

Langevin Forces and Generalized Transfer Fields for Noise Modeling in Deep Submicron Devices

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Abstract—We show that the standard impedance field method that considers as noise source the spectral density of velocity fluctuations is not appropriate for the calculation of noise spectra in deep submicron devices where spatial correlations between velocity fluctuations cannot be neglected. To overcome this drawback, we develop a new scheme in which the noise sources are given by the instantaneous accelerations of relevant dynamic variables caused by scattering events. Accordingly, generalized transfer fields describing the propagation of fluctuations to the device terminals are introduced. By using this scheme, we show that, in contrast with the standard impedance field method, noise modeling in submicron structures can be performed with no major difficulty and the dual representation of voltage and current noise is recovered.

Index Terms—Electronic noise, Green functions, hydrodynamic modeling, Langevin forces.

I. INTRODUCTION

THE STANDARD impedance field (SIF) method [1] and successive modifications such as the transfer impedance method [2], is a deterministic approach able to provide analytical and numerical solutions for the voltage noise spectra of electronic devices. Since its introduction by Shockley *et al.* [1], several efforts have been made [1]–[18] to place the SIF method at a level of theoretical rigor comparable with more microscopic approaches, mostly motivated by the appealing features and flexibility of this method to interpret experiments. The general strategy of the SIF method consists in factorizing the whole noise problem into two separate problems aiming at determining: 1) the noise source, with dimension of spectral density of current-density fluctuations; 2) the transfer property of a local current perturbation, with dimension of impedance per unit volume, usually able to reproduce the small-signal impedance

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of the device by integration over the real space. The spectral density of voltage fluctuations is then represented as a convolution in real space of an appropriate product of the two above quantities. Then, by assuming that the current fluctuations are spatially uncorrelated, the SIF method provides a final formula that relates the spectral density of voltage fluctuations to the local spectral density of current fluctuations. While justifiable for long semiconductor devices, this assumption loses its validity with the decrease of device dimensions to length scales comparable with the carrier mean free-path, that is into the submicron size typical of modern microelectronics. Here, the importance of spatial correlations between velocity fluctuations is expected to increase significantly [15]. The aim of this paper is to develop an alternative approach, able to overcome the SIF drawback and thus being appropriate for noise modeling in deep submicron devices.

In Section II, we briefly review the SIF theory underlining the main problems and inconsistencies which arise. Section III is devoted to the new scheme based on a generalized transfer field (GTF) theory. In Section IV, the new scheme is validated by comparison with direct Monte Carlo (MC) simulations. Section V draws the main conclusions.

II. THE STANDARD IMPEDANCE FIELD METHOD

According to the most advanced formulation of the SIF method, the spectral density of voltage fluctuations $S_U(\omega)$ at the terminals of a one dimensional device operating under constant-current condition takes the form [19]

$$S_U(\omega) = \int_0^L \int_0^L dx' dx'' \nabla Z(x', \omega) \nabla Z^*(x'', \omega) K(x', x'', \omega) \quad (1)$$

where $\nabla Z(x, \omega)$ is the SIF and $K(x', x'', \omega)$ the two-point noise source. The SIF can be calculated by Fourier transforming the voltage-response function to an initial perturbation of the conduction current in point x . Being some kind of small-signal analysis of the system, the most appropriate approach to calculate $\nabla Z(x, \omega)$ consists in solving some system of deterministic equations, such as the hydrodynamic (HD) equations. The noise source is given by the Fourier transform of the two-point correlation function of conduction current fluctuations $C_{\delta j}$ according to

$$K(x', x'', \omega) = 2 \int_{-\infty}^{\infty} C_{\delta j}(x', x'', s) \exp(i\omega s) ds. \quad (2)$$

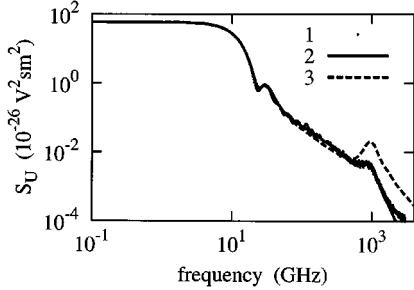


Fig. 1. Spectral density of voltage fluctuations of a 0.5–7.5–0.5 μm n^+nn^+ GaAs structure with doping levels $n = 2 \times 10^{14} \text{ cm}^{-3}$ and $n^+ = 10^{16} \text{ cm}^{-3}$ at $T = 300 \text{ K}$ and $U_d = 8.0 \text{ V}$. Calculations are performed by the MC method (curve 1), by the SIF approach based on the HD model with (curve 2) and without (curve 3) the frequency dependence of the velocity fluctuations noise source evaluated from the same HD model.

