Theoretical Study of Hetrostructure Bipolar Junction Transistor

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ABSTRACT

A numerical analysis method is used to analyse heterostructure junction bipolar transistor (HJBT) . The macroscopic semiconductor equations for materials with position-dependent dielectric constant, band gap, and densities of states are first cast into a form identical to that commonly used to model heavily doped semiconductors. Fermi-Dirac statistics are also included within this simple ,Boltzmann like formulation. Because of the similarity in formulation to that employed for heavily doped semiconductors, well developed numerical techniques can be directly applied to hetero-structure simulation .A simple one-dimensional, finite difference solution is presented. The accuracy of the numerical method is assessed by comparing numerical results with special-case, analytical solutions.

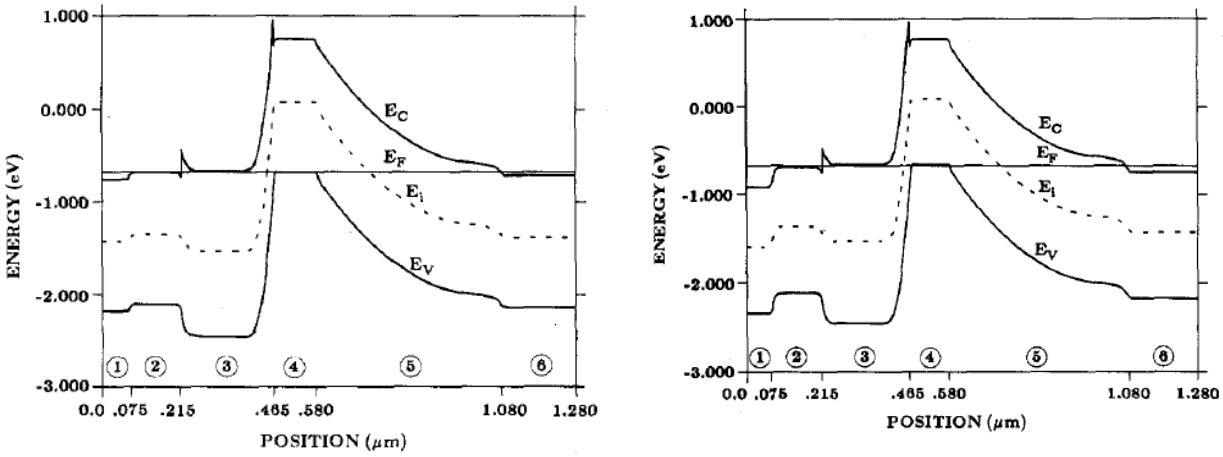
Key words :Numerical method ,hetrostructure ,simulation

INTRODUCTION

Hetero structure semiconductor devices show promise for use in high-performance integrated circuits; with the advent of new fabrication technologies, this well-known potential is being realized [l],[2]. The design flexibility possible with hetero structures has been used to improve the performance of bipolar transistors [2] and to realize new devices such as the modulation-doped field-effect, transistor (MODFET) which has already achieved a switching speed of less than 20 ps [3], [4]**.** To aid in understanding the physical operation of these devices and to optimize their design, numerical hetero structure device models are required.

APPLICATIONS

In this paper we discuss some examples of numerical analysis of heterostructures. Two devices, the heterostructure bipolar transistor and the two-dimensional electron gas (2DEG) MESFET, are considered. In the examples that follow, we adjusted the value of χ for Al_xGa_{1-X} . As to provide discontinuities in agreement with the Dingle rule [8]. There combination mechanism assumed is Shockley-Read-Hall recombination [7] with the trap energy level located at the intrinsic level. Auger recombination, radiative recombination, and explicit generation mechanisms are not considered.



(a) **(b)**

Fig. 1. Equilibrium energy band diagrams for a hetero structure bipolar transistor Fig. 1(a) assumes Boltzmann statistics and Fig1(b), Fermi-Dirac statistics.

The computed equilibrium energy band diagram for an n^+ GaAs/nGaAs/nGaAlAs/p^+ GaAs/nGaAs/n^+ GaAs HBT is shown in Fig.1. Table I provides the details of this HBT which is similar to one described by Asbeck *et al.* [9]. Two cases, Boltzmann statistics (Fig1(a)) and Fermi-Dirac statistics (Fig. 1(b)) are considered. The increased penetration of the Fermi level into the conduction band of the heavily doped n^+ regions is readily apparent. Another important difference between the two cases is the slight lowering of the barrier height for the nGaAs/nGaAlAs junction caused by carrier degeneracy (an effect discussed by Kroemer [6]).

