DEVICE CHARACTERISTICS OF THE PNP
ALGAAS/INGAASN/GAAS DOUBLE HETEROJUNCTION
BIPOLAR TRANSISTOR

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ABSTRACT

We have demonstrated a functional PnP double heterojunction bipolar transistor (DHBT) using AlGaAs, InGaAsN, and GaAs. The band alignment between InGaAsN and GaAs has a large ΔEc and a negligible ΔEv, and this unique characteristic is very suitable for PnP DHBT applications. The metalorganic vapor phase epitaxy (MOCVD) grown Al0.3Ga0.7As/In0.03Ga0.97As0.99N0.01/GaAs PnP DHBT is lattice matched to GaAs and has a peak current gain of 25. Because of the smaller bandgap (Eg = 1.20 eV) of In0.03Ga0.97As0.99N0.01 used for the base layer, this device has a low VON of 0.79 V, which is 0.25 V lower than in a comparable PnP AlGaAs/GaAs HBT. And because GaAs is used for the collector, its BVCEO is 12 V, consistent with BVCEO of AlGaAs/GaAs HBTs of comparable collector thickness and doping level.

INTRODUCTION

InGaAsN has received a lot of attention lately. Incorporating a small amount of nitrogen (N) into InGaAs results in a reduction of its lattice constant, thus reducing the strain of InGaAs layer grown on GaAs1, 2. In addition, due to a large bandgap (Eg) bowing, the Eg decreases as N is added1, 2, a desirable characteristic for GaAs based device structures that require material with a smaller Eg than the 1.42 eV of GaAs. Recent advances in the InGaAsN material system has led to much progress on the application of this material system for a variety of devices3, 4, 5. A heterojunction bipolar transistor (HBT) for low-power electronic application is a device that could take advantage of InGaAsN by means of a lower device turn on voltage (VON). The HBT with a small Eg in the base has lower VON, a desirable characteristic for reducing power dissipation in circuits. One approach uses strained InGaAs on GaAs, however, the range of In composition for growing strained InGaAs on GaAs without formation of misfit dislocations is very limited. In addition, due to the compressive strain, the Eg of InGaAs increases, reducing the benefits of having InGaAs in the base layer5. For this reason,
most of the earlier work on low-power HBT have focused on the InP/InGaAs material system. However, the InP technology is expensive, and its application has been limited. The InGaAsN HBT is based on GaAs, allowing it can take advantage of the existing GaAs foundry technology, and it may be an excellent alternative for low-cost, low-power electronics.

The band alignment of the InGaAsN material system is illustrated in Figure 1. As N is incorporated into GaAs, a tensile strain develops. Adding N to GaAs lowers both the conduction band ($E_C$) and the valence band ($E_V$). On the other hand, a compressive strain builds up as indium (In) is added to GaAs, the $E_C$ is lowered, and the $E_V$ is raised. By incorporating proper amount of In and N into GaAs simultaneously, InGaAsN that is lattice matched to GaAs can be obtained. The $E_C$ of the resulting InGaAsN would be significantly lower because of the aggregate lowering effect from the incorporation of N and In. The effects on $E_V$ from the incorporation of N and In are compensated, and the $E_V$ is relatively unchanged compared to the $E_V$ level of GaAs. The resulting band alignment, as shown in Figure 2, is favorable for PnP DHBT applications.

Using AlGaAs for emitter and GaAs for the collector, a large conduction band discontinuity ($\Delta E_C$) on the emitter side suppresses the electrons from being injected into the emitter from the base, while a small valence band discontinuity ($\Delta E_V$) facilitates hole transport from the emitter to the base. On the collector side, the $\Delta E_V$ is negligible, thus GaAs can be used for the collector layer and the device does not have to resort to complicated grading or doping schemes to eliminate the non-ideal effects suffered by most DHBTs. In this work, we report the operation of an AlGaAs/InGaAsN/GaAs PnP DHBT.
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Figure 2: The band alignment of the 
Al_{0.3}Ga_{0.7}As/In_{0.03}Ga_{0.97}As_{0.99}N_{0.01}/GaAs DHBT. At the base-emitter junction, the In_{0.03}Ga_{0.97}As_{0.99}N_{0.01} has a large $\Delta E_c$ and a small $\Delta E_v$ with respect to Al_{0.3}Ga_{0.7}As. Compared to GaAs at the base-collector junction, InGaAsN has negligible $\Delta E_v$. This band alignment is very suitable for PnP DHBT applications.

