Study on Possible Double Peaks in Cutoff Frequency Characteristics of AlGaAs/GaAs HBTs by Energy Transport Simulation

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By using an energy transport model, we simulate cutoff frequency $f_T$ versus collector current density $I_C$ characteristics of $n^+n$ AlGaAs/GaAs heterojunction bipolar transistors (HBTs) with various $n^-$-collector thickness and $n^-$-doping densities. It is found that the calculated $f_T$ characteristics show double peak behavior when the $n^-$-layer is thick enough and the $n^-$-doping is high enough to allow existence of neutral $n^-$-region. The mechanism of the double peak behavior is discussed by studying energy band diagrams, electron-energy profiles and electron-velocity profiles. Particularly, we discuss the origin of the second peak (at higher $I_C$) which is not usually reported experimentally.

Keywords: GaAs, heterojunction bipolar transistor, energy transport model, cutoff frequency, double peaks, velocity overshoot

1. INTRODUCTION

Recently, AlGaAs/GaAs heterojunction bipolar transistors (HBTs) have received great interest for application to high-speed and high-frequency devices. Since non equilibrium carrier transport becomes important in the HBTs, carrier energy should be considered in the modeling of them. For this purpose, the Monte Carlo simulation [1, 2] and so-called an energy transport model [3–7] have been applied to analyze the characteristics of AlGaAs/GaAs HBTs.

Cutoff frequency $f_T$ is one of the figure-of-merits of HBTs' high-frequency performance. Usually, the cutoff frequency of AlGaAs/GaAs HBTs increases with the collector current density $I_C$ and begins to decrease at a certain $I_C$, showing a single peak in the experimental $f_T-I_C$ characteristics. However, according to the simulation using a drift-diffusion model, the $f_T-I_C$ characteristics show a steep second peak in some cases [5, 8]. This is attributed to the fact that in the drift-diffusion approximation, electron mobility is given as a function of local electric field and the electron

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velocity versus electric field curve of GaAs shows a peak behavior. By the other simulation methods, the second peak has not been reported yet.

In this work, we have systematically and carefully analyzed the $f_T$ characteristics of AlGaAs/GaAs HBTs by using an energy transport model [9] in which electron mobility is determined by an electron energy (not by local electric field) and velocity overshoot can be treated. As a result, we have found that the second peak can arise (at rather high current levels) also when using this model. Therefore, we discuss here the physical reason why the double peak behavior in the $f_T$ characteristics arises.

2. PHYSICAL MODEL

2.1. Device Structure and Basic Equations

Figure 1 shows an npn-n AlGaAs/GaAs HBT structure analyzed here. Al composition changes from 0.3 to 0 in the emitter and base regions, and so this is a graded band-gap base HBT. Doping densities are different in respective regions, and hence in general, transport parameters should be given as functions of Al composition, doping density and carrier energy. We have simulated the device characteristics as parameters of $n^+$-collector thickness $L_{C1}$ and its doping density $N_{C1}$.

Next we describe the derivation of electron transport equations. Assuming parabolic energy bands, three conservation equations, that is, a particle conservation equation, a momentum conservation equation and an energy conservation equation are obtained by taking moments of the Boltzmann equation [10]. To make these equations tractable and applicable to the HBTs, the following assumptions are made [5]. Firstly, we adopt relaxation time approximation for collision terms. Secondly, we adopt an equivalent one-valley model. If we assume that electron drift energy is negligible small as compared to its thermal energy, the average electron energy $w_n$ can be written as

$$w_n = \frac{3}{2} kT_n + F_U \Delta_{LU}$$

where $T_n$ is electron temperature, $F_U$ is upper-valley fraction and $\Delta_{LU}$ is energy difference between upper and lower valleys. To treat HBTs, some factors are also considered. Carrier recombination is treated by SRH statistics, and an effective field acting on electrons which arises due to the position dependence of band structure is included. Then the electron transport equations are simplified as follows.

$$\frac{dJ_n}{dz} = qU$$

$$J_n = -qnv_n = q\mu_n(w_n) \left\{ nE_n + \frac{d}{dz} \left( \frac{n}{q} kT_n \right) \right\}$$

$$- \frac{d}{dz} \left( \frac{J_n}{q} (w_n + kT_n) \right) = J_n E_n - w_n U - n \frac{w_n - w_0}{\tau_w}$$

where $U$ is the recombination rate, $v_n$ is the average electron velocity, $\mu_n$ is the electron mobility, $E_n$ is the effective field acting on electrons, $\tau_w$ is the energy relaxation time and $w_0$ is the equilibrium value of $w_n$. In the electron transport equations, parameters that should be given are
the electron mobility $\mu_m$, the energy relaxation time $\tau_w$ and the upper-valley fraction $F_U$.

