Microscopic Simulation of Electronic Noise in Semiconductor Materials and Devices

Luca Varani, Lino Reggiani, Tilmann Kuhn, Tomás González, and Daniel Pardo

Invited Paper

***Abstract*— We present a microscopic interpretation of electronic noise in semiconductor materials and two-terminal devices. The theory is 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 application we consider the cases of homogeneous materials, resistors, n^+nn^+ structures, and Schottky-barrier diodes. Phenomena associated with coupling between fluctuations in carrier velocity and self-consistent electric field are quantitatively investigated for the first time. At increasing applied fields hot-carrier effects are found to be of relevant importance in all the cases considered here. As a general result, noise spectroscopy is found to be a source of valuable information to investigate and characterize transport properties of semiconductor materials and devices.**

I. Introduction

ELECTRONIC noise is here synonymous of current or voltage fluctuations around a stationary value. Its existence reflects the presence of a large number of degrees of freedom on a microscopic level which are averaged out in the measurement of a given macroscopic quantity [1], [2]. 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, as documented in a systematic series of Noise Conferences [3]–[9].

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 [10], [11] 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: 1) to present a general theory and the algorithms for the calculation of the current and voltage spectral densities; 2) to investigate systems with increasing degree of complexity; and 3) to decompose the obtained spectra in terms of their sources and spatial contributions.

The paper is organized as follows. In Section II we present the fundamentals of the theoretical approach. Section III is devoted to applications of the theory to physical systems with increasing degree of complexity. Major conclusions are summarized in Section IV.

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II. Theory

We develop a general theory of noise for a simple two-terminal (one-port) device. After defining the basic quantities of interest, the equilibrium properties are briefly recalled. Then, we present the two modes of operation which are used to study electronic noise: i.e., the current and voltage noise operations. In this context, we derive algorithms to calculate the current and voltage fluctuations. Finally, we discuss the main advantages of using separately the current or voltage noise spectra.

A. Basic Properties

In studying electronic noise two different modes of operation, which are mutually exclusive, can be used: current noise operation and voltage noise operation [12]. 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 (Norton generator). This mode is realized by placing an ideal voltage generator between the terminals of the sample, current fluctuations being measured at the boundaries of a very small load resistance in series with the device. In the latter the current in the device is kept constant in time and the voltage fluctuations at its terminals are analyzed (Thevenin generator). This mode is realized by placing the sample in parallel with a dc current generator and measuring voltage fluctuations at the boundaries. Both modes are of interest since in general they provide different and complementary information.

Let us first concentrate on current fluctuations. From the Wiener–Khintchine theorem [13] it is

$$S_I(f) = 2\int_{-\infty}^{+\infty} \exp(i2\pi ft)C_I(t)dt \qquad (1)$$

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$$C_I(t) = \overline{\delta I^V(t')\delta I^V(t'+t)} \tag{2}$$

where $\delta I^V(t) = I^V(t) - \overline{I^V}$ is the total current fluctuation around the average value $\overline{I^V}$, the superscript V is to remind that the applied voltage is taken to be constant in time, i.e. current noise operation is considered, and the bar denotes time average over t'. We notice that because of stationary conditions this average is independent of t'.

By inverting (1) and setting $t = 0$ we obtain the power spectrum relation [13]:

$$\overline{\delta I^2} = \int_0^\infty S_I(f)df. \tag{3}$$

By simply exchanging current with voltage, the analogous of (1)–(3) can be written for voltage fluctuations when the total current is taken to constant in time, i.e. voltage noise operation is considered. Since spectral densities and correlation functions describe second-rank tensorial properties, in the following we assume cubic structures so that by applying the field along high symmetry directions second-rank tensors are diagonal with one longitudinal and two transverse components with respect to the applied field.

At equilibrium, and for continuity under linear response regime (i.e., $V \to 0$), fundamental relationships such as Nyquist and Einstein relations (i.e., fluctuation-dissipation theorem) give an exact theoretical framework [14]. The former relates the value of the current (voltage) spectral-density to the real part of the complex admittance $Y(f)$ (complex impedance $Z(f)$) through:

$$S_I(f) = 4K_BT \ \mathrm{Re}[Y(f)] \tag{4}$$

$$S_V(f) = 4K_BT \ \mathrm{Re}[Z(f)] \tag{5}$$

where K_B is the Boltzmann constant and T the lattice temperature. (We remark here the fact that the frequency dependencies of $S_I(f)$ and $S_V(f)$ are in general different.) The latter relates the static conductance $G(0) = \mathrm{Re}[Y(0)]$ to the diffusion coefficient D and, for a homogeneous device with cross-sectional area A and length L, is given by [14], [15]:

$$G(0) = \frac{e^2}{L^2}\overline{N}D\frac{\partial ln\overline{N}}{\partial \mu_0} \tag{6}$$

where e is the electron charge, $\overline{N}$ the average number of free carriers inside the sample and μ_0 the chemical potential of the system treated within a grand-canonical statistical ensemble.

By substituting (6) in (4), a so called Nyquist–Einstein relationship is obtained which, for a nondegenerate system (i.e., $\partial ln\overline{N}/\partial\mu_0 = 1/K_BT$), assumes the interesting form [16], [17]:

$$S_I(0) = 4\frac{e^2}{L^2}\overline{N}D \tag{7}$$

thus providing a direct relationship between noise (a many-particle property) and diffusion (a single-particle property). From (4)–(7) we learn that in the linear response regime a noise measurement does not add any information yet available from conductance (or diffusion for nondegenerate systems). However, under nonlinear response (i.e., when quadratic effects in the applied fields become noticeable) Nyquist and Einstein relationships no longer hold in general. As a consequence, a noise measurement can provide new information on the transport properties of the device. Furthermore, provided the device exhibits a positive differential resistance (or conductance), via the small-signal impedance of the sample, $Z'(f)$, a so-called Langevin relationship holds [18]:

$$\frac{S_V(f)}{S_I(f)} = |Z'(f)|^2. \tag{8}$$

Under nonlinear response, excess noise contributions (so-called because they vanish for vanishing applied fields) can be detected [13], [19]. It should be noticed that the fluctuations which are responsible for this excess noise are often present also in equilibrium. However, being associated with resistance fluctuations, they manifest themselves only under nonequilibrium conditions [19]. In this context, the presence of a low frequency $1/f$ contribution (also called flicker noise) has been found to be a common feature of excess noise, the origin of which being the subject of many investigations [20]–[24], as reported in other contributions of the present review. Here we will not consider $1/f$ noise explicitly.