**DESIGN AND FABRICATION**

The structure of the PnP Al_{0.3}Ga_{0.7}As/In_{0.03}Ga_{0.97}As_{0.99}N_{0.01}/GaAs DHBT investigated in this work is shown in Table I. The base layer is made of In_{0.03}Ga_{0.97}As_{0.99}N_{0.01}, which is lattice matched to GaAs and its $E_g$ is approximately 1.2 eV. The resulting band structure should resemble the diagram shown in Figure 2. For the Al_{0.3}Ga_{0.7}As/In_{0.03}Ga_{0.97}As_{0.99}N_{0.01} emitter-base junction, the $\Delta E_v$ at the base emitter junction would be around 0.15 eV, while the $\Delta E_c$ would be more than 0.5 eV. At the base-collector junction, the $\Delta E_v$ between In_{0.03}Ga_{0.97}As_{0.99}N_{0.01} and GaAs is negligible. As discussed earlier, this is very suitable for PnP DHBT applications. Thus, GaAs can be used instead of InGaAsN in the collector without typical penalties suffered by DHBTs, at
the same time, taking advantage of the larger $E_G$ of GaAs, which allows for higher breakdown voltages, especially when compared to other low-power HBTs based on InP/InGaAs material system. In addition, the hole mobility ($\mu_p$) of the best InGaAsN reported to date is about half of the $\mu_p$ typically observed in GaAs, therefore using GaAs as the collector material would affect the rf performance of this device positively. The DHBT structure under study was grown by metalorganic-chemical vapor deposition (MOCVD) using an Emcore D180 system. The material compositions were calibrated using photoluminescence measurement (PL) and x-ray diffraction (XDR). The doping levels were confirmed with polaron and Hall measurement. The surface morphology of the sample is uniform and smooth. The DHBT device was fabricated using a triple mesa process. Wet etching was used to expose the base and the subcollector surface, as well as for achieving device isolation. All three etches were done using the 1 H$_3$PO$_4$ : 4 H$_2$O$_2$ : 45 H$_2$O solution. Pt/Ti/Pt/Au forms non-alloyed ohmic contacts for the emitter and the collector. In order to avoid spiking through the base layer, Pd/Ge/Au annealed at 175°C for 1 hour was used for the base contact metal. For this work, the device was not passivated. The emitter area of the final device is about 500 $\mu$m$^2$.

<table>
<thead>
<tr>
<th>Material</th>
<th>Thickness [Å]</th>
<th>Doping [cm$^{-3}$]</th>
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<tbody>
<tr>
<td>Contact Cap Layer</td>
<td>$p^+$ GaAs</td>
<td>2000</td>
</tr>
<tr>
<td>Emitter Layer</td>
<td>$p$ Al$<em>{0.3}$Ga$</em>{0.7}$As</td>
<td>1000</td>
</tr>
<tr>
<td>Spacer Layer</td>
<td>$u$- Al$<em>{0.3}$Ga$</em>{0.7}$As</td>
<td>50</td>
</tr>
<tr>
<td>Base Layer</td>
<td>$n$ In$<em>{0.03}$Ga$</em>{0.97}$As$<em>{0.99}$N$</em>{0.01}$</td>
<td>1000</td>
</tr>
<tr>
<td>Collector Layer</td>
<td>$p^+$ GaAs</td>
<td>5000</td>
</tr>
<tr>
<td>Subcollector Layer</td>
<td>$p^+$ GaAs</td>
<td>5000</td>
</tr>
<tr>
<td>Substrate</td>
<td>S. I. GaAs</td>
<td></td>
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</tbody>
</table>

**RESULTS**

The fabricated device was tested using a HP-4145 Semiconductor Parameter Analyzer. The Gummel plot and the measured common-emitter current-voltage (IV) plot are shown in Figure 3 and Figure 4, respectively. As shown in Figure 3, the Al$_{0.3}$Ga$_{0.7}$As/In$_{0.03}$Ga$_{0.97}$As$_{0.99}$N$_{0.01}$/GaAs DHBT has a current gain ($B$) of 25, which is sufficient gain to be useful for many circuit applications. More importantly, the $V_{ON}$ of...
the Al$_{0.3}$Ga$_{0.7}$As/In$_{0.03}$Ga$_{0.97}$As$_{0.99}$N$_{0.01}$/GaAs DHBT, as defined by the base-emitter junction bias ($V_{BE}$) at which the collector current ($I_C$) exceeds 1.0 $\mu$A, is only 0.79 V, which is significantly lower than the 1.03 V measured in a Al$_{0.3}$Ga$_{0.7}$As/GaAs HBT with similar structure, confirming that HBTs with an InGaAsN base layer can be used as an alternate approach for reducing power dissipation in a low-power circuit. Also, because GaAs is used for the collector layer, the emitter collector breakdown voltage ($BV_{CEO}$) is about 12 V, comparable to the $BV_{CEO}$ observed in an AlGaAs/GaAs HBT with similar collector thickness and doping level.

