DESIGN OF QUANTUM-WELL HETEROJUNCTION BIPOLAR TRANSISTOR BASED ON PHYSICAL PARAMETERS

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Abstract - The paper mainly focuses on the design of quantum-well Heterojunction Bipolar Transistor based on physical parameters of III-V materials and compound. The analyses have been done with quantum-well band diagram design, the unity beta frequency, rise time, storage delay time, fall time, minority carrier distribution and biasing modes for developed HEBT design by using physical parameters of the III-V compound based quantum well design. The mathematical modeling for proposed HEBT design was completed with the physical parameters. The design was performed the related consideration on quantum-well structure and the analyses was finalized with the help of numerical analysis by using MATLAB. The results confirm that the proposed quantum-well HEBT was observed the high performance condition in semiconductor device fabrications.

Keywords - Quantum-well structure, Heterojunction Bipolar Transistor, Semiconductor Device Fabrication, Numerical Analysis, MATLAB

I. INTRODUCTION

Heterojunction bipolar transistors (HBTs) have been widely studied for many decades [1-3]. It is known that the energy discontinuity ΔEv in the valence band of emitter-base heterojunctions can efficiently block the back injection of hole currents and leads to a high current gain. Therefore, the large band discontinuity ΔEv improves the thermal stability, and this enables, for example, the high-temperature operation of InGaP/GaAs HBTs with current gains which are only reduced slightly at an elevated temperature [4]. With the embeddedness of a quantum well (QW) into the base region, the light-emitting transistor (LET), which is not only a QW-HBT but also a novel high-speed light source with three-port inputs for optical communication, was demonstrated in 2004 [5-6]. Due to the reduced valence band discontinuity ΔEV between the emitter and the base and raised thermal energy at an elevated temperature, the current gain of typical HBTs is usually a decreasing function of the operation temperature. The QW-HBT, on the other hand, exhibits a totally different trend to that of a typical HBT [7-15].

In view of these, we develop a modified charge-control model to describe the temperature-dependent electrical characteristics of QW-HBTs. The thermionic emission is adopted to model the escape rate of electrons out of the QW, which influences both the minority carrier distribution in the base and current gain. The temperature dependencies of diffusion, capture, and escape processes of electrons in the heavily p-doped base are incorporated into the modified charge-control model of QW-HBTs. Among these factors, the faster escape of electrons out of the QW at the higher temperature is shown to be the main cause to the unusual temperature-dependent current gain of QW-HBTs.

II. PROPOSED QUANTUM-WELL HEBT STRUCTURE

Most of Single Junction Semiconductor Devices were formulated as simple heterojuction structure for observing the confinement of electron in the junction. For two junctions Semiconductor Devices like Heterojunction Emitter Bipolar Transistors (HEBTs), the Quantum-Well layers are challenging issues to acquire the better performance results on switching and amplification. The III-V compound-based Quantum Well Transistor Design (n-$Al_{0.3}Ga_{0.7}As$/p-GaAs/i-$In_xGa_{1-x}As$/p-GaAs/n-$Al_{0.3}Ga_{0.7}As$) is an idea to solve the high performance applications in Semiconductor Electronics areas.

The Quantum-Well structure for HEBTs device modeling with mathematical analysis has to be designed. (MBE is the technique for fabrication by experimental studies). The Band Diagram for Quantum Well Transistor device has to be analyzed. The carrier dynamics and transport in the Quantum Well layer of HEBT has to be evaluated. The physical properties of HEBT device (Electrical, Vibration) has to be measured.

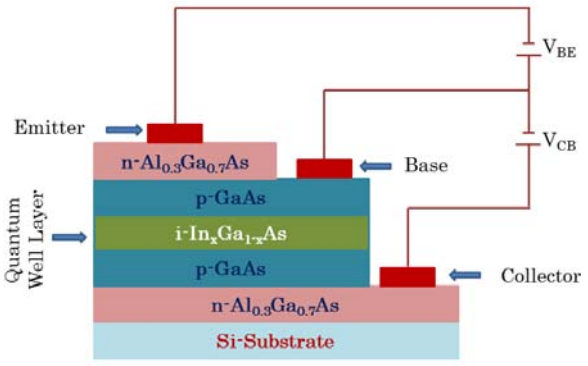


Fig.1. Proposed Quantum-Well HEBT Structure [16]

In order to solve the real problem to design the quantum-well HEBT structure, the proposed quantum-well HEBT structure is shown in Figure.1.

