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Monte Carlo analysis of voltage noise in sub-micrometre semiconductor structures under large-signal regime

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Abstract
Using an ensemble Monte Carlo technique, we investigate voltage noise (related to diffusion noise sources) in GaAs n^+nn^+ structures operating under large-amplitude periodic signals. A pronounced noise contribution around the frequency of the excitation signal f_0 is evidenced. This contribution is mainly associated with the time-varying field sustained by the n region. Its presence and importance depends on the length of the n region and the value of f_0. This additional contribution in the voltage noise spectrum tends to disappear for values of f_0 beyond the cut-off of the noise related to the n region. On the other hand, the level of low-frequency noise under large-signal conditions is higher than under small-signal operation due to the increase of the effective resistance of the structures.

1. Introduction

Recent advances in telecommunications systems, particularly broadband services and mobile networks, have pushed amplifier circuits, oscillators, mixers and frequency multipliers to achieve higher output power and efficiency at very high frequencies [1, 2]. In these circuits, active devices commonly operate under large-signal conditions, and hence classical small-signal models are useless for their analysis. In particular, an accurate simulation of the noise performance of these devices is crucial to ensure that the overall system will work correctly. Due to the complex nonlinear phenomena involved in the large-signal time-varying regime, such as harmonic generation, current saturation, etc, new effects can be expected in the noise behaviour of the devices. Some of these have already been investigated, such as the upconversion of low-frequency noise [3, 4].

During the last few decades, much effort has been devoted to achieve a physical understanding of microscopic noise mechanisms within solid-state electron devices and to model electronic noise under small-signal conditions. However, very little research has been invested into the study of noise in devices operating under large-amplitude time-varying signals [3–6], and hence a full theory for nonlinear noise modelling is still under development. To this end, a microscopic approach, such as the Monte Carlo (MC) method, can be very useful, since it includes intrinsically, at a microscopic level, the effects at the origin of the nonlinearities (hot carriers, velocity overshoot, intervalley transfer, etc) taking place in electronic devices operating under large-signal conditions. Moreover, this technique has been proven to be especially powerful to provide a microscopic description of electronic noise [7].

A first attempt to use the MC method for the analysis of diffusion noise under large-signal conditions has been developed by Shiktorov *et al* [8] for the case of bulk GaAs. Under large-amplitude periodic electric fields they have detected a peak in the spectral density of velocity fluctuations, which appears around the frequency of the large-signal excitation, provided such a frequency is high enough. However, to our knowledge, this effect has not been shown in more complex structures including the influence of the self-consistent electric field, like those analysed in this paper, where we present a MC analysis of diffusion noise in sub-micrometre GaAs n^+nn^+ structures operating under large-signal conditions. These structures have been chosen because they form the basis for various high-frequency semiconductor devices, such as field-effect transistors, switchers, transferred electron oscillators, etc. We simulate electronic transport in the structures when they are driven by a periodic current density of amplitude J_0 and frequency f_0, given by $J(t) = J_0 \sin(2\pi f_0 t)$. In particular, we analyse the frequency response and the voltage noise behaviour of the structures as a function of the amplitude (when going from small-signal to large-signal operation) and frequency of the excitation current, and also by varying the length of the n region. The results show that voltage noise is strongly affected by the excitation, even leading to new spectral components in the voltage fluctuations.

This paper is organized as follows. In section 2 we describe the physical model used in the simulations and the procedure for the numerical calculation of voltage noise under large-signal conditions. In section 3 we report and discuss the results of the MC simulations. The main conclusions and future trends are drawn in section 4.

2. Physical model and noise calculation

An ensemble MC simulator, three-dimensional in momentum space, coupled with a self-consistent one-dimensional Poisson solver is developed for the calculations. We analyse a GaAs n^+nn^+ structure with doping levels of $n = 10^{15}$ cm^{-3} and $n^+ = 10^{17}$ cm^{-3}, and with lengths of 0.15 μm and 0.45 μm for the cathode and anode n^+ regions, respectively, varying from 0.3 μm to 1.0 μm for the n region. The microscopic modelling is the same as that of [9]. To solve the Poisson equation, a time step shorter than 2.5 fs is used (the ratio between the period of the excitation signal and the time step must be an integer) and the structure is divided into meshes of 100 Å each. The cross-sectional area of the simulated structure, A, is 10^{-13} m^2. Ohmic boundary conditions are considered at the structure terminals.

