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Monte Carlo Simulation of InP/InGaAs HBT with a Buried Subcollector

G. Khrenov[a], E. Kulkova[b]

[a]Computer Solid State Physics Laboratory, The University of Aizu,
Aizu-Wakamatsu City, 965-80, JAPAN
[b]Research Center "MICROEL",
Krasikov Str. 25a, Moscow, 117218, RUSSIA

Abstract

The effect of structure parameters and operation conditions on the base-collector capacitance and intrinsic transit time of HBT with buried subcollector has been investigated by using a numerical model. It is shown that non-planar geometry of HBT with buried subcollector leads to specific features of voltage dependence of the base-collector capacitance. The non-uniform collector doping profile has been proposed to reduce collector transit time and to optimize HBT structure for low-voltage operation.

1. Introduction

Heterostructure bipolar transistors (HBTs) lattice matched to InP have emerged as potential candidates for high-speed digital, microwave and long-wavelength fiber-optic communication systems because of the excellent transport property of InP and its related materials. High-speed InP/InGaAs HBT having a current gain cutoff frequency about 175 GHz has been demonstrated in [1]. The analysis of experimental data has shown that the collector capacitance charging time and intrinsic transit time dominate among the components of the total emitter-collector delay time. As a result, the main problem concerning further extension of the HBT frequency range is to reduce these times. Vertical scaling of HBT structure, resulting in the reduction of the intrinsic transit time, leads to increase of the collector capacitance and hence to increase of the collector capacitance charging time [2]. Thus, there is trade-off between the transit time and collector charging time. Effective way to reduce collector capacitance has been recently proposed in [3] and consists in reducing of the base-collector junction area in HBT with a buried subcollector. Unfortunately, fabricated HBT with buried subcollector has demonstrated large intrinsic transit time. As a result, parameters of HBT with buried subcollector must be optimized in order to realize great potential of its structure.

2. Device Structure and Model

The layout and cross-section of simulated HBTs are presented in Fig.1. As can be seen, the main feature of HBT with buried subcollector is the small area of overlap

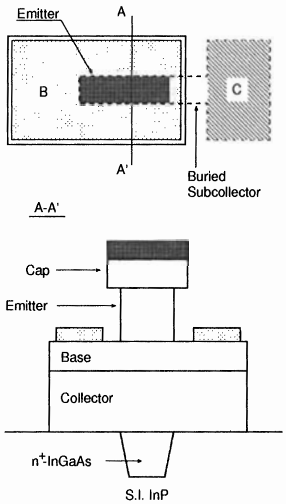

Figure 1: Schematic layout and cross-section of simulated HBT with buried subcollector.

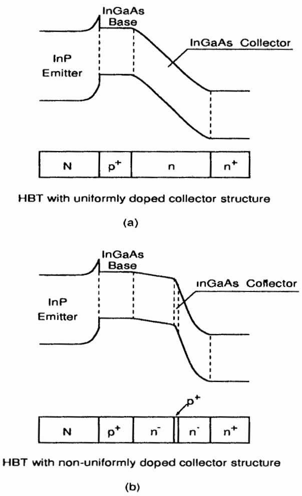

Figure 2: Schematic band diagrams and doping of HBTs with buried subcollector: (a) uniformly doped collector and (b) non-uniformly doped collector.

between the base layer and subcollector, which leads to small total base-collector capacitance. In this study, we concentrate our attention on how base-collector capacitance and base-collector transit time are affected by applied voltages, HBT geometry and collector doping profile. The value of the total base-collector capacitance is determined from the solution of two-dimensional Poisson equation for the electrostatic potential with boundary conditions corresponding to the HBT structure presented in Fig.1. To calculate the intrinsic transit time of HBTs with buried subcollector time-dependent ensemble Monte Carlo particle simulator has been implemented. The value of the base-collector transit time is calculated directly from results of Monte Carlo simulation by using the Fourier analysis of the non-stationary collector current response [4].

3. Results and Discussion

The operation of HBTs with buried subcollector and various collector doping profiles has been investigated at temperature 300 K in the wide range of applied voltages and parameters of HBT structure. First, we have considered the HBT with conventional collector doping profile (Fig.2a). The collector capacitance C versus collector-base voltage V_{CB} is presented in Fig.3. The normalization factor C_0 corresponds to the total base-collector capacitance of the planar HBT with fully depleted collector layer. Analysis shows that the collector capacitance of HBT with buried subcollector is extremely small under the high voltages ($V_{CB} > 2.25V$), and is practically equal to the capacitance of planar HBT under the low voltages ($V_{CB} < 1.75V$). To explain this fact, a detailed analysis of the distributed base-collector capacitance $c(x)$ has been made. The distributions of $c(x)$ for voltages corresponding to different regions of C-V curve are illustrated in Fig.4. Under the low V_{CB} the value of $c(x)$ is practically constant and is the same as in the case of HBT with planar structure, because the

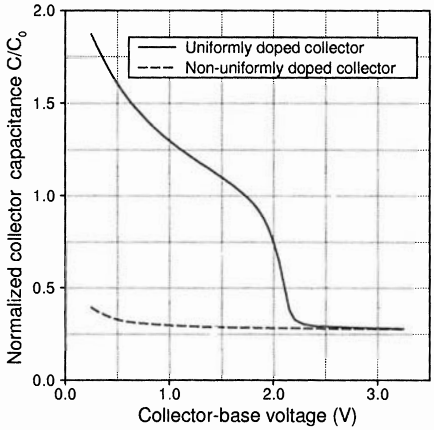

Figure 3: The normalized collector capacitance versus collector-base voltage for HBTs with buried subcollector and different collector doping profiles.

