Noise Modeling in Lateral Asymmetric MOSFET

A. S. Roy[1] and C. C. Enz[1,2]

[1]Ecole Polytechnique Fédérale de Lausanne (EPFL)
Laboratoire d'Electronique Générale (LEG), CH-1015 Lausanne, Switzerland

[2]Swiss Center for Electronics and Microtechnology (CSEM)
CH-2007 Neuchâtel, Switzerland.

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Introduction

- HV devices are used more and more in RF switched mode power supplies and power amplifiers

- High Voltage (HV) devices are made of an intrinsic MOSFET and a drift region close to the drain

- Physical modeling of the intrinsic part has received considerable attention recently because of its lateral asymmetry

- Noise modeling of these devices are very important

- Conventional noise analysis do not work for lateral asymmetric device

- We present a new noise modeling methodology to account for lateral asymmetry

Lateral asymmetric MOSFET

- Doping N is much higher in the source end
- Doping N depends on $x \rightarrow V_T \propto \sqrt{N} \rightarrow V_T$ depends on x
- Doping N is much higher in the source end $\rightarrow V_T$@source > V_T@drain

Lateral asymmetric MOSFET

- $Q_{inv} \propto (V_G - V_T(x) - nV) \to Q_{inv}$ has explicit x dependence

- In a conventional MOSFET x dependence comes only through channel potential V

- $I(x) = W\mu(x, E)Q_{inv}(x, V)\frac{dV}{dx}$: where $E = \frac{dV}{dx}$

- $I(x) = g(x, V, E)\frac{dV}{dx}$

- $g(x, V, E) = W\mu(x, E)Q_{inv}(x, V)$

Need for a new noise calculation method

- Conventional noise calculation predicts that drain current PSD is proportional to the total inversion charge stored in the device

- $S_{I_D^2} \propto \int_0^L g \, dx \propto \int_0^L Q_{inv} \, dx$

- $V_{DS} = 0$, $N_S = 5 \times 10^{17}$ cm^{-3}, $N_D = 1 \times 10^{16}$ cm^{-3}, $L = 2\mu$m, $W = 1\mu$m, $t_{ox} = 8$nm

Need for a new noise calculation method

- Conventional noise calculation predicts that drain current PSD is proportional to the total inversion charge stored in the device

- $S_{I_D^2} \propto \int_0^L g dx \propto \int_0^L Q_{inv} dx$

- Conventional Klaassen-Prins (KP) based methods cannot be used in lateral asymmetric device

- A noise calculation method needs to be formulated

- $\Delta i_d(x)$ denotes contribution to terminal noise Δi_d from the noise source at position x

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- $\Delta i_d(x) = \Delta A_d(x)\delta i_n(x)$

- $\Delta A_d(x)$ is vector impedance field and $\delta i_n(x)$ is local noise source

- Noise source PSD $\overline{\delta i_n(x_1)\delta i_n(x_2)} = S_{\delta i_n^2}\delta(x_1 - x_2)$

- Terminal noise current $\Delta i_d = \int_0^L \Delta A_d(x)\delta i_n(x)dx$

- Drain noise PSD $S_{i_D^2} = \int_0^L |\Delta A_d(x)|^2 S_{\delta i_n^2}dx$

Noise calculation

- What changes compared to uniform case? $\Delta A_d(x)$ or $S_{\delta i_n^2}$

- $S_{\delta i_n^2} = 4 \cdot q \cdot W \cdot Q_{inv} \cdot D_n$

- D_n is the noise diffusivity given as $D_n = \frac{KT_n}{q}\mu$, T_n is the noise temperature

- As the channel length is relatively high T_n does not differ much from lattice temperature

- $S_{\delta i_n^2}$ remains same in the presence of lateral asymmetry

- Presence of lateral asymmetry drastically change the noise propagation through vector impedance field

Noise calculation: Calculation of $\Delta A_d(x)$

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

- $i(x) = \left(g_0 + \frac{\partial g_0}{\partial E_0} \frac{dV_0}{dx}\right) \frac{dv}{dx} + \left(\frac{\partial g_0}{\partial V_0} \frac{dV_0}{dx}\right) v + \delta i_n(x)$

- $i(x) = \Delta i_d$ is constant over the channel.

- v vanishes at source (0) and drain (L).

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

- We will treat the system as a ODE of product $g_0 v$

Noise calculation: Calculation of $\Delta A_d(x)$

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

- Integration factor $R(x) = \exp\left(-\int_0^x \frac{1}{g}\left(\frac{g}{g + \frac{\partial g}{\partial E}E}\right)\frac{\partial g}{\partial x}dx\right)$

- $\frac{d(R(x)gv)}{dx} = \left(\frac{gR(x)}{g + \frac{\partial g}{\partial E}E}\right)(\Delta i_d - \delta i_n(x))$

- v vanishes at 0 and L; $\int_0^L f(x)(\Delta i_d - \delta i_n(x)) = 0$; $f(x) = \frac{gR(x)}{g + \frac{\partial g}{\partial E}E}$

