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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 ΔE_C and a negligible ΔE_V, and this unique characteristic is very suitable for PnP DHBT applications. The metalorganic vapor phase epitaxy (MOCVD) grown $Al_{0.3}Ga_{0.7}As/In_{0.03}Ga_{0.97}As_{0.99}N_{0.01}/GaAs$ PnP DHBT is lattice matched to GaAs and has a peak current gain 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, which is 0.25 V lower than in a comparable Pnp AlGaAs/GaAs HBT. And because GaAs is used for the collector, its BV_{CEO} is 12 V, consistent with BV_{CEO} 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 GaAs[1, 2]. In addition, due to a large bandgap (E_G) bowing, the E_G decreases as N is added[1, 2], 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[3, 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 (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. 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 E_G of InGaAs increases, reducing the benefits of having InGaAs in the base layer[6]. 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[7, 8]. 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.[9] 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 (ΔE_C) on the emitter side suppresses the electrons from being injected into the emitter from the base, while a small valence band discontinuity (ΔE_V) facilitates hole transport from the emitter to the base. On the collector side, the ΔE_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.

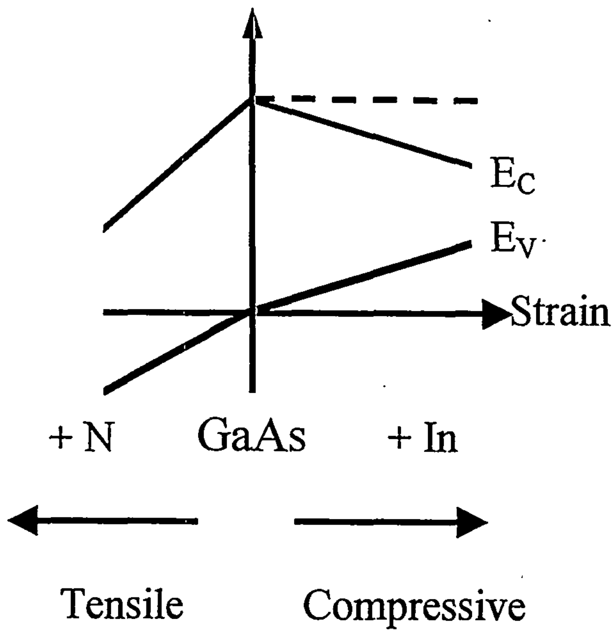

Figure 1 : The effect on the conduction band and valence band edges by incorporating N and In into GaAs.[9]

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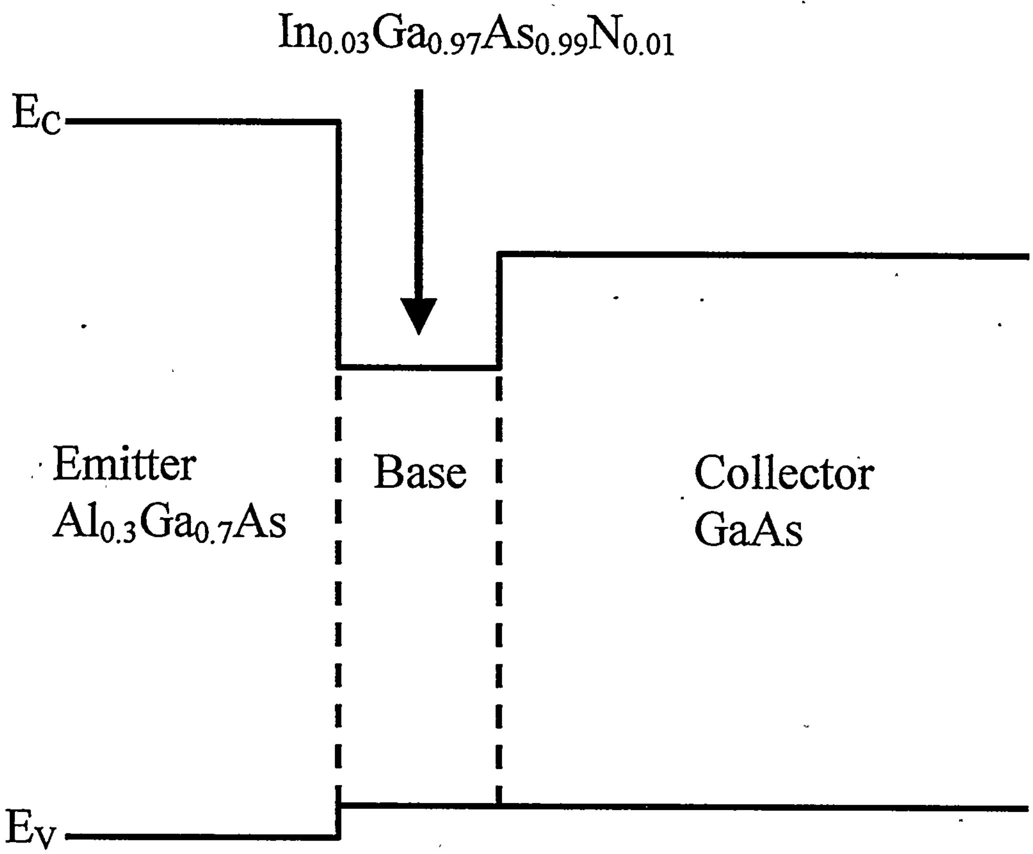

Figure 2 : The band alignment of the $Al_{0.3}Ga_{0.7}As/In_{0.03}Ga_{0.97}As_{0.99}N_{0.01}/GaAs$ DHBT. At the base-emitter junction, the $In_{0.03}Ga_{0.97}As_{0.99}N_{0.01}$ has a large ΔE_C and a small ΔE_V with respect to $Al_{0.3}Ga_{0.7}As$. Compared to GaAs at the base collector junction, InGaAsN has negligible ΔE_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 ΔE_V at the base emitter junction would be around 0.15 eV, while the ΔE_C would be more than 0.5 eV. At the base-collector junction, the ΔE_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 (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. 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_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.[10] For this work, the device was not passivated. The emitter area of the final device is about 500 μm^2.

