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Comparative Study of GaN and GaAs Based Heterojunction Bipolar Transistors

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ABSTRACT

In this study, the base-width modulation of GaN and GaAs based heterojunction bipolar transistor is analyzed using an enhanced drift-diffusion model. This work has been done to understand the concept of base width modulation clearly for designing GaN and GaAs based power transistors. The considered structure of this study is: n-type AlGaN/AlGaAs layer as an emitter, p-type GaN/GaAs as a base and n-type GaN/GaAs as a collector. In order to illustrate the difference between GaAs and GaN we have changed the material of the structure without changing the doping concentrations. The emitter and collector widths are remain fixed, while the base width is varied in order to find the optimized base for providing high collector current density. For these structures the emitter-base junction turn on voltage must be greater than 2.7 V. The effect of C-B voltage on the base width is significant. The neutral base-width X_b is a function of C-B voltage which is varied by varying the C-B voltage changes from 2 to 70 volt. The change in neutral base width leads to a significant change in the collector current density. Finally an optimized GaN and GaAs based structure is proposed and also which structure gives better performance between these two has been investigated later.

Keywords: Heterojunction, BJT, GaN, GaAs

1. Introduction

In the last two decades, the III-V nitride materials have been viewed as highly promising for many semiconductor device applications. The increasing development of commercial system creates a need for high performance devices. Therefore many engineers and researchers are working on this nitride materials for further development.

III-nitride (III-N) material system and related transistors offer greatly increased power switching performance and dramatic theoretical advantages over other semiconductor material systems. Recent developments of III-N HBTs, in particular GaN/AlGaN, GaAs HBTs have shown that III-N bipolar transistors could be suitable for next generation high power switching and amplification [1]. In comparison with Si bipolar transistor, HBTs show better performance in terms of emitter injection efficiency, base resistance, base-emitter capacitance and cut-off frequency [2].

In case of high power and high frequency applications, the performance of nitride alloys is preferable in comparison to other alloys. The main reason behind this is wide band gap of the material that permit devices to operate at much higher voltages, frequencies and temperatures than conventional semiconductor material like Silicon. GaN materials possess higher band gap of 3.4 eV [3] whereas silicon materials possess 1.12 eV [4]. GaN can operate at much higher temperature on the order of 300^{o}C [5]. This makes them highly attractive in military applications [6]. Because of wide band gap they can operate at higher frequencies (>20 kHz) [7] which is not possible for other alloys like silicon. Power density of GaN materials is much higher than GaAs or even Si [8]. All these properties make GaN based materials attractive to fabricate much smaller heterojunction devices.

In addition the unique properties of GaAs based materials make it comparable with GaN materials. They have high electron mobility (8500 cm^{2}V^{-1}s^{-1}) [9] than GaN based materials (<1000 cm^{2}V^{-1}s^{-1}) [10]. Higher saturation electron velocities, high electron drift velocities and the existence of thermally stable semi-insulating substance make GaAs material such a compelling one. GaAs materials are less sensitive to heat because of their wide band gap (1.42-1.43 eV) [11] and less noise than Si at high operating frequency. Moreover GaAs makes the band gap in base layer narrower and reduces the threshold voltage. The best cost/performance ratios are achieved by GaAs based transistors which are establishing a firm position in the market. It is one of the most popular semiconductor materials with favorable electronic properties.

Here in this study, GaN and GaAs based heterojunction bipolar transistors have been taken for the numerical analysis of base width modulation of transistor. Though FET, MOSFET, HEMT show better performances than HBT, but to simplify the study a simple HBT model has been designed as it can be driven by a single positive power source. Here the base width of HBT is varied in order to find the optimized base for providing high collector current density. Hence we have examined their current profile by taking voltage vs current density values and plotted it in a MATLAB to examine properly. Then we compare the values that have been produced by varying width of the base. GaAs based transistors give better performance than GaN based transistors if we modulate the width of the base. But in this study we focused on GaN based transistors as high electron velocities and high thermal conductivity make GaN-based semiconductors very promising for high-power, high-frequency applications rather than GaAs based HBTs. The comparison between the two HBTs based on their current profiles and other parameters are illustrated briefly in the following sections of this paper.