B. Microscopic Calculation

The theory underlying the above noise operations is developed in the following for the semiclassical case when a single type of carriers (electrons or holes) is present. Provided the length of the device is small compared to its lateral dimensions, the flux of the displacement current density through the lateral surfaces can be neglected and a one-dimensional treatment can be applied [25]. By neglecting magnetic effects, which for devices operating up to microwave frequencies (i.e., 300 THz) is always well justified [26], the total current through each cross-sectional area is the same and given by the so-called Ramo–Schockley theorem [25], [27], [28]:

$$\begin{aligned} I(t) =& \frac{e}{L}\sum_{i=1}^{N_T(t)} v_{ix}(t) \\ & - \epsilon_0\epsilon_r\frac{A}{L}\frac{d}{dt}[V(L,t) - V(0,t)] \end{aligned} \tag{9}$$

where $N_T(t)$ is the total number of carriers at time t inside the device, $v_{ix}(t)$ the instantaneous value of the velocity component in the field direction of the i-th particle, ϵ_0 the vacuum permittivity, and ϵ_r the relative static dielectric constant of the background medium.

Under current noise operation, the applied voltage is kept constant in time, and from (9) for the total current $I^V(t)$ as measured in the outside circuit we obtain:

$$I^V(t) = \frac{e}{L}\sum_{i=1}^{N_T(t)} v_{ix}(t) = \frac{e}{L}N_T(t)v_d(t) \tag{10}$$

where $v_d(t) = [1/N_T(t)]\sum_{i=1}^{N_T(t)} v_{ix}(t)$ is the drift velocity.

Under voltage noise operation, the total current flowing in the sample is kept constant in time, i.e., $I(t) = I_0$, and from (9) for the time derivative of the voltage drop at the contacts

$\Delta V^I(t) = [V(L,t) - V(0,t)]$ we obtain:

$$\frac{d}{dt}\Delta V^I(t) = \frac{L}{A\epsilon_0\epsilon_r}\left[\frac{e}{L}\sum_{i=1}^{N_T(t)} v_{ix}(t) - I_0\right]. \quad (11)$$

The instantaneous voltage drop between the terminals can be obtained from a numerical integration of (11) over time [29].

C. Simulation

The determination of the current (voltage) correlation function is performed from the knowledge of the time series $I^V(t)$ ($\Delta V^I(t)$) 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 $C_X(t)$ ($X = I^V$, ΔV^I) is obtained as:

$$C_X(j\Delta t) = \overline{X(t')X(t'+j\Delta t)} = \frac{1}{M-m}\sum_{i=1}^{M-m} X(i\Delta t)X[(i+j)\Delta t] \quad (12)$$

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

Unless otherwise stated, in the following we consider periodic boundary conditions at the contacts, which means that the total number of carriers is kept constant, i.e., $N_T(t) = N$, thus fulfilling the neutrality condition for the whole device at any time. This condition is well verified provided the length of the active region of the device is longer than the Debye length.

D. Discussion

Here we present separately the main advantages of current and voltage noise operations (representations) and review simple cases of relevant interest. The use of the current representation enables a decomposition analysis to be carried out. Three cases are considered in the following, namely: 1) diagonal and off-diagonal velocity; 2) carrier number and drift-velocity; and 3) carrier mobility and drift-velocity.

Case 1) is of interest when some source of coupling among carriers is present and $C_I(t)$ can be decomposed in a diagonal (single-particle) and off-diagonal (many-particle) term as [30]:

$$C_I(t) = \left(\frac{e}{L}\right)^2 \left[N\overline{\delta v_i(0)\delta v_i(t)} + \sum_{i \neq j}\overline{\delta v_i(0)\delta v_j(t)}\right]. \quad (13)$$

Case 2) is of interest when the number of free carrier fluctuates (number fluctuation) together with the drift-velocity (this may happen because of the presence of trapping centers and/or of different conducting bands). (Notice that this number fluctuation should not be confused with shot-noise which is related to the fluctuation of the total number of carriers inside the sample [31] and which here is not considered.) Within a two-level model for the number fluctuator, which consists of a conducting band and an impurity level supplying carriers, $C_I(t)$ can be decomposed as [32]:

$$C_I(t) = \left(\frac{eN}{L}\right)^2 \{\overline{u}^2\overline{\delta v_d(0)\delta v_d(t)} + \overline{v_d}^2\overline{\delta u(0)\delta u(t)} + \overline{u}\ \overline{v_d}[\overline{\delta u(0)\delta v_d(t)} + \overline{\delta v_d(0)\delta u(t)}]\} \quad (14)$$

where $u(t)$, defined as the ratio between the number of free carriers and the total number of impurities, is the instantaneous fraction of free carriers in the conducting band. Case 3) is of interest when the scatterer center fluctuates (mobility fluctuation) together with the drift-velocity. Within a two-level model for the mobility fluctuator, $C_I(t)$ can be decomposed as [11]

$$C_I(t) = \left(\frac{eN}{L}\right)^2 \left\{\overline{\delta v_d^{(0)}(0)\delta v_d^{(0)}(t)} + \left(\frac{\overline{v_d}}{\overline{\mu}}\right)^2 \overline{\delta\mu(0)\delta\mu(t)} + \frac{\overline{v_d}}{\overline{\mu}}[\overline{\delta\mu(0)\delta v_d^{(0)}(t)} + \overline{\delta v_d^{(0)}(0)\delta\mu(t)}]\right\} \quad (15)$$

where the drift velocity has been decomposed into the sum of two contributions responsible for thermal and excess noise as $v_d(t) = \delta v_d^{(0)}(t) + \mu(t)E$, $\delta v_d^{(0)}(t)$ being associated with the Brownian-like motion of the carriers due to all scattering mechanisms and $\mu(t)E$, E being the electric field, with the stochastic carrier mobility. We remark that in all cases cross contributions are present together with diagonal contributions. When the respective time scales are sufficiently different, one can neglect the cross contributions whose time dependence is in general quite difficult to be determined. On the other hand, the diagonal contribution can often admit a simple relaxation decay of the form:

$$C_{I,\alpha}(t) = C_{I,\alpha}(0)\exp(-t/\tau_\alpha) \quad (16)$$

where, for the cases reported above, the subindex α refer to fluctuations of single carrier velocity (δv), carrier drift velocity (δv_d), carrier number (δu), carrier mobility ($\delta\mu$) as

$$C_{I,\delta v}(0) = \left(\frac{e}{L}\right)^2 N\overline{\delta v_i(0)^2} \quad (17a)$$