It must be noticed that the calculation of the noise source must be performed with care [19]. As a matter of fact, only the part of the conduction current fluctuations which is related to average velocity fluctuations must be taken as noise source, while the part related to the induced fluctuations of concentration must be omitted. Moreover, such a noise source and its spatial dependence must be calculated in the absence of fluctuations of the self-consistent electric field that acts on carriers. The noise source $K(x', x'', \omega)$ is in general a complex quantity, whose imaginary part reflects the violation of the spatio-temporal symmetry. Moreover, being a two-point function its calculation requires a lengthy kinetic simulation of the full device [15], [19]. For this reason, the two-point correlation is usually approximated with a one-point expression which takes the form

$$S_U(\omega) = e^2 \int_0^L n(x) |\nabla Z(x, \omega)|^2 S_v(x, \omega) dx \quad (3)$$

where e is the electronic charge, $n(x)$ the carrier concentration, and $S_v(x, \omega)$ the spectral density of velocity fluctuations at point x .

A. Problems and Inconsistencies

As far as noise calculations concern with long devices, the simplified formulation of (3) yields reliable results as shown in Fig. 1 for an n^+nn^+ structure with an active region of 7.5 μm . Here, in the whole frequency range, an excellent agreement is found between the results obtained with MC simulations and with the HD approach using the SIF method (curves 1 and 2, respectively). Curve 3 reports $S_U(f)$ (where $\omega = 2\pi f$) calculated with the HD approach but neglecting the frequency dependence of the local noise source, i.e., taking $S_v(x, \omega) = S_v(x, 0)$. By comparing curves 1 and 2 with curve 3 in Fig. 1 we find that, even if the frequency dependence of the noise source is omitted, the $S_U(f)$ obtained represents a very good approximation in the wide frequency range $f < 500 \text{ GHz}$, which is the range of main practical interest for over-micron structures. However, at the highest frequencies significant differences appear, thus indicating that a rigorous approach needs a frequency dependent spectrum for the spectral density of velocity fluctuations.

The spectral density of voltage fluctuations between the terminals of a submicron n^+nn^+ structure with an active region of 0.3 μm is reported in Fig. 2. When compared with MC sim-

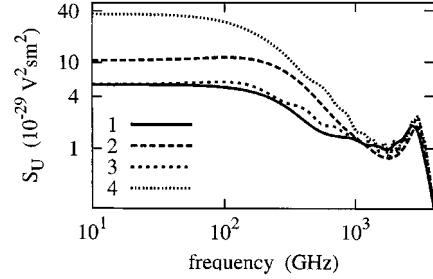


Fig. 2. Frequency dependence of the spectral density of voltage fluctuations for a 0.21–0.3–0.39 μm n^+nn^+ GaAs structure with dopings $n = 5 \times 10^{15} \text{ cm}^{-3}$ and $n^+ = 10^{17} \text{ cm}^{-3}$. $T = 300 \text{ K}$. $U_d = 0.5 \text{ V}$. Calculations are performed by the MC method (curve 1), and by the SIF method under the following conditions: (i) neglecting spatial correlations (curve 2), (ii) including spatial correlations and considering a noise source related only to velocity fluctuations (curve 3) as well to velocity and concentration fluctuations (curve 4).

ulations, the results obtained with the SIF are found to be in excellent agreement (within the few per cent of numerical uncertainty) when the two-point noise source accounts only for velocity fluctuations. By contrast, when also concentration fluctuations are considered, a relevant overestimation of the noise over a factor of six is found. Finally, when the one-point approximation is used the overestimation of the noise reduces to a factor of two. Of course, a further reduction in the size of the active region implies an enhancement of the overestimation.

