Compact Modeling of Noise in Nonuniform Channel MOSFET

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ABSTRACT

Compact MOSFET noise models are mostly based on the Klaassen-Prins (KP) approach. However, the noise properties of lateral nonuniform MOSFETs are considerably different from the prediction obtained with the conventional KP-based methods which, at low gate voltages, can overestimate the thermal noise by 2-3 orders of magnitude. The presence of lateral nonuniformity makes the vector impedance field (IF) (the quantity responsible for noise propagation) position and bias dependent. This insight clearly explains the observed discrepancy and shows that the bias dependence of the important noise parameters cannot be predicted by conventional KP-based methods. Interestingly, this bias dependence of the noise parameters in the presence of lateral nonuniformity can be effectively used in the channel engineering of MOSFET to optimize the RF noise performance.

Keywords: MOSFET, compact modeling, nonuniform doping, thermal noise

1 INTRODUCTION

MOSFET devices often have nonuniform doping profile along the channel. Lateral double-diffused MOS (LDMOS) devices are well-known examples of MOS devices with a lateral nonuniform channel doping profile. Another important example of this kind of devices are single halo devices where the source end is highly doped to improve the short channel effect. Even the standard MOSFETs are also laterally nonuniform because of the halo implants. Uniformly doped MOSFET noise models are based on Klaassen-Prins (KP) [1] or some equivalent methods [2], which are all denoted here as KP method. Although, there is a trend in the community to directly apply KP method even in the presence of lateral nonuniformity, depending on the noise mechanism and doping profile, this kind of approach can give totally erroneous prediction [3], [4].

In this paper we first present a noise modeling methodology taking lateral nonuniformity into account [3], [4]. The very general nature of the treatment will alow the methodology to be used with any arbitrary doping profile and field-dependent mobility. The main result is that the lateral nonuniform doping makes the vector impedance field for the drain terminal bias dependent. This fact explains the failure of KP-based methods which assumes a constant impedance field

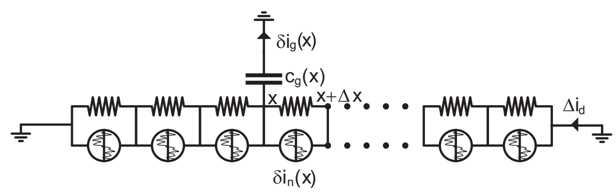


Figure 1: Illustration of noise calculation by using a Langevin approach. The current at any position has two components. One component is set up by the voltage perturbation caused by the noise source (which can be thought of following through the resistances) and other one is the noise current itself (which is represented by the noisy current sources $\delta i_n(x)$). Δi_d is the total noise current flowing through the channel and is constant along the channel. The induced gate current noise $\Delta i_g(x)$ originates due to the fluctuation of the channel potential across the gate capacitance $C_g(x)$ and lies in quadrature with the drain current noise

and predicts unique bias dependence of the correlation coefficient between drain and induced gate noise. Interestingly, this bias dependence can be effectively used in the channel engineering of MOSFET to optimize the RF noise performance. In this paper we will show how to model noise in lateral nonuniform device and how the position and bias dependence of impedance fields can be exploited to improve the RF noise performance of a nonuniformly doped MOSFET.

2 MODEL DESCRIPTION

In a lateral nonuniform MOSFET, the doping varies with position. This kind of doping makes the threshold voltage of the channel position dependent, which causes the inversion charge and mobility to become an *explicit* function of the position. Under drift-diffusion approximation, the current at any position x along the channel can be written as

$$I(x) = W\mu(x, \frac{dV}{dx})(-Q_i(x, V))\frac{dV}{dx} = g(x, V, \frac{dV}{dx})\frac{dV}{dx} \quad (1)$$

where V is the channel potential, W is the width of the device, Q_i is the inversion charge and μ is the mobility. In our analysis we always assume the source to be located at $x = 0$ and the drain at L. Now, presence of a noise current in the channel generates a perturbation v of the channel potential, which then causes a change in transport current. Therefore the total current flowing at position x can be expressed as a sum of transport current (including the effect of perturbation in channel potential) and the noise current itself. Fig. 1 illustrates this situation. So the effect of adding the Langevin noise source $\delta i_n(x)$ in (1) can be written as