$$C_{I,\delta vd}(0) = \left(\frac{eN\overline{u}}{L}\right)^2 \overline{\delta v_d(0)^2} \quad (17b)$$

$$C_{I,\delta u}(0) = \left(\frac{eN\overline{v_d}}{L}\right)^2 \overline{\delta u(0)^2} \quad (17c)$$

$$C_{I,\delta\mu}(0) = \left(\frac{eN\overline{v_d}}{L\overline{\mu}}\right)^2 \overline{\delta\mu(0)^2} \quad (17d)$$

with τ_v and τ_{vd} momentum relaxation times, τ_u the carrier lifetime, τ_μ the scatterer lifetime. In addition, for the case of Boltzmann statistics it is $\overline{\delta v_d(0)^2} = \overline{\delta v_i^2}/(N\ \overline{u})$ and $\overline{\delta u(0)^2} = \overline{u}/N$. Thus for independent fluctuators the current spectral density is expressed as a sum of Lorentzians:

$$S_I(f) = 4\sum_\alpha C_{I,\alpha}(0)\frac{\tau_\alpha}{1+(2\pi f\tau_\alpha)^2}. \quad (18)$$

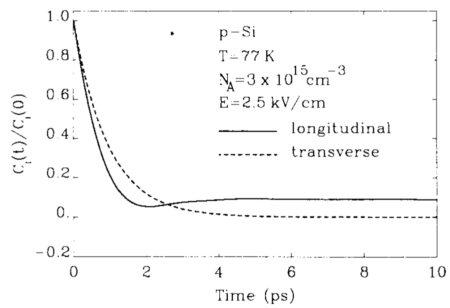

Fig. 1. Autocorrelation function of current fluctuations normalized to their initial values in p-type Si at 77 K with $N_A = 3 \times 10^{15}$ cm^{-3} at an electric field of 2500 V/cm as obtained from the MC simulation. Full curve refers to the longitudinal and dashed to the transverse component with respect to the applied field.

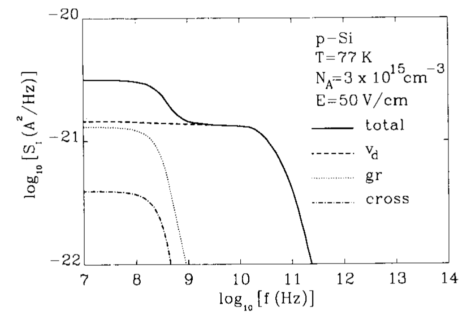

Fig. 2. Longitudinal component of the current spectral-density as a function of frequency in p-type Si at 77 K with $N_A = 3 \times 10^{15}$ cm^{-3} for $E = 50$ V/cm, $L = 1.5 \times 10^{-2}$ cm, and $A = 3.6 \times 10^{-3}$ cm^2. Continuous, dashed, dotted, and dot-dashed lines refer respectively to total, drift-velocity, GR, and cross contributions.

The use of the voltage representation enables one to carry out a spatial resolution-analysis which cannot be achieved using the current noise operation since in that case the only information given is the total current flowing in the outside circuit (see (10)). To this end, the voltage spectral density between the two contacts of a one-dimensional structure $S_V(0, L; f)$ calculated with the MC technique can be usefully compared with the analytical expression given by the field-impedance method [33], [34], as illustrated in the following. By defining $\delta V_i(f)$ as the voltage fluctuation on electrode i induced by an impressed harmonic current-density source $\delta \mathbf{j}(\mathbf{r}', f)$ at point $\mathbf{r}'$ as:

$$\delta V_i(f) = \int_\Omega \nabla_{r'} \widetilde{Z}(\mathbf{r}_i, \mathbf{r}'; f) \cdot \delta \mathbf{j}(\mathbf{r}'; f) d\mathbf{r}' \tag{19}$$

where Ω is the volume of the device and $\nabla \widetilde{Z}$ the vector Green function (impedance field) associated with the linear problem $\widehat{Y}'\delta V = -\nabla \cdot \delta \mathbf{j}$, $\widehat{Y}'$ being the small-signal admittance operator per unit volume, the voltage spectral density for a many terminals three-dimensional device with one-terminal grounded is expressed through the impedance field-method as [35]

$$\begin{aligned} S_{\delta V i \delta V j}(f) = \int_\Omega d\mathbf{r}_1 \int_\Omega d\mathbf{r}_2 \nabla_{r1} \widetilde{Z}(\mathbf{r}_i, \mathbf{r}_1; f) \\ \cdot S_{\delta j(r1) \delta j(r2)}(\mathbf{r}_1, \mathbf{r}_2; f) \\ \cdot \nabla_{r2} \widetilde{Z}^*(\mathbf{r}_j, \mathbf{r}_2; f) \end{aligned} \tag{20}$$

where $S_{\delta j \delta j}$ is the spectrum of the noise source, and * denotes complex conjugate.

The complexity of (20) is significantly reduced for a one-dimensional structure of cross-sectional area A (i.e., $i = j$ and only diagonal terms are considered), with uncorrelated velocity-fluctuation sources (i.e., $S_{\delta j \delta j}(x_1, x_2; f) = e^2 n(x_1) S_v(x_1; f)(1/A)\delta(x_1 - x_2)$), so that it simplifies to

$$S_V(0, L; f) = e^2 A \int_0^L n(x) S_v(x; f) |\nabla_x Z(x; f)|^2 dx \tag{21}$$

where $n(x)$ is the free carrier concentration and $S_v(x; f)$ the local spectral density of a single-carrier velocity fluctuations. We remark that one can define a local additive voltage-noise source given by $dS_V(0, x; f)/dx$. Both the voltage spectral density and its spatial derivative can be directly obtained from MC simulations and used to identify the most noisy part of a given device [29].

III. Applications

In this Section we report results obtained by the MC technique as applied to different systems with increasing degree of complexity. The accuracy of the final values is estimated to be at worst within 10%.

