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Significant Impact of Transport Noise Enhancement in Scaled-Down MOSFET's

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1. Introduction

MOSFET miniaturization is going beyond the feature size of 0.1 μm (in the laboratory) [1-3]. 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. This paper describes a theoretical approach to understand the impact of carrier-density-fluctuation-induced high-frequency transport noise in scaled-down MOSFET's.

2. Theory

We considers the carrier-density fluctuation in an n-channel MOSFET being operated in the linear region of drain current. It is assumed that the channel current is mainly ruled by the drift current component ($J = env_d$) and that the dc drift current component (J_o) satisfies the current continuity condition ($\partial J_o/\partial x = 0$). Under these assumptions, we derive the partial-differential equation for the carrier-density fluctuation from the charge-density conservation equation in one dimension [4];

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

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

where v_d is the drift velocity, n_o is the averaged carrier density, τ is the relaxation time for carrier-density fluctuation in the quasi-thermal equilibrium condition and τ^* is the effective relaxation time of fluctuation. van Vliet and Fassett [5] studied the transport noise by using a partial-differential equation similar to eq. (1) without the second term in the right-hand side of eq. (2). As found in eq. (2) our theory is still applicable to a high drain-to-source electric field regime because it takes account of the current continuity.

We introduce Fourier expansion on the basis of the conventional Langevin's method [6] and obtain thus the solution of eq. (1) ($\delta n_m(x)$). In addition, Wiener-Khintchine theorem gives us the spatial self-correlation function of carrier-density fluctuation ($<\delta n_m \delta n_m^*>$) [6]. We consider the medium-field operation of MOSFET; that is, $V_D < F_cL$. Here, V_D is the drain voltage, F_c is the critical electric field defined as v_s/μ_{oo}, v_s is the saturation velocity and μ_{oo} is the low-field mobility. Under this condition, $<\delta n_m \delta n_m^*>$ is obtained as $|\delta n_{mo}|^2$ f(f, V_D, V_G) where f is the fluctuation frequency, V_G is the gate voltage, $|\delta n_{mo}|^2$ is the power source of fluctuation and the function f(f, V_D, V_G) is yields the modulation of fluctuation source by the carrier transport phenomena. In this paper, we discuss f(f, V_D, V_G) obtained with the above approach.

The relation between drain current noise and carrier-density fluctuation should be also discussed because drain current noise characteristics, not carrier-density fluctuation characteristics, are directly measured in actual MOSFET's. Following the past approach of [6], which is on the basis of the quasi-thermal equilibrium approximation, the spectral density of drain current noise ($S_{ID}(f)$) including the transport effect f(f, V_D, V_G) can be approximately obtained.

3. Simulation Results and Discussion

Since MOSFET's are historically scaled down on the basis of $1/\sqrt{K}$ law (K is the scaling factor) for the supply voltage, $1/\sqrt{K}$ law scaling is only considered hereafter. Initial parameters of a 1.0 μm channel device are listed in Table 1. The normalized carrier-density fluctuation power (the function f(f, V_D, V_G)) is shown in Fig. 1 as a function of $1/\sqrt{K}$ in the frequency range 120 MHz to 3.0 GHz. The fluctuation power is almost independent of K at frequencies under 600 MHz, while it monotonously increases above 600 MHz. The carrier transit time ($T^* = L/v_d$, where L is the channel length), from source to drain, decreases as K increases. Since we consider the condition of $V_G - V_{TH} >> V_D$, the gradient of inversion carrier density is very small along the channel. Consequently, τ^* is almost equal to τ in eq. (2), and the carrier transit time to effective fluctuation relaxation time ratio (T^*/τ^*) is in proportion to T^*. The reduction in T^* due to down-scaling suppresses the averaging effect of fluctuation power, resulting in enhancement of the fluctuation power as K increases.

The normalized fluctuation power enhancement in the high frequency range in scaled-down MOSFET's must be observed at the drain terminal if the device operates in RF region; the high-frequency noise component increases when short channel devices are used in circuits.

