An Overview of InP/GaAsSb/InP DHBT in Millimeter and Sub-millimeter Range

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Abstract— We present an overview of Dual Heterojunction Bipolar Transistor approaching Gigahertz frequencies based on latest device technology. Highlights include the best reported data from GaAsSb Dual Heterojunction Bipolar Transistor. We will discuss the best reported cut of frequency in DHBT. Short review of the journey from BJT to DHBT is also discussed with their advantages and disadvantages.

Index Terms— DHBT, GaAsSb, HBT, InGaAs, InP.

1. INTRODUCTION

In electronics industry, Silicon has been first choice from last few decades. But due to lack of linearity and degradation of current gain in silicon based BJT devices operate in microwave frequency, Group III-V based NpN heterojunction bipolar transistor have achieved tremendous performance in term of microwave frequencies of operation and higher current gain because of their superior material properties, such as higher electron mobility and unique bandgap alignment.

NPN HBT differ from BJT in term that emitter is replaced by a material with larger bandgap than base. This leads to a lowering of barrier for electron injection into base, but an increased barrier for holes which prevents their back injection into emitter, resulting in higher current gains. As a result base can be made thinner and doped higher than emitter to reduce the base resistance and further increase its high frequency performance. Earlier there were difficulties in develop, defect free III-V materials but advancement in epitaxial growth technologies, such as Molecular Beam Epitaxy (MBE) and metal organic Chemical Vapor Deposition (MOCVD) shows the full potential of HBTs. Recently, InP/GaAsSb/InP DHBT has shown highest cutoff and maximum oscillation frequencies of 428 GHz & 621 GHz respectively recorded for any DHBT.

Development of double heterojunction bipolar transistor is driven by increasing demand for higher data rates in optical and wireless communication network. These DHBT devices exhibit electron mobility several times higher than those achievable by present known devices. Tremendous growth in research and development effort are being made for semiconductor integrated circuit composed of field effect transistor and bipolar junction transistor using compound semiconductor material such as GaAsSb, InGaAs, and InP. Example of such semiconductor devices are DHBT, HBT, High Electron Mobility Transistors. In this paper, we present review of DHBTs. Section 2 refer to journey from BJT to InP/GaAsSb/InP DHBT, Section 3 refer to high frequency operation of InP/GaAsSb/InP DHBT, Section 4 refer to conclusion.

2. JOURNEY FROM BJT TO INP/GAASSB DHBT

2.1 Homojunction Bipolar Transistor

Review of basic operation of homojunction BJT is important before the discussion of InP/GaAsSb DHBTs. Emitter, Base and Collector of BJT is made up of silicon material. Doping of same type is used for emitter and collector. Slightly change in base current controlled the flow of current from emitter to collector [1]. Let us assume npn transistor for explaining the functioning of transistor. Injection of minority carrier across the junction in forward bias plays significant role in the operation of BJT’s. For normal operation base-emitter junction is forward bias and base-collector junction should be reverse bias. In forward bias, concentration of minority carrier in base at base-emitter junction is amplified by a factor exp (qv/kt). Width of base region should be less than diffusion length of electron [1][2]. Electron injected into base from emitter must diffuse across base to collector without excessive recombination with majority carrier’s holes in base. High electric field in reversed bias base-collector junction attracts minority carriers electron of base when they reach base collector junction and form collector current. Band diagram of BJT in thermal equilibrium is shown in Fig1.

Solving the carrier continuity equations, the base current and the collector current are given as follows: [1][2].

$$I_B = \frac{qA_E D_{pE}}{X_E} \frac{n_{iE}^2}{N_E} \exp\left(\frac{qV_{BE}}{KT}\right) \quad (1)$$

$$I_C = \frac{qA_E D_{nB}}{X_B} \frac{n_{iB}^2}{N_B} \exp\left(\frac{qV_{BE}}{KT}\right) \quad (2)$$

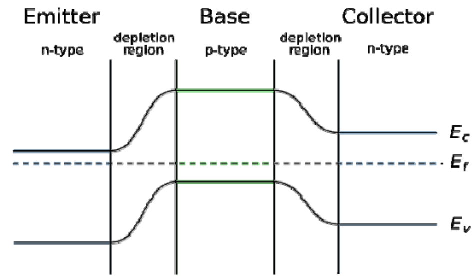


Fig. 1 Band diagram of an npn homojunction bipolar

transistor under thermal equilibrium.