A. Material (Bulk)

The system we consider is p-type Si at 77 K and the results, which are obtained by applying a constant electric field without solving the Poisson equation, are shown in Figs. 1–4 [36], [37]. The microscopic model [38] uses a single valence band (the heavy one) warped with nonparabolic effects accounted for. Acoustic, nonpolar optical and ionized impurity scattering mechanisms are considered. A nonradiative generation-recombination (GR) mechanism assisted by acoustic phonons is introduced [39]. Here we consider uncompensated samples and neglect Poole–Frenkel effect. Time steps of 0.1 ps and 10 ps are employed for the short and the long time behavior of the correlation functions, respectively. Because of the partial freeze-out of holes, generation-recombination (GR) noise adds to thermal noise. Fig. 1 shows the correlation function of the longitudinal and transverse current at an intermediate field strength of 2.5 kV/cm. We remark that the longitudinal component evidences three time scales: momentum relaxation at the shortest times, energy relaxation, which is responsible for the minimum at intermediate times and carrier lifetime which is responsible for the long time tail. The correlation function finally vanishes on a nanosecond time scale. Conversely, the transverse component exhibits only momentum relaxation.

Fig. 2 shows the numerical results of the longitudinal current-spectral-density, here decomposed into the three contributions corresponding to the right-hand-side terms of (14), for a low field of 50 V/cm. As can be seen, at low frequencies the GR and drift-velocity contributions are comparable and the cross term, even if of weaker relevance, is easily detectable. Both GR and cross contributions decay with a Lorentzian

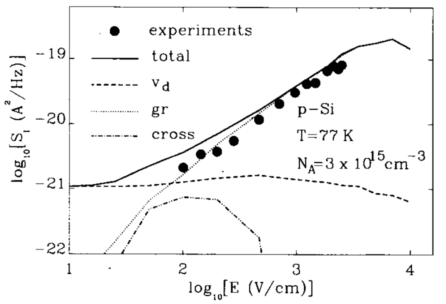

Fig. 3. Low-frequency longitudinal current spectral-density as a function of the electric field in p-type Si at 77 K with $L = 1.5 \times 10^{-2}$ cm, $A = 3.6 \times 10^{-3}$ cm^2 and $N_A = 3 \times 10^{15}$ cm^{-3}. Symbols refer to experiments obtained at the lowest frequency of 220 MHz, curves to MC calculations [37]. Continuous, dashed, dotted, and dot-dashed lines refer respectively to total, drift-velocity, GR, and cross contributions. The theoretical values obtained directly from the MC simulation have been scaled by a factor $(2 - \overline{u})^{-2}$ in order to account for a quadratic recombination kinetics.

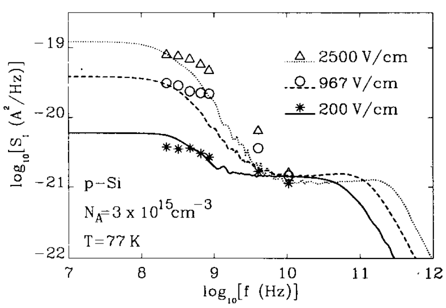

Fig. 4. Longitudinal current spectral-density as a function of frequency in p-type Si at 77 K with $L = 1.5 \times 10^{-2}$ cm, $A = 3.6 \times 10^{-3}$ cm^2, and $N_A = 3 \times 10^{15}$ cm^{-3} at different electric fields. Symbols refer to experiments, curves to MC calculations [37]. *(Reprinted from: T. Kuhn, L. Reggiani, L. Varani, D. Gasquet, J. C. Vaissiere, and J. P. Nougier, "Field dependent electronic noise of lightly doped p-type Si at 77 K," Phys. Rev., vol. B44, p. 1074, 1991.)*

shape characterized by a corner frequency given by $1/(2\pi\tau_u)$, while the velocity contribution decays similarly but with a corner frequency given by $1/(2\pi\tau_{vd})$.

Fig. 3 reports the relative contributions into which the longitudinal spectral-density at low-frequency can be decomposed as a function of the electric field. At the lowest fields, in agreement with Nyquist relationship the drift-velocity contribution is found to dominate. In the intermediate region of fields, both GR and cross contributions increase, the former becoming the leading term above 50 V/cm. We notice that the cross term peaks in the region where GR and velocity contributions become comparable and then decreases systematically. In the whole range of fields theory well agrees with experiments.

To complete the theoretical interpretation, Fig. 4 reports the full spectrum of the longitudinal current spectral-density for three significative fields. The calculations well reproduce the main features of the experiments within a factor 2 at worst, thus providing a satisfactory interpretation.

We remark that to calculate current fluctuations in the material we have performed only a MC simulation in momentum space. As a consequence, no direct information is available on voltage fluctuations. In order to obtain the voltage spectral density and/or include the fluctuations of the self-consistent electric field the geometry of the sample in real space must be fixed *a priori*. This leads us to the next section.

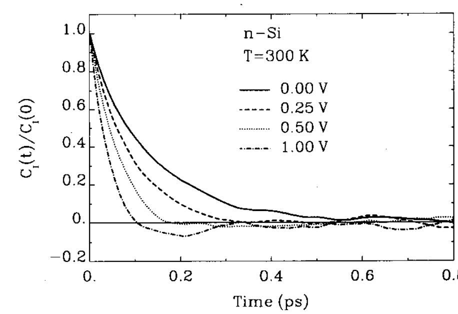

Fig. 5. Autocorrelation functions of current fluctuations for the different applied voltages reported. Calculations refers to a Si homogeneous structure with $n = 10^{17}$ cm^{-3}, $L = 0.6$ μm, at $T = 300$ K. *(Reprinted from: L. Varani, T. Kuhn, L. Reggiani, and Y. Perles, "Current and number fluctuations in submicron n^+nn^+ structures," Solid State Electron., vol. 36, p. 251, 1993.)*

B. Resistor

The system we consider is a space-homogenous submicron Si resistor of length $L = 0.6$ μm with a donor concentration of 10^{17} cm^{-3} at 300 K [40]. The silicon model used [41] takes into account an isotropic nonparabolic band structure, which is appropriate when the electric field is oriented along the $\langle 111 \rangle$ crystallographic direction, and scattering mechanisms with acoustic and intervalley phonons. The total length of the device is equally divided into cells (typically of the order of 100 cells) and initially each cell is taken to be electrically neutral. A time step of 1 fs has been employed. Fig. 5 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 [36].

Figs. 6 and 7 show the voltage correlation functions and the corresponding spectral densities for the same resistor. Here, plasma and differential dielectric-relaxation times are responsible for the oscillatory and dumping behaviors of the correlation functions reported in Fig. 6. At increasing applied voltages the subohmic 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.

The next step is now to introduce a spatial inhomogeneity in the structure. To this end, we devote the next section to the study of fluctuations in a n$^+$nn$^+$ diode, which represents the prototype of most semiconductor devices and can be easily simulated by the MC technique.

