# EFFICIENT MODELING OF MICROSCOPIC AND MACROSCOPIC NOISE BEHAVIOR OF SUBMICRON-HIGHLY-DOPED SEMICONDUCTOR DEVICES AT MILLIMETER-WAVE FREQUENCIES

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## ABSTRACT

An efficient rigorous physical simulator is developed to determine both microscopic and macroscopic noise behavior of submicron and highly doped semiconductor devices at millimeter-wave frequencies. The model is applied to determine the internally generated microscopic noise in the different device regions and their correlation with the externally measured noise fluctuations at the device terminals. Finally, both bias and frequency dependence of important noise parameters are extracted.

## INTRODUCTION

Recently, we have suggested a rigorous physical model which can be used to accurately determine the noise fluctuations in semiconductor devices and their correlations [1]. For submicron-highly-doped devices, which are required in different applications at millimeter-wave frequencies, the computational efficiency of the suggested simulator was, however, deteriorated what limited its use in noise calculation when long time periods are required to be simulated [2]. The aim of the present work is (1) to introduce a highly efficient rigorous simulator to characterize the operation of submicron-highly-doped devices at millimeter-wave frequencies, (2) to study the microscopic noise generated in the different device regions and their correlations with the output noise quantities by using the developed simulator, and finally (3) to use it to extract the important noise parameters.

## MODELING

The model is based on a two-dimensional Monte-Carlo code which is efficiently constructed to determine the microscopic and non-stationary transport properties in submicron millimeter-wave devices [3]. In order to achieve a self-consistent solution of particle motion with the space and time dependent electric field, an iterative forward integration scheme must be used, which solves the Poisson equation together with the equation of particle motion within a time step $\Delta T$. In the conventional Monte-Carlo simulator [1] [3], an explicit coupling scheme is applied in which the electric field distribution is kept constant within $\Delta T$ and coupled to the Monte-Carlo code. In general it is necessary to choose a small $\Delta T$ (in particular for highly doped devices and at low temperatures [4]) in order to avoid instabilities and artificial heating up of the carrier gas. In the present work, variations of the electric field within $\Delta T$ are implicitly included in the model what allows using a much larger time step. Although the integration of particle motion and the solution of the Poisson equation gets more demanding per time step, the required CPU time to simulate a certain physical time-period decreases in total due to the larger time-step (for details see [5]).

## RESULTS

Fig. 1 illustrates the time dependence of the average electron energy in the source region (doped with $2.10^{18}\ cm^{-3}$) of a 0.15 $\mu$m gate-length FET. It can be seen, that the conventional model produces significant artificial heating of the particle gas if $\Delta T \geq 1fs$ (fig. 1a) for the given doping concentration of the contact regions. By applying the present implicit scheme, one still obtains stable results with $\Delta T = 10fs$ (fig. 1b). In this case an effective reduction of the CPU time of about a factor of 7 is achieved compared to the explicit method.

For noise modeling, the generalized noise current spectral density matrix [1], which describes the noise fluctuations in the different device regions and at the device electrodes and their correlations, is determined. It has to be mentioned that all temporal and spatial variations of microscopic and macroscopic quantities, and consequently the noise current spectral densities, are directly calculated with the simulator.

Considering the microscopic noise, the noise fluctuations in the different device regions (see fig. 2a) and their correlations with the output drain current (fig. 2b) are determined. From these results, the superior noise performance of Hetero-FETs at high frequencies (compared to that of MESFETs), for example, can be explained by the reduction of the noise in the under-

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gate region in a Hetero-FET (fig.2b) due to the better transport characteristics within the 2DEG region.

