Semi-classical consideration of velocity overshoot effect on transport noise in short-channel MOSFETs

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Abstract

This paper examines the characteristics of transport noise created by carrier-density fluctuation in MOSFETs with various channel lengths down to 0.1 μm using a semi-classical theoretical scheme. The carrier-density fluctuation is derived from a partial differential equation on the basis of charge-density conservation. The theoretical expression for the spectral density of carrier-density fluctuation power is applied to the analysis of transport noise in a high-frequency range. At first, we discuss how the characteristics of fluctuation power are influenced by channel length. As channel length is reduced, the high frequency component of fluctuation power is enhanced, and interference between the forward and backward propagating carrier-density fluctuation power components becomes significant. Next, we discuss the spectral density of drain current noise for various channel lengths. As channel length is reduced, the spectral density increases through the increase in carrier velocity.

At short channel lengths, such as 0.1 μm, the velocity overshoot effect becomes significant. We discuss the influence of the velocity overshoot effect on drain current noise spectral density for the channel length of 0.1 μm. When the velocity overshoot effect is taken into account, the drain current noise spectral density is enhanced, and the high frequency component of drain current noise spectral density is also enhanced. It is predicted that the transport noise stemming from carrier-density fluctuation would be significant in 0.1-μm channel MOSFETs.

1. Introduction

The conventional approach to assessing MOSFET drain current noise is based on quasi-equilibrium approximation [1]. However, state-of-the-art MOSFETs now operate under very high internal electric fields and high-field phenomena play important roles in circuit operations because device dimensions are now entering the sub-micron range. In this situation, the quasi-equilibrium assumption is no longer valid. In addition, the application of MOSFET for radio frequency (RF) operation is attracting attention [2]. Unfortunately, the noise characteristics of MOSFETs in the RF regime have not been adequately examined [3,4]. The noise properties in sub-micron MOSFETs were numerically analyzed using the Boltzmann transport equation and/or a Monte Carlo technique [5,6]. With regard to theoretical approaches, van Vliet and Fansset derived transport noise from the differential equation of carrier-density fluctuation [7]. Recently, we studied the carrier-density fluctuation based on charge conservation [8], where we assumed that the channel current consists of only the drift current component. The study well explained the carrier-density-fluctuation-induced high-frequency noise in a high-field regime. However, we should not neglect the diffusion current component in a low field condition, and in short-channel MOSFETs in general.

This paper derives the carrier-density-fluctuation-induced high-frequency noise by considering the contribution of both drift and diffusion current components with a semi-classical theoretical scheme. At present, MOSFET miniaturization is going beyond the feature size of 0.1 μm [9]. In such short channel MOSFETs, non-stationary carrier transport, such as velocity overshoot effect (VOE), becomes significant [10-12]. VOE causes drain current enhancement in comparison to that predicted by simple drift-diffusion models [13]. Therefore, in the noise analysis for sub-micron MOSFETs, we must take into account the non-stationary carrier transport effects such as VOE. The carrier-density fluctuation is derived from a partial differential equation on the basis of charge-density conservation. At first, we will discuss the characteristics of transport noise for various channel lengths.

2. Theoretical Basis

2.1 Calculation of carrier-density fluctuation

We derive the carrier-density fluctuation from a partial differential equation on the basis of charge conservation. This article premises that the n-channel MOSFET is operated in the linear region of drain current. In the relaxation time approximation, the charge conservation equation for electrons in the one-dimensional model is described as

$$\frac{\partial n}{\partial t} = \frac{1}{e}\frac{\partial J}{\partial x} - \frac{n - n_0}{\tau}, \tag{1}$$

where n is the local electron density, e is the elementary charge, J is the current density, n_o is the averaged electron density in a steady state, τ is the relaxation time for the carrier-density fluctuation in a quasi-thermal equilibrium condition, the x axis is along the SiO_2/Si interface in the source-to-drain direction, and the origin of the x axis is in front of the source junction. The local electron density can be described as the sum of steady-state value and a small variation, and we can assign it as

$$n(x, t) = n_0(x) + \delta n(x, t). \tag{2}$$

In our study, for simplicity s sake, the mobility fluctuation [14, 15] and its correlation with carrier-density fluctuation are not considered for simplicity. Here, we assume that the channel current density consists of drift component (J_{drift}) and diffusion component (J_{diff}), and that the dc current density satisfies the current continuity condition ($\partial J_o / \partial x = 0$). Under these assumptions, a partial differential equation for the carrier-density fluctuation in the channel region (δn_{ch}) is obtained as

$$\frac{\partial \delta n_{ch}}{\partial t} = D_n \frac{\partial^2 \delta n_{ch}}{\partial x^2} - v_d \frac{\partial \delta n_{ch}}{\partial x} \left(\frac{1}{\tau} + \frac{\partial v_d}{\partial x}\right) \delta n_{ch}, \tag{3}$$

where D_n is the diffusion constant and v_d is the drift velocity. The effective relaxation time (τ^*) is defined with

$$\frac{1}{\tau^*} = \frac{1}{\tau} + \frac{\partial v_d}{\partial x}. \tag{4}$$

The first term in eq. (4) expresses the relaxation in quasi-thermal equilibrium condition, and it approximately corresponds to the generation-recombination process; here we assume $\tau = 10^{-3}$ sec. The second term in eq. (4) is the contribution from the non-equilibrium state, and it plays a very important role in high-field regime.

In our previous article [8], we studied transport noise by using a partial-differential equation without J_{diff} at the first step. In the present article, we analyze the transport noise by using a partial-differential equation having J_{drift} and J_{diff}, because it is necessary to take into account the J_{diff} component in order to evaluate the transport noise accurately.