$$I_0(x)+i_d(x) = g\left(x, V_0+v, \frac{d(V_0+v)}{dx}\right)\frac{d(V_0+v)}{dx} + \delta i_n(x), \tag{2}$$

where $I_0(x)$ and V_0 are the unperturbed current and voltage in the channel and $i_d(x)$ is the total noise current at the position x. In the following derivation, subscript '0' will be used to denote unperturbed quantities and $\frac{dV}{dx}$ and E will be used interchangeably. Using a perturbation analysis [3], [4], $i_d(x)$ can be expressed as

$$i_d(x) = \frac{g_0 + \frac{\partial g_0}{\partial E_0}E_0}{g_0} \cdot \frac{d}{dx}(g_0 v) - \frac{\partial g_0}{\partial x} v + \delta i_n(x). \tag{3}$$

As $i_d(x) = \Delta i_d$ is constant along the channel, we can express equation (3) as

$$\frac{d}{dx}(g_0 v) - \frac{1}{g_0}\left(\frac{g_0}{g_0 + \frac{\partial g_0}{\partial E_0}E_0}\right)\frac{\partial g_0}{\partial x}(g_0 v) = \frac{g_0}{g_0 + \frac{\partial g_0}{\partial E_0}E_0}\left(\delta i_n(x) - \Delta i_d\right). \tag{4}$$

This equation can be thought of a first order ODE with respect to $g_0 v$ with an integration factor $R(x)$ given by

$$R(x) = \exp\left(-\int_0^x \frac{1}{g_0}\left(\frac{g_0}{g_0 + \frac{\partial g_0}{\partial E_0}E_0}\right)\frac{\partial g_0}{\partial x}dx\right). \tag{5}$$

Multiplying both sides by $R(x)$ and defining $f(x)$ as

$$f(x) = \frac{g_0 R(x)}{g_0 + \frac{\partial g_0}{\partial E_0}E_0}, \tag{6}$$

we obtain

$$\frac{d(R(x)g_0 v)}{dx} = f(x)\left(\delta i_n(x) - \Delta i_d\right). \tag{7}$$

Now we integrate both sides from 0 to L. Noticing that Δi_d is constant along the channel and v vanishes at the end points, we obtain the total drain current Δi_d as

$$\Delta i_d = \frac{\int_0^L f(x)\delta i_n(x)dx}{\int_0^L f(x)dx} = \int_0^L \Delta A_d(x)\delta i_n(x)dx, \tag{8}$$

where, IF for drain, $\Delta A_d(x)$, is clearly

$$\Delta A_d(x) = \frac{f(x)}{\int_0^L f(x)dx}. \tag{9}$$

It is easy to check that when there is neither nonuniformity nor mobility degradation, $f(x)$=1 and (8) reduces to $\Delta i_d = \int_0^L \delta i_n(x)dx/L$ (final result of KP method) and in the presence of mobility degradation only, it reduces to our previous result [2].

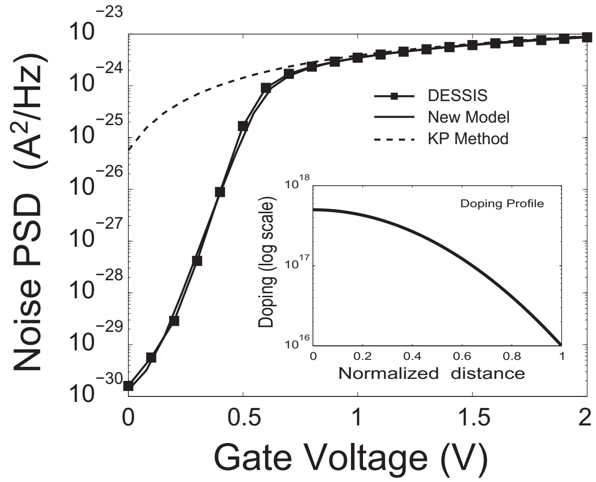


Figure 2: Plot of drain thermal noise PSD versus gate voltage for a lateral nonuniform MOSFET at $V_{DS} = 0$. The structure simulated has a source doping of 5×10^{17} cm^{-3} and a drain doping of 1×10^{16} cm^{-3} (with a gaussian profile [1]), channel length of 2 μm, width of 1 μm, and a oxide thickness of 8 nm

