing the gate length, which is stronger channel length dependent than predicted by the conventional $1/LW$ linear relationship [1]. Thus, our objective is to develop the $1/f$ noise model for circuit simulation valid for all gate lengths and bias conditions with a single parameter set.

2 Analysis of Measured $1/f$ and Non-$1/f$ Low Frequency Noise Characteristics

The $1/f$ noise spectrum is obtained by assuming uniform trap density and energy distribution in the gate oxide layer [2]. Figs. 1a and 1b show measured noise spectra under the linear and saturation conditions, respectively. The measurements with exchanged source (forward) and drain (backward) contacts are compared in the figures. The carrier density distribution along the channel is schematically depicted for each condition. Under the linear condition the difference in the noise spectra between the forward and backward measurement is hardly observable. On the contrary, the difference becomes clear under the saturation condition. However, no difference is observed in the measured drain current by the exchange.

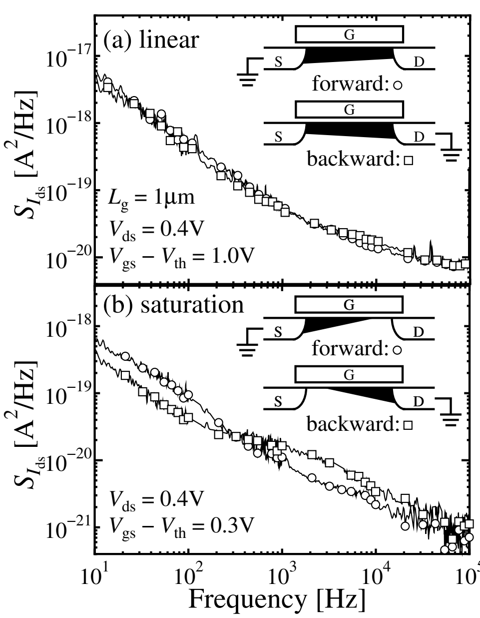

Fig. 1: Comparison of $S_{I_{ds}}$ between forward measurement and backward measurement under (a) linear and (b) saturation condition for $L_g = 1.0\mu$m. The insets show schematics of the inversion charge distribution in the forward and backward measurement.

From the measurements, the $1/f$ noise and the Lorentzian noise components are extracted as shown in Figs. 2a and 2b. The measured Lorentzian noise is reproduced with three different trap features. The noise spectrum S_1 is due to a uniform trap site of the depth direction in the oxide layer, which is the origin of the $1/f$ noise spectrum, and the its feature is kept the same between the forward and the backward measurements.

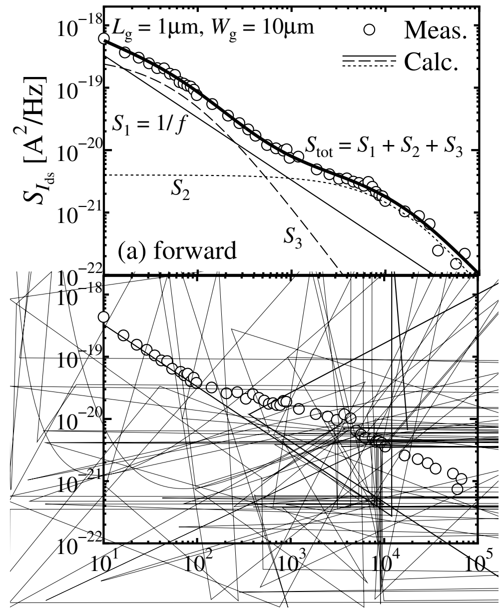

Fig. 2: (a) Comparison of measured (open symbols) and calculated (solid curves) drain current noise under the saturation condition for $L_g = 1.0\mu$m. (b) The same comparison as (a) but the source and drain are exchanged.

The above investigation proved that the non-$1/f$ noise is due to the non-uniform trap density. Thus, by averaging the noise spectra over chips on a wafer, it is expected that the noise reduces to the $1/f$ characteristics [3]. Fig. 3 shows measured noise spectra of about 30 different chips on a wafer for $L_g = 0.46\mu$m. The average of all these noise spectra exhibits really the $1/f$ noise characteristics as shown by a thick line. This concludes that trap sites causing the Lorentzian noise spectra distribute randomly on a wafer. Thus as a circuit-simulation model it is a subject to describe only this averaged $1/f$ noise characteristics with boundaries as the worst and the best case.

3 Model Description and Results

The general description for the $1/f$ noise power spectrum density of a MOSFET ($S_{I_{ds}}$) [2, 4] is obtained by integration of the inversion-charge density ($N(x)$) along the channel direction x. To develop an precise $1/f$ noise model, therefore, not only the current I_{ds} itself, but also

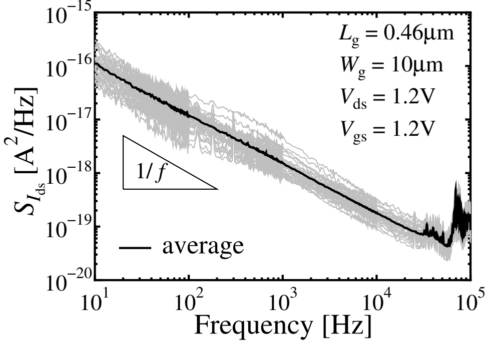

Fig. 3: Measured drain current noise spectra of about 30 devices with the same size under the same bias condition on a wafer. The fat curve represents an averaged noise spectrum.

the position dependent carrier concentration $N(x)$ is necessary. Our new $1/f$ noise model is linked with the circuit simulation model HiSIM [5], based on the drift-diffusion approximation. HiSIM provides the carrier concentrations at the source N_0 and drain side N_L determined by surface potentials consistently. In order to perform the integration analytically an assumption is applied. Namely, $N(x)$ is linearly decreasing from N_0 to N_L.