We solve eq. (3) by using Fourier expansion based on the conventional Langevin method. The Fourier expansion of $\delta n(x, t)$ in eq. (2) is described as

$$\delta n(x, t) = \sum_{m=0}^{\infty} \delta n_m(x) \exp(i\omega_m t) \quad (m = 0, 1, 2, \cdots), \tag{5}$$

where ω_m is the angular frequency. Substituting eq. (5) into eq. (3), the partial-differential equation for $\delta n_{m,ch}(x)$, the Fourier component of fluctuation in the channel, is obtained as

$$i\omega_m \delta n_{m,ch} = D_n \frac{\partial^2 \delta n_{m,ch}}{\partial x^2} - v_d \frac{\partial \delta n_{m,ch}}{\partial x} - \frac{\delta n_{m,ch}}{\tau^*}. \tag{6}$$

It is not easy to solve eq. (6) because the drift velocity and the effective relaxation time, based on the current continuity condition, are complicated functions of x along the channel [16]. This study considers the low-field operation of MOSFET. So, for simplicity's sake, they can be approximately replaced with values averaged over the channel region [16]. In that case, the solution of eq. (6) is given by the following superposition of forward propagation (δn_1) and backward propagation components (δn_2).

$$\delta n_{m,ch}(x) = \delta n_1(x) + \delta n_2(x), \tag{7a}$$

$$\delta n_1(x) = C \exp[(\beta_1 - ik)x], \tag{7b}$$

$$\delta n_2(x) = D \exp[(\beta_2 + ik)x], \tag{7c}$$

where C and D are the unknown amplitudes, β_1 and β_2 are the damping factors, and k is the wave number. Since we take into account the J_{diff} component, the carrier-density fluctuation has, in addition, the backward propagation component ignored in the past article [7, 8]. This component causes the interference of carrier-density fluctuation transport.

To determine C and D, we assume the following transport process. The fluctuation source is located at x = 0, and the emitted fluctuation power is transported toward the drain terminal by carriers in the channel. At another boundary of $x = L$, where L is the channel length, the carrier-density fluctuation power is partially transferred to the drain terminal and the rest is reflected backward.

The carrier density fluctuation in the n^+ region is derived from the charge conservation equation. In the n^+ region, it is assumed that the carrier transport is mainly ruled by the diffusion process because the internal electric field is sufficiently low. Under the above consideration, a partial differential equation in the n^+ region for Fourier component of the carrier-density fluctuation, $\delta n_{m,n^+}$, is expressed as

$$i\omega_m \delta n_{m,n+} = D_{n+}\frac{\partial^2 \delta n_{m,n+}}{\partial x^2} - \frac{\delta n_{m,n+}}{\tau_{n+}}, \tag{8}$$

where D_{n^+} is the diffusion constant and τ_{n^+} is the effective relaxation time. $\delta n_{m,n^+}$ is defined with eq. (5). The solution of eq. (8) is given as

$$\delta n_{m,n+}(x) = A\exp[-(\beta_{n+} + ik_{n+})x], \tag{9}$$

where A is the amplitude, β_{n^+} is the damping factor, and k_{n^+} is the wave number. At the boundary of $x = L$, δn_m satisfies the following boundary condition;

$$\delta n_{m,ch}(L) = \delta n_{m,n+}(L), \tag{10a}$$

$$\left.\frac{\partial \delta n_{m,ch}}{\partial x}\right|_{x=L} = \left.\frac{\partial \delta n_{m,n+}}{\partial x}\right|_{x=L} \tag{10b}$$

Thus the relation between forward and backward components at $x = L$ is obtained as

$$\delta n_2(L) = \Gamma \delta n_1(L), \tag{11a}$$

$$\Gamma = \frac{\beta_1 + \beta_{n+} - i(k - k_{n+})}{\beta_2 + \beta_{n+} + i(k - k_{n+})}, \tag{11b}$$

where Γ is the ratio of δn_2 to δn_1. Assuming that the fluctuation source (δn_{mo}) is located at x = 0, the coefficients C and D are obtained as

$$C = \frac{\delta n_{mo}}{1 + \Gamma\exp[-(\beta_2 - \beta_1 + i2k)L]}, \tag{12a}$$

$$D = \frac{\delta n_{mo}}{1+\frac{1}{\Gamma}\exp\left[(\beta_2-\beta_1+i2k)L\right]}. \tag{12b}$$

Derivation of the carrier-density fluctuation power is described below.

2.2 Spectral density of carrier-density fluctuation

The Wiener-Khintchine theorem gives us the spectral density of noise. The spectral density of carrier-density fluctuation in the channel, $S_n(f)$, is defined with [1]

$$\begin{aligned} S_n(f) &= 2\int_{-\infty}^{\infty}\overline{\delta n\delta n^*}\exp(i\omega_n t)dt \\ &= 2\overline{\delta n_m\delta n_m^*}/\Delta f, \end{aligned} \tag{13}$$

where $\overline{xx^*}$ stands for time averaging, δn^* and $\delta n_m{}^*$ are the complex conjugates of δn and δn_m, respectively, and Δf is the frequency band width. To account for the fluctuation caused by carrier transport inside the channel, Δf must satisfy a certain condition: $1/\Delta f$ is much longer than the source-to-drain transit time of carriers. According to the Ergodic theorem, the time averaging in eq. (13) can be replaced with the ensemble averaging.

$$\begin{aligned} \overline{\delta n_m\delta n_m^*} &= \left\langle \delta n_m\delta n_m^*\right\rangle_x \\ &= \mathrm{Re}\left[\frac{1}{L^2}\int_0^L\int_0^x\delta n_m(x)\delta n_m^*(x')\,dx'dx\right], \end{aligned} \tag{14}$$

where <xx*> stands for the ensemble averaging. In this integration, the spatial-correlation of carrier-density fluctuation successfully reflects transport effects. Substituting eq. (7a) into eq. (14), eq. (14) is rewritten as

$$\begin{aligned} \left\langle \delta n_m\delta n_m^*\right\rangle_x &= \left\langle \delta n_1\delta n_1^*\right\rangle_x + \left\langle \delta n_2\delta n_2^*\right\rangle_x + \left\langle \delta n_1\delta n_2^*\right\rangle_x + \left\langle \delta n_2\delta n_1^*\right\rangle_x \\ &= |\delta n_{mo}|^2\, T(V_D, V_G, f), \end{aligned} \tag{15}$$

where $T(V_D, V_G, f)$ presents the modulation of the fluctuation source, which is characteristic of the carrier transport. It decomposes into 4 components as

$$T(V_D, V_G, f) = T_{11} + T_{12} + T_{21} + T_{22}, \tag{16}$$

where T_{11} and T_{22} are the modulation components obtained by the self-correlation of δn_1 and δn_2, and T_{12} and T_{21} (which are derived from the cross-correlations of δn_1 and δn_2) show the interference of δn_m. Detailed algebra is described in [16]. Consequently, we have the following expression for $Sn(f)$.

$$S_n(f) = 2|\delta n_{mo}|^2 T(V_D, V_G, f)/\Delta f. \tag{17}$$

Before derivation of spectral density of drain-current noise, we discuss availability of the present derivation of $Sn(f)$ and limitation of the present procedure. In the previous paper [8], we discussed the transport noise in MOSFET, assuming that the dc current is expressed by the drift component. The carrier transport is characterized by the drift velocity (v_d) which is the centroid velocity of carrier distribution function. In this case, the effective transit time (T_0^*) of carriers from source to drain characterized the noise behavior. Consequently, the noise spectra show beating behavior shown in ref. [8].