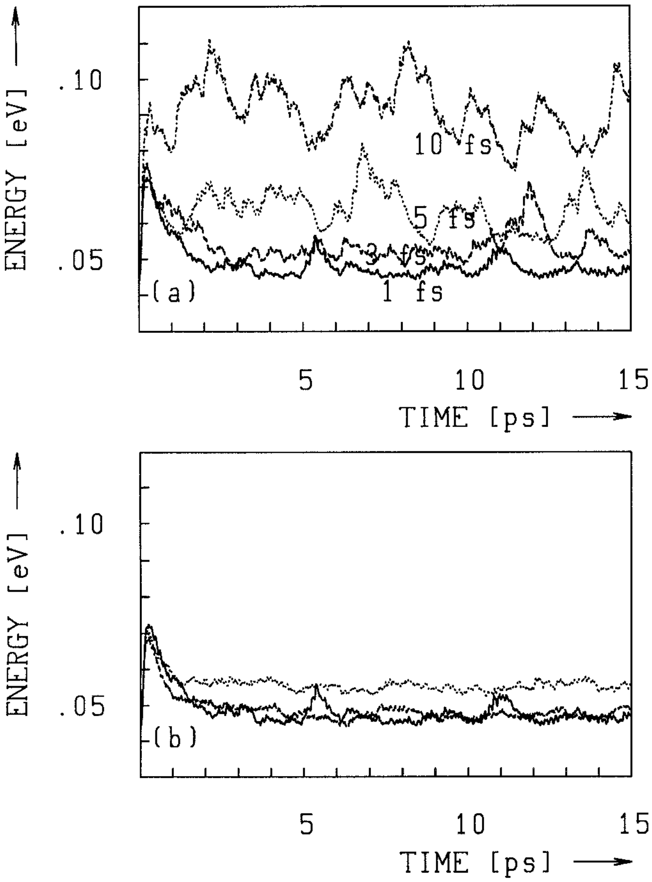


**Fig. 1:** Total mean energy of electrons in the source-contact of a MESFET for a switching-on situation. (a) Results calculated with the explicit method ($\Delta T$=1, 3, 5, 10 fs). (b) Comparison between the results of the explicit method with $\Delta T$=1 fs (solid line) to those of the implicit method with $\Delta T$=10 fs (dashed line) and 15 fs (dotted line).

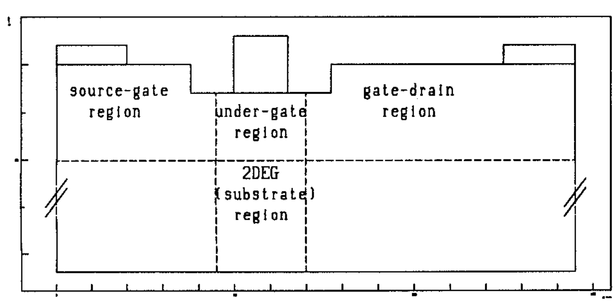


**Fig. 2a:** The simulated Hetero-FET (MESFET) structure which consists of a 30 $nm$ thick $GaAs$ cap layer ($N_d$ = $2.10^{18} cm^{-3}$), a 42 $nm$ $Al_xGa_{1-x}As$ ($GaAs$) layer ($N_d$ = $10^{18} cm^{-3}$), and a $GaAs$ buffer layer. A 0.15$\mu m$ gate length is recessed at a depth of 30 $nm$ with source-gate and source-drain electrode separations of 0.3 and 1.05 $\mu m$, respectively. The simulations were performed at temperature of 300 $K$ and drain voltage of 2 V.

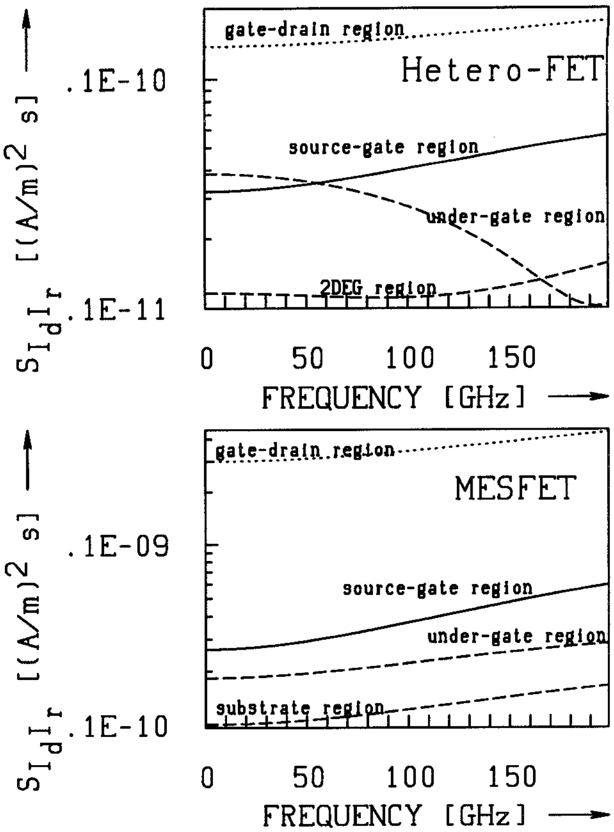


**Fig. 2b:** Cross-correlation $S_{I_dI_r}$ ($I_d$ and $I_r$ refer to drain current and current in a region, respectively) of the internally generated noise current $I_r$ with the drain current $I_d$ (Vg=-.2 V).

