MICROSCOPIC SIMULATION OF ELECTRONIC NOISE IN SEMICONDUCTOR UNIPOLAR STRUCTURES

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Abstract

We present a microscopic analysis of electronic noise in semiconductor unipolar structures based on Monte Carlo simulations of the carrier motion self-consistently coupled with a Poisson solver. Current and voltage noise operations are applied and their respective representations discussed. As applications we consider the cases of homogeneous resistors, n^+nn^+ structures, and Schottky-barrier diodes. As a general result, noise spectroscopy is proven to be a source of valuable information to investigate and characterize transport properties of semiconductor materials and devices.

I. INTRODUCTION

The primary quantity which describes electronic noise is the spectral density of current (voltage) fluctuations $S_I(f)$ $[S_V(f)]$. It can be measured more or less directly in different ranges of the frequency f and microscopically interpreted from the calculation of its theoretical counterpart which is the associated correlation function $C_I(t)$ $[C_V(t)]$. This methodology has recently led to the development of a noise-spectroscopy which has proven to be very fruitful for investigating transport properties of materials and devices [1]. In this paper we deal with the problem of how simulating electronic noise from a microscopic point of view. To this end, we make use of the Monte Carlo (MC) technique which, by naturally incorporating all the microscopic noise sources, has recently emerged as a very powerful method. The main issues which will be addressed are: (i) to present a general theory and the algorithms for the calculation of the current and voltage spectral densities; (ii) to investigate systems with increasing degree of complexity; (iii) to decompose the obtained spectra in terms of their sources and spatial contributions.

II. THEORY

In studying electronic noise two different modes of operation, which are mutually exclusive, can be used: current noise operation and voltage noise operation. In the former, the voltage drop at the terminals of the device is kept constant in time and the current fluctuations in the external circuit are analyzed. In the latter the current in the device is kept constant in time and the voltage fluctuations at its terminals are analyzed. Both modes are of interest since, as it will be shown in the following, they provide different and complementary information.

From the Wiener-Khintchine theorem [2] it is:

$$S_X(f) = 2\int_{-\infty}^{+\infty} exp(i2\pi ft)C_X(t)dt \tag{1}$$

$$C_X(t) = \overline{\delta X(t')\delta X(t'+t)} \tag{2}$$

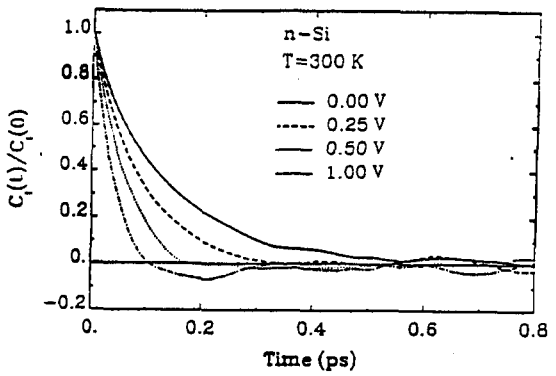

Fig. 1 - *Autocorrelation functions of current fluctuations for the different applied voltages reported. Calculations refers to a Si homogeneous structure with* $n = 10^{17}\ cm^{-3}$, $L = 0.6\mu m$ *at* $T = 300\ K$.

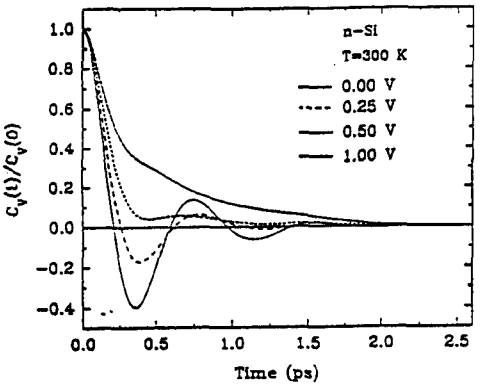

Fig. 2 - *Autocorrelation function of voltage fluctuations in the same structure and conditions as Fig. 1.*

where $\delta X(t) = X(t) - \overline{X}$ is the fluctuation of X around the average value $\overline{X}$, X being the current or the voltage. The problem is to provide a microscopic calculation of $C_X(t)$.

III. MICROSCOPIC CALCULATION

Under current noise operation the total current $I(t)$ as measured in the outside circuit is calculated as [3]:

$$I(t) = \frac{e}{L}\sum_{i=1}^{N_T(t)} v_i(t) = \frac{e}{L} N_T(t) v_d(t) \tag{3}$$

where e is the absolute value of the electronic charge, L the length of the sample, v_i the instantaneous value of the velocity component in the field direction of the i-th carrier, $N_T(t)$ the total number of carriers which are instantaneously present in the sample and $v_d(t) = [1/N_T(t)]\sum_{i=1}^{N_T(t)} v_i(t)$ is the drift-velocity.