For holes, we use drift-diffusion type equations. In addition to the transport equations, we include Poisson’s equation, which completes the basic equations for device simulation.

2.2. Transport Parameters

Here we describe methods of giving transport parameters such as $\mu_m$, $\tau_w$ and $F_U$. To do this, usually, homogeneous bulk is assumed ($d/dz=0$). Then, the following two equations are obtained from the previous electron transport equations.

$$v_n = -\mu_n E \tag{5}$$

$$w_n = w_0 - q\tau_w v_n E \tag{6}$$

where $E$ is electric field. By using the Monte Carlo method, $v_n$, $w_n$ and $F_U$ are obtained as a function of electric field $E$. Thus, by using Eqs. (5) and (6), the energy-dependent $\mu_m$, $\tau_w$ and $F_U$ can be obtained.

In this work, we must give the transport parameters as functions of Al composition $x$, electron energy $w_n$ and doping density $N$. To do this, we first evaluate $\mu_m$, $\tau_w$ and $F_U$ for $x = 0$, 0.05, 0.1, 0.15, 0.2, 0.25 and 0.3 by a Monte Carlo method. Doping densities are also varied. Once these parameters are available as fit curves or tables for a given doping density, parameters for any $x$ between 0 and 0.3 can be obtained (as a function of $w_n$) by a linear extrapolation method. That is, if $x$ lies between $x_1$ and $x_2$, the parameter $f$ is given by the following equation.

$$f(w_n) = f_1 + \frac{x-x_1}{x_2-x_1}(f_2-f_1) \tag{7}$$

where $f_1$ and $f_2$ are corresponding values of $f$ for $x=x_1$ and $x_2$, respectively.

Next we show some examples of transport parameters estimated by a Monte Carlo method. Figure 2 shows electron mobility $\mu_m$, energy relaxation time $\tau_w$ and upper valley fraction $F_U$ as a parameter of $x$ in Al$_x$Ga$_{1-x}$As, calculated by a Monte Carlo method. The energy difference between upper and lower valleys $\Delta_{L,U}$ and upper-valley effective mass $m_U$ are set to 0.284–0.605 eV and 0.23 $m_0$, respectively.

3. SIMULATED $f_T–I_C$ CHARACTERISTICS

We calculate $f_T–I_C$ characteristics of the AlGaAs/GaAs HBT as parameters of the $n^+$ collector
thickness \( L_{C1} \) and its doping density \( N_{C1} \). Here \( f_T \) is calculated from the following equation.

\[
f_T = \left( \frac{1}{2\pi} \right) \frac{\partial I_C}{\partial Q_n} V_{CE} \tag{8}
\]

where \( Q_n \) is electron charges in the device and \( V_{CE} \) is the collector-emitter voltage. \( V_{CE} \) is set to 1.5 V in this study.

Figure 3 shows calculated \( f_T - I_C \) characteristics of the HBT as a parameter of \( n^- \)-layer doping density \( N_{C1} \), where \( L_{C1} \) is set to 0.5 \( \mu \)m. Figure 4 shows calculated \( f_T - I_C \) characteristics of the HBT as a parameter of \( n^- \)-layer thickness \( L_{C1} \), where \( N_{C1} \) is set to \( 5 \times 10^{16} \) cm\(^{-3} \). As \( I_C \) increases, \( f_T \) increases because the emitter charging time and the collector charging time are reduced. From these figures, we see that for lower \( N_{C1} \) (10\( 16 \) cm\(^{-3} \) in Fig. 3) and for thinner \( L_{C1} \) (0.1 \( \mu \)m and 0.2 \( \mu \)m in Fig. 4), \( f_T \) characteristics show a single peak. These cases correspond to the situation that \( n^- \)-collector layer is almost or fully depleted already when the base-emitter voltage (\( V_{BE} \)) is 0 V. In the other cases, two peaks are clearly seen in the \( f_T \) characteristics. In these cases, neutral \( n^- \)-region exists at \( V_{BE} = 0 \) V.