C. n^+nn^+ Structures

The system we consider is a submicron Si n$^+$nn$^+$ structure at 300 K with two abrupt homojunctions along the x-direction [40]. The lengths of the three regions are indicated, respectively, as L_1, L and L_2. The microscopic model is the same used in Section III-B. A time step of 1 fs has been

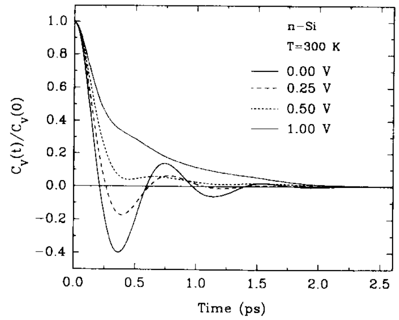

Fig. 6. Autocorrelation function of voltage fluctuations in the same structure and conditions as Fig. 5.

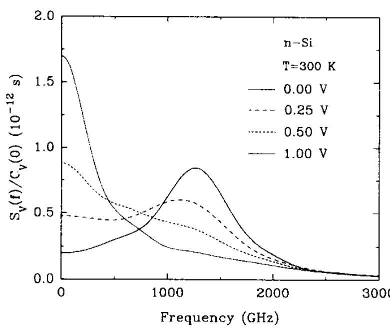

Fig. 7. Voltage spectral density corresponding to Fig. 6.

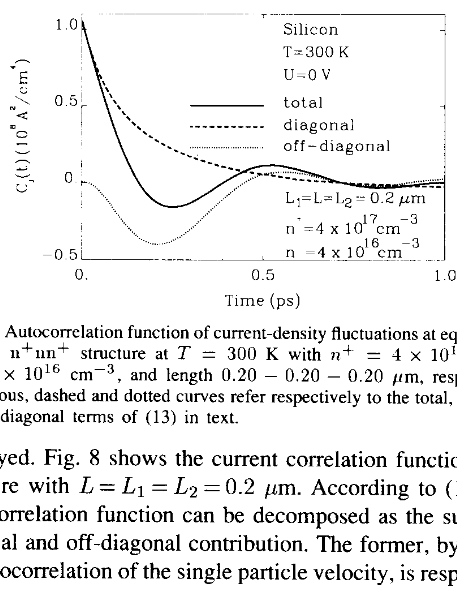

Fig. 8. Autocorrelation function of current-density fluctuations at equilibrium for a Si n^+nn^+ structure at $T = 300$ K with $n^+ = 4 \times 10^{17}$ cm^{-3}, $n = 4 \times 10^{16}$ cm^{-3}, and length $0.20 - 0.20 - 0.20$ μm, respectively. Continuous, dashed and dotted curves refer respectively to the total, diagonal, and off-diagonal terms of (13) in text.

employed. Fig. 8 shows the current correlation function for a structure with $L = L_1 = L_2 = 0.2$ μm. According to (13), the total correlation function can be decomposed as the sum of a diagonal and off-diagonal contribution. The former, by giving the autocorrelation of the single particle velocity, is responsible for the exponential decay. The latter, being associated with the long-range Coulomb interaction, is responsible for an oscillatory behavior related to the plasma frequency of the n^+ and n regions.

Fig. 9 shows a 3-D plot of the voltage correlation-function $C_V(0, x; t)$ for different sampling points of the same structure with $n = 10^{16}$ cm^{-3} and $n^+ = 10^{17}$ cm^{-3}. The time evolution of $C_V(0, x; t)$ depends on the contribution to the voltage fluctuations which comes from each region in the structure through the value of its resistance and doping. In this way

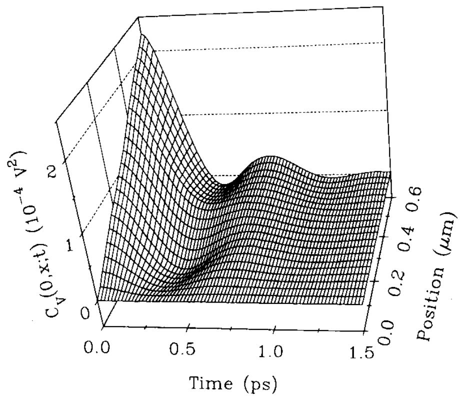

Fig. 9. Autocorrelation function of voltage fluctuations as a function of time and position at equilibrium for a Si n^+nn^+ structure at $T = 300$ K with $n^+ = 10^{17}$ cm^{-3}, $n = 10^{16}$ cm^{-3}, and length $0.20 - 0.20 - 0.20$ μm, respectively. (*Reprinted from: T. Gonzalez, D. Pardo, L. Varani, and L. Reggiani, "Spatial analysis of electronic noise in submicron semiconductor structures," Appl. Phys. Lett., vol. 63, p. 84, 1993.*)

we observe that, through the plasma time, the n^+ regions are responsible for an oscillatory behavior that at increasing times is suppressed by dielectric relaxation [29]. In the n region the evolution is mainly determined by dielectric relaxation through a contribution which decreases exponentially with time. It is remarkable the very good agreement found for $C_V(0, x; 0) = K_B T x / (\epsilon_0 \epsilon_r A)$ [12].

Fig. 10 shows the voltage spectral-density corresponding to Fig. 9. 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. It is interesting to notice that the presence of the self-consistent field in the homojunctions produces some smoothing from the three-slope linear behavior which is expected for a simple series-resistance model $S_V(0, x; 0) = 4 K_B T R(0, x)$, where $R(0, x)$ is the ohmic resistance of the structure up to the point x. 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 for 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.

Fig. 11 shows the voltage spectral-density for a GaAs n^+nn^+ structure with $n^+ = 10^{17}$ cm^{-3}, $n = 10^{14}$ cm^{-3} and length 0.15–0.25–0.50 μm, at $T = 300$ K with an average applied voltage of 0.45 V [29]. The GaAs model [42] takes into account the first conduction band within a three-valley model (Γ, L, X) all isotropic and nonparabolic. Intravalley acoustic and polar-optical, as well as intervalley scattering between each couple of valley is considered. Analogously to the case of Si, the structure exhibits a noticeable peak at the plasma frequency corresponding to the n^+ region. Furthermore, in the lowest frequency region the contribution of the drain region to noise is found to be of great importance. Indeed, here the presence of carriers in the higher satellite valleys implies a deeper penetration of hot carriers in the drain before they can thermalize. Therefore, this region becomes highly resistive and thus highly noisy. We remark the evidence of a minor peak

