Compact Modeling of Noise in Nonuniform Channel MOSFET

A. S. Roy[1], C. C. Enz[1,2], T. C. Lim[3] and F. Danneville[3]

[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.

[3]IEMN, UMR CNRS 8520, France.

Workshop on Compact Modeling 2008
Boston, USA

Outline

- Introduction
- General model formulation
- Effect of lateral nonuniform doping
  - Drain noise
  - Induced gate noise
- Effect on RF noise
- Conclusion

Outline

- Introduction
- General model formulation
- Effect of lateral nonuniform doping
  - Drain noise
  - Induced gate noise
- Effect on RF noise
- Conclusion

Introduction

- Compact noise models are based on the well-known Klaassen-Prins (KP) approach

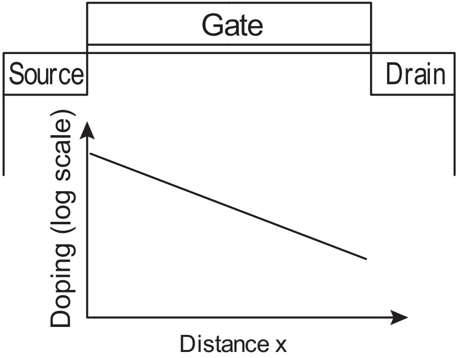
$$S_{\Delta i_d^2} = \frac{1}{L^2} \cdot \int_0^L S_{\delta i_n^2} \cdot \mathrm{d}x$$

- For thermal noise

$$S_{\delta i_n^2} = 4 \cdot q \cdot W \cdot (-Q_i) \cdot D_n$$

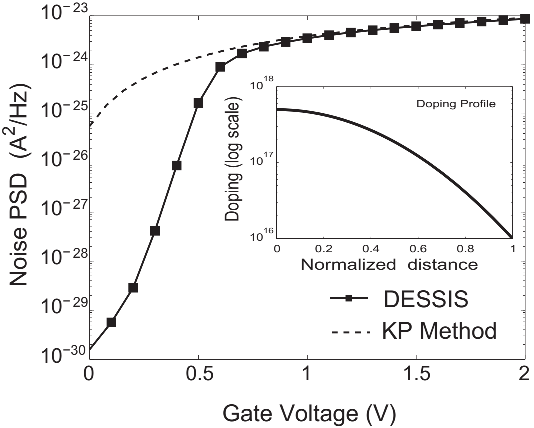
- Does this KP-based formula always hold?

Lateral Nonuniform MOSFET



- Doping N_b is much higher at the source than at the drain: N_b depends on x
- Since $V_T \propto \sqrt{N_b}$ therefore V_T also depends on x
- And hence V_T @source > V_T @drain

Need for a New Noise Calculation Method



$N_S = 5\text{x}10^{+17}$ cm^{-3}
$N_D = 1\text{x}10^{+16}$ cm^{-3}
$V_{DS} = 0$ V
L = 2 μm
W = 1 μm
$t_{ox} = 8$ nm

- The KP approach totally fails in a lateral nonuniform device
- A reformulation is clearly needed!

Outline

- Introduction
- General model formulation
- Effect of lateral nonuniform doping
  - Drain noise
  - Induced gate noise
- Effect on RF noise
- Conclusion

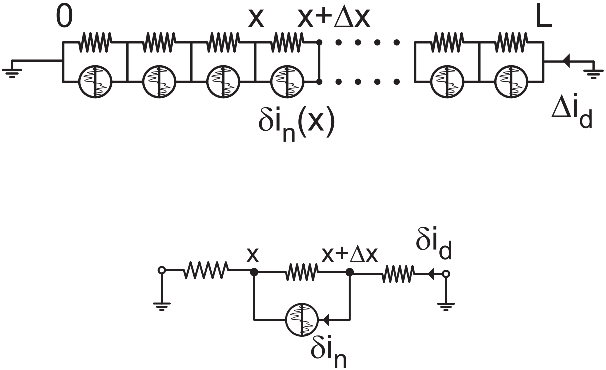
General Model Formulation

- Drain current given by

$$I(x) = g(x,V,E)\cdot\frac{\mathrm{d}V}{\mathrm{d}x} \quad \text{where} \quad g(x,V,E) = -W\cdot\mu(x,E)\cdot Q_i(x,V)$$