2. Theory And Simulation

In the common emitter configuration of transistor biasing to operate in the active region, the emitter-base junction is forward biased and the collector-base junction is in reverse biased condition. The increase in reverse bias voltage increases the space charge width of the C-B junction. We should note that, the space charge width is proportional to the square root of reverse bias voltage in case of abrupt junction but in linear junction it's proportional to cube root of reverse bias voltage. There is no effect of the forward bias voltage in the thickness of the space charge width of C-B junction. As the base is lightly doped compared to the collector the depletion region, C-B junction penetrates deeper into the base region. This reduces the effective width of the base. This variation is known as the Base-Width Modulation or Early-Effect. Due to Base Width Modulation or Early Effectthe recombination factor in the base region is reduced, which increases the current density of the collector. An extremely large collector base voltage may reduce the effective base width to zero, causing the voltage breakdown. This effect is known as Punch through Effect.

In Fig 1, it is illustrated that by varying the collector-base voltage, the base width is changed. Also the increase in space charge width with increasing CB voltage can also be understood clearly from the Fig 1. There will be a reduction in neutral base width with higher C-B voltage. The basic structures of AlGaN/GaN and AlGaAs/GaAs based HBT that we have studied here are also shown in Fig 1. The structures are mainly three layered simple bipolar junction transistors. The layers are- Emitter cap, Base and Collector. Layer specifications are presented in Table 1.

The width (X_{dB}) of the space charge layer is a function of B-C voltage, B-E voltage and the doping concentration of base and collector region [11-13].

$$X_{dB} = \sqrt[2]{\{2\epsilon\,(V_{bi} + V_{CB})/e[(N_c/N_B) \times 1/(N_c + N_B)]\}} \text{..(1)}$$

Where, the built-in voltage $V_{bi} = KT/e\ln[N_B N_C/n_i{}^2]$…….. (2)

Here we have taken the following values for

Boltzman's Constant, K= 1.38×10^{-23}J/K

Intrinsic Carrier Concentration,

n_i= $1.9 \times 10^{-10}\text{cm}^{-3}$ (for AlGaN/GaN)

=$1 \times 10^{9}\text{cm}^{-3}$ (for AlGaAs/GaAs)

Electron's charge, e = 1.6×10^{-19}coulomb

Room Temperature, T =300K

N_B= Carrier concentration of base region

N_C= Carrier concentration of collector region

V_{CB} = Collector Base Voltage

From the above equation the calculated value ofV_{bi} for AlGaN/GaN is found 3.12 V and for AlGaAs/GaAs it is found 1.7 V.

$$J_C = \{(eD_B n_{Bo})/X_b e^{(eV_{BE}/KT)}\} \text{……….........……..... (3)}$$

Current density=J_C

Minority carrier concentration of base region = n_{Bo}

Electron mobility, $D_B = KT\mu/e$;μ=800 cm^2/V/s ……….(4)

In order to find the optimum structure of GaN-based transistor, we have used MATLAB to plot different graphs. In the following sections the results are shown.

3. Results And Discussion

In this study we have varied the CB voltage and its effect on the base width has been analyzed. For that purpose, the value of V_{CB} is changed from 2 to 70 volts. We have taken different metallurgical width to compare their respective results. In order to illustrate the difference between GaAs and GaN we've changed the material of the structure without changing the doping concentrations. We have taken GaAs based bipolar junction transistor having same doping concentrations which were mentioned in the Table 1.

Table 1: Layer Specification

Layer Name	Material	Layer Size (A^0)	Layer Types	Concentration (cm^{-3}) [12]
Emitter cap	$Al_{0.2}Ga_{0.8}N$/ Al0.2Ga0.8As	1000	N type	1×10^{19}
Base	GaN/GaAs	900	P type	2×10^{18}
Collector	GaN/GaAs	5000	N type	5 10^{16}

