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# Generalized transfer-fields and Langevin forces for hot-carrier fluctuations in semiconductor submicron devices

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**Abstract**

We present a unifying scheme for the hydrodynamic calculation of electronic noise in semiconductor devices operating under various conditions. In the framework of the Green-function formalism the noise sources corresponding to the Langevin forces originated by single scattering events are included into the equations describing medium properties. The scheme is validated by numerical calculations of the voltage and current noise in submicron $n^+nn^+$ GaAs structures. 

*Keywords:* Hot-carrier noise; Hydrodynamics; Langevin forces; Green functions

## 1. Introduction

Within the Boltzmann transport equation (BTE) the most comprehensive description of the spatio-temporal evolution of fluctuations is usually based on the Green-function formalism, where the source of fluctuations is represented by the Langevin force describing fluctuations of the occupation number caused by single scattering events. However, because of its mathematical complexity, the BTE approach meets with serious difficulties when applied to calculate transport and noise characteristics of real devices in the presence of hot-carrier conditions. As a consequence, deterministic approaches at a hydrodynamic (HD) level are better suited for this sake. The aim of this work is to address this issue by constructing a similar formalism at a HD level which includes the Langevin force and keeps the main features of the BTE. We notice that, in the absence of generation–recombination mechanisms, the HD approach is intrinsically based on a separate description of carrier concentration from dynamic characteristics such as velocity, energy, etc. Therefore, to develop the HD-Langevin scheme we have adopted a two step procedure which: (i) reformulates the Langevin forces of the BTE in terms of fluctuations of the corresponding HD variables; and (ii) constructs the appropriate response functions to the perturbing HD Langevin forces.

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## 2. Model and procedure

Within a one-dimensional geometry in real space, the HD model consists of conservation equations for carrier concentration $n(x,t)$, average velocity $v(x,t)$, and mean energy $\varepsilon(x,t)$. Without the Langevin forces the model takes the usual form [1]. Then, the Langevin forces are added into the velocity and energy conservation equations. The spectral power of the Langevin forces is assumed to depend exclusively on the mean energy, and is obtained from Monte Carlo (MC) simulations of bulk material [2]. The numerical procedure of noise calculations includes the following steps:

(i) A stationary solution of HD equations without the Langevin forces is determined together with the Poisson equation for self-consistent electric field $E(x)$ and, if necessary, with an equation describing the external circuit [1].

(ii) A perturbation of the stationary values of velocity or energy, given by $\Delta_\alpha \delta(x - x_0)$, $\alpha = v, \varepsilon$ is introduced at time $t = 0$ at the point $x_0$.

(iii) A direct numerical solution of the HD conservation equations jointly, if necessary, with the Poisson and circuit equations is obtained thus providing the relaxation of the system to the stationary state at $t > 0$.

(iv) The Green-function corresponding to a certain $Q$-characteristic (e.g., the conduction current, the energy flux, the voltage drop between the structure terminals, etc.) is evaluated 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

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

where $1/n_s(x)$ gives the normalization to one particle.

(v) The spatio-temporal dependence of auto-correlation ($Q = Q'$) and cross-correlation ($Q \neq Q'$) functions of various $Q$-characteristics of interest is then calculated as [3,4]

$$\overline{\delta Q(x', t)\delta Q'(x'', t - s)}^t = \sum_{\alpha,\beta = v,\varepsilon} \int_0^L \mathrm{d}x_0 \, n_s(x_0) S_{\alpha\beta}(x_0) \times \int_0^\infty G_Q^\alpha(x', x_0, u) G_{Q'}^\beta(x'', x_0, u + s)\, \mathrm{d}u, \quad (2)$$

where $S_{\alpha\beta}(x_0)$ is the single-carrier local spectral density of the fluctuation power of the HD Langevin forces [2].

(vi) By applying the Wiener–Khintchine theorem, the spectral density of fluctuations of both the current and voltage can be expressed through the spectral density of the Langevin force in a unique form as [2,5]

$$S_Q(\omega) = \sum_{\alpha,\beta = v,\varepsilon} \int_0^L \nabla Q_\alpha(x_0,\omega) \nabla Q_\beta^*(x_0,\omega) n_s(x_0) \times S_{\alpha\beta}(x_0)\, \mathrm{d}x_0, \quad (3)$$

where $\nabla Q_\alpha$ is the *generalized impedance* $\nabla Z_\alpha$ (IF) *or admittance* $\nabla Y_\alpha$ (AF) *fields*, i.e. the Fourier transform of the Green-functions associated with the linear response of voltage or current to perturbations of velocity and energy [2,5].

