Abstract—This is the Part I + Part II project reports for EECS 521. The focus of the first portion of this project is the fundamental operation of an InP npn SHBT device—single heterojunction bipolar transistor. This portion of the project surveys literature—textbooks and research publications—of InP SHBT devices. This report also reviews the fundamental limitations of homojunction BJT’s, compares the advantages of InP-based HBT’s over GaAs-based HBT’s, and looks briefly into the state-of-the-art InP HBT devices.

The second portion of this report (Part II) delves into the theory and design of a double heterojunction bipolar transistor (DHBT) with GaAsSb p-doped bases. The discussion of design touches upon key material parameters in this novel material system. Simulations present results that confirm recent findings that such an InP/GaAsSb/InP npn transistor can have cutoff and maximum oscillation frequencies well into the >300 GHz regime while maintaining useable breakdown voltages > 5 V.

Index Terms—III-V devices, DHBT, GaAsSb, heterojunction bipolar transistor, heterojunction device physics, InAlAs, InGaAs, InP HBT, microwave transistors, transistor operation “type II” heterojunction.

I. INTRODUCTION

The need for very high frequency devices arises in microwave applications at 70+ GHz or 110+ GHz, as well as in ultra-fast A/D converters and 100 Gbit/sec laser drivers. GaAs-based devices have traditionally dominated microwave device applications above 20 GHz. With the development of better growth processes, however, InP is emerging as the choice of material for next-generation microwave devices.

Major device fabrication companies are tooling for InP with preliminary circuit designs already on line in the fabs. Most of the InP technology is slated for power amplifier design, high-frequency (70+ GHz) microwave circuits, and A/D converters. InP, like GaAs, allows the option of designing HBT’s, heterojunction bipolar transistors, as well as higher frequency HEMT’s (high-electron mobility transistors). For now, the primary focus of microwave power applications is on HBT’s because of their high current gains (500-1000, typically), high transconductance, and superior device matching properties.

A. Bipolar for Power and Microwave

Bipolar transistors remain the primary choice of high-frequency power applications due to the high $f_t$’s and high transconductances, $g_m$. Compared to FET devices, bipolar and devices can maintain high $f_t$’s and $g_m$’s at larger lateral dimensions. Larger lateral dimensions allow for better device matching, critical for microwave/analog circuit design.

B. Transition to Heterojunctions

Homojunction bipolar transistors—BJTs made of one type of material—have fundamental device limitations that do not allow high gain and low base resistance (affecting the high-frequency performance) to be achieved simultaneously, limited the upper performance of BJT’s.

Schokley and Kroemer, in the 1950s, developed a way of overcoming constrains of homojunction bipolar transistors by intentionally using two different materials—a wider bandgap material in the emitter and a narrower bandgap material in the base. The two envisioned the use of the heterojunction to improve bipolar device performance.

The technique of changing the bandgap across a device allows for engineering of forces on electrons and holes separately. By changing bandgap and electric field combinations, individual forces on holes and electrons can be tailored to improve device characteristics.

Although the idea of the heterojunction has existed since the 1950’s, fabrication technology has been the limited factor in the development of HBT’s. Initially, there were many problems growing different materials with few imperfections due to lattice mismatch or structural defects resulting from limited growth technologies.

Taking advantage of GaAs-based techniques that have been refined since the 1970’s, InP-based HBT’s are becoming the popular choice for next-generation high-performance microwave devices. InP utilizes the techniques developed in the GaAs processes to launch another revolution of high-speed devices [1].

C. Summary of Advantages

The anisotropic heterojunction (n-p heterojunction) will be the focus of the heterojunction analyses in this paper. Isotropic junctions (n-n or p-p) can also be formed, but will not be considered for standard HBT devices discussed here.

Heterojunction bipolar transistors have many potential advantages over homojunction bipolar transistors [2]:

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1. Higher emitter injection efficiency due to larger hole energy barriers in the valence band
2. Lower base resistance since the base can be heavily doped without decreasing the emitter injection efficiency
3. Less current crowding in the emitter because of a lower voltage drop across the base-emitter junction
4. Improved frequency response due to higher current gain and lower base resistance
5. Wider temperature operation range due to large bandgap (high temperatures) and very shallow impurity doping levels (low temperatures).

Industrial InP HBT processes (e.g. Hitachi) have achieved $f_T$’s of 200 GHz [3]. Research labs have achieved $f_T$’s beyond 300 GHz [1].

II. SEMICONDUCTOR HOMOJUNCTION

A. Semiconductor Homojunction Limitations

1) Base Doping Limitations

In homojunction BJT’s, the primary design parameters after a material is chosen (Si, GaAs, InP) are
- doping levels
- device dimensions (geometries)

The lack of other design parameters limits the high-frequency performance of homojunction BJT’s. There is a fundamental tradeoff between $\beta$ and the base resistance—both are important parameters for high-performance bipolar devices. $\beta$ can be found from the emitter-to-collector current gain, $\alpha$, where $\alpha < 1$ [4]:

$$\alpha = \left[1 - \frac{p_{eo} D W_{bn}}{n_{bo} D_B L_E} \right] \left[ 1 - \frac{W_{bn}^2}{2 L_E^2} \right]$$ \hspace{1cm} (1).

$$\beta = \frac{\alpha}{\alpha + 1}$$ \hspace{1cm} (2).

For high $\beta$, the emitter doping must be much higher than the base doping in order for ($n_{eo} \gg n_{bo}$), that is ($p_{eo} \ll n_{bo}$). The base doping should be as small as possible to reduce $W_{bn}$. The tradeoff between $\beta$ and base resistance exists because a lightly-doped base gives rise to a high base resistance.

Although the base doping can be increased (to decrease the base resistance) while increasing the emitter doping to maintain $n_{eo} \gg n_{bo}$ condition for high $\beta$, high emitter doping results in bandgap narrowing or shrinking in the emitter.

2) Emitter Doping Limitations

The emitter injection efficiency

$$\gamma \equiv \frac{1}{1 + \frac{n_{E}}{n_{E}^f} \frac{D_B}{D_B^f} \frac{x_B}{x_E}}$$ \hspace{1cm} (3),

where $x_B \ll L_B$ and $x_E \ll L_E$, can be increased by increasing the emitter doping concentration, $N_E$. A more heavily-doped emitter results in a lower value of minority holes in the emitter at thermal equilibrium—higher injection efficiency and better current gain. As emitter doping is increased, however, bandgap-narrowing effects offset the improvements seen in $\gamma$.

If heavy emitter doping changes the emitter bandgap by $\Delta E_g$, the electron and hole densities also change according to the change in intrinsic carrier concentration, $n_{ie}(E_g - \Delta E_g)$. Assuming that hole injection across the base-emitter junction is the dominant factor,

$$\beta = \frac{\alpha}{\alpha + 1} = \frac{n_{bo} D_B L_E}{p_{eo} D_B W_{bn}}$$ \hspace{1cm} (4).

The hole concentration, under emitter bandgap narrowing, is

$$p_{eo}(E_g - \Delta E_g) = p_{eo}(E_g) \exp \left( \frac{-\Delta E_g}{kT} \right)$$ \hspace{1cm} (5),

since the intrinsic carrier concentration in the emitter, $n_{ie}$, changes with the bandgap narrowing:

$$n_{ie}(E_g - \Delta E_g) = n_{ie}(E_g) \exp \left( \frac{-\Delta E_g}{kT} \right)$$ \hspace{1cm} (6).