III. RESULTS AND DISCUSSIONS

The single quantum-well structure was analyzed in [16] and it has some limitation for designing the high performance HEBT design in real world applications. The multi quantum-well design may be suitable for high performance HEBT structure for high frequency applications. The quantum-well layers are very important to design the high frequency condition and it was developed by using MATLAB. Figure.2 demonstrates the Multi Quantum-Well Design for HEBT for real applications.

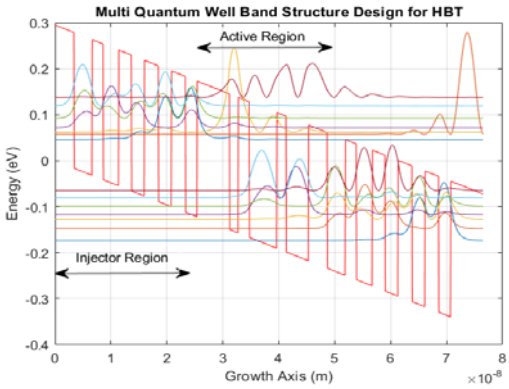


Fig.2. Multi Quantum-Well Design for HEBT [16]

The factor of W/LB is from 0.1 to 10 for VCB=0 condition is shown in Figure.3. If the factor is lower and lower, the minority distribution might be linear.

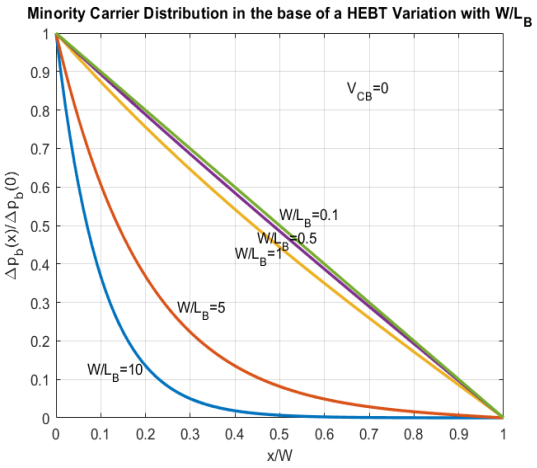


Fig.3. Minority Carrier Distribution in Base of a HEBT variation with W/L_B

The three regions for HEBT could be observed. The active region is started from the highest minority distribution to lowest level. The cut off region is always constant level below the zero distribution line. The saturation region is gradually decreased from the highest level to approximately two-third level of distribution.