In our analysis we use voltage noise operation. A current density $J(t) = J_0 \sin(2\pi f_0 t)$ is imposed to flow through the structure, and we analyse the voltage noise that this excitation induces at the terminals by following the technique described in [10]. We use these working conditions since, in comparison with the current operation mode (the magnitude that fluctuates is the current), where the n^+ regions have the strongest influence on the noise, voltage noise is more sensitive to the processes taking place in the n region due to its higher resistance; and it is precisely in the n region where large-signal conditions are expected to exert their greatest influence. We consider that the frequency of the ac signal f_0 lies in the microwave range or beyond, so that affordable computation times are achieved. The time constant associated with diffusion noise sources is about 10^{-13} s, shorter than the period of the large signal. Under these conditions, while other models must introduce assumptions about the modulation of the noise sources by time-dependent variables [5, 6, 11], the MC method has the advantage that it includes noise sources without any assumptions.

Under dc conditions, fluctuations are evaluated over an average stationary value, however, when a periodic large-signal excitation is applied to the structure, fluctuations are calculated over the cyclostationary response [3, 8]. To quantify the level of noise, we determine the spectral density of voltage fluctuations $S_V(f)$ by Fourier transformation of the autocorrelation function $C_V(t)$, which is obtained as the average of the two-time correlation function $C_V(s,t)$ over all possible initial times s within one period of the large signal. As shown in [8], this estimation of $S_V(f)$ is equivalent to that obtained from the square of the modulus of the finite Fourier transform of the voltage fluctuations.

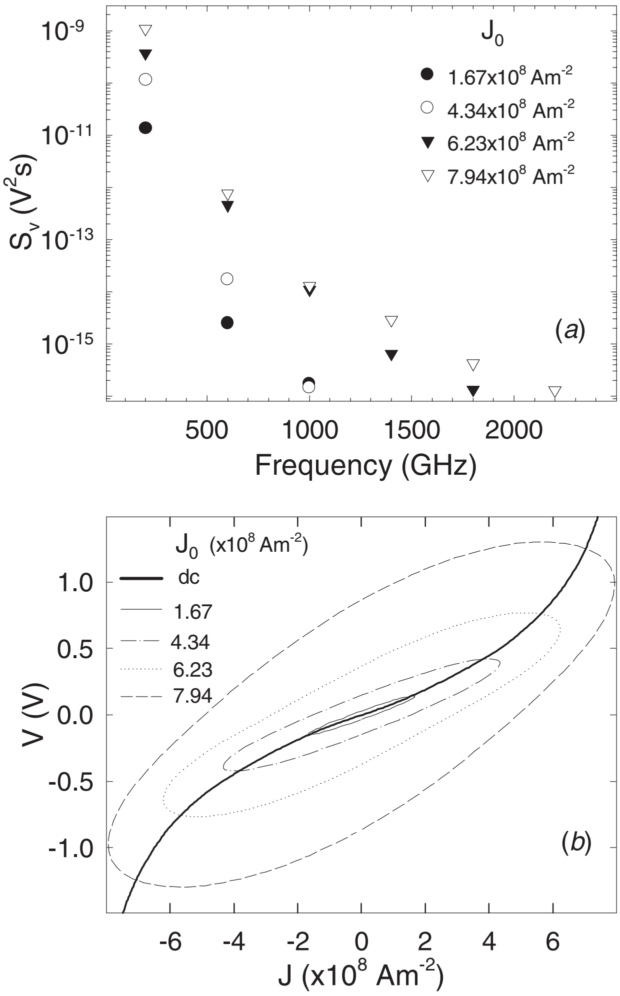

Figure 1. (*a*) Spectral density components of the cyclostationary voltage response (during 40 ps) of an n^+nn^+ structure with $n = 10^{15}$ cm^{-3} and $n^+ = 10^{17}$ cm^{-3}, and with lengths 0.15, 0.30 and 0.45 μm, respectively, for excitation signals of frequency $f_0 = 200$ GHz and different amplitudes of current density J_0.
(*b*) Corresponding hysteresis cycles together with the static (dc) behaviour of the structure.