By dividing the simulated device into different regions (fig. 3a), the generated noise in these regions can be resolved, what is shown in fig. 3b-d. As can be seen a relatively high generated noise is produced in the source as well as in the drain region. Furthermore the two-dimensional distributions of different correlations of the microscopic noise current spectral densities with the measurable noise quantities are calculated.

From the results shown in fig. 3c and 3d, it can be seen that also the transformation of the internally generated noise to the output drain and gate noise-currents is dominated by a relatively high contribution of the source-region and the drain-region as well.

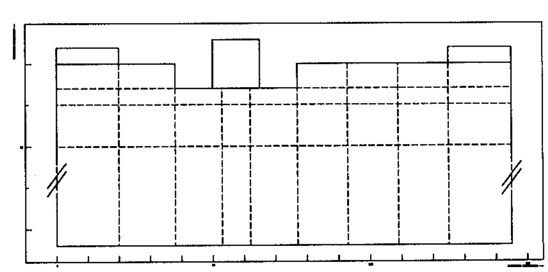

**Fig. 3a:** Simulated fine two-dimensional noise regions in a Hetero-FET.

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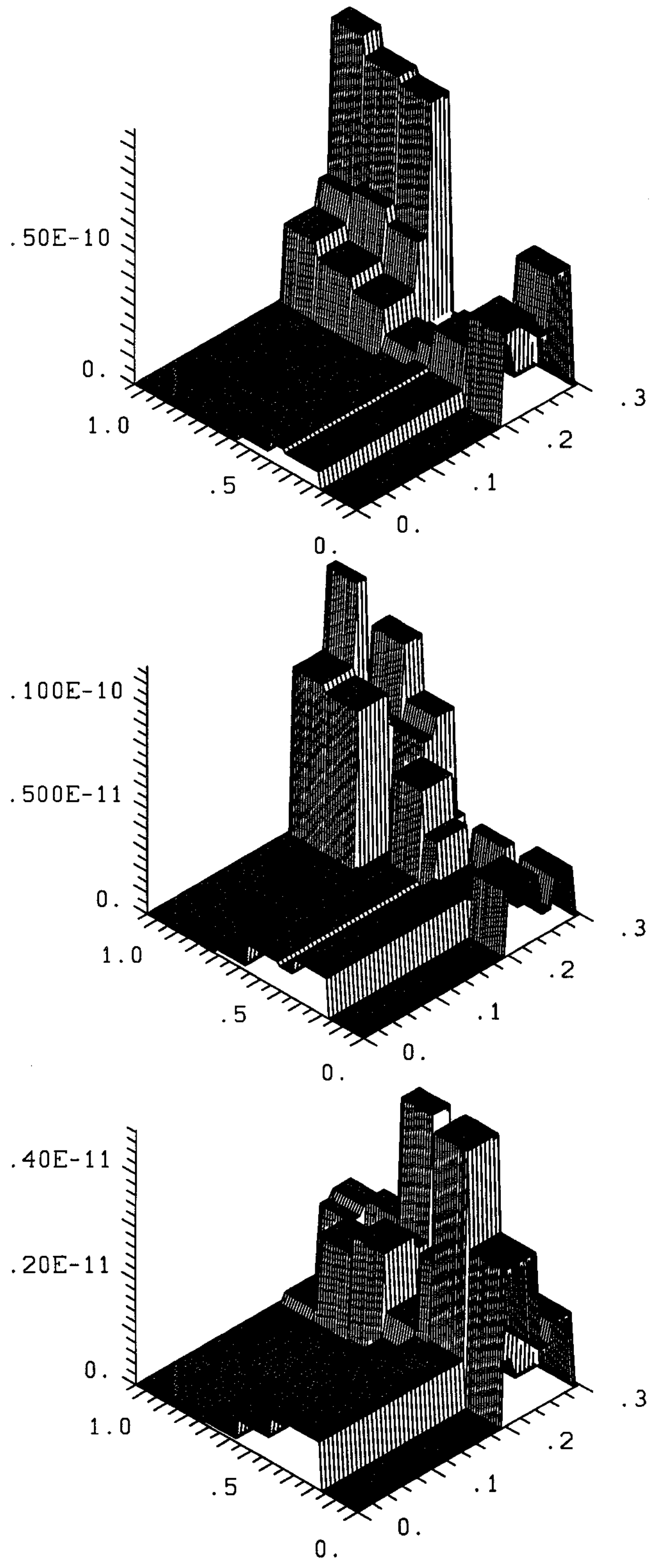


