InGaAsN/AlGaAs Pnp Heterojunction Bipolar Transistor

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OSTI**Abstract**

We have demonstrated a functional Pnp heterojunction bipolar transistor (HBT) using InGaAsN. The metalorganic vapor phase epitaxy (MOCVD) grown $\text{Al}_{0.3}\text{Ga}_{0.7}\text{As}/\text{In}_{0.03}\text{Ga}_{0.97}\text{As}_{0.99}\text{N}_{0.01}$ HBT takes advantage of the narrower bandgap energy ($E_g = 1.25\text{eV}$) of $\text{In}_{0.03}\text{Ga}_{0.97}\text{As}_{0.99}\text{N}_{0.01}$, which is lattice matched to GaAs. Compared with the $\text{Al}_{0.3}\text{Ga}_{0.7}\text{As}/\text{GaAs}$ material system, the $\text{Al}_{0.3}\text{Ga}_{0.7}\text{As}/\text{In}_{0.03}\text{Ga}_{0.97}\text{As}_{0.99}\text{N}_{0.01}$ material system has a larger conduction band offset, while the valence band offset remains comparable. This characteristic band alignment is very suitable for Pnp HBT applications. The device's peak current gain is 23 and it has a turn on voltage of 0.77V, which is 0.25V lower than in a comparable Pnp $\text{Al}_{0.3}\text{Ga}_{0.7}\text{As}/\text{GaAs}$ HBT.

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Incorporation of a small amount of nitrogen 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 gap bowing, the bandgap (E_G) decreases while the conduction band offset (ΔE_C) increases. Recent advances in the InGaAsN material system has led to much progress on the application of this material system for devices such as long wavelength lasers^{3,4} and high-efficiency multijunction solar cells.^{5,6} However, there has been little attention paid to its potential for electronic device applications, such as heterojunction bipolar transistors (HBTs).

To reduce the power dissipation of HBT circuits, a smaller bandgap material in the base region would be more desirable. HBT with a narrower bandgap material in the base has lower device turn on voltage (V_{ON}), an essential property of lower electronic devices. 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 bandgap of InGaAs increases, reducing the benefits of having InGaAs in the base layer.⁷ That is why most of the earlier works on low-power HBT have focused on the InP/InGaAs material system. But the InP technology is expensive, and its application has been limited.^{8,9} The InGaAsN material system should be an excellent alternative for low-power electronics application. It is compatible with the existing GaAs foundry technology; thus, it is more likely to be used in inexpensive low-power electronics.

The band alignment of the InGaAsN material system is illustrated in Figure 1.¹⁰ As nitrogen is incorporated into GaAs, a tensile strain develops. Except for very low nitrogen incorporation, adding nitrogen 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 In is added to GaAs, the E_C is lowered, and the E_V is raised. By incorporating proper amount of In and nitrogen into GaAs

simultaneously, InGaAsN that is lattice matched to GaAs can be obtained. The E_C of the resulting InGaAsN would be much lower because of the aggregated lowering effect from the incorporation of nitrogen and In. The energy level of E_V would depend on the amount of nitrogen incorporation, and for $\text{In}_{0.03}\text{Ga}_{0.97}\text{As}_{0.99}\text{N}_{0.01}$, the effects on E_V from incorporation of nitrogen 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, results in unique physics favorable for Pnp HBTs; a large conduction band discontinuity (ΔE_C) to suppress minority carrier electrons from being injected into the emitter, while a small valence band discontinuity (ΔE_V) facilitates hole transport from the emitter to the base. In this letter, we report the first demonstration of a HBT using the InGaAsN material system.

The Pnp $\text{Al}_{0.3}\text{Ga}_{0.7}\text{As}/\text{In}_{0.03}\text{Ga}_{0.97}\text{As}_{0.99}\text{N}_{0.01}$ HBT structure is shown in Table I. The $\text{In}_{0.03}\text{Ga}_{0.97}\text{As}_{0.99}\text{N}_{0.01}$ is lattice matched to GaAs and its bandgap energy (E_g) is approximately 1.25 eV. The resulting band structure should resemble the diagram shown in Figure 2. For an $\text{Al}_{0.3}\text{Ga}_{0.7}\text{As}$ emitter, the ΔE_V at the base emitter (BE) junction should be less than 0.2 eV, while the ΔE_C would be more than 0.4 eV. The HBT structure shown in Table I is grown by metalorganic-chemical vapor deposition (MOCVD) using an Emcore D180 system. The material compositions are calibrated using photoluminescence measurement (PL) and X-Ray diffraction (XDR). The doping levels are confirmed with polaron and Hall measurement. The surface morphology of the sample is uniform and smooth.

The HBT device is fabricated using a triple mesa process. Wet etching is used to expose the base and the subcollector surface, as well as for achieving device isolation. All three etches are 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 at the base layer, Pd/Ge/Au

annealed at 175°C for 1 hour is used for the base contact metal.¹¹ For this work, the device is not passivated. The emitter area of the final device is 100×100μm².

The fabricated device is tested using a HP-4145 Semiconductor Parameter Analyzer. The gummel plot and the measured common-emitter current-voltage (IV) plot are shown on 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} HBT has a current gain (β) of 23, which is sufficient gain to be useful for many circuit applications. More importantly, however, is V_{ON}, as defined by the bias level at which the base current exceeds 1.0 μA. The V_{ON} of the Al_{0.3}Ga_{0.7}As/In_{0.03}Ga_{0.97}As_{0.99}N_{0.01} HBT is only 0.77 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 InGaAsN can be used as an alternate material for low-power HBT applications.