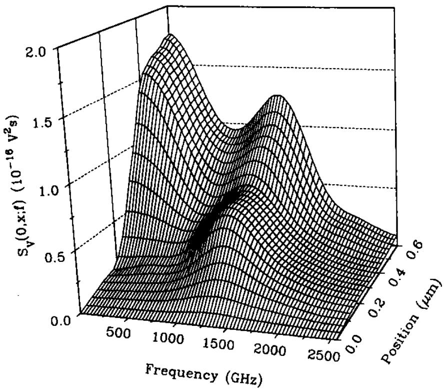

Fig. 10. Spectral density of voltage fluctuations as a function of frequency and position at equilibrium in the same structure and conditions as Fig. 9. *(Reprinted from: T. Gonzalez, D. Pardo, L. Varani, and L. Reggiani, "Spatial analysis of electronic noise in submicron semiconductor structures," Appl. Phys. Lett., vol. 63, p. 84, 1993.)*

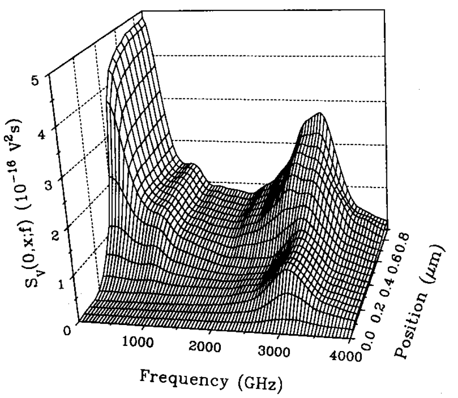

Fig. 11. Spectral density of voltage fluctuations as a function of frequency and position in a GaAs n^+nn^+ structure for an average voltage $\Delta V^I(L) = 0.45$ V at $T = 300$ K with $n^+ = 10^{17}$ cm^{-3}, $n = 10^{14}$ cm^{-3}, and length $0.15-0.25-0.50$ μm, respectively. *(Reprinted from: T. Gonzalez, D. Pardo, L. Varani, and L. Reggiani, "Spatial analysis of electronic noise in submicron semiconductor structures," Appl. Phys. Lett., vol. 63, p. 84, 1993.)*

at about 500 GHz, the origin of which is attributed to the presence of $\Gamma - L$ intervalley mechanism in the vicinity of the second homojunction.

A further increase in the complexity of the studied system leads to substitute one of n^+ regions of the n^+nn^+ diode with a metal contact, thus obtaining a so called Schottky-diode. As a matter of fact, the asymmetry of this structure and its strong deviation from the Ohmic behavior are known to introduce new peculiarities in the noise spectra. This is the subject of the next section.

D. Schottky Diode

The system we consider is a one-dimensional GaAs $n^+ - n$ *-metal* structure at 300 K [43]. The microscopic model is the same already used in Section III-C The structure is divided into equal cells of length 10 nm. Time steps of 10 fs and 2.5 fs are employed for the current and the voltage noise, respectively. The doping of the n^+ region is 10^{17} cm^{-3} and

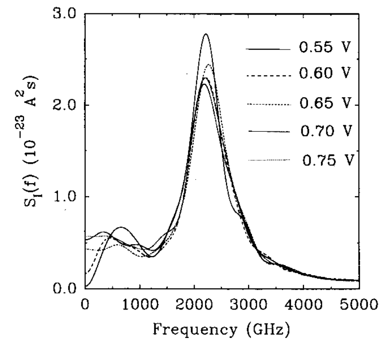

Fig. 12. Current spectral-density as a function of frequency for a GaAs Schottky barrier diode at $T = 300$ K with $n = 10^{16}$ cm^{-3}, $n^+ = 10^{17}$ cm^{-3} and length of each region of 0.35 μm. Different curves refer to the reported applied voltages.

it is 0.35 μm long. At its left side, where the carriers are injected into the device, an ohmic contact is simulated, and the number of electrons considered is updated. Charge neutrality is assured at each time step in the cell closest to the contact by injecting carriers with a thermal distribution at the lattice temperature. The n region is 0.35 μm long and its doping is 10^{16} cm^{-3}. At its end it is the Schottky barrier with the metal contact acting as a perfect absorbing boundary, that is, all the carriers reaching the metal leave the device and no carrier is injected from the metal into the semiconductor. 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. The cross-sectional area adopted for the device is 2×10^{-9} cm^2, which means an average number of simulated carriers around 7600 depending on the bias.

Fig. 12 shows $S_I(f)$ at increasing applied voltages where the current-voltage characteristic exhibits an exponential behavior. The complexity of the spectrum is understood 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 2.2×10^3 GHz. The first is attributed to carriers that have insufficient kinetic energy to surpass the barrier and return to the neutral semiconductor region, as explained in [44]. 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 [43].

By reporting $S_I(0)$ as a function of the current, Fig. 13 enables an analysis of noise sources to be carried out. Accordingly, at low currents shot-noise [19] is found to be dominant, so that $S_I(0)$ exhibits a $2eI$ dependence. At higher currents, $S_I(0)$ approaches a thermal noise behavior $S_I(0) = 4K_BT/R_s$, R_s being the differential series resistance, and finally exhibits a steep increase associated with hot-carrier effects. By considering the first two behaviors, $S_I(0)$ can be expressed as [44]:

$$S_I(0) = \frac{2eIR_j^2 + 4K_BTR_s}{(R_s + R_j)^2} \tag{22}$$

where R_j is the differential resistance of the junction space-

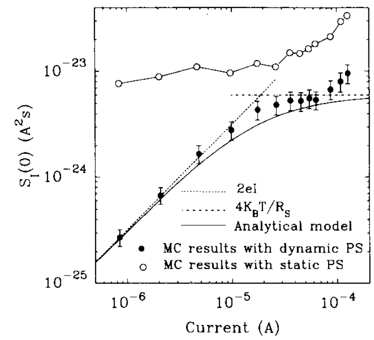

Fig. 13. Low-frequency value of the spectral density of current fluctuations as a function of the current flowing through the same structure as Fig. 12. Symbols refer to MC calculations performed considering a dynamic (closed circles) and a static (open circles) Poisson solver, respectively, the continuous line to the analytical model from [44].

