RF Noise Simulation for Submicron MOSFET's Based on Hydrodynamic Model

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Introduction

As the cutoff frequency of CMOS technology improves, RF designs are increasingly taking advantage of CMOS technology because of the promise of integrating whole systems on a single chip [1]. Although accurate noise modeling of MOSFET's is indispensable for low noise design, the noise behavior in short channel MOSFET's is not well understood yet. This problem is particularly acute in state-of-art MOSFET technologies because of various second-order effects caused by complex processing such as new drain structures, gate overlap effects, nonuniform doping profiles in the substrate, etc. Therefore, the capability to exploit multi-dimensional device simulation to extract these physical dependencies of noise is highly attractive. Recently several studies have reported MOSFET noise simulation results based on IFM (Impedance Field Method) and DD (Drift-Diffusion) model [2]. However, in contrast to single transport models like DD, higher order moments such as captured by the HD (Hydrodynamic) formulation are needed for noise modeling. Nevertheless, the HD model in two-dimensional noise simulation involves four times larger matrices and to date has not been used for noise analysis. In this paper, a mixed approach of one-dimensional active transmission line modeling and two-dimensional HD device simulation is used. The active transmission line analogy greatly saves computation time while the local information from the device simulator retains simulation accuracy. Validity and error of noise simulation are also discussed.

Simulation Method

The MOSFET can be considered as a nonuniform-lossy-active transmission line [3], in which each infinitesimal segment produces local fluctuations of velocity. As shown in Fig. 1, an MOSFET segment can be represented by a well-known small-signal equivalent circuit. The current source i_n superimposed across the segment represents uncorrelated local fluctuations in the chosen segment.

While multi-dimensional physics are needed to solve DC carrier transport in the MOSFET, they are no longer needed for small-signal transport analysis once detailed and localized DC solutions for each node are obtained. Small-signal transport is a linear process confined to the shallow inversion layer. MEDICI, a commercial two-dimensional numerical device simulator, is used to extract local static quantities, taking into account second order effects in short channel MOSFET's – for example local carrier heating due to spatially rapidly varying electric fields. Fig. 2 illustrates how local quantities are determined. The local small-signal equivalent circuit is verified by comparing first order terminal characteristics to network parameters deduced for the entire MOSFET as shown in Fig. 3.

In order to examine the validity of our approach, a limiting case solution under zero drain bias is compared with results of a non-segmented transmission line. Fig. 4 shows the error in noise calculation caused by segmentation for different sizes and frequencies. It is obvious that the error is negligible as long as the device is properly segmented and the device is considered as a lump. To maintain an error less than 1 percent, $\frac{\Delta x L}{\lambda}$ should be less than $10^{-5}\mu m$, which corresponds to an upper frequency limit of 280 GHz for a 0.25 μm device divided into 20 segments.

Results and Discussion

Simulation results for an actual MOSFET structure are shown in Fig. 5 using the $\gamma - \delta - c$ representation [5] as indicated. The long channel results in Fig. 5 (a) are in quite good agreement with the classical values ($\gamma = 0.667$, $\delta = 1.333$, and $c = j0.395$ in saturation region) regardless of device simulation model. The short channel results in Fig. 5 (b), however, show that HD results are quite different from those of DD. It has been reported that short channel nMOSFET's exhibit larger values of γ and δ, however DD simulations give equal or smaller values. Hence the HD model shows promise in capturing the physics needed for accurate noise simulation.

A 0.25 μm nMOSFET with W = 200 μm was measured using the ATN NP5B system. The gate electrode was silicided and divided into 5 μm-width-fingers in layout so that the noise contribution from gate resistance is negligible. Note that noise performance at high frequencies is always subject to parasitic losses. The pad loss is especially severe in silicon technology due to the conductive substrate. An accurate de-embedding procedure is also critical to get correct intrinsic noise performance [4]. The de-embedded measurement data is compared to simulation results that are transformed from the noise power spectral densities and their cross correlation based on the equivalent circuit in Fig. 3. Detailed formulae used in transformations are given in Fig. 6.

