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Non-Stationary Transport HBT Modeling Under Non-Isothermal Conditions

A. Benvenuti, G. Ghione, and C. U. Naldi

Dipartimento di Elettronica, Politecnico di Torino
Corso Duca degli Abruzzi 24, I-10129 Torino, ITALY

Abstract

Because of the interaction between thermal and hot carriers effects, neither isothermal nor conventional macro-thermal models are adequate for state-of-the-art power heterojunction bipolar transistors (HBTs); instead, a non-isothermal hot carrier transport model, such as the *thermal-fully hydrodynamic* model, is required. We apply such a detailed thermal model to the simulation of an AlGaAs/GaAs HBT, comparing the results with those provided by simplified models, and highlighting how deeply both non-stationary transport and self-heating affect the predicted device performance.

1. Introduction and modeling approach

The dynamical behaviour of each of the subsystems composing the semiconductor (electron, hole and phonon populations) can be conveniently and quite generally described by means of a Boltzmann transport equation, relating the time evolution of the corresponding distribution function to the collision contribution.

Applying the method of moments in $\underline{k}$ space to such Boltzmann equations, three coupled sets of partial differential equations are obtained in the single electron and hole gases approximation. Retaining the moments of order $0 \div 2$ for the electron gas subsystem, conservation equations for the electron concentration, average velocity and average kinetic energy, respectively, are obtained [1]. In particular, we restricted ourselves to the steady-state, 1D case, and closed the system by expressing the electron gas heat flux with the Fourier law [2].

As to the lattice, the moment of order 2 suffices for the description of its dynamics:

$$\frac{\partial(\rho c_l T_l)}{\partial t} + \nabla \cdot \underline{Q}_l = \left.\frac{\mathrm{d}(\rho c_l T_l)}{\mathrm{d}t}\right|_{\mathrm{coll}} . \tag{1}$$

Being physically related to scattering events, the collision terms can be split into an intraband contribution, described with the relaxation time approximation, plus an interband contribution, depending on generation-recombination mechanisms [3].

The charge, momentum and energy conservation equations for the electrons, a similar set for the holes, the Poisson equation and the lattice heat equation together have been named *thermal-fully hydrodynamic* (T-FH) model [1]. The T-FH formulation is

completed by imposing a set of coupled, mixed boundary conditions for the electron, hole and lattice temperatures T_n, T_p and T_l, accounting for the 3D heat spreading through the metallization and the substrate by means of a geometrical transformation.

If the so-called convective terms [4] are neglected, the *thermal-energy balance* (T-EB) model [5] is recovered as a particular case, and the moments of order $0 \div 1$ can be joined into a single second-order current continuity equation.

Both T-FH and T-EB may be considered as *detailed* thermal models, since they allow for a separate description of the energy stored in (and carried by) the electron, hole and phonon subsystems. Just a few detailed thermal simulations have been reported up to now; the T-FH model has been proposed in [6, 3], and applied to HBT simulation in [1], while the simpler T-EB model has been proposed in [7] and applied to BJT simulation in [5].

Most thermal models are based on a *macroscopic* approach, whereby the thermal contributions arising from electrons, holes and phonons are considered as a whole. In fact, if optical generation-recombination mechanisms are neglected, applying a global energy balance principle for the collision terms [8, 9], a lumped heat equation is obtained, which describes the time evolution of the total energy density stored in the semiconductor. Assuming $T_n \simeq T_p \simeq T_l$, and neglecting the Peltier term $5k_BT_l/2q\nabla\cdot(\underline{J}_n + \underline{J}_p)$, the widely-used *macro-thermal* model [10, 11] is recovered:

$$\frac{\partial(\rho c T_l)}{\partial t} - \nabla\cdot(\kappa\nabla T_l) = \underline{J}_n \cdot \underline{\mathcal{E}}_n + \underline{J}_p \cdot \underline{\mathcal{E}}_p + E_g R, \tag{2}$$

where $c = c_l + 3k_B(n+p)/(2\rho)$ and $\kappa = \kappa_l + \kappa_n + \kappa_p$ are the lumped specific heat and thermal conductivity.

To preserve the main advantage of the macro-thermal approach, that is its simplicity, the differential equations expressing conservation of carrier energy must be eliminated from the electrical model as well. Usually, this is implicitly accomplished resorting to the drift-diffusion formalism of carrier transport, *i.e.* neglecting the carrier energy fluxes and assuming local quasi-field dependent mobilities (T-DD model).

An appropriate modeling of the T_l-dependence of some key parameters is critical in obtaining accurate thermal simulations: the relaxation times can be conveniently expressed [2] in terms of the low field mobility μ_0 and saturation velocity v_{sat}, for whose T_l dependence both experimental data and analytical expressions are available, while the Varshni formula can be applied for the thermal band gap shrinkage [2].

We introduced both surface and bulk trap-related recombination, described with the conventional SRH model, direct band-to-band recombination, and avalanche generation: for the latter we tested average velocity [6] and average energy [3] dependent impact ionization coefficients, as well as the conventional field dependence. Also, we modified the model proposed in [12] to describe hot carrier effects on the Auger recombination coefficients.

All of the mentioned thermal models (T-FH, T-EB, T-DD) and their isothermal counterparts (FH, EB, DD) have been implemented in the framework of a highly flexible device simulation code [1] based on the 1-liner technique, exploiting generalized continuation, grid adaption and automatic jacobian calculation, and allowing for an arbitrary number of differential/algebraic equations. Several discretization schemes (including Scharfetter-Gummel, pure 1-sided and optimal upwinding [4]) may be applied, while all equations are solved self-consistently applying the full-Newton method.