To calculate the induced gate current we need to find out the voltage perturbation induced by this elementary noise source as a function of position. A potential fluctuation $v(x)$ between x and $x + \Delta x$ causes a fluctuation of the gate current by capacitive coupling. Therefore, the gate noise current Δi_g is given by

$$\Delta i_g = -j\omega W \int_0^L C_g(x)v(x)dx, \tag{10}$$

where $C_g = \frac{dQ_g}{dV}$, Q_g is the charge stored per unit area in the gate. Integrating (4) we obtain $v(x)$ as

$$v(x) = \frac{1}{R(x)g_0}\int_0^x f(x_1)\left(\delta i_n(x_1) - \Delta i_d\right)dx_1. \tag{11}$$

Therefore Δi_g becomes

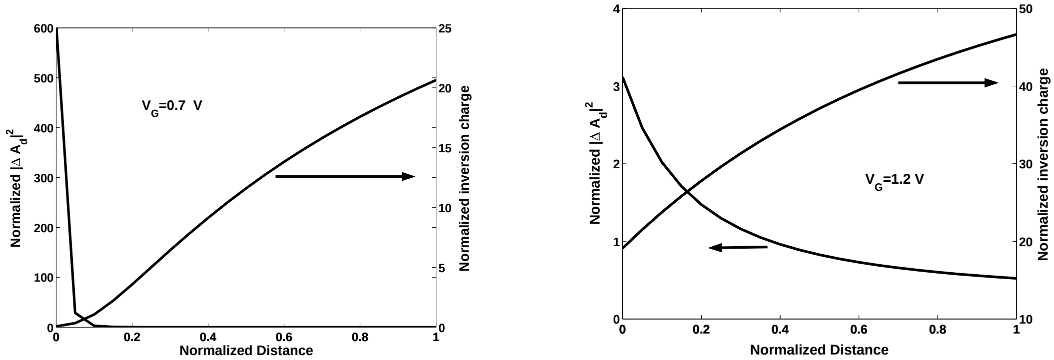
$$\Delta i_g = -j\omega W \int_0^L \frac{C_g(x)}{R(x)g_0}\int_0^x f(x_1)\left(\delta i_n(x_1) - \Delta i_d\right)dx_1 dx. \tag{12}$$

We introduce the notation

$$\lambda(x) = \int_0^x \frac{C_g(x)}{R(x)g_0}dx, \tag{13}$$

and integrating by parts we obtain

$$\Delta i_g = -j\omega W \left(\lambda(L)\int_0^L f(x)\delta i_n(x)dx - \int_0^L \lambda(x)f(x)\delta i_n(x)dx - \lambda(L)\Delta i_d \int_0^L f(x) + \Delta i_d \int_0^L \lambda(x)f(x)dx\right). \tag{14}$$



(a) (b)

Figure 3: Profile of squared drain IF (normalized with respect to the inverse of channel length) and inversion charge density (normalized by $C_{ox}U_T$) at $V_{DS} = 0$ (a) for low gate voltage ($V_G = 0.7$ V) and (b) for high gate voltage ($V_G = 1.2$ V). The PSD of the local noise source is proportional to the inversion charge. For normal MOSFET the normalized IF is equal to 1 but it is peaked near the source for lateral nonuniform MOSFET. This considerably changes the noise behavior of lateral nonuniform MOSFET

To clearly understand why conventional KP-based methods fail for a nonuniform MOSFET, let us ignore the effect of field-dependent mobility, which implies $\partial g/\partial E = 0$. Therefore, $f(x)$ now becomes

$$f(x) = \exp\left(-\int_0^x \frac{1}{g}\frac{\partial g}{\partial x}dx\right). \tag{15}$$