On the other hand, here we took into account both the drift component and the diffusion component in the dc current. It may be easily anticipated from statistical physics that the diffusion current component eliminates the monochromatic feature of fluctuation; the effective transit time simply does not characterize the noise behavior. In this sense, we think that the use of averaged drift velocity does not change the substantial physics that should be considered here, while the preciseness of fluctuation power estimation is slightly degraded. In addition, the ignorance of position dependence of the drift velocity, diffusivity and relaxation time does not eliminate significant physics in the present analysis because, as is well-known, the diffusive process in the carrier transport in itself promotes the thermalization of carrier transport.

Finally, we will address the physical meanings of eqs. (6), (7) and (15). Solutions of eq. (6) have features of forward propagation and backward propagation, as mentioned previously. Correlation function, eq. (15), expresses the interference of two propagation modes. In other words, the net energy flow of fluctuation power reflects wave mechanics, and it must follow quantum mechanical and statistical physics in this analysis. As a result, the following simulation results should prove to be acceptable.

2.3 Spectral density of drain-current noise

The previous section described the spectral density of carrier-density fluctuation. However, drain-current noise characteristics are directly observed in actual MOSFETs. In this section, we discuss the relation between drain-current noise and carrier-density fluctuation.

In the previous paper [8], we studied the spectral density of drain-current noise using the conventional approach formulated by van der Ziel [1]. In this paper, however, the fluctuation of drain current, δI_D, did not include the contribution of diffusion current. To take into account both the drift and diffusion currents, we start from the following expression for δI_D:

$$\delta I_D = W\mu \frac{\partial V}{\partial x}\delta Q_n + I_D \frac{\partial \delta Q_n}{\partial x} \Big/ \frac{\partial Q_n}{\partial x}, \tag{18}$$

where I_D is the dc drain current, W is the gate width, μ is the carrier mobility, and V is the local potential. Q_n and δQ_n are defined as

$$Q_n = -C_{ox}(V_G - V_{TH} - V), \tag{19a}$$

$$\delta Q_n = C_{ox}\delta V, \tag{19b}$$

where C_{ox} is the gate capacitance, V_G is the gate voltage, and V_{TH} is the threshold voltage. Differentiating eq. (19b) with x, the relation of the derivative of δQ_n to the fluctuation of electric field δF ($= -\partial \delta V / \partial x$) is obtained as

$$\frac{\partial \delta Q_n}{\partial x} = -C_{ox}\delta F. \tag{20}$$

In addition, δQ_n causes the fluctuation of quasi-Fermi level for electrons. The quasi-Fermi level ϕ_{Fn} is defined as

$$\phi_{Fn} = -\frac{k_B T}{e}\log\frac{n}{n_i}, \tag{21}$$

where ϕ_{Fn} is measured from the intrinsic Fermi level, k_B is the Boltzmann's constant, T is the absolute temperature, and n_i is the intrinsic carrier density. Eq. (21) yields the expression for the fluctuation of ϕ_{Fn}, $\delta\phi_{Fn}$, or δF as

$$\delta\phi_{Fn} = -\frac{k_B T}{e}\frac{\delta n}{n_o}, \tag{22a}$$

$$\delta F = -\frac{\partial \delta\phi_{Fn}}{\partial x} = \frac{k_B T}{e}\left(-\frac{\delta n}{n_o^2}\frac{\partial n_o}{\partial x} + \frac{1}{n_o}\frac{\partial \delta n}{\partial x}\right). \tag{22b}$$

It should be noted that Q_n and δQ_n are also expressed as

$$Q_n = -e t_{ch} n_o, \tag{23a}$$

$$\delta Q_n = -e t_{ch} \delta n, \tag{23b}$$

where t_{ch} is the effective inversion layer thickness. Thus, eq. (22b) can be rewritten as

$$\delta F = \frac{k_B T}{e}\left(-\frac{\delta Q_n}{Q_n^2}\frac{\partial Q_n}{\partial x} + \frac{1}{Q_n}\frac{\partial \delta Q_n}{\partial x}\right). \tag{24}$$

Substituting eq. (20) into eq. (24), the relation between δQ_n and the derivative of δQ_n is obtained as

$$\frac{\partial \delta Q_n}{\partial x}\Big/\frac{\partial Q_n}{\partial x} = \frac{k_B T/e}{Q_n/C_{ox} + k_B T/e}\frac{\delta Q_n}{Q_n}. \tag{25}$$

Thus, the expression of eq. (18) is rewritten as

$$\delta I_D = \left(W\mu \frac{\partial V}{\partial x} + I_D \frac{k_B T/e}{Q_n/C_{ox} + k_B T/e} \frac{1}{Q_n} \right) \delta Q_n$$

$$= \left(W\mu \frac{\partial V}{\partial x} + I_D \frac{k_B T/e}{Q_n/C_{ox} + k_B T/e} \frac{1}{Q_n} \right) . \left(-e t_{ch} \delta n \right). \tag{26}$$

According to the relation between δI_D and δn, the spectral density of drain current noise $S_{ID}(\ )$, including the transport effect, is obtained as

$$S_{ID}(f) = W^2 P_v e^2 t_{ch}^2 S_n(f)$$

$$= 2W^2 P_v e^2 t_{ch}^2 \left| \delta n_{mo} \right|^2 T(V_D, V_G, f)/\Delta f, \tag{27}$$

where the velocity power factor (P) is expressed as

$$P_v = \frac{1}{L} \int_0^L \left(\mu \frac{\partial V}{\partial x} + \frac{k_B T/e}{Q_n/C_{ox} + k_B T/e} \frac{I_D}{W Q_n} \right)^2 dx. \tag{28}$$

$S_{ID}(\ )$ is estimated by numerical calculation of P.