From the analysis of above two expressions, we get that in order for collector current to be greater than base current, it is necessary that emitter doping exceed base doping. In doing so, we have trade-off an important transistor design parameter. For keeping base doping at a lower value means that base resistance will be high. This can be compensated by widening the base, but it will cause significant effect on base transit time thus lowering the device maximum frequency of operation. Therefore, for a fixed base doping level, current gain of BJT can be increased initially by increasing the emitter doping. But significantly emitter bandgap narrowing occurs when emitter doping is around $N_E \sim 10^{18}/cm^3$, causing current gain to degrade.

Therefore in homojunction BJT there is conflicting set of requirements, where base doping cannot be increased without sacrificing current gain. This limits the operation of BJT to low frequency amplifiers and oscillators. The performance of HBT can be significantly better than that of BJT, if we dope base high and at same time comparatively reduce emitter doping, which is more feasible because of wide band gap emitter in HBT. This is where HBT have made tremendous progress in term of frequency of operation in millimeter band.

2.2 Heterojunction Bipolar Transistor

Heterojunction bipolar transistor (HBT) uses differing semiconductor materials for emitter and base regions, creating a heterojunction. Advantage of heterojunction bipolar transistor compare to homojunction transistor lies in the possibility of increasing frequency performance while maintaining high gain. Emitter injection efficiency depends upon relative doping of emitter and base as well as on base/emitter band difference. Electrons are injected thermally into base from emitter and diffuse across base and electric field in base-collector depletion region sweep them into collector at high speed.

Hole injection from base into emitter region is reduced, because valence band has greatest potential barrier compare to conduction band. Hence lower doping density required for emitter in comparison to base besides maintaining gain. Base thickness reduced which result in improvement of unity gain cutoff frequency and maximum oscillation frequency, higher current amplification, lower base resistance, lower base emitter capacitance and high early voltage [1] of HBT in millimeter range. HBT is used in modern ultrafast circuit, generally radio frequency (RF) system and in high power efficiency application. For example RF power amplifiers in phones.

Heterojunction are of two types. Abrupt heterojunctions and Graded heterojunction. In abrupt heterojunction, two different semiconductors with different bandgap are brought together and interface is abrupt, i.e. composition changes abruptly. In graded heterojunction, composition is gradually changed across heterojunction and suppression of energy band spikes due to energy band edge discontinuity seen at abrupt heterojunction interface. Here we are considering abrupt heterojunction for research work. Shown in Fig. 2 is an abrupt emitter-base heterojunction in an npn HBT [1].

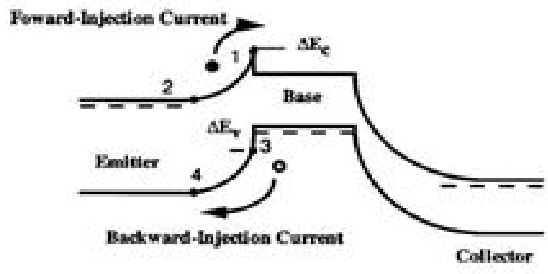


Fig. 2 Band diagram of NPN HBT under normal forward active mode.