Other important parameters considered are the offset voltage ($V_{offset}$) and the saturation voltage ($V_{sat}$). As can be observed from Figure 4, the $V_{offset}$ of our device is about 220 mV, which is slightly higher than what is measured in an AlGaAs/GaAs HBT. The $V_{sat}$ is also slightly higher than expected, ranging from 0.55 V to 0.85 V for $I_C$ ranging from about 1.4 mA to 12.0 mA. This discrepancy probably arises because the material quality of the In$_{0.03}$Ga$_{0.97}$As$_{0.99}$N$_{0.01}$ still does not match that of the GaAs. The base sheet resistance ($R_h$) of the In$_{0.03}$Ga$_{0.97}$As$_{0.99}$N$_{0.01}$ base layer is about 3 K$\Omega$/Square, this is because the electron mobility ($\mu_n$) in the base layer is significantly lower than the $\mu_n$ in a comparable GaAs material. At about 350 cm$^2$V$^{-1}$s$^{-1}$, it is much lower than the $\mu_n$ typically observed in GaAs, which is around 2000 cm$^2$V$^{-1}$s$^{-1}$. Therefore, despite a base
doping concentration ($N_{DB}$) of $1.2 \times 10^{18}$ cm$^{-3}$, the $R_B$ is still high. The high value of $R_B$ leads to the high $V_{offset}$ and high $V_{sat}$ as observed in Figure 4.

![Graph of common-emitter IV plot](image)

**Figure 4**: The common-emitter IV plot of the Al$_{0.3}$Ga$_{0.7}$As/In$_{0.03}$Ga$_{0.97}$As$_{0.99}$N$_{0.01}$/GaAs PnP DHBT. The five curves correspond to $I_B$ of 0.2, 0.4, 0.6, 0.8, and 1.0 mA. The $V_{offset}$ is about 220 mV, and the $V_{sat}$ varies from about 0.55 V to 0.85 V.

In addition, the $\beta$ for a typical Al$_{0.3}$Ga$_{0.7}$As/GaAs Pnp HBT is greater than 100. Considering the presence of a larger $\Delta E_C$ at the Al$_{0.3}$Ga$_{0.7}$As/In$_{0.03}$Ga$_{0.97}$As$_{0.99}$N$_{0.01}$ base-emitter junction, and the fact that $\beta$ should increase exponentially with increasing $\Delta E_C$, $\beta$ should ideally be greater than 25. A possible cause may be the presence of recombination centers in the In$_{0.03}$Ga$_{0.97}$As$_{0.99}$N$_{0.01}$ base, thus resulting in high levels of recombination current and lower $\beta$. One indication that the material could be improved is the high ideality factor of the base current ($n_B$). A high $n_B$ indicates high level of recombination current, thus reducing the value of $\beta$. However, as shown in Figure 3, the $n_B$ is very large (about 3.2), indicating that there is more than just intrinsic base recombination effects. Since the device tested has not been passivated, a possible source of recombination current is the surface recombination. The type of surface states present on In$_{0.03}$Ga$_{0.97}$As$_{0.99}$N$_{0.01}$ is still unknown. More study would be needed to understand it better, and a proper passivation method for InGaAsN would need to be determined to improve the performance of this device.
CONCLUSION

The quality of the InGaAsN material has now been improved to the point that an operational $\text{Al}_{0.3}\text{Ga}_{0.7}\text{As/In}_{0.03}\text{Ga}_{0.97}\text{As}_{0.99}\text{N}_{0.01}/\text{GaAs}$ PnP DHBT is demonstrated. The near ideal band alignment between InGaAsN and GaAs results in near ideal IV characteristics without resorting to grading or delta doping schemes needed in typical DHBTs. The AlGaAs/InGaAsN/GaAs DHBT has a peak $\beta$ of 25. Since the collector is made of GaAs, the $V_{\text{CEO}}$ of 12 V is comparable to the $V_{\text{CEO}}$ observed in a AlGaAs/GaAs HBTs with similar collector thickness and doping. The narrower $E_G$ of In$_{0.03}$Ga$_{0.97}$As$_{0.99}$N$_{0.01}$ has led to the low $V_{\text{ON}}$ of 0.79 V, an important parameter for HBT application in circuits that require reduced power dissipation. However, due to the limitation of the InGaAsN material available today, the $R_B$ is still high, causing the $V_{\text{offset}}$ and the $V_{\text{sat}}$ to be high. Further improvements on the InGaAsN material would benefit the performance of AlGaAs/InGaAsN/GaAs DHBTs for low-power applications. And, the existence of surface states on InGaAsN also needs to be characterized, so that a proper passivation scheme can be determined to improve the performance of the AlGaAs/InGaAsN/GaAs DHBT.

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