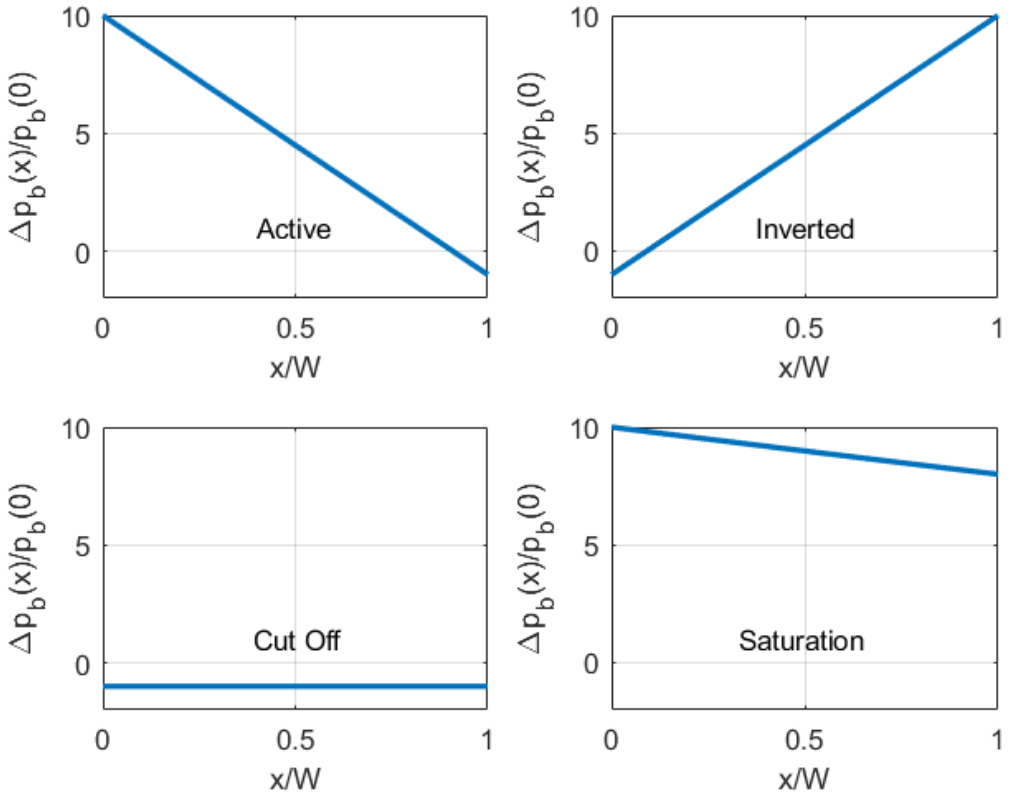


Fig.4. HEBT Biasing Mode Illustration

The four ratios of N_E/N_{E0}, N_B/N_{B0}, τ_E/τ_{E0} and τ_B/τ_{B0} is mentioned. The calculation results on β w.r.t N_E/N_{E0} is changing from 8×10^{-3} to 3×10^{-3}. The calculation results on β w.r.t N_B/N_{B0} is changing from 1×10^{-3} to 1×10^{-1}. The calculation results on β w.r.t τ_E/τ_{E0} is changing from 100 to 500. The calculation results on β w.r.t τ_B/τ_{B0} is changing from 1×10^{-1} to 1×10^{-3}.

