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High frequency analysis of fast devices using small-signal Monte Carlo simulations : application to a 0.1 μm -gate MODFET

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Résumé. — Nous présentons une méthode d'analyse petits signaux de composants rapides à partir de simulations Monte Carlo. Elle consiste à développer en séries de Fourier les tensions et courants aux électrodes. Elle permet de déterminer la fréquence de coupure du gain en courant et d'extraire les paramètres d'un schéma équivalent. Cette méthode est appliquée à un MODFET AlGaAs/InGaAs/GaAs de longueur de grille 0,1 μm .

Abstract. — A method of small signal analysis of fast devices using Monte Carlo simulations is presented. It consists in expanding the terminal currents and voltages in Fourier series. It allows to determine the current gain cutoff frequency and to extract the parameters of an equivalent circuit. This method is applied to a 0.1 μm -gate AlGaAs/InGaAs/GaAs MODFET.

1. Introduction.

The particle Monte Carlo technique is generally acknowledged as the most powerful tool for semiconductor device modelling. It allows to take into account most of the microscopic processes that influence the carrier transport without requiring any assumption about the macroscopic transport properties. Furthermore, the transport parameters, such as relaxation times or mobilities, whose knowledge is necessary for other simplified models are just supplied by Monte Carlo simulations [1]. However, one usually makes two criticisms related to the statistical nature of simulated phenomena and to the limited number of simulated particles, which lead to a very noisy behaviour. Firstly, large computation times are required to accurately calculate the average values of all relevant quantities, e.g., currents and carrier velocities. Secondly, the Monte Carlo method seems unsuited for studying dynamic or transient regimes. In fact, concerning this last point, a suitable processing can allow, in certain cases, to get rid of the noise.

For instance, Patil *et al.* [2] have studied the transient response of a MESFET after a single step-change of 0.3 V in the gate voltage. The method is based on the fact that the cumulative

charge $Q(t)$ through a contact, i.e., the integral from 0 to time t of the current $I(t)$, is a much less noisy function than $I(t)$. After fitting the $Q(t)$ function by a polynomial, they have calculated the transient current by differentiating the polynomial. In the same spirit, we have recently presented a small signal analysis of a HEMT [3] which consisted in applying a small sine-signal to the gate voltage and fitting the terminal cumulative charges by sine functions. But this method is inapplicable if currents are not linear functions of input voltage, as in a bipolar transistor [4]. In fact, in case of small sine-signals, a simple Fourier analysis of terminal currents provides excellent results. This method, more precisely described in this paper, can be easily generalized to any other devices.

The small signal analysis at a given operating point can be carried out following two approaches. In one hand, from simulations performed with drain short circuited, one can calculate the current gain as function of frequency, which leads to a direct determination of the cutoff frequency f_T . In the other hand, owing to a supplementary simulation performed with drain loaded at given frequency, an equivalent circuit can be extracted.

In section 2 the method of small signal analysis using Monte Carlo simulation is described. In section 3 the results obtained with a 0.1 μm -gate AlGaAs/InGaAs/GaAs MODFET are presented.

2. The method of small signal analysis.

The instantaneous total current $I(t)$ through a contact is calculated by the summation of the current due to the particle flow through the contact and the displacement current due to the electric field variation at the contact. In our model no particle can be injected in the device through a Schottky-contact and tunneling effect is not taken into account. Thus, the gate current is a purely displacement current whose average value is zero at a given operating point.