The final analytical equation of the $1/f$ noise, valid for all bias conditions, is derived

$$S_{I_{\rm ds}}(f) = \frac{I_{\rm ds}^2 N_{\rm trap} kT}{(L-\Delta L)Wqf}\left\{\frac{1}{(N_0+N^*)(N_L+N^*)} + \frac{2\alpha v}{N_L - N_0}\log\left(\frac{N_L+N^*}{N_0+N^*}\right) + (\alpha v)^2\right\} \quad (1)$$

$$N^* = \frac{kT}{q^2}(C_{\rm ox} + C_{\rm dep} + C_{\rm it}) \quad (2)$$

In Eq. (1) the mobility μ, conventionally applied, is replaced by velocity v. The reason is that the field increase along the channel has to be considered together with the mobility distribution.

Fig. 4 shows the measured $V_{\rm gs}$ dependence of $S_{I_{\rm ds}}$ of n-MOSFETs for $L_{\rm g}$ = 1.0, 0.46 and 0.12μm at f = 100Hz by symbols. All measured points are average values over 30 samples on a wafer. Calculated results with our model are also shown by solid curves. It is seen that the bias dependences of the noise characteristics for all channel lengths are well reproduced with a single model-parameter set. Among three model parameters ($N_{\rm trap}$, α, $C_{\rm it}$), two parameters (α and $C_{\rm it}$) were extracted to be negligibly small. And only $L_{\rm g}$ independent $N_{\rm trap}$ is responsible for the measured $1/f$ characteristics.

The dotted curves in Fig. 4 are calculated results with averaged $N(x)$ in the channel ($N_{\rm ave}$) conventionally adopted:

$$S_{I_{\rm ds}}(f) = \frac{I_{\rm ds}^2 N_{\rm trap} kT}{(L-\Delta L)Wqf}\left\{\frac{1}{N_{\rm ave}+N^*} + (\alpha v)\right\}^2 \quad (3)$$

It is seen that the results with $N_{\rm ave}$ cannot reproduce the bias dependences of the $S_{I_{\rm ds}}$ for all channel lengths with a single model-parameter set. Especially the noise enhancement for larger $V_{\rm ds}$ is not well reproduced. Thus, we can conclude that the position dependence of the carrier concentration plays an important role for the $1/f$ noise characteristics.

4 Conclusion

We have demonstrated that the non-$1/f$ noise characteristic is caused the inhomogeneous trap density distribution along the channel. Averaged noise spectra on a wafer reduces to the $1/f$ characteristic. The developed $1/f$ noise model for circuit simulation based on the drift-diffusion approximation, reproduces the bias and $L_{\rm g}$ dependence of the averaged noise spectrum with only three model parameters, practically only one model parameter responsible for the measured $1/f$ characteristics.

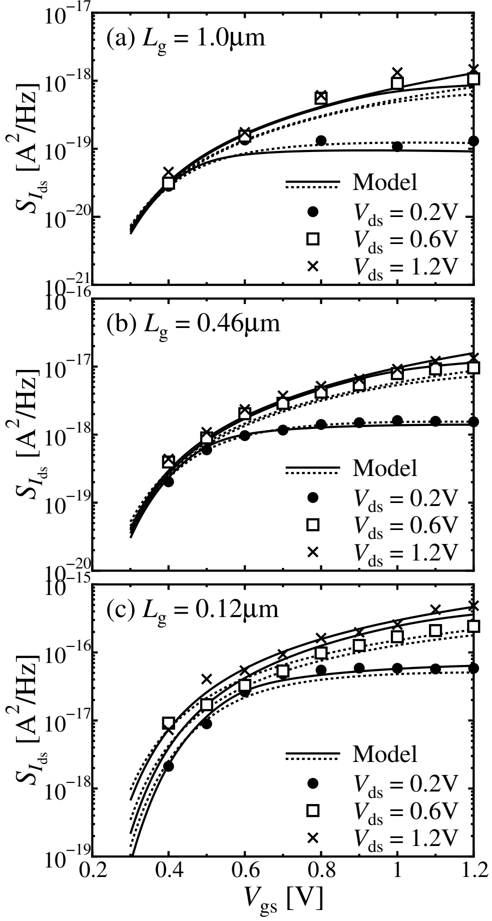

Fig. 4: Comparison of the $V_{\rm gs}$ dependence of the measured and simulated drain current noise by our model for (a) $L_{\rm g}$ = 1.0μm, (b) 0.46μm and (c) 0.12μm at frequency 100Hz. Model parameter values are the same for all $L_{\rm g}$ values. Dotted curves represent calculated results with $N_{\rm ave}$ instead of N_0 and N_L.

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