Taking the emitter bandgap narrowing effect into account, the current gain, $\beta$, of the BJT becomes

$$\beta = \frac{N_D L_D}{N_A W_{bn} D_E} \exp \left( \frac{-\Delta E_g}{kT} \right)$$ \hspace{1cm} (7),

where $\Delta E_g$ is a positive value for bandgap narrowing. Typical values of $\Delta E_g$ are in the 100 meV range for high emitter doping concentrations.

So, for a fixed base doping level, the current gain of the BJT can be increased, initially, by increasing the emitter doping, but at the onset of significant emitter bandgap narrowing (at higher doping levels), the current gain begins to decrease.

Thus, the criteria of very high current gain and low base resistance cannot be simultaneously satisfied in a homojunction BJT by increasing emitter doping, decreasing base doping and decreasing base width.

B. Heterojunction Solutions

The HBT design can result in a lower base sheet resistance than the homojunction BJT. Larger emitters in the HBT give rise to higher current gains than similarly-sized emitters in homojunction BJT’s, as well. Both lower base resistance and higher current gain help boost the HBT’s performance over homojunction BJT’s at high frequency power applications.
III. SEMICONDUCTOR HETEROJUNCTION

A. Heterojunction Physics

1) Bandgap Engineering

A heterojunction is created when two dissimilar semiconductor materials form a junction. The two semiconductors usually have different

- bandgaps, \( E_g \)
- dielectric permittivities, \( \varepsilon \)
- work functions, \( \phi_s \)
- electron affinities, \( \chi \)

Fig. 1. shows the energy band diagrams of two isolated semiconductors [5]. The difference in conduction-band energies, (8), and difference in valence-band energies, (9), are of particular interest in heterojunction operation.

\[
\Delta E_c = q(\chi_2 - \chi_1) \tag{8}
\]

\[
\Delta E_v = (E_{g1} + q\chi_1) - (E_{g2} + q\chi_2) = \Delta E_g - \Delta E_c \tag{9}
\]

Once the two materials are joined to form a heterojunction, the energy band diagram changes. If there are a negligible number of traps and generation-recombination centers at the junction between the two dissimilar semiconductors, the thermal equilibrium band diagram of the ideal n-p heterojunction will resemble Fig. 2. The number of traps is reduced by insuring that the two materials are lattice-matched.

The band diagram of Fig. 2. follows from two basic requirements/boundary conditions for a semiconductor in thermal equilibrium:

1. A flat Fermi level exists through both semiconductor materials (\( \bar{E}_f \))
2. The vacuum level (\( E_{\bar{f}} \)) is continuous and parallel to the conduction/valence band edges.

If the semiconductor materials are nondegenerate, the \( E_g \)'s and \( \chi \)'s will be fairly independent of doping concentrations. As a result, the conduction band discontinuity, \( \Delta E_c \), as well as the valence band discontinuity, \( \Delta E_v \), will be independent of doping, as well— primarily determined by semiconductor materials.

2) Depletion Widths and Junction Voltages

The depletion widths and junction voltages for the ideal n-p heterojunction are

\[
x_1 = \frac{2e_x e_z N_2 (V_{bi} - V_A)}{q N_1 (e_x N_1 + e_z N_2)} \tag{10}
\]

\[
x_2 = \frac{2e_x e_z N_1 (V_{bi} - V_A)}{q N_2 (e_x N_1 + e_z N_2)} \tag{11}
\]

\[
V_{bi} = \frac{e_z N_2 (V_{bi} - V_A)}{e_x N_1 + e_z N_2} \tag{12}
\]

\[
V_{b2} = \frac{e_z N_1 (V_{bi} - V_A)}{e_x N_1 + e_z N_2} \tag{13}
\]

The total depletion width and built-in voltage can be found from (11) to (13):

\[
W_d = x_1 + x_2 \tag{14}
\]

\[
V_B = V_{b1} + V_{b2} \tag{15}
\]

Fig. 2. Energy band diagram of an ideal n-p heterojunction (anisotropic heterojunction) at thermal equilibrium. Carrier traps are assumed to be negligible— lattice matched condition and high-quality semiconductor junction formation [5].

B. Fundamental Heterojunction Operation

The primary semiconductor compounds that are used to build on top of InP substrates include In\(_{0.53}\)Ga\(_{0.74}\)As, In\(_{0.52}\)Al\(_{0.48}\)As, and InP. All three materials are highly desirable because they are lattice-matched to the InP substrate (Fig. 3.)
The In$_{0.53}$Ga$_{0.74}$As has a bandgap of only 0.75 eV and is used for the base. The wider bandgap materials of InP (1.34 eV) and In$_{0.52}$Al$_{0.48}$As (1.50 eV) are used as the base materials.

In further discussion of InGaAs and InAlAs materials, lattice-matching is assumed— In$_{0.53}$Ga$_{0.74}$As, In$_{0.52}$Al$_{0.48}$As—, and the fractional composition subscripts will be dropped for simplicity.

The HBT structure allows a device to have different hole and electron barriers at the base-emitter junction. The emitter can be made from either InAlAs or InP— both are wide bandgap semiconductors. Abrupt heterojunctions made with an InP emitter and InGaAs base have a larger valence-band step than the InAlAs-InGaAs system resulting in a larger hole barrier seen from the base into the emitter. The energy band alignment of InP-based heterojunction materials are shown in Fig. 5.

**TABLE I**

<table>
<thead>
<tr>
<th>Example of Material Compositions for InP SHBT's and DHBT's</th>
</tr>
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<tbody>
<tr>
<td><strong>Single Heterojunction (SHBT)</strong></td>
</tr>
<tr>
<td>n⁺ cap</td>
</tr>
<tr>
<td>n emitter</td>
</tr>
<tr>
<td>p base</td>
</tr>
<tr>
<td>n⁻ collector</td>
</tr>
<tr>
<td>n⁺ subcollector</td>
</tr>
<tr>
<td>substrate</td>
</tr>
</tbody>
</table>

The conduction band discontinuity, shown in Fig. 1 and Fig. 5, tends to retard the electron flow from emitter to base. The emitter injection efficiency, thus, is lower, but the discontinuity insures that electrons that do overcome the energy barrier are injected with high forward velocities and high forward momentum leading to shorter base transit times (ballistic transport via thermionic emission) [7].

To improve the current gain via improving the emitter injection efficiency, a graded heterojunction can be used to reduce the conduction band maximum “peak” at the discontinuity. The conduction band “peak” can be minimized or eliminated by grading the alloy composition. Quadratic grading of the alloy composition results in a quadratic grading of $\chi$, the electron affinity, at the junction. If uniform doping is used, the electrostatic potential also varies quadratically with distance (e.g. pure GaAs to In$_{0.53}$Ga$_{0.74}$As). Grading distances are on the order of a few hundred Angstroms (100’s Å).