Up to the first peak, \( f_T \) is higher for higher \( N_{C1} \), as seen from Figure 3. Also, the value of \( I_C \) where \( f_T \) begins to decrease is higher for higher \( N_{C1} \). These are because around the peak region, the transit time through \( n^- \)-collector depletion layer (which is thinner for higher \( N_{C1} \)) is dominant [5] and \( f_T \) begins to decrease due to a high injection effect which leads to expanding the depletion layer and increasing the collector transit time. As seen in Figure 4, the \( f_T \) characteristics are essentially similar between the two cases with \( L_{C1} = 0.5 \) \( \mu \)m and 0.7 \( \mu \)m. This is because the thickness of \( n^- \)-collector depletion layer is determined by \( N_{C1} \). As shown in Figure 3, when \( N_{C1} \) is higher, the value of \( I_C \) where \( f_T \) takes the second peak is higher. We will discuss below why the \( f_T \) characteristics show double peak behavior.

Figure 5 shows energy band diagrams as a parameter of \( I_C \) for the HBT where \( N_{C1} = 5 \times 10^{16} \) cm\(^{-3} \) and \( L_{C1} = 0.5 \) \( \mu \)m. Figures 6 and 7 show the corresponding electron-energy profiles and electron-velocity profiles, respectively. In these figures \( I_C = 10^4 \) A/cm\(^2\), \( 3 \times 10^4 \) A/cm\(^2\), \( 8 \times 10^4 \) A/cm\(^2\), \( 1.2 \times 10^5 \) A/cm\(^2\) and \( 1.5 \times 10^5 \) A/cm\(^2\) correspond to the regions before the first peak, around the first peak,
at the local minimum, at the second peak, and after the second peak respectively, in the $f_T-I_C$ characteristics. From these, we interpret the double peak behavior in the following way.

As is understood from Figure 5, the first peak arises because the depletion layer in the $n^-$-collector layer expands due to a high injection effect, and hence the collector transit time increases. The fall of $I_C$ should last until the $n^-$-collector layer becomes entirely depleted. Around $I_C=8\times10^4$ A/cm$^2$, the $n^-$-layer is entirely depleted as seen from Figure 5 and at this current, $f_T$ characteristics show the local minimum. As can be seen from the band diagrams, the electric field at the $n^-$-collector layer near the base becomes weaker when $I_C$ increases further. Hence, as shown in Figure 6, the electron energy in this region becomes lower. Consequently, the electron mobility becomes high, leading to the higher electron velocity than the saturation velocity, for example, at $I_C=1.2\times10^5$ A/cm$^2$ as shown in Figure 7. Therefore, the collector transit time becomes shorter temporarily and hence $f_T$ begins to increase again. In the end, however, $f_T$ falls because of the base-push-out effect (Kirk effect) which leads to a lower electron velocity around the base-collector interface and higher collector capacitance due to the injected electrons whose densities become higher than $N_{C1}$. Thus the second peak arises. As is evident from the above discussion, the value of $I_C$ where $f_T$ shows a second peak becomes higher for higher $N_{C1}$.

As described above, we have shown theoretically that double peak behavior can be seen in the $f_T-I_C$ characteristics of AlGaAs/GaAs HBTs. Physical mechanism of this behavior has been explained.

4. CONCLUSION

By using an energy transport model, we have simulated $f_T-I_C$ characteristics of AlGaAs/GaAs HBTs with various $n^-$-collector thickness and $n^-$-doping densities. It is found that the calculated $f_T$ characteristics show the double peak feature when the $n^-$-layer is thick enough and the $n^-$-doping is high enough to allow existence of the neutral $n^-$-region. It is interpreted that the first peak arises because the depletion region in the $n^-$-layer begins to expand due to a high injection effect and the collector transit time increases. The fall of $f_T$ lasts until the $n^-$-layer becomes entirely depleted. When the base voltage is raised further, the electric field in the $n^-$-layer near the base becomes lower, leading to the lower electron energy there. Then, the electron velocity in the $n^-$-layer becomes higher, resulting in shorter collector transit time. Therefore, $f_T$ begins to increase again. Finally, $f_T$ decreases due to the base-push-out effect (Kirk effect), resulting in the second peak. We can say that the double peak behavior can be seen in the $f_T$...
characteristics of real AlGaAs/GaAs HBTs if the collector current is raised rather high.

References


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