From the previous considerations, it is evident that the main drawbacks of the SIF method concerns with devices in the deep submicron scale, when the characteristic lengths of the device become comparable with the carrier mean free-path. From a theoretical point of view, the SIF expressed through (1) is formally valid even at these small scale lengths. However, the evaluation of the two-point noise source becomes a very difficult task which demands for a MC simulation (or some equivalent kinetic calculations) of the whole device in the absence of fluctuations of the electric field. Furthermore, another calculation (usually deterministic) is necessary to obtain the impedance field [19]. Thus, from a practical point of view, it is much more convenient to solve the noise problem just once at a kinetic level (e.g., with the MC method), by calculating directly the voltage fluctuations in the device under constant-current operation [21].

The simplified formula in (3) contains also the internal contradiction of being local but with a frequency-dependent noise source (since its time-domain counterpart, the correlation function, exhibits a complicated time behavior [15], [19]). Indeed, the contradiction stems from the fact that, if there is no $\delta(x)$ -correlation in space, then there should neither be $\delta(t)$ -correlation in time for the conduction current fluctuations.

We remark also that the possibility of providing the analogue of the SIF for constant-voltage conditions (i.e., an admittance field method) has never been considered, to our knowledge. This means that, in contrast with kinetic approaches such as the MC method, the use of the SIF seems to be restricted to constant-current conditions.

III. THE GENERALIZED TRANSFER FIELD THEORY

The several drawbacks of the SIF evidenced in the previous section can be overcome by replacing this method with a more

convenient alternative scheme. To this purpose, we have recently proposed a GTF theory [18], [20], which takes the acceleration fluctuations as noise sources. This choice has the advantage that, in the present context, acceleration fluctuations are local in time and space thus exhibiting a white spectrum. The theory can be formally developed at a kinetic level through the Boltzmann–Langevin approach, which here is implemented at a simpler but more affordable HD level. Accordingly, as starting point we take the following conservation equations for velocity v and energy ε which includes the Langevin forces ξ_v and ξ_ε :

$$\frac{\partial v}{\partial t} + v \frac{\partial v}{\partial x} + \frac{1}{n} \frac{\partial}{\partial x} (n Q_v) - e E m^{-1} + v \nu_v = \frac{1}{n} \xi_v \quad (4)$$

$$\frac{\partial \varepsilon}{\partial t} + v \frac{\partial \varepsilon}{\partial x} + \frac{1}{n} \frac{\partial}{\partial x} (n Q_\varepsilon) - e E v + (\varepsilon - \varepsilon_{th}) \nu_\varepsilon = \frac{1}{n} \xi_\varepsilon. \quad (5)$$

Equations (4) and (5) contain five energy parametric dependences, namely, the average of the reciprocal effective mass m^{-1} in the direction of the electric field E , the velocity and energy relaxation rates, ν_v and ν_ε , the variance of velocity-velocity fluctuations, $Q_v = \langle \delta v^2 \rangle_0$ and the covariance of velocity-energy fluctuations, $Q_\varepsilon = \langle \delta v \delta \varepsilon \rangle_0$, where brackets mean average over the hot-carrier distribution function in momentum space and the subscript “0” indicates steady-state conditions corresponding to constant and homogenous applied electric field. The Langevin forces ξ_v and ξ_ε have zero average values and their variances and covariances are other three parameters which describe the noise associated with the stationary state, as detailed in next subsection. Of most importance, these eight parameters are assumed to depend only on the local mean energy, and as such they can be obtained from a stationary MC simulation of the bulk semiconductor.

Without the Langevin forces the set of HD equations (4) and (5) has been proved to describe satisfactorily both static and dynamic characteristics of deep submicron structures [9].

