Robust Simulation of GaAs Devices Using Energy Transport Model

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The carrier transport mechanism in GaAs which includes a negative different mobility in the carrier velocity-field curve when implemented in the 2D device simulator, causes grid-dependent numerical instability and poor convergence behavior. It has well been established in the literature [1, 2] that the conventional drift-diffusion (DD) approximation which assumes a local thermal equilibrium among the same type of carriers (electrons or holes) has significant shortcomings in the description of GaAs device operation. In this paper we report an extension of the energy transport (ET) model [3, 4] in which carrier energy conservation equations are solved to GaAs device simulation. A technique whereby the empirical form of the field-dependent mobility is transformed to an energy-dependent one used in the ET model is presented.

The empirical formula describing the dependence of mobility on electric field implemented in the 2D device simulator PISCES [6] has the form $\mu(N_T,E) = \frac{\mu_o(N_T)+\frac{v_{sat}}{E}(\frac{E}{E_o})^4}{1+(\frac{E}{E_o})^4}$, where μ_o is the low-field mobility, E is the magnitude of the electric field, E_o is the critical electric field, and v_{sat} is the saturation drift velocity. In applying the ET model to GaAs, a formulation describing the dependence of carrier velocity on local temperature needs to be determined. From the second-order moment of the Boltzmann transport equation, the energy conservation equation at steady state is given by $\nabla\cdot\mathbf{S} = \mathbf{E}\cdot\mathbf{J} - n\left\langle \frac{\partial E}{\partial t}\Big|_{coll}\right\rangle$. The macroscopic quantities are: energy flux $\mathbf{S}$, electric field vector $\mathbf{E}$, electron current density $\mathbf{J}$, electron concentration n, and the average electron energy loss due to collision $\langle \partial E/\partial t|_{coll}\rangle$. Since the empirical formula for $\mu(\mathbf{E})$ were obtained experimentally under uniform field condition where $\nabla\cdot\mathbf{S} = 0$ and $\mathbf{J} = qn\mu(E)E$, by using the assumptions in that the average energy loss term $\left\langle \frac{\partial E}{\partial t}\Big|_{coll}\right\rangle = \frac{3}{2}\frac{k(T_e-T_L)}{\tau_\omega}$, we arrive at a transcendental relation of local field and carrier energy,

$$\mu(E)E^2 = \frac{3}{2}\frac{k(T_e-T_L)}{q\tau_\omega}. \tag{1}$$

Here, k is the Boltzmann constant, τ_ω‡ denotes the energy relaxation time, and T_e and T_L are the electron and lattice temperatures respectively. Hence, the carrier temperature can be solved for a given field strength, and the dependence of mobility on local carrier energy can be obtained.

During actual implementation in the device simulator PISCES, it is more convenient to have an analytical form in which the mobility dependence on local carrier temperature can be solved directly. At low fields we assume $J = qn\mu_o E$, hence

$$E = \sqrt{\frac{3}{2}\frac{kT_L}{q}\frac{(T_e/T_L-1)}{\mu_o\tau_\omega}}; \quad \text{and} \quad \mu_L(T_e) = \frac{\mu_o+\frac{v_{sat}}{E_o}[\frac{3}{2}\frac{kT_L}{q\mu_o\tau_\omega E_o^2}(\frac{T_e}{T_L}-1)]^{3/2}}{1+[\frac{3}{2}\frac{kT_L}{q\mu_o\tau_\omega E_o^2}(\frac{T_e}{T_L}-1)]^2} \quad . \tag{2}$$

At high fields we make the assumption that $J = qnv_{sat}$, hence

$$E = \frac{3}{2}\frac{kT_L}{qv_{sat}}\frac{1}{\tau_\omega}(\frac{T_e}{T_L}-1); \quad \text{and} \quad \mu_H(T_e) = \frac{\mu_o+\frac{v_{sat}}{E_o}[\frac{3}{2}\frac{kT_L}{qv_{sat}\tau_\omega E_o}(\frac{T_e}{T_L}-1)]^3}{1+[\frac{3}{2}\frac{kT_L}{qv_{sat}\tau_\omega E_o}(\frac{T_e}{T_L}-1)]^4} \quad . \tag{3}$$

The mobility relations can thus be formulated approximately as a weighted average of

$$\mu(N_T,T_e) = 0.5\cdot(1-\mathcal{F})\cdot\mu_L(N_T,T_e) + 0.5\cdot(1+\mathcal{F})\cdot\mu_H(N_T,T_e) \quad , \tag{4}$$

where $\mathcal{F} = \tanh[\alpha(T_e-T_c)]$ is a fitting function in which α and T_c are fitting parameters. The average carrier velocities as a function of carrier temperature, $v = \mu(T_e)E(T_e)$, by using the transcendental relation of Eq. (1) and fitting function of Eq. (4), are shown in Fig. 1.

We simulated a non-homogeneous GaAs n^+-n-n^+ diode featuring a 5-μm n-region doped to 1×10^{17} cm^{-3} and 0.1-μm n^+-region doped 5×10^{19} cm^{-3} at two ends. The corresponding current-voltage characteristics using different grids of uniform spacing are shown in Fig. 2. The DD model which uses the local field formulation tends to converge very slowly. It can be seen that near electric field strengths at which intervalley carrier transfer occurs and Gunn-domain forms, simulated currents display non-physical 'zig-zags', and their periodicity is extremely grid sensitive. Simulated net charge distribution for a 1-μm GaAs n^+-n-n^+ diode at V_{dd}=1.0 volt is shown in Fig. 3.