  where $E = \mathrm{d}V/\mathrm{d}x$
- Arguments of μ and Q_i denote explicit position and voltage/field dependence
- Mobility $\mu(x,E)$ includes
  - Vertical and longitudinal field-dependence
  - Doping (position) dependence
- Inversion charge $Q_i(x,V)$ models nonuniform doping
- $Q_i \propto (V_G - V_T(x) - nV) \rightarrow Q_i$ has explicit x dependence in addition to its implicit x dependence through V

Noise Calculation – Noise Sources Definitions



- $\delta i_d(x)$ denotes contribution to total terminal noise Δi_d due to local noise source δi_n at position x

Noise Calculation – Vector Impedance Field

- The contribution of the local noise source δi_n to the terminal noise current δi_d is given by

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

where $\Delta A_d(x)$ is the vector impedance field

- The local noise source can be assumed to be uncorrelated along the channel

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

- Drain noise PSD

$$S_{\Delta i_d^2} = \int_0^L |\Delta A_d(x)|^2 \cdot S_{\delta i_n^2} \cdot \mathrm{d}x$$

Noise Calculation – Calculation of $\Delta A_d(x)$

- The vector impedance field for the drain noise is given by

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

where

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

and

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

with

$$E_0 \triangleq \frac{\mathrm{d}V}{\mathrm{d}x}$$

Outline

- Introduction
- General model formulation
- Effect of lateral nonuniform doping
  - Drain noise
  - Induced gate noise
- Effect on RF noise
- Conclusion

Outline

- Introduction
- General model formulation
- Effect of lateral nonuniform doping
  - Drain noise
  - Induced gate noise
- Effect on RF noise
- Conclusion

Effect of Lateral Nonuniform Doping

- If mobility field-dependence is ignored, i.e. $\frac{\partial g}{\partial E} = 0$, we have

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

- If in addition no explicit position dependence is assumed i.e. $\frac{\partial g}{\partial x} = 0$

$$f(x) = 1 \quad \text{and therefore} \quad \Delta A_d = \frac{1}{L}$$

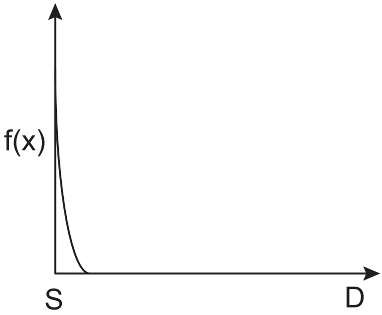
- We get back the classical long-channel formulation

$$S_{\Delta i_d^2} \propto \int_0^L S_{\delta i_n^2} \cdot \mathrm{d}x \propto \int_0^L g \cdot \mathrm{d}x \propto \int_0^L Q_i \cdot \mathrm{d}x$$

- Lateral nonuniformity makes the vector impedance field $A_d(x)$ position dependent

Effect of Lateral Nonuniform Doping – Low V_G

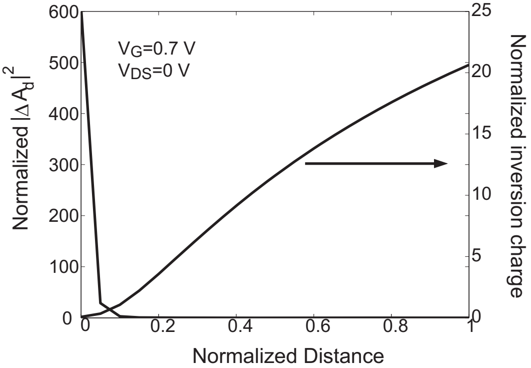
- Since V_T at source $>$ V_T at drain, for low V_G the source is in weak and the drain is in strong inversion
- With $\Delta A_d(x) = \frac{f(x)}{\int_0^L f(x) \cdot dx}$ and $f(x) = \exp\left(-\int_0^x \frac{1}{g_0}\frac{\partial g_0}{\partial x} dx\right)$
- g is very small near the source $\rightarrow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



