Extended Abstracts of the 19th Conference on Solid State Devices and Materials, Tokyo, 1987, pp. 399-402

# A Particle Simulation for Transport Phenomena in Heavily Doped Base HBTs

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A one-dimensional full Monte Carlo simulator was developed for (AlGa)As/GaAs heterojunction bipolar transistors (HBTs) to investigate how various non-equilibrium electron transport mechanisms affect the entire device performance. Hole plasmon scattering and screened LO phonon scattering were proved for the first time to play an essential role in determining the minority carrier temperature in a heavily doped base layer. Simulation was carried out for various types of HBTs with structual variation of the base. A graded-gap base HBT was shown to reveal the best performance for intrinsic device characteristics providing that adequate Al composition was adopted at the base emitter junction.

## 1. Introduction

Taking advantage of the wide-gap emitter, heterojunction bipolar transistors (HBTs) have been fabricated with increased base doping over  $10^{19}$  do reduce base resistance. Although electron transport in these HBTs is seriously affected by a peculiar phenomena to heavy doping, which will be explained below, strict treatment of these phenomena has not been taken into account in previous device analyses<sup>1),2)</sup>.

Thus, a one-dimensional full Monte Carlo simulator was developed for heavily doped base HBTs in order to investigate these phenomena themselves as well as their effects on the entire device performance, where hole plasmon scattering and screened LO phonon scattering were taken into account as heavy doping effects.

Using this simulator, electron transport phenomena in the base collector region are mainly discussed in conjunction with a variety of base structures.

# 2. Device Model

A particle model for electrons, a fluid

dynamic model for holes, and Poisson's equation were solved consistently for an entire device, where the differential method was used to solve with a constant mesh spacing of 50Å.

In formulating the model, a non-parabolic  $\Gamma$ ,L,X band structure, position dependent effective mass, and quantum mechanical reflection at the heterointerface<sup>3)</sup> were considered to make the model more realistic. Physical constants were extracted from the



Fig.1 Calculated HBT structures.

literature listed in the references  $^{4),5)}$ . In to the standard scattering addition mechanisms<sup>6),7),8)</sup>, hole plasmon scattering and screened LO phonon scattering were newly taken into account corresponding to the recent tendency to increase base doping. Plasmon scattering was formulated so as to realize detailed balance for a low energy level, at least in equilibrium. As for LO phonon scattering, the scattering potential was considered to be screened statically with hole plasma.

Simulation was carried out for various types of HBTs with structual variation of the base, as illustrated in Fig.1, where a uniform-base HBT, an abrupt-gap emitter-base HBT (abrupt HBT), and a graded-gap base HBT (graded base HBT) were considered. The collector-to-emitter bias voltage was fixed at 1.5V and the base-to-emitter bias voltage was adjusted to yield a constant current density of  $2x10^4$ A/cm<sup>2</sup>.

## 3. Computation Results

Figure 2 shows a comparison of the carrier temperature between computation and



Fig.2 Comparison of carrier temperature between computation and experiment for abrupt HBT.



Fig.3 Calculated results for abrupt HBT (a)electron energy distribution (b)average electron velocity profile

experiment<sup>9)</sup> for an abrupt HBT. A good agreement is shown at high base doping to justify our model, thus proving the importance of the aforementioned scattering mechanisms in the heavily doped base region.

Figures 3 (a) and (b) show the electron energy distribution and the average drift velocity profile for an abrupt HBT, respectively. From (a), a majority of the electrons are observed near the conduction band edge ( $\Gamma$ -valley minimum) in the base, because of a strong energy relaxation of the hole plasmon, while, in the collector space charge region, a majority of the electrons exist near the upper-valley (L,X) minimums because of strong intervalley scattering. From (b), the following three points are found; (1)the electron velocity in the base is not so high as expected, (2) a remarkable velocity overshoot with a peak velocity of  $6 \times 10^7$  cm/sec is observed but lasts only 500Å from the base-collector junction, (3)the magnitude of the saturation velocity is about  $6 \sim 8 \times 10^6$  cm/sec which is smaller than the commonly used value of  $1 \times 10^7$  cm/sec.

Figures 4 (a) and (b) show the electron energy distribution and the average electron drift velocity for a graded base HBT, respectively. The energy distribution in the base-collector region is almost the same as







Fig.5 Base transit times for various types of base structures.

for an abrupt HBT except for the smaller ratio of hot electrons in the base compared with an abrupt HBT. From (b), both the drift velocity in the base and the overshoot peak velocity in the collector are found to be greater than those for the abrupt HBT. The former result the shows existence of velocitv overshoot the in base region strong scattering. The despite of latter shows that the peak value of overshoot depends on the energy distribution in the base region.

Figure 5 shows the base transit times for various types of base structures with variation in the Al mole fraction for abrupt and graded base HBTs as well as for a lightly doped base HBT  $(3x10^{16} \text{ cm}^3)$ , where only plasmon scattering was considered for the lightly doped base HBT. The base transit time is shown to be improved by increasing the Al mole fraction both for abupt and graded base HBTs. Transit times of less than lps, however, are attainable only by graded HBTs base under heavily doped base a condition.

Figure 6 shows the electron transit times measured from the base-collector junction for base variation, where the heavy dashed line indicates the transit time in case of using the standard saturation velocity of





 $1 \times 10^7$  cm/sec. No essential difference in transit time is observed for the structual variation of the base in spite of the remarkable difference in peak velocities. This is because the transit time in the spatial range with а large velocity contribute very little to the total transit fact that time. According to the the computation results cross over the dashed line, the collector depletion layer length indicated to be reduced to less than is 1500Å in order to utilize the velocity overshoot effect.

minority carrier mobility Finally. is derived from the calculated results for uniform base HBTs. Calculated mobilities of 862cm/volt · sec and 1380cm/volt · sec were obtained for the case with and without heavy effects, respectively. The latter doping used value for agrees with the commonly This indicates that bulk GaAs. n-type minority carrier mobility in a heavily doped base is expected to be smaller than mobility in n-type bulk GaAs.

#### 4. Conclusions

A one dimensional full Monte Carlo simulator was developed for heavily doped base HBTs to investigate non-equilibrium electron transport dynamics. A comparison of the carrier temperature between computation and experiment shows good agreement to justify our model. Thus the importance of hole plasmon scattering and screened L0 phonon scattering in the heavily doped base region was proved. A base transit time of less than 1ps is shown to be attainable only by adopting graded base HBTs under a heavily doped base condition. It was found that, for any base structure, the collector depletion layer length should be less than 1500Å in order to utilize the velocity overshoot effect.

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