**Fig. 3:** 2D distribution of the noise current spectral densities (b, top) $S_{I_r I_r}$, (c) $S_{I_d I_r}$, and (d, bottom) $S_{I_g I_r}$ ($I_d$, $I_g$ and $I_r$ refer to drain current, gate current, and current in a region, respectively. The left axis and the right axis at the bottom of each graph equal the x-axis and the y-axis of fig. 3a, respectively. The first row at small x-values of each graph refers to the second row at the left side of fig. 3a. The source-contact and the drain-contact are at high y-values).

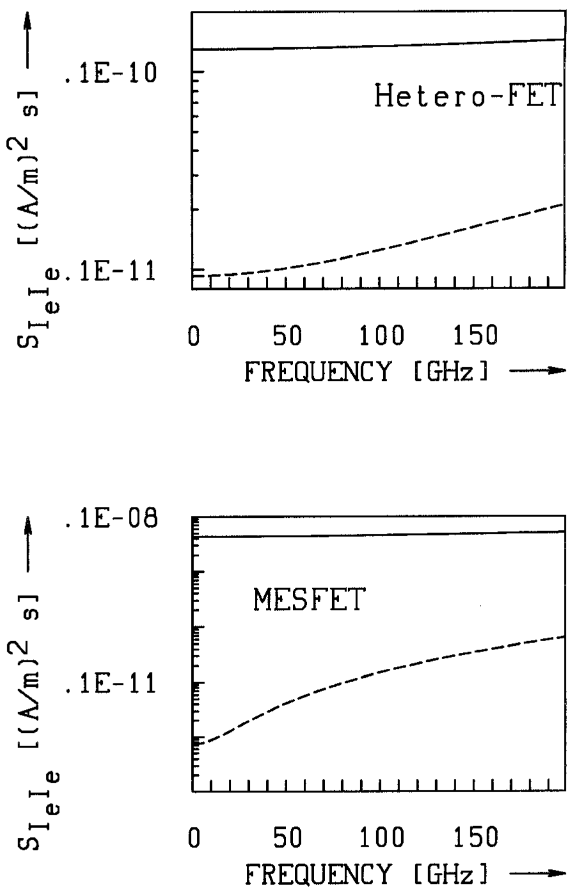


**Fig. 4a:** Drain (solid line) and gate (dashed line) noise current spectral densities of the Hetero-FET and of the MESFET. (Vg=-.6 V, $I_e$ refers to electrode current)

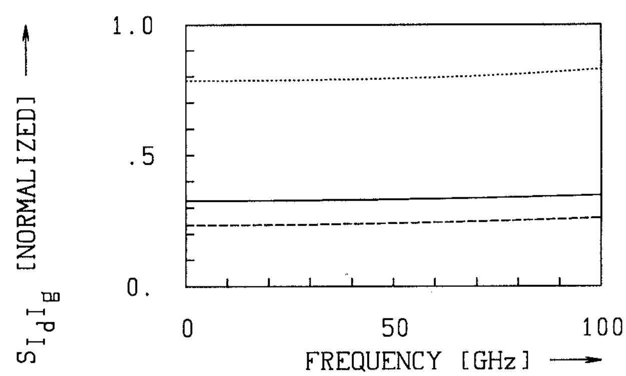


**Fig. 4b:** Frequency dependence of $S_{I_d I_g}$ normalized to $\sqrt{S_{I_d I_d} S_{I_g I_g}}$. (Solid line $V_{gs} = -.8V$, dashed line $V_{gs} = -.2V$, and dotted line $V_{gs} = 0.6V$)

The frequency and the bias dependence of important macroscopical noise parameters can also be determined with the present model. For example, we have calculated both frequency (fig. 4a) and bias (fig. 4c) dependence of gate and drain noise currents, and also frequency (fig. 4b) and bias (fig. 4d) dependence of their cross-correlation.