3. Results

Figure 1 illustrates the response of an n^+nn^+ structure with an n region of 0.3 μm in the transition from small-signal to large-signal operation under a current excitation of the type $J = J_0 \sin(2\pi f_0 t)$, with $f_0 = 200$ GHz and values of $J_0 = 1.67 \times 10^8$, 4.34×10^8, 6.23×10^8 and 7.94×10^8 A m^{-2}, corresponding to dc voltages of 0.15, 0.5, 0.9 and 1.75 V, respectively. Figure 1(*a*) shows the spectral components of the cyclostationary (without noise) voltage response for the different values of J_0, while figure 1(*b*) reports the hysteresis cycle exhibited by the voltage in response to the excitation current density. The thick solid line corresponds to the dc behaviour of the structure, drawn for comparison. When a small signal is applied to the structure ($J_0 = 1.67 \times 10^8$ A m^{-2}), the response is quite similar to the static case. But when the value of the excitation current increases, the structure is not capable of following the excitation current. The hysteresis cycle broadens and the voltage reaches a maximum value lower than that corresponding to the static case, which is dephased

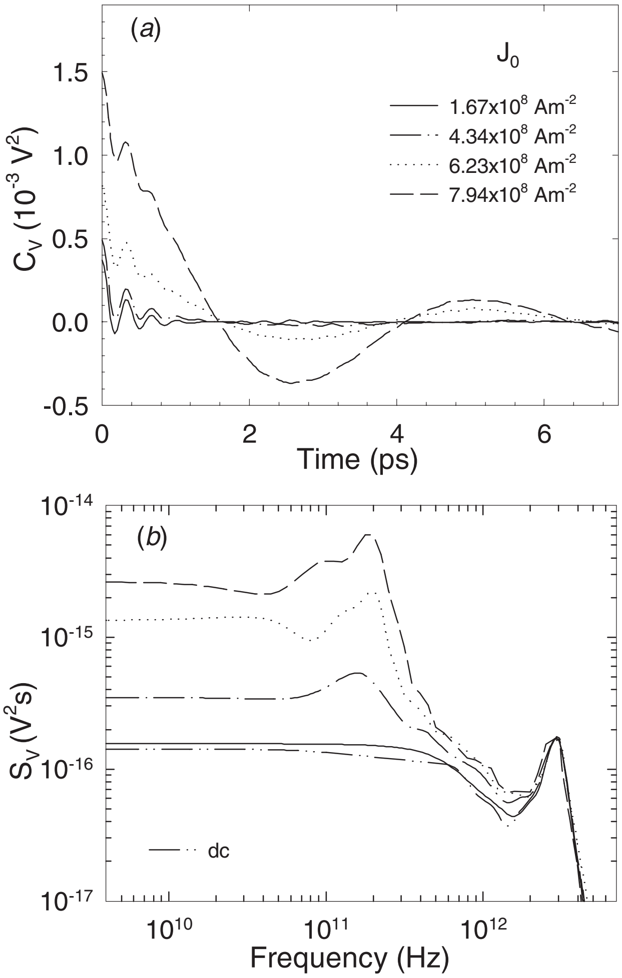

Figure 2. (*a*) Autocorrelation functions and (*b*) spectral densities of voltage fluctuations for the same cases as in figure 1.

with respect with the maximum excitation current. All these effects increase with the magnitude of the excitation current. As concerns the spectral components of the voltage response, since no dc current is applied to the structure, only odd harmonics are excited, whose number and amplitude increases with the current, corresponding to the stronger nonlinearities of the system. Thus, only three harmonics are detected for the lowest current while six harmonics are observed for the highest current. All these facts indicate that nonlinearities become very important under large-signal operation, and it is expected that the noise behaviour of the structure could exhibit significant differences with respect to dc conditions due to the influence of such nonlinearities.

