InGaP/InGaAsN/GaAs NpN Double Heterojunction Bipolar Transistor

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@STI**Abstract**

We have demonstrated a functional NpN double heterojunction bipolar transistor (DHBT) using InGaAsN for the base layer. The InGaP/In_{0.03}Ga_{0.97}As_{0.99}N_{0.01}/GaAs DHBT has a low V_{ON} of 0.81 V, which is 0.13 V lower than in a InGaP/GaAs HBT. The lower V_{ON} is attributed to the smaller bandgap ($E_g = 1.20$ eV) of MOCVD grown In_{0.03}Ga_{0.97}As_{0.99}N_{0.01} base layer. GaAs is used for the collector; thus the BV_{CEO} is 10 V, consistent with the BV_{CEO} of InGaP/GaAs HBTs of comparable collector thickness and doping level. To alleviate the current blocking phenomenon caused by the larger ΔE_C between InGaAsN and GaAs, a graded InGaAs layer with δ -doping is inserted at the base-collector junction. The improved device has a peak current gain of 7 with ideal IV characteristics.

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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 layer⁶. For this reason, most of the earlier works 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 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 used in inexpensive low-power electronics. Recently, a functional InGaAsN based Pnp HBT has been demonstrated with a significantly lower V_{ON} than their equivalent GaAs based devices,⁹ confirming the potential of InGaAsN based HBTs as a viable alternative for low power electronics applications.

As N is incorporated into GaAs, a tensile strain develops, and the E_G is lowered. On the other hand, a compressive strain builds up as indium (In) is added to GaAs, and E_G is reduced. By incorporating proper amount of In and N into GaAs simultaneously, InGaAsN that is lattice

matched to GaAs can be obtained. The E_G of the resulting InGaAsN would be significantly lower because of the aggregate lowering effect from the incorporation of N and In.¹⁰ The resulting band alignment of InGaP/InGaAsN/GaAs DHBT along with the band alignment of a conventional InGaP/GaAs HBT is shown in Figure 1. The narrower bandgap of the InGaAsN base would lead to a lower base-emitter (BE) V_{ON} . However, due to the large electronegativity of N atoms, most of the E_G reduction occurs at the conduction band (E_C), the resulting structure has larger conduction band discontinuity (ΔE_C) at both the BE and the base-collector (BC) junctions. The effect of the larger ΔE_C at the BC junction is detrimental for transporting electrons out of the base into the collector. This current blocking phenomenon causes electrons to stay in the base layer longer, thus resulting in increased level of recombination current, and the current gain (β) is reduced. Using InGaAsN for collector is not an option because undoped metalorganic-chemical vapor deposition (MOCVD)-grown InGaAsN usually is p-type with a background concentration of $2 \times 10^{17} \text{ cm}^{-3}$, making it difficult to grow a high-quality lightly-doped n-type InGaAsN epilayer with a carrier concentration of $n = 1\text{--}3 \times 10^{16} \text{ cm}^{-3}$ for single heterojunction HBTs. Therefore, in this letter, a n-type GaAs is chosen as the collector of InGaP/InGaAsN/GaAs DHBTs. The larger ΔE_C at the BE junction also has adverse effects, it leads to a large energy barrier for carriers to overcome before they can be injected into the base, resulting in higher V_{ON} , thus reducing the benefit of the smaller bandgap of the InGaAsN.

The structure of the NpN InGaP/In_{0.03}Ga_{0.97}As_{0.99}N_{0.01}/GaAs DHBTs investigated in this work are listed in Table I. The base layer is made of p-type In_{0.03}Ga_{0.97}As_{0.99}N_{0.01} lattice matched to GaAs, and its E_g is approximately 1.2 eV. δ -doping in the emitter near the BE junction has been inserted to minimize the effect of ΔE_C on the V_{ON} . Two designs for the BC junction has been considered to understand the effect of ΔE_C on the transport of electrons at this junction.

The first design (device 1) has an abrupt BC junction, where the ΔE_C is about 0.2 eV. To reduce this barrier, the second design (device 2) uses a strained InGaAs grading layer to gradually increase the E_C from the level of $\text{In}_x\text{Ga}_{1-x}\text{As}$ to that of GaAs. For the E_C of $\text{In}_x\text{Ga}_{1-x}\text{As}$ to become level with the E_C of the $\text{In}_{0.03}\text{Ga}_{0.97}\text{As}_{0.99}\text{N}_{0.01}$, the In composition needs to be 0.26. However, due to the limitation of strain, In composition in our structure is limited to 0.20. The In composition grading is linear over a thickness of 30 nm. The $\text{In}_{0.2}\text{Ga}_{0.8}\text{As}$ leaves a ΔE_C of about 0.02 eV at the BC junction, thus a δ -doping layer is inserted in the collector near the BC junction to further improve the transport characteristics of electrons across this interface.