Knowing the drain noise current, the gate noise current, their correlation, the transconductance $g_m$ and the gate-source capacitance $C_{gs}$ ($g_m$ and $C_{gs}$ can also be determined by the present model), one can directly determine the important FET noise parameters (P, R, and C).

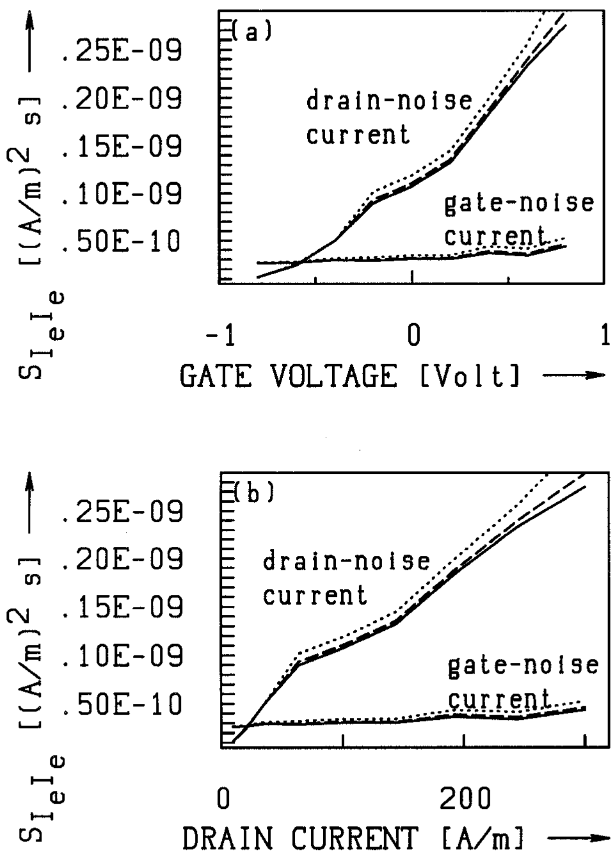


**Fig. 4c:** Drain and gate noise current spectral densities of the Hetero-FET as a function of the gate voltage (a) and the drain current (b) at 10 (solid lines), 100 (dashed lines), and 200 (dotted lines) GHz.

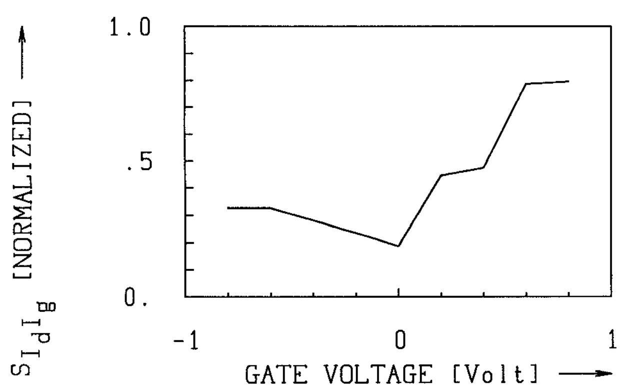


**Fig. 4d:** Bias dependence of $S_{I_d I_g}$ normalized to $\sqrt{S_{I_d I_d} S_{I_g I_g}}$ (f=60 GHz).

## CONCLUSIONS

We have presented an efficient Monte Carlo Simulator that enables to study the microscopical and macroscopical noise physics occurring in semiconductor devices. High numerical efficiency for the simulation of highly doped devices is achieved through the application of implicit coupling of particle motion with the time dependent electric field. This allows to increase the timesteps of the calculations. The noise densities at all device regions and as a function of frequency can be calculated from the presented model. For a Hetero-FET and a MESFET, a detailed characterization of noise sources within the devices and their transformation to the contacts has been presented.

## ACKNOWLEDGEMENT

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