A. Langevin Forces

A comprehensive description of the sources of fluctuations entering the HD equations (4) and (5) is obtained by considering the first two moments of the Boltzmann–Langevin equation. Accordingly, the local spectral density, $S_{\dot{\alpha}\dot{\beta}}(x_0)$, of the fluctuation power of the HD Langevin forces ($\alpha = \beta$) and their cross-correlations ($\alpha \neq \beta$) are expressed through the corresponding spectral density $S_\xi(\mathbf{p}, \mathbf{p}', x_0)$ of the Boltzmann–Langevin forces by [18], [20]

$$S_{\dot{\alpha}\dot{\beta}}(x_0) = \int d\mathbf{p} \int d\mathbf{p}' \alpha(\mathbf{p}) \beta(\mathbf{p}') S_\xi(\mathbf{p}, \mathbf{p}', x_0). \quad (6)$$

The power of the HD noise source is distributed in the volume proportionally to the carrier concentration $n_s(x_0)$ and is determined in terms of the rates of change of dynamical characteristics of a carrier occurring during a single scattering event. To separate these properties it is convenient to introduce the single-particle spectral densities

$$\tilde{S}_{\dot{\alpha}\dot{\beta}}(x_0) = S_{\dot{\alpha}\dot{\beta}}(x_0)/n_s(x_0). \quad (7)$$

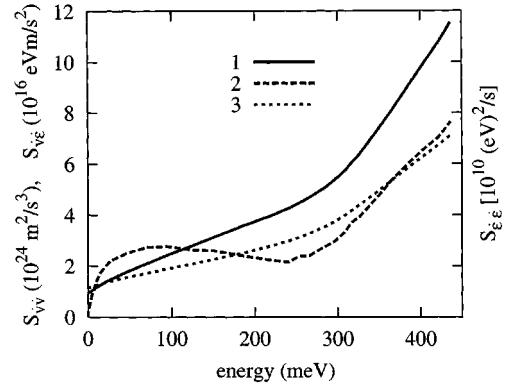


Fig. 3. Spectral density of the microscopic noise sources S_{vv} , $S_{v\xi}$, and $S_{\xi\xi}$ (respectively, curves 1 to 3) as function of the excess mean energy $\varepsilon = \langle \varepsilon \rangle - \varepsilon_{th}$, calculated by MC simulations of homogeneous bulk GaAs.

Since for most of scattering mechanisms the scattering rates depend on carrier energy only, we assume, as done for all other parameters of the HD model, that the density of the HD sources (7) depends on the local value of the mean energy only. In this case numerical values of $\tilde{S}_{\dot{\alpha}\dot{\beta}}(\varepsilon)$ as functions of ε can be obtained from MC simulations of the homogeneous bulk material in accordance with the expression

$$\tilde{S}_{\dot{\alpha}\dot{\beta}} = \frac{2}{T} \sum_{i=1}^N \Delta \alpha_i \Delta \beta_i \quad (8)$$

where $\Delta \alpha_i, \Delta \beta_i$ are the instantaneous variations of velocity and energy ($\alpha, \beta = v, \varepsilon$) during the i th scattering event, and T is the total time elapsed during N scattering events. The noise sources described by (8) are shown in Fig. 3. The diagonal terms $S_{vv}(\varepsilon)$ and $S_{\xi\xi}(\varepsilon)$ start from their thermal equilibrium values and then monotonously increase with increasing excess mean energy. This increase reflects both the broadening of the carrier distribution in momentum space and the increase with energy of the total scattering rate. Furthermore, one can detect two different slopes at relatively low ($\varepsilon < 300$ meV) and high ($\varepsilon > 300$ meV) energy values, which correspond to the fact that most of electrons are in the lower and upper valleys, respectively. Being an odd momentum of the distribution, the velocity-energy cross-correlation term vanishes at thermodynamic equilibrium. This is no longer the case under hot-carrier conditions when the electric field couples velocity and energy relaxations. Indeed, during each scattering event a carrier loses in average both the extra velocity and the energy gained by the electric field. Thus, the changes of velocity and energy during scattering events are negative in average, so that their average product, $S_{v\xi}(\varepsilon)$, is positive. Therefore, starting from zero, the cross-correlation term rapidly increases due to velocity-energy cross-correlation in the lower valley, and finally attains a nearly constant slope determined by the relaxation processes in the upper valleys. Remarkably, in the intermediate energy range the cross-correlation term exhibits an N -shape behavior.

