Noise Modeling in Lateral Asymmetric MOSFET

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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.
- 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

- $Q_{inv} \propto (V_G - V_T(x) - nV) \rightarrow Q_{inv}$ 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.

\[ S_{I_d} \propto \int_0^L gdx \propto \int_0^L Q_{inv} dx \]
Need for a new noise calculation method

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

\[ S_{I_D} \propto \int_0^L gdx \propto \int_0^L Q_{inv} dx \]

- 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 \( \Delta i_d \) from the noise source at position \( x \)
Noise calculation

\[ \Delta i_d(x) \] denotes contribution to terminal noise \( \Delta i_d \) from the noise source at position \( x \)

\[ \delta i_n(x) \]
Δi_d(x) denotes contribution to terminal noise Δi_d from the noise source at position x

Δi_d(x) = ΔA_d(x)δi_n(x)

ΔA_d(x) is vector impedance field and δi_n(x) is local noise source

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

Terminal noise current Δi_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 $\Delta A_d(x)$

\[ l_0(x) + i(x) = g \left( x, V_0 + v, \frac{d(V_0 + v)}{dx} \right) \frac{d(V_0 + v)}{dx} + \delta n(x) \]

\[ i(x) = \left( g_0 + \frac{\partial g_0}{\partial E_0} \frac{dV_0}{dx} \right) \frac{dv}{dx} + \left( \frac{\partial g_0}{\partial V_0} \frac{dV_0}{dx} \right) v + \delta n(x) \]

\[ i(x) = \Delta i_d \text{ is constant over the channel.} \]

\[ v \text{ vanishes at source (0) and drain (L).} \]

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

\[ \text{We will treat the system as a ODE of product } g_0 v \]
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 $R(x) = \exp \left( - \int_0^x \frac{1}{g} \left( \frac{g}{g + \frac{\partial g}{\partial E}} \right) \frac{\partial g}{\partial x} dx \right)$

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

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

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

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

$$\Delta A_d = f(x) / \int_0^L f(x) dx$$
Noise calculation: Effect of lateral asymmetry

- 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

- $V_T@\text{source} > V_T@\text{drain}$: 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 $V_G \Delta A_d$ to be very highly peaked near the source
Noise calculation: Effect of lateral asymmetry

\[ S_{f_D}^2(x) \propto |\Delta A_d|^2 S_{\delta i_n^2} \propto |\Delta A_d|^2 Q_{inv} \]

Charges near the strongly inverted drain do 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 $V_G$, $\Delta A_d$ should be more or less uniform
Noise calculation: Effect of lateral asymmetry

\[ S_{D_D}(x) \propto |\Delta A_d|^2 S_{\delta i_n} \propto |\Delta A_d|^2 Q_{inv} \]

Effect of position dependence of \( |\Delta A_d| \) much less pronounced

\[ V_g = 1.2 \text{ V} \]
Plot of drain thermal noise PSD versus gate voltage for a lateral asymmetric MOSFET at $V_{DS} = 0$
$R_w \gg R_s$: Weakly inverted region determines noise
Model validation: Bias dependence

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

- As an increase in drain voltage always decreases the total charge, the KP method can only predict a monotonically decreasing behavior of \( \gamma \).
Noise parameters: \( \gamma = \frac{S_{I^2}(V_G,V_D)}{S_{I^2}(V_G,0)} \)

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 $\Delta i_g(x)$ 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 $S_{i_G} = \int_0^L |\Delta A_g(x)|^2 \delta i_n^2 \, dx$

- Drain-Gate cross PSD $S_{I_D I_G} = \int_0^L \Delta A_d \Delta A_g S_{\delta i_n^2} \, dx$
**Induced gate noise modeling**

- $\Delta A_g$ is proportional to the area of the potential.
- $\Delta A_g$ changes sign from source to drain.
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  \[ \Delta A_g = -\frac{j\omega W}{\int_0^L f(x)dx} f(x) \left( \int_0^L f(x_1)(\lambda(x_1) - \lambda(x))dx_1 \right) \]
- 
  \[ \lambda(x) = \int_0^x \frac{\partial Q_g}{\partial V} \frac{dx}{R(x)g} \]
Model validation

- Noise parameters: \( c_g = \frac{S_{I_D} I_G}{\sqrt{S_{I_D}^2 S_{I_G}^2}} \)

- KP based method introduces a sign error at low gate voltages \( \gamma \)
Model validation

- Noise parameters: \( c_g = \frac{S_{ID/IG}}{\sqrt{S_{D}^2 S_{G}^2}} \)

![Graph showing Drain Voltage vs. \( c_g \) for different gate voltages]

- Sign error persists even at high gate voltages
Reason for sign error in $C_g$

- $\Delta A_g$ 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
Reason for sign error in $C_g$

- Situation somewhat improves with increase in gate voltage

- Sign error still occurs at low $V_{DS}$ where delicate balancing take place
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.