3. Simulation Results and Discussion

3.1 Influence of diffusion current on carrier-density fluctuation

In a previous paper [8], we discussed the influence of the current continuity condition on the carrier transport noise in a comparison with the theoretical result derived by van Vliet and Fassett [7]. In the paper, we took into account just the contribution of J_{drift}. It was shown that the current continuity condition suppresses the fluctuation power near the saturation region of drain current [8].

In this section, we demonstrate the significance of the contribution of J_{diff} to carrier-density fluctuation power. We characterize the influence of J_{diff} on the carrier-density fluctuation by comparing two cases: one is for a realistic D_n value estimated by Einstein's relation, $D_n = (\kappa \beta T/e)\ \mu_0$, and the other is for a D_n value much smaller than expected. The latter corresponds to a case in which the contribution of J_{diff} is effectively neglected. In spite of the non-equilibrium condition, we estimate the D_n value by Einstein's relation, resulting in D_n = 18 cm^2/sec. In the non-equilibrium condition, estimation of D_n value is in itself difficult. Canali et al. evaluated D_n value in the non-equilibrium condition, and demonstrated that D_n value is almost around 11 cm^2/sec for an electric field higher than 20 kV/cm [17]. Therefore, we think that the use of fixed D_n value (D_n = 18 cm^2/sec) does not change substantially the physics of transport noise discussed here, while the preciseness of fluctuation power estimation is slightly degraded. The device parameters used in the simulations are summarized in Table 1.

Table 1. Device parameters in simulation

Parameters	Values
Channel length (L)	0.1 – 1.0 (μm)
Gate width (W)	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)
Perpendicular critical electric field (F_{ox})	5×10^6 (V/cm)

Dependence of normalized carrier-density fluctuation power ($<\delta n_m^* \delta n_m>/|\delta n_{mo}|^2$) on normalized drain voltage (V_D/V_{DSAT}) for two different D_n values is shown for a device with L of 1 μm at 100 MHz in Fig. 1(a) and with the same at 1 GHz in Fig. 1(b). The normalized carrier-density fluctuation power ($<\delta n \delta n_m>/|\delta n_{mo}|^2$), is the same as $T(V_D, V_G, f)$ as defined by eq. (15); it represents a fraction of fluctuation power observed at the drain. V_{DSAT} is the drain saturation voltage; V_{DSAT} is equal to 0.56 V for the realistic D_n value, and 0.51 V for the small D_n value. In the figures, the simulation range of V_D is limited because V_D must be smaller than $F_C L$. When the expected J_{diff} component is taken into account, the fluctuation power is seen to be basically suppressed because of the interference between the forward and backward propagating components of carrier-density fluctuation. In addition, the carrier-density fluctuation power increases with V_D/V_{DSAT}, but decreases when V_D/V_{DSAT} exceeds a certain value.

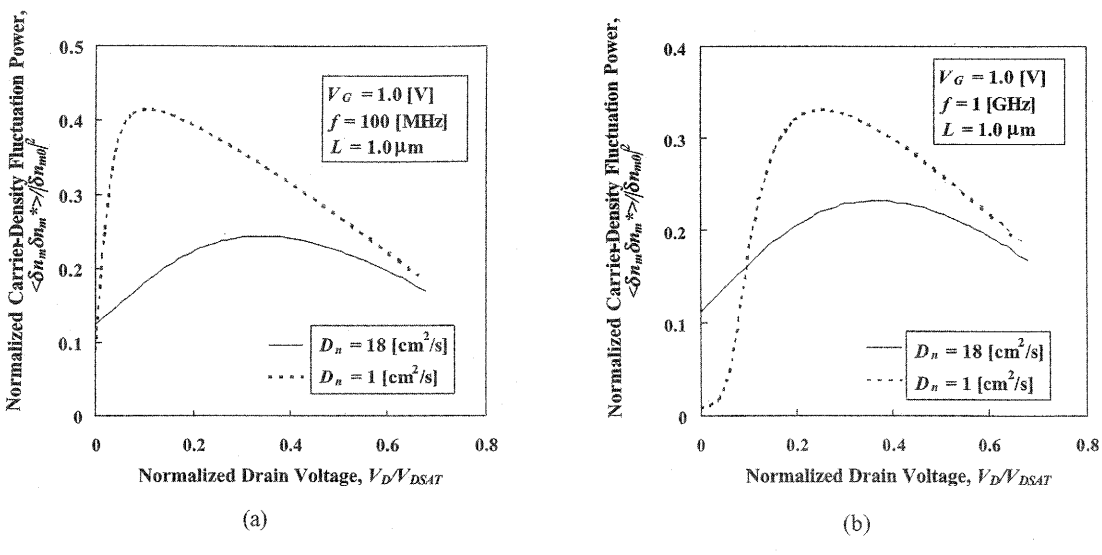

Fig. 1. Dependence of normalized carrier-density fluctuation power ($<\delta n_m^* \delta n_m>/|\delta n_{mo}|^2$) on normalized drain voltage (V_D/V_{DSAT}). Here, V_{DSAT} for Dn = 1 and 18 cm^2/s is equal to 0.33 and 0.47 V, respectively. (a) Simulation result at f = 100 MHz. (b) Simulation result at f = 1 GHz.

These characteristics can be explained as follows. When the drain-to-source electric field increases with drain voltage, the contribution of the J_{diff} component diminishes and the contribution of the J_{drift} component becomes significant. Thus the fluctuation power initially increases with V_D/V_{DSAT} due to the suppression of interference. Once V_D/V_{DSAT} exceeds a certain value, the J_{drift} component dominates the drain current. In this regime, the high-field behavior of fluctuation power stems from the same mechanism as that described in the previous paper [8]; the fluctuation power decreases as V_D/V_{DSAT} increases because the increase of T^*/τ^* promotes fluctuation averaging, where T^* is the effective transit time ($\sim L/v_d$).

There is a notable difference between the behavior of fluctuation power at 100 MHz and that at 1 GHz. In a low V_D/V_{DSAT} regime, the fluctuation power at 1 GHz is suppressed compared with that at 100 MHz for the small D_n value. These characteristics can be explained as follows. The frequency dependence of fluctuation power is characterized by the specific time constant (τ_1) stemming from carrier transport in the channel region. Since the diffusion process is significant in a low V_D/V_{DSAT} regime, it can be expected that the time constant (τ_1) characterizing the carrier transport is approximated by $\tau_1 = L^2/2D_n$. For the realistic D_n value, the cut-off frequency (f_c), dominated by τ_1, is approximately equal to 576 MHz, and fc decreases as D_n value decreases. Accordingly, for the small D_n value, the fluctuation power at 1 GHz attenuates under low drain voltages more than is true at 100 MHz.

