2D Hierarchical Radio–Frequency Noise Modeling Based on a Langevin–Type Drift–Diffusion Model and Full–Band Monte–Carlo Generated Local Noise Sources

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Abstract

An accurate and efficient 2D drift-diffusion model for thermal noise simulation based on full–band Monte–Carlo (MC) generated local noise sources is presented. Good agreement of the new model and MC device simulations is found for NMOSFETs, whereas previously developed DD based noise models fail. Verification with experiment is shown for a SiGe HBT.

1 Introduction

Noise modeling of semiconductor devices in the framework of a 2D drift–diffusion (DD) model is based on an efficient numerical calculation of the admittance fields and full-band Monte-Carlo (MC) generated local noise sources. In this framework the modeling of the local noise sources for diffusion noise is investigated by comparing three different models consisting of the two approximations usually used in this framework and a new alternative employing directly the spectral density of the velocity fluctuations. For consistency all nonconstant coefficients of the local noise sources are derived from MC bulk simulations and MC device simulation is used to verify the DD based results for an ultra–short channel MOSFET. Finally, based on the new local noise model the noise behavior of a SiGe HBT is simulated and compared to measurement.

2 Theory

In this work, terminal current noise is modeled rigorously physics–based on a Langevin–type DD ansatz. The electron contribution — the hole contribution is analogous — has the following form:

$$S_{II}(\omega) = \int_{\Omega} (\nabla \underline{H}_I(\vec{r},\omega))^T q^2 n S_N \nabla \underline{H}_I^*(\vec{r},\omega) d^3\vec{r} = \int_{\Omega} \Delta S_{II}(\vec{r},\omega) d^3\vec{r}$$

S_{II} is the spectral density of the noise of the terminal current I, $\underline{H}_I$ the electron admittance field, n the electron density, Ω the device area, $\vec{r}$ a real space vector, ω the angular frequency, S_N the local diffusion noise source and ΔS_{II} the spatial distribution of S_{II}.

The most accurate formulation would be to replace S_N by the spectral density matrix of the velocity fluctuations at each point within the device. In all previous

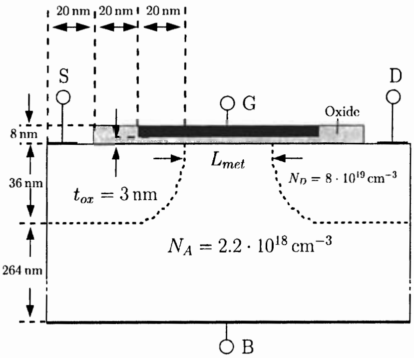

Fig. 1. n–MOSFET test structure

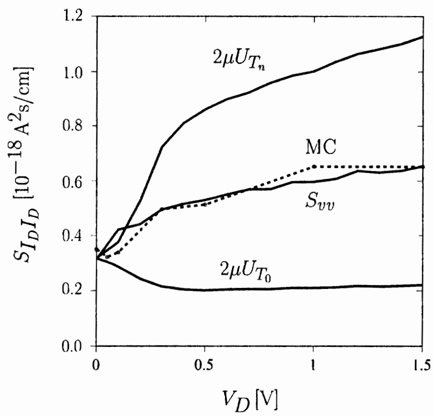

Fig. 2. MC and DD results for the spectral density of the drain current fluctuations as a function of V_D ($V_G = 1.5V$)

studies simple isotropic approximations for this matrix were used [1, 2, 3, 4, 5]. S_N was replaced by either $2\mu_n U_{T_0}$ or $2\mu_n U_{T_n}$, where $U_T = k_B T/q$ is the thermal voltage, μ_n the electron (hole) mobility, T_0 the lattice, T_n the electron (hole) temperature, k_B Boltzmann's constant, and q the elementary charge. These approximations are only justified close to equilibrium. In this paper — for the first time — terminal current noise in 2D devices is modeled by a less stringent isotropic approximation. S_N is replaced by S_{vv}, which is derived from MC bulk simulations [6] and is the spectral density of the velocity fluctuations parallel to the driving field. S_{vv} is evaluated for a number of different driving fields, doping densities, germanium concentrations, and lattice temperatures from which a table model is generated that is subsequently used in the DD model. Since transport models of vastly different physical accuracy are used to establish this new approach, we call it hierarchcal numerical noise modeling. Moreover, this new method is validated by a direct comparison with the terminal current noise resulting from consistent MC device simulations. The overall 2D methodology described here is in some details similar to the 1D approach published in [7], but the local noise sources are evaluated in a different way. In order to simplify the comparison between the particle and the classical simulation all interface effects degrading transport are neglected. To allow a consistent comparison hierarchical numerical modeling is employed not only for S_{vv} but also μ_n and U_{T_n}.

3 Results

At first, an n–channel MOSFET with variable channel length L_{met} is investigated. L_{met} shown in fig. 1 varies between $100\,\mu$m and 40 nm. In fig. 2 the spectral density of the drain current fluctuations is shown for the different models, for the shortest device, and $V_G = 1.5\,\mathrm{V}$ as a function of V_D ($V_S = V_B = 0$). The solid lines show the DD results using S_{vv} and the two approximations $2\mu_n U_{T_0}$ and $2\mu_n U_{T_n}$. The result of the MC device simulator shown by the dashed line is in close agreement with the DD result using S_{vv}. This good agreement validates the new efficient hierarchcal numerical noise modeling method based on S_{vv}.