Generally conduction band of emitter lies above that of base. Ratio of electron to hole current across emitter-base heterojunction i.e. current gain, is given as: [1].

$$\frac{I_n}{I_p} = \beta_{max} = \frac{N_E}{N_B}\frac{v_{nb}}{v_{pe}}\exp\left(\Delta E_g/kT\right) \qquad (3)$$

Where NE and NB represent emitter and base doping respectively. Vpe and Vnb represent thermal velocity of hole and electron in emitter and base respectively. ΔE_g is bandgap difference between base and emitter. Current gain has exponential dependent on valence band discontinuity ΔE_V between base and emitter for npn devices [1]. Emitter injection efficiency is ideally unity, irrespective of doping level of base and emitter [2]. Maximum current gain is obtained when negligible recombination in base and $\Delta E_V = \Delta E_G$. When $E_V \approx \Delta E_G$ then emitter-base energy bandgap difference increases I_n/I_p ratio by a factor of exp (ΔE_V / kt) relative to that of BJT. Valence band ΔE_V discontinuity at heterojunction replaces E_G in equation (3) and related to current gain as follows: [1].

$$\frac{I_n}{I_p} \sim \exp\left(\Delta E_v / kT\right) \qquad (4)$$

Spike in conduction band at emitter-base junction causes injection of electron into base region with a high velocity (~10^8cm/s) that exceeds the saturation velocity. This results in a highly efficient and very fast electron transport through base. Tremendous developments in material growth technologies have enabled precise control of layer thickness, doping and possibility to change composition by replacing one with another III-V semiconductor material. So that HBT can be designed for high frequency of operation.

2.3 Double Heterojunction Transistor

HBT is suitable for low voltage operation. For high voltage operation, it is necessary to improve the breakdown voltage. One can use double heterojunction bipolar transistors, having base-collector heterojunction in addition to emitter-base heterojunction. The second heterojunction has the effect of improving the breakdown voltage through the use of material with high forbidden band width (like InP) for the collector. Use of same material for emitter and collector forms a double heterojunction transistor. Collector form by wide bandgap material causes suppression of hole injection efficiency from base to collector [2]. Material like InP have shown excellent transport and thermal properties than conventional GaAs and other materials.

2.4 InP Based Heterojunctions

InP based HBT can perform best in millimeter and sub-millimeter band compare to any other solid state devices [3]. Comparison of InP over GaAs and Si semiconductor is shown in Fig.3 [4]. Fig. 3(a) represent InP HBT have lower turn on voltage than other semiconductor devices due to small bandgap of base. Fig. 3(b) represent InP HBTs have a higher breakdown voltage at a given collector doping, while Fig. 3(c) represents InGaAs and InP have higher electron mobility than GaAs. Finally, Fig. 3(d) represents InP HBT has a larger thermal conductivity than GaAs, though less than that of Silicon. Larger thermal conductivity of InP HBT results in the lower device heating [5]. InP devices are compatible with long wavelength laser and led sources. This allows for direct integration and tight coupling of light sources and also use in transmitter/receiver circuitry [5]. Lower surface recombination velocity of InP-based HBTs results in a reduction of surface leakage currents and improved gain at low current densities, enhancing the ability to scale down devices to smaller dimensions for LSI implementation [3]. InP based devices have the significantly lower 1/f noise and higher power added efficiency (PAE) than GaAs devices which is extremely important for portable devices like mobile phones [3]. As a result InP-based devices dominate over other conventional devices in millimeter and sub- millimeter band. Earlier InGaAs, because of narrow band gap is used as base in InP-based heterojunction devices. Outstanding features of InGaAs such as mobility, electron saturation velocity, Scaling and minimization of collector area junction have shown good result in InP/InGaAs-based single HBTs in term of cut-off frequencies in millimeter range [6].Now the question arises, why we are moving to GaAsSb when InGaAs is performing well. Low break down voltage due to narrow collector gap in InGaAs was the major drawback of InP/InGaAs HBT [7].

