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Influence of Velocity Overshoot on Transport Noise in 0.1-μm MOSFETs

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1.Introduction

MOSFET miniaturization is going beyond the feature size of 100nm (in the laboratory) [1-2]. The conventional approach to MOSFET scaling is based on the empirical scaling rule. However, the signal to noise ratio (dynamic range) degrades as the supply voltage is lowered with down-scaling. In this paper, we theoretically derive carrier-density-fluctuation-induced high-frequency transport noise using a drift-diffusion model and examine noise characteristics in sub-100nm MOSFETs. In addition, we discuss the influence of the velocity overshoot effect (VOE) on transport noise in anticipated short-channel devices.

2.Theorical basis

We consider the carrier-density fluctuation (CDF) in a short-channel nMOSFET being operated in the linear drain current (I_D) region. It is assumed that dc drain current consists of drift current (I_{drift}) and diffusion current (I_{diff}), and that it satisfies the current continuity condition. Under this assumption, we derive a partial-differential equation (eq.(1)) for CDF from the charge-density-conservation equation in one dimension;

$$\partial \delta n/\partial t = D_n(\partial^2 \delta n/\partial x^2) - v_d (\partial \delta n/\partial x) - \delta n/\tau^*, \qquad (1)$$

$$1/\tau^* = 1/\tau - (\partial v_d/\partial x). \qquad (2)$$

D_n is the diffusion constant, v_d is the drift velocity, δn is the CDF, τ is the relaxation time for CDF in the quasi-thermal equilibrium condition, and τ^* is the effective relaxation time of fluctuation. Sumino studied the transport noise by using a partial-differential equation that omitted I_{diff} [3]. In order to consider a more accurate carrier transport phenomena, we analyze the transport noise by using a partial-differential equation (eq.(1)) that includes I_{drift} and I_{diff}.

We solve eq. (1) by using Fourier expansion ($\delta n_m(x)$) based on the conventional Langevin method [4]. Here, we consider the medium-field operation of a MOSFET; that is, $V_D < E_C L$, where L is the channel length, V_D is the drain voltage, E_C is the critical electric field defined as v_s/μ_{eff}, v_s is the saturation velocity, and μ_{eff} is the effective mobility. Under this condition, CDF ($\delta n_m(x)$) is given by the superposition of forward ($\delta n_1(x)$) and backward waves ($\delta n_2(x)$); that is, $\delta n_m = \delta n_1 + \delta n_2$. The Wiener-Khintchine theorem [4] gives us the self-correlation function of CDF ($<\delta n_m \delta n_m^*>$). In addition, $<\delta n_m \delta n_m^*>$ can be expressed as $|\delta n_{mo}|^2\ T(f, V_D, V_G)$, where f is the frequency, V_G is the gate voltage, and $|\delta n_{mo}|^2$ is the power source of fluctuation; the function $T(f, V_D, V_G)$ represents modulation of the fluctuation source which is characterized by carrier transport.

The relation between the drain-current noise and CDF should also be discussed because the drain current noise characteristics, not CDF, are directly observed in MOSFETs. By following the approach of [4], which is based on the quasi-thermal equilibrium approximation, we can obtain an approximation of the spectral density of drain current noise, $S_{ID}(f)$, including the transport effect ($T(f, V_D, V_G)$).

3. Simulation results and discussion

The device parameters used in the simulations are summarized in Table. 1. Figure 1 shows the normalized CDF power (= $T(f, V_D, V_G)$) at f = 1 GHz as a function of the normalized drain voltage (V_D/V_{DSAT}). Here, V_{DSAT} is the drain saturation voltage. Figure 1 compares two cases: a very small D_n value, and a normal D_n value. The former corresponds to the case in which the contribution of I_{diff} is effectively neglected [3]. When the I_{diff} component is taken into account, the fluctuation power is suppressed because the CDF consisting of the forward wave and the backward wave results in wave interference. Figure 2 shows the normalized drain current noise spectral density ($S_{ID}/(|\delta n_{mo}|^2 I_D^2)$) as a function of V_D/V_{DSAT}. When the I_{diff} component is effectively neglected, it can be seen that $S_{ID}/(|\delta n_{mo}|^2 I_D^2)$ is overestimated in comparison to the case with the normal I_{diff} component. Thus evaluating S_{ID}(f) accurately demands that we take into account the I_{diff} component.

