Ensemble Monte Carlo Simulation of the Hot Electron Transport in the Heterojunction Bipolar Transistors

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Abstract

The effect of the electron transport regime in the base-collector junction on the steady-state and high-frequency characteristics of a heterojunction bipolar transistor (HBT) is examined. A new technique based on the Fourier analysis of the induced collector current to evaluate HBT high frequency performance is used. The non-stationary electron transport, velocity overshoot effects and effects of the high-current density are taken into account using self-consistent time-dependent ensemble Monte Carlo particle simulation.

I. Introduction

Submicrometer heterojunction bipolar transistors (HBTs) are now widely investigated because of their great promise for microwave, millimeterwave and ultra-high-speed digital operations. In a typical $N-p-n$ HBT with abrupt emitter-base heterojunction electrons are injected from wide-gap emitter with considerable excess energy into a p-type narrow-gap base region. As a result the electron transport in the submicrometer HBT is far from equilibrium. To improve the HBT high-frequency performance the different base-collector junction designs have been proposed and investigated experimentally in [1,2] and using numerical simulation in [3-5]. For these designs the electrons stay longer in central valley and therefore achieve high average velocities into the collector region. Thus, extreme nonequilibrium electrons transport in the base and collector regions plays a role in determining device performances. Therefore to calculate transistor electrical characteristics with high accuracy the numerical simulation seems to be the only powerful way.

II. Numerical Model

To investigate the operation and design principles of the HBTs one-dimensional ensemble Monte Carlo simulator was developed [5]. Our Monte Carlo model incorporates complicated non-parabolic electron energy spectra and all essential scattering mechanisms. Motion of the holes in the base region and the electrons in the heavily doped collector contact region is evaluated using the drift-diffusion approach. Two distinctive features are inherent in the model. First feature is concerned with the choice of the self-scattering events. To minimize the number of the self-scattering events a special procedure is used where the total scattering rates are represented by the tabulated momentum-dependent step-like

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functions. These functions are chosen taking into account local values of the electric field and impurity concentration. Applications of this technique permits to reduce the number of self-scattering events to 7% of the scattering events total number.

Other novice of the model is concerned with the calculation of the HBT small-signal high-frequency performance. The HBT high-frequency performance is determined by the base resistance, the emitter and collector capacitances effects and the carrier transit effects in the base and collector regions. To characterize the HBT as an microwave and millimeter-wave amplifier the cut-off frequency f_T is usually used. As a rule the following expression derived from the small-signal equivalent circuit analysis is used to estimate f_T in a HBT [1]:

$$f_T = \{2\pi \cdot [r_E \cdot C_{BE} + \tau_{BC} + (r_E + R_E + R_C) \cdot C_{BC}]\}^{-1}, \tag{1}$$

where r_E is the emitter resistance, R_E is the emitter series resistance, R_C is the collector series resistance, C_{BE} and C_{BC} are the emitter and collector capacitance respectively, τ_{BC} is the base-to-collector transit delay time. In this expression all the carrier transit effects are considered by the only carrier transit delay time through the base and collector τ_{BC} usually being estimated from the steady-state distribution of the mean electron velocity [1,6]. It is obvious that this τ_{BC} formulation is not absolutely correct because it does not take into account the electron velocity profile in the collector region and detail shape of the electron distribution function. The last reason is especially important in the presence of the non-stationary carrier transport. Therefore method based on the Fourier analysis of the non-steady-state induced collector current is used in present model.

Simple high-frequency equivalent circuit of HBT is shown in Fig.1. For this circuit frequency-dependent common-emitter short-circuit current gain h_{21} may be written as follows:

$$h_{21}(\omega) = \left[\frac{(1 + j\omega C_{BE} r_E) \cdot (1 + j\omega C_{BC} R_C)}{\gamma(\omega) - j\omega C_{BC}(r_E + R_E) + \omega^2 C_{BE} C_{BC} r_E R_E} - 1\right]^{-1}, \tag{2}$$

$$\gamma(\omega) = \gamma_E(\omega) \cdot \beta(\omega) \cdot \gamma_C(\omega)$$

where γ_E is the emitter efficiency, β is the base transmission coefficient and γ_C is the collector transmission coefficient. The values of the resistances and capacitances in (2) are calculated from the numerical simulation of the required steady state or are estimated from the experimental results. Further in our analysis, $C_{BC}, C_{BE}, r_E, R_E, R_C$ and γ_E are assumed to be independent on frequency and to be dependent on the applied bias. The only problem is the calculation of the complex frequency-dependent coefficient $\gamma(\omega)$.

