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Monte Carlo Analysis of Voltage Fluctuations in Two-Terminal Semiconductor Devices

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Abstract

Electronic noise in two-terminal semiconductor devices is investigated by an original Monte Carlo procedure which provides a spatial map of voltage fluctuations in the structures. Voltage-noise operation is employed. The results obtained for submicron n^+nn^+ structures and Schottky-barrier diodes show that the high-resistivity regions are responsible for the low-frequency noise, while the low-resistivity regions mostly contribute to the noise at the highest frequencies.

1. Introduction

The analyses of velocity fluctuations in electronic devices are of great importance when trying to optimize their performances. In fact, the magnitudes employed for the characterization of fluctuations provide specific information about the transport processes which limit the efficiency of the devices. In this paper we present an original Monte Carlo method for the analysis of voltage fluctuations in one-dimensional semiconductor devices. More traditional methods, such as the impedance-field [1] or the transfer-impedance [2], introduce approximations related to the statistical properties of the microscopic noise sources. On the contrary, by employing an ensemble Monte Carlo simulation coupled with a one-dimensional Poisson solver, fluctuations in carrier velocity and electric field are self-consistently accounted for, thus avoiding any approximation. Moreover, from the simulation we provide a spatial map of voltage fluctuations in the devices. To this end, the spectral density of voltage fluctuations of the open circuit, $S_V(x,f)$, is determined as a function of different positions x inside the device as measured from one of the terminals.

2. Theoretical analysis

The theory underlying the present method is based on the following. In a one-dimensional structure of length L, the total current, $I(t)$, is given by [3, 4]:

$$I(t) = I_c(t) - \frac{\varepsilon_0 \varepsilon_r A}{L} \frac{d}{dt} \Delta V(L,t) \qquad (1)$$

where ε_0 is the free space permittivity, ε_r the relative static dielectric constant of the material, A the cross-sectional area, $\Delta V(L,t)$ the instantaneous voltage drop between the terminals, and $I_c(t)$ the conduction current defined by:

$$I_c(t) = -\frac{e}{L}\sum_{i=1}^{N_T(t)} v_i(t) \tag{2}$$

with e the absolute value of the electron charge, $N_T(t)$ the total number of carriers inside the device, and $v_i(t)$ the instantaneous velocity along the field direction of the ith particle.

By imposing that the total current is constant in time, $I(t)=I_0$, from Eq. 1 we obtain:

$$\frac{d}{dt}\Delta V^I(L,t) = \frac{L}{\varepsilon_0\varepsilon_r A}\left[I_c(t) - I_0\right] \tag{3}$$

where the superscript I is to recall the use of voltage-noise operation. From this expression the instantaneous voltage drop between the terminals can be calculated with the following procedure:

(i) Starting from the stationary operation point in the device corresponding to I_0, $[\Delta V^I(L,0), I_0]$, one solves the Poisson equation, simulates one time step Δt and gets the conduction current $I_c(\Delta t)$.

(ii) Once $I_c(\Delta t)$ is evaluated, Eq. 3 is integrated by employing a finite-differences scheme. The new instantaneous voltage drop between the terminals, $\Delta V^I(L,\Delta t)$, is thus calculated as:

$$\Delta V^I(L,\Delta t) = \Delta V^I(L,0) + \frac{L}{\varepsilon_0\varepsilon_r A}\left[I_c(\Delta t) - I_0\right]\Delta t \tag{4}$$

(iii) With the new value $\Delta V^I(L,\Delta t)$ one solves the Poisson equation and obtains the value of the voltage drop at each position x of the structure as measured from the first terminal $\Delta V^I(x,\Delta t)=V^I(x,\Delta t)-V^I(0,\Delta t)$.

(iv) A successive time step is then simulated to obtain the new value of I_c, and the process is iterated by repeating from point (ii). The number of simulated time steps must be enough to get a sufficient resolution in the calculation of the autocorrelation function of voltage fluctuations, $C_V(x,t)=\overline{\delta\Delta V^I(x,0)\delta\Delta V^I(x,t)}$, where the bar indicates time average and $\delta\Delta V^I(x,t)=\Delta V^I(x,t)-\overline{\Delta V^I(x)}$. By Fourier transformation, the corresponding spectral density as a function of frequency, $S_V(x,f)$, is obtained.

3. Results

This method has been applied to two types of devices: Si and GaAs n^+nn^+ structures, and a GaAs Schottky-barrier diode. The calculations are performed by coupling self-consistently a Monte Carlo simulator with a one-dimensional Poisson solver. The microscopic models for Si and GaAs are the same of [5] and [6], respectively. The devices are divided into equal cells of 100 Å each. The value of the time step is 10 fs for the case of Si and 2.5 fs for GaAs. Periodic boundary conditions have been employed for the n^+nn^+ structures [5], so that $N_T(t)=N_T$ is constant with time. In the case of the

Schottky diode one of the terminals is an ohmic contact which updates $N_T(t)$ in each time step, and the other terminal is the Schottky contact, which acts as a perfect absorbing boundary. The cross-sectional area adopted in the simulations is 10^{-13} m^2 for the n^+nn^+ structures and $2{\cdot}10^{-13}$ m^2 for the Schottky-barrier diode, which means an average number of simulated carriers between 4200 and 8000 depending on the device.