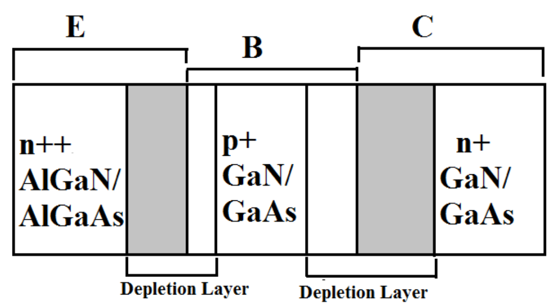

Fig. 1: Basic structure of GaN and GaAs characteristic devices

The effect of base width on collector base voltage in the case of GaN has been shown in Fig 2. As collector-base voltage is changed from 2 to 70 volts, X_b (which is the effective base width) decreases. At higher collector-base voltage, the width of space charge region is large enough that it enters fully into the base. For the metallurgical width 10 nm, we get the value of X_{dB} 30 nm. As a result the effective base width X_b is -20 nm. The negative value (-20 nm) can easily be described from the concept of early effect. Then we have changed the value of metallurgical width. The values of metallurgical width that we have taken herein are 10, 20, 30, 40, 50 and 60 nm respectively. From the graph it is clearly viewed that if we take metallurgical width above 30 nm then we'll not obtain any negative values. Thus it's required to take metallurgical width above 30 nm to see the optimum result or to see the optimum modulation.

In case of metallurgical width of 30 nm, for the variation of V_{CB} from 2 to 70 volts, the value of X_b changes from 22.3068 nm to 0.926521 nm.

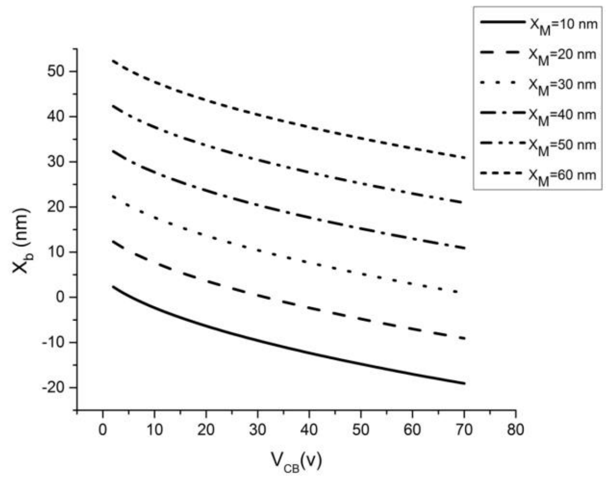

Fig. 2: Effect of CB voltage on the base width of GaN

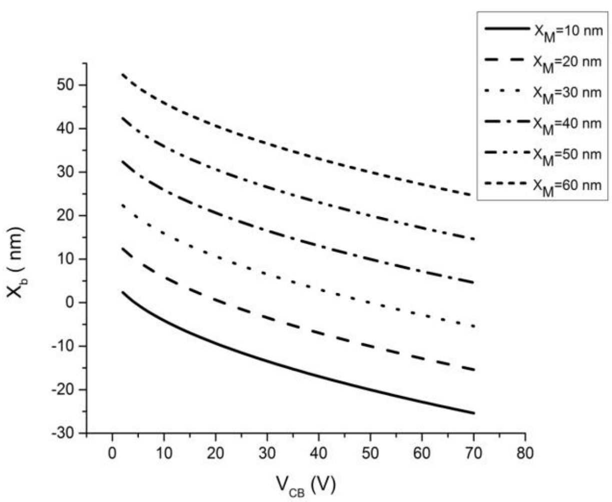

Fig. 3: Effect of CB voltage on base width of GaAs

We have also examined the effect of CB voltage on base width for GaAs based transistor which is shown in Fig 3. The above procedure has been followed in this case as well and we do not obtain any significant change. In this case it is required to take metallurgical width above 40 nm to see the modulation. In case of 40 nm metallurgical width, for the variation of V_{CB} from 2 to 70 volts, X_b changes from 32.3494 nm to 4.6115 nm.