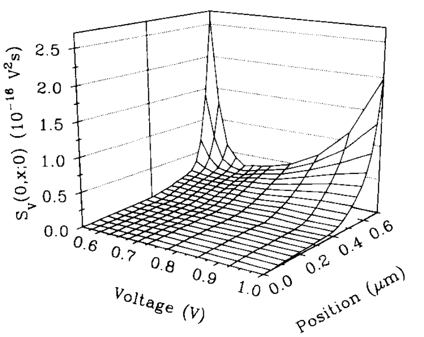

Fig. 14. Low-frequency value of the spectral density of voltage fluctuations as a function of position and mean voltage in the same structure as Fig. 12.

charge region. In Fig. 13 the results of the simulation are favorably compared with this analytical model and the two limit behaviors. Fig. 13 also reports the values obtained for $S_I(0)$ when a static Poisson solver is considered in the simulation by using the field profile corresponding to the stationary situation. While the static characteristics are checked to remain the same, the results for $S_I(0)$ differ considerably, and no transition from a shot-noise behavior to a thermal-noise behavior is noticed. These results prove the essential role played by the coupling between fluctuations in carrier velocity and self-consistent electric field in determining the noise spectra.

Fig. 14 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, 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. In this range, electrons become hot after traveling some distance in the n region. This is the reason why $S_V(0, x; 0)$ takes these higher values near the end of the n region.

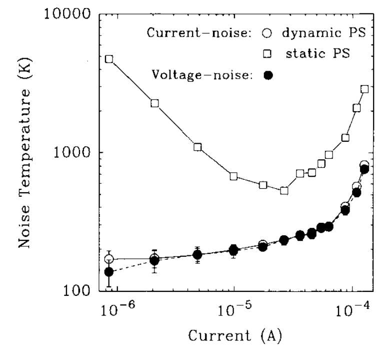

Fig. 15. Equivalent noise temperature at low frequency as a function of the current flowing through the same structure as Fig. 12. Circles correspond to MC calculations performed considering a dynamic Poisson solver in the simulation and employing: current noise operation (open circles) and voltage noise operation (full circles). Squares correspond to calculations considering a static Poisson solver and making use of current noise operation.

Fig. 15 reports the equivalent noise temperature at zero frequency T_n with which T must be replaced for the two sides of (4), (5) to be equal when they are independently calculated [15]. For low currents, corresponding to the exponential region of the current-voltage characteristics, $T_n \simeq T/2$, thus revealing a full shot-noise behavior. As the current increases, the effect of the thermal noise in the series resistance becomes important and T_n approaches T to finally cross over because of the onset of hot-carrier effects. This behavior of the noise temperature agrees favorably with available experiments [45]–[47]. We remark the essential role of the dynamic Poisson solver which substantially suppresses the noise temperature.

IV. Conclusion

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. Both current and voltage correlation functions and their respective spectral densities are investigated. 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. For the case of homogeneous structures, the presence of hot-carrier conditions is found to couple number, velocity and energy fluctuations. When considering nonhomogeneous structures, the coupling between fluctuations in carrier velocity and self-consistent electric field is proven to essentially modify the noise-spectrum. In particular, the Schottky-diode is analyzed within a microscopic model which naturally describes most of the salient features of its noise spectrum without invoking phenomenological shot and thermal noise sources. Finally, 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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REFERENCES

