Device Characteristics of the GaAs/InGaAsN/GaAs P-N-P Double Heterojunction Bipolar Transistor

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Abstract—We have demonstrated the dc and rf characteristics of a novel p–n–p GaAs/InGaAsN/GaAs double heterojunction bipolar transistor. This device has near ideal current–voltage (I–V) characteristics with a current gain greater than 45. The smaller bandgap energy of the InGaAsN base has led to a device turn-on voltage that is 0.27 V lower than in a comparable p–n–p AlGaAs/GaAs heterojunction bipolar transistor. This device has shown fMAX values of 12 GHz. In addition, the aluminum-free emitter structure eliminates issues typically associated with AlGaAs.

Index Terms—Aluminum-free emitter, complementary HBT, InGaAsN, low-power electronic, p–n–p HBT.

I. INTRODUCTION

The trend in portable electronics is to extend the battery lifetime without sacrificing the performance. One approach toward this goal is to reduce the device turn-on voltage (VON) to minimize power consumption. For heterojunction bipolar transistors (HBTs), a lower bandgap energy (Eg) base layer reduces the VON, leading to greater efficiency at low-bias conditions. HBTs with InGaAs base layers lattice matched to InP substrates offer one possibility that has not been adopted by commercial foundries due to high substrate cost, concerns over breakage, and lack of 6-in wafers. InGaAsN lattice matched to GaAs is a new material that has received a lot of attention lately [1]–[5]. Incorporating small amount of N into InGaAs on GaAs would significantly reduce strain and Eg, making it very suitable for low-power HBT applications. Recently, we have demonstrated an n–p–n InGaP/InGaAsN/GaAs double heterojunction bipolar transistor (DHBT) [4], and an p–n–p AlGaAs/InGaAsN HBT [5]. Both of these devices show VON values that are significantly lower than in their corresponding GaAs based HBTs [4], [5], confirming the potential of InGaAsN based HBTs for low-power applications.

The complementary heterojunction bipolar transistor (CHBT) technology has the potential for enhanced circuit performance for digital, linear, and microwave applications compared to circuits using only n–p–n HBTs [6]. The focus in this work is the realization of a p–n–p GaAs/InGaAsN/GaAs DHBT, which in conjunction with the n–p–n InGaAsN based HBT technology, would allow realization of a low-power CHBT technology that is compatible with existing GaAs foundries.

II. THEORY

The Eg of GaAs is reduced as In is incorporated, while a compressive strain develops. On the other hand, by adding N into GaAs, a tensile strain develops, while the Eg is further reduced. By incorporating proper amount of In and N into GaAs simultaneously, InGaAsN that is lattice matched to GaAs can be obtained. The Eg of the resulting InGaAsN would be significantly lower because of the aggregate Eg reduction effect from the incorporation of N and In [1]. The InGaAsN lattice matched to GaAs would have almost all of its Eg reduction in the form of conduction band (Eg) lowering, thus resulting in a large conduction band offset (ΔEg) with negligible valence band discontinuity (ΔEV). The resulting band alignment is especially suitable for p–n–p HBT applications.

In this work, we have investigated application of In0.70Ga0.30As0.96N0.04 for p–n–p DHBTs. Due to the presence of DX centers associated with Al in an AlGaAs emitter, reliability of the AlGaAs/GaAs HBT is a concern [7],

TABLE I

<table>
<thead>
<tr>
<th>Layer Structure of the P–N–P GaAs/InGaAsN/GaAs DHBT</th>
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<tbody>
<tr>
<td>Material</td>
</tr>
<tr>
<td>p⁺ GaAs</td>
</tr>
<tr>
<td>Emitter Layer</td>
</tr>
<tr>
<td>Base Layer</td>
</tr>
<tr>
<td>Collector Layer</td>
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<tr>
<td>Substrate</td>
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</table>

Fig. 1. Band diagram of the p–n–p GaAs/InGaAsN/GaAs DHBT.
thus it is very advantageous to eliminate the use of Al in the emitter layer. InGaP is typically used instead of AlGaAs in GaAs based n–p–n HBTs. However, with a large $\Delta E_C$ and only 0.12 eV of $\Delta E_G$, the band alignment between InGaP and GaAs is not ideal for p–n–p applications. The InGaAsN with 3% In and 1% N is lattice matched to GaAs has an $E_G$ of approximately 1.2 eV. According to Kondow et al. [1], at low In and N composition, the band alignment between GaAs and InGaAsN is such that about 90% of $\Delta E_G$ occur at the conduction band. This translates to a $\Delta E_C$ of approximately 0.2 eV between GaAs and In$_{0.03}$Ga$_{0.97}$As$_{0.67}$N$_{0.33}$. Taking advantage of this band alignment, we have designed an aluminum-free GaAs/InGaAsN/GaAs p–n–p DHBT as shown in Table I, with the corresponding band diagram of this structure shown in Fig. 1. Since the $\Delta E_V$ is negligible, GaAs is also used as the collector material, the hole transport across the base-collector (BC) junction can be achieved without need of any exotic junction grading designs. A GaAs collector is adopted for this design to take advantage of the larger $E_G$ of GaAs, which would result in improved breakdown voltage ($BV_{CE}$). In addition, because the InGaAsN has a background acceptor concentration in the low-$10^{17}$ cm$^{-3}$, the GaAs collector is preferred.