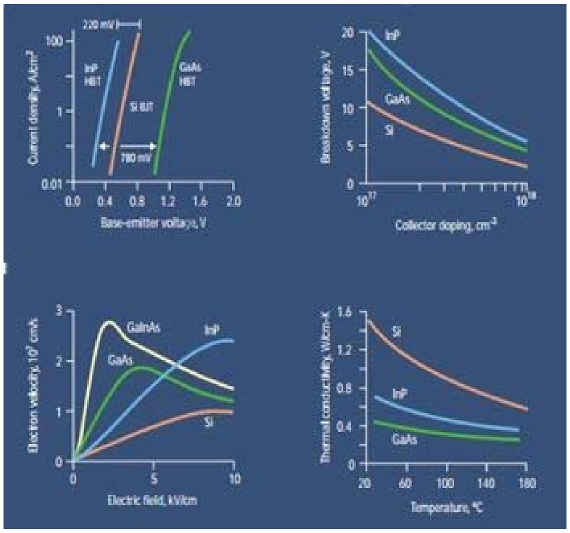


Fig. 3 Comparison of material properties of InP, GaAs and Silicon [4].

This drawback is over come by using an wide bandgap AlInAs or InP collector layers in the double heterojunction transistor [8][9]. But AlInAs or InP collector has shown collector current blocking problem caused by conduction band discontinuity between InGaAs base and wider bandgap InP collector. Fig.4 shows conduction band energy diagram in various doping and/or composition grading schemes developed for base-collector region to overcome this blocking effect [10].For InP collector, a blocking barrier of 0.25 eV must be overcome between base and collector as shown by curve (a) in Fig.4 where the base-collector discontinuity ΔE_C increase the transit time of electron minority carriers, and reduce HBT performance in term of frequency and current gain. Fig. 4(b) shows reduction in blocking effect and improvement in current gain by using an undoped InGaAs spacer layer between base and collector. Fig. 4(c) shows using of compositional grading to minimize blocking effect. Fig. 4(d) shows favorable band lineup for InP/GaAsSb DHBT.

Grading methods discussed in [8, 9, 10] introduce significant epitaxial growth complexity and impose stringent uniformity and repeatability requirements on the epitaxial growth. Even these grading schemes are not best method for eliminating collector-blocking effect at base collector interface, because high collector current densities cause a retarding potential, eventually degrading transistor performance [11]. Specifics of any grading and/or doping schemes at the base/collector junction need to be considered carefully because they can have a dominant impact on DHBT performance at high current densities [12]. GaAsSb base layer provides an excellent solution for collector blocking effect occurring in InGaAs-based DHBT designs.

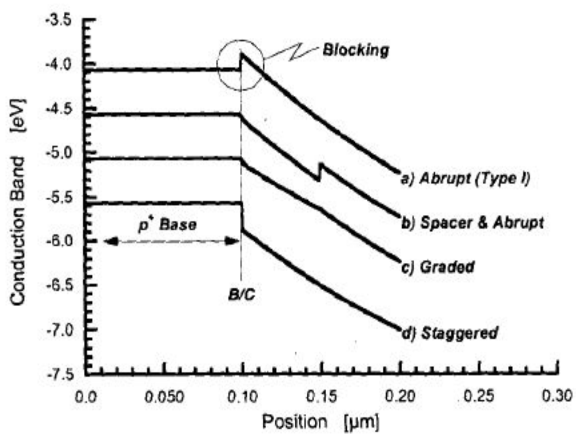


Fig. 4 Conduction band profiles of B/C junction in dhbt [10].

2.5 InP/GaAsSb/InP Double Heterojunction Bipolar Transistors

Replacing InGaAs from base layer by GaAsSb and formation of type II bandgap at base-collector junction in GaAsSb/InP HBT has shown a better solution for the collector blocking problem as shown in Fig. 4(d) [13][14]. Electrons travels from base-collector depletion region with a high velocity exceeding their saturation velocity, a phenomenon known as velocity overshoot [1]. Hence InP/GaAsSb DHBTs benefit from two fundamental advantages over InP/InGaAs DHBTs.

(1) No graded transition layers require at collector- or emitter-base junctions, hence simplifying growth of epitaxial layers.

(2) C-doped GaAsSb feature high doping efficiency [15] and displays little or no H-passivation effects [11].