Once the ΔA_ks are calculated, PSDs and cross PSDs are easily obtained. We will assume that the noise sources are spatially uncorrelated. So the PSD of the local noise source $S_{\delta i_n^2}(x, x')$ can be written as

$$S_{\delta i_n^2}(x_1, x_2) = S_{\delta i_n^2}(x_1)\delta(x_1 - x_2). \tag{16}$$

Therefore the drain current PSD $S_{i_d^2}$, gate PSD $S_{i_g^2}$, and cross PSD $S_{i_d i_g}$ become

$$S_{i_d^2} = \int_0^L |\Delta A_d|^2 S_{\delta i_n^2}\,dx, \tag{17}$$

$$S_{i_g^2} = \int_0^L |\Delta A_g|^2 S_{\delta i_n^2}\,dx, \tag{18}$$

$$S_{i_g i_d} = \int_0^L \Delta A_g \Delta A_d^* S_{\delta i_n^2}\,dx. \tag{19}$$

The analytical method we just developed is applicable to any kind of noise mechanism. However, the PSD of the local noise source $S_{\delta i_n^2}$ depends on the noise mechanism and needs to be chosen carefully. In the rest of the paper we will consider mainly thermal noise. For thermal noise $S_{\delta i_n^2} = 4 \cdot q \cdot W \cdot Q_{inv} \cdot D_n$, where D_n is the noise diffusivity [5], [6]. Details about the definition of $S_{\delta i_n^2}$ and D_n can be found in [5]–[7]. For simple electron mobility model this definition of $S_{\delta i_n^2}$ reduces to the one used in [8] i.e. $S_{\delta i_n^2} = 4kT_L g$, where T_L is the lattice temperature and k is the Boltzmann's constant.

3 EFFECT OF LATERAL NONUNIFORM DOPING ON DRAIN NOISE

In a lateral nonuniformly doped MOSFET, the doping varies with position. This kind of doping makes the threshold voltage of the channel position dependent and application of KP-based method in this situation can give totally erroneous prediction. Fig. 2 illustrates this by a plot of the drain current PSD for thermal noise in equilibrium versus the gate voltage obtained from a 2-D device noise simulation (DESSIS) and the noise PSD predicted by the KP method. The figure clearly shows that even in equilibrium, at low value of gate voltages the KP method grossly overestimates (by 2-3 orders of magnitude) the noise.

In a uniformly doped MOSFET $\partial g/\partial x = 0$, which results in $f(x) = 1$ and hence $\Delta A_d(x) = 1/L$ (see (9)). The point is, IF in a uniformly doped MOSFET is independent of position and bias, whereas in nonuniform MOSFET it depends on both position and bias (because of the non vanishing $\partial g/\partial x$). Now the question is why is this effect so much pronounced at low gate voltages? The answer lies in the doping profile of these devices. The source end has a much higher doping than the drain end which results in a higher threshold voltage at the source end compared to the drain end. At low gate voltages the source will be in weak inversion and the drain will be in strong inversion. In this case, since g is very small near the source, the function $f(x)$ levels off very rapidly near the source (because of the $1/g$ term present in the expression of $f(x)$). This causes ΔA_d to highly peak near the source end. Eq. (17) reveals that the contribution to the drain terminal noise from any point gets determined by the product of two terms. The first one is the $|\Delta A_d|^2$, which represents the noise propagation and the second term is the local noise source PSD, which is proportional to the inversion charge. Fig. 3(a) shows the plot of $|\Delta A_d|^2$ and inversion charge density versus nor-