The dependence of $S_{ID}(f)/|\delta n_{mo}|^2$ on scaled drain voltage ($V_D/\sqrt{K}$) is shown in Fig. 2 for two devices (one with 1.0 μm and another 0.1 μm channel) in the frequency range 120 MHz to 15 GHz. For the two devices, $S_{ID}(f)/|\delta n_{mo}|^2$ is in proportion to V_D^2 in the low V_D range at low frequencies, which is the same as the result in quasi-thermal equilibrium condition [6], while $S_{ID}(f)/|\delta n_{mo}|^2$ is in proportion to $V_D^{1.5}$ in a high V_D range at low frequencies; the increase rate of $S_{ID}(f)/|\delta n_{mo}|^2$ is suppressed in the high V_D range. When V_D increases, both T^* and τ^* decrease because of increase of the drift velocity gradient along the channel. Since T^*/τ^* also increases with V_D, the averaging of carrier-density fluctuation is promoted (f(f, V_D, V_G) decreases) [4]; the carrier transport process suppresses drain current noise.

For the 0.1 μm channel device, the dependence of $S_{ID}(f)/|\delta n_{mo}|^2$ on scaled drain voltage is almost independent of the frequency in the frequency range 120 MHz to 15 GHz. For the 1.0 μm channel device, on the other hand, $S_{ID}(f)/|\delta n_{mo}|^2$ in the high frequency range oscillates as a function of V_D. The difference in the behavior of $S_{ID}(f)/|\delta n_{mo}|^2$ stems from the difference in T^*. When the device size is scaled up, T^* increases. For the 1.0 μm channel device, T^* is of the order of about 10^{-9} seconds and the condition of $\omega T^* > 1$ (ω is the angular frequency of fluctuation) is achieved at frequencies more than 3.0 GHz. When $(\pi/\omega)(2n-1) = T^*$ (n = 1, 2...), f(f, V_D, V_G) is enhanced at the drain terminal [4]. When $(2\pi/\omega)n = T^*$ (n =1, 2...), f(f, V_D, V_G) is suppressed at the drain terminal [4]. This gives rise to $S_{ID}(f)/|\delta n_{mo}|^2$ oscillation as a function of V_D in the high frequency range for the 1.0 μm channel device.

In addition, the low-frequency component of $S_{ID}(f)/|\delta n_{mo}|^2$ for the 0.1 μm channel device is only about one order larger than that for the 1.0 μm channel device because the gate area (WL) is decreased with the increase in K and the low-frequency component of f(f, V_D, V_G) is almost independent of scaling, as seen in Fig. 1. The high-frequency component of $S_{ID}(f)/|\delta n_{mo}|^2$ for the 0.1 μm channel device is several-order larger than that for the 1.0 μm channel device because the high-frequency component of f(f, V_D, V_G) increases with K, as seen in Fig. 2. Thus, the high-frequency component of drain current noise is significant in scaled-down MOSFET's.

4. Summary

This paper theoretically examined carrier-density-fluctuation-induced high-frequency transport noise in scaled-down MOSFET's. As the scaling factor (K) increases, the high-frequency component of normalized fluctuation power is enhanced because of the decrease in the ratio of carrier transit time to effective fluctuation relaxation time (T^*/τ^*). The high-frequency component of drain current noise for the a 0.1-μm-channel device is several-order larger than that for a 1.0-μm-channel device because the high-frequency component of normalized fluctuation power is enhanced as K increases. Thus, it is anticipated that the high-frequency component of drain current noise will be significant in future scaled-down MOSFET's.