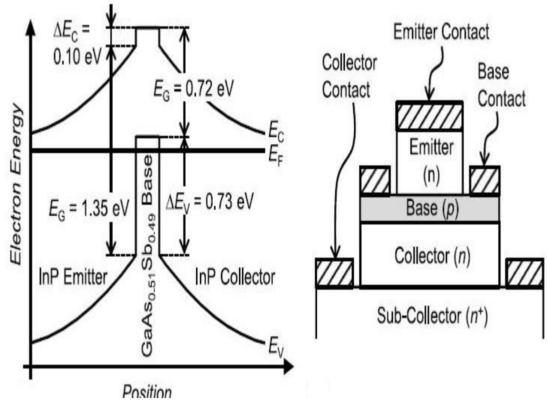
Also low diffusivity and good donor properties of Carbon doping ensures that base-collector junction is precisely and permanently self-aligned to GaAsSb/InP interface leading to stability and improves device characteristics. At 300 K, $GaAs_{0.51}Sb_{0.49}$ conduction band edge is above that of InP by 0.15 eV and valence band discontinuity is 0.78 eV [16][17] causes non-blocking conduction band profile at the base-collector heterojunction. Here compositional grading is also not required. Earlier, lots of difficulties were facing like developing GaAsSb layers with low resistivity, mobility of GaAsSb is roughly 50-60% of that in InGaAs for a given concentration. These devices had f_T and f_{MAX} performance of around 30GHz and 45GHz, respectively [18][11].

These results discouraged further development using this material system for a while. While there is a conduction band barrier at emitter-base junction impeding electron injection into base from emitter, effect is not fatal and high performance InP/GaAsSb DHBTs have been reported [19]. Recent developments have shown impressive performance gains in terms of cut-off and maximum oscillation frequency of operation. Recently Type-II InP/GaAsSb DHBT with f_{MAX} of 621 GHz and simultaneous f_T of 428 GHz has been demonstrated [20]. The present transistors are the first InP/GaAsSb DHBTs with an f_{MAX} in excess of 600 GHz. Results also show f_T/f_{MAX} = 470/540 GHz [21]. MOCVD grown, Carbon doped, abrupt heterojunction, InP/GaAsSb/InP DHBTs feature a very small VCE offset voltage < 0.1V and a low turn-on voltage of V_{BE} of 0.4 V at a current density of J_C =1 A/cm^2, by taking advantage of the staggered band lineup at the InP/GaAsSb interfaces [7]. Minority carrier electron mobility in the p-doped base is the order of 600-800 cm^2/Vs. This is low when compared to similarly doped InGaAs layers with electron mobility of 2000-3000 cm^2/ Vs in InP/InGaAs HBTs. This lower mobility necessitates the use of thinner bases for GaAsSb than InGaAs to achieve comparable base transit times. However, to maintain acceptable base sheet resistance and high maximum oscillation frequency, higher base doping is necessary. This requirement for higher doping is solved by GaAsSb affinity for Carbon doping and low H-passivation effects [13].

3. HIGH FREQUENCY OPERATION OF InP/GaAsSb DHBT

3.1 InP/GaAsSb DHBT Energy Band Diagram

InP/GaAsSb DHBT consists of lattice matched $GaAs_{0.51}Sb_{0.49}$ base ($E_G \approx 0.72$ eV) and InP based emitter and collector region ($E_G \approx$ 1.35eV). Heterojunction between InP and GaAsSb has Type II band alignment. Equilibrium energy band diagram is shown below in Fig 5 (a) and schematic cross section view of Triple mesa device structure (b). Valence and conduction band discontinuities are $\Delta E_V \approx 0.73$ eV and $\Delta E_C \approx 0.10$ eV. The carrier flow vertically across emitter, base, collector by their respectively transport mechanism. A schematics representation of cross section of a standard DHBT is shown in Fig 6. The device consists of emitter, base, collector and sub collector mesas. A heavily N doped sub collector region is used in order to reduce collector series resistance.



(a) (b)

Fig. 5 Energy Band Diagram of an InP/GaAsSb (a) and schematic view of mesa structure (b).