TABLE 1

HJBT Device Structure

Layer	ND-NA (cm-3)	Al fraction	Thickness (μm)
1	1×10^{19}	0	0.075
2	5×10^{17}	0	0.125
3	5×10^{17}	0.30	0.25
4	-1×10^{19}	0	0.10
5	1×10^{16}	0	0.5
6	2×10^{18}	0	0.2

We now consider the injection characteristics of the HJBT's emitter-base junction. The material parameters used for these calculations are displayed in Table 2**.** The bandgaps, effective masses, dielectric constants, and electron affinities for GaAs and AlAs are those given by Casey and Panish [10]. The corresponding parameters for $Al_{0.3}Ga_{0.7}As$ were obtained by the methods described by Sutherland and Hauser [5]. The minority-carrier lifetimes are typical of those obtained in GaAs solar cells[11]. Mobilities for GaAsare from [7] and for electrons in AlGaAs from

TABLE 2

MATERIAL PARAMETERS FOR THE EMITTER-BASE JUNCTION

Material Parameter	Emitter	Base
All fraction	0.30	0.0.
N_D-N_A	5×10^{17} cm^{-3}	1×10^{19} cm^{-3}
τ_n, τ_p	10^{-9} sec	10^{-9} sec
μ_n	2000 cm^2/V-sec	1200 cm^2/V-sec
μ_p	200 cm^2 / V-sec	100 cm^2 / V-sec
E_G	1.798	1.424
m_p^*	0.52 m_0	0.48 m_0
m_n^*	0.080 m_0	0.067 m_0
χ	3.75	4.07
k_S	12.0	13.1

String fellow [12]. The hole mobility of AlGaAs was set to its value in correspondingly doped GaAs [7]. For the base contact, we assumed a surface recombination velocity of 5×10^6 cm/s to simulate the drift of carriers through the collector base space-charge region at the saturated velocity. The computed forward biased current (assuming Boltzmann statistics) showed an ideality factor of 1.05 for biases above 0.8 V where recombination within the space-charge region was not dominant.

The computed energy band diagram of the 1.0-V for-ward-biased emitter-base junction shown i.n Fig. 2 reveals a large change inthe electron quasi-Fermi level across the space-charge region. This effect, caused b y the spike in the conduction band, suppresses current injection and reduces the gain of an HBT [2]. The operation of this heterojunction was further investigated by numerical experiments. When the base contact was made ohmic, lthe diode current at 1 V (1.57×10^{-4} A/cm^2) increased by less than one percent. Similarly, when the base length was increased by a factor of 100, (from ~ 0.05 to ~ 5 minority-carrier diffusion lengths) the diode current was reduced by less than 15 percent. Since the base width is only 0.1 μm, the validity of a drift-diffusion description within the base is doubtful [13], but the numerical experiments demonstrate that Ihe diode current is not dominated by minority-carrier transport through the narrow quasi-neutral base region.

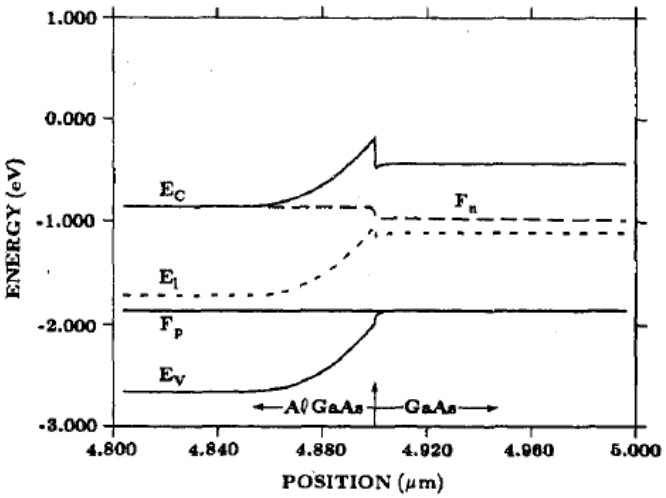


Fig. .2 : AlGaAs : GaAs abrupt n-p heterojunction under 1.0-V forward bias (only the region near the junction is shown).