A graded heterojunction also results in an increased hole barrier from base to emitter because the bandgap difference now appears across the valence band energy barrier. The emitter injection efficiency goes up because the holes see a larger barrier. Hole injection is improved by

$$\frac{I_{\text{emitter}, \text{p}}(\text{HBT})}{I_{\text{emitter}, \text{p}}(\text{BJT})} = \exp\left(\frac{-\Delta E_g}{kT}\right)$$

where $E_g$ is a positive quantity (emitter-base bandgap difference).

If the gain, is limited by the emitter injection, then

$$\beta_{\text{max}} = \frac{N_{\text{in}} L_{\text{d}} D_{\text{r}}}{N_{\text{a}} W_{\text{p}} D_{\text{r}}} \exp\left(\frac{\Delta E_g}{kT}\right)$$

The expression is similar to (7) except that $\beta$ is increased due to the bandgap difference and emitter injection efficiency (compared to the emitter bandgap narrowing of the highly doped homojunction BJT).

The $\Delta E_g/kT$ value is chosen to be on the order of 10, typically, so that a $\beta$ improved of $10^4$ is seen [4]. With high gain arising from the heterojunction structure, the base doping can be increased by a few orders of magnitude to decrease the base resistance— with little penalty on the achievable current gain, $\beta$.

2) Benefits of High Base Doping

Another beneficial effect arising from the high base doping capability is the reduction of base-punch through at the collector junction. The output resistance is increased since base encroachment of the base-collector junction is lowered— base charges are essentially independent of $V_{\text{CB}}$. So, higher base doping reduces Kirk effect, somewhat, and the Early effect.

3) Benefits of Lower Emitter Doping

Emitter doping in a heterojunction HBT does not need to be as heavy as a homojunction BJT. A positive consequence of lowering the emitter doping is a larger base-emitter depletion region which leads to smaller emitter capacitance (without sacrificing current gain).

1) Abrupt and Graded Heterojunctions

The abrupt heterojunction at the emitter-base interface results in a conduction band (and valence band) discontinuity.
Ec
Ev
Ec
Ev
Fig. 4. Abrupt heterojunction (left) and graded heterojunction (right) examples. The abrupt heterojunction has a larger conduction-band discontinuity at the junction interface.

4) Ballistic Carriers and Abrupt Heterojunctions

An offset voltage exists in the InAlAs/InGaAs HBT (SHBT) because of the difference of turn-on voltages between the base-emitter and the base-collection junctions. Also, breakdown voltage is low due to the small InGaAs bandgap (in the base region). These two limitations can be improved by using wide bandgap collectors such as InP or InAlAs (creating a second heterojunction at the base-collector junction—DHBT) and by using graded base-emitter junctions [8].

A graded base-emitter junction is needed in both InP/InGaAs and InAlAs/InGaAs devices if low turn-on voltage is desired. The conduction band step is reduced in a graded junction, but if any of the step is still present (usually the case), the base-emitter junction ballistically launches/injects electrons from the emitter into the base. If low turn-on voltage is not necessary the full conduction band step is present at the abrupt, un-graded heterojunction.

With abrupt heterojunctions, ballistic launching/injection of electrons results in high forward-momentum electrons traveling into the base. The high-momentum electrons reduce the base transit time significantly if the base is kept narrow in width. This is one of the major benefits of a heterojunction bipolar device. InGaAs can provide a much higher forward momentum to the electrons because the energy limit of InGaAs electrons is higher since the energy separation between \( \Gamma \) and satellite valleys is greater than that in GaAs.

5) Velocity Overshoot

The velocity overshoot in InP HBT’s allows for electrons to obtain high values of velocity well above \( 10^7 \) cm/sec for brief times after electrons enter regions of high electric fields. Velocity overshoot can be utilized in the base-collector junction of the HBT to reduce the transit time (of electrons) across the junction. Electrons are injected over the emitter-base barrier by thermionic emission [9].

A higher \( f_T \) can be achieved than a material/device without electrons in velocity overshoot. For a fixed or desired value of \( f_T \), velocity overshoot characteristics also decrease the base-collector capacitance.

HBT’s can take advantage of electron velocity overshoot because critical dimensions in the device can be made very small with a high reproducibility.

C. Double Heterojunction Bipolar Transistor (DHBT)

As discussed in the previous section, if the base and collector regions are chosen to be InGaAs, the small bandgap of InGaAs (0.75 eV) can lead to small collector-base breakdown voltages. A second, important effect is that the small bandgap can lead to significant collector-base leakage currents.

In order to suppress the devices limitations of small bandgap base and collector regions, a second heterojunction can be introduced at the base-collector junction. If a wide bandgap semiconductor such as InAlAs or InP is chosen, breakdown and leakage currents can be improved drastically.

Although the base-collector heterojunction is very similar to the base-emitter heterojunction, one extremely important difference is that the base-collector heterojunction must be graded whereas the grading of the base-emitter junction is just an option to reduce the base-emitter turn-on voltage—optional, not critical. If the base-collector junction is not graded, a conduction-band barrier is formed (as in Fig. 4—left), reducing the collection efficiency of electrons from the base.

IV. InP Versus GaAs

The concept of the heterojunction was realized in many GaAs-based devices until InP processing technology improved. Much is already known about GaAs-based heterojunction formation in terms of theory as well as practical device design. For InP to succeed in becoming the next generation high-speed device—picking up where GaAs devices waiver—, InP must have enough value-added in terms of performance and manufacturability to succeed GaAs devices.

Table II shows some fundamental material comparisons between GaAs and InGaAs (base material). A discussion follows regarding the performance differences.

<table>
<thead>
<tr>
<th>TABLE II</th>
<th>MATERIAL PERFORMANCE COMPARISONS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>GaAs</td>
</tr>
<tr>
<td>( E_g ) (eV)</td>
<td>1.42</td>
</tr>
<tr>
<td>( \Delta E(\Gamma - L) ) (eV)</td>
<td>0.3</td>
</tr>
<tr>
<td>( \Delta E(\Gamma - X) ) (eV)</td>
<td>0.48</td>
</tr>
<tr>
<td>( m_e^* / m_0 )</td>
<td>0.067</td>
</tr>
<tr>
<td>( m_h^* / m_0 )</td>
<td>0.07</td>
</tr>
<tr>
<td>( \mu_e ) (cm(^2)/V/sec)</td>
<td>8000</td>
</tr>
<tr>
<td>( v_{\text{peak}} ) (cm/sec)</td>
<td>( 2 \cdot 10^7 )</td>
</tr>
<tr>
<td>( m_{\text{light hole}}^* / m_0 )</td>
<td>0.62</td>
</tr>
<tr>
<td>( m_{\text{heavy hole}}^* / m_0 )</td>
<td>0.62</td>
</tr>
</tbody>
</table>
HBT’s using InP or InAlAs wide-gap emitters and InGaAs bases have many features for high-performance device design [8]:

1) Growth Technology

The growth technology of the epitaxial layers has matured greatly, and high-quality InGaAs and InAlAs growth is available via MBE. Similarly, matured MOMBE and MOCVD growth technologies are available for InGaAs and InP.

2) Electron Mobility

InGaAs has high electron mobility—1.6 times higher than GaAs—and the transient electron velocity overshoot is greater in InGaAs, InP, and InAlAs than in GaAs. InGaAs, InP, and InAlAs have larger velocity overshoot than GaAs because the separation between the Γ–L, and Γ–X valleys is greater. The superior electron velocity characteristics result in high $f_T$ values for the InP/InGaAs/InAlAs device.