The DHBT structures under study were grown by 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 samples is uniform and smooth. The DHBT devices were fabricated using a triple mesa process. Selective wet etching was used to expose the base and the subcollector surface, as well as for achieving device isolation. The GaAs and InGaAsN etches were done using the 1 H_3PO_4 : 4 H_2O_2 : 45 H_2O solution, while a diluted HCl solution was used to etch the InGaP emitter layer. In order to avoid metal spiking through the emitter layer, Pd/Ge/Au annealed at 175°C for 1 hour was used for the emitter and collector contact metal.¹¹ Pt/Ti/Pt/Au forms non-alloyed ohmic contacts for the p-type base. For this work, the devices were not passivated. The emitter of the final device is of circular geometry with a diameter of 50 μm . The fabricated devices were tested using a HP-4145 Semiconductor Parameter Analyzer.

The β of the two DHBTs as function of BC reverse bias (V_{BC}) is shown in Figure 2. The β of these devices increase with increasing V_{BC} , especially in the case of device 1, which has an

abrupt BC junction. The β of device 1 increases from 0.5 to 4.9 as V_{BC} is increased from 0 to 8 V. The dependence of β on V_{BC} is a result of the current blocking phenomenon discussed earlier. The abrupt BC junction of device 1 hinders the electron flow from quick exit into the collector, and β decreases to less than 1 due to high level of recombination. As V_{BC} increases, the current blocking barrier is lowered, and β increases. In contrast, the β of device 2 is a lot less dependent, increasing from 5.4 to 7.0 under the same range of V_{BC} . The In composition grading and δ -doping at the BC junction of device 2 has improved the β at zero V_{BC} by more than 10-fold, from 0.52 to 5.4. The common-emitter (CE) IV characteristics of both devices are shown in Figure 3, as shown in Figure 3, device 2 has nearly ideal IV characteristics compared to the characteristics of device 1.

The Gummel plot of device 2 is shown in Figure 4. The ideality factor of I_B and I_C are 1.10 and 1.08, respectively, indicating high-quality InGaP/InGaAsN BE and InGaAsN/GaAs BC junctions. An important merit of the InGaP/In_{0.03}Ga_{0.97}As_{0.99}N_{0.01}/GaAs DHBT is its V_{ON} , which is defined as the BE junction bias (V_{BE}) at which the collector current (I_C) exceeds 1.0 μ A. The V_{ON} of device 2 is only 0.84 V, which is 0.13 V lower than the 0.97 V measured in a InGaP/GaAs HBT. Even more promising is the lower base current turn on voltage (V_{ONB}). The V_{ONB} of device 2 is only 0.81 V, which is 0.26 V lower than the 1.07 V measured in a InGaP/GaAs HBT. The lower V_{ON} is strong evidence that HBTs with an InGaAsN base layer has potential to be 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 10 V, comparable to the BV_{CEO} observed in an InGaP/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}). The V_{offset} of device 2 is about 220 mV, higher than what is measured in an InGaP/GaAs HBT. The V_{sat} is also slightly higher than in the case of InGaP/GaAs HBT, for I_C of 3 mA, the V_{sat} is about 490 mV. This discrepancy probably arises because the base sheet resistance (R_B) is high. The hole mobility (μ_p) of the InGaAsN in the base layer is about 90 $\text{cm}^2\text{V}^{-1}\text{s}^{-1}$, comparable to the μ_p in GaAs with comparable doping. However, limited by the current material technology, the ^{base} doping (N_{AB}) is limited to about $1 \times 10^{19} \text{ cm}^{-3}$. Therefore, for a base layer thickness of 70 nm, the R_B is about 1.2 $\text{K}\Omega/\text{Square}$, comparable to the R_B of GaAs base layer with comparable thickness and doping.

In conclusion, an operational InGaP/ $\text{In}_{0.03}\text{Ga}_{0.97}\text{As}_{0.99}\text{N}_{0.01}$ /GaAs NpN DHBT has been demonstrated. The use of InGaAs grading layer and δ -doping at the BC junction results in near ideal IV characteristics. The InGaP/InGaAsN/GaAs DHBT has a β of 5.4 under zero V_{BC} , and a peak β of 7 for a biased BC junction. Since the collector is made of GaAs, the BV_{CEO} of 10 V is comparable to the BV_{CEO} observed in an InGaP/GaAs HBTs with similar collector thickness and doping. The narrower E_G of $\text{In}_{0.03}\text{Ga}_{0.97}\text{As}_{0.99}\text{N}_{0.01}$ has led to the low V_{ON} of 0.84 V, a 0.13 V improvement over a typical InGaP/GaAs HBT, demonstrating great potentials for application of InGaAsN in low-power electronics. 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 are still need to reduce R_B and improve β , so that the full potential of InGaAsN for low-power applications can be realized.