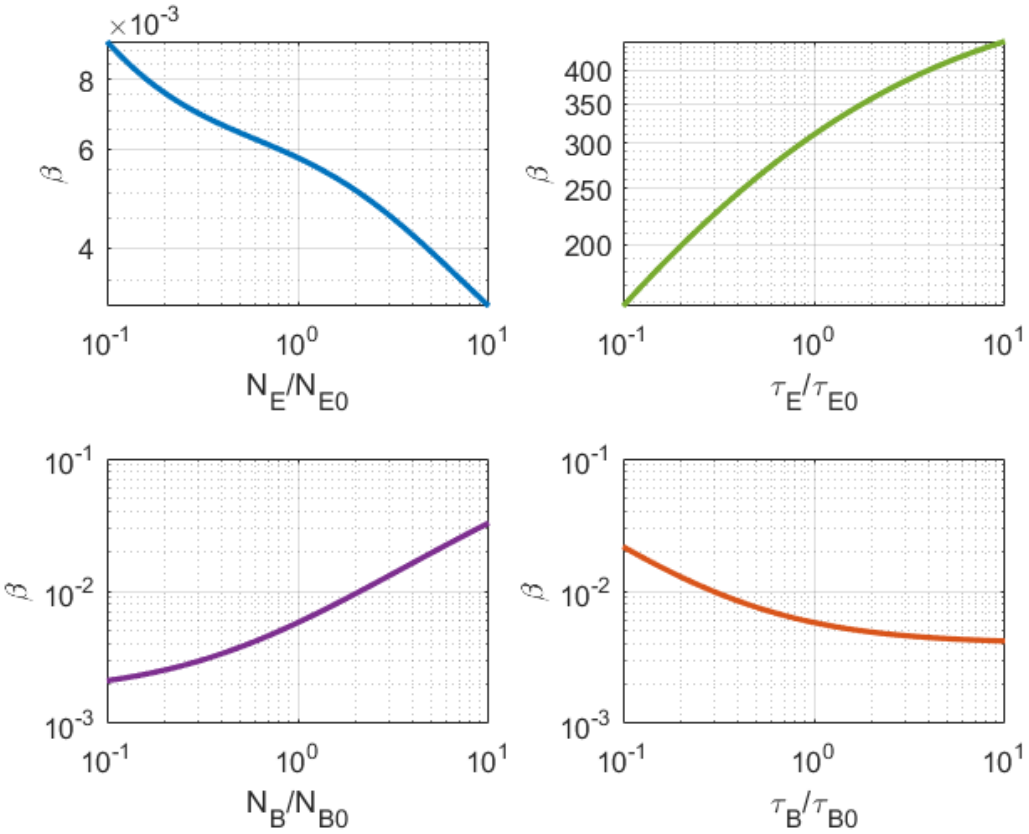


Fig.5. β Calculation

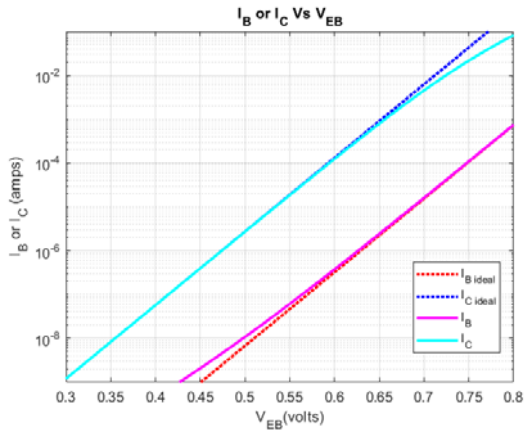


Fig.6. I_B or I_C Vs V_{EB}

The actual results of I_C and I_B are very close to ideal values of I_C and I_B based on the values change of V_{EB} from 0.3 to 0.8 volts for numerical analysis.

The changes of β values is started from 1×10^{-9} to 1×10^{-1} with between 50 and 300 in real condition.

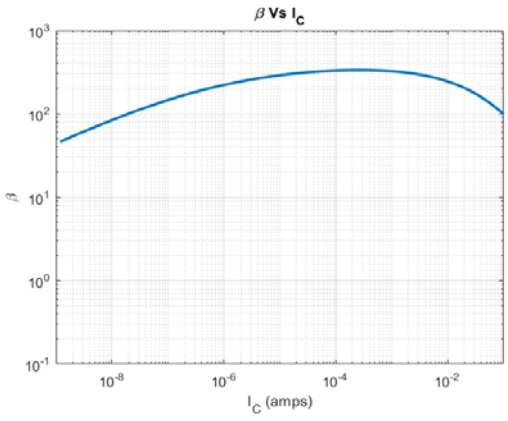


Fig.6. β Vs I_C

Figure.7 illustrates the Current Gain Vs Unity Beta Frequency. The changes of frequency effects on the current gain of the developed quantum-well HEBT design could be observed in this picture. The values of current gain gradually change from 200 to 0.03 from 1MHz to 1GHz frequency ranges. It depends on the materials properties for designing the HEBT structure.

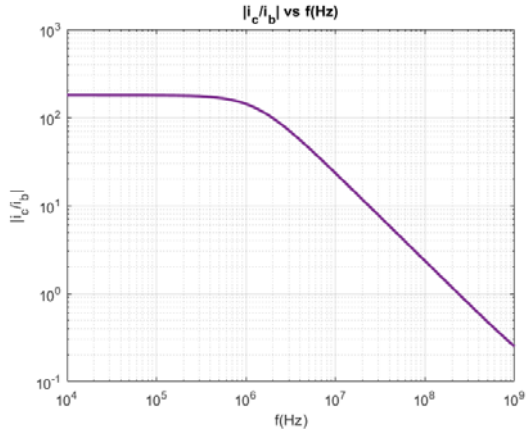


Fig.7. Current Gain Vs Unity Beta Frequency

And also the rise time analysis on $I_{CC}\ \tau_t/I_{BB}\ \tau_B$ is shown in Figure.8. According to this result, if the value of the ratio of t_r/τ_B could be started from 0 to maximum of 5 based on the value of that ratio of $I_{CC}\ \tau_t/I_{BB}\ \tau_B$ gradually increase from 0 to 1. That result could be accepted to design the HEBT structure based on one of the physical parameter for analysis.