To calculate $\beta(\omega) \cdot \gamma_C(\omega)$ the Fourier analysis of the non-steady-state induced collector current is used [3]. Initially the steady-state simulation for the given applied bias is performed and stationary distributions of the potential and carriers concentrations are calculated. After that the electron bunch consists of several thousand electrons is launched from the base-emitter interface during short time interval and the time dependent collector current response $J_C(t)$ is calculated. Here we assume that the injected non-steady-state electrons travel through base and collector in the known stationary electric field. When all launched electrons leave the modeling region the Fourier transformation of the injected non-stationary emitter current $J_E(t)$ and induced collector current are carried out. The frequency-dependent base-collector transmission coefficient is defined as follows:

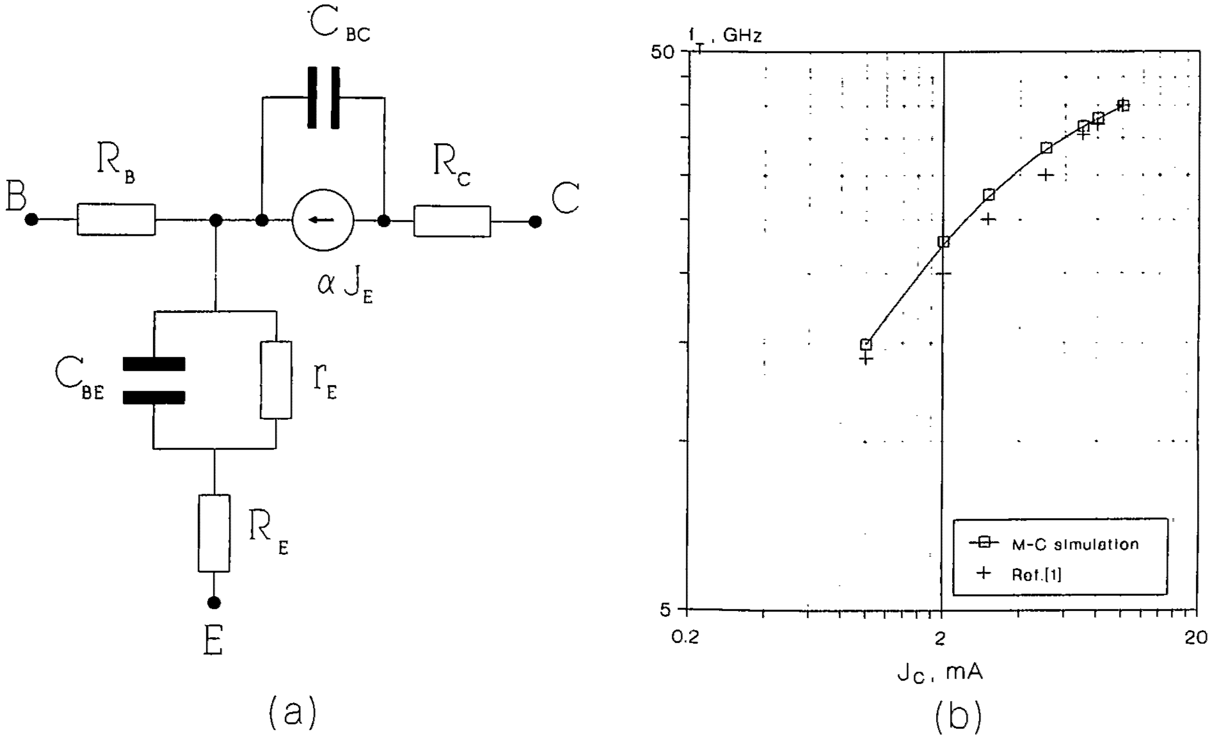

Fig.1 Small-signal equivalent circuit (a) and cut-off frequency f_T as a function of the collector current J_C (b).

$$\beta(\omega) \cdot \gamma_C(w) = \frac{F[J_C(t)]}{F[J_E(t)]}, \tag{3}$$

where F denotes the Fourier transform. Cut-off frequency f_T is defined from the analysis of the $h_{21}(\omega)$ computed by (3) as a frequency where $|h_{21}(\omega)| = 1$. It should be noted that proposed method is also appropriate to calculate other HBT high-frequency characteristics such as power gain, stability factor, scattering matrix and so on.

To verify proposed Monte Carlo particle model and method of evaluation of the HBT high-frequency performance the submicrometr HBT with the same structure as in [1] was simulated. The comparison of the simulated results with the experimentally observed results have shown high accuracy and validity of the model (see Fig.1).