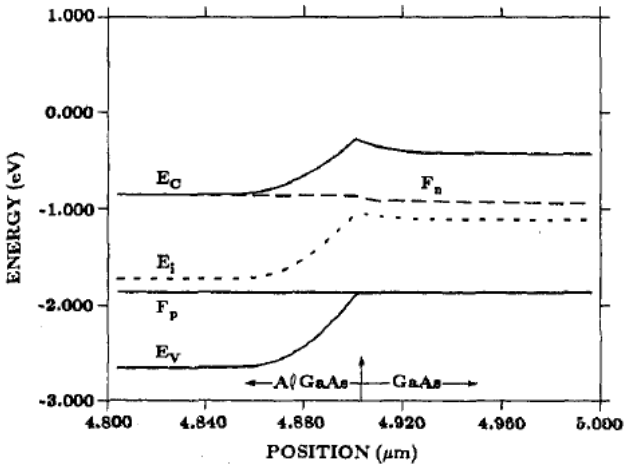


Fig 3 : AlGaAs graded n-p heterojunction under 1.0-V forward bias.

Table 3

MATERIAL PARAMETERS FOR THE 2D ELECTRON GaAs DEVICES

Material Parameter	Layer	
	GaAs	GaAlAs
Al Fraction	-	0.17
N_D	1×10^{16} cm^{-3}	2.6×10^{17} cm^{-3}
E_G	1.424	1.64
m_p^*	0.48 m_o	0.49 m_o
m_n^*	0.067 m_o	0.074 m_o
χ	4.07	3.89
k_S	13.1	12.5

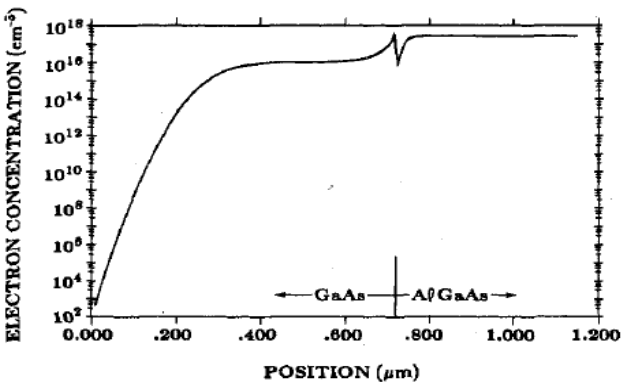


Fig4. Equilibrium electron concentration in the 2DEG structure.

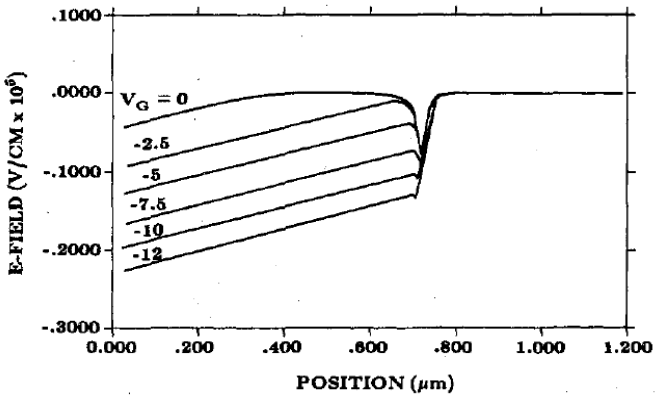


Fig.5 Electric field versus position in the 2DEG structure. The identifying numbers on the curves refer to the bias applied between the gate and substrate.

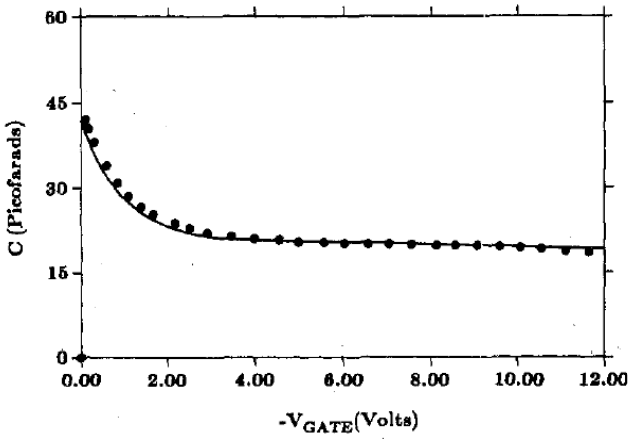


Fig. 6. Capacitance versus reverse gate voltage for the 2DEG structure. The data points are from [3].

