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A Closed Hydrodynamic Model for Hot-Carrier Transport in Submicron Semiconductor Devices

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Abstract

We develop a closed hydrodynamic model within the framework of the single-electron gas approach. Calculations are presented for the small-signal response, diffusion coefficient, spectral density of velocity fluctuations of bulk semiconductors as well as for the concentration, velocity, energy and electric-field profiles of n^+nn^+ structures. The validation of the present model is confirmed by a favourable comparison with analogous Monte Carlo simulations.

1. Introduction

In recent years significant efforts have been devoted to develop hydrodynamic (HD) approaches to be used for the modeling of submicron semiconductor devices [1,2]. These approaches are based on a set of conservation equations obtained under the so called single-electron gas approximation. To describe the dynamics of carrier heating and to account for the nonparabolicity and multivalley effects, the velocity and energy relaxation rates as well as the energy dependent effective mass are introduced in more or less similar ways. However, the diffusion effects are often included by assuming a Maxwellian shape of the hot-carrier distribution function thus introducing the concept of an effective temperature. This is far from being an acceptable assumption, especially for multi-valley semiconductors [3]. The aim of this work is to go beyond the use of an effective temperature. To this purpose, we propose a total energy scheme which consistently accounts for diffusion and convective contributions within the single-electron gas model.

2. Theory and results

The procedure is a generalization of the moment method. It consists in multiplying by an arbitrary function $A(\mathbf{p})$ the Boltzmann equation and then integrating all over

the momentum space $\mathbf{p}$ thus providing a conservation equation for the macroscopic quantity $< A(z,t) >$ in the form:

$$\frac{\partial}{\partial t}(n < A >) + \frac{\partial}{\partial z}(n < vA >) - eE\, n\left\langle \frac{\partial A}{\partial p_z} \right\rangle = -\nu_A(< A > - A_{th})n \qquad (1)$$

where the brackets $< ... >$ mean ensemble-averaging over the distribution function $f(\mathbf{p}, z, t)$, $n(z,t)$ is the carrier concentration, $v(\mathbf{p})$ the carrier velocity along the field, e the electron charge, $E(z,t)$ the electric field taken along the z direction, ν_A the relaxation rate of $< A >$ to its equilibrium value A_{th}. It is evident that the term under the spatial derivative always involves moments of higher order. Therefore, to close the system of equtions we assume that $< vA >$ consists of a dynamic and chaotic contributions as:

$$< vA >=< v(z,t) >< A(z,t) > + Q_A(< \epsilon(z,t) >) \qquad (2)$$

where $< v(z,t) >$ is the average drift-velocity, $< \epsilon(z,t) >$ the mean energy, and $Q_A =< \delta v \delta A >_0$ the covariance of the instantaneous fluctuations of $v(\mathbf{p})$ and $A(\mathbf{p})$ averaged over the stationary distribution function of the homogeneous case at the same mean energy. By substituting 1, $v(\mathbf{p})$ and $\epsilon(\mathbf{p})$ in place of $A(\mathbf{p})$ into Eqs. (1) and (2), one obtains, respectively, the concentration, velocity and energy conservation equations:

$$\frac{\partial n}{\partial t} = -\frac{\partial}{\partial z}(n < v >) \qquad (3)$$

$$\frac{\partial < v >}{\partial t} = eE < m^{-1} > - < v > \nu_v - < v > \frac{\partial < v >}{\partial z} - \frac{1}{n}\frac{\partial}{\partial z}(nQ_v) \qquad (4)$$

$$\frac{\partial < \epsilon >}{\partial t} = eE < v > -(< \epsilon > -\epsilon_{th})\nu_\epsilon - < v > \frac{\partial < \epsilon >}{\partial z} - \frac{1}{n}\frac{\partial}{\partial z}(nQ_\epsilon) \qquad (5)$$

The model contains five parameters, namely: the average of the reciprocal effective-mass $< m^{-1} >$, the velocity and energy relaxation rates, ν_v and ν_ϵ, the instantaneous velocity-velocity and velocity-energy fluctuations, $Q_v =< \delta v^2 >_0$ and $Q_\epsilon =$ $< \delta v \delta \epsilon >_0$. All the parameters are assumed to depend on the local instantaneous energy only, and as such they are obtained from a stationary Monte Carlo (MC) simulation of the bulk semiconductor [3].

The small signal analysis is performed by linearizing the homogeneous and stationary conservation equations with respect to small perturbaions of field, velocity and energy [3]. As an application, Fig. 1 shows the frequency dependence of the real part of the differential mobility calculated with the HD and MC approaches for the case of $n - InP$. It should be noticed that the model gives good quantitative agreement for the threshold of negative differential mobility that is of great importance for the Gunn device simulations.

The diffusion and noise analysis is based on the knowledge of the correlation function of velocity fluctuations. These functions can be constructed from the general solution of the linearized equation used for the small-signal analysis. Under hot-carrier conditions, both $< \delta v^2 >_0$ and $< \delta v \delta \epsilon >_0$ give contributions to velocity fluctuations. Figure 2 shows the field dependence of the longitudinal diffusion coefficient calculated by the present HD and MC approaches. Figure 3 presents the comparison between the spectral density of velocity fluctuations calculated in the framework of the HD and the MC approaches. The overall good agreement so found

between the HD and MC results validates the present model and supports its application to nonhomogeneous situations. Moreover, one can use the $S_v(f)$ provided by this model as a local noise sources for a self-consistent calculations of the voltage spectral density using the impedance field method [4]. As application of present results to the modelling of submicron devices we have considered the case of n^+nn^+ structures. As an example, Fig. 4 shows the concentration, velocity, energy and electric field distributions along an InP diode calculated by the HD and MC methods ($n^+ = 10^{18}$, $n = 3 \times 10^{16}$ cm^{-3}, $l_1^+ = 0.1$, $l_n = 0.5$, $l_2^+ = 0.3$ μm). Apart from some discrepancies which appear as a rule near the anode contact, good agreement is found between the results obtained with the two methods.

