Monte Carlo simulation of electronic noise in MESFETs

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Abstract

We present a two-dimensional Monte Carlo analysis of electronic noise associated with velocity fluctuations in GaAs MESFETs. By applying two operation modes, the current and voltage fluctuations at the different terminals of the device are investigated. Moreover, we provide the spatial location of the voltage fluctuations. The noise in the drain current increases with the level of the current, and remains constant with frequency at least up to 100 GHz. In the case of the gate current, the noise is null at low frequency and then increases quadratically.

Introduction

The widespread use of GaAs MESFETs for low-noise applications makes necessary a detailed characterization of the noise performances in these devices. The methods usually employed to this end need to introduce approximations related to the statistical properties of the microscopic noise sources, generally by characterizing the local velocity fluctuations through the diffusion coefficient corresponding to the local electric field [1, 2]. As an alternative to these models, the Monte Carlo method has the advantage that the sources of diffusion noise are naturally accounted for in the simulation, which provides directly their behavior. Therefore, it is not necessary to incorporate them externally.

The Monte Carlo method has already been employed to study noise in one-dimensional devices [3-5]. However, in the case of MESFETs, while widely used for the study of the static characteristics, it has been scarcely applied to analyze the noise characteristics [6]. The main difficulty involved in this analysis is to have a good estimator of the currents at the terminals of the device. To this purpose, the usual approach which is employed consists, for the conduction current, in counting the net number of particles crossing the terminals at each time step and, for the displacement current, in making the time derivative of the field at the contacts. This approach, which is appropriate to obtain the average stationary currents, is not sufficiently accurate to study fluctuations. Nevertheless, the recent technique proposed in [7] makes possible an improvement in the accuracy of the calculations to the extent of analyzing the intrinsic noise of the device.

Physical model

A. *Simulated structure*

The device under study is schematically shown in Fig. 1. It consists of a n^+nn^+ structure with a one-micron channel modulated by a gate contact of 0.5 μm. The source and drain contacts are placed at the end of the n^+ regions. The value adopted for the non-simulated dimension of the device is 0.714 μm, which means an average number of simulated carriers between 9500 and 13000 depending on the bias. The model for the GaAs conduction band consists of three non-parabolic spherical valleys (Γ, L and X). The Monte Carlo simulation follows the standard scheme. To solve Poisson's equation, a grid formed of 160x25 meshes of 100x80 Å is used. The field is updated each 10 fs for the current-noise calculations, and each 2.5 fs for the voltage-noise calculations, by employing a two-dimensional Poisson solver.

B. *Operation modes*

The noise in the MESFET is analyzed with two operation modes. In the first one, current-noise operation, the gate and drain voltages remain constant in time, and the fluctuations of the short-circuit currents are investigated. In the second one, voltage-noise ope-

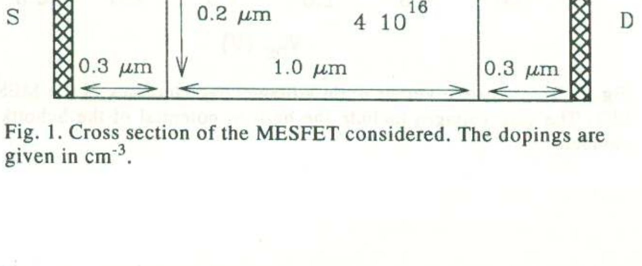

Fig. 1. Cross section of the MESFET considered. The dopings are given in cm^{-3}.

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ration, the gate voltage and the drain current remain constant, and the fluctuations of the short-circuit gate current and of the open-circuit drain voltage are investigated. In both modes the fluctuations are analyzed through the calculation of the respective autocorrelation functions, which, after Fourier transform, give the spectral densities. To provide an adequate resolution of the autocorrelation functions, the carrier kinetics inside the device is simulated under stationary conditions during 650 ps. With the second operation mode we perform a spatial analysis of the voltage fluctuations by calculating the voltage spectral density as a function of the position (x,y), as already reported in one-dimensional structures [4].

The currents at the terminals are calculated according to the technique described in [7]. For example, the drain current per unit length at a time t is given by:

$$I_d(t) = \frac{1}{x_d - x_{g2}} \left[Q \sum_{i}^{x_{g2}-x_d} v_{xi}(t) + \frac{\varepsilon_0 \varepsilon_r}{\Delta t} \sum_{j=1}^{M_y} \Delta y_j \Big(\varphi(x_{g2}, y_j, t) - \varphi(x_{g2}, y_j, t-\Delta t) \Big) - \frac{\varepsilon_0 \varepsilon_r h}{\Delta t} \big(V_D(t) - V_D(t-\Delta t) \big) \right] \qquad (1)$$

where x_{g2} is the x position of the right edge of the gate, x_d the x position of the drain, Q the linear charge density of a particle, v_{xi} the velocity in the x direction of the i-th particle, Δt the time step, M_y the number of vertical meshes, Δy_j the vertical dimension of the j-th vertical mesh, y_j its y position, φ the potential, h the vertical dimension of the device, and V_D the drain voltage. The summation over i is performed over the particles with x position between x_{g2} and x_d.