The noisy character of this kind of modelling seems obvious in figure 1 that represents the typical variations of drain current *versus* time for a 0.1 μm gate MODFET in such bias conditions that the average value of drain current is $I_0 = 353$ mA/mm while a small sine-signal is applied to the gate voltage. The number of simulated particles is about 25 000 and the time step Δt between two solutions of Poisson's equation is 1 fs. The amplitude of the input signal is 30 mV, and its frequency f_1 is 100 GHz. Assuming that $i(t) = I(t) - I_0$ has the same period than the input voltage, it can be expanded in Fourier series :

$$i(t) = \sum_{m=1}^{\infty} i_m(t) = \sum_{m=1}^{\infty} [\sqrt{a_m^2 + b_m^2} \sin(2\pi f_m t + \phi_m)] \quad \text{with} \quad f_m = m f_1. \quad (1)$$

The coefficients a_m and b_m and the phase ϕ_m are calculated as :

$$\begin{aligned} a_m &= \frac{2}{T} \int_0^T i(t) \cos(2\pi f_m t) dt \\ b_m &= \frac{2}{T} \int_0^T i(t) \sin(2\pi f_m t) dt \\ \phi_m &= \tan^{-1} \left(\frac{a_m}{b_m} \right). \end{aligned} \quad (2)$$

For instance, the amplitude of fundamental component $i_1(t)$ of the total current $I(t)$ is 32 mA/mm, to be compared to the fluctuations of the instantaneous current (about ± 2000 mA/mm) shown in figure 1.

An important point is the minimum time, or number of periods, needed for the calculation of Fourier coefficients. If the numerical noise is white, it contributes randomly to the integration

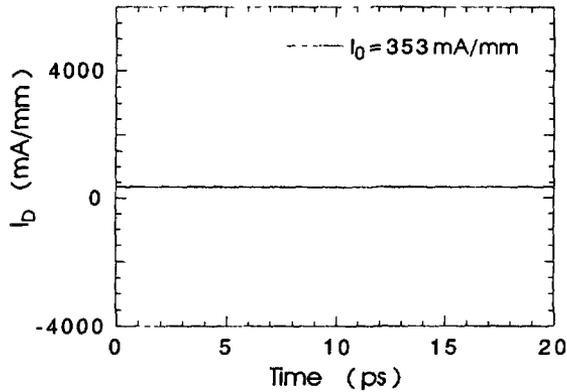


Fig. 1. — Example of instantaneous drain current as a function of time. The average current is $I_0 = 353$ mA/mm.

over a single period, whatever the frequency. It is then enough to integrate the signal over a sufficient number of periods to eliminate the part due to the noise and to obtain the Fourier coefficients with a good accuracy. In the same bias conditions than in figure 1, the variations of the coefficient a_1 of drain current are plotted in figure 2 against the time of integration for several frequencies. It seems that the main criterion is not the number of period of integration but the total time of integration. For this device and whatever the frequency, a minimum simulation time of about 50 ps is needed to extract accurately the Fourier coefficients. This has to be compared with the time of about 8 ps necessary to obtain non noisy average values of currents and of all relevant physical quantities in steady-state regime. It should be noted that the time step Δt is here much less than the period of the input signal so its value does not influence the Fourier expansion. But the simulation noise being very dependent on the number of simulated particles this parameter should also influence the minimum integration time.

We now describe two possible applications of such a Fourier analysis, i.e., the determination of current gain as function of frequency and the extraction of a small signal equivalent circuit at a given operating point.

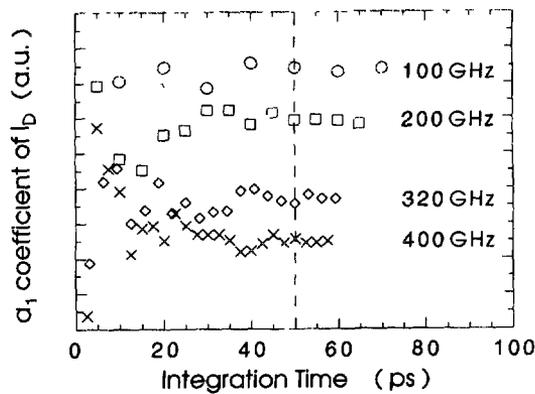


Fig. 2. — Evolution of Fourier coefficients a_1 as function of time of integration at different frequencies ranging from 100 to 400 GHz. The dashed line ($t = 50$ ps) represents the minimum integration time necessary for an accurate calculation.