The contribution of J_{diff} to transport noise will be described elsewhere in detail [16]. In this paper, we mainly wish to discuss how the transport characteristics of fluctuation power should vary in short-channel devices.

3.2 Characteristics of transport noise for various channel lengths

A. Spatial-correlation of carrier-density fluctuation

In this section, we discuss the drain voltage dependence of carrier-density fluctuation power for various channel lengths (L = 0.1, 0.5, and 1.0 μm). When the channel length is varied, other device parameters are fixed at those suitable for a 0.1 μm channel device (see Table 1). In the following discussion, we assume a realistic D_n value.

Dependence of $<\delta n_m^* \delta n_m>/|\delta n_{mo}|^2$ on V_D/V_{DSAT} for various channel lengths is shown in Fig. 2. Here, V_{DSAT} for $L = 0.1\,\mu$m is equal to 0.47 V, for 0.5 μm, 0.53 V, and for 1.0 μm, 0.56 V, respectively. In a low V_D/V_{DSAT} regime, the normalized fluctuation power for L = 1.0 μm is smaller than that for L = 0.1 μm and 0.5 μm. In a high V_D/V_{DSAT} regime, however, the normalized fluctuation power for L = 0.1 μm is dramatically suppressed in comparison with that for longer channel devices. In addition, the fluctuation power for L = 1.0 μm is slightly suppressed in comparison with that for L = 0.5 μm. We can explain the characteristics in a low V_D/V_{DSAT} regime as follows. As mentioned above, the frequency dependence of normalized fluctuation power is characterized by the cut-off frequency ($f_c \sim 1/\tau_1$). This cut-off frequency rises as L decreases. Therefore, the normalized fluctuation power for L = 1.0 μm is smaller than that for L = 0.1 μm and 0.5 μm as is discussed later.

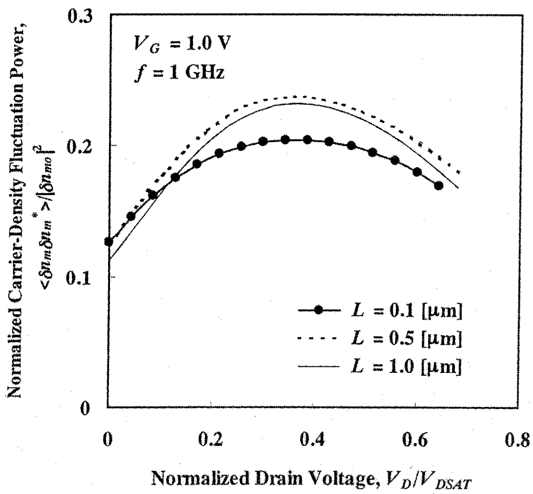

Fig. 2. Dependence of normalized carrier-density fluctuation power ($<\delta n_m^* \delta n_m>/|\delta n_{mo}|^2$) on normalized drain voltage (V_D/V_{DSAT}) for various channel lengths. Here, V_{DSAT} for L = 0.1, 0.5, and 1.0 μm is equal to 0.47, 0.53, and 0.56 V, respectively.

Next, we discuss the characteristics of carrier-density fluctuation power in a high V_D/V_{DSAT} regime. As V_D/V_{DSAT} increases, the contribution of the J_{drift} component becomes significant, and the cut-off frequency should be characterized by T^*. The cut-off frequency for L = 1.0 μm is approximately equal to 1 GHz, while that for shorter-channel devices is higher than 1 GHz, so the normalized fluctuation power for L = 1.0 μm is smaller than that for L = 0.5 μm. On the other hand, the behavior of normalized fluctuation power for L = 0.1 μm cannot be explained by the cut-off frequency, because the normalized fluctuation power for L = 0.1 μm is smaller than that for L = 1μm. To address this point, we must consider the channel-length dependence of the interference between the forward and backward propagation components of fluctuation power, and we should discuss the ratio of backward to forward propagation components of fluctuation power ($<\delta n_2^* \delta n_2>/<\delta n_1^* \delta n_1>$). This ratio reflects the magnitude of the interference effect.

In Fig.3, the dependence of $<\delta n_2^* \delta n_2>/<\delta n_1^* \delta n_1>$ on L is shown for various V_D values. $<\delta n_2^* \delta n_2>/<\delta n_1^* \delta n_1>$ increases as the channel length becomes shortens, regardless of V_D value; $<\delta n_2^* \delta n_2>/<\delta n_1^* \delta n_1>$ is roughly proportional to $L^{1/2}$. This means that the contribution of the J_{diff} component becomes significant as the channel length shortens. This behavior can be explained as follows. The contribution of the J_{diff} component is roughly evaluated by the ratio of channel length to effective diffusion length (L_n/L), where L_n^2 is (approximately) inversely proportional to the difference of drift velocity between drain and source terminals [16]. Since L_n is also a function of $L^{1/2}$ (approximately) [16], the value of L_n/L increases at the rate of $L^{1/2}$ as L deceases. This means that the contribution of the J_{diff} component becomes significant as L decreases. Thus, in Fig. 2, in comparison with that for L= 1 μm, the normalized fluctuation power for L = 0.1 μm is drastically suppressed by the enhancement of interference.

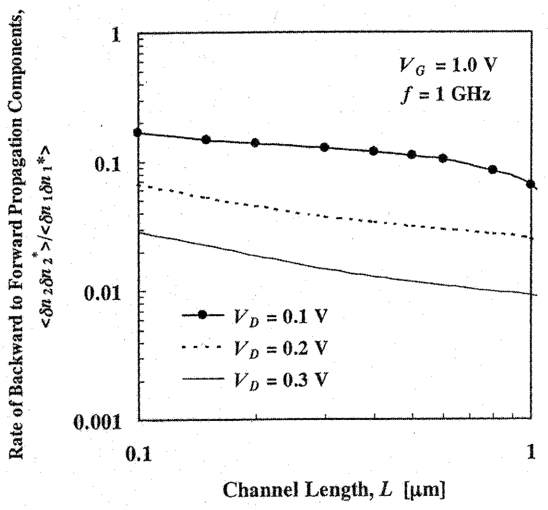

Fig. 3. Ratio of backward to forward propagation component ($<\delta n_2^* \delta n_2>/<\delta n_1^* \delta n_1>$) for various drain voltages as a function of channel length (L).