B. Generalized Transfer Fields

To complete the theoretical framework, we need the GTF describing the propagation of an initial random perturbation

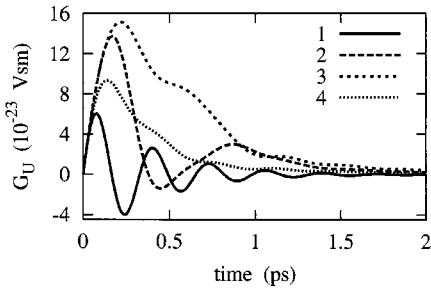


Fig. 4. Generalized voltage-response functions calculated under constant-current conditions. Curves 1 to 4 correspond to initial perturbations of velocity placed, respectively, in points $x_0 = 0.105, 0.225, 0.315, 0.435 \mu\text{m}$ of the same submicron structure of Fig. 2 at the same operation point.

inside the structure. To this purpose we apply the Green-function formalism to an arbitrary local characteristic of the system, $Q(n, v, \varepsilon, E, x)$. The calculation of the Green-function proceeds as follows [20].

- A stationary solution of the HD equations without the Langevin forces is found together with the Poisson equation for the self-consistent electric field $E(x)$ and, if necessary, additional equations describing the external circuit.
- A perturbation of the stationary values of velocity or energy, given by $\Delta_\alpha \delta(x - x_0)$, is introduced at time $t = 0$ at some point x_0 .
- A direct numerical solution of the HD conservation equations jointly, if necessary, with the Poisson and circuit equations is performed, thus providing the relaxation of the system to the stationary state at $t > 0$.
- The Green-function of a certain Q -characteristic is obtained from the difference between local values of $Q(x, x_0, t)$ calculated during the relaxation process and $Q_s(x)$ corresponding to stationary conditions as

$$G_Q^\alpha(x, x_0, t) = \frac{1}{\Delta_\alpha n_s(x_0)} [Q(x, x_0, t) - Q_s(x)]. \quad (9)$$

- The factor $1/n_s(x)$ ensures the normalization to one particle at the point of perturbation.
- The Fourier transform of the Green-function gives the spectral representation of the GTF as

$$F_Q^\alpha(x, x_0, \omega) = \int_0^\infty G_Q^\alpha(x, x_0, t) \exp(-i\omega t) dt. \quad (10)$$

An example of the Green functions at step (iv) is shown in Figs. 4 and 5. They report the response functions, respectively, of a) the voltage drop between the structure terminals and b) the conduction current flowing through the structure. These functions are calculated under a) constant-current and b) constant-voltage operations, respectively. In case a), the perturbations of the electric field induced by velocity or energy fluctuations lead to perturbations of the voltage drop between the structure terminals. Since at $t = 0$ any perturbation of the electric field inside the structure is absent, all curves of the voltage response functions start from zero. Then, they exhibit a more or less pronounced wavy behavior to finally go to zero on a time scale of

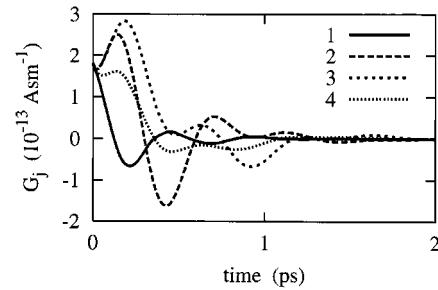


Fig. 5. Generalized conduction-current response functions calculated under constant-voltage conditions. Curves 1 to 4 correspond to initial perturbations of velocity placed, respectively, in points $x_0 = 0.105, 0.225, 0.315, 0.435 \mu\text{m}$ of the same submicron structure of Fig. 2 at the same operation point.

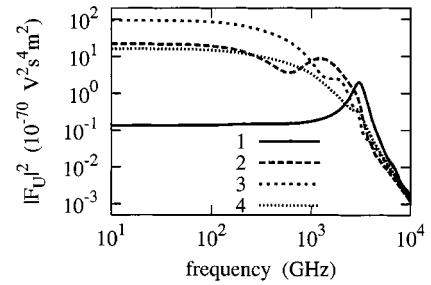


Fig. 6. Square modules of the generalized impedance field. Curves 1 to 4 correspond to initial perturbations of velocity placed, respectively, in points $x_0 = 0.105, 0.225, 0.315, 0.435 \mu\text{m}$ of the same submicron structure of Fig. 2 at the same operation point.