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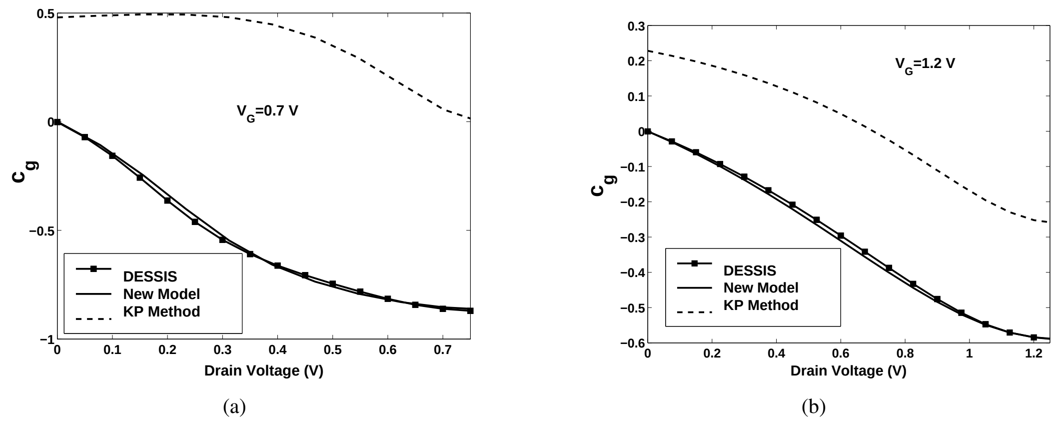


Figure 4: Plot of the imaginary part of c_g versus drain voltage at (a) low gate voltage ($V_G = 0.7$ V) and (b) at high gate voltage ($V_G = 1.2$). KP method is totally incapable of predicting the behavior and even gives a wrong sign

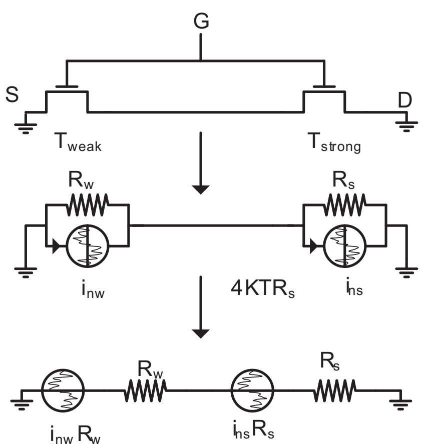


Figure 5: Intuitive explanation of the noise behavior in lateral nonuniform MOSFET. If the effect of distributed doping is lumped in to two transistor, the transistor near the source will have a higher threshold voltage(because of higher doping). At low gate voltages, the source end will be weakly inverted and transistor near drain end will be strongly inverted. As the weakly inverted transistor has a much higher resistance, it follows that the noise current of the total combination will be determined by the weakly inverted transistor

malized position at low gate voltage. Since the drain end is more strongly inverted compared to the source end, the inversion charge towards the drain end is much higher. But these charges do not contribute to the drain PSD because $|\Delta A_d|^2$ near the drain end is negligible. On the other hand, KP method predicts a ΔA_d independent of position (equal to the inverse of the channel length) which assigns the same weight to both strongly inverted region near the drain and weak/moderately inverted region near the source. As the strongly inverted drain region incorrectly gets a much higher weight, KP grossly overestimates the drain noise. Note that when the bias dependent IF is included, our model satisfactorily matches the device simulation as shown in Fig. 2.

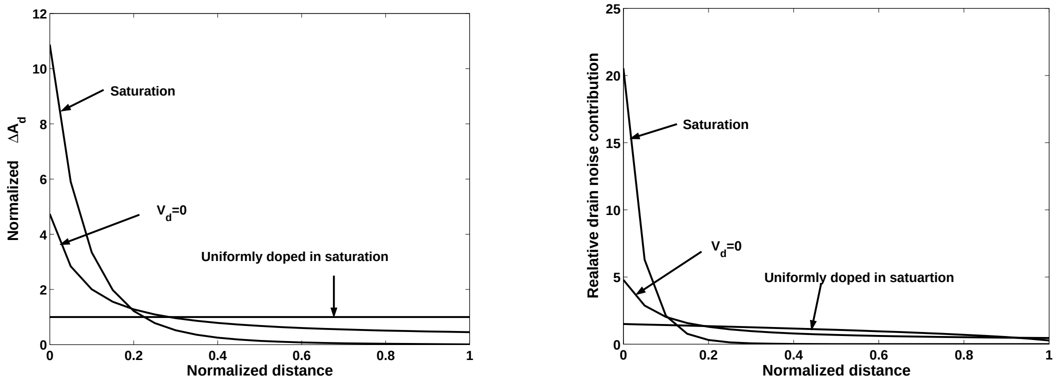
4 EFFECT OF LATERAL NONUNIFORM DOPING ON CORRELATION COEFFICIENT AND RF NOISE PERFORMANCE