III. Results and Discussions

A series of $AlInAs/GaInAs$ HBTs with arrange of base thickness W_B from $0.02\mu m$ to $0.4\mu m$ and doped at $1.5 \cdot 10^{19} cm^{-3}$ was simulated at the temperature $300K$ to investigate the base thickness effect on the electron transport regime in the base.

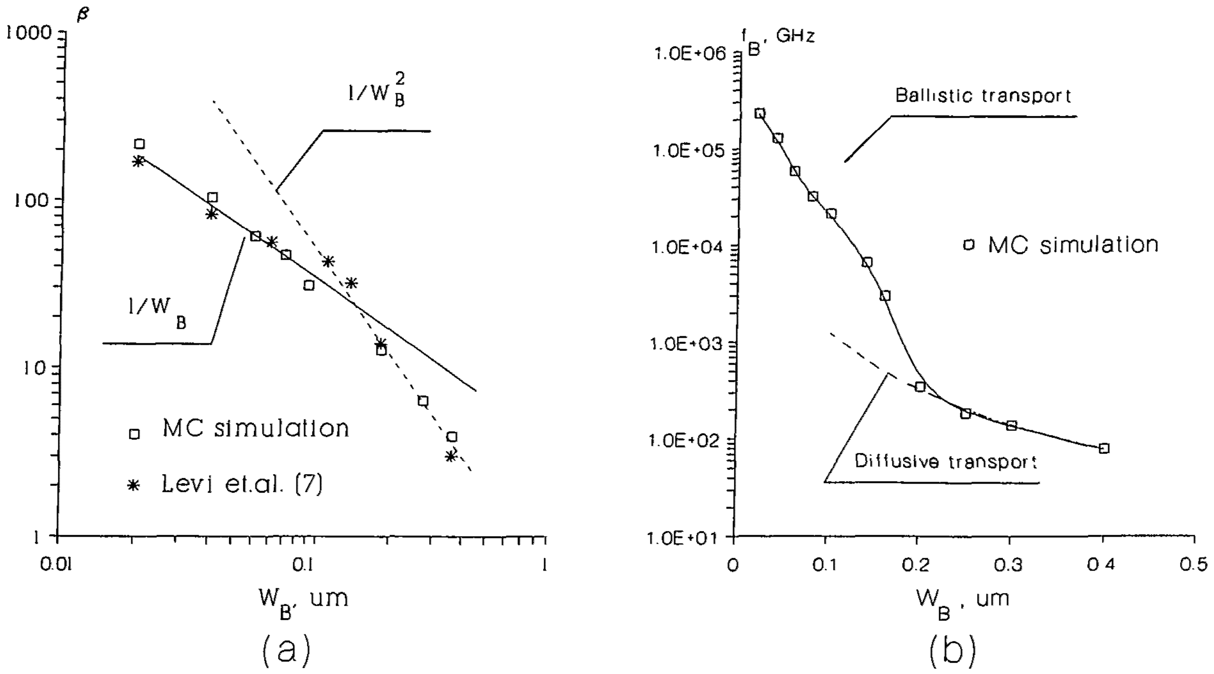

Fig.2 Common emitter current gain β (a) and base cut-off frequency f_B (b) as a function of the base thickness W_B.

The HBT common emitter current gain β dependence as a function of the base region thickness is shown in Fig.2. The analysis of this figure shows that $\beta(W_B)$ is proportional $1/W_B$(corresponds to ballistic transport) for $W_B < 0.1\mu m$ and is proportional $1/W_B^2$(corresponds to diffusive transport) for $W_B > 0.1\mu$m.

The base cut-off frequency $f_B = \frac{1}{2 \cdot \pi \cdot \tau_B}$, where τ_B is a base delay time, dependence as a function of the base layer thickness is presented in Fig.2. Solid curve in the figure presents the dependence calculated by the numerical simulation (method based on the Fourier decomposition of the non-steady-state base current was used in present work to estimate the τ_B). Dashed curve presents the dependence calculated for diffusive transport and dotted curve corresponds to ballistic transport. It is seen that the ballistic transport take place only for $W_B \leq 0.06\mu m$ and pure diffusive transport occurs while the base thickness is more than 0.2μm. For $0.06\mu m \leq W_B \leq 0.2\mu m$ the electrons transport in the base region is far from equilibrium but is neither pure ballistic nor pure diffusive. In this situation correct estimation of the base delay time is possible only by numerical simulation.

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