In the first operation mode the last two terms in (1) cancel each other, since V_D is constant. In the second operation mode, if we consider that the drain current is constant and equal to I_{D0}, the instantaneous value of V_D at a time t is given by:

$$V_D(t) = V_D(t-\Delta t) - \frac{\Delta t}{\varepsilon_0 \varepsilon_r h} \left(I_{D0} \big(x_d - x_{g2} \big) - Q \sum_{i}^{x_{g2}-x_d} v_{xi}(t) + \frac{1}{h} \sum_{j=1}^{M_y} \Delta y_j \Big(\varphi(x_{g2}, y_j, t) - \varphi(x_{g2}, y_j, t-\Delta t) \Big) \right) \qquad (2)$$

which is obtained in the simulation by applying an iterative technique, since it is not possible to have the value of $\varphi(x,y,t)$ without knowing previously $V_D(t)$.

It must be stressed that the analysis performed in this way is only related to the intrinsic noise of the device, without considering any external noise sources (like those associated with the contacts) or parasitic effects.

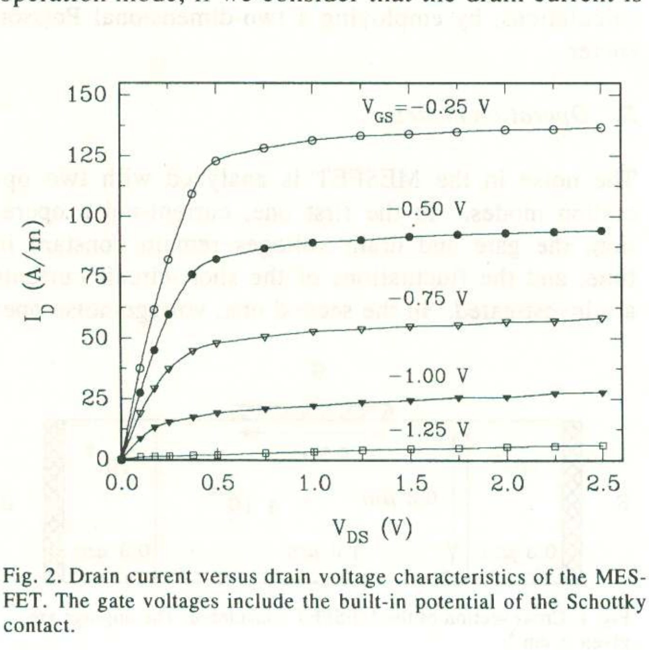

Fig. 2. Drain current versus drain voltage characteristics of the MESFET. The gate voltages include the built-in potential of the Schottky contact.

Results and discussion

Before reporting the results concerning the noise analysis, Fig. 2 shows the drain current versus drain voltage characteristics of the MESFET. The gate voltage includes the built-in potential of the Schottky contact (−0.7 V). The absence of a substrate leads to a rather marked saturation of the current. To give an idea of the electrical performances of the device, for the operation point V_{GS}=−0.25 V, V_{DS}=1.5 V, the transconductance g_m is about 190 mS/mm, and the current-gain cut-off frequency 47.5 GHz.

A. Current-noise operation

Fig. 3 shows the dependence on frequency we find for the spectral density of the short-circuit drain- and gate-current fluctuations, S_{i_D} and S_{i_G}, in the saturation region of the MESFET. S_{i_D} is practically constant with frequency, and increases proportionally with the value of the drain current. S_{i_G} exhibits a f^2 behavior, with a

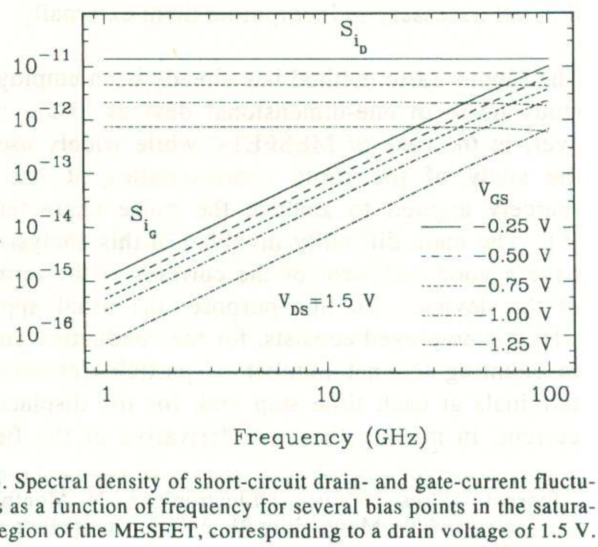

Fig. 3. Spectral density of short-circuit drain- and gate-current fluctuations as a function of frequency for several bias points in the saturation region of the MESFET, corresponding to a drain voltage of 1.5 V.

