AlGaAs/InGaAsN/GaAs PnP Double Heterojunction Bipolar Transistor

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We have demonstrated a functional MOCVD-grown AlGaAs/InGaAsN/GaAs PnP DHBT that is lattice matched to GaAs and has a peak current gain (β) of 25. Because of the smaller bandgap (E_g = 1.20 eV) of $In_{0.03}Ga_{0.97}As_{0.99}N_{0.01}$ used for the base layer, this device has a low V_{ON} of 0.79 V, 0.25 V lower than in a comparable Pnp AlGaAs/GaAs HBT. The BV_{CEO} is 12 V, consistent with its GaAs 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 GaAs [1], a desirable characteristic for GaAs-based device structures that require material with a smaller E_G 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 devices [2-4]. 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 (V_{ON}). The HBT with a small E_G in the base has lower V_{ON}, a desirable characteristic for reducing power dissipation in circuits. The InGaAsN material system may be an excellent alternative for low-power HBTs. It is compatible with the existing GaAs foundry technology; thus, it is more likely to be us in inexpensive low-power electronics.

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Device Theory : 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 structure of the PnP AlGaAs/InGaAsN/GaAs DHBT investigated in this work is shown in Table I. The base layer is made of $In_{0.03}Ga_{0.97}As_{0.99}N_{0.01}$, hereby referred to as InGaAsN, which is lattice matched to GaAs and its E_g is approximately 1.2 eV. The emitter layer and collector layers are made of $Al_{0.3}Ga_{0.7}As$ and GaAs, respectively. The resulting band alignment, as shown in Figure 1, is favorable for PnP DHBT applications. At the AlGaAs/InGaAsN emitter-base junction, the valence band discontinuity (ΔE_V) at the base emitter junction would be around 0.15 eV, while the conduction band discontinuity (ΔE_C) would be more than 0.5 eV. The large ΔE_C on the emitter side suppresses the electrons from being injected into the emitter from the base, while a small ΔE_V facilitates hole transport from the emitter to the base. At the base-collector junction, the ΔE_V between InGaAsN and GaAs is negligible. On the collector side, the ΔE_V is negligible, thus GaAs can be used for the collector layer without resorting to complicated grading or doping schemes to eliminate the non-ideal effects suffered by most DHBTs. At the same time, this device takes 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 (μ_p) of the best InGaAsN reported to date is about half of the μ_p typically observed in GaAs, therefore using GaAs as the collector material would affect the rf performance of this device positively. In this letter, we report the operation of an AlGaAs/InGaAsN/GaAs PnP DHBT.

Device Fabrication : 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 and x-ray diffraction. 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_3PO_4 : 4 H_2O_2 : 45 H_2O 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 [5]. For this work, the device was not passivated. A circular emitter with a diameter of 50 μm was used. The fabricated device was tested using a HP-4145 Semiconductor Parameter Analyzer.

Results : The Gummel plot of the AlGaAs/InGaAsN/GaAs DHBT is shown in Figure 2, the peak β is 25, which is sufficient gain to be useful for many circuit applications. More importantly, the V_{ON} of the AlGaAs/InGaAsN/GaAs DHBT, as defined by the base-emitter junction bias (V_{BE}) at which the collector current (I_C) exceeds 1.0 μA, is only 0.79 V, which is significantly lower than the 1.03 V measured in a AlGaAs/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. However, the base resistance (R_B) is high due to the lower electron mobility (μ_n) of InGaAsN ($\mu_n = 350\ cm^2V^{-1}s^{-1}$) compared to GaAs ($\mu_n = 2000\ cm^2V^{-1}s^{-1}$. The base current ideality factor (n_{Ib}) is high ($n_{Ib} = 3.2$), possibly due to lack of device passivation.

Conclusion : The first operational AlGaAs/InGaAsN/GaAs PnP DHBT is demonstrated. The near ideal band alignment between InGaAsN and GaAs results in good IV characteristics without resorting to grading or delta doping schemes typically needed in DHBTs. The AlGaAs/InGaAsN/GaAs DHBT has a peak β of 25. Since the collector is made of GaAs, the BV_{CEO} of 12 V is comparable to the BV_{CEO} observed in a AlGaAs/GaAs HBTs with similar collector thickness and doping. The narrower E_G of InGaAsN has led to the low V_{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. 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.

Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy under Contract DE-AC04-94AL85000.

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Table Captions :

Table 1 : 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.

Figure Captions :

Figure 1 : 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.