3) Turn-On Voltage

InGaAs (In$_{0.53}$Ga$_{0.47}$As) has a small bandgap of 0.75 eV—much smaller than GaAs. If a graded heterojunction structure is used, the turn-on voltage of the base-emitter junction will be lower. A lower base-emitter turn on voltage allows circuit designers to use lower power supply voltages, which can result in lower power dissipation.

4) Surface Recombination Velocity

InGaAs has a much lower surface recombination velocity than GaAs—$10^3$ cm/sec in InGaAs versus $10^6$ cm/sec in GaAs. The base current due to recombination at the emitter periphery is thus much lower in InGaAs. Scaling to smaller device dimensions becomes easier, as well. Current gains in the InGaAs HBT can be very high due to the low surface recombination velocities.

5) Substrate Thermal Conductivity

InP has a higher substrate thermal conductivity than GaAs (0.68 versus 0.46 W-cm/K) which allows better microwave power devices to be made—better thermal dissipation in power devices.

6) Optical Integration/Applications

The InP system is compatible with light sources (laser and LED) and detectors at 1.3 µm. GaAs and Si don’t efficiently detect or generate light at this optical wavelength. This deep IR region is critical for optical applications since fiber optic losses are minimum around 1.5 µm, and some of the fastest semiconductor lasers (fastest modulation capabilities) exist at this wavelength.

V. RECENT DEVELOPMENTS

A. Fabrication Technology

Fabrication technology for InP-based HBT’s have taken advantage of the matured, refined GaAs-based fabrication techniques. Solid P is a difficult material to work with due to its high vapor pressure. To grown InP, MBE is avoided and replaced with MOMBE or MOCVD. MOMBE and MOCVD work around the solid P obstacle by using a gas source, PH$_3$.

Graded junctions can be formed using quaternary alloys closely lattice-matched to InP—InGaAlAs or InGaAsP. Since the necessary quaternary composition control is difficult to achieve, an alternative method is to use periodic superlattices with alternating compositions in 10 to 20 Å thicknesses—“quasi quaternary” composition.

B. State-of-the-Art

State of the art npn InP-based HBT’s have ([1], [3], [10], [11], [12])

- $\beta$ from 50 to 200
- $f_T$ as high as 400 GHz
- $f_{max}$ as high as 600 GHz

“Industrial” InP-based HBT’s can achieve $f_T$’s nearing 200-250 GHz while GaAs-based HBT’s are currently limited to 100-150 GHz $f_T$’s.

<table>
<thead>
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<th>TABLE III</th>
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<tbody>
<tr>
<td>MATERI AL PERFORMANCE COMPARISONS</td>
</tr>
<tr>
<td>InP/InGaAs</td>
</tr>
<tr>
<td>Mobility (cm$^2$/V/sec)</td>
</tr>
<tr>
<td>Peak Velocity (10$^7$ cm/sec)</td>
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<tr>
<td>Thermal Conductivity (W/cm/collector)</td>
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<tr>
<td>Bandgap (eV)</td>
</tr>
<tr>
<td>InGaAs</td>
</tr>
</tbody>
</table>

VI. PART I SUMMARY

InP HBT technology provides the device performance needed for high-frequency microwave and optical applications as well as high-speed A/D converters. InP boasts high $f_T$, better
power handling than GaAs, and reliable material growth techniques. A double heterojunction, DHBT, (heterojunction at the base-collector junction) can improve the breakdown voltage and other collector characteristics over the SHBT, but the device design will not be addressed in great detail in this project.

Part II of the project will focus on device design and simulation. Specifically, the emitter-base heterojunction will be examined in detail, and the HBT device will be optimized for microwave applications, focusing on \( f_T, f_{max}, g_m, \beta \), and other performance criteria.

Part II will cover much more device physics, junction design, and numerical calculations as well as simulations for recent research-level concepts for improved InP-based HBT's.

VII. PART II INTRODUCTION

In Part II of the EECS 521 project, focus is placed on the design and simulation of the HBT device. As further investigations into new high-performance devices useful for high-speed, high-frequency circuit design, the project has been shifted to the double heterojunction bipolar transistor (DHBT).

Although, in general, SHBTs (single heterojunction transistors) offer higher \( f_T \)'s and \( f_{max} \)'s than DHBTs, the major drawback of SHBTs is the very low collector breakdown voltages— ~ 0.5-2 V. Thus, the DHBT is investigated in great detail for the second portion of the project.

A novel DHBT device, based on a GaAsSb base, is the focus of the design and simulation. The work in this project is closely based on the work of C.R. Bolognesi at Simon Fraser University in British Columbia, Canada [13].

A. GaAsSb: a New Material System in InP

Since GaAsSb is a new material in the HBT domain, little detail is known about its carrier transport properties. Currently, the performance of the GaAsSb material is growth-limited in terms of material performance— carrier mobilities, carrier lifetimes, uniformity, etc.

The simulation portion relies on empirical data compiled from several sources— measured results as well as empirical expressions obtained from simple theory. Although the simulations cannot be considered rigorous in terms of modeling accuracy, general trends in the InP/GaAsSb/InP DHBT can be observed, and educated predictions of the next generation of InP-based devices can be made with some confidence.

B. Design Goals

There are three primary design goals for the DHBT device:
1. “High” cutoff frequency: \( f_{max} > 300 \) GHz
2. “High” maximum oscillation frequency: \( f_{max} > 300 \) GHz
3. “Moderate” collector breakdown voltage: \( V_{BCEO} \sim 5 \) V

Although there are other important parameters to consider for device performance and design (such as current gain, \( \beta \), and current density vs. terminal voltages, turn-on voltage, saturation regime frequency cutoff, etc.), the three primary design goals are reasonable figures of merit around which to optimize as long as other performance parameters are “reasonable.”

A high \( f_T, f_{max} \), and \( V_{BCEO} \) device is appropriate for target HBT applications in both the analog and digital domains. Microwave HBT oscillators for low-power, wireless communications and mixed-signal ADC designs are two areas of circuits that will benefit from such an optimized device. In the future, appropriate tradeoffs can be made to sacrifice parameters such as frequency cutoff for gain; for now, the device design and simulation revolves around a proof-of-concept philosophy which will estimate device capabilities of the InP/GaAsSb/InP DHBT.

VIII. DHBT CONSIDERATIONS

A. Single Heterojunction Bipolar Transistor Limitations

InP SHBTs have demonstrated, relative to current microwave bipolar devices, excellent \( f_T \)'s and \( f_{max} \)'s. A recent work, [14], has demonstrated a transferred-substrate SHBT with an \( f_{max} \) of 425 GHz. Another work, [15] has demonstrated an \( f_T \) of 254 GHz. No InP HBT work, outside of InP/GaAsSb/InP DHBTs, has demonstrated simultaneous \( f_T \) and \( f_{max} \) > 300 with breakdown voltages above 5 V.

The InP-based SHBT, despite its high \( f_T \) and \( f_{max} \) values, is limited by the narrow bandgap collector. The Ga_{0.47}In_{0.53}As collector of most SHBT designs has a bandgap of only 0.75 eV. The breakdown voltage \( V_{BCEO} \) is normally 0.5 to 2.0 V in most conventional, \( f_T > 200 \) GHz, SHBT designs.