Table I : 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. The device was grown on S. I. GaAs substrate by MOCVD using the Emcore D180 system.

	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		

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 (β) 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 μA, 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.

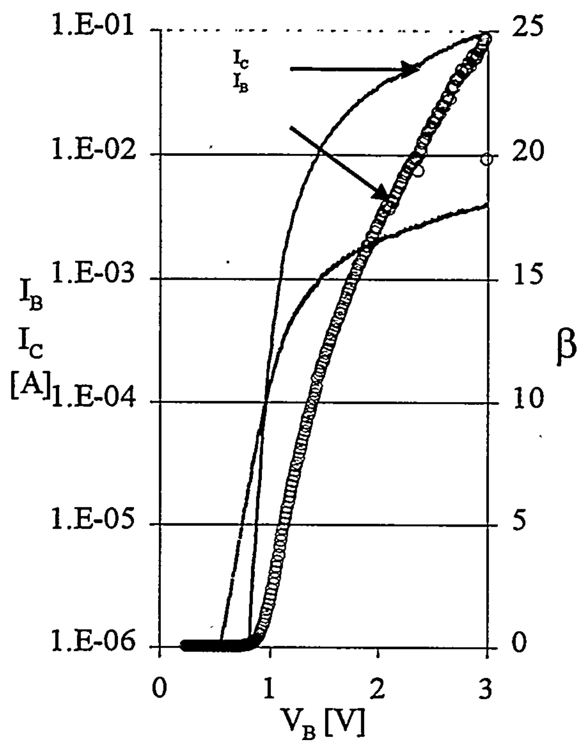

Figure 3 :

The Gummel 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 β of this device is 25. The V_{ON} is only 0.79 V, significantly lower than the 1.03 V of a comparable AlGaAs/GaAs HBT. But the n_{Ib} is poor, indicating high level of recombination current.

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_B) of the $In_{0.03}Ga_{0.97}As_{0.99}N_{0.01}$ base layer is about 3 KΩ/Square, this is because the electron mobility (μ_n) in the base layer is significantly lower than the μ_n in a comparable GaAs material. At about 350 $cm^2V^{-1}s^{-1}$, it is much lower than the μ_n typically observed in GaAs, which is around 2000 $cm^2V^{-1}s^{-1}$. Therefore, despite a base doping concentration (N_{DB}) of 1.2×10^{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.

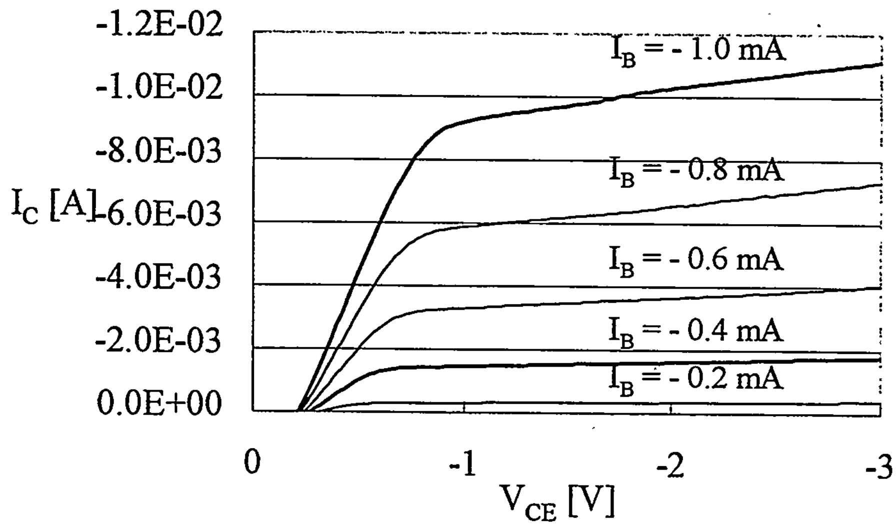

Figure 4: The common-emitter IV plot of the $Al_{0.3}Ga_{0.7}As/In_{0.03}Ga_{0.97}As_{0.99}N_{0.01}/GaAs$ PnP DHBT. The five curves corresponds to I_B of 0.2, 0.4, 0.6, 0.8, and 1.0 mA. The V_{offset} is about 220 mV, and the V_{sat} varies from about 0.55 V to 0.85 V.

In addition, the β for a typical $Al_{0.3}Ga_{0.7}As/GaAs$ Pnp HBT is greater than 100. Considering the presence of a larger ΔE_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 β should increase exponentially with increasing ΔE_C, β 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 β. One indication that the material could be improved is the high ideality factor of the base current (n_{Ib}). A high n_{Ib} indicates high level of recombination current, thus reducing the value of β. However, as shown in Figure 3, the n_{Ib} 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 need 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 $Al_{0.3}Ga_{0.7}As/In_{0.03}Ga_{0.97}As_{0.99}N_{0.01}/GaAs$ 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 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 $In_{0.03}Ga_{0.97}As_{0.99}N_{0.01}$ 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, causing the V_{offset} and the V_{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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