The comparison in Fig. 6 shows that the DD model underestimates noise. The HD case also shows some discrepancy in F_{min} and Y_{opt}, while R_n is in good agreement. Since Y_{opt} is mainly determined by the small signal equivalent circuit of the MOSFET which is verified using the current and capacitance of the device, a large discrepancy in Y_{opt} implies that the de-embedding procedure is not satisfactory. Accurate MOSFET modeling in the GHz range requires many reactive components even for the intrinsic part due to layout parasitics. Because F_{min} is closely related to G_{opt}, correction of G_{opt} may improve agreement of simulated F_{min}. In Fig. 7, an increase in G_{opt} by a factor of 1.7 is used in the transformation to fit model results with the measured G_{opt}; excellent agreement of F_{min} is then observed in both bias and frequency dependencies. The accuracy of intrinsic noise simulation is thus clearly satisfactory and estimation of circuit level noise performance is possible.

Conclusion

Using an active transmission line concept and a two-dimensional HD device simulator, accurate RF intrinsic noise simulation results for deep submicron MOSFET's are presented for the first time. The segmentation error is negligible up to hundreds of GHz. Results show that the HD model captures physical effects that are important for these small devices. The simulation results for 0.25 μm MOSFET show good agreement with measured data when the loss due to G_{opt} is considered.

Acknowledgments

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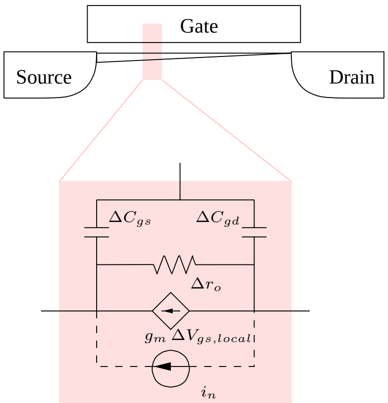
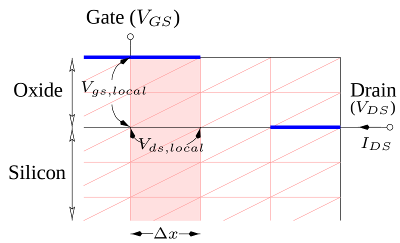


Fig. 1 Local small-signal equivalent circuit for a segment of MOSFET.



$$\Delta C_{gs} + \Delta C_{gd} = \frac{\Delta Q_{inv}}{\Delta V_{gs,local}}$$

$$\Delta r_o = \frac{\Delta V_{ds,local}}{\Delta I_{DS}}$$

$$g_m = \frac{\Delta I_{DS}}{\Delta V_{gs,local}}$$

$$\Delta S_{i_n} = 4\,k\,T_n\,\frac{I_{DS}}{V_{ds,local}}$$

Fig. 2 Illustration for local quantity extraction from two-dimensional device simulation result.

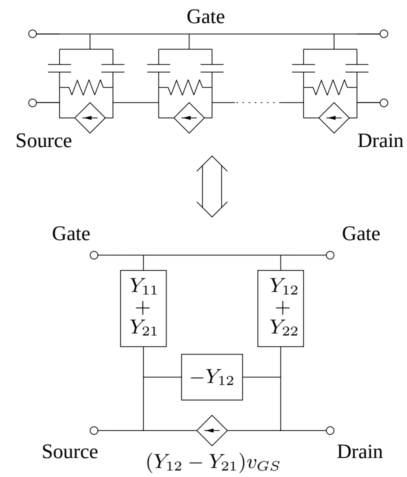
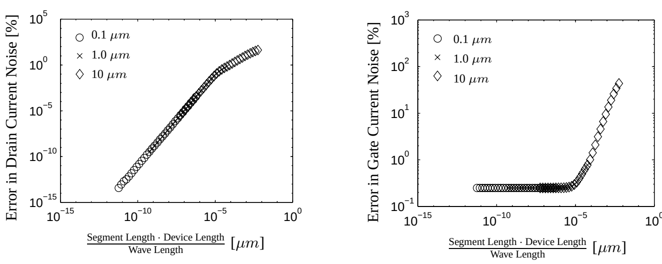
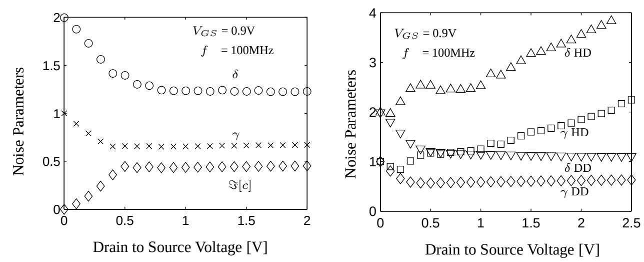


Fig. 3 Small-signal equivalent representation for an MOSFET at high frequency with common-gate configuration.



