ACCURATE MODELING OF NOISE FLUCTUATIONS IN MM-WAVE SEMICONDUCTOR DEVICES AND THEIR SPATIAL AND FREQUENCY DEPENDENCE

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ABSTRACT

A rigorous model is developed to determine the noise fluctuations in millimeter-wave semiconductor devices and their spatial and frequency dependence. First the model is generally described and then it is applied to characterize the operation and to accurately interpret the noise performance of sub-quarter micrometer gate-length FETs by making use of the noise matrix which describes the noise fluctuations in the different device regions and electrodes and their correlations.

INTRODUCTION

Heterostructure field effect transistors (Hetero-FET) have been demonstrated a superior performance, and in particular noise behavior, by utilizing the transport properties of the two-dimensional electron gas (2DEG) channel. Although several experimental and theoretical studies have been carried through to characterize the operation and to optimize the structure of these devices [1-3], there is still a lag of models which can be used to accurately interpret the noise behavior at microwave and millimeter-wave frequencies. For example, it has been recently stated that optimized MESFET structures are able to produce noise figures which are comparable to or even better than those of Hetero-FETs with the same gate-lengths [1-2]. The average velocity model which has been used in [2] is not suitable, however, to take into account the non-stationary transport properties in subhalf-micrometer gate length FETs and, moreover, the quantization effects in Hetero-FETs. This makes the accuracy of the calculated results and the validity of the interpretation questionable. Furthermore, most of the previous studies have been performed below certain frequency limits what represents another limitation to the conclusions which were drawn.

The aim of the present work is to extract the generalized noise matrix which describes the noise fluctuations in the different device regions and electrodes and their correlations by using a rigorous physical microscopic model. First the model will be described and then it will be applied to determine the d.c. and the noise performance of similar MESFET and Hetero-FET structures and to interpret the operation of these devices based on the physical understanding of the microscopic transport properties. Finally different possibilities to improve the noise performance at millimeter wave frequencies are discussed.

MODELING

The model is based on a self-consistent coupling of a Monte-Carlo code with Poisson's and Schrödinger's equations. A two-dimensional Monte-Carlo code is efficiently constructed to determine the microscopic and non-stationary transport properties by following the carrier motion inside the semiconductor device taking into account

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the different scattering processes, the temporal, and the spatial variations of the electric field and the carrier concentration [4]. The variations in the electric field are determined by solving Poisson's equation in two dimensions within a time step, while the variations of the carrier concentration are automatically known from the Monte-Carlo code. To determine the quantization effects in heterostructure devices accurately, Schrödinger's equation is self-consistently solved in the direction perpendicular to the heterointerface. This means that all temporal and spatial variations of microscopic quantities (like carrier velocity and carrier concentration), macroscopic quantities (like terminal currents and voltages), and consequently the noise spectra can be directly extracted without any approximation or simplifying assumption.

According to a regional approximation approach, the simulated semiconductor device is advantageously divided into different regions which are expected to have a dominant influence on its performance. An efficient choice of these regions largely depends on the understanding of the physical operation of that device. For a semiconductor device which has M electrodes and which is divided into N different regions, the generalized noise matrix $\mathcal{S}$ which defines the noise spectral densities of the currents i_{e_m} at the m^{th} device electrode and i_{r_n} in the n^{th} region is given by

$$\mathcal{S} = \begin{pmatrix} S_{i_{e_1}i_{e_1}} & \cdots & S_{i_{e_1}i_{e_m}} & S_{i_{e_1}i_{r_1}} & \cdots & S_{i_{e_1}i_{r_n}} \\ \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\ S_{i_{e_m}i_{e_1}} & \cdots & S_{i_{e_m}i_{e_m}} & S_{i_{e_m}i_{r_1}} & \cdots & S_{i_{e_m}i_{r_n}} \\ S_{i_{r_1}i_{e_1}} & \cdots & S_{i_{r_1}i_{e_m}} & S_{i_{r_1}i_{r_1}} & \cdots & S_{i_{r_1}i_{r_n}} \\ \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\ S_{i_{r_n}i_{e_1}} & \cdots & S_{i_{r_n}i_{e_m}} & S_{i_{r_n}i_{r_1}} & \cdots & S_{i_{r_n}i_{r_n}} \end{pmatrix} \quad (1)$$

