

Modeling of Non-equilibrium Carrier Transport in HBTs

-Problem Definition

Xiu Xing

When scaling down or applied to some heterostructures, the conventional drift-diffusion equation is inadequate to analyze ballistic effects in HBTs. The Boltzmann Transport Equation (BTE) is used to simulate the carrier transport in the base of such HBTs, producing the electron density variation of different base width and its evolution along the base. Then the current terms are expected to be calculated and plugged into a general model of abrupt HBTs.

I. Introduction

In the last two decades, high-speed heterostructure bipolar transistors (HBTs) have been achieved, and the representative InP based HBT has both a current gain cut-off frequency and a maximum oscillation frequency over 300GHz. As is commonly done in the other electron devices, scaling down is one reason contributing to this remarkable improvement, another significant contributor is the advantages of carrier transport of III-V semiconductor materials, like higher electron mobility than that in Si. One of the consequences is electrons with high energy can be easily out of equilibrium and their velocity can be much higher than that in a steady state. Moreover, Kroemer originally proposed that an abrupt conduction band barrier of an n-p-n HBT can provide an energy step which acts as a launching ramp for energetic electrons from the emitter to the base [1,2]. When tunneling exists, the electrons can transport ballistically across the base, with high kinetic energy (almost the same as the conduction band discontinuity ΔE_c) and momentum directed towards the collector (Fig.1 [3]). All these non-equilibrium effects will reduce the base transit time τ_B and the recombination rate in base, as well as improve the high speed performance of modern HBTs.

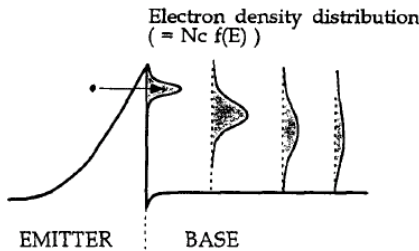


Fig. 1. The density distribution of tunneling electrons at the heterojunction and along a long base. Electrons lose energy and momentum through collisions as they move along the base.

Obviously, the conventional drift-diffusion equation is insufficient to analyze such non-equilibrium effects as ballistic effect. As used here, the term “non-equilibrium” describes a condition where carrier transport deviates from a steady state determined by velocity-field characteristics and carrier diffusive motion as lattice temperature [4]. Previous works indicate when extreme non-equilibrium electron transport in the base dominates, one of the direct consequences is the dependence of the current gain to the base thickness is $1/w_B$, suggesting tunneling and ballistic transport [5] (Fig. 2).

A general question is under what dimension electrons can be non-equilibrium in III-V materials at a practical temperature. Monte-Carlo analysis on InP/InGaAs HBTs performed by Dodd and Lundstrom [6] indicates for thin base ($<200 \text{ \AA}$) the current gain scales as $1/W_B$, while a diffusive behavior is observed for long base HBTs ($>1000 \text{ \AA}$) and the current gain becomes approximately proportional to $1/W_B^2$.

In this paper, a simulation based on the carrier density balance, momentum balance and energy balance equations which are derived from Boltzmann Transport Equations (BTE) is presented to characterize the non-equilibrium carrier transport in the base region of an HBT, and integrated to a general model of abrupt HBTs [7].

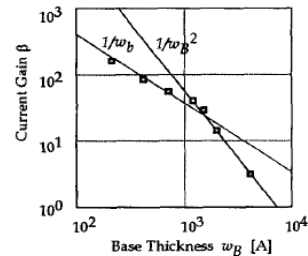


Fig. 2. Dependence of the current gain on the base thickness (A. F. J. Levi, B. Jalali, R. N. Nottenburg and A. Y. Cho).