2. Results and discussion

We simulated a 10-emitter fingers AlGaAs/GaAs HBT with a base-emitter junction linearly graded over 20 nm; since hot holes effects are expected to play a minor role in the electro-thermal behaviour of such Npn devices, we adopted the drift-diffusion model to describe hole transport.

The dramatic impact of self-heating on the peak cutoff-frequency is apparent in Fig.1; furthermore, neglecting non-stationary transport, the DD model (and even more the T-DD model) gives a much lower f_T in high injection conditions, where the collector delay dominates.

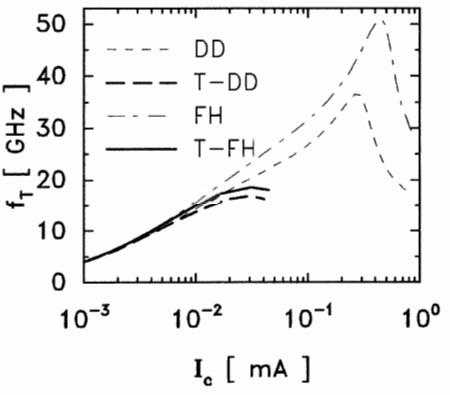

Figure 1: Cutoff frequency for the different models.

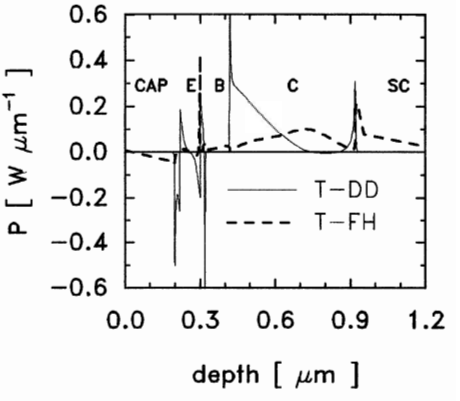

Figure 2: Lattice thermal sources profiles for the T-FH and T-DD models.

Conventional macro-thermal models do not correctly locate the lattice heat sources, for the same reason that they cannot describe non-stationary transport, *i.e.* beacause they neglect the energy flux related to the electron and hole populations. Due to such fluxes, the lattice heat source profile is much smoother than suggested by the Joule terms ($\underline{J}_n \cdot \underline{\mathcal{E}}_n + \underline{J}_p \cdot \underline{\mathcal{E}}_p$), with a maximum substantially displaced from the base-collector to the collector-subcollector junction (Fig.2). In contrast with the results of Liou and co-workers [11], no $T_l < T_a$, where T_a is the ambient temperature, is observed in the emitter, even though a substantial lattice cooling takes place.

The performances of high-power HBTs can be severely limited by the onset of a negative output differential resistance (NDR). Although this effect, which is frequently observed in measured output characteristics, is commonly ascribed to device heating, our simulations (see Fig. 3) point out that NDR might not be entirely due to thermal effects. In fact, only the isothermal DD model results in flat output I-V characteristics, while, even for $T_l = 300$ K, both non-stationary transport models (EB and FH) predict a decreasing I_c *versus* V_{ce}. This appears to be due to the drift current being opposed by a higher thermal (*i.e.*, due to a diffusivity gradient, related to a T_n gradient) diffusion current in the collector region.

Even if the DD model is modified in order to take into account the carrier energy fluxes (and thus non-stationary transport), I_c remains nearly flat in the saturation region, though at a higher value than for DD, as long as the diffusivity/mobility ratio is assumed to be proportional to T_l. The estimate of the electron temperature T_{eff}, provided by the DD model on the basis of the static field-temperature relationship, can be very inaccurate, especially near the b-c junction; therefore, assuming a

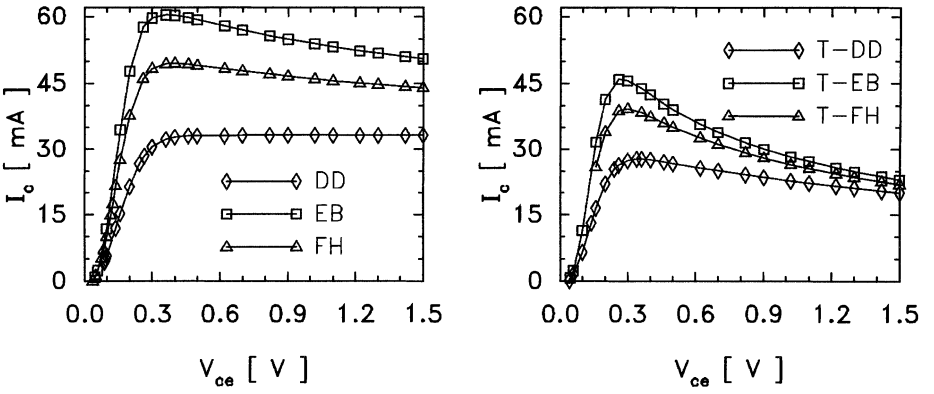

Figure 3: I-V curves predicted by the isothermal (left) and the thermal (right) models.

T_{eff}-dependent Einstein relationship would result in even more unphysical diffusion currents. Of course, when self-heating is taken into account, an additional NDR contribution (due to the decrease of μ_0 and v_{sat} with T_l) adds up, as shown in Fig. 3, right.

3. Conclusions

A hot-carrier transport model under non-isothermal conditions has been applied to the simulation of multi-emitter power HBTs. Comparisons with previous models confirm that the interplay between non-stationary and thermal effects is essential in power HBT modeling. Further work will aim at gaining a deeper insight on the electrical and thermal mechanisms limiting the performances of these devices.

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