where the self-spectral densities $S_{i_xi_x}(f)$ and cross-spectral desities $S_{i_xi_y}(f)$ are given by

$$\mathrm{S_{i_xi_x}(f)} = 2\int_{-\infty}^{+\infty} \overline{\mathrm{i_x(t)i_x(t+\tau)}}\mathrm{e}^{-\mathrm{j}\omega\tau}\mathrm{d}\tau \quad (2)$$

$$\mathrm{S_{i_xi_y}(f)} = 2\int_{-\infty}^{+\infty} \overline{\mathrm{i_x(t)i_y(t+\tau)}}\mathrm{e}^{-\mathrm{j}\omega\tau}\mathrm{d}\tau. \quad (3)$$

By making use of the microscopic nature of our model, the electrode noise current $i_{e_m}(t)$ around its average value $\overline{I_{e_m}}$ is calculated from the particle counting (PC) method by

$$\mathrm{i_{e_m}(t)} = \mathrm{Q}\frac{\Delta \mathrm{N}}{\Delta \mathrm{T}} + \mathrm{A}\,\varepsilon\,\frac{\Delta \mathrm{E}}{\Delta \mathrm{T}} - \overline{\mathrm{I_{e_m}}}, \quad (4)$$

while the noise current $i_{r_n}(t)$ around $\overline{I_{r_n}}$ is given from the Shockley-Ramo (SR) theorem by

$$\mathrm{i_{r_n}(t)} = \frac{\mathrm{Q}}{\mathrm{L}}\sum_{\mathrm{i=1}}^{\mathrm{N_n}} \mathrm{v_i(t)} - \overline{\mathrm{I_{r_n}}}. \quad (5)$$

In PC method, Q means particle charge, ΔN net number of particles which are crossing the m^{th} electrode, ΔE change in electric field, ΔT time step, A area of the m^{th} electrode, and ε dielectric constant, while in SR method, L means length, N_n number of particles, and $v_i(t)$ velocity of i^{th} particle in the n^{th} region.

NUMERICAL RESULTS

The model is applied to determine the dc and the noise performance of the Hetero-FET (MESFET) structure (fig. 1) which consists of a 30 nm thick $GaAs$ cap layer, a 42 nm $Al_{0.3}Ga_{0.7}As$ ($GaAs$) layer, and a $GaAs$ buffer layer doped with a donor concentration of $2.10^{18}cm^{-3}$, $1.10^{18}cm^{-3}$, and $1.10^{14}cm^{-3}$, respectively. A $0.15\mu m$ gate length is recessed at a depth of 30 nm with $0.12\mu m$ separation between the gate edges and the highly doped source and drain regions. The source-gate and source-drain electrode separations are 0.3 and 1.05 μm, respectively. The simulations have been performed at temperature of 300 K and the drain voltage was set equal to 2 V. The different regions which dominate the noise performance are: the source-gate, the $AlGaAs$ ($GaAs$) gate, the gate-drain, and the 2DEG (substrate) regions.

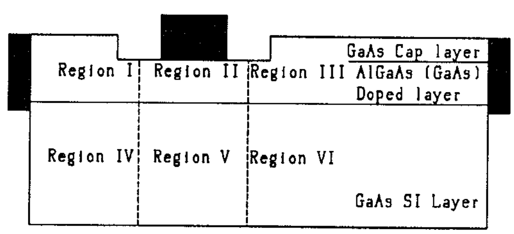

Fig. 1: The simulated FET structures.

The obtained dc current (fig. 2) and the transconductance of the MESFET are higher than the same quantities of the Hetero-FET because the simulated MESFET has an optimized structure which leads to the best performance [1-2] while for the Hetero-FET a better performance can still be expected if both device geometry and doping level are optimized. Other quantities, for example the drain current percentage which flows in the 2DEG region (fig. 2), can also be determined.