II. Balance Equations

Minority carriers in the base are treated as neutral particles, which is reasonable if the dielectric relaxation time of majority carriers is shorter than ω^{-1} , where ω is the angular frequency of a periodic perturbation [8]. Then, the carrier can be characterized with their position and momentum as a function of time. The distribution function $f(\mathbf{r}, \mathbf{p}, t)$, the probability of finding a carrier with the crystal momentum \mathbf{p} , at the position \mathbf{r} , at time t , can be solved from the Boltzmann Transport Equation:

$$\frac{\partial f}{\partial t} = -\nabla_{\mathbf{r}} \cdot \left(\frac{d\mathbf{r}}{dt} f \right) - \nabla_{\mathbf{p}} \cdot \left(\frac{d\mathbf{p}}{dt} f \right) + \frac{df}{dt}|_{G-R} \quad (1)$$

Since solving BTE directly is too laborious, a simplified approach is using the following balance equations derived from BTE, assuming 1-D problem and no source or sinks for carriers, $n(x)$, $v(x)$ and $T_c(x)$ are the 3 unknowns:

$$\frac{\partial n}{\partial t} = \frac{1}{q} \frac{\partial J_{nx}}{\partial x} \quad \text{Carrier density balance (2)}$$

$$\frac{\partial P_x}{\partial t} = -\frac{\partial (nm^* v_{dx}^2 + nkT_c)}{\partial x} + n(-q)\epsilon_x - \left\langle \left\langle \frac{1}{m} \right\rangle \right\rangle P_x \quad \text{Momentum balance (3)}$$

$$\frac{\partial W}{\partial t} = -\frac{\partial}{\partial x} \left[(W + nkT_c) v_{dx} - \kappa \frac{\partial T_c}{\partial x} \right] + J_{nx} \epsilon_x - \left\langle \left\langle \frac{1}{\tau_E} \right\rangle \right\rangle (W - W^0) \quad \text{Energy balance (4)}$$

Where κ is the thermal conductivity and omitted for computational simplicity. P_x is the momentum along x direction, W is the electron energy, W^0 is the energy at equilibrium, and ϵ is the electric field in the x -direction. $\left\langle \left\langle \frac{1}{m} \right\rangle \right\rangle$ is ensemble average momentum relaxation time, and $\left\langle \left\langle \frac{1}{\tau_E} \right\rangle \right\rangle$ is energy relaxation time.

III. Solving the equations

To start with analyzing the situation where tunneling of ballistic electrons dominated the current, we need define the initial and boundary conditions.

Relaxation time

The total scattering rate can be calculated as the sum of the rates of each of the individual processes.

$$\Gamma(p) = \sum_i \frac{1}{\tau_i(p)} \quad (5)$$

The simplest case is assumed here and the average energy and momentum relaxation times are taken to be constants. The starting points are in the range of $0.5 \times 10^{-14} - 10^{-16} s$.

Initial velocity

The electrons are assumed to be injected from the emitter into the base with a certain initial average velocity, which depends on the band structure of the heterostructures and voltage bias V_{BE} . It is chosen between 1.0 and 0.1 times of group velocity of the electrons in the central valley.

Emitter-base boundary condition

The average electron velocity, number of electrons injected and average temperature defines the emitter boundary condition in the base.

Base-collector boundary condition

Electric field in the space charge region and the equilibrium current density determine the collector boundary.

Then, apply conservative Lax method in computational physics to solve the balance equations.

The selected HBT is a single heterojunction InP-based HBT.

REFERENCES

1. H. Kroemer, *Proc. IEEE* **70**, 13 (1982).
2. H. Kroemer, *J. Vacuum Sci. Technol.* **B 1**, 126 (1983).
3. Melih Ozaydin and L. F. Eastman, *Solid-State Electronics* **Vol. 39 No. 5**, 731 (1996).
4. Tadao Ishibashi, *IEEE Electron Devices*, **Vol. 48 No. 11**, 2595 (2001).
5. A.F.J.Levi, B. Jal ali, R. N. Nottenburg and A.Y. Cho, *Apply. Phys. Lett.* **60**, 460 (1992).
6. P. Dodd and m. Lundstrom, *appl. Phys. Lett.* **61**, 465 (1992).
7. Antonio J. Garcia-Loureiro and Juan m. Lopez-Gonzalez, *Int. J. Numer. Model.* **17:29-42**, (2004).