Indeed, the current gain at given frequency can be directly determined with biasing the transistor in usual conditions of current gain measurements, i.e., with drain short circuited. One only has to applied a small signal to the gate voltage and to expand in Fourier series the resulting gate and drain currents. The current gain at fundamental frequency is then obtained as the ratio of fundamental components i_{D1}/i_{G1} . A set of simulations performed at different frequencies leads to f_T .

Furthermore, a small signal equivalent circuit can be extracted from the set of Z parameters of the two-port representing the transistor. The first step is thus the determination of the four Z -parameters at given frequency. The four necessary equations connecting drain and gate currents and voltages can be obtained from two simulations. The first one may be performed with drain short-circuited, as previously, and the second has to be performed at the same frequency but with drain loaded by a resistance R_L , as in figure 3. However, the very noisy drain current through the load resistance would induce strong variations in drain potential. To filter this current, a capacitance C_L has to be connected between drain and source. Its value must be chosen so that the time constant $\tau_L = R_L C_L$ is less than the period of the input signal. After each time step Δt , i.e., the time step between two solutions of Poisson's equation, the drain voltage V_{DS} is updated according to the load line, as following :

$$V_{DS}(t + \Delta t) = V_{DS}(t) + (V_{CC} - V_{DS}(t) - R_L I_D) \frac{\Delta t}{\tau_L} \quad (3)$$

The Z parameters at fundamental frequency are then easily calculated after expanding in Fourier series $I_G(t)$, $I_D(t)$ and $V_{DS}(t)$. From the complex values of the four Z parameters, one can extract, numerically if necessary, the parameters of an equivalent circuit including at best eight elements, which is generally sufficient for intrinsic devices.

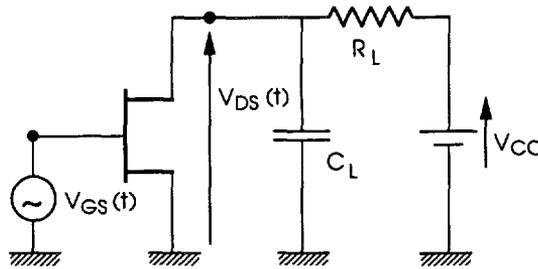


Fig. 3. — Small signal input voltage applied to a FET with drain loaded.

3. Results.

The simulated device is a $0.1 \mu\text{m}$ gate AlGaAs/InGaAs/GaAs MODFET whose geometry has been previously described [5]. The source-to-gate distance is $0.1 \mu\text{m}$ while the gate-to-drain distance is $0.5 \mu\text{m}$. The drain characteristics of this device are shown in figure 4. The operating point that has been chosen for the small signal analysis is ($V_{GS} = 0.2 \text{ V}$, $V_{DS} = 1 \text{ V}$). It corresponds to a current $I_{D_0} = 353 \text{ mA/mm}$ and to the maximum transconductance ($g_m = 1090 \text{ mS/mm}$) obtained by differentiating the $I_D(V_{GS})$ function at $V_{DS_0} = 1 \text{ V}$.

For the simulation performed with drain loaded, the chosen bias drain voltage was $V_{CC} = 2 \text{ V}$ and the load resistance was thus $R_L = (V_{CC} - V_{DS_0})/I_{D_0} = 2.83 \Omega \text{ mm}$. The load

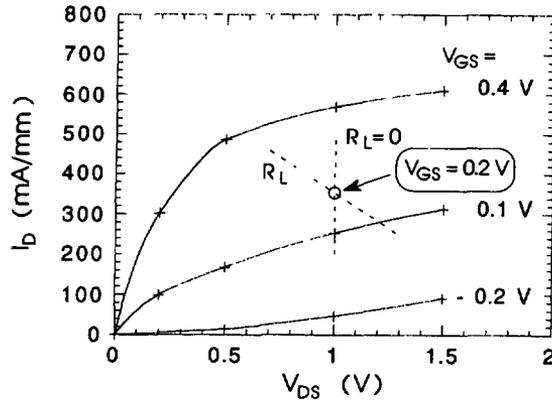


Fig. 4. — Drain characteristics of simulated MODFET with load lines ($R_L = 0$, and $R_L = 2.83 \Omega \text{ mm}$) used for small signal analysis about the chosen operating point ($V_{GS} = 0.2 \text{ V}$, $V_{DS} = 1 \text{ V}$).