B. Spectral density of drain current noise

Before discussing our simulation of $S_{ID}(f)$, the Δf value in eq. (27) should be estimated. Compared to the effective transit time from source to drain T^*, $1/\Delta f$ must be long enough to allow the transport effects to become discernible. The effective transit time is largest, T_0^*, at $V_D = 0$ V and can be estimated from $T_0^* = \tau L/L_n$ (~10^{-6} sec) for $L = 1.0$ μm, where L_n is the effective diffusion length [16]. Therefore, we set $1/\Delta f = 1$ sec ($>> T_0^*$) in the following discussion.

The dependence of drain current noise spectral density, $S_{ID}(f)/|\delta n_{mo}|^2$, on V_D/V_{DSAT} is shown for various channel lengths in Fig. 4. $S_{ID}(f)/|\delta n_{mo}|^2$ increases at the rate of $1/L^2$ as L decreases, which is well known [1]. In a high V_D/V_{DSAT} range, the increase rate of $S_{ID}(f)/|\delta n_{mo}|^2$ for $L = 0.1$ μm is suppressed relative to the other ranges. Since $S_{ID}(f)$ is characterized by the product of $T(V_D, V_G, f)$ and P_v, we consider at first how the characteristics of $S_{ID}(f)/|\delta n_{mo}|^2$ are modulated by the velocity power factor, P_v. Accordingly, we show in Fig. 5 the dependence of P_v on V_D/V_{DSAT} for various channel lengths. P_v also increases as L decreases. In a high V_D/V_{DSAT} range, the increase rate of P_v for $L = 0.1$ μm is also suppressed relative to the other ranges.

These characteristics can be explained as follows. When L decreases, the internal electric field and carrier velocity increase, which is followed by increase in P_v. In addition, in a high V_D/V_{DSAT} regime, the carrier mobility for $L = 0.1$ μm is degraded by the high internal electric field. As a result, the increase rate of P_v is suppressed for $L = 0.1$ μm. The behavior of P_v directly reflects that of $S_{ID}(f)/|\delta n_{mo}|^2$; P_v is the primary determinant of the fundamental characteristic of $S_{ID}(f)/|\delta n_{mo}|^2$, as described in eq. (27).

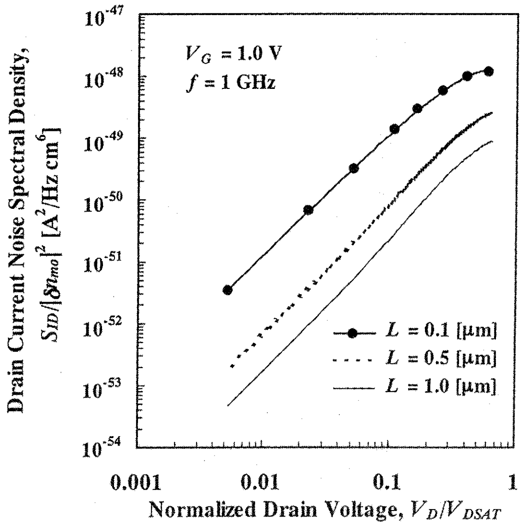

Fig. 4. Dependence of drain current noise spectral density ($S_{ID}(f)/|\delta n_{mo}|^2$) on normalized drain voltage (V_D/V_{DSAT}) for various channel lengths.

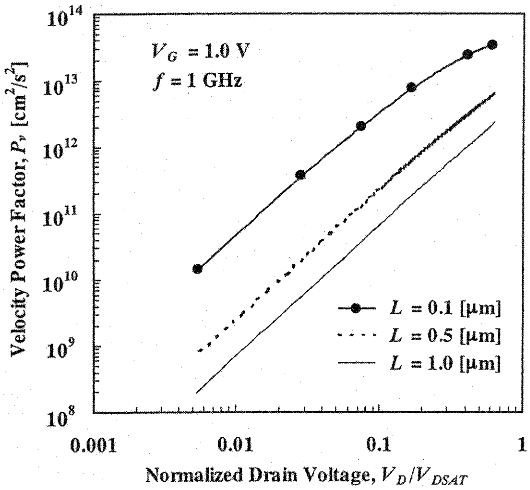

Fig. 5. Dependence of velocity power factor (P_v) on normalized drain voltage (V_D/V_{DSAT}) for various channel lengths.

3.3 Influence of velocity overshoot effect on transport noise in a 0.1-μm channel device

A. Spatial-correlation of carrier-density fluctuation

In the pervious section, we discussed the transport effects of carrier-density fluctuation power for various channel lengths (L = 0.1, 0.5, and 1.0 μm). In short channel lengths, such as L = 0.1 μm, non-stationary carrier transport, such as the velocity overshoot effect (VOE), becomes pronounced. This causes drain current enhancement greater than that predicted by the simple drift-diffusion model.

In this section, we will discuss the influence of VOE on transport noise in MOSFETs with L of 0.1 μm. Since we derived the expression for $S_{ID}(f)$ on the basis of local-field approximation, $S_{ID}(f)$ cannot apply to a non-stationary effect, such as VOE. However, we think that the present expression is still valid when the non-stationary effect is not prominent. VOE may be estimated approximately 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). In addition, 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. Here, we consider that non-stationary phenomena are not dominant. In other words, we don't consider carrier-density fluctuation mechanisms in deep sub-100nm MOSFETs. For deep sub-100nm MOSFETs, the present theory is inappropriate because the major transport phenomena differ considerably from the simple drift-diffusion process.