In order to validate our induced gate noise modeling approach, we plot the correlation between drain and induced gate noise, c_g, defined as $c_g = S_{i_d i_g}/\sqrt{S_{i_d^2} S_{i_g^2}}$, as a function of the drain voltage. Fig. 4(a) and Fig. 4(b) show the plots of the imaginary part of c_g for low and high gate voltages respectively and our model again gives a very good match. Note that this term also behaves considerably different from conventional MOSFET where c_g saturates to 0.6 in weak inversion [9] and to 0.4 in strong inversion. From these plots, we make two very interesting observations. First one is that KP-based methods [2], [8] for induced gate noise produces even a sign error in the correlation coefficient. This happens because the induced gate current changes sign as one moves from source to drain [2]. Here also a conventional method incorrectly puts a lower weight to the source end, and, since the charge is much higher near the drain end, the total contribution gets dominated by the drain end. But in reality, the gate noise gets dominated by the source end (note that ΔA_d is highly peaked near the source, it causes the product of ΔA_d and ΔA_g determine the sign of c_g, see (19)). As ΔA_g changes sign from source to drain, it is evident that KP method will cause a sign error. The second important observation is that the value of c_g, especially in weak inversion and high drain voltage, is higher than that of a uniformly doped MOSFET. This fact has tremendous impact on the RF noise performance of MOSFET.

The minimum noise figure F_{min} of a MOSFET is given by [10], [11]

$$F_{min} = 1 + 2\frac{\omega}{\omega_t}\sqrt{\gamma\beta}\sqrt{1 - |c_g|^2}, \qquad (20)$$

where γ, β are the excess noise factor for drain and gate respectively [10], [11]. From (20), it is clear that as $|c_g|$ gets



(a) (b)

Figure 6: Profile of a) drain impedance field (normalized to the inverse of channel length) b) relative contribution to drain noise over the position ($|\Delta A_d|^2 \quad S_{\delta i_n^2}/S_{i_d^2}$) for lateral nonuniformly and uniformly doped MOSFET at $V_G = 0.7$ V. The plots shows that compared to uniformly doped MOSFET, impedance field is highly localized near the source end and the localization increases as the drain voltage is applied. As a result, in a lateral nonuniform device, only a portion near the source actually generates noise and as the drain voltage increases the fraction of the channel that actually contributes to the noise shrinks

closer to unity in a lateral nonuniform device, this kind of device will have a much smaller minimum noise figure as demonstrated in [12].

In the rest of this Section, we will explain the physical mechanism which causes a very high correlation between drain and gate noise in lateral nonuniform devices. If the effect of distributed doping is lumped into two transistors as shown in Fig. 5, then the transistor near the source will be weakly inverted and the transistor near the drain will be strongly inverted. If the noise current of the weakly inverted transistor is i_{nw} and the noise current of the strongly inverted transistor is i_{ns}, the total terminal noise current i_{nt} would be,

$$i_{nt} = \frac{R_w}{R_w + R_s} i_{nw} + \frac{R_s}{R_w + R_s} i_{ns}, \tag{21}$$

where R_w and R_s are the channel resistances of the weakly and strongly inverted transistor, respectively.

Now, as $R_w >> R_s$, the terminal current mainly gets determined by the transistor near the source end which would imply that the impedance field ΔA_d is localized near the source. Now what happens if the drain voltage is increased? As $R_w >> R_s$, the channel potential drops mainly across the weakly inverted transistor. The resistance of the weakly inverted channel depends exponentially on the channel potential whereas the strongly inverted transistor has a linear dependence. As a result, the change in the resistance of the weakly inverted transistor ΔR_w is much greater than the change in the strongly inverted transistor $\Delta R_w >> \Delta R_s$. It makes the impedance field even more strongly localized near the source (see Fig. 6). Fig. 6 also shows the relative contribution to the drain noise from position x (i.e. $|\Delta A_d|^2 S_{\delta i_n^2}/S_{i_d^2}$), which clearly indicates that in a lateral nonuniform device only a portion near the source end actually generates noise and as the drain voltage increases, the fraction of the channel that actually contributes to the noise, shrinks.

