Ballistic and Diffusive Carrier Transport in HBTs

Xiu Xing

When scaling down or applied to some heterostructures, the conventional drift-diffusion equation is inadequate to analyze ballistic effects in HBTs. Different methods have been used to simulate the carrier transport in the base of such HBTs, producing the electron density variation of different base widths and its evolution along the base. The simulated results show that both the ballistic and diffusive transport can be present in the base, depending on the base thicknesses and relaxation times.

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 Ш-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 ΔEc) 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.

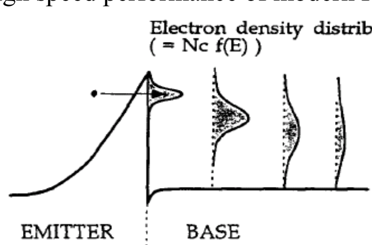


Fig. 1. The density distribution of tunneling electrons at the heterojunction and along a long base. Electrons lose energy and momentum through collisions as they move along the base.

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).

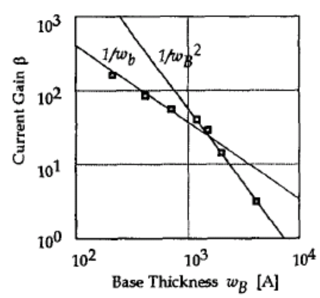


Fig. 2. Dependence of the current gain on the base thickness (A. F. J. Levi, B. Jalali, R. N. Nottenburg and A. Y. Cho).

A general question is under what dimension electrons can be non-equilibrium in Ш-V materials at a practical temperature. For thin-base InP/InGaAs heterojunction bipolar transistors (HBTs), electron transport across the p base can be very far from thermal equilibrium because electrons are launched into the base with an energy of ~ 10 k_BT and the electron scattering rate in InGaAs is low. Although there is clear evidence that base transport in InP/InGaAs and AlInAs/InGaAs HBTs is quasiballistic, a study suggested that it is diffusive for base widths as small as 200 A[6].

Many groups have reported their works on this issue based on different simulation methods.

Introducing their works is helpful for us to understand the insights.

II. Monte-Carlo analysis

In Dodd and Lundstrom's work[7], Electron transport across an InGaAs base was examined with a semi-classical treatment using a Monte Carlo simulation program. A three-valley model was assumed, and screened polar optical phonon, nonpolar acoustic phonon, intervalley, ionized impurity, and hole plasmon scattering were treated. Electrons are injected from a thermal Maxwellian distribution across a 0.24 eV launching ramp. The base is $In_{0.53}Ga_{0.47}As$-doped p-type to 7e19 /cm^3, and the temperature is 300 K.

A series of Monte Carlo simulations for base widths ranging from 10 to 20 000 A was performed. The base transit times obtained are plotted in Fig. 3. Except for ultra thin bases, the transit times are observed to scale roughly as W_B^2, which suggests diffusive transport.

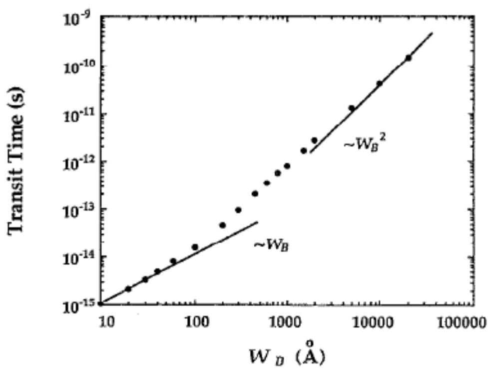


Fig.3 Base transit time Vs. base width as evaluated by Monte Carlo simulation in [7].

To understand these results, a computed impulse response is shown in Fig. 4 for a 300A thick base. For ballistic transport, carriers would traverse the base at the injected velocity (9.0e7cm/s). The ballistic transit time, τ_{ball}, is noted in Fig. 3, as is the actual transit time τ_B. The few carriers that scatter and exit the base at long times significantly lengthen the base transit time. So, Monte Carlo simulations reveal that the base transit time is strongly influenced by small amounts of carrier scattering.