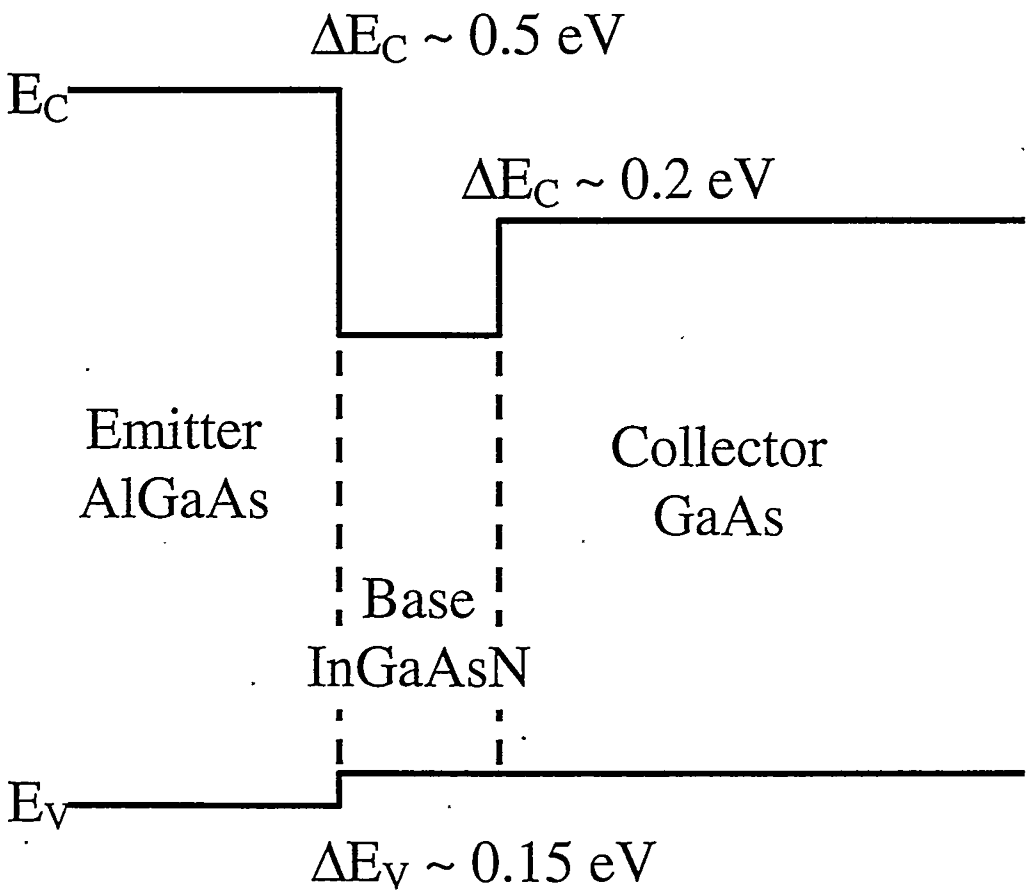
Figure 2 : The Gummel plot of the AlGaAs/InGaAsN/GaAs PnP DHBT.

Figure 3 : The common-emitter IV characteristics of the AlGaAs/InGaAsN/GaAs PnP DHBT.

Table 1 :

