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Extraction of Temperature Dependent Conduction Band Offset in InGaP/GaAs HBT Using 1-D Simulation

Chih-Hao Liao, Chien-Wei Gwan, Chien-Ping Lee[1]

[1]National Chiao Tung Univ., Dept. of Electronics Engineering,
1001 Ta-Hsueh Road, Hsinchu, Taiwan, R.O.C
Phone: +886-3-571-2121-54240 E-mail: liawch.ee88g@nctu.edu.tw

1. Introduction

Compared with other technologies or material systems, InGaP/GaAs heterojunction bipolar transistors (InGaP HBTs) attract more attention as they start to dominate the huge field of power amplifier, especially in cellular phone application. One of the most important parameters in the operation of modern HBTs is the conduction band offset (ΔEc). It is the key factor that affects the device electrical behavior and performance. Many authors have investigated how much this value should be [1-2]. Because of the spontaneous ordering nature of the GaInP layer, band gap and band offset are greatly dependent on growth condition and are not easy to measure. In this study, we use 1-D simulator to extract the band offset by fitting the experimental data under variant temperatures.

2. Method

Devices

Our devices are single heterojunction InGaP HBT (SHBT) grown by metal–organic chemical vapor deposition (MOCVD). The epitaxial structure consists of a Si-doped (3 x 10^{17}cm^{-3}) 400 Å $In_{0.49}Ga_{0.54}P$ emitter, a carbon-doped (4 x 10^{19}cm^{-3}) 1200 Å GaAs base, and a Si-doped (1 x 10^{16}cm^{-3}) 1-μm GaAs collector. The emitter cap and sub-collector are both heavily doped. Finally, devices cover with SiN for passivation. The measurement results shown in this work are 2μm x 4μm emitter size devices.

Parameters

The low field mobility formulas are taken from Sotoodeh's work [3]. The recombination parameters are selected as follow: Copt = 1 x 10^{-11} cm^{3}s^{-1}, Cn = 7 x 10^{-30} cm^{6}s^{-1}, Cp = 1 x 10^{-30} cm^{6}s^{-1}, τn = 2.9 x 10^{-6} s, and τp = 5 x 10^{-8} s for GaAs; Copt = 1 x 10^{-10} cm^{3}s^{-1}, Cn = 3 x 10^{-30} cm^{6}s^{-1}, Cp = 3 x 10^{-30} cm^{6}s^{-1}, τn = 2 x 10^{-9} s, and τp = 2 x 10^{-9} s for InGaP, where Copt is radiative recombination coefficient, Cn is electron Auger recombination coefficient, Cp is hole Auger recombination coefficient, τn is electron SRH lifetime, and τp is hole SRH lifetime. The GaAs effective mass and band gap data are taken from Blakemore's paper [4]. For InGaP, the electron effective mass is taken to be 0.088 [5], the temperature dependent band gap relation are obtained by fitting Ishitani's PL data [6] as,

$$E_{g,InGaP} = 1.985 - 7.19\times10^{-4}\,\frac{T^2}{T+482} \qquad (1)$$

Other data are from Brennan's work [7].

We take band gap narrowing (BGN) into account for GaAs by using Luo's data [8] for n-type GaAs BGN and Harmon's [9] for p-type GaAs BGN. Those are,

$$\Delta E_{gp} = 2.55\times10^{-8}\,p^{\frac{1}{3}} \qquad (2)$$

$$\Delta E_{gn} = 3.60\times10^{-8}\,n^{\frac{1}{3}} \qquad (3).$$

Simulations

Because different regions have different doping and different ΔEg, every junction grid point must be treated as a heterojunction, and we choose ΔEc = 0.5ΔEg. As all junctions having band offset, we use thermionic emission boundary conditions based on the theory by Wu and Yang [10] to calculate the quasi-Fermi level splitting at junction. Additionally, we follow Blakemore's formulation [4] to simulate the non-parabolic effect and re-formulate thermionic emission with non-parabolic effect in heavily doped degenerate regions, like base, to see the influence on band offset.

The simulation code uses the finite difference relaxation method [11] to solve the Poisson equation, the electron current continuity equation, and the hole current continuity equation together with different converge requirement.