III. EXPERIMENT

The p–n–p DHBT shown in Table I was grown with an Emcore D180 turbodisk reactor. Trimethylindium, trimethylgallium, 100% arsine (AsH$_3$), and 1,1-dimethylhydrazine (DMHy) were used as the In, Ga, As, and N precursors, respectively, for the growth of InGaAsN/GaAs p–n–p DHBT as shown in Table I, with the corresponding band diagram of this structure shown in Fig. 1. Since the $\Delta E_V$ is negligible, GaAs is also used as the collector material, the hole transport across the base-collector (BC) junction can be achieved without need of any exotic junction grading designs. A GaAs collector is adopted for this design to take advantage of the larger $E_G$ of GaAs, which would result in improved breakdown voltage ($BV_{CE}$). In addition, because the InGaAsN has a background acceptor concentration in the low-$10^{17}$ cm$^{-3}$, the GaAs collector is preferred.

IV. RESULTS

The GaAs/InGaAsN/GaAs DHBT has a median current gain ($\beta$) of 45, and the device $I$–$V$ characteristics are nearly ideal. The Gummel plot and the common-emitter $I$–$V$ characteristics of a typical device are shown in Figs. 2 and 3, respectively. The $\beta$ of 45 is lower than what is expected of an AlGaAs/GaAs HBT with similar doping and thickness. However, the $\beta$ reduction is expected because despite recent advances in the InGaAsN material quality, the crystalline quality of the InGaAsN base is still inferior to that of a GaAs base, resulting in higher recombination current and lower $\beta$. In addition, the $\Delta E_C$ present at the GaAs/InGaAsN BE junction is significantly reduced compared to the AlGaAs/GaAs interface. However, because the $\beta$ obtained from a comparable AlGaAs/InGaAsN/GaAs DHBT have also been around 45, indicating that the dominating factor for the lowered $\beta$ is the crystalline quality of the InGaAsN base. The $BV_{CE}$ of the InGaAsN based DHBT is about 12 V, which is the same as the similar AlGaAs/GaAs HBT, as expected.

In this study, we have defined $V_{ON}$ as the BE bias at which collector current ($I_C$) becomes greater than 1 $\mu$A. As expected, the $V_{ON}$ of the InGaAsN DHBT is about 0.27 V lower than in the comparable AlGaAs/GaAs HBT. This $V_{ON}$ is also about 0.02 V lower than that of a comparable AlGaAs/InGaAsN HBT because of the reduced $\Delta E_V$ at the BE junction. In addition, due to the DHBT design, the resulting offset voltage ($V_{offset}$) of 0.06 V is also significantly lower than the 0.13 V observed in the AlGaAs/GaAs HBT. These low-power properties are expected from the reduced $E_G$ in the base material, and from the near-ideal band alignment for this p–n–p DHBT design.

Both the cutoff frequency ($f_T$) and the maximum oscillation frequency ($f_{MAX}$) of the p–n–p GaAs/InGaAsN/GaAs DHBT are about 12 GHz. The base sheet resistance ($R_B$) of these de-
The $R_T$ of the InGaAsN base is high due to the low electron mobility ($\mu_n$) of this novel material. At about 350 cm$^2$V$^{-1}$s$^{-1}$, the $\mu_n$ of InGaAsN is much lower than the $\mu_n$ typically observed in GaAs, which is around 2000 cm$^2$V$^{-1}$s$^{-1}$. Both $f_T$ and $f_{MAX}$ should be higher if the quality of InGaAsN could be improved. For comparison, we have taken an AlGaAs/GaAs HBT with similar layer thickness and doping concentration as the device shown in Table I, then we fabricated devices with comparable $R_B$ by over-etching into the base layer. We have observed $f_T$ and $f_{MAX}$ values of 12 GHz and 10 GHz, respectively, on these comparable AlGaAs/GaAs devices. The results are comparable within the margin of 2 GHz of variability. The similar results are expected because these two devices have similar base and collector characteristics.

V. Conclusion

In conclusion, we have demonstrated a GaAs/InGaAsN/GaAs p–n–p DHBT that has shown near-ideal dc characteristics with a $\beta$ of 45, while its rf characteristics are comparable or better than in a similar AlGaAs/GaAs HBT. The GaAs emitter in this design eliminates the problems associated with AlGaAs emitters. In addition, the $V_{ON}$ reduction of 0.27 V compared to AlGaAs/GaAs HBT makes it very useful for implementation of low-voltage complementary electronics that is compatible with the existing GaAs foundries. The performance of this device is mainly limited by the quality of the available InGaAsN. Further improvements on InGaAsN crystalline quality would lead to more optimized device performances.

REFERENCES