B. Double Heterojunction Bipolar Transistor Considerations

Current double heterojunction HBTs (DHBTs) boast improvements in the collector breakdown voltage, \( V_{BCEO} \), at the expense of collector design complexity. A wide bandgap material, such as InP or AlInAs increases breakdown by reducing impact ionization in the collector.

The design challenge of a DHBT lies in the collector conduction-band discontinuity. An abrupt base-collector heterojunction of GaInAs/InP or GaInAs/AlInAs results in a conduction-band blocking barrier of ~ 0.25 eV. The barrier is a current block and degrades the operational characteristics of the transistor, preventing high-frequency, high-current operation.

The collector blocking effect reduces the \( f_T \) of the device via increased electron carrier storage in the base [16]. The stored charge in the base results in higher neutral-base recombination that leads to gain reduction.

To overcome the conduction band discontinuity of an abrupt GaInAs/InP or GaInAs/AlInAs base-collector junction, dopant grading and/or compositional grading must be employed to reduce the conduction band spike—a positive conduction band discontinuity between base and collector materials, respectively. The design of a non-blocking collector junction is not trivial and requires a detailed understanding of
heterojunction grading schemes. The formation of a non-blocking junction is one of the predominant limitations in extending DHBT performance at high current densities.

DHBT devices have yet to be implemented in commercial InP/GaInAs/InP systems because of the stringent epitaxial growth control and uniformity required for doped or compositional gradings.

C. GaAsSb DHBT Features

The relatively new alloy, GaAsSb, offers great performance enhancements in DHBTs. A great deal of the design innovations is based on the recent publication of InP/GaAsSb/InP double HBTs (DHTs) by M. Dvorak, C. Bolognesi, O. Pitts, and S. Watkins [13]. The Project 2 design utilizes the GaAsSb base in a double HBT InP structure.

1) GaAsSb/InP Collector Junctions

A GaAsSb base layer allows a simple abrupt collector heterojunction to be formed without current blocking. The GaAsSb/InP base-collector heterojunction utilizes the GaAsSb staggered band lineup with InP. Lattice-matched to the InP collector, the GaAs0.51Sb0.49 band edge of the GaAsSb base layer’s conduction band lines up ~0.15 eV above the InP conduction band edge [17], [18].

The InP/GaAsSb/InP offers an elegant solution to the obstacles faced by InP/GaInAs/InP DHBTs. The primary feature of the GaInAs material is the “staggered” band lineup with InP [19]. As seen in Fig. 6, the staggered GaAsSb/InP base-collector junction results in a non-blocking conduction-band profile, eliminating the collector blocking effect faced by abrupt junctions in conventional GaInAs-base DHBTs.

The staggered band lineup allows electrons at the base-collector junction to be ballistically launched into the collector at high initial energy values. The velocity overshoot of electrons allows for shorter transport times through the collector. The electron velocity should not be launched with “excessive” velocity because the additional energy will cause undesirable satellite valley transfers in the InP collector region—electrons reaching a critical energy for intervalley transfers. Fig. 7 shows the concept of the base-collector ballistic electron launcher at the GaAsSb/InP B-C junction.

The graded junction or spacer-separated junction in conventional base-collector GaInAs/InP DHBTs can only approach the performance of the staggered GaAsSb/InP lineup—in terms of overcoming retarding grading potentials at the heterojunction at high current densities. Even in a well-graded base-collector junction, the GaInAs/InP system experiences retarding potentials in the B-C depletion region at high currents [20], [21].

D. GaAsSb Material Characteristics

1) GaAsSb/InP Heterojunctions

The InP/GaAsSb emitter-base heterojunction boasts a very large valence-band discontinuity of 0.78 eV. Base-to-emitter hole back-injection is nearly negligible, even at very high base-doping concentrations. The isolation of the holes in the base from the emitter results in a high emitter injection efficiency. By the same token, base pushout effects are negligible in InP/GaAsSb/InP DHBTs because holes from the base also see the same ~ 0.78 eV barrier to the collector region. Fig. 8 diagrams the InP/GaAsSb/InP band lineup.

Optical-based characterizations of the bandgap have determined lattice-matched GaAs 0.51Sb0.49 (to InP) to have a 300 K bandgap of 0.72 eV. The resulting conduction band lies 0.15 eV above InP [18], and the resulting valence band discontinuity is 0.78 eV with InP.

From an HBT device standpoint, the conduction band discontinuity serves to ballistically launch electron carriers into the wide bandgap InP collector. The electrons then drift at a high average velocity (with some velocity overshoot) into the subcollector. The impact ionization rate is lower in the DHBT than the SHBT because of the larger bandgap, even though the ballistically-launched carriers carry much more energy in the DHBT case. An example of an InP/GaAsSb/InP DHBT equilibrium band diagram is present in Fig. 9.
At the base-emitter junction of the InP/GaAsSb/InP DHBT, there is no conduction band spike as seen in abrupt SHBT heterojunctions. From a processing standing, the InP/GaAsSb/InP presents an elegant solution to complex grading schemes. No grading is needed at the InP/GaAsSb E-B heterojunction due to the staggered band lineup of InP and GaAsSb. Carriers cross the E-B heterojunction via thermionic emission due to the absence of a conduction band spike.

2) GaAsSb Bandgap
The GaAs$_{1-x}$Sb$_x$ bandgap has been estimated to be, at 300 K, [24], [25],

$$E_g = 1.43 - 1.9x + 1.2x^2$$  \hspace{1cm} (18).

Like other InP-based SHBT designs, the small bandgap of the GaAsSb base allows for a low B-E turn-on voltage. Unlike abrupt InP/GaInAs or AlInAs/GaInAs base-emitter junctions, the abrupt InP/GaAsSb junction does not suffer from a conduction-band spike at the B-C junction, which results in a higher turn-on voltage in the GaInAs-base transistors. Low B-E turn-on voltages are an important consideration, especially in low-power devices. One of the great advantages of InP/GaAsSb/InP DHBT’s is that the transistor can be implemented without compositional or doping gradings—high quality, abrupt interfaces can be formed without employing complex grading mechanisms [26].

B-E turn-on and collector-emitter offset voltages are determined primarily by band lineups, dopings, and junction areas. The material symmetry in the InP/GaAsSb/InP system offers the possibility of emitter-up or collector-up device fabrication on the same wafer. Moreover, the symmetry benefits low-power applications due to very low collector-emitter offsets on the order of 0.1 V or smaller [23].

IX. InP/GaAsSb/InP DEVICE DESIGN
The next section of the report summarizes the design considerations used in choosing appropriate parameters for the InP/GaAsSb/InP DHBT device. As with any device design, many different parameters factor into the optimization of chosen figures of merit.

Again, the optimization goals for this portion of the design project have been chosen to be $f_T$ and $f_{max}$ for a reasonable—useable— collector breakdown voltage of approximately 5 V. Intricate tradeoff in other performance parameters will be discussed, but not documented in great details. Focus will be placed on the potential of the InP/GaAsSb/InP device with simulations and empirical calculations to support conclusions.