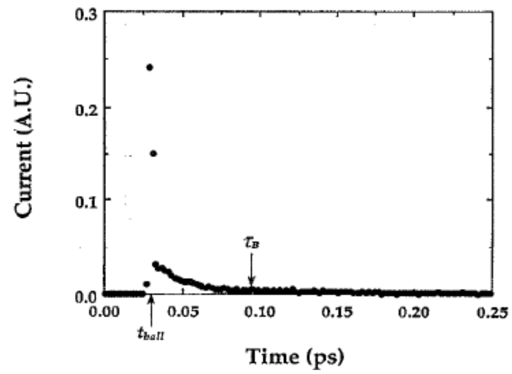


Fig.4 Current response due to a δ function of electrons injected into the base at t=0. [7]

II. Balance Equations Method

Monte-Carlo simulations are in general more thorough but too laborious to use in device analysis, and a more practical and efficient method is needed to characterize the base region of an HBT. Melih Özaydin and Lester F. Easterman reported their simulation work based on a set of balance equations derived from the Boltzmann Transport Equation [3]. Here 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(**r**,**p**,t), the probability of finding a carrier with the crystal momentum **p**, at the position **r**, at time t, can be solved from the Boltzmann Transport Equation:

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

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 Tc(x) are the 3 unknowns:

$$\frac{\partial n}{\partial t} = \frac{1}{q}\frac{\partial \mathbf{J}_{nx}}{\partial x}$$ Carrier density balance (2)

$$\frac{\partial \mathbf{Px}}{\partial t} = -\frac{\partial\left(nm^* v_{dx}^2 + nkT_c\right)}{\partial x} + n(-q)\mathcal{E}_x - \left\langle\left\langle \frac{1}{\tau_m}\right\rangle\right\rangle \mathbf{Px}$$

Momentum balance (3)

$$\frac{\partial W}{\partial t} = -\frac{\partial}{\partial x}\left[(W + nkTc)v_{dx} - \kappa\frac{\partial T_c}{\partial x}\right] + J_{nx}\varepsilon_x$$
$$-\left\langle\left\langle\frac{1}{\tau_E}\right\rangle\right\rangle\left(W - W^0\right)$$

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. $\left\langle\left\langle\frac{1}{\tau_m}\right\rangle\right\rangle$ is ensemble average momentum relaxation time, and $\left\langle\left\langle\frac{1}{\tau_E}\right\rangle\right\rangle$ is energy relaxation time.

To start with analyzing the situation where tunneling of ballistic electrons dominated the current, the initial and boundary conditions are confined as following:

Relaxation time

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

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

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 $0.5\times10^{-14} - 10^{-16}s$.

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.

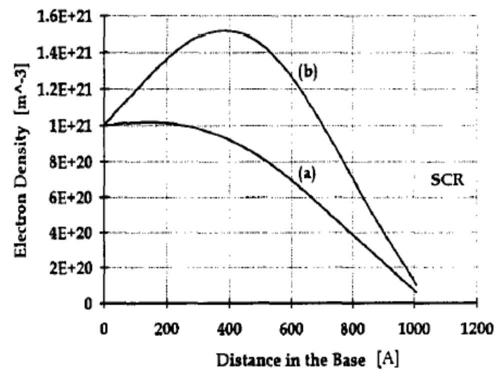
Emitter-base boundary condition

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.

The conservative Lax method is applied to solve these equations, a typical result is shown in Fig.5[3].



Ι. Comparison of simulation results where the initial and the final velocities are kept constant, and the relaxation times are varied: $J = 1.6\times10^7$ A m^{-2}; $v_{ini} = 1\times10^5$ m s^{-1}; (a) $\tau_E = 5\times10^{-15}$ s, $\tau_m = 5\times10^{-16}$ s; (b) $\tau_E = 1\times10^{-15}$ s, $\tau_m = 1\times10^{-16}$ s.

Fig.5 [3]

When the electrons are injected into the base from the emitter by a tunneling mechanism, at least in the initials part of the base, the electrons have high directed momentum, and act like ballistic particles. Their energy and momentum is lost within a distance on the order of the momentum relaxation through the electron-electron and electron-phonon interaction and scattering as they move into the base, and the momentum is randomized.

At equilibrium the constant current must be maintained everywhere. Thus the electron concentration increases. As the electrons lose their velocity, they start to accumulate in the middle of the base region, and electron concentration increases. The smaller the momentum relaxation time, the more the electrons pile up in the middle of the base region. On the collector end of the base, a high and sudden high electric field in the base-collector space-charge region accelerates the electrons. Because of the increasing concentration in the middle of the base and the low concentration on the collector side of the base, diffusion forces start acting on the carriers.

III. Conclusion

As the conclusion, if the electrons are injected through tunneling, both the ballistic and diffusive transport can be present in the base, depending on the base thickness and relaxation times. For a long base transistor, initially, electrons are transported ballistically, and then, the transport is generally diffusive. If the base thickness is short and the momentum relaxation time is high, however, electrons stay energetic and the average velocity is high and almost constant throughout most of the base. In this case, the current gain depends on the base thickness as $1/w_B$.Depending on the thickness of the base and relaxation times, the current gain dependence on base thickness changes from l/w_B (ballistic), to l/w_B^2 (diffusive); as the base thickness increases.

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