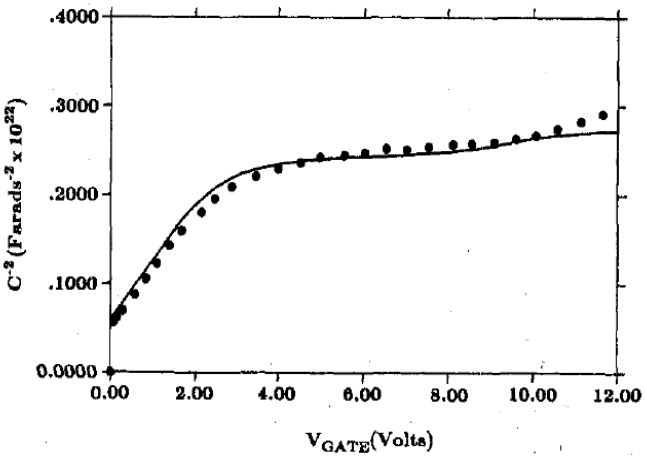


Fig 7. Inverse capacitance squared versus gate voltage. The data points are from [3].

The computed equilibrium electron density for this device is plotted in Fig. 4. As expected, the results show the depletion of electrons near the surface and on the AlGaAs side of the heterojunction and a strong accumulation layer of electrons on the GaAs side of the junction. To modulate the electron density in the accumulation layer (and, therefore, the conductance of the FET) a reverse bias is applied to the gate. The increasing penetration of the gate-controlled electric field for increasing reverse bias is illustrated in Fig.5. As shown, the surface depletion layer expands rapidly withreverse bias until the accumulation layeris encountered (at V_G ~ -2.5 V). Further bias simply decreases the electron concentration in the accumulation layer without further penetration of the gate-controlled electric field. Finally, the accumulation layer is removed (at V_G ~ - 10 V) and additional reverse bias depletes the AlGaAs substrate. As Fig. 6 shows, the computed quasistatic capacitance agrees well with the reported characteristics[3]. The inverse capacitance squared plot in Fig. 7 shows the expected linear region while the top (GaAs) layer is being depleted and also when the AlGaAs substrate depletes. The computed results shows excellent agreement with the measured characteristics except at high bias where break-down may be occurring. For structures showing more pronounced quantum confinement of electrons at the heterojunction, the two-dimensional nature of the electron gas should be considered [8].

CONCLUSIONS

In this paper, a convenient formulation of the basic semiconductor equations for heterostructure device analysis was presented, discussed, and illustrated. The device equations for parabolic band semiconductors were reviewed and the similarity to the heavily doped semiconductor stressed. Two simplifying assumptions not valid in general, however, are usually made when modeling heavily doped devices. Specifically, the total band change V_G, is arbitrarily split into its components V_p and V_n and the spatial variation of the dielectric constant is ignored. Conventional device analysis codes, both one-and two-dimensional, are readily converted to heterostructure device simulation when these two simplifying assumptions are removed.

A significant advantage of the formulation presented here is that it is a unified method for modeling both heavily doped silicon and heterostructure devices. In the past, different formulations have been used for these two problems [5]-[7]. Also important is the technique for including Fermi-Dirac statistics. The method presented retains the simple, widely used Boltzmanm-like formulation by incorporating additional drift-like terms in the carrier transport equations. This technique for incorporating Fermi-Dirac statistics is applicable for both homostructure and heterostructure devices.

Finally, some cautions regarding the classical formulation are in order. Our formulation of the semiconductor equations assumes a slow variation in material composition [14], [15]. While such an assumption may be valid for intentionally graded junctions, it is obviously violated for abrupt heterojunctions. At an abrupt junction, quantum mechanical reflection and tunneling may be important [1] and should be included. Since heterostructure devices are likely to be small, high-field and transient carrier transport will also occur [13] .

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