This is observed in figure 2, which presents the voltage noise spectra $S_V(f)$ (and the corresponding autocorrelation functions) for the previous excitations. In all cases a peak corresponding to the plasma oscillation frequency associated with the n^+ region appears markedly around 3×10^3 GHz [10], with a magnitude that hardly changes with the excitation. In contrast, the level of the low-frequency plateau is very sensitive to the amplitude of the excitation, its value increasing with J_0. This increase reflects the fact that as J_0 is enlarged the voltage swing is wider (figure 1(*b*)) and, as a consequence, the effective resistance exhibited by the structure during one period of the cyclostationary response becomes higher, thus leading to an

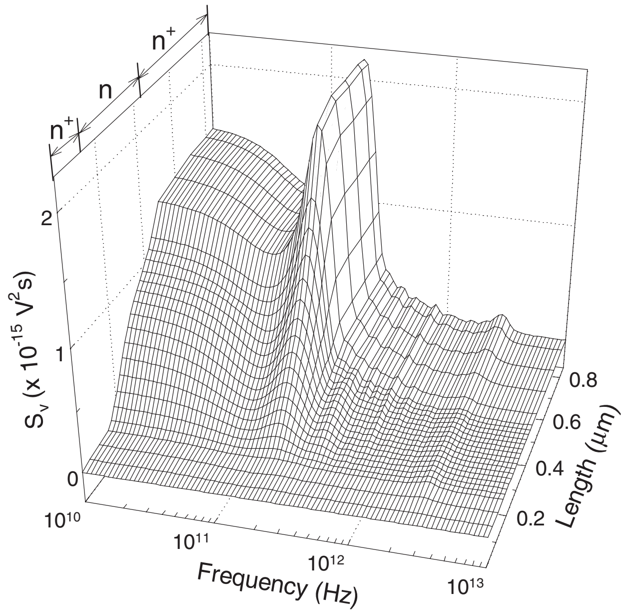

Figure 3. Spatial profile of the voltage noise spectral density (as measured from the left contact) for the structure of figure 1 excited with a signal with $f_0 = 200$ GHz and $J_0 = 6.23 \times 10^8$ A m^{-2}.

increase in the low-frequency voltage noise. For the lowest value of J_0, when the device works close to small-signal conditions and the response is nearly linear, $S_V(f)$ is quite similar to the spectrum found at equilibrium in the absence of the ac signal ($J_0 = 0$), showing no special signature related to the time-varying excitation. However, when J_0 increases, a significant peak appears around the excitation frequency, more noticeable for high currents, when nonlinearities are more important. This pronounced component of the noise around f_0 is evidenced by the corresponding autocorrelation functions shown in figure 1(*a*), where two characteristic oscillations can be detected: one with a short characteristic time corresponding to the plasma frequency, and the other with a longer period (about 5 ps) related to the frequency of the external signal, more pronounced the higher J_0 is.

To identify the spatial origin of the new effects related to large-signal operation found in the spectra, figure 3 shows $S_V(f)$ for $J_0 = 6.23 \times 10^8$ A m^{-2} as a function of frequency and position inside the structure as measured from the left contact [10]. As expected, it is observed that the n^+ regions are responsible for the noise at the plasma frequency. However, the influence of the time-varying signal on the spectrum takes place in the *n* region. This is the region providing the main contribution to the low-frequency noise and where the peak around 200 GHz arises, reaching its maturity at the beginning of the second n^+ region. This result is expected, since the oscillatory behaviour of the electric field associated with the time-varying excitation is mainly sustained by the *n* region.

In figure 4 we analyse how the noise spectra change when the length of the *n* region L_n varies from 0.3 to 1 μm, for $f_0 = 200$ GHz. The value of J_0 for each case is the static current corresponding to the voltage for which the average electric field present in the *n* region is 30 kV cm^{-1}. Thus, for $L_n = 0.3$ μm the value of J_0 applied to the device corresponds to a static voltage of 0.9 V; and for $L_n = 1.0$ μm to 3 V.