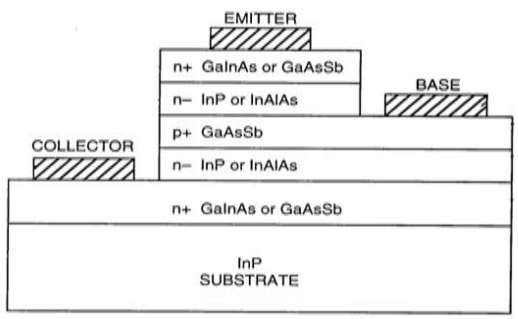


Fig. 6 InP/GaAsSb dhbt schematic diagram

3.2 Current Gain Cutoff Frequency

Cutoff frequency f_T is defined as frequency at which magnitude of common emitter short circuit gain h_{21} decreases to unity. Expression of h_{21} as a function of frequency f is shown below: [1].

$$\beta_{ac} = \frac{\beta_{dc}}{1+jw\beta_{dc}(C_p+C_{jc})/g_m} \qquad (5)$$

Where c_p is total input capacitance, c_{jc} is base collector junction capacitance and g_m is transconductance of device.

For finding f_T , $|\beta_{ac}|$ = 1

$$\tau_{EC} = \frac{1}{2\pi f_T} \qquad (6)$$

Where $\tau_{EC} = \tau_e + \tau_b + \tau_{sc} + \tau_c$

Where, τ_{EC} is the total HBT input response delay time, τ_e is the emitter charging time, τ_b is the base transit time, τ_{sc} is the space charge transit time, and τ_c is the collector charging time. Relation between cutoff frequency and common emitter current gain is shown in Fig. 7 shows current gain calculated for constant emitter collector transit time and values of β ranging from 10 to 100.

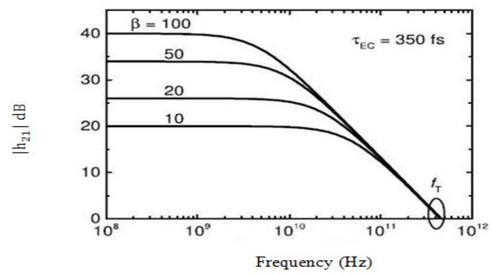


Fig. 7 Common–emitter short circuit gain $|h_{21}|$ versus frequency with current gain β.

3.3 Maximum Oscillation Frequency

Unilateral power gain of transistor is the power gain after transistor plus loss less network. It is define as the frequency at which mason's unilateral power gain U is reduced to unity. The expression of U is given below: [22]

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$$U = \frac{f_T}{8\pi f^2 (R_B C_{BC})_{EFF}} \qquad (7)$$

Where f is the frequency and $(R_B C_{BC})_{EFF}$ is an effective time constant. The expression of maximum oscillation frequency f_{MAX} is given below: [23].

$$f_{MAX} = \sqrt{\frac{f_T}{8\pi Rb Cc}} \qquad (8)$$

Where R_b is base series resistance and C_c is collector junction capacitance. Increasing R_b does not affect Ft, while the increased C_c has minor affect on f_T. However both has a more pronounced effect on $f_{MAX.}$

3.4 Doping of base in DHBT

Compound used for the formation of base is GaAsSb. Various base grading schemes improve current gain compared to uniform doped baseline. C doping grade improve device DC current gain. DHBT with built-in electric field in the base has improved DC current gain and high speed characteristics over DHBT without built-in electric field. Built-in voltage can be introduced by either doping grading or composition grading in the base [24]. There are at least four ways to implement base grading in GaAsSb/InP DHBTs:

1. $In_xGa_{1-x}As_ySb_{1-y}$
2. $Al_xGa_{1-x}AsSb$
3. $GaAs_ySb_{1-y}$ Compositional Grading
4. GaAsSb: C Doping Grade

It is difficult to simultaneously control both composition grading in $In_xGa_{1-x}As_ySb_{1-y}$ and $Al_xGa_{1-x}AsSb$ produces unnecessary higher turn on voltage than rest of grading schemes. Hence GaAsSb: C doping grades improve DC current gain. In the given Fig. 8, base thickness is constant. Relation between DC current gain and base sheet resistance is obtain to evaluate effectiveness of certain base grading scheme.