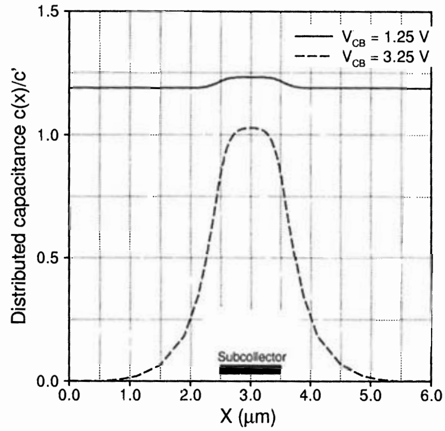

Figure 4: The distributed base-collector capacitance $c(x)$ as a function of position for HBT with uniformly doped collector structure.

lightly-doped collector layer is not fully depleted. As a result, the base-collector capacitance approximately equals the corresponding capacitance of planar HBT and varies in inverse proportion to the square root of the collector-base voltage. When the collector-base voltage increases, free carriers are driven out of the periphery part of the collector layer to center, and $c(x)$ corresponding to passive part of the base decreases. Under the high voltages (V_{CB}=3.25V), the collector layer is fully depleted and base-collector capacitance is determined as a geometrical capacitance between high conductive base layer and buried subcollector region. Thus, HBT with buried subcollector has an advantage over planar HBT only under high voltages. However, it is well known that the ultimate speed of InP/InGaAs HBT is obtained under very low collector-base voltages [5]. To overcome this contradiction we have proposed and investigated the HBT with non-uniform collector doping profile (see Fig.2b). Proposed design provides small value of the base-collector capacitance down to very low applied voltages (dashed curve in Fig.3) and has an important side benefit. The distribution of electric field corresponding to this structure is very favorable to exploit overshoot effect in collector space-charge region and hence it is possible to expect the reduction of intrinsic transit time.

The typical average electron velocity profiles for HBTs with two different collector structures are shown in Fig.5 (here the left boundary of the plot corresponds to the emitter-base interface). It is seen, that the peak values of electron velocity are practically the same for both collector structures and approximately equal to 8×10^7 cm/s. In both case the end of velocity overshoot region is associated with rapid population of the satellite valleys. The position of the peak velocity depends on the position of the high electric field domain in the collector space-charge region. For conventional uniformly doped collector structure the electric field is maximum near the base-collector interface. As a result, the electron traveling across the collector space-charge region rapidly populate the satellite valleys and lose their directional velocity. In contrast, for proposed collector structure the electric field between the base region and collector p^+ layer is low and electrons remain high velocity over a wide area, that leads to substantial reduction of the collector transit time in HBT

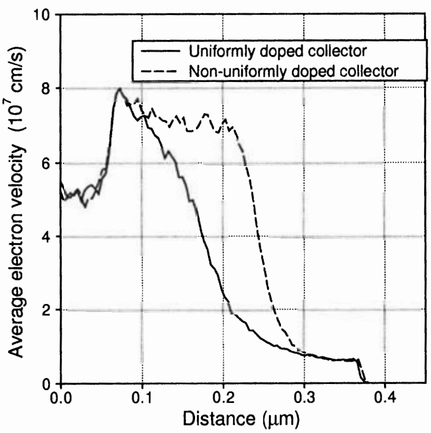

Figure 5: Average electron drift velocity corresponding to HBTs with conventional (solid curve) and proposed (dashed curve) collector structures.

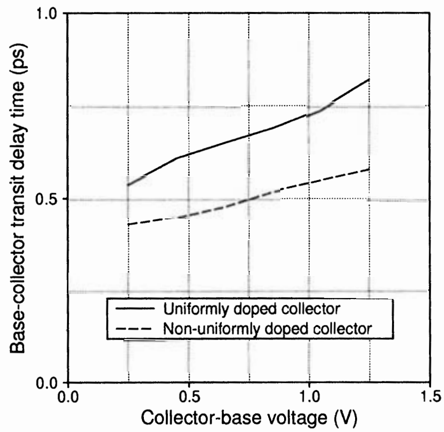

Figure 6: The base-collector transit delay time versus collector-base voltage for HBTs with buried subcollector and different collector doping profiles.

with non-uniformly doped collector structure.

The base-collector transit delay times as functions of applied voltage are presented in Fig.6. It is seen, that the base-collector transit delay time of non-uniformly doped HBT is approximately 30% less than that of uniformly doped HBT, resulting from the extension of overshoot region in the collector depletion layer. This makes essential contribution to reduction of the total delay time for HBT with sub-picosecond delay. In closing we would like to point out one additional feature of non-uniformly doped collector structure. Varying sheet density of acceptors in collector p^+ layer and position of this layer it is possible to adjust HBT structure to obtain the ultimate speed at the desired range of applied voltages.

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