The results for the spectral density of voltage fluctuations in Si and GaAs n^+nn^+ structures are shown in Fig. 1. The dopings are n^+=10^{17} cm^{-3} and n=10^{16} cm^{-3}, and T=300 K. The fluctuations are around an average voltage $\Delta V'(L)$=0.4 V. The effects observed in the voltage fluctuations are similar for both materials. When the operation point is near equilibrium most of the low-frequency noise originates from n region of the device, due to its lager resistance. At increasing voltages (like in the case of Fig. 1) the onset of hot-carriers conditions leads to the penetration of the noise sources into the drain region, and an important part of the low-frequency noise comes from the beginning of the second n^+ region. This effect is more pronounced in the case of GaAs [Fig. 1(b)], due to the presence of carriers in the upper satellite valleys, with higher effective mass, which involves a deeper penetration of hot carriers into the drain before they can thermalize, making this region highly resistive and thus an important source of noise. When going to higher frequencies the contribution of the n region in the structures decreases, while that of the n^+ regions increases, reaching its maximum value for the associated plasma frequency (around 1300 GHz for Si, and 3000 GHz for GaAs) [3].

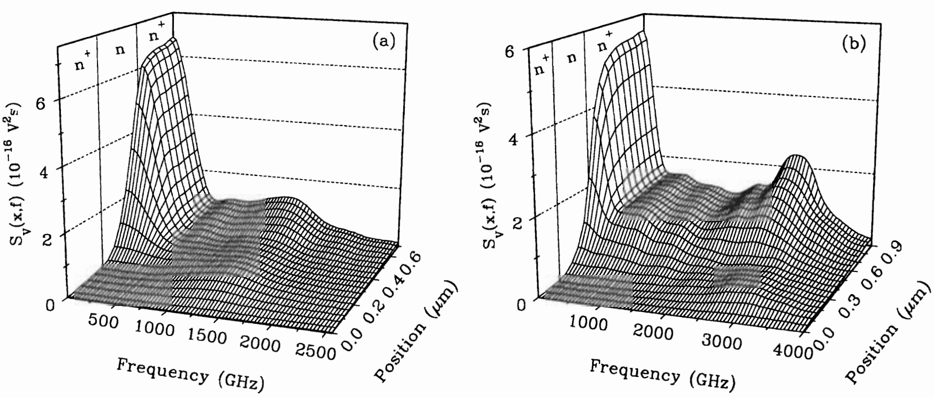
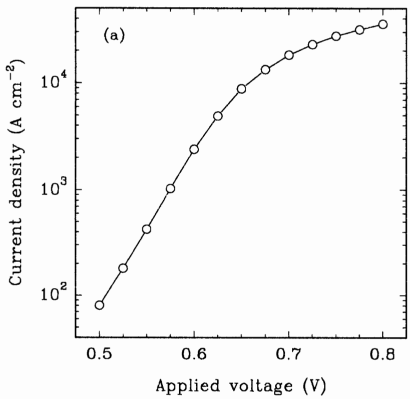


Fig. 1. Spectral density of voltage fluctuations as a function of frequency and position around an average voltage of 0.4 V in (a) Si and (b) GaAs n^+nn^+ structures at T=300 K, with n^+=10^{17} cm^{-3} and n=10^{16} cm^{-3}. The length of each of the regions is (a) 0.20-0.25-0.25 µm and (b) 0.15-0.25-0.50 µm, respectively.

The GaAs Schottky-barrier diode that is simulated consists of a first n^+ region (10^{17} cm^{-3}) of 0.35 µm, and a second n region (10^{16} cm^{-3}) of 0.35 µm at which end is the Schottky barrier. The barrier height is 0.735 V, which leads to an effective built-in voltage at equilibrium of 0.640 V. Fig. 2(a) shows the diode current-voltage characteristic. Only the forward-bias range can be simulated with the present model. Two different regions can be clearly observed: a first exponential region where the current is determined by the thermoionic emission of carriers over the barrier, and a second one where the current is determined by the series resistance and tends to assume a linear behavior due to the disappearance of the barrier.



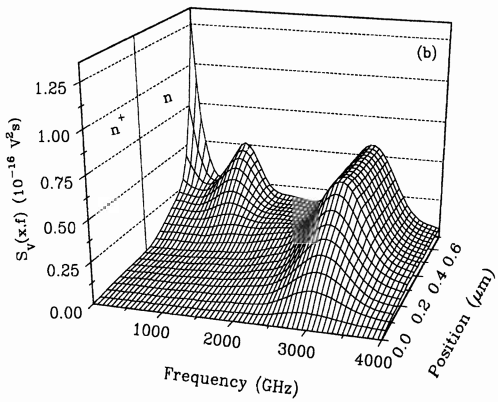


Fig. 2. (a) Current-voltage characteristic under forward-bias conditions, and (b) spectral density of voltage fluctuations as a function of frequency and position for an average voltage of 0.575 V, at T=300 K, in the GaAs Schottky-barrier diode described in the text.

Fig. 2(b) shows the spectral density of voltage fluctuations in the Schottky-barrier diode for an average voltage of 0.575 V, corresponding to the exponential region of the I-V characteristic. At low frequency the main contribution to S_V comes from the n region, more specifically from the section of the device close to the barrier. This is due to its high differential resistance, originated by the space-charge region near the barrier. At increasing frequencies we observe two maxima, which correspond to the plasma frequencies of the n and n^+ regions, respectively.

4. Conclusions

We have presented an original Monte Carlo analysis of voltage fluctuations in two-terminal semiconductor devices. In this way, the coupling between fluctuations of carrier velocity and self-consistent electric field is naturally accounted for. A spatial map of the voltage spectral density enables the identification of the local strength of the noise source to be carried out.

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