A. GaAsSb Base Design

1) Importance of Base Material
Most of the InP/GaAsSb/InP DHBT performance evolution is driven by improving growth technologies in the GaAsSb base. GaAsSb, as a material, is still in its development infancy [27]. As the growth techniques (not discussed here) are refined, critical growth-dependent parameters, such as carrier mobilities and maximum doping concentration, will improve. The advancement of GaAsSb growth technologies should have an accompanying advancement in InP/GaAsSb/InP DHBT device performance.

The design of the GaAsSb base is the most critical design step for the DHBT. The choice of base doping and dimensions not only affect the base transit time, but also the current density operating point, thereby influencing emitter charging time, among other parameters.

HBTs utilize heavy base doping concentrations (unlike traditional homojunction BJTs) in order to reduce the base resistance while maintaining emitter injection efficiency (attributed to the valence band discontinuity at the heterojunction). For GaAs alloys, doping concentrations above $10^{19}$ cm$^{-3}$ cause most p-type dopants to diffuse into other regions of the HBT, degrading the performance and reliability of the device [28], [29].

The elimination of In from the p-base of the DHBT is hypothesized to be the key factor in very heavy, active C in the GaAsSb base. C doping in GaAsSb bases saturates at five to ten times the saturation concentration of GaInAs bases. MOCVD-grown GaAsSb also boasts the advantage of high base doping (C-doped) to $3 \cdot 10^{20}$ cm$^{-3}$ without H-passivation effects. No post-annealing cycle is required in the GaAsSb base because H-passivation problems are eliminated in GaAsSb material. The elimination of annealing confines the dopants to the base and is critical to the success of very high doping levels in the base.

Finally, low p-type Schottky barrier heights of Sb-based compounds leads to low resistance ohmic contacts. Base resistances have been found to be lower than 10 $\Omega \cdot$cm$^2$ [30].

2) Base Doping Selection
Recent findings in [31] have shown that the conductivity of the GaAsSb base increases linearly (log-log scale) with the base doping. Fig. 10 illustrates this finding with measured results fit to a trend line.

The increase of conductivity with doping can be attributed to the property that the hole mobility in the p-type base degrades very little with increasing doping concentrations above $10^{19}$ cm$^{-3}$. The hole mobility behavior was measured in [31] and is presented here in Fig. 11.
Fig. 10. Conductivity as a function of carrier concentration in GaAsSb. The different families of values on the graph indicate the fraction of Sb in GaAsSb [31]. The lattice-matched InP case lies at GaAs_{0.51}Sb_{0.49}. Because the conductivity is increasing with dopant (carrier) concentration, the base of the proposed DHBT devices uses the highest dopant concentration allowed—3·10^{20} cm^{-3}.

Fig. 11. Mobility as a function of carrier concentration in GaAsSb. The mobility varies little with carrier concentration when dopant concentration is heavy—>10^{19} cm^{-3}. Because there is little degradation in mobility, an extremely high base doping concentration can be used to decrease the sheet resistance of the base [31].

### TABLE IV

<table>
<thead>
<tr>
<th>p-DOPED GaAsSb: KEY MATERIAL PROPERTIES</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Bandgap</strong>, (E_g)</td>
</tr>
<tr>
<td><strong>Electron affinity</strong>, (\chi)</td>
</tr>
<tr>
<td><strong>Hole mobility</strong>, (\mu_p)</td>
</tr>
<tr>
<td><strong>Electron mobility</strong>, (\mu_e)</td>
</tr>
</tbody>
</table>

Data for 2.5·10^{20} cm^{-3} C-doped p-type GaAs_{0.51}Sb_{0.49} (lattice matched to InP). All parameters are based on current achievable GaAsSb growth in MOCVD and GSMBE systems. Higher mobility values are forecasted—conservative estimates of mobility improvements to come in the next two years.

Base doping, for the device design and optimization, has been chosen to be as high as possible in the GaAsSb material—3·10^{20} cm^{-3} C doping. The high doping concentration reduces the sheet resistance of the intrinsic base.

One important drawback of the GaAsSb material system is the very low hole mobility at 20-30 cm²/(V·sec). Such a hole mobility results in a high sheet resistance compared to other material systems (600-1400 Ω/□ for typical mobility values and base widths in GaAsSb).

Advances in growth processes can boost hole mobility values to 50-60 cm²/(V·sec). Also, the heavy base doping helps to offset some of the low mobility effects. Table IV outlines the key material parameters taken into account for the base design.

### B. DC and RF Performance: Design Considerations

#### 1) Current Gain, \(\beta\)

The current gain, \(\beta\), is highly dependent on the base layer thickness. To increase the current gain, the base layer can be reduced. Unfortunately, due to the already high sheet resistance of the GaAsSb base, the base layer cannot be shrunk arbitrarily thin.

If the base recombination dominates the base current—a good assumption—then

\[
\beta = \frac{I_C}{I_{B,bulk}} = \frac{\tau_n}{\tau_b} \quad (19),
\]

where the base transit time, for a uniformly-doped base, is given as

\[
\tau_b = \frac{qA}{I_C} \int \frac{n(x)}{\tau_{\text{doping}}} \quad (20),
\]

and \(\tau_n\) gives the effective minority electron recombination time—a material parameter that varies with growth quality and doping concentration (slight decrease with increasing doping concentration). Measurements in [34] confirms that \(\beta\) varies, to the first order, linearly with dopant concentration (linear-log scale).

\[
\tau_n = \left[ \frac{1}{\tau_{\text{radiative}}} + \frac{1}{\tau_{\text{Auger}}} + \frac{1}{\tau_{\text{Shockley-Hall-Read}}} \right]^{-1} \quad (21).
\]

Equations (19)-(21) indicate that the DC current gain may be increased by decreasing the base width and by improving electron minority lifetimes in the base—a growth and material parameter, at the moment. (Once refined growth techniques are developed, the recombination times will primarily be a function of material choice and doping.)

Because passivation is not necessary in the GaAsSb material and because surface recombination effects are negligible in the device, \(\beta\) is primarily dependent on base width [33]. (Later in this report, base compositional grading is explorer to improve frequency response.)

#### 2) Intrinsic Base Resistance

An important tradeoff exists between the current gain and the intrinsic base resistance. The transverse intrinsic base resistance, sometimes known as the base spreading resistance, is given by

\[
R_{B,i} = \rho_B \frac{W_x}{L_x X_B} \quad (22),
\]
where the resistivity of GaAsSb is
\[ \rho_B = \frac{1}{\varrho \mu_B N_{AB}} \]  \hspace{1cm} (23).

The base resistance can also be given in \( \Omega \square \), known as sheet resistance [35]:
\[ R_{\text{sheet}} = \rho_B = \frac{1}{\varrho \mu_B N_{AB} W_E} \]  \hspace{1cm} (24).

3) Maximum Oscillation Frequency, \( f_{\text{max}} \)

To understand the base sheet resistance tradeoff with the current gain, \( \beta \), the dependence of \( f_{\text{max}} \), on sheet resistance must be examined:
\[ f_{\text{max}} = \frac{f_T}{8\pi R_B C_{\text{JBC}}} \]  \hspace{1cm} (25),
\[ R_B = \frac{R_{\text{B,sheet}} W_E}{12L_E} \]  \hspace{1cm} (26).

Smaller base widths result in higher current gain by (19) and (20), but sheet resistance also increases by (24), resulting in a higher \( r_B \).