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Table I : The two NpN InGaP/In_{0.03}Ga_{0.97}As_{0.99}N_{0.01}/GaAs DHBTs structures investigated in this work. The first device uses an abrupt InGaAsN/GaAs BC junction, which has a significant ΔE_C , resulting in current blocking. Graded InGaAs and δ -doping are introduced in device 2 to improve the carrier transport across the BC junction.

Layer	Device 1			Device 2		
	Material	Thickness	Doping	Material	Thickness	Doping
Emitter	n^+ In _{0.5} GaAs	300 Å	$2 \times 10^{19} \text{ cm}^{-3}$	n^+ In _{0.5} GaAs	300 Å	$2 \times 10^{19} \text{ cm}^{-3}$
	n^+ In _{0.5} GaAs	300 Å	$2 \times 10^{19} \text{ cm}^{-3}$	n^+ In _{0.5} GaAs	300 Å	$2 \times 10^{19} \text{ cm}^{-3}$
	n^+ GaAs	1000 Å	$2 \times 10^{18} \text{ cm}^{-3}$	n^+ GaAs	1000 Å	$2 \times 10^{18} \text{ cm}^{-3}$
	n InGaP	450 Å	$7 \times 10^{17} \text{ cm}^{-3}$	n InGaP	450 Å	$7 \times 10^{17} \text{ cm}^{-3}$
	InGaP	0 Å	$5 \times 10^{12} \text{ cm}^{-2}$	InGaP	0 Å	$5 \times 10^{12} \text{ cm}^{-2}$
	n InGaP	50 Å	$7 \times 10^{17} \text{ cm}^{-3}$	n InGaP	50 Å	$7 \times 10^{17} \text{ cm}^{-3}$
Base	p^+ InGaAsN	700 Å	$1 \times 10^{19} \text{ cm}^{-3}$	p^+ InGaAsN	700 Å	$1 \times 10^{19} \text{ cm}^{-3}$
Grading	None			n^- In _{0.2} GaAs	50 Å	$3 \times 10^{16} \text{ cm}^{-3}$
				n^- In _{0.2} GaAs	0 Å	$5 \times 10^{12} \text{ cm}^{-2}$
				n^- In _{0.2} GaAs	250 Å	$3 \times 10^{16} \text{ cm}^{-3}$
Collector	n^- GaAs	5000 Å	$3 \times 10^{16} \text{ cm}^{-3}$	n^- GaAs	5000 Å	$3 \times 10^{16} \text{ cm}^{-3}$
Sub-Coll.	n^+ GaAs	5000 Å	$5 \times 10^{18} \text{ cm}^{-3}$	n^- In _{0.2} GaAs	5000 Å	$3 \times 10^{16} \text{ cm}^{-3}$
S. I. GaAs Substrate						

- Figure 1 :** The band alignment of the two InGaP/In_{0.03}Ga_{0.97}As_{0.99}N_{0.01}/GaAs DHBT devices used in this work. The band alignment of InGaP/GaAs HBT is also shown for comparison.
- Figure 2 :** The β of the two InGaP/In_{0.03}Ga_{0.97}As_{0.99}N_{0.01}/GaAs DHBTs plotted as function of V_{BC} . The β of device 1, which has an abrupt BC junction, increases from 0.5 to 4.9 as V_{BC} grows. The effect of V_{BC} on the β of device 2 is significantly reduce due to the improved BC junction.
- Figure 3 :** The CE IV plot of the two InGaP/In_{0.03}Ga_{0.97}As_{0.99}N_{0.01}/GaAs DHBTs. Three curves of I_C corresponding to I_B of 6, 8, and 10 mA are plotted for each device. The IV characteristic of device 2 is nearly ideal due to its improved BC junction.
- Figure 4 :** The Gummel plot of the InGaP/In_{0.03}Ga_{0.97}As_{0.99}N_{0.01}/GaAs DHBT under 8 V of BC reverse bias. The peak β of this device is about 7. The V_{ON} is 0.84 V, lower than the 0.97 V of a comparable InGaP/GaAs HBT. The ideality factor of I_B and I_C are 1.10 and 1.08, respectively, indicating high-quality InGaP/InGaAsN BE and InGaAsN/GaAs BC junctions.

Figure 1

Figure 2

Figure 3

Figure 4