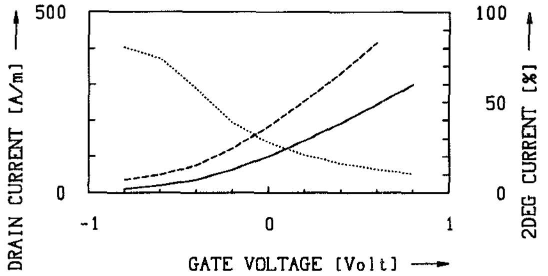

Fig. 2: Drain current of the MESFET (dashed line) and of the Hetero-FET (solid line), and its percentage (dotted line) in the 2DEG channel.

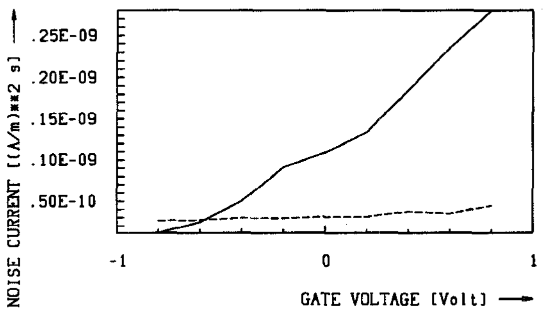

Fig. 3: Drain (solid line) and gate (dashed line) noise currents of the Hetero-FET. (V_g=-.2V, f=60 GHz)

Considering the noise behavior, the gate and drain noise currents (fig. 3), their autocorrelation functions (fig. 4), and their spectral densities S_{i_D} and S_{i_G} (fig. 5) have been dertermined. The calculated results are in very good agreement with other experimental measurements and theoretical studies [5]. To our best knowledge, this is, however, the first time that they are quantitatively calculated for Hetero-FETs by using a fully self-consistent particle simulator. The long tail oscillations of the autocorrelation functions around zero (fig. 4) increase the uncertainty in the calculated results, especially for smaller values, at lower frequencies. On the expense of CPU time, the accuracy of the results can, however, be improved by increasing the number of simulated particles, by using a smaller mesh size and smaller time steps, and by increasing the simulated time period.

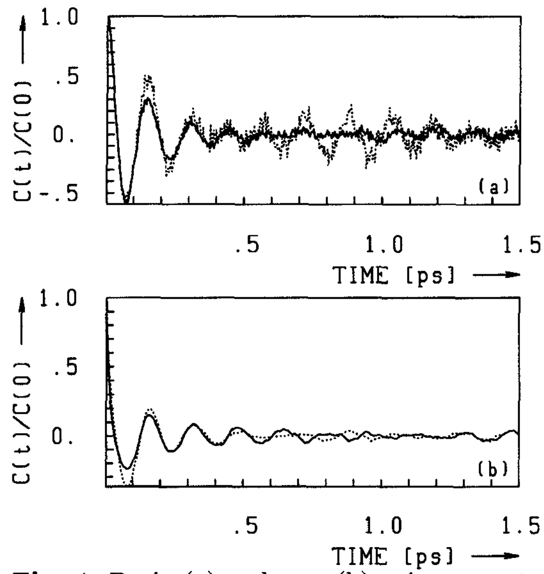

Fig. 4: Drain (a) and gate (b) noise current autocorrelation functions of the Hetero-FET for V_g=0.6 V (solid line) and V_g=-.2V (dashed line).

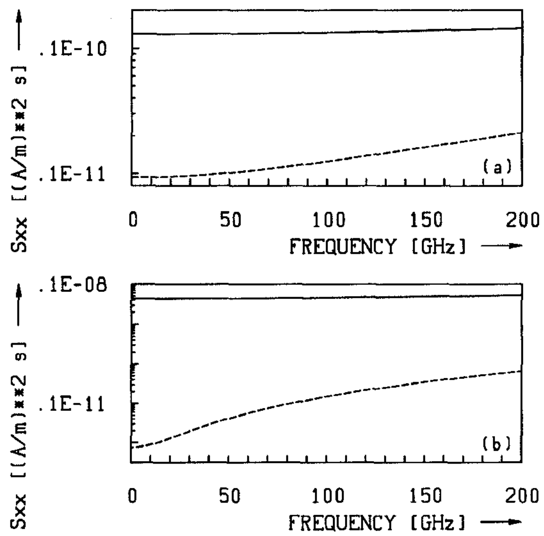

Fig. 5: Drain (solid line) and gate (dashed line) noise current spectral densities of the Hetero-FET (a) and of the MESFET (b). (V_g=-.6V)