$<\delta n_m{}^* \delta n_m>/|\delta n_{mo}|^2$ is shown in Fig. 6 for L = 0.1 μm as a function of V_D/V_{DSAT}. Here, V_{DSAT} with VOE is equal to 0.49 V. When the velocity overshoot effect is taken into account, the carrier-density fluctuation power is enhanced in a high V_D/V_{DSAT} regime. This suggests that in this regime the characteristics are mainly determined by the interference between two different carrier density fluctuation components. Accordingly, we must discuss the influence of VOE on $<\delta n_2{}^* \delta n_2>/<\delta n_1{}^* \delta n_1>$. $<\delta n_2{}^* \delta n_2>/<\delta n_1{}^* \delta n_1>$ is shown in Fig. 7 for L = 0.1 μm as a function of V_D/V_{DSAT}. When VOE is taken into account, $<\delta n_2{}^*\delta n_2>/<\delta n_1{}^*\delta n_1>$ decreases in a high V_D/V_{DSAT} regime. These characteristics can be explained as follows. When we take account of VOE, the contribution of the J_{diff} component weakens because the contribution of the J_{drift} component reflects its ability to increase the carrier velocity. As a result, the backward propagation component of fluctuation power stemming from the J_{diff} component decreases, and so $<\delta n_2{}^* \delta n_2>/<\delta n_1{}^* \delta n_1>$ decreases. This means that VOE suppresses the interference between the carrier density fluctuation components, and hence enhances the carrier-density fluctuation power in a high V_D/V_{DSAT} regime, as shown in Fig. 6.

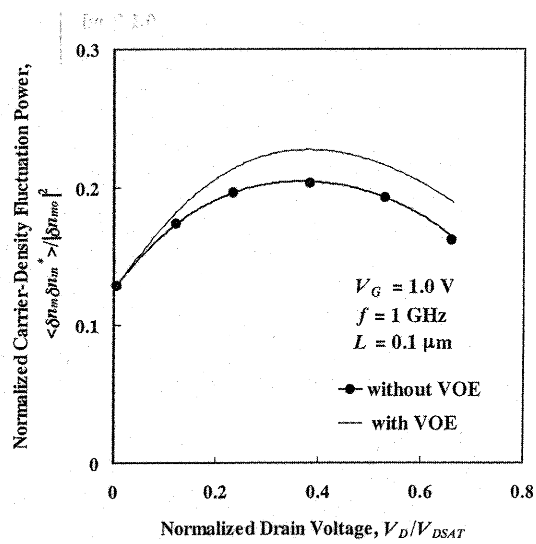

Fig. 6. Normalized carrier-density fluctuation power ($<\delta n_m{}^* \delta n_m>/|\delta n_{mo}|^2$ for L = 0.1 μm as a function of normalized drain voltage (V_D/V_{DSAT}). Here, V_{DSAT} with VOE is equal to 0.49 V.

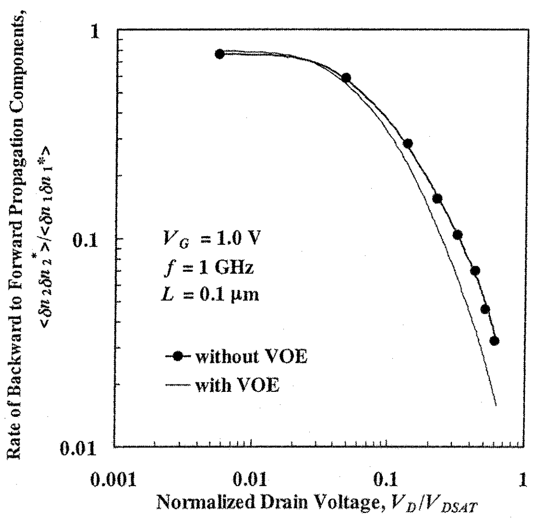

Fig. 7. Ratio of backward to forward propagation component ($<\delta n_2{}^* \delta n_2>/<\delta n_1{}^* \delta n_1>$) for L = 0.1 μm as a function of normalized drain voltage (V_D/V_{DSAT}).

B. Spectral density of drain current noise

We will now discuss the influence of VOE on drain current noise spectral density. $S_{ID}(f)/|\delta n_{mo}|^2$ is shown in Fig. 8 for L = 0.1 μm as a function of V_D/V_{DSAT}. When VOE is taken into account, $S_{ID}(f)/|\delta n_{mo}|^2$ increases. This VOE-induced enhancement of $S_{ID}(f)/|\delta n_{mo}|^2$ becomes more significant in a high V_D/V_{DSAT} regime. As mentioned before, the fundamental characteristic of $S_{ID}(f)/|\delta n_{mo}|^2$ is primarily determined by that of P_v. It is easily anticipated from eq. (28) that VOE enhances P_v. This can be explained by the fact that velocity overshoot results in drain current enhancement. As a result, P_v with VOE is larger than that without VOE, which leads to an increase in $S_{ID}(f)/|\delta n_{mo}|^2$.

Since the RF application of short channel MOSFETs is attracting great attention, we evaluated drain current noise spectral density and its dependency on frequency, f. $S_{ID}(f)/|\delta n_{mo}|^2$ is shown in Fig. 9 for L = 0.1 μm as a function of f. $S_{ID}(f)/|\delta n_{mo}|^2$ is almost constant for $f < f_c$, where f_c is the cut-off frequency. f_c rises when VOE is considered, as the effective transit time from source to drain (T^*) is reduced by the increase in carrier velocity. The reduction in transit time enhances the high frequency component of transport noise. Hence, f_c rises when VOE is taken into account.

From the above material, we anticipate that the transport noise stemming from carrier-density fluctuation would be significant in 0.1 μm and sub-0.1 μm MOSFETs. However, for cases where non-stationary carrier transport becomes quite dominant, we are going to need a new theoretical understanding. This is an issue for the future.

4. Conclusion

In this paper, characteristics of transport noise stemming from carrier-density fluctuation were theoretically examined for MOSFETs with various channel lengths (L =

0.1, 0.5, and 1.0 μm). The carrier-density fluctuation was derived from a partial differential equation on the basis of charge-density conservation. The theoretical expression for the spectral density of carrier-density fluctuation power was applied to the analysis of the transport effects of carrier-density fluctuation in a high-frequency range. At first, we discussed how the characteristics of fluctuation power are influenced by channel length. It was shown that the high frequency component of fluctuation power is enhanced as the channel length is reduced, and that interference between the forward and backward propagating components of carrier-density fluctuation power becomes significant in short-channel devices. Next, we discussed the spectral density of drain current noise for various channel lengths. It was also shown that the spectral density increases, through the increase in carrier velocity, as the channel length is reduced.