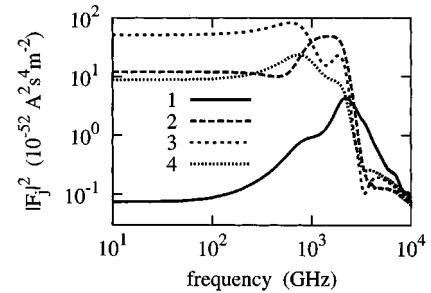


Fig. 7. Square modules of the generalized admittance field. Curves 1 to 4 correspond to initial perturbations of velocity placed, respectively, in points $x_0 = 0.105, 0.225, 0.315, 0.435 \mu\text{m}$ of the same submicron structure of Fig. 2 at the same operation point.

about 2 ps when any perturbations inside the structure vanish (see Fig. 4). In case (b), since an instantaneous velocity fluctuation leads immediately to the perturbation of conduction current, all curves of the conduction current response start from some nonzero value and tend to zero similarly to case (a) (see Fig. 5).

Figs. 6 and 7 report the Fourier transforms of the response functions of Figs. 4 and 5 [step vi)], i.e., they represent the generalized impedance and admittance fields calculated under constant-current and constant-voltage operations, respectively. The frequency dependence of the GTFs is quite similar for both operation modes. Each spectrum exhibits a plateau in the low frequency range, followed by a spike related to the oscillatory behavior in the time domain, to finally tend to zero at the highest frequencies $f > 1 \div 10 \text{ THz}$.

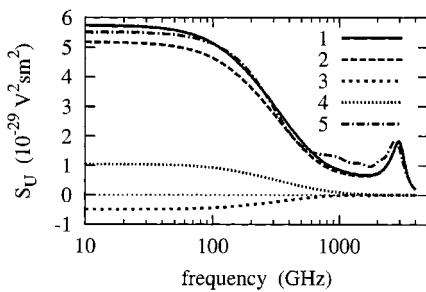


Fig. 8. Spectral density of voltage fluctuations calculated by the generalized impedance field method for the structure of Fig. 2 at the same operation point (curve 1) and contributions coming from velocity-velocity, velocity-energy and energy-energy microscopic noise sources (curves 2 to 4). Curve 5 shows the result of the direct MC simulation of voltage noise.

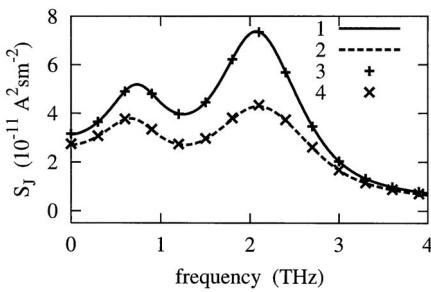


Fig. 9. Spectral density of current fluctuations calculated with the generalized admittance field method for the unloaded structure of Fig. 2 at the same operation point (curve 1) and at the load resistance $R = 10^{-10} \Omega m^2$ connected in series with the structure (curve 2). Curves 3 and 4 show the results obtained by recalculating the corresponding spectral densities with the small-signal impedance and the spectral density of voltage fluctuations evaluated within the same HD approach.

IV. VALIDATION OF THE NEW SCHEME

By combining the noise source $\tilde{S}_{\dot{\alpha}\dot{\beta}}$ with the GTF calculated in previous sections, the corresponding spectral density takes the general form [20]

$$S_Q(\omega) = \sum_{\alpha, \beta=v, \varepsilon} \int_0^L F_Q^\alpha(x_0, \omega) F_Q^{\beta*}(x_0, \omega) \times n_s(x_0) \tilde{S}_{\dot{\alpha}\dot{\beta}}(x_0) dx_0 \quad (11)$$