To accurately interpret the measured noise behavior of MESFETs and Hetero-FETs [1-2], one must keep in mind that the improvement of the performance of Hetero-FETs is coming from the separation of the carriers in the 2DEG channel from their parent atoms in the *AlGaAs* layer. This means that ionized impurity scattering in a Hetero-FET is much lower than in a MESFET.

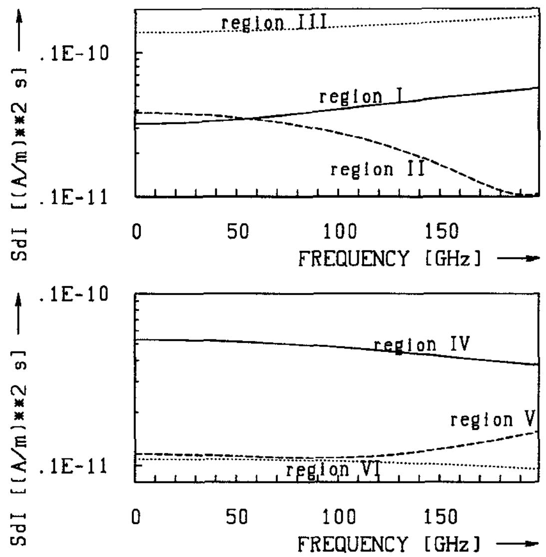

Fig. 6a: Crosscorrelation of the drain noise current and the currents flowing in the different regions of the simulated Hetero-FET. (V_g=-.2V)

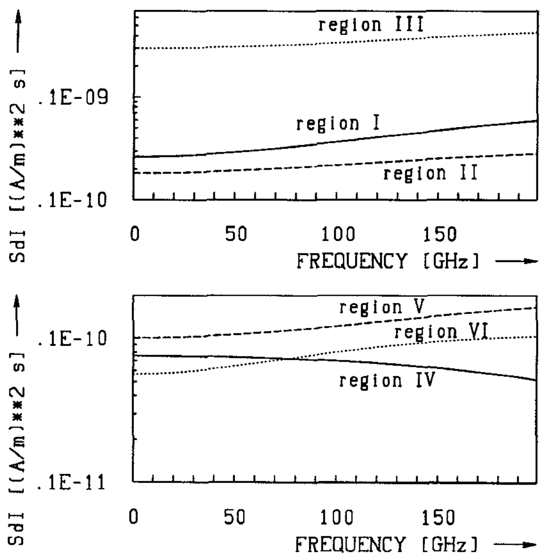

Fig. 6b: Crosscorrelation of the drain noise current and the currents flowing in the different regions of the simulated MESFET. (V_g=-.2V)

At lower frequencies of operation, however, optical phonon and intervalley scattering play a dominant role so that one can expect that the noise behavior of a MESFET should be better than that of a Hetero-FET. For higher frequencies, on the other side, the effect of ionized impurity scattering shows a larger influence on the transport properties what improves the noise behavior of a Hetero-FET compared to a MESFET (fig. 6). One must keep in mind that the overall noise performance is also affected by the noise generated in the source-gate and gate-drain regions (regions I and III, respectively) which further deteriorates the noise performace at high frequencies (fig. 6).

CONCLUSIONS

The steady-state behavior of subquarter micrometer gate-length FETs as well as the self- and cross-spectral noise densities at different device regions and electrodes have been accurately determined by using a microscopic physical simulator. The superior noise performance of a Hetero-FET, and in particular at high frequencies, results from the reduction of the ionized impurity scattering in the 2DEG channel. This effect depends on the current which flows through that region and its percentage from the overall current. All physical phenomena which affect the spatial and temporal fluctuations are generally included in the model what makes it an efficient tool for analyzing the noise behavior of other devices as well.

ACKNOWLEDGEMENT

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