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Table 1. Initial parameters of a 1.0 μm channel device

Parameters	Values
Channel length (L) and Channel width (W)	1.0 (μm)
Gate oxide thickness (t_{ox})	20 (nm)
Acceptor concentration of substrate (N_A)	10^{17} (cm^{-3})
Donor concentration of source and drain (N_D)	10^{20} (cm^{-3})
Curvature radius of source and drain diffusion regions (x_j)	0.3 (μm)
Supply voltage (V_{DD})	5.0 (V)
Low-field mobility (μ_{oo})	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)

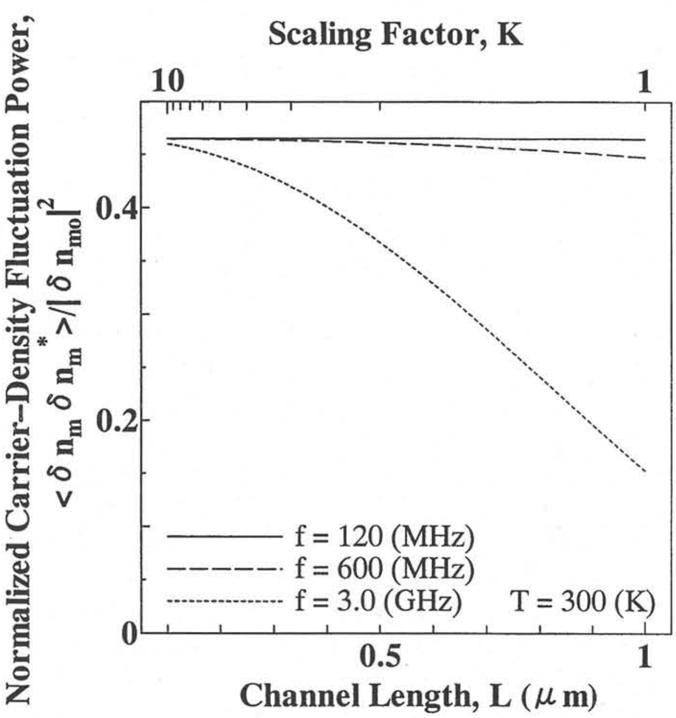

Fig. 1 Normalized carrier-density fluctuation power (the function f(f, V_D, V_G)) as a function of $1/\sqrt{K}$. For a device with a 1.0 μm channel, the gate voltage is 5.0 V, the drain voltage is 0.6 V and the threshold voltage is 0.88 V.

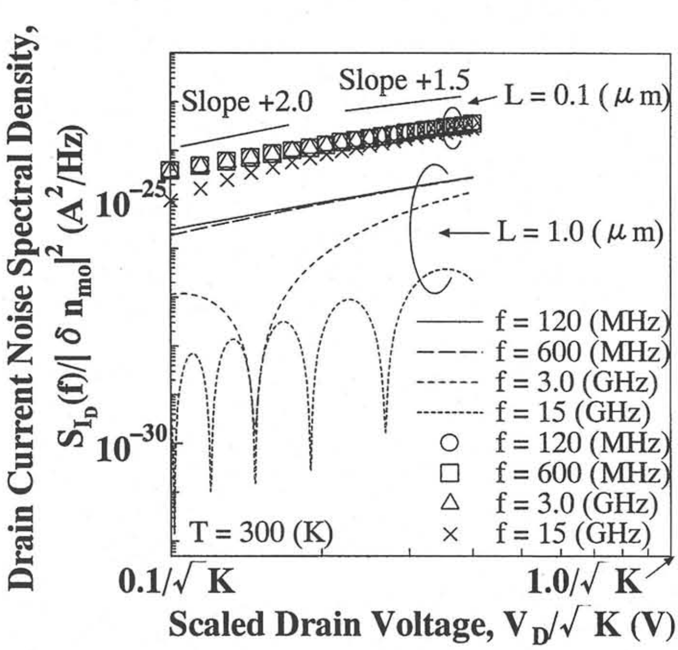

Fig. 2 Spectral density of drain current noise as a function of scaled drain voltage ($V_D/\sqrt{K}$) for two devices with a 0.1 μm or 1.0 μm channel. For the 1.0 μm channel device (K = 1.0), the $V_D/\sqrt{K}$ range is from 0.1 to 0.4 V at V_G = 5.0 V. For the 0.1 μm channel device (K = 10), the drain voltage and the gate voltage is scaled down by the factor of $\sqrt{10}$.