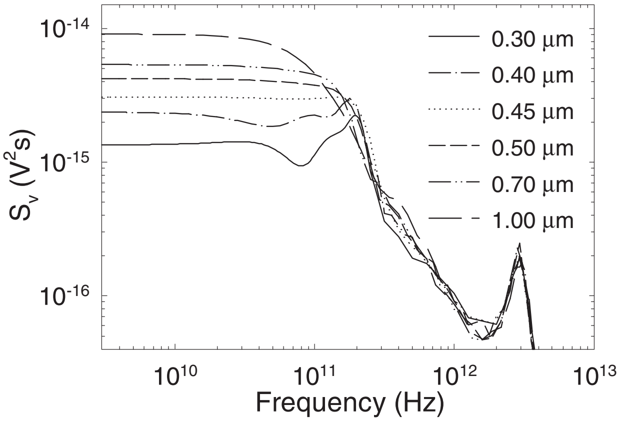

Figure 4. Voltage noise spectral density for n^+nn^+ structures with the same dopings and lengths of n^+ regions as those of the structure in figure 1, with different lengths of the n region. In each case, the value of J_0 is the static current corresponding to the voltage for which the average electric field present in the n region is 30 kV cm^{-1}. The excitation frequency is 200 GHz.

We remark that these voltages are never reached in the time-varying behaviour. In fact, the maximum value reached by the voltage is quite similar for all samples, around 0.85 V. As observed before, the peak at the plasma frequency of the n^+ regions remains unaltered, since it is only the length of the n region that changes. The level of the low-frequency plateau is observed to increase with L_n, accordingly with the higher resistance of the structures. However, the most remarkable phenomenon observed in the spectra is the disappearance of the peak at the excitation frequency when L_n becomes longer than 0.45 μm. This can be attributed to the joint influence of: (i) the increase of the low-frequency noise, which becomes much higher than the contribution around f_0; (ii) the lower amplitude of the electric field swing in the n region, so that the noise contribution around f_0 is lower, as observed in figure 2; (iii) the longer transit time of carriers through the n region τ_T; and (iv) the shorter cut-off frequency of the voltage noise due to the longer dielectric relaxation time in the n region τ_{dn} [10], so that the excitation frequency lies beyond the noise cut-off. τ_{dn} increases due to the lower average carrier concentration present in the n region when L_n is enlarged, since the flood of carriers diffused from the n^+ regions is less important.

To complete our analysis, figure 5(a) represents $S_V(f)$ in a structure with an n region of 0.3 μm for excitation signals of frequency f_0 ranging between 25–800 GHz and the same amplitude $J_0 = 6.48 \times 10^8$ A m^{-2}. Figure 5(b) shows the hysteresis cycles corresponding to these excitations. As expected, the lower f_0 is, the closer the cycle is to the static case. As f_0 increases, the voltage is no longer able to follow the current excitation and, thus, the hysteresis cycle broadens, the voltage reaches lower maximum values (J_0 corresponds to a static voltage of 1 V) and larger phase shifts between current and voltage are observed. This behaviour is reflected in the noise. Again, the peak at the plasma frequency is independent of f_0. The level of low-frequency noise increases when f_0 decreases, due to the higher values of voltage sustained by the structure the lower the frequency is (as observed in the hysteresis cycles), which increases the effective resistance of the structures. Concerning the peak at the excitation