line is drawn on drain characteristics (Fig. 4). Since the simulation has been performed at a frequency of 100 GHz, the load capacitance C_L has been chosen so that the time constant $\tau_L = R_L C_L$ was 1 ps, i.e., ten times less than the period of the input signal. An equivalent circuit including six parameters, as in figure 5, has been assumed. In fact, it is sufficient for this device at this operating point. If R_i and R_{DS} are included in the equivalent circuit, the calculated values of these parameters are very low and non significant. Finally the six following parameters have been extracted at 100 GHz :

$$C_{GS} = 0.47 \text{ pF/mm} , \quad C_{GD} = 0.08 \text{ pF/mm} , \quad C_{DS} = 0.12 \text{ pF/mm} , \\ R_{DS} = 7.3 \Omega \text{ mm} , \quad g_m = 1110 \text{ mS/mm} , \quad \tau = 0.019 \text{ ps} .$$

From these equivalent circuit parameters, and assuming they are independent of frequency, the current gain h_{21} can be calculated as a function of frequency by :

$$h_{21}(f) = \frac{g_m}{2 \pi f (C_{GS} + C_{GD})} \sqrt{\left(1 + \frac{2 \pi f C_{GD}}{g_m} \left(2 \sin(2 \pi f \tau) + \frac{2 \pi f C_{GD}}{g_m} \right) \right)} . \quad (4)$$

This leads to the curve drawn in figure 6 (solid line) and to a cutoff frequency of 340 GHz. The slope of the curve is very close to -20 dB/decade except about f_T where the terms in $\frac{f C_{GD}}{g_m}$ in equation (4) become perceptible.

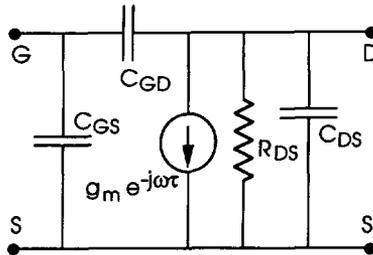


Fig. 5. — Small signal equivalent circuit of intrinsic FET used in this work.

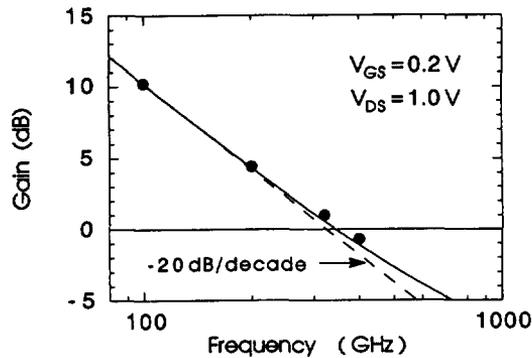


Fig. 6. — Current gain as a function of frequency at chosen operating point ($V_{GS} = 0.2$ V, $V_{DS} = 1$ V). Solid line results from the equivalent circuit parameters determined at 100 GHz ; dark circles result from simulations with drain short circuited.

This curve of gain can be compared to the values of gain directly deduced from simulations at different frequencies with drain short circuited (dark circles in Fig. 6). The agreement is very good with a so-determined f_T of about 350 GHz, which justifies the concept of equivalent circuit (including here six elements) independent of frequency.

4. Conclusion.

We have developed and applied a method of small signal analysis of fast devices using Monte Carlo simulation that consists in expanding the instantaneous terminal currents and voltages in Fourier series. It allows to determine f_T and to extract a small signal equivalent circuit including, at best, eight elements. Such an analysis is applicable to any other transistor and can be a useful complement to microwave measurements although a good accuracy in the calculation of Fourier coefficients requires large computation times.

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