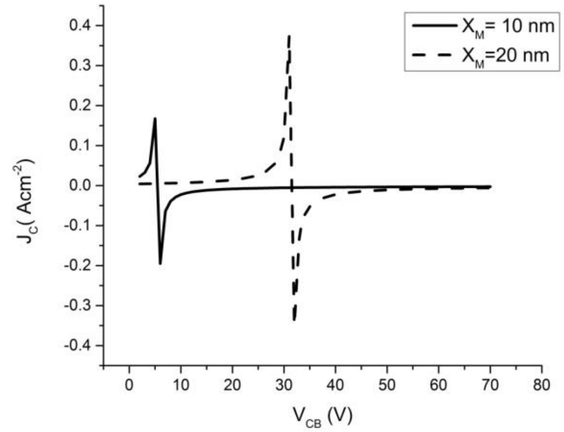

Fig. 4: Effect of CB voltage on current density for GaN based material

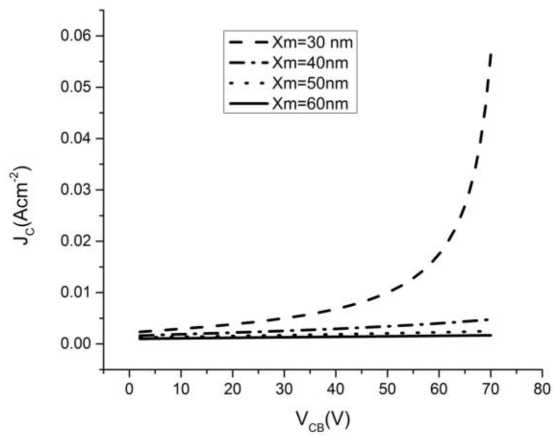

Fig. 5: Effect of CB voltage on current density for GaN based material

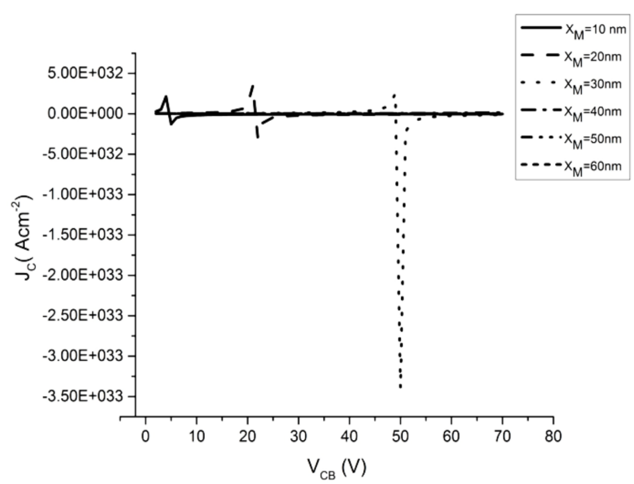

Fig. 6: Effect of CB voltage on Current density for GaAs based materials

In Fig 4 and 5 it is shown how current density changes with the change in collector-base voltage. In Fig 4 we can see that for 10 nm and 20 nm base width we get different results compared to the others shown in Fig 5. For the case shown in Fig 4 the base region is fully covered by space charge region. In npn sandwich structure if the base region is reduced significantly and literally there is no more base p region, then there would be no separating region between the emitter and collector, which may results short circuit effect. The occurrence of spike in Fig 4 is likely the short circuit effect. In this case an excessive amount of current will flow through the circuit at that time. If we take larger metallurgical width and it is not fully covered by space charge region, then there will be no spike as can be seen in Fig 5. We see that as collector-base voltage increases, the current density also increases. In case of 40 nm metallurgical width, for the variation of V_{CB} from 2 to 70 volts, J_C changes from 0.001615 to 0.004777 A/cm^2

By varying the width we have studied current profile of the GaAs based transistors. The effect of collector voltage on current density of GaAs based material is illustrated in Fig 6. From the graph we can see that, the occurrence of spikes is present up to 30 nm base width. In case of 40 nm metallurgical width, for the variation of V_{CB} from 2 to 70 volts, J_C changes from 2.148418E+30 to 1.5071059E+31 A/cm^2.

4. Conclusions

We have investigated the possibility of being able to create gallium nitride and gallium arsenide bipolar junction transistors (GaN and GaAs BJTs) which are suitable for high power performances. From the study, it is seen that the performance of HBTs improved as the width of the base has been modulated, though the reduction in mettalurgical width (X_b) is very small (in the nm range). It is clear that base width modulation has a great impact on device performance. Reduction in neutral base width produces an increase in current density which is shown in detail in this study. So we could have an optimum structure by using this modulation which would give satisfactory performance. Transistors fabricated on these semiconductor materials offer a wide range of performance capabilities, from low noise figures to high output powers, from the high-frequency (HF) range through millimeter-wave frequencies [14]. The results that we have gained indicate that demonstrated vertical GaN and GaAs devices are very promising for future high power application.

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