Figure 3 shows $S_{ID}/(|\delta n_{mo}|^2 I_D^2)$ as a function of V_D/V_{DSAT} for various L values ranging from 0.1 to 1.0 μm. Here, only L is varied and the other device parameters are fixed at those suitable for a 0.1 μm channel device. For all L values, $S_{ID}/(|\delta n_{mo}|^2 I_D^2)$ is almost independent of V_D/V_{DSAT} at low V_D values (V_D/V_{DSAT} < 0.1) because $T(f, V_D, V_G)$ is suppressed by the interference of the forward and backward components of CDF (see Fig. 2). For L = 0.5 or 1.0 μm, $S_{ID}/(|\delta n_{mo}|^2 I_D^2)$ is proportional to $V_D^{0.5}$ at high V_D values (V_D/V_{DSAT} > 0.1). As V_D increases, the dc channel conductance ($\partial I_D/\partial V_D$) decreases, which leads to the saturation of I_D. Consequently, $S_{ID}/(|\delta n_{mo}|^2 I_D^2)$ increases with V_D. For L = 0.1 μm, however, $S_{ID}/(|\delta n_{mo}|^2 I_D^2)$ is in proportion to $V_D^{0.3}$ at high V_D values. When V_D exceeds a certain value, $S_{ID}/(|\delta n_{mo}|^2 I_D^2)$ decreases. When L decreases, the effective mobility decreases because of an increase in the longitudinal electric field. Compared to a long channel device, the drain current noise spectral density is relatively suppressed. When V_D/V_{DSAT} exceeds the certain value, the transport efficiency ($\exp(-L/L_n^*)$) of the CDF power decreases; $T(f, V_D, V_G)$ decreases, and then $S_{ID}/(|\delta n_{mo}|^2 I_D^2)$ decreases. L_n^* represents the characteristic length of the spatial relaxation of CDF.

Since short-channel MOSFETs, sub-0.1-μm channels, should manifest the velocity overshoot effect (VOE) [5], we must discuss the influence of VOE on $S_{ID}(f)$. Here, we consider VOE when calculating S_{ID} by increasing the low-field mobility (μ_o = 700 cm^2/Vs → 900 cm^2/Vs) and the saturation velocity (v_s = 1.0×10^7 cm/s → 3.0×10^7 cm/s). D_n increases with μ_o because D_n is derived from Einstein's relation; D_n = 18 cm^2/s → 23 cm^2/s. Figure 4 shows simulated $S_{ID}/(|\delta n_{mo}|^2 I_D^2)$ for L = 0.1 µm as a function of V_D/V_{DSAT}. It can be seen in Fig. 4 that VOE enhances $S_{ID}/(|\delta n_{mo}|^2 I_D^2)$ at high V_D values. Since VOE raises the channel conductance and L^*_n, $S_{ID}/(|\delta n_{mo}|^2 I_D^2)$ increases (relatively) when VOE is significant. Consequently, we can suggest that the drain current noise spectral density stemming from CDF is significant in sub-0.1 µm MOSFETs.

4.Summary

This paper described theoretical simulation results of carrier-density-fluctuation-induced high-frequency transport noise in short-channel MOSFETs. When the diffusion current component of the drain current is taken into account when calculating the carrier-density fluctuation power, it has been shown that the transferred fluctuation power is reduced. It is predicted that sub-0.1-µm channel devices will suffer enhanced drain current noise if the velocity overshoot effect is significant.

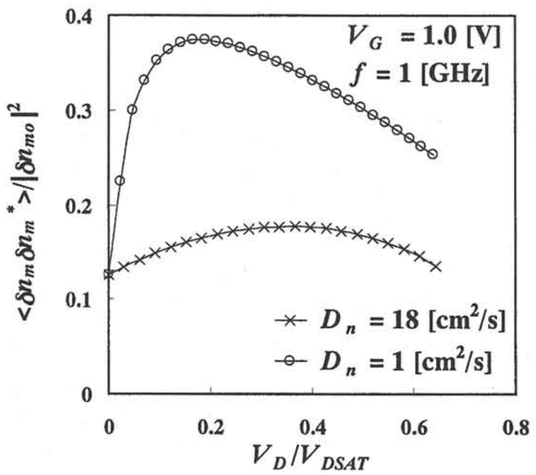

Fig.1. The normalized CDF power as a function of V_D/V_{DSAT} ; L = 0.1 µm.