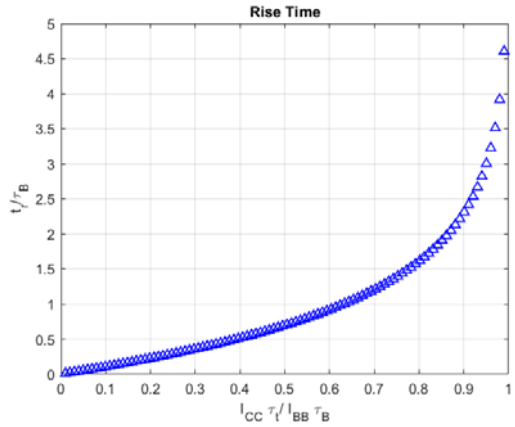


Fig.8. Rise Time

The storage delay time response for analyzing the performance of the HEBT structure is mentioned in Figure. 9. In this figure, there have been two values of 0 and 1 for x_i for storage delay time response analyses. According to this result, if the value of the ratio of t_{sd}/τ_B could be started from 0 to maximum of 5 based on the value of that ratio of $I_{CC}\ \tau_t/I_{BB}\ \tau_B$ gradually increase from 0 to 1. The response for x_i=0 shows the ratio of t_{sd}/τ_B could be observed the maximum value at the value of the ratio of $I_{CC}\ \tau_t/I_{BB}\ \tau_B$ was zero and it was decaying from the value of 5 to 0. Similarly, the response for x_i=1 shows the ratio of t_{sd}/τ_B could be observed the maximum value at the value of the ratio of $I_{CC}\ \tau_t/I_{BB}\ \tau_B$ was zero and it was decaying from the value of 0.6 to 0. Therefore, the value of x_i is very important and significant effects to design the high performance device fabrication.

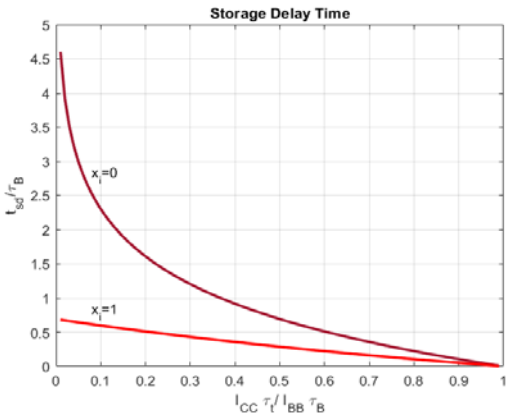


Fig. 9. Storage Delay Time

The fall time response is also mentioned based on the ratio of $I_{CC}\ \tau_t/I_{BB}\ \tau_B$ and it is also demonstrated in Figure.10. The two conditions of x_i=0 and 1 for fall time analysis in this figure. For x_i=0 condition, the fall time values are constant at 2.2 of t_r/τ_B. For x_i=1 condition, the fall time values would be increase from 0 to 0.55 of t_r/τ_B.

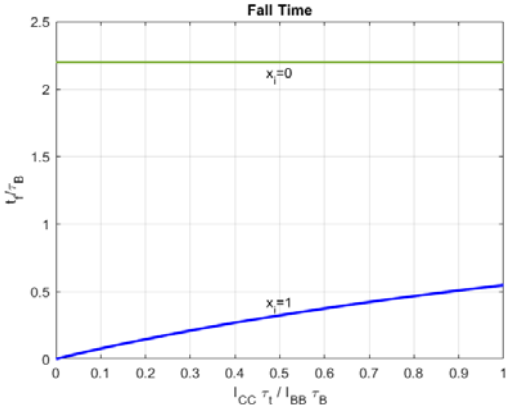


Fig.10. Fall Time

IV. CONCLUSION

The Minority Carrier Distribution in the Base of a HEBT Variation with W/LB has been evaluated based on the physical parameters. The HEBT Biasing Mode Illustration for three operating regions of active, cut off and saturation with numerical analyses. The four ratios of N_E/N_{E0}, N_B/N_{B0}, τ_E/τ_{E0} and τ_B/τ_{B0} is mentioned and checked based on the physical parameters for proposed HEBT. The actual results of IC and IB are also calculated based on VEB. Based on the numerical analyses on multi quantum-well HEBT structure, the physical characteristics of proposed transistor model were evaluated. The results on current gain, rise time, storage delay time and fall time responses are vital role to enhance the high performance of HEBT structure in reality. The results confirmed that the proposed HEBT structure is appropriate for PNP configuration for high frequency applications.

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