(a) Error in Drain Noise Calculation (b) Error in Gate Noise Calculation

Fig. 4 Noise calculation error by segmentation for uniform transmission line case. The MOSFET's are divided into 20 segments.



(a) 5μm nMOSFET (b) 0.25μm nMOSFET

Fig. 5 Drain bias evolution of noise parameters comparing Hydrodynamic and Drift-Diffusion model results.

$$\gamma = \frac{\overline{i_d^2}}{4\,k\,T\,\Delta f\,g_{d0}}$$

$$\delta = \frac{\overline{i_g^2}}{4\,k\,T\,\Delta f\,\Re[Y_{GS}]}$$

$$c = \frac{\overline{i_g i_d^*}}{\sqrt{\overline{i_g^2}\,\overline{i_d^2}}}$$

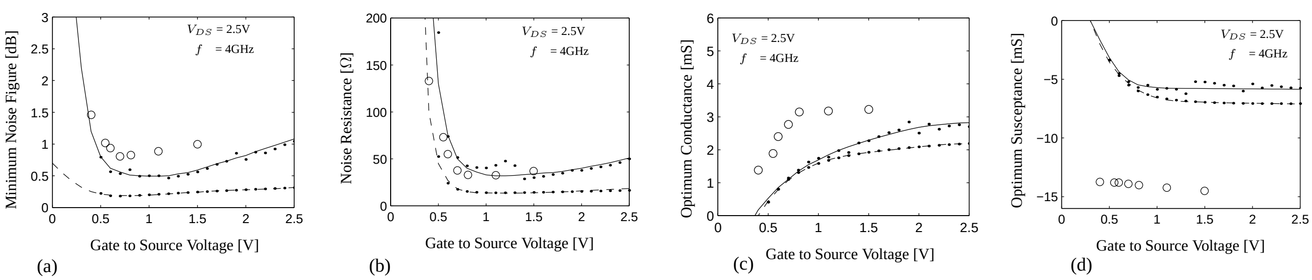


Fig. 6 Comparison of simulated noise parameters (dots) to measured data (circles) for 0.25μm nMOSFET. Solid and dashed lines refer to smoothed simulation results of Hydrodynamic and Drift-Diffusion, respectively. (No correction for the loss due to G_{opt}).

$$F_{min} = 1 + 2R_n(G_{opt} + G_c) \approx 1 + 2R_n G_{opt}$$

$$R_n = |B|^2\,\frac{\overline{i_d^2}}{4\,k\,T\,\Delta f}$$

$$G_{opt} = \sqrt{\frac{G_u}{R_n} + G_c^2} \approx \sqrt{\frac{G_u}{R_n}}$$

$$B_{opt} = -B_c$$

$$Y_c = \frac{D}{B} - \frac{c}{B}\sqrt{\frac{\overline{i_g^2}}{\overline{i_d^2}}} \approx \frac{D}{B}$$

$$G_u = (1 - |c|^2)\,\frac{\overline{i_g^2}}{4\,k\,T\,\Delta f}$$

$$B = \frac{1}{Y_{21} + Y_{22}}$$

$$D = \frac{Y_{11} + Y_{12}}{Y_{21} + Y_{22}} + 1$$

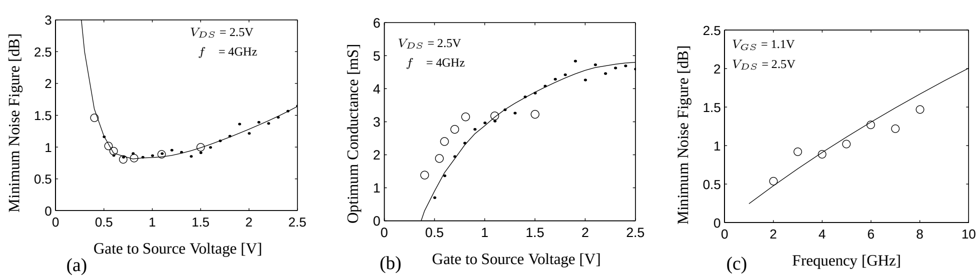


Fig. 7 Measured and simulated noise parameters, corrected for the loss due to G_{opt}.