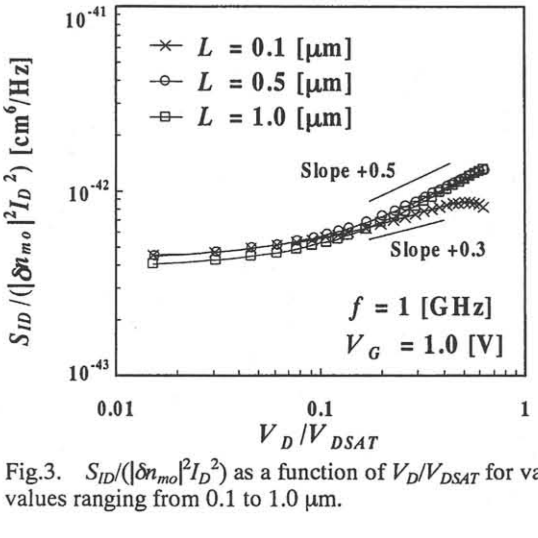

Fig.3. $S_{ID}/(|\delta n_{mo}|^2 I_D^2)$ as a function of V_D/V_{DSAT} for various L values ranging from 0.1 to 1.0 µm.

Acknowledgement

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Table. 1. Device parameters in simulations

Parameters	Values
Channel length (L)	0.1 (µm)
Gate oxide thickness (t_{ox})	2 (nm)
Acceptor concentration of substrate (N_A)	10^{18} (cm^{-3})
Donor concentration of source and drain (N_D)	10^{20} (cm^{-3})
Low-field mobility (μ_o)	700 (cm^2/Vs)
Saturation velocity (v_s)	10^7 (cm/s)
Relaxation time for carrier-density fluctuation in quasi-thermal equilibrium condition (τ)	10^{-3} (s)

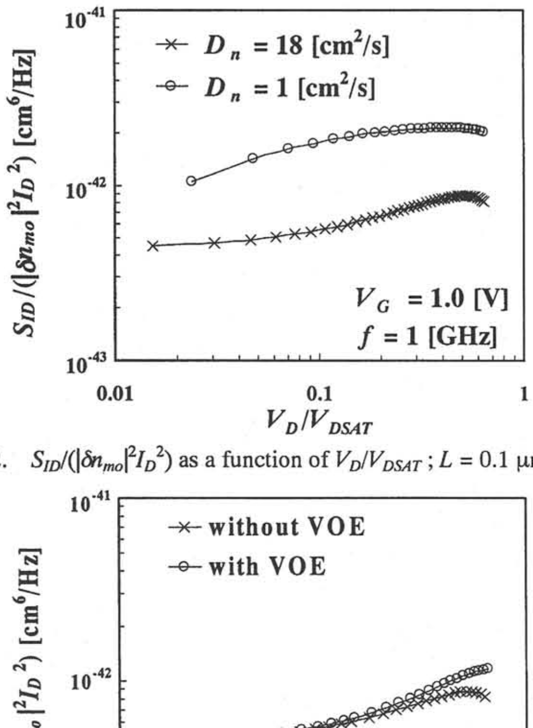

Fig.2. $S_{ID}/(|\delta n_{mo}|^2 I_D^2)$ as a function of V_D/V_{DSAT} ; L = 0.1 µm.

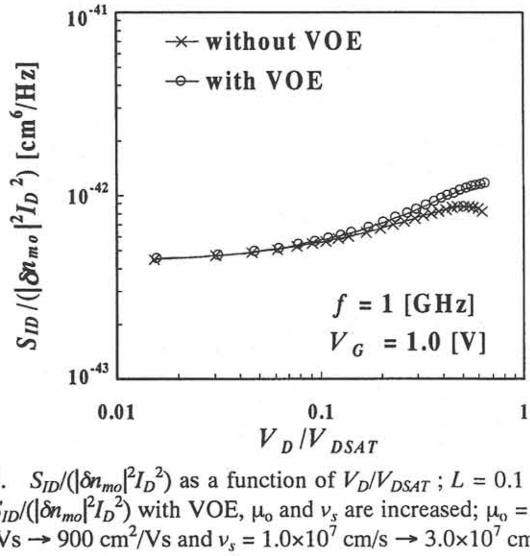

Fig.4. $S_{ID}/(|\delta n_{mo}|^2 I_D^2)$ as a function of V_D/V_{DSAT} ; L = 0.1 µm. For $S_{ID}/(|\delta n_{mo}|^2 I_D^2)$ with VOE, μ_o and v_s are increased; μ_o = 700 cm^2/Vs → 900 cm^2/Vs and v_s = 1.0×10^7 cm/s → 3.0×10^7 cm/s.