Induced gate current originates because the drain noise current generated from a local noise source sets up a fluctuation in the surface potential. Because the nonuniform doping drastically reduces the impedance field ΔA_d near the drain, the noise sources located at the drain end are not very efficient in creating a drain noise current which is the cause of induced gate current. As a result ΔA_g also becomes localized near the source and this localization increases as the drain voltage increases. Fig. 7 shows the profile of ΔA_g and the relative contribution to the gate noise (i.e. $|\Delta A_g|^2 S_{\delta i_n^2}/S_{i_g^2}$) from position x. This figure clearly indicates that the gate noise contribution is also localized near the source. Notice that the relative gate and drain noise contributions plotted along the channel (Fig. 6(b) and Fig. 7(b)) are almost of the same magnitude and shape, which is the signature of a high correlation between the induced gate and drain noise currents.

Up to this, we have understood that in a lateral nonuniform MOSFET both ΔA_d and ΔA_g are strongly localized near the source and this localization increases as the drain bias increases. Now consider what happens to c_g if ΔA_d and ΔA_g are localized at some point x_0. Then the contribution to the PSDs and cross PSDs comes mainly from a region Δx_0 around x_0. Therefore, $S_{i_d^2} = |\Delta A_d(x_0)|^2 S_{\delta i_n^2}(x_0)\Delta x_0$, $S_{i_g^2} = |\Delta A_g(x_0)|^2 S_{\delta i_n^2}(x_0)\Delta x_0$ and $S_{i_g i_d} = \Delta A_g(x_0)\Delta A_d^*(x_0)$ $S_{\delta i_n^2}(x_0)\Delta x_0$. From the definition of c_g, it follows that $c_g \approx -j$, meaning that induced gate and drain noise currents are fully correlated (c_g is purely imaginary because of the capacitive coupling occurring between channel noise and the gate). This result is also very intuitive. Had there been a single noise source in the channel, drain and gate noise would have been fully correlated (because they originate from the same noise source) and localized impedance fields actually turns the situation in the channel closer to this ideal one.

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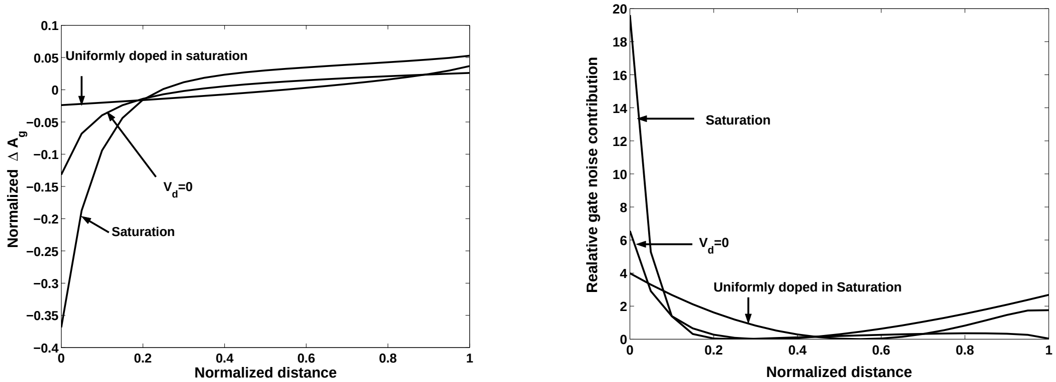

(a) (b)