- At low V_G, ΔA_d is very highly peaked near the source

Effect of Lateral Nonuniform Doping – Low V_G

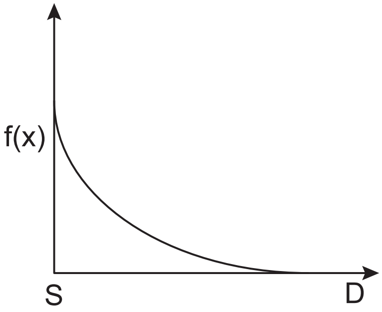
$$S_{\delta i_d^2}(x) \propto |\Delta A_d|^2 \cdot S_{\delta i_n^2} \propto |\Delta A_d|^2 \cdot Q_i$$



- Charges near the strongly inverted drain do not contribute to noise!

Effect of Lateral Nonuniform Doping – High V_G

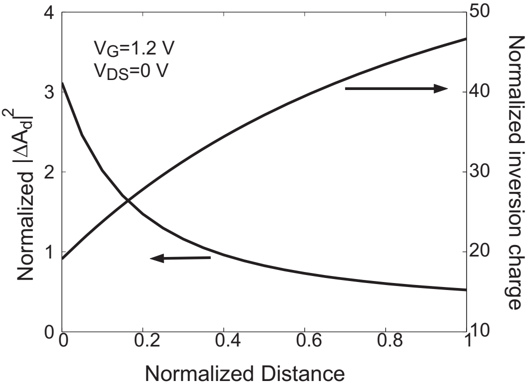
- When V_G exceeds the threshold voltage of the source end, the region near the source starts to enter also into strong inversion
- g near the source starts to increase
- g is not that small near the source $\rightarrow f(x)$ decays off slowly



- At high V_G, $\Delta A_d(x)$ should be more or less uniform

Effect of Lateral Nonuniform Doping – High V_G

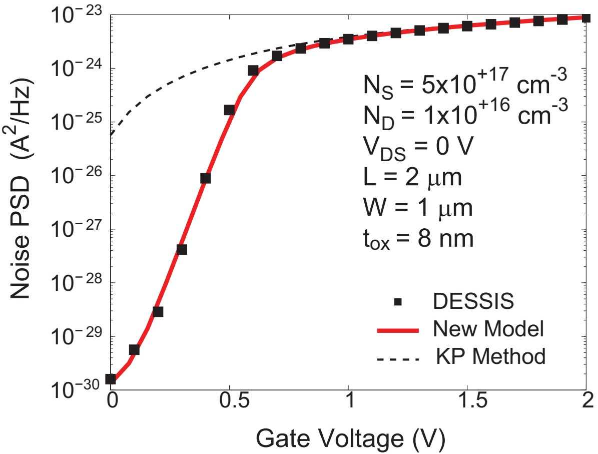
$$S_{\delta i_d^2}(x) \propto |\Delta A_d|^2 \cdot S_{\delta i_n^2} \propto |\Delta A_d|^2 \cdot Q_i$$



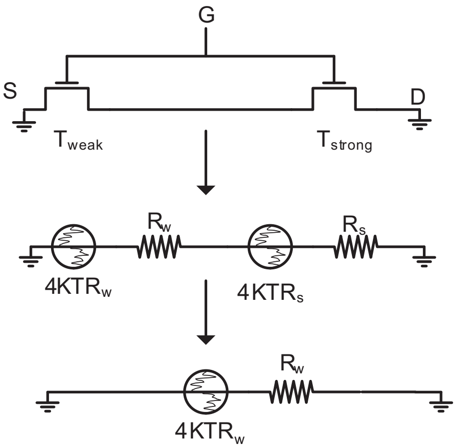
- Effect of position dependence of ΔA_d much less pronounced