## 3. Results and discussion

To illustrate the general procedure, Fig. 1 shows the spectral densities of fluctuations calculated under different operation modes for a $0.21 - 0.3 - 0.39$ μm $n^+nn^+$ GaAs structure with doping levels $n = 5 \times 10^{15}$ and $n^+ = 10^{17}$ cm$^{-3}$ at $T = 300$ K for a voltage drop $U_d = 0.5$ V between the structure terminals. Fig. 1(a) shows the total value of the spectral density of voltage fluctuations, $S_U$ (curve 1), together with the contributions coming from velocity–velocity, velocity–energy and energy–energy microscopic noise sources (curves 2–4) calculated by the generalized IF method under constant current operation and considering $U_d$ as $Q$-characteristic. For comparison, curve 5 reports the result of a direct simulation of voltage noise by the MC method. We find that the main contribution to $S_U$ comes from the microscopic noise source related to the rate of velocity changes during scattering events (curve 2). Fig. 1(b) reports the spectral density of total current fluctuations, $S_J$, calculated by the generalized AF method under constant voltage operation, and considering the total current

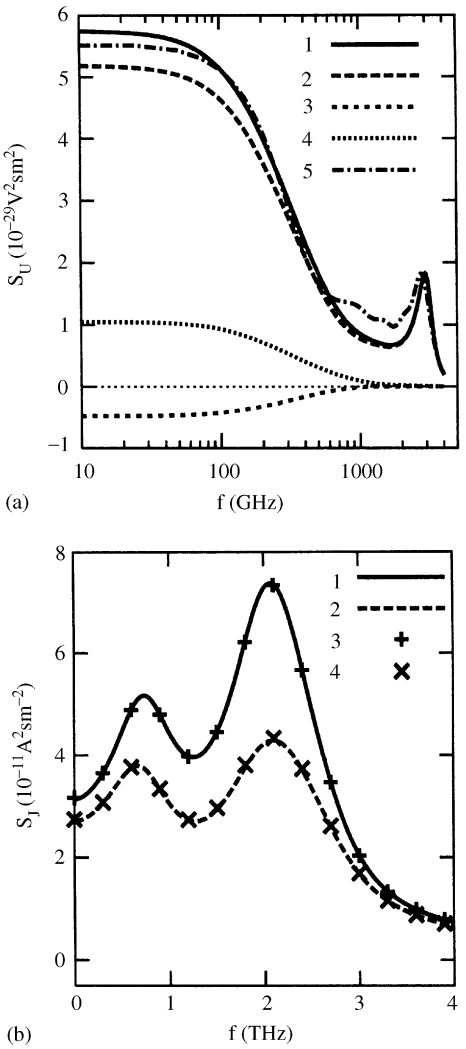


Fig. 1. Spectral densities of: (a) voltage and (b) current fluctuations, calculated by the generalized HD-Langevin method for a submicron GaAs structure (curves 1–4). Curve 5 shows the result of direct MC simulations of voltage noise.

density $J$ as $Q$-characteristic. Curves 1 and 2 correspond, respectively, to the unloaded structure ($R = 0$) and to the case when a load resistance $R = 10^{-10}\ \Omega\,\mathrm{m}^2$ is connected in series with the structure. For comparison, symbols show the corresponding spectral densities recalculated with the relation $S_J(\omega) = S_U(\omega)/|Z_\mathrm{d}(\omega) + R|^2$, by using the small-signal impedance $Z_\mathrm{d}$ and $S_U$ obtained by the same HD approach. The good agreement shown by the MC and various HD calculations in Fig. 1 validates the HD-Langevin approach developed here.

## 4. Conclusions

We have shown that by representing the noise source in the medium equations by means of Langevin forces directly connected with the rates of velocity and energy change during single scattering events we can construct a unifying scheme at a HD level for the analysis of electronic noise in semiconductor devices. The scheme is validated for a GaAs submicron structure which operates under various conditions including voltage, current, and circuit noise operation modes.

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