Figure 7: Profile of a) gate impedance field (normalized with respect to $-j\omega L/\mu U_T$) b)relative contribution to gate noise over the position ($|\Delta A_g|^2 \quad S_{\delta i_n^2}/S_{i_g^2}$) for a lateral nonuniformly and uniformly doped MOSFET at $V_G = 0.7$ V. The plots shows that compared to uniformly doped MOSFET, impedance field is highly localized near the source end and the localization increases as the drain voltage is applied. As a result, in a lateral nonuniform device, only a portion near the source end actually generates noise and as the drain voltage increases, the fraction of the channel that actually contributes to the noise shrinks

5 CONCLUSION

In this work we have presented a general analytical noise modeling methodology accounting for both lateral nonuniformity and field-dependent mobility. This methodology is applicable to any kind of noise mechanism, doping profile and field-dependent mobility. It is shown that conventional KP-based methods, at low gate voltages, can overestimate the thermal noise by 2-3 orders of magnitude. In addition, a very high correlation between drain and induced gate noise improves the RF noise properties of the MOSFET. The high correlation between drain and gate noise essentially arises from the strong localization of drain and gate impedance field, the quantity responsible for noise propagation. This high localization of impedance fields occurs because of the fundamental fact that the presence of nonuniform doping makes the drain impedance field, contrary to the uniformly doped MOSFET, position and bias dependent.

REFERENCES

[1] F. M. Klaassen and J. Prins, "Thermal Noise of MOS Transistors," *Philips Res. Repts*, vol. 22, pp. 505–514, Oct. 1967.

[2] A. S. Roy, C. C. Enz, and J.-M. Sallese, "Noise Modeling Methodologies in the Presence of Mobility Degradation and Their Equivalence," *IEEE Trans. Electron Devices*, vol. 53, no. 2, pp. 348–355, Feb. 2006.

[3] A. S. Roy, Y. S. Chauhan, C. C. Enz, and J.-M. Sallese, "Noise Modeling in Lateral Asymmetric MOSFET," in *IEEE International Electron Devices Meeting*, Dec. 2006, pp. 751 – 754.

[4] A. S. Roy, C. C. Enz, and J.-M. Sallese, "Noise Modeling in Lateral Nonuniform MOSFET," *IEEE Trans. Electron Devices*, vol. 54, no. 8, pp. 1994–2001, Aug. 2007.

[5] J. P. Nougier, "Noise and diffusion of hot carriers ," in *Physics of nonlinear transport in semiconductors*, D. K. Ferry, J. R. Barker, and C. Jacoboni, Eds. Plenum Press, 1980, pp. 415–477.

[6] ——, "Fluctuations and Noise of Hot Carriers in Semiconductor Materials and Devices," *IEEE Trans. Electron Devices*, vol. 41, no. 11, pp. 2034–2048, Nov. 1994.

[7] A. S. Roy and C. Enz, "Compact Modeling of Thermal Noise in the MOS Transistor," *IEEE Trans. Electron Devices*, vol. 52, no. 4, pp. 611–614, Apr. 2005.

[8] J. C. J. Paasschens, A. J. Scholten, and R. van Langevelde, "Generalisations of the Klaassen-Prins Equation for Calculating the Noise of Semiconductor Devices," *IEEE Trans. Electron Devices*, vol. 52, no. 11, pp. 2463– 2472, Nov. 2005.

[9] A.-S. Porret and C. C. Enz, "Non-Quasi-Static (NQS) Thermal Noise Modelling of the MOS Transistor," *IEE Proceedings Circuits, Devices and Systems*, vol. 151, no. 2, pp. 155–166, April 2004.

[10] A. Cappy, "Noise Modeling and Measurement Techniques," *IEEE Trans. Microwave Theory Tech.*, vol. 36, no. 1, pp. 1–10, Jan. 1988.

[11] C. Enz and Y. Cheng, "MOS Transistor Modeling for RF IC Design," *IEEE Journal of Solid-State Circuits*, vol. 35, no. 2, pp. 186–201, Feb. 2000.

[12] T. C. Lim, R. Valentin, G. Dambrine, and F. Danneville, "MOSFETs RF Noise Optimization via Channel Engineering," *IEEE Electron Device Letters*, vol. 29, no. 1, pp. 118–121, Jan. 2008.