As will be shown in the next section, \( f_T \), the cutoff frequency, does not depend on the base width or resistance. The base can theoretically be made arbitrarily thin in order to maximize the cutoff frequency—the increased base resistance given by (22) has no effect. However, with an extremely thin base, power gain is lowered due to increased base resistance, and \( f_{\text{max}} \) is sacrificed, making the device useless for power gain above the maximum oscillation frequency, \( f_{\text{max}} \). A practical tradeoff, thus, exists between the current gain and the maximum oscillation frequency of the proposed device.

The junction capacitance, \( C_{\text{JBC}} \), also plays a role in the consideration of collector doping and collector width. A higher doping in the collector results in an increased junction capacitance, thereby decreasing the maximum oscillation frequency for a given current density. To be discussed in the \( f_T \) considerations is the increase of cutoff frequency (and \( f_{\text{max}} \) indirectly via (25)) for higher collector doping. An increase in the maximum cutoff frequency is seen, but at a higher current density.

The collector can be unintentionally doped to high values (1·10^{17}) by the sub-collector doping tail. Process control and sub-collector material choice, including choice of dopants, can help greatly in suppressing the doping tail. The effects of collector doping on \( f_{\text{max}} \) can be seen indirectly from Fig. 12.

Lastly, the emitter width and length contribute to the effective base resistance and to the maximum oscillation frequency. To increase the maximum oscillation frequency, the width of the emitter stripe, \( W_E \), should be chosen to be small—around 0.4-0.8 \( \mu \text{m} \)—while the emitter length can be made long—6-12 \( \mu \text{m} \), at least. For the emitter dimension parameter, the emitter width should be kept as small as possible (0.4 \( \mu \text{m} \)) for high-frequency performance; the emitter length can be scaled to the desired current density with noise, power efficiency, or impedance in mind for different circuits and applications.

A brief aside: The project concentrates on the intrinsic device design, but the excellent extrinsic base contact to the GaAsSb is worth noting. The GaAsSb base can form an excellent Schottky contact since hole barrier height to Sb-based compounds are very low compared to As and P materials in other HBTs [36].

![Image](image-url)
The GaAsSb/InP base-collector junction exhibits Kirk-like effects—roll off of \( f_T \) with current density—only at current densities much higher than other HBT devices due to the fact that the effect is caused by an induced dipole at the B-C junction, not base push-out.

The massive valence band discontinuity at the B-C junction prevents base pushout due to hole injection. The frequency roll-off is due to a charge dipole being set up between the induced holes in the base and the excess electrons in the collector. Hole accumulation at the B-C junction causes a local electric-field reversal, inducing a thermionic barrier and decreasing the electron exit velocity from the base. The Kirk-like effect, however, happens only at very large current densities compared to other SHBTs and DHBTs.

Also of interest is the device output conductance. Recent measurements of the InP/GaAsSb/InP DHBT has confirmed that output conductance, at high currents, is not a strong function of the base width modulation since the base doping is extremely high. Instead, the output conductance is more dependent on the temperature coefficient [13].

\[ \tau_B = \frac{X^2_{de}}{2D_n} \]  
(29).

\( \tau_B \) can be decreased by thinning the base, but \( f_{max} \) is affected via (25) and the earlier discussions.

\( \tau_{C,SCR} \) is the space-charge transit time—the time it takes for electron carriers to drift through the depletion region of the collector:

\[ \tau_{C,SCR} = \frac{X_{dep}}{2v_{sat}} \]  
(30).

\( \tau_{C,SCR} \) can be optimized by adjusting collector doping and thickness. The electric field should not be so high so as to cause intervalley scattering. The collector design can be optimized such that the field at the base-side of the collector is small enough to keep electrons in the \( \Gamma \) valley. Simulations of the ballistic injection of the GaAsSb/InP B-C heterojunction help to determine an optimal thickness and doping concentration.

Fig. 13 shows the dependence of collector doping and width on the overall cutoff frequency, \( f_T \). One general trend is that thinner collectors increases the maximum \( f_T \). Another important trend is that the maximum \( f_T \) increases with collector doping. The maximum \( f_T \) value, however, is located at higher collector current densities as the collector doping is increased. Also, Kirk-like effect (due to induced dipole charges) are more apparent at lower doping concentrations.

Although the collector thickness cannot be made arbitrarily small and the doping cannot be increased very much (due to discussions of \( f_{max} \) and junction capacitances), \( f_T \) and \( f_{max} \) can be traded off to obtain nearly equal \( f_T \)'s and \( f_{max} \)'s, to some degree. In particular, the collector can be designed for appropriate velocity overshoot in order to reduce the average transit time across the region.

Collector design—width and doping—also affects the breakdown voltage. Breakdown voltage can be increased by trading off \( f_T \) for \( V_{BCEO} \). Breakdown voltages are dependent on the InP (wide bandgap) material properties as well as the width of the depletion region. The wider the depletion region, the lower the electric field, and consequently, the higher the breakdown voltage [39]. In this project, \( f_T \) is optimized with respect to material design parameters while keeping the breakdown voltage above 5 V. Breakdown optimizations with respect to \( f_T \) are done via simulation.

The collector charging time is

\[ \tau_{RC} = (R_E + R_C)C_{JC} \]  
(31).

At high current densities, the parasitic emitter resistance, \( R_E \), is often the dominating term. The collector charging time can be influenced by extrinsic resistances. Contact quality and placement (alignment close to the base mesa) can significantly reduce extrinsic effects on the parasitic terms.

Finally, we have the expression for the total transit time from emitter to collector:

\[ \tau_{EC} = \frac{nK T}{qL_C} (C_{JC} + C_{je}) + \frac{X^2_{de}}{2D_n} + \frac{X_{dep}}{2v_{sat}} + (R_E + R_C)C_{JC} \]  
(32).

Fig. 13. Cutoff frequency, \( f_T \) versus collector current density for a measured 4 x 12 µm² device. Collectors are designed in InP with different dopings and thicknesses. Collectors with lower doping exhibit more Kirk-like effects [23].

X. Simulation Results and Predictions

Avant! Medici was used as the primary device simulator for the simulation portion of the project. Many material parameters were extracted from research papers listed in the references. Most of the material data came from empirical sources. As a result simulations should only provide a rough guideline of expected device performance. “Real” device performance hinges on growth technologies and the improvement of GaAsSb processing techniques. As more is understood about this new material alloy, better models can be fit to measured data of high-quality materials.

A. Base Grading Implementation

Although no detailed discussions of graded bases were made in the previous sections of the report, due to time and report constraints, a \( \Delta 100 \) meV grading has been employed to significantly reduce base transit time while insuring that
intervalley scattering is no dominating the transport mechanism across the collector. Fig. 14 graphically shows the base transit time improvement with base grading. A compositional grading of Al introduced into the GaAsSb base is employed (a quaternary compound). A 10-12% composition of Al is sufficient to grade the base to the desired $\Delta E_{g}=100$ meV value. First-order simulations on the proposed device show that the base grading improves the $f_T$ by 10-15%.

![Graph showing base transit time vs. base width for different values of base grading](image)

Fig. 14. Base transit time, $\tau_B$, vs. base width, $W_B$, for different values of base grading ($\Delta E_{g}=0$, 50, 100 meV). A minority electron mobility of 800 cm$^2$/(V·sec) is assumed for the heavily-doped $3.0 \cdot 10^{20}$ cm$^{-3}$ base. Mobility values, at this point, are being improved with refined growth techniques.