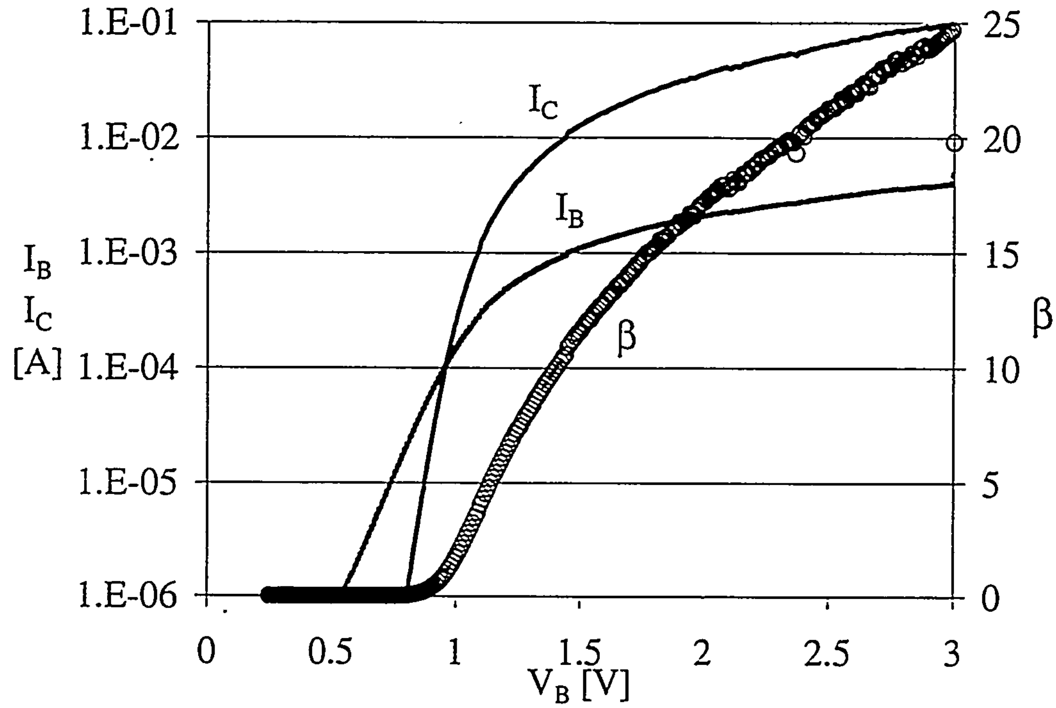
	Material	**Thickness [Å]**	**Doping [cm^{-3}]**
Contact Cap Layer	p^+ GaAs	2000	2.00E+19
Emitter Layer	p $Al_{0.3}Ga_{0.7}As$	1000	3.00E+18
Spacer Layer	u- $Al_{0.3}Ga_{0.7}As$	50	*Undoped*
Base Layer	n $In_{0.03}Ga_{0.97}As_{0.99}N_{0.01}$	1000	1.20E+18
Collector Layer	p^- GaAs	5000	3.00E+16
Subcollector Layer	p^+ GaAs	5000	2.00E+19
Substrate	S. I. GaAs		

Figure 1 :



$\Delta E_C \sim 0.5$ eV
E_C
$\Delta E_C \sim 0.2$ eV
Emitter
AlGaAs
Collector
GaAs
Base
InGaAsN
E_V
$\Delta E_V \sim 0.15$ eV

Figure 2 :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1.E-02
1.E-03
1.E-04
1.E-05
1.E-06
I_B
I_C
[A]
I_C
I_B
β
25
20
15
10
5
0
β
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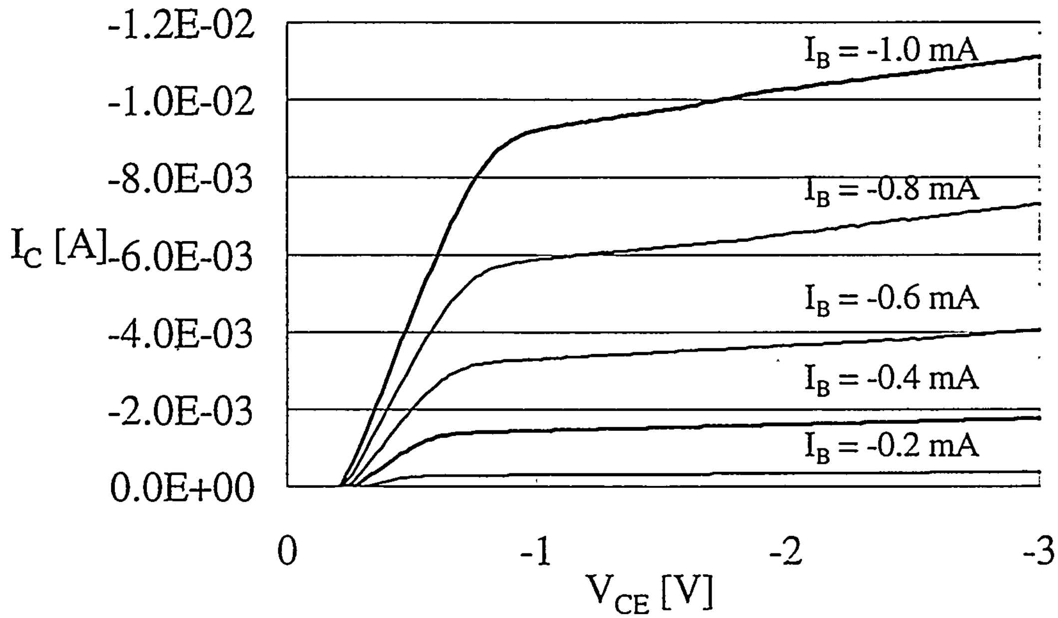
0.5
1
1.5
2
2.5
3
V_B [V]

Figure 3 :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I_B = -1.0 mA
I_B = -0.8 mA
I_B = -0.6 mA
I_B = -0.4 mA
I_B = -0.2 mA
0
-1
-2
-3
V_CE [V]