Other important parameters are the offset voltage (V_{offset}) and the saturation voltage (V_{sat}). As can be observed from Figure 4, the offset voltage (V_{offset}) of our device is about 280 mV, which is slightly higher than what is expected for a device with very low V_{ON}. The V_{sat} is also slightly higher than expected, ranging from 0.65 V to 1.20 V for collector current ranging from about 1.5 mA to 15.0 mA. This discrepancy probably arises because the material quality of the In_{0.03}Ga_{0.97}As_{0.99}N_{0.01} is still not as ideal as 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 cm²V⁻¹s⁻¹, it is much lower than the mobility typically observed in GaAs, which is around 2000 cm²V⁻¹s⁻¹. Therefore, despite a base doping concentration (N_{DB}) of 1.2×10¹⁸ cm⁻³, the R_B is still high. The high value of R_B leads to the high V_{offset} and high V_{sat} that are observed in Figure 4.

In addition, for a typical $\text{Al}_{0.3}\text{Ga}_{0.7}\text{As}/\text{GaAs}$ Pnp HBT, the β is greater than 100.

Considering the presence of a larger ΔE_C in the $\text{Al}_{0.3}\text{Ga}_{0.7}\text{As}/\text{In}_{0.03}\text{Ga}_{0.97}\text{As}_{0.99}\text{N}_{0.01}$ material system, and the fact that β should increase exponentially with increasing ΔE_C , β should ideally be greater than 23. A possible cause may be the presence of recombination centers in the $\text{In}_{0.03}\text{Ga}_{0.97}\text{As}_{0.99}\text{N}_{0.01}$ base, thus resulting in high levels of recombination current and lower than expected β . 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, therefore a reduced value of β . However, as shown in Figure 3, the n_b is about 3.1, 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 $\text{In}_{0.03}\text{Ga}_{0.97}\text{As}_{0.99}\text{N}_{0.01}$ is still unknown. More study would be need to understand it better, and proper passivation for InGaAsN would need to be determined to improve the performance of this device.

In conclusion, the quality of the InGaAsN material has now improved to the point that an operational $\text{Al}_{0.3}\text{Ga}_{0.7}\text{As}/\text{In}_{0.03}\text{Ga}_{0.97}\text{As}_{0.99}\text{N}_{0.01}$ Pnp HBT is demonstrated. A β of 23 has been achieved. The narrower bandgap 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 0.77 V, an important parameter for low power HBT applications. Due to limitation of the material quality available today, the base sheet resistance is still high, causing the V_{offset} and the V_{sat} to be high. The existence of surface states on InGaAsN also needs to be characterized, so that a proper passivation can be determined to improve the performance of the AlGaAs/InGaAsN HBT.

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Table I : The structure of the Pnp $\text{Al}_{0.3}\text{Ga}_{0.7}\text{As}/\text{In}_{0.03}\text{Ga}_{0.97}\text{As}_{0.99}\text{N}_{0.01}$ HBT investigated in this work. The device is grown by MOCVD using the Emcore D180 system.

	Material	Thickness [nm]	Doping [cm^{-3}]
Contact Cap Layer	p^+ GaAs	200	$2.00\text{E}+19$
Emitter Layer	p $\text{Al}_{0.3}\text{Ga}_{0.7}\text{As}$	100	$3.00\text{E}+18$
Spacer Layer	u - $\text{Al}_{0.3}\text{Ga}_{0.7}\text{As}$	5	<i>undoped</i>
Base Layer	n $\text{In}_{0.03}\text{Ga}_{0.97}\text{As}_{0.99}\text{N}_{0.01}$	100	$1.20\text{E}+18$
Collector Layer	p^- $\text{In}_{0.03}\text{Ga}_{0.97}\text{As}_{0.99}\text{N}_{0.01}$	300	$2.00\text{E}+17$
Subcollector Layer	p^+ GaAs	500	$2.00\text{E}+19$
Substrate	S. I. GaAs		

Figure 1 : The effect on conduction band and valence band edges by incorporating nitrogen and In into GaAs.¹⁰

Figure 2 : The band alignment of the $\text{Al}_{0.3}\text{Ga}_{0.7}\text{As}/\text{In}_{0.03}\text{Ga}_{0.97}\text{As}_{0.99}\text{N}_{0.01}$ HBT compared to the $\text{Al}_{0.3}\text{Ga}_{0.7}\text{As}/\text{GaAs}$ HBT. The $\text{In}_{0.03}\text{Ga}_{0.97}\text{As}_{0.99}\text{N}_{0.01}$ has a greater ΔE_C with $\text{Al}_{0.3}\text{Ga}_{0.7}\text{As}$ than what GaAs has, thus, ideally it is more suited for Pnp HBT applications.

Figure 3 : The gummel plot of the $\text{Al}_{0.3}\text{Ga}_{0.7}\text{As}/\text{In}_{0.03}\text{Ga}_{0.97}\text{As}_{0.99}\text{N}_{0.01}$ Pnp HBT. The β of this device is 23. The V_{ON} is only 0.77 V. But the n_{ib} is 3.1, indicating high level of recombination current.

Figure 4 : The common-emitter IV plot of the $\text{Al}_{0.3}\text{Ga}_{0.7}\text{As}/\text{In}_{0.03}\text{Ga}_{0.97}\text{As}_{0.99}\text{N}_{0.01}$ Pnp HBT. 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 280 mV, while the V_{sat} varies from about 0.65 V to 1.2 V.

Figure 1

Figure 2

Figure 3

Figure 4