We also simulated a GaAs MESFET structure featuring a 1 μm gate and 0.8 μm spacers. The drain-source current-voltage relationship is compared using both the DD and ET model in Fig. 4. The DD model exhibits similar non-physical 'zig-zags' in the drain current – an indication that the present grid density is insufficient to

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^{0}‡Monte-Carlo Simulation results reported in Ref. [5] were used to extract the energy relaxation time, $\tau_\omega = 0.8\times10^{-12}$ second.

resolve the Gunn-domain. On the other hand, the ET model yields numerically stable solutions with excellent convergency rate without incurring an additional computation cost.

In summary, the energy transport formulation that accounts for the principle nonstationary effect has been applied to GaAs MESFET device simulation. The excellent convergence behavior of the ET model as demonstrated in the GaAs-based devices permits a wide application to III-V material based devices.

References

[1] W. R. Curtice, and Y.-H. Yun, "A temperature model for the GaAs MESFET," *IEEE Tran. Electron Devices* vol. ED-28, no. 8, pp. 914-962, Aug. 1981.

[2] C. M. Snowden, and D. Loret, "Two-dimensional hot electron models for short-gate length GaAs MESFETS" *IEEE Tran. Electron Devices* vol. ED-34, no. 2, pp. 212-223, Feb. 1987.

[3] D. Chen, E. C. Kan, U. Ravaioli, C. Shu and R. W. Dutton, "An improved energy transport model including non-parabolic and non-Maxwellian distribution effects, " *IEEE Elec. Dev. Lett.*, vol. 13, no. 1, pp. 26-28, Jan. 1992.

[4] D. Chen, E. Sangiorgi, M. R. Pinto, E. C. Kan, U. Ravaioli and R. Dutton, "Analysis of spurious velocity overshoot in hydrodynamic simulations of ballistic diodes, " *Proceeding of NUPAD V (Numerical Process and Device Modeling Workshop)*; Seattle, May 31 – June 1, 1992.

[5] M. V. Fischetti, "Monte Carlo simulation of transport in technologically significant semiconductors of diamond and zinc-blende structures. Part I: Homogeneous Transport," *IEEE Trans. Electron Devices*, vol. 38, no. 3, pp. 634-649, Mar. 1991.

[6] M. R. Pinto, C. S. Rafferty, and R. W. Dutton, *PISCES-II User's Manual,* Stanford University, CA, 1984.

Figures:

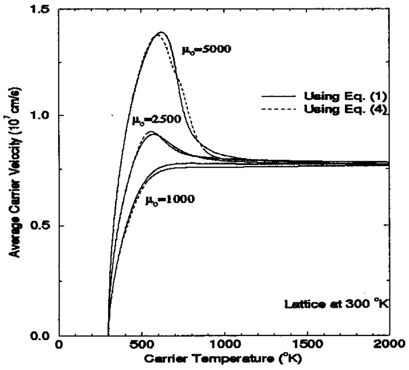

Fig. 1: GaAs average carrier drift velocity as a function of electron temperature for different low-field mobility values.

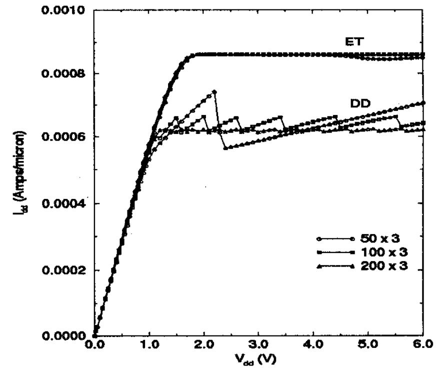

Fig. 2: Current-voltage characteristics of a 5-μm GaAs $n^+ - n - n^+$ diode using different grids.

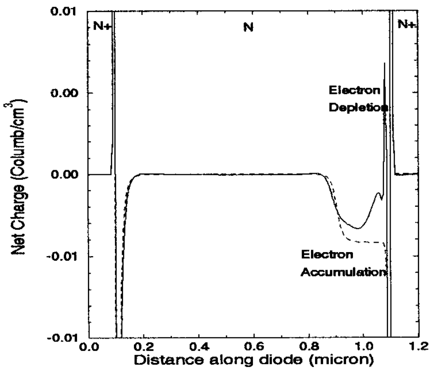

Fig. 3: Simulated net charge distribution along a 1 diode using a 200×3 uniform grid. —— ET and - - - - DD model.

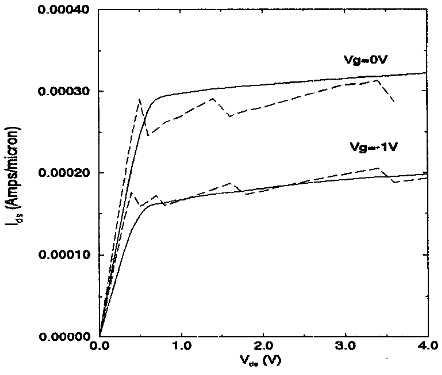

Fig. 4: Comparison of simulated drain current of GaAs MESFET using —— ET model and - - - - DD model.