[1] K. M. Van Vliet, "Markov approach to density fluctuations due to transport and scattering. I. Mathematical formalism," *J. Math. Phys.*, vol. 12, p. 1981, 1971; ibidem "II. Applications," vol. 12, p. 1998, 1971.
[2] Van Kampen, *Stochastic Processes in Physics and Chemistry*. Amsterdam: North-Holland, 1981.
[3] *Proc. 6th Int. Conf. on Noise in Physical Systems and 1/f Noise*, P. H. E. Meijer, R. D. Mountain, and R. J. Soulen, Eds. Washington: National Bureau of Standards, 1981.
[4] *Proc. 7th Int. Conf. on Noise in Physical Systems and 1/f Noise*, M. Savelli, G. Lecoy, and J. P. Nougier, Eds. Montpellier: North-Holland, 1983.
[5] *Proc. 8th Int. Conf. on Noise in Physical Systems and 1/f Noise*, A. D'Amico and P. Mazzetti, Eds. Rome: North-Holland, 1985.
[6] *Proc. 9th Int. Conf. on Noise in Physical Systems and 1/f Noise*, C. M. Van Vliet, Ed. Montreal: World Scientific, 1987.
[7] *Proc. 10th Int. Conf. on Noise in Physical Systems and 1/f Noise*, A. Ambrozy, Ed. Budapest: Akademiai Kiado, 1989.
[8] *Proc. 11th Int. Conf. on Noise in Physical Systems and 1/f Noise*, T. Musha, S. Sato, and M. Yamamoto, Eds. Kyoto: Ohmsha Ltd., 1991.
[9] *Proc. 12th Int. Conf. on Noise in Physical Systems and 1/f Noise*, P. H. Handel and A. L. Chung, Eds. New York: AIP Press, 1993.
[10] C. Jacoboni and L. Reggiani, "The Monte Carlo method for the solution of charge transport in semiconductors with application to covalent materials," *Rev. Mod. Phys.*, vol. 55, p. 645, 1983.
[11] L. Reggiani, T. Kuhn, and L. Varani, "Noise and correlation functions of hot carriers in semiconductors," *Appl. Phys. A*, vol. 54, p. 411, 1992.
[12] J. Zimmerman and E. Constant, "Application of Monte Carlo techniques to hot carrier diffusion noise calculation in unipolar semiconducting components," *Solid State Electron.*, vol. 23, p. 914, 1980.
[13] A. Van der Ziel, *Noise, Source, Characterization, Measurement*. Englewood Cliffs, NJ: Prentice-Hall, 1970.
[14] M. Toda, R. Kubo, and N. Saito "Statistical Physics I," vol. 30 of Springer Series in *Solid-State Science*, M. Cardona, P. Fulde, and H. J. Queisser, Eds. Berlin: Springer-Verlag, 1983.
[15] L. Reggiani and T. Kuhn, "Noise in small and ultra-small geometries," in *Granular Nanoelectronics*, D. K. Ferry, Ed. New York: Plenum, 1991, p. 287.
[16] P. J. Price, "Fluctuations of hot electrons" in *Fluctuation Phenomena in Solids*, R. E. Burgess, Ed. New York: Academic, 1965, p. 355.
[17] L. Reggiani, P. Lugli, and V. Mitin, "Generalization of Nyquist-Einstein relationship to conditions far from equilibrium in non-degenerate semiconductors," *Phys. Rev. Lett.*, vol. 8, p. 736, 1988.
[18] J. P. Nougier: "Methodes de calcul du bruit de fond," *Cours de D.E.A. sur le Bruit de Fond*, Univ. Montpellier, unpublished, 1975.
[19] A. Van der Ziel, *Noise in Solid State Devices and Circuits*. New York: Wiley, 1986.
[20] P. Dutta and P. M. Horn, "Low-frequency fluctuations in solids: $1/f$ noise," *Rev. Mod. Phys.*, vol. 53, p. 497, 1981.
[21] F. N. Hooge, T. G. M. Kleinpenning, and L. K. J. Vandamme, "Experimental studies on $1/f$ noise," *Rep. Progress Phys.*, vol. 44, p. 479, 1981.
[22] Sh. M. Kogan, "Low-frequency current noise with a $1/f$ spectrum in solids," *Sov. Phys. Usp.* vol. 28, p. 170, 1985.
[23] M. B. Weissman, "$1/f$ noise and other slow, nonexponential kinetics in condensed matter," *Rev. Mod. Phys.*, vol. 60, p. 537, 1988.
[24] C. M. Van Vliet, "A survey of results and future prospects on quantum $1/f$ noise and $1/f$ noise in general," *Solid-State Electron.*, vol. 34, p. 1, 1991.
[25] B. Pellegrini, "Electrical charge motion, induced current, energy balance, and noise," *Phys. Rev.*, vol. B34, p. 5921, 1986.
[26] C. M. Snowden, *Introduction to Semiconductor Device Modelling*. Singapore: World Scientific, 1986.
[27] W. Shockley, "Current to conductors induced by a moving point charge," *J. Appl. Phys.*, vol. 9, p. 635, 1938.
[28] S. Ramo, "Currents induced by electron motion," *Proc. IRE*, vol. 27, p. 584, 1939.
[29] T. Gonzalez, D. Pardo, L. Varani, and L. Reggiani, "Spatial analysis of electronic noise in submicron semiconductor structures," *Appl. Phys. Lett.*, vol. 63, p. 84, 1993.
[30] P. Lugli and L. Reggiani, "Electron-electron interaction effect on the spectral density of current fluctuations of hot electrons in Si," *Proc. 8th Int. Conf. on Noise in Physical Systems and 1/f Noise*, A. D'Amico and P. Mazzetti, Eds. Rome: North-Holland, 1985, p. 235.
[31] L. Varani, L. Reggiani, P. Houlet, and T. Kuhn, "Shot noise in hot carrier transport," *Proc. 21st I.C.P.S.*, P. Jiang and H. Z. Zheng, Eds. Singapore: World Scientific, 1992, p. 333.
[32] T. Kuhn, L. Reggiani, L. Varani, and V. Mitin, "Monte Carlo method for the simulation of electronic noise in semiconductors," *Phys. Rev.*, vol. B42, p. 5702, 1990.
[33] W. Shockley, J. A. Copeland, and R. P. James, "The impedance field method of noise calculation in active semiconductor devices," in *Quantum Theory of Atoms, Molecules and Solid State*, P. O. Lowdin, Ed. New York: Academic, 1966, p. 537.
[34] K. M. van Vliet, A. Friedman, R. J. J. Zijlstra, A. Gisolf, and A. van der Ziel, "Noise in single injection diodes. I: A survey method," *J. Appl. Phys.*, vol. 46, p. 1804, 1975.
[35] G. Ghione and F. Filicori, "A computationally efficient unified approach to the numerical analysis of the sensitivity and noise of semiconductor devices," *IEEE Trans. Comp.-Aided Design Integrated Circ. Syst.*, vol. 12, p. 425, 1993.
[36] T. Kuhn, L. Reggiani, and L. Varani, "Correlation functions and electronic noise in doped semiconductors," *Phys. Rev.*, vol. B42, p. 11133, 1990.
[37] T. Kuhn, L. Reggiani, L. Varani, D. Gasquet, J. C. Vaissiere, and J. P. Nougier, "Field dependent electronic noise of lightly doped p-type Si at 77 K," *Phys. Rev.*, vol. B44, p. 1074, 1991.
[38] L. Reggiani, R. Brunetti, and E. Normantas, "Diffusion coefficient of holes in silicon by Monte Carlo simulation," *J. Appl. Phys.*, vol. 59, p. 1212, 1986.
[39] L. Reggiani, P. Lugli, and V. Mitin, "Monte Carlo algorithm for generation recombination in semiconductors," *Appl. Phys. Lett.*, vol. 51, p. 925, 1987.
[40] L. Varani, T. Kuhn, L. Reggiani, and Y. Perles, "Current and number fluctuations in submicron n^+nn^+ structures," *Solid State Electron.*, vol. 36, p. 251, 1993.
[41] P. Lugli, "A Monte Carlo study of transient phenomena in silicon," Ph.D dissertation, Colorado State Univ., 1981, unpublished.
[42] T. Gonzalez Sanchez, J. E. Velasquez Perez, P. M. Gutierrez Conde, and D. Pardo Collantes, "Five-valley model for the study of electric transport properties at very high electric fields in GaAs," *Semicond. Sci. Technol.*, vol. 6, p. 862, 1991.
[43] T. Gonzalez, D. Pardo, L. Varani, and L. Reggiani, "Monte Carlo analysis of noise spectra in Schottky-barrier diodes," *Appl. Phys. Lett.*, vol. 63, p. 3040, 1993.
[44] M. Trippe, G. Bosman, and A. van der Ziel, "Transit-time effects in the noise of Schottky-barrier diodes," *IEEE Trans. Microw. Theory Tech.*, vol. 34, p. 1183, 1986.
[45] E. Kollberg, H. Zirath, and A. Jelenski, "Temperature-variable characteristics and noise in metal-semiconductor junctions," *IEEE Trans. Microw. Theory Tech.*, vol. 34, p. 913, 1986.
[46] A. Jelenski, E. Kollberg, and H. Zirath "Broad-band noise mechanisms and noise measurements of metal-semiconductor junctions," *IEEE Trans. Microw. Theory Tech.*, vol. 34, p. 1193, 1986.
[47] S. Palczewski, A. Jelenski, A. Grüb, and H. Hartnagel, "Noise characterization of Schottky barrier diodes for high-frequency mixing applications," *IEEE Microw. Guid. Wave Lett.*, vol. 2, p. 442, 1992.

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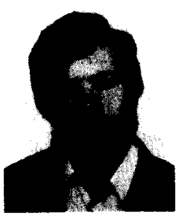

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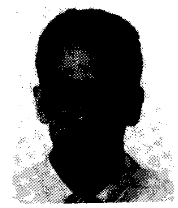

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