Model Validation – V_G Dependence at $V_{DS} = 0$

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

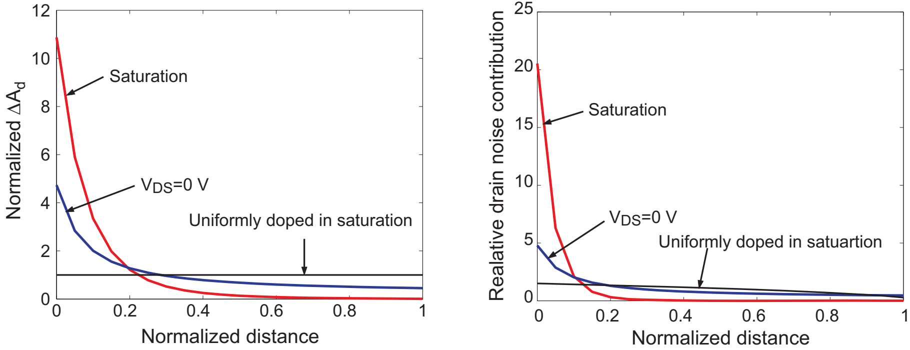


Physical Explanation



- Since $R_w \gg R_s$, weakly inverted region determines noise

Model Validation – Drain Voltage Dependence

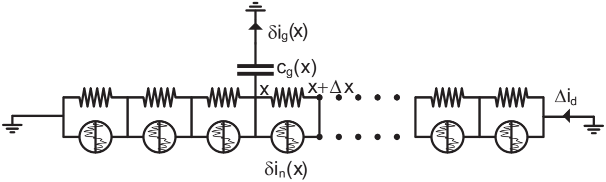


- R_w depends exponentially on channel potential whereas R_s has linear dependence, hence $\Delta R_w \gg \Delta R_s$ when increasing V_{DS}
- Impedance field even more strongly localized near the source when drain voltage increases

Outline

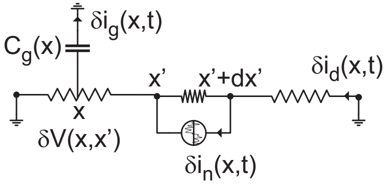
- Introduction
- General model formulation
- Effect of lateral nonuniform doping
  - Drain noise
  - Induced gate noise
- Effect on RF noise
- Conclusion

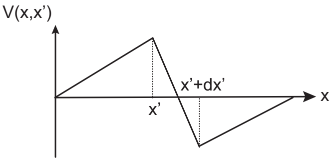
Induced Gate Noise (IGN) Modeling



- Induced gate noise (IGN) $\Delta i_g(x)$ originates from the fluctuation of channel potential across the gate capacitance $C_g(x)$
- Terminal noise current $\Delta i_g = \int_0^L \Delta A_g(x) \cdot \delta i_n(x) \cdot \mathrm{d}x$
- Drain noise PSD $S_{\Delta i_g^2} = \int_0^L |\Delta A_g(x)|^2 \cdot S_{\delta i_n^2} \cdot \mathrm{d}x$
- Drain-Gate cross PSD $S_{\Delta i_d \Delta i_g} = \int_0^L \Delta A_d \cdot \Delta A_g \cdot S_{\delta i_n^2} \cdot \mathrm{d}x$

IGN Modeling – Calculation of $\Delta A_g(x)$



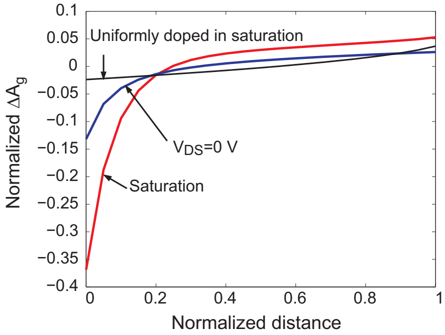


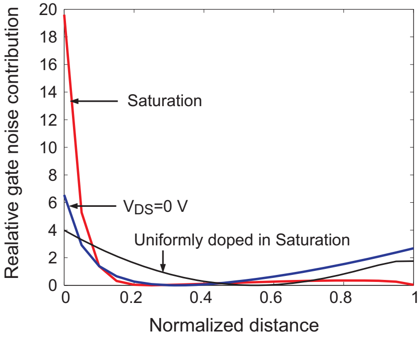
- ΔA_g is proportional to the total area below $V(x, x')$
- ΔA_g changes sign when source is moved from source to drain
- ΔA_g given by