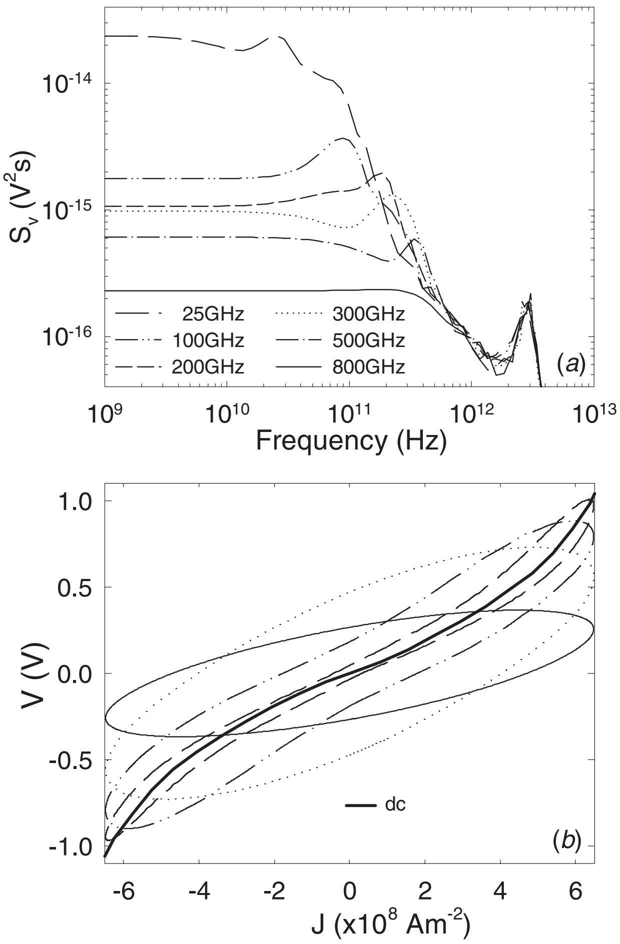

Figure 5. (a) Voltage noise spectral density and (b) hysteresis cycles for the structure of figure 1 excited with a signal of amplitude $J_0 = 6.48 \times 10^8$ A m^{-2} and several values of f_0. The static (dc) behaviour of the structure is also plotted in (b) for comparison.

frequency, it is always present except at the highest value of f_0 (800 GHz). At 25 GHz, the level of low-frequency noise is so high that it almost masks the peak at f_0. For intermediate excitation frequencies (100–300 GHz) the peak is much more noticeable. In these conditions the dynamics of electrons is strongly affected by the ac signal, since these frequencies are of the order of the transit time of carriers through the n region ($1/f_0 \sim \tau_T$). If higher frequencies are considered, the excitation signal changes so quickly in comparison with τ_T that the noise is scarcely affected by the swing of the signal. Moreover, the excitation frequency lies beyond the cut-off of voltage noise (which increases with f_0, since the higher mobility of carriers in the n region when voltage swings are lower leads to a shorter dielectric relaxation time τ_{dn}). As a result, the peak at the oscillation frequency decreases until disappearing at 800 GHz.

It is reasonable to consider the possibility that the behaviour of velocity fluctuations under large-amplitude periodic electric fields found in [8] could be at the origin of the peak around f_0 present in our simulations of voltage noise in n^+nn^+ structures. In fact, the spectral density of velocity fluctuations also exhibits a significant peak near the excitation frequency. However, this peak appears only when f_0 is high enough (beyond 300 GHz), while in our results it is present for much lower frequencies. Since the two physical systems (bulk semiconductor and $n^{+}nn^{+}$ structure) are rather different, they cannot be directly compared. Nevertheless, both results can be considered as complementary; presumably the dynamic behaviour of the $n^{+}nn^{+}$ structures and related transfer fields modulate (and thus transform) the contribution of the velocity noise sources to the voltage noise at the terminals of the device.

4. Conclusions

Using an ensemble MC simulation, we have analysed voltage noise in an $n^{+}nn^{+}$ structure operating under large-signal high-frequency conditions. Our results indicate that, apart from the effects found in the noise at low frequency, associated with the effective resistance of the structure, large-signal conditions can be responsible for the appearance of a peak in the noise spectra around the excitation frequency, which can limit the applications of these structures. The presence and significance of this peak is related to the length of the n region, and to the amplitude and frequency of the excitation. The possible link existing between the large-signal effects presented here and those reported in [8] remains an open problem. Our future work is oriented to the investigation of the influence on the noise of a dc bias additional to the large-signal excitation, and to extend this type of analysis to more complex structures.

Acknowledgments

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