At short channel lengths, such as 0.1 μm, the velocity overshoot effect (VOE) becomes significant. We discussed the influence of VOE on the drain current noise spectral density for the channel length of 0.1 μm by assuming that the non-stationary effect is not so prominent. When we take VOE into account, it is predicted that the drain current noise spectral density will be enhanced, and that the high frequency component of drain current noise spectral density will be, too. Therefore, it is anticipated that the transport noise stemming from carrier-density fluctuation would be significant in 0.1-μm channel MOSFETs.

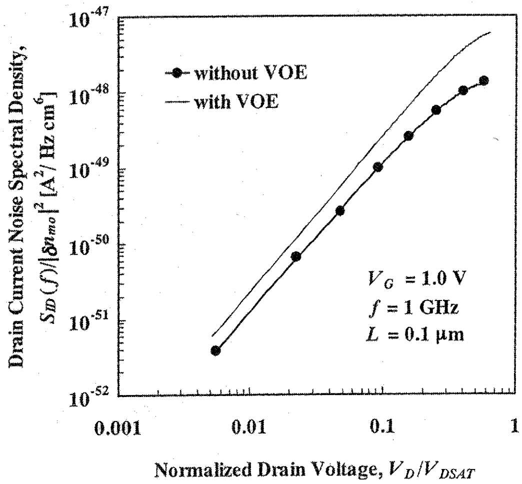

Fig. 8. Drain current noise spectral density ($S_{ID}(f)/|\delta n_{mo}|^2$) for L = 0.1 μm as a function of normalized drain voltage (V_D/V_{DSAT}).

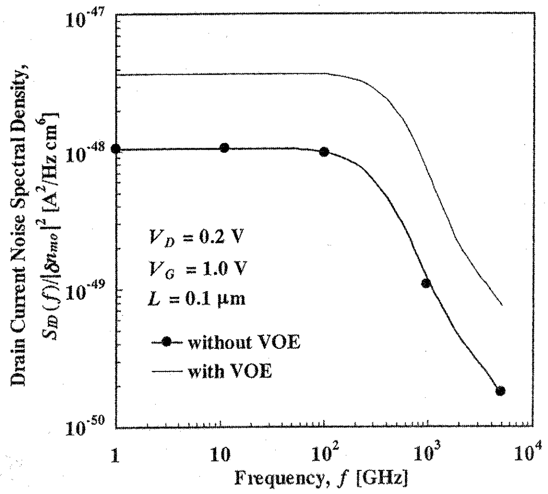

Fig. 9. Drain current noise spectral density ($S_{ID}(f)/|\delta n_{mo}|^2$) for L = 0.1 μm as a function of frequency (f).

References

1. A. Van Der Ziel, *Noise*: Sources, Characterization and Measurements (Prentice-Hall, 1970).
2. J. J. Liou and Frank Schwierz, "Evolution and current status of RF semiconductor devices", Ext. Abstr. 2001 Int. Conference on Solid State Devices and Materials, p. 74 (JSAP, Tokyo, Sept. 2001).
3. L. M. Franca-Neto, E. Mao, J. S. Harris Jr., and P. G. Allen, "Low noise FET design for wireless communications," Tech. Dig. 1997 IEEE Int. Electron Device Meet, p. 305 (IEEE, Washington, D. C., Dec. 1997).
4. D. Sumino and Y. Omura, "Simulation of high-frequency thermal noise in silicon-on-insulator MOSFETs using distributed-transmission-line model," *IEICE Trans. Electronics*, E85-C, p. 1443 (2002).
5. P. Shiktorov, E. Starikov, V. Gruzinskis, T. Gonzalez, J. Mateos, D. Pardo, L. Reggiani, L. Varani, J. C. Vaissiere and J. P. Nougier, "Spatio-temporal correlation of conduction current fluctuations within a hydrodynamic-Langevin scheme," *Appl. Phys. Lett.*, 74, p. 723(1999).
6. N. Sano, "Sub-0.1 mm device simulation technology: another problems for Monte Carlo simulations," Ext. Abstr. 1999 Int. Conference on Simulation of Semiconductor Processes and Devices (SISPAD), p. 23 (IEEE, Osaka, Japan, Oct. 1999).
7. *Fluctuation Phenomena in Solids* , ed. R. E. Burgess, Chap. 7, p. 268 (Academic Press, New York, 1965).
8. D. Sumino and Y. Omura, "Theoretical consideration for carrier transport noise in nonequilibrium steady-state operation of metal-oxide-semiconductor field-effect transistor," *J. Appl. Phys.*, 88, p. 2092 (2000).
9. B. Yu, "Scaling planar CMOS towards its limit," Abstr. 2002 IEEE Silicon Nanoelectronics Workshop, p. 17 (IEEE, Honolulu Hwaii, June 2002).

10. S. Y. Chou, D. A. Antoniadis and H. I. Smith, "Observation of electron velocity overshoot in sub-100-nm-channel MOSFETs in silicon," *IEEE Electron Device Lett.*, EDL-6, p. 665(1985).
11. G. G. Shahidi, D. A. Antoniadis and H. I. Smith, "Electron velocity overshoot at room and liquid-Nitrogen temperatures in Silicon inversion-layers," *IEEE Electron Device Lett.*, 9, p. 94 (1988).
12. G. A. Sai-Halasz, M. R. Wordeman, D. P. Kern, S. Rishton and E. Ganin, "High transconductance and velocity overshoot in NMOS devices at the 0.1-μm gate-length level", *IEEE Electron Device Lett.*, 9, p. 464 (1988).
13. J. H. Song, Y. J. Park and H. S. Min, "Drain current enhancement due to velocity overshoot effects and its analytic modeling," *IEEE Trans. Electron Devices*, 43, p. 1870 (1996).
14. F. N. Hooge, "1/f noise," *Physica B.*, 83, p. 14 (1976).
15. F. N. Hooge, T. G. M. Kleinpenning, and L. K. J. Vandemme. "Experimental studies on 1/f noise," *Rep. Prog. Phys.*, 44, p. 479 (1981).
16. A. Masaoka, D. Sumino and Y. Omura, "Theory of Carrier-Density-Fluctuation-Induced Transport Noise in Metal-Oxide-Semiconductor Field-Effect Transistors," *J. Appl. Phys.*, 93, p. 5359 (2003).
17. C. Canali. C. Jacoboni, G. Otaviani and A. Alberigi-Quaranta, "High-field diffusion of electrons in silicon," *Appl. Phys. Lett.*, 27, p. 278 (1975).