where F_Q^α is the GTF associated with the linear response of voltage ($Q = U$) or current ($Q = J$) to perturbations of velocity ($\alpha = v$) and energy ($\alpha = \varepsilon$) initiated by scattering events. The results of the calculations are summarized in Figs. 8 and 9, which report the spectral densities of fluctuations calculated under different operation modes for the same GaAs structure of Fig. 2 at the same operation point. Fig. 8 shows the total value of the spectral density of voltage fluctuations (curve 1) together with the contributions coming from velocity-velocity, velocity-energy and energy-energy microscopic noise sources (respectively, curves 2 to 4). Calculations make use of the GTF method under constant-current operation (generalized impedance field) and consider the voltage drop at the terminals U_d as Q -characteristic. For comparison, curve 5 reports the result of a direct simulation of voltage fluctuations by the MC method. The main contribution to S_U is found to come from the microscopic noise source related to rates of velocity

changes during scattering events (curve 2). Fig. 9 reports the spectral density of total current fluctuations calculated with the GTF under constant-voltage operation (generalized admittance field), and considering the total current density J as Q -characteristic (curve 1). Curve 2 corresponds to the case when a load resistance $R = 10^{-10} \Omega m^2$ is connected in series with the structure (circuit-noise operation mode). This situation can be simulated by adding to the system of HD equations the additional equation $J(t) = -[U - U_d(t)]/R$, U_d being the voltage drop at the terminals of the diode, U the total voltage drop, $J(t)$ the total current and R the load resistance. For comparison, symbols show the corresponding spectral densities recalculated with the relation $S_J(\omega) = S_U(\omega)/|Z_d(\omega) + R|^2$, by using the small-signal impedance Z_d and S_U obtained by the same HD approach.

In all the cases considered above (i.e., current-, voltage-, and circuit-noise operation modes), a good agreement is achieved between HD and MC calculations thus validating the generalized scheme here developed.

The total computation time to evaluate a noise spectrum results from the following steps.

- 1) Computation of the stationary state corresponding to the applied voltage. This step is of course the same for SIF and GTF methods.
- 2) Introduction of local perturbations of velocity and energy (for GTF) and of electric field (for SIF) in different points of the structures. This computation requires approximately some minutes on a Pentium PC for each point in real space. In this case, the CPU time of the GTF is double with respect to that of SIF. Since we use typically 30 points this means that the CPU time is of the order of 1 h for SIF and 2 h for GTF.
- 3) Calculation of the microscopic noise sources. This is the point which makes GTF much more preferable than SIF since the noise sources for GTF are computed only one time as functions of the carrier energy (typically 1 h for each energy) while the correlated noise source for SIF must be computed each time for the specific simulated device and even each time the applied voltage is changed. In this case the CPU time varies between 25 and 75 h depending on the number of points in real space and the applied voltage.
- 4) The final convolution between the noise sources and the transfer fields takes typically some minutes for both methods.

V. CONCLUSION

We have presented a new scheme for the modeling of electronic noise in submicron semiconductor devices. The basic difference with respect to the SIF method stems from a noise source which is connected with the rates of velocity and energy change during single scattering events (acceleration fluctuation scheme). In a Markov context, this noise source is white and does not contain any spatial correlation, thus overcoming one of the main drawbacks of the SIF method which relies on a noise source which is frequency dependent and contains spatial correlations. Starting from this choice,

we have constructed at a HD level a unifying scheme which strictly separates the source of fluctuations, represented by the Langevin force, from the further spatio-temporal evolution of a perturbation, described by the GTF calculated on the basis of a Green function formalism. In contrast with the SIF method, the GTF's can be computed easily under constant-current as well as constant-voltage conditions (see Section IV), thus recovering the property of the dual description of electronic noise in terms of current or voltage fluctuations, in close analogy with the MC approach. By combining the new noise sources with the GTF, the spectral density of the fluctuations of any macroscopic quantity can be represented in a form similar to that given by the SIF method, i.e., as the convolution in real space of the noise source with a GTF according to (11). This scheme is validated for n^+nn^+ GaAs submicron structures which operate under various conditions including voltage, current, and circuit-noise operation modes. The fact of avoiding spatial correlations between noise sources makes this method particularly suitable for multidimensional applications, where the computational burden associated with correlated noise sources is expected to increase significantly. Moreover, an additional advantage with respect to the standard method is offered by the possibility to choose between constant current and constant voltage between couples of terminals.

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