3. Conclusions

A closed hydrodynamic model which accounts for the nonparabolicity of the band and the non-Maxwellian shape of the hot carrier distribution function is developed. The small-signal and diffusion-noise characteristics of bulk n-InP as well as a n^+nn^+ diode modelling have been evaluated and compared with a full Monte Carlo approach. The excellent agreement found fully supports the physical reliability of the proposed model which has the advantage of requiring reasonably cheap computanional facilities (e.g a 486 pc) and short running times (e.g. few minutes for characterizing a n^+nn^+ structure as reported above).

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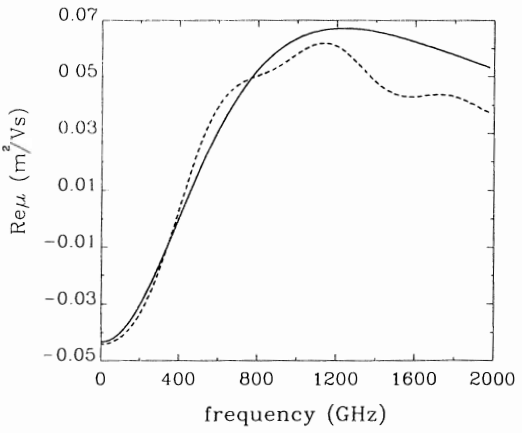

Figure 1: Real part of the differential mobility $Re\mu(f)$ calculated by the HD and MC approaches (solid and dashed lines, respectively). n-InP, $n = 10^{16}$ cm^{-3}, 300 K, $E = 25$ kV/cm.

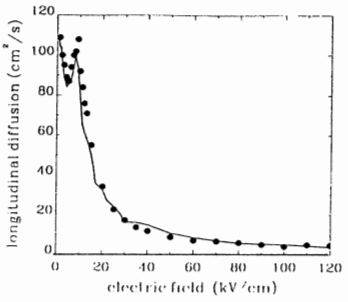

Figure 2: Longitudinal diffusivity obtained with HD and MC approaches (solid lines and dots).

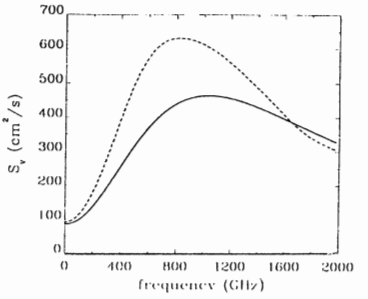

Figure 3: Spectra of velocity fluctuations obtained with HD and MC approaches (solid and dashed lines).

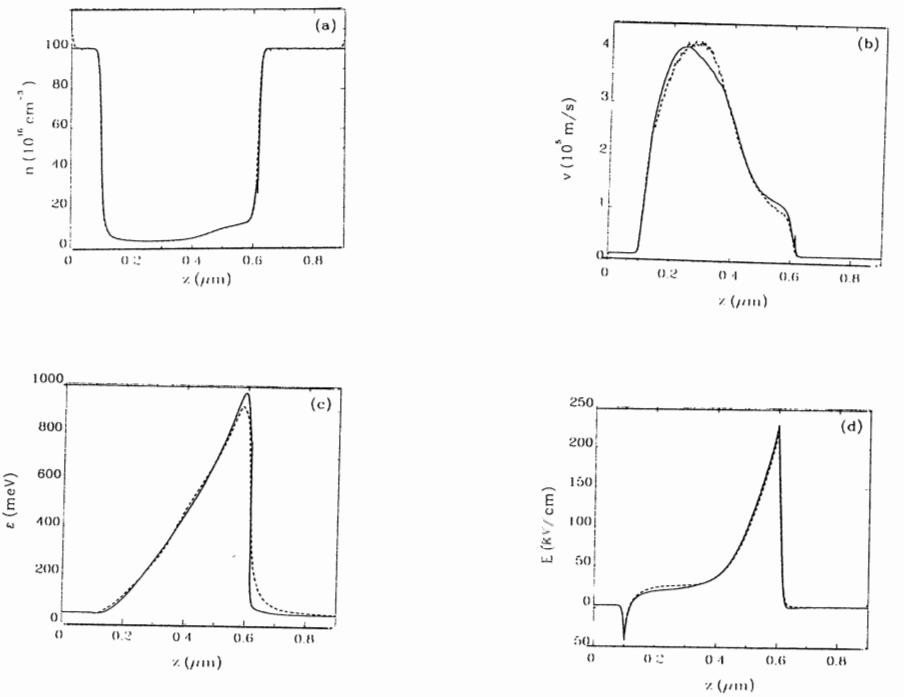

Figure 4: (a) concentration, (b) velocity, (c) energy and (d) electric field profiles, obtained with HD and MC approaches (solid and dashed lines).