Under voltage noise operation $I(t) = I_0$ and the time derivative of the voltage drop at the contacts $\Delta V(t) = [V(L,t) - V(0,t)]$ is calculated as [3]:

$$\frac{d}{dt}\Delta V(t) = \frac{L}{A\epsilon_0\epsilon_r}[\frac{e}{L}\sum_{i=1}^{N_T(t)} v_i(t) - I_0] \tag{4}$$

where A is the cross-sectional area of the sample, ϵ_0 the vacuum permittivity and ϵ_r the relative static dielectric constant of the background medium. The instantaneous voltage drop between the terminals can be obtained from a numerical integration of Eq. (4) over time.

In practice, the determination of $C_X(t)$ is performed from the knowledge of the time series $I(t)$ $[\Delta V(t)]$ as calculated from an ensemble MC simulation eventually coupled with a self-consistent Poisson solver, and taking appropriate boundary conditions concerning carrier injection-extraction from the contacts of the device. To this end, the total simulation, neglecting the initial transient, is recorded on a time-grid of step-size Δt. Then, by defining the time length in which the correlation function should be calculated as $m\Delta t$, with m integer, the correlation function is obtained as:

$$C_X(j\Delta t) = \overline{X(t')X(t'+j\Delta t)} = \frac{1}{M-m}\sum_{i=1}^{M-m} X(i\Delta t)X[(i+j)\Delta t] \tag{5}$$

with $j = 0, 1, ..., m$; $M > m$. Typical values are: $M = 50\ m$, $m = 100$. The corresponding $S_X(f)$ is determined by Fourier transformation.

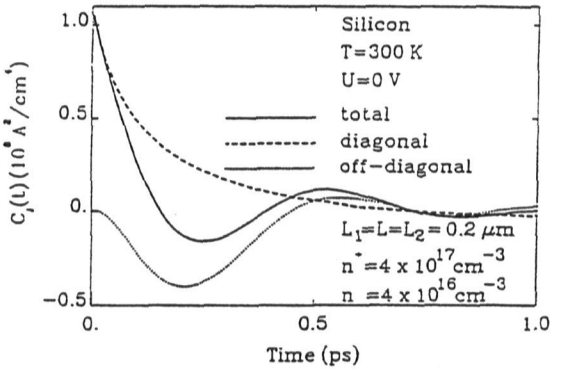

Fig. 3 - *Autocorrelation function of current-density fluctuations at equilibrium for a Si n^+nn^+ structure at $T = 300\ K$ with $n^+ = 4 \times 10^{17}\ cm^{-3}$, $n = 4 \times 10^{16}\ cm^{-3}$, and length $0.20 - 0.20 - 0.20\ \mu m$, respectively.*

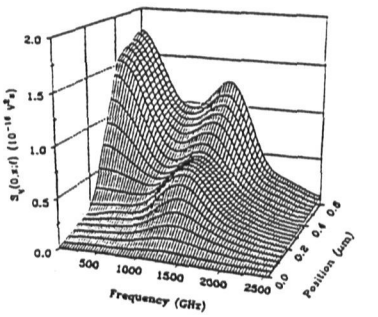

Fig. 4 - *Spectral density of voltage fluctuations as a function of frequency and position at equilibrium for a Si n^+nn^+ structure at $T = 300\ K$ with $n^+ = 10^{17}\ cm^{-3}$, $n = 10^{16}\ cm^{-3}$, and length $0.20 - 0.20 - 0.20\ \mu m$, respectively.*

IV. APPLICATIONS

In this Section we report the results obtained by the MC technique applied to different systems with increasing degree of complexity.

1. Resistor

The system we consider is a submicron Si resistor of length $L = 0.6\ \mu m$ with a donor concentration $n = 10^{17}\ cm^{-3}$ at 300 K. Figure 1 shows the current correlation function calculated at increasing applied voltages where its faster decay is associated with the onset of hot-carrier conditions. The presence of a negative part in $C_I(t)$ is attributed to the coupling between energy and velocity relaxation processes [3]. Figure 2 shows the voltage correlation functions $C_V(t)$ for the same resistor. At low voltages plasma and differential dielectric-relaxation times are responsible for the oscillatory and damping behaviors, respectively. At increasing applied voltages the sub-ohmic behavior of the current-voltage characteristics implies a significant increase of the dielectric relaxation time which, by becoming longer than the plasma time, washes-out the oscillations.