- $\Delta i_d = \frac{\int_0^L f(x)\delta i_n(x)dx}{\int_0^L f(x)dx}$

- $\Delta i_d = \int_0^L \Delta A_d(x)\delta i_n(x)dx$

- $\Delta A_d = f(x)\Big/\int_0^L f(x)dx$

- Ignore the impact of mobility degradation $\frac{\partial g}{\partial E} = 0$

- $f(x) = \exp\left(-\int_0^x \frac{1}{g_0} \frac{\partial g_0}{\partial x} dx\right)$

- No explicit position dependence $\rightarrow \frac{\partial g}{\partial x} = 0$

- $f(x) = 1 \rightarrow \Delta A_d = \frac{1}{L}$

- $S_{I_D^2} \propto \int_0^L S_{\delta i_n^2} dx \propto \int_0^L g \, dx \propto \int_0^L Q_{inv} \, dx$

- *Lateral asymmetry makes vector impedance field position and bias dependent*

- The effect is more pronounced on weak inversion

Noise calculation: Effect of lateral asymmetry

- V_T @source $> V_T$ @drain : for low V_G the source is in weak and the drain is in strong inversion
- $f(x) = \exp\left(-\int_0^x \frac{1}{g_0}\frac{\partial g_0}{\partial x}dx\right)$
- g is very small near the source $\rightarrow f(x)$ decays off very rapidly

- At low V_G ΔA_d to be very highly peaked near the source

- $S_{I_D^2}(x) \propto |\Delta A_d|^2 S_{\delta i_n^2} \propto |\Delta A_d|^2 Q_{inv}$
- Charges near the strongly inverted drain does not contribute to noise !

- As V_G exceeds the threshold voltage of source end the region near the source starts to enter into the strong inversion region
- g near the source end starts to increase
- g is not that small near the source $\rightarrow f(x)$ decays off slowly

- At high V_G ΔA_d should be more or less uniform

- $S_{i_D^2}(x) \propto |\Delta A_d|^2 S_{\delta i_n^2} \propto |\Delta A_d|^2 Q_{inv}$
- Effect of position dependence of $|\Delta A_d|$ much less pronounced

- Plot of drain thermal noise PSD versus gate voltage for a lateral asymmetric MOSFET at $V_{DS} = 0$

- R_w » R_s : Weakly inverted region determines noise

- Noise parameters: $\gamma = \dfrac{S_{I_D^2}(V_G, V_D)}{S_{I_D^2}(V_G, 0)}$

- As an increase in drain voltage always decreases the total charge, the KP method can only predict a monotonically decreasing behavior of γ

- Noise parameters: $\gamma = \dfrac{S_{I_D^2}(V_G, V_D)}{S_{I_D^2}(V_G, 0)}$

- Effect of position dependence of $|\Delta A_d|$ much less pronounced at high $V_G \rightarrow \gamma$ decreases monotonically with V_{DS}

Induced gate noise modeling

- Induced gate noise $\Delta i_g(x)$ originates due to the fluctuation of channel potential across the gate capacitance $C_g(x)$

- Terminal noise current $\Delta i_g = \int_0^L \Delta A_g(x)\delta i_n(x)dx$

- Drain noise PSD $S_{I_G^2} = \int_0^L |\Delta A_g(x)|^2 S_{\delta i_n^2} dx$

- Drain-Gate cross PSD $S_{I_D I_G} = \int_0^L \Delta A_d \Delta A_g S_{\delta i_n^2} dx$

- ΔA_g is proportional to the area of the potential.

- ΔA_g changes sign from source to drain

- $\Delta A_g = -\frac{j\omega W}{\int_0^L f(x)dx} f(x) \left(\int_0^L f(x_1)(\lambda(x_1) - \lambda(x))dx_1 \right)$

- $\lambda(x) = \int_0^x \frac{\partial Q_g}{\partial V} \frac{dx}{R(x)g}$

Model validation

- Noise parameters: $c_g = \dfrac{S_{I_D I_G}}{\sqrt{S_{I_D^2} S_{I_G^2}}}$

- KP based method introduces a sign error at low gate voltages γ

Model validation

- Noise parameters: $c_g = \dfrac{S_{I_D I_G}}{\sqrt{S_{I_D^2} S_{I_G^2}}}$

- Sign error persists even at high gate voltages

- ΔA_g changes sign from source to drain

- KP method incorrectly puts a lower weight to the source end, and as the charge is much higher near drain end, the total contribution incorrectly gets dominated by the drain

- Situation somewhat improves with increase in gate voltage

- Sign error still occurs at low V_{DS} where delicate balancing take palce

Conclusion

- The noise properties in presence of lateral asymmetry are drastically different from conventional MOSFET

- At low gate voltages Klaassen-Prins (KP) based methods can overestimate the noise by 2-3 orders of magnitude

- We have presented a general analytical noise modeling methodology accounting for both lateral asymmetry and field dependent mobility

- Our analysis clearly points out the discrepancy arises due to position dependence of impedance field

- As impedance field for gate changes sign from source to drain, KP based methods produces a sign error in correlation coefficient