### B. Optimized Parameters

The finalized, optimized device parameters, based on the theoretical and empirical tradeoffs discussed earlier in the report, are summarized in Table V. To prevent data clutter, all simulation results have been conglomerated into a few tables and charts.

<table>
<thead>
<tr>
<th>Material</th>
<th>Dopant</th>
<th>Doping (cm$^{-3}$)</th>
<th>Thickness (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Emitter cap contact layer</td>
<td>Ga$<em>{0.47}$In$</em>{0.53}$As</td>
<td>S (n-type)</td>
<td>2 · $10^{19}$</td>
</tr>
<tr>
<td>Emitter cap</td>
<td>InP</td>
<td>S (n-type)</td>
<td>3 · $10^{19}$</td>
</tr>
<tr>
<td>Emitter</td>
<td>InP</td>
<td>S (n-type)</td>
<td>3 · $10^{17}$</td>
</tr>
<tr>
<td>Base ($\Delta E_{g}=100$ meV)</td>
<td>Ga$<em>{0.51}$Sb$</em>{0.49}$</td>
<td>C (p-type)</td>
<td>3 · $10^{20}$</td>
</tr>
<tr>
<td>Collector</td>
<td>InP</td>
<td>S (n-type)</td>
<td>3 · $10^{16}$</td>
</tr>
<tr>
<td>Sub-collector</td>
<td>InP</td>
<td>S (n-type)</td>
<td>3 · $10^{19}$</td>
</tr>
<tr>
<td>Sub-collector contact layer</td>
<td>Ga$<em>{0.47}$In$</em>{0.53}$As</td>
<td>S (n-type)</td>
<td>2 · $10^{19}$</td>
</tr>
</tbody>
</table>

### C. Performance Results

The results of the optimized device given in Table V are summarized in Table VI. Transit times have been extracted from velocity predictions, calculations of parasitics based on Medici device parameter outputs, and frequency response has been extrapolated from simulation data.

The simulation results are for a 0.4 µm x 12 µm device. Best-case material parameters have been used to estimate the current performance ceiling of InP/GaAsSb/InP DHBTs. The material parameters are discussed early in the report and in more detail in the reference papers.

![Simulation results summary](image)

**Table VI**

**Simulation Results Summary**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\beta$</td>
<td>70</td>
</tr>
<tr>
<td>$\tau_E$</td>
<td>0.14 psec</td>
</tr>
<tr>
<td>$\tau_B$</td>
<td>0.04 psec</td>
</tr>
<tr>
<td>$\tau_C$</td>
<td>0.15 psec</td>
</tr>
<tr>
<td>$\tau_{C,SCR}$</td>
<td>0.10 psec</td>
</tr>
<tr>
<td>$\tau_{tot,E-C}$</td>
<td>0.362 psec</td>
</tr>
<tr>
<td>$f_T$</td>
<td>360 GHz</td>
</tr>
<tr>
<td>$f_{max}$</td>
<td>385 GHz</td>
</tr>
<tr>
<td>$BV_{CEO}$</td>
<td>$\sim$ 5.3 V</td>
</tr>
<tr>
<td>Average collector velocity</td>
<td>$4.3 \cdot 10^7$ cm/sec</td>
</tr>
<tr>
<td>$v_{sat}$</td>
<td>$3.3 \cdot 10^7$ cm/sec</td>
</tr>
<tr>
<td>Turn-on voltage (@ 1 A/cm$^2$)</td>
<td>0.46 V</td>
</tr>
<tr>
<td>$V_{CE}$ offset voltage</td>
<td>0.08 V</td>
</tr>
</tbody>
</table>

Aside comment on temperature stability: InP/GaAsSb/InP DHBT transistors have better temperature stability than GaAs-based SHBTs or AlInAs/GaInAs/AlInAs DHBTs. GaInAs collectors tend to suffer severe electron transport degradation due to a strong temperature dependence, resulting in lower $f_T$ values at higher temperatures. [40]

Fig. 14 on the next page shows the simulated $f_T$ versus collector current density relationship for the proposed 0.4 µm x 12 µm device. A maximum $f_T$ is obtained around 600 mA/µm$^2$ current density. A plot of $f_{max}$ is not included (due to lack of simulation time), but the characteristic curve should follow that of Fig. 14.
Fig. 15. Cutoff frequency, $f_T$ versus collector current density for 0.4 µm x 12 µm device at $V_{CE} = 1.5$ V. The 1.5 V insures that the transistor is operating in the forward active region. Also, the $f_T$ can be roughly maximized by choosing an appropriately large value of $V_{CE} > 1.2$ V.

Lastly, a Gummel plot of the collector current density versus $V_{BE}$ is included to show that the GaAsSb base has electrons injected thermally from the emitter-base heterojunction. The collector ideality factor is nearly 1.00, indicating a thermal process across the E-B junction. The $J_C$, therefore, closely follows

$$J_C = \frac{q n_{mB}^2 D_n}{N_A W_B} \left( \frac{\sqrt{V_{BE}}}{e^{q V_{BE}/kT} - 1} \right) $$

where parameters have been extracted to create the dotted line in Fig. 16. The turn-on voltage (at 1 A/cm$^2$) can be found to be approximately 0.46 V.

No I-V data is presented in this report due to lack of sufficient simulation time. The “homemade,” empirical models suffer from very long simulation times, so simulated I-V device data is limited. Enough data was extracted to insure that the frequency cutoff could be predicted and that transit times could be estimated.

XI. CONCLUSION/SUMMARY

The design project was a simulation challenge in terms of material modeling and data convergence in *Medici*, but device performance parameters have been extracted from many simulations.

A 0.4 µm x 12 µm device has been predicted to have an $f_T$ and $f_{max} > 350$ GHz with a $BV_{CEO} \sim 5.2$ V using optimistic device data supplied by projected growth advancements in GaAsSb.

The major benefits of the InP/GaAsSb/InP DHBT lies in the fact that the staggered band lineup results in thermally-injected electrons at the emitter-base interface, ballistic injection of electron from base to collector, and massive valence band discontinuities to isolate holes in the base. All these benefits, strategically, come without complicated grading or doping schemes.

Future areas of investigation can look into the use of a hot-electron launcher at the emitter-base junction. Such a launched can be made from AlInAs/GaAsSb emitter-base junction with dopant and compositional gradings optimized to provide desired carrier velocities.

Many of the improvements in simulation accuracy lies in better material data modeling. No hot-electron data, for instance is available for the GaAsSb base, making the hot-electron launcher simulation a difficult one to process. As seen by the device simulations, the InP/GaAsSb/InP DHBT offers great potential for high-frequency HBT devices. The device innovations and improvements are now critically dependent on the advancement of growth technology in Sb-based materials.

The InP/GaAsSb/InP DHBT seems to have a very promising, useful future ahead of it!

XII. ADDENDUM

![Collector current density vs. collector-emitter voltage plot. Breakdown voltage simulation for 0.4 µm x 12 µm device at $I_B$ steps of 100 μA. $BV_{CEO}$ is approximately 5.3 V, as shown in the plot.](image)