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

where $\lambda(x) = -\int_0^x \frac{C_g(x)}{R(x) \cdot g} \cdot \mathrm{d}x$

IGN Model Validation – Drain Voltage Dependence

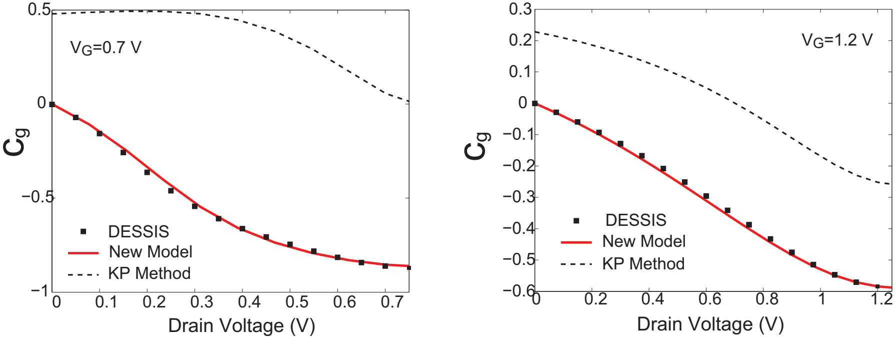




- Impedance field even more strongly localized near the source when drain voltage increases
- Effect of increased V_D even stronger for IGN than for drain noise

IGN Validation – Gate-Drain Noise Correlation Factor

- Noise correlation coefficient $c_g = \frac{S_{\Delta i_d \Delta i_g}}{\sqrt{S_{\Delta i_d^2} \cdot S_{\Delta i_g^2}}}$



- KP-based method completely fails predicting c_g correctly and even introduces a sign error at low V_G
- $|c_g|$ higher than uniformly doped MOSFET (0.6 in WI and 0.4 in SI) especially in weak inversion and high drain voltage

Outline

- Introduction
- General model formulation
- Effect of lateral nonuniform doping
  - Drain noise
  - Induced gate noise
- Effect on RF noise
- Conclusion

Minimum Noise Figure

- The minimum noise figure F_{min} of a MOSFET is given by

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

where γ and δ are the noise excess factors for the drain and gate thermal noise

$$\gamma \triangleq \frac{G_{nD}}{G_m} = \begin{cases} \frac{n}{2} & \text{in WI and sat.} \\ \frac{2n}{3} & \text{in SI and sat.} \end{cases}$$

$$\beta \triangleq G_{nG} \cdot \frac{G_m}{(\omega \cdot C_{GS})^2} = \begin{cases} \frac{1}{5n} & \text{in WI and sat.} \\ \frac{4}{15n} & \text{in SI and sat.} \end{cases}$$

- Larger $|c_g|$ reduces the minimum noise factor
- Nonuniform MOSFET show lower minimum noise factor

Outline

- Introduction
- General model formulation
- Effect of lateral nonuniform doping
  - Drain noise
  - Induced gate noise
- Effect on RF noise
- Conclusion

Conclusions

- The noise properties in presence of lateral nonuniformity are drastically different from conventional MOSFET
- A general analytical noise modeling methodology accounting for lateral nonuniformity was presented
- It clearly points out the discrepancy arises due to position dependence of the impedance fields
- Localization of the impedance fields towards the source is increased in saturation for both drain and gate noise
- As impedance field for gate changes sign from source to drain, KP based methods produces a sign error in correlation coefficient $|c_g|$
- Increased $|c_g|$ leads to lower minimum figure compared to uniform case