2. n^+nn^+ structure

The system we consider is a submicron Si n^+nn^+ structure at 300 K with two abrupt homojunctions. According to Ref. [3], the total correlation function can be decomposed as the sum of a diagonal and an off-diagonal contribution which are shown in Fig. 3. The former, describing the autocorrelation of the single particle-velocity, is responsible for the exponential decay. The latter, being associated with correlations due to the long-range Coulomb interaction, is responsible for an oscillatory behavior related to the plasma frequency of the n^+ and n regions.

Figure 4 shows the spectral density of the voltage fluctuations between $x = 0$ and the position x as function of x and frequency for the same structure of Fig. 3 but with $n = 10^{16}\ cm^{-3}$ and $n^+ = 10^{17}\ cm^{-3}$. Here, the different influence of each region in the structure is clearly emphasized. At low frequencies, most of the noise is originated in the n region due to its larger resistance. When going to higher frequencies, the contribution to the spectral density coming from the n region decreases, while that of the n^+ regions increases, reaching its maximum value near the associated plasma frequency (1275 GHz). At this frequency it can be clearly observed that the only contribution to the spectral density comes from the n^+ regions.

3. Schottky-Barrier diode

The system we consider is a one-dimensional GaAs $n^+ - n - metal$ structure at $300K$. The height of the barrier considered in the simulation is 0.735 V, which leads to an effective built-in voltage between the n region of the semiconductor and the metal of 0.640 V.

Figure 5 shows $S_I(f)$ at increasing applied voltages. The complexity of the spectrum is under-

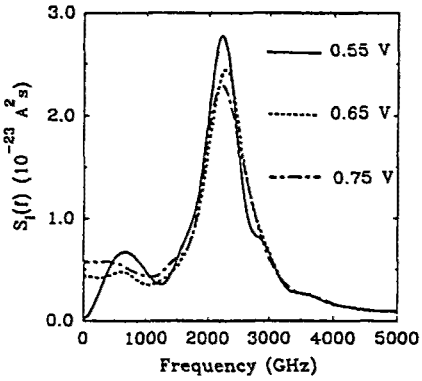

Fig. 5 - *Current spectral-density as a function of frequency for a GaAs Schottky barrier diode at* $T = 300\ K$ *with* $n = 10^{16}\ cm^{-3}$, $n^+ = 10^{17}\ cm^{-3}$ *and length of each region of* $0.35\ \mu m$.

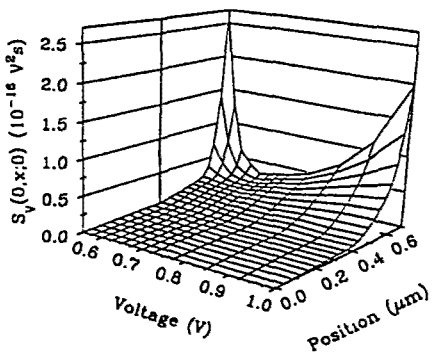

Fig. 6 - *Low-frequency value of the spectral density of voltage fluctuations as a function of position and mean voltage in the same structure as Fig. 5. The semiconductor-metal contact is at* $x = 0.7\ \mu m$.

stood on the basis of a strong coupling between fluctuations in carrier velocity and the self-consistent electric field. Two peaks are observed, one in the region below $10^3\ GHz$ and another at about $2.2 \times 10^3\ GHz$. The first is attributed to carriers that have insufficient kinetic energy to surpass the barrier and return to the neutral semiconductor region. The second originates from the coupling between fluctuations in carrier velocity and in the self-consistent field due to the inhomogeneity introduced by the $n^+ - n$ homojunction as discussed in Section 2.

Figure 6 shows a spatial analysis of the low-frequency value of the voltage spectral density. For voltages lower than $0.640\ V$ shot-noise is dominant [2], and most of the noise arises in the depletion region close to the barrier. At increasing voltages, thermal noise associated with the series resistance prevails, and the noise becomes spatially more distributed, mainly originating from the n region of the device. Finally, at the highest voltages, the presence of hot carriers and intervalley mechanisms in the n region leads to the appearance of an excess noise.

V. CONCLUSIONS

We have presented a theoretical simulation of electronic noise in semiconductor materials and two-terminal devices. Calculations are based on the Monte Carlo technique which, to include fluctuations of the self-consistent electric field, is coupled with a Poisson solver. The current representation, by allowing a decomposition in terms of different noise contributions, is found to provide useful information on the nature of the noise sources. The voltage representation, by allowing a spatial analysis to be carried out, is found to provide a local information on the strength of the noise sources. We believe that the generality of the approach here proposed, besides providing a rigorous basis for the interpretation of noise-spectroscopy measurements, still leaves wide possibilities of implementation for the analysis of more complicated systems.

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