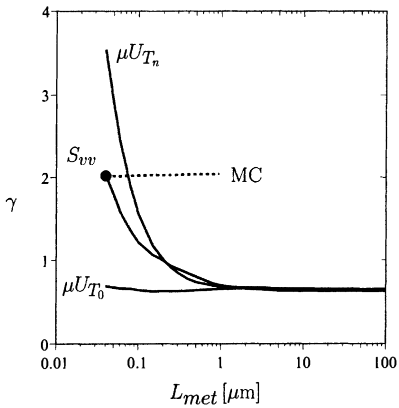

Fig. 3. Excess noise factor γ as a function of L_{met} ($V_D = 0$ and $V_D = 1.5\,\text{V}$) The dot indicates the MC device simulation result

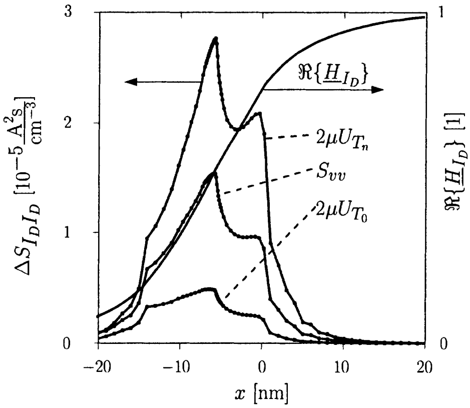

Fig. 4. Spatial distribution of the drain current noise and the real part of the transfer function field $\underline{H}_{I_D}$ ($L_{met} =$ 40nm, $V_G = V_D = 1.5\,\text{V}$). x is the position along the channel

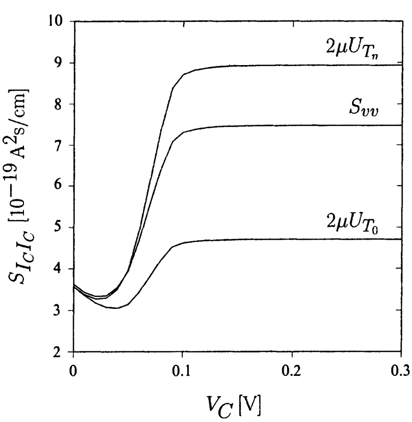

Fig. 5. Autocorrelation spectrum of the collector current as a function of V_C for $V_B = 0.85\,\text{V}$ and $V_E = 0$

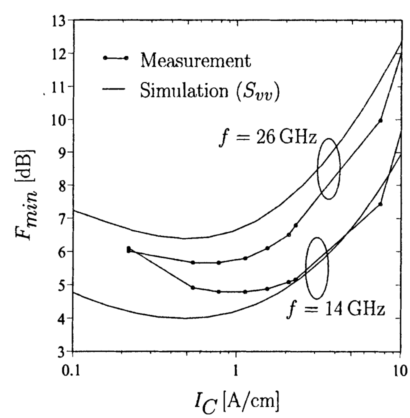

Fig. 6. Comparison of measured and simulated F_{min} for the SiGe HBT as a function of I_C ($V_C = 2\,\text{V}$, $V_E = 0$)

Moreover, the large deviations of the other results shown in fig. 2 from the MC reference clearly indicate that the approximations for S_N typically used in previous studies (e.g. [1],[4]) lead to large errors. In fig. 3 the excess noise factor $\gamma = S_{I_D I_D}/(2k_B T_0 \Re\{Y_{DD}|_{V_D=0}\})$ [8] is shown for $V_G = 1.5\,\text{V}$ as a function of L_{met} and V_D. All DD local noise source models investigated here yield $\gamma = 2/3$ for large L_{met} and $V_D = 1.5\,\text{V}$ consistent with [9]. However, for small L_{met}

and $V_D = 1.5\,\mathrm{V}$ large deviations among the different local noise sources can be observed. In fig. 4 for $V_G = V_D = 1.5\,\mathrm{V}$ and $L_{met} = 40\,\mathrm{nm}$ the local contributions $\Delta S_{I_D I_D}$ in the channel region close to the oxide interface are plotted as a function of the channel position. The large deviations between the different local noise sources are again clearly visible. The dominating contributions to $S_{I_D I_D}$ originate from the source side of the channel consistent with [1], and not from the drain side as previously thought.

The SiGe HBT described in [10] is investigated as a second example. Fig. 5 shows the spectral density of the collector current fluctuations resulting from the three different local noise sources as a function of the collector voltage. The results are comparable to those in fig. 2. In Fig. 6 an experimental verification for the minimum noise figures F_{min} resulting from our new methodology is shown.

4 Conclusions

In conclusion, a new accurate and efficient methodology for terminal current noise modeling called hierarchical numerical noise modeling is presented. The accuracy of this approach is validated by MC device reference simulations as well as by experimental data. It is shown that the usual approximations for the local noise source — typically used in the framework of the DD model — lead to large errors.

Acknowledgment

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