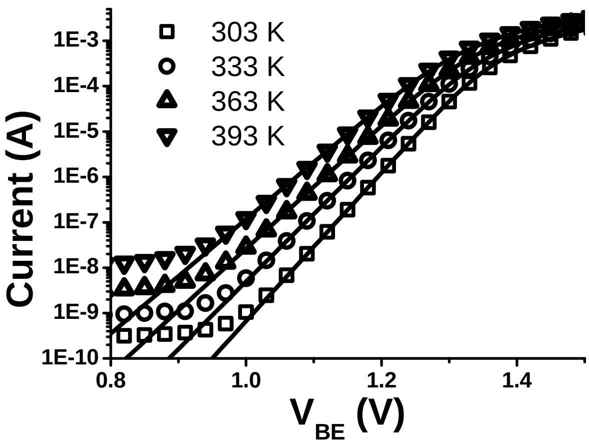

Fig. 1 Collector current of Gummel plot measured under different chuck temperature. Symbols are measurement data and lines are simulation results.

3. Results

It is easy to find that the collector current (Ic) is significantly affected by ΔEc. Change mobility will change Ic also, but it is not as effective as ΔEc. This is because an increased ΔEc will decrease the electron quasi-Fermi level inside the base and the base electron concentration will decrease. As a result, Ic will be suppressed. Fig. 1 illustrates the fitting results at different measurement temperatures. The fitting is very good except at low bias voltage where leakage current dominates. Fig. 2 shows the Gummel plot under two different temperatures. The base currents (Ib) also fit well. Although Ib is insensitive to ΔEc, it is very sensitive to recombination coefficients. The valence band offset (ΔEv) only affects 2kT base current component (space-charge recombination current) and has no effect on Ic. Therefore, change ΔEv only change the low bias current gain.

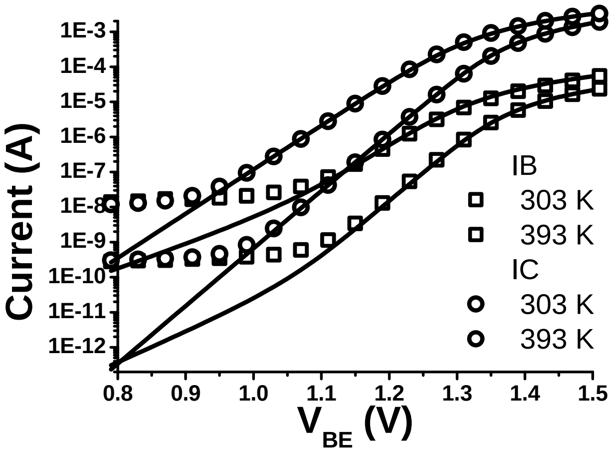

Fig. 2 Gummel plot measured under different chuck temperature. Symbols are measurement data and lines are simulation results.

In our work, we use three different models to extract ΔEc. They are: the pure drift-diffusion model, the thermionic emission model, and the thermionic emission model including the band non-parabolicity. The extracted values are listed in Table I. One might find that ΔEc increases as temperature increases for all models. The reason for the increase is not clear at this moment. The thermionic emission model causes the quasi-Fermi level to split at each junction. This splitting changes the electron distribution across the junction and causes ΔEc to be smaller. With band non-parabolicity included, which is important for highly degenerate materials, the ΔEc is further reduced. While the reported ΔEc of InGaP/GaAs heterojunction varys in a wide range, Kobayashi et. al. reported an ΔEc of 30 meV based on an temperature dependent modeling of HBT [1]. Our model, which includes all important effects, is a much improved model than that of ref. [1]. The value of ΔEc from 0.054 eV to 0.097 eV, is reasonable and can be used in device simulators to predict device behaviors at different temperatures.

Table I ΔEc Extract from Different Model

Temperature (K)	ΔEc (eV)		
303	0.085	0.063	0.054
333	0.096	0.074	0.064
363	0.107	0.084	0.074
393	0.117	0.090	0.079
	A	B	C

A : pure drift-diffusion model

B : thermionic emission model

C : thermionic emission model include non-parabolicity

3. Conclusions

Three different temperature dependent models have been used to fit the ΔEc of InGaP HBT. We found that ΔEc will increase as temperature increase and the most completed model has the lowest ΔEc. It could be believed that the smaller value of ΔEc is more correct.

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