proportionality factor which also increases with the drain-current. The results of the Monte Carlo simulation for the values of S_{i_G} at zero frequency are very small, and can be considered to be null inside the uncertainty of this method. In order to get exactly the f^2 dependence at low frequencies (up to 10 GHz), it is necessary to subtract $S_{i_G}(0)$ from $S_{i_G}(f)$. The results given in Fig. 3 were calculated in this way. The behaviors obtained for S_{i_D} and S_{i_G} are well known from the literature [2, 8]; but, to our knowledge, this is the first time which they are obtained from a self-consistent Monte Carlo simulation.

Fig. 4 reports the low-frequency value of the drain-current spectral density as a function of V_{DS} for several V_{GS}, together with the current spectral density in the n^+nn^+ structure corresponding to the MESFET without gate (before the onset of Gunn oscillations). As the absolute value of V_{GS} increases, reducing the n channel, the device becomes more resistive and S_{i_D} becomes smaller. In the case of the n^+nn^+ structure, where the whole n region is a conducting channel, S_i is larger and increases significantly near the threshold voltage for the Gunn oscillations. On the contrary, S_{i_D} in the MESFET exhibits smooth variations with V_{DS} for constant V_{GS}, and remains practically constant after the onset of saturation.

With the current-operation mode it is not possible to know *a-priori* which is the spatial origin of the current fluctuations. Nevertheless, several models point out that the main noise contributions come from the ohmic part of the channel, i.e., the part under the gate in the side of the source [2, 8, 9]. This explains why S_{i_D} does not change with V_{DS} when the MESFET is saturated, since under such conditions that region of the device is not substantially affected by the increase of the drain voltage. However, when V_{GS} is modified, the concentration of free carriers in such part of the channel is altered, and therefore the level of noise changes.

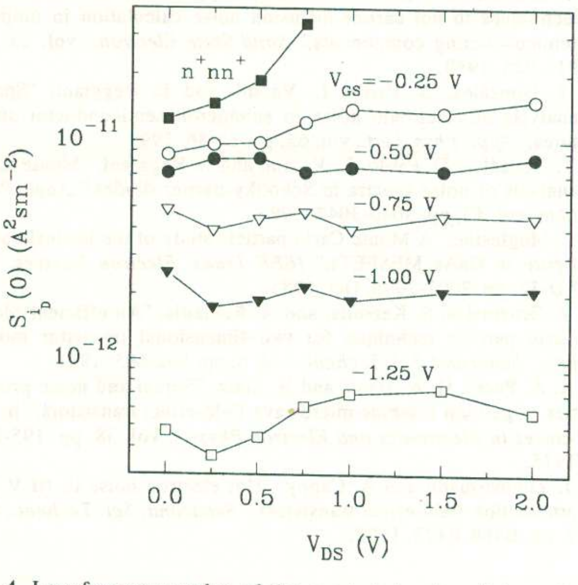

Fig. 4. Low-frequency value of the spectral density of short-circuit drain-current fluctuations as a function of the drain voltage for several gate voltages. The current spectral density in the n^+nn^+ structure corresponding to the MESFET without gate is also included.

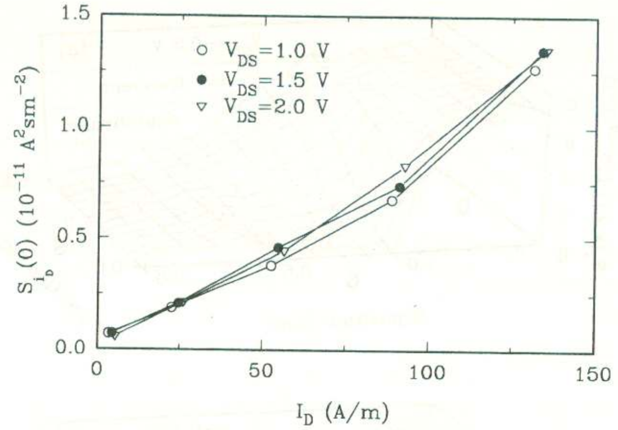

Fig. 5. Low-frequency value of the spectral density of short-circuit drain-current fluctuations as a function of the drain current for several drain voltages in the saturation region of the MESFET.