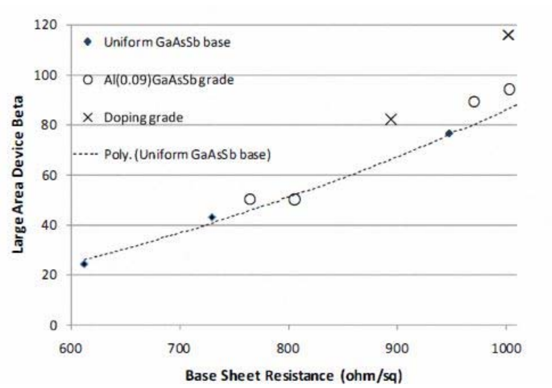

Fig. 8 Effectiveness of various base grading schemes

compared with Ga$As_{0.8}Sb_{0.8}$ baseline [25].

3.5 Diffusion Coefficient And Base Transit Time

Emitter-collector delay in InP/GaAsSb DHBT is given by equation (9). Using single pole approximation of $h_{21}(f)$ of small signal T-model, the total delay time τ_{EC} is estimated as a sum of internal delay times [25]:

$$\tau_{EC} = \tau_T + (C_{JE} + C_{JC})\frac{\eta kT}{qIc} \quad (9)$$

Where $\tau_T = \tau_B + \tau_C + (R_C + R_E)C_{jc}$

Delay time τ_T followed quadratic equation versus base thickness W_B as shown in fig 9.

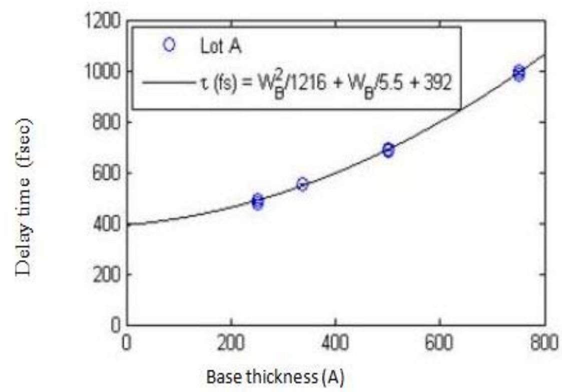

Fig. 9 Delay time τ_T versus base thickness W_B [26].

Base thickness is given by [26].

$$\tau_B = W_B^2/2D_{nB} + W_B/V_{exit} \quad (10)$$

Minority carrier diffusion coefficient in ultrafast speed HBT is calculated from above equation 10. There is currently no estimate for exit velocity V_{exit} of electrons in GaAsSb/InP transistors during non equilibrium transport, but the value of 5.5E7 cm/s, which was extracted for InGaAs/InP DHBTs by Monte Carlo simulation, is a viable approximation and was used to enhance the quadratic fit shown in Fig 9.

4. CONCLUSION

Continuously increasing demand for higher data rates in optical and wireless communication network working in gigahertz frequencies causes tremendous growth in research and development efforts. In this review paper we have discussed the device well suitable for sub-millimetre and millimetre band. Homojunction bipolar transistor cannot function efficiently due to increase in transit time of electron from emitter to collector in gigahertz frequency band. Heterojunction transistors have solved this problem. The performance of Heterojunction bipolar transistor is evaluated in term of breakdown voltage, transit time, doping type of base.

InP based DHBT dominates the HBTs in removing the collector blocking effect and also in enhancing the collector breakdown voltage. Type II InP/GaAsSb/InP Double Heterojunction Bipolar Transistors have shown best result in term of cutoff frequency, maximum oscillation frequency, high linearity and low noise ever reported by any solid state device in high frequency operation.

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