Fig. 5 reports the dependence of S_{i_D} on the drain current in the saturation region. The spectral density increases almost linearly with the current except for the highest values. As already mentioned, S_{i_D} does not depend on the value of V_{DS}, but on the level of the current flowing through the device.

B. *Voltage-noise operation*

Within this operation mode we shall focus on the drain-voltage fluctuations and their spatial origin. Fig. 6 shows the low-frequency value of the spectral density of voltage fluctuations (as measured from the source contact) as a function of the position inside the device, for fixed values of V_{GS} and I_D corresponding to the situations of equilibrium and saturation. The spatial distribution of the voltage noise can be clearly observed. Of course, in the drain contact the value of the spectral density must be the same for all the y positions, and in the gate contact must be null since its voltage remains constant in time.

In contrast with the drain-current noise, for a fixed V_{GS} the low-frequency value of the drain-voltage noise increases as the average value of V_{DS} becomes higher. Such increase is initially smooth in the linear region of the I_D-V_{DS} characteristic, and then becomes sharp when the saturation region is reached. In Fig. 6 it can be observed that there is a difference of more than three orders of magnitude between the values of the spectral density at equilibrium and in the saturation region. Moreover, the spatial origin of the noise is quite different in the two regions.

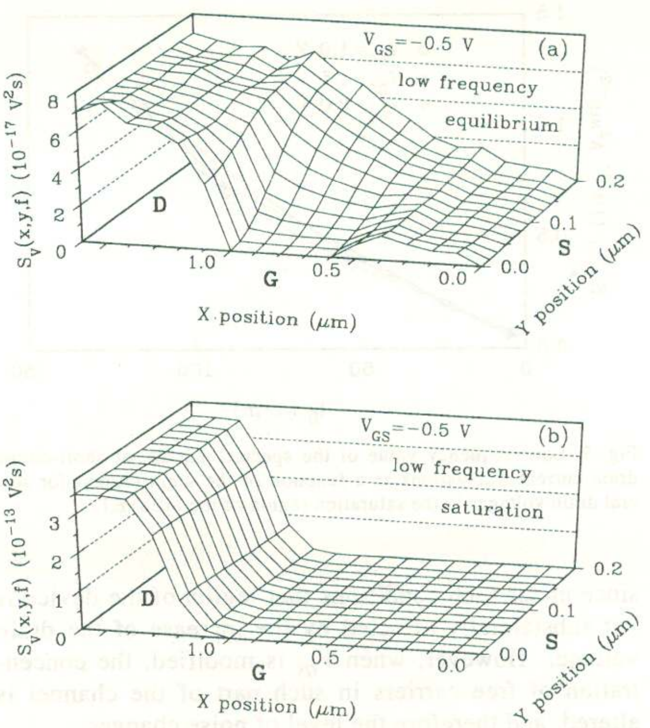

Fig. 6. Spatial map inside the MESFET of the low-frequency value of the spectral density of voltage fluctuations with respect to the source for two bias points: (a) V_{GS}=−0.5 V, I_D=0.0 A/m (corresponding to an average drain voltage of 0.0 V), (b) V_{GS}=−0.5 V, I_D=91.1 A/m (corresponding to an average drain voltage of 1.3 V). The positions of the source (S), gate (G) and drain (D) are indicated in the figure.

At equilibrium, the presence of the constant voltage in the gate modulates the voltage spectrum in the *y* direction along the channel. Thus, in the regions which are far from the gate, the voltage fluctuations are found to be distributed mainly along the whole *n* region, while approaching the gate these are concentrated in the vicinity of the drain n^+ region. In the case of saturation, the distribution of the voltage noise changes drastically. There is almost no dependence on the *y* position. The spatial origin of the fluctuations is localized in the zone of the *n* channel between the gate and the drain, and even penetrates the drain n^+ region. It is due to the fact that this is the part of the device which absorbs all the variations of the drain voltage in saturation, screening their effect on the source region. Moreover, an important presence of hot carriers (and upper-valley population) takes place in this same region, which makes it highly resistive and increases the voltage fluctuations. This presence of hot carriers extends into the drain n^+ region, and makes the low-frequency noise penetrate inside it. This effect was already seen in n^+nn^+ structures [4].

Conclusions

We have presented a two-dimensional Monte Carlo analysis of noise in a GaAs MESFET by investigating the current and voltage spectral densities. The noise in the drain current has been found to be independent from frequency in the whole range of device operation and to increase with the level of the current. The noise in the gate current increases quadratically with frequency. The spatial origin of the voltage noise has been determined. Accordingly, under current saturation the voltage fluctuations are localized in the zone of the *n* channel between the gate and the drain, and penetrate into the drain n^+ region due to the presence of carriers in the upper valleys. As final remark, the Monte Carlo method has been proven to be a useful tool for the analysis of noise in two-dimensional devices.

Acknowledgments

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