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The Aluminum-Free P-n-P InGaAsN Double Heterojunction Bipolar Transistors

P. C. Chang[1], N. Y. Li[2], A. G. Baca[1], C. Monier[3*], J. R. Laroche[4], H. Q. Hou[2], F. Ren[3], and S. J. Pearton[3]

[1] Sandia National Laboratories, 1515 Eubank S. E., Albuquerque, NM 87185-0603.
[2] Emcore PhotoVoltaics, Emcore Corp., 10420 Research Rd. SE, Albuquerque, NM 87123.
[3] University of Florida, Department of Material Science and Engineering, 100 Rhines Hall, Gainesville, FL 32611-6400.
[4] University of Florida, Department of Chemical Engineering, Chemical Engineering Blvd., Room 317, Gainesville, FL 32611.
[*] Current address at Sandia National Laboratories, 1515 Eubank S. E., Albuquerque, NM 87185-0603.

Abstract

We have demonstrated an aluminum-free P-n-P GaAs/InGaAsN/GaAs double heterojunction bipolar transistor (DHBT). The device has a low turn-on voltage (V_{ON}) that is 0.27 V lower than in a comparable P-n-p AlGaAs/GaAs HBT. The device shows near-ideal D. C. characteristics with a current gain (β) greater than 45. The high-speed performance of the device are comparable to a similar P-n-p AlGaAs/GaAs HBT, with f_T and f_{MAX} values of 12 GHz and 10 GHz, respectively. This device is very suitable for low-power complementary HBT circuit applications, while the aluminum-free emitter structure eliminates issues typically associated with AlGaAs.

Introduction

The trend in portable electronics is to extend the battery lifetime without sacrificing the performance. One approach toward this goal is low-voltage devices that operate at lower power. For heterojunction bipolar transistors (HBTs), a lower bandgap (E_G) base reduces the turn-on voltage (V_{ON}), and leads to greater efficiency at low-bias conditions. HBTs with InGaAs bases lattice matched to InP substrates offer one possibility that has not been adopted by commercial foundries due to substrate cost, concern over breakage, and lack of 6" wafers. InGaAsN lattice matched to GaAs is a new material that has received a lot of attention lately [1-5]. Incorporating small amount of In and N would result in a significantly reduced E_G compared to GaAs, making it very suitable to low-power HBT applications. Recently, we demonstrated a N-p-N InGaP/InGaAsN/GaAs double heterojunction bipolar transistor (DHBT) [4], and a P-n-p AlGaAs/InGaAsN HBT[5]. Both of these devices show V_{ON} that are significantly lower than in their corresponding GaAs based HBTs [4-5], showing 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 the low-power InGaAN based CHBT technology to take advantage of the matured GaAs foundries.

Theory

The InGaAsN has received a lot of attention lately mainly due its potentials for optoelectronic applications [1-3]. The E_G 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 E_G 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 E_g of the resulting InGaAsN would be significantly lower because of the aggregate E_G reduction effect from the incorporation of N and In. The band alignment of the InGaAsN material system is illustrated in Figure 1 [1]. The InGaAsN that is lattice matched to GaAs would have almost all of its E_G reduction in the form of conduction band (E_C) lowering, thus resulting in a large conduction band offset (ΔE_C) with negligible valence band offset (ΔE_V). This band alignment is especially suitable for P-n-p HBT applications.

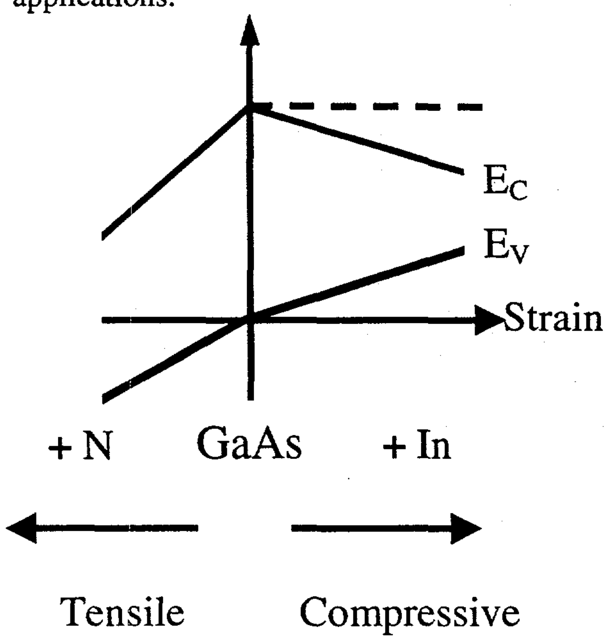

Figure 1 : The effect on the band alignment of incorporating In and N into

In this work, we have investigated application of $In_{0.03}Ga_{0.97}As_{0.99}N_{0.01}$ for P-n-P DHBTs. The InGaAsN used in this work is lattice matched to GaAs with an E_G of approximately 1.2 eV, with almost 0.2 eV of ΔE_C when it is stacked next to GaAs. Since the ΔE_C is significant while ΔE_V is negligible, GaAs can be used as the emitter and the collector material, the hole transport across the emitter-base and the base-collector junction can be achieved without resorting to any exotic junction grading designs. The GaAs collector would allow this device to take advantage of the larger E_G of GaAs, thus allowing good breakdown voltage, in addition, the hole mobility in GaAs is

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almost 6 time better than in GaAs, thus permitting much improved collector characteristics. Similarly, GaAs is better than AlGaAs as the emitter material because it allows an aluminum-free structure, with improved material properties. Taking advantage of this unique band alignment, we have designed a novel aluminum-free GaAs/InGaAsN/GaAs P-n-P DHBT as shown in Table I, with corresponding band diagram of this structure shown in Figure 2.

Experiments

The P-n-P DHBT shown in Table I was grown by 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 base layer. The flow rate ratio of DMHy/(DMHy+AsH_3) was fixed at 0.95. The indium and nitrogen compositions were determined by secondary ion mass spectroscopy and high-resolution x-ray diffraction measurements. The doping concentrations in epilayers were confirmed with Polaron and Hall measurements. A comparable P-n-p AlGaAs/GaAs HBT structure was grown along for comparison purpose.

Table I : The layer structure of the P-n-P aAs/InGaAsN/GaAs DHBT.

	Material	Thickness [Å]	Doping [cm^{-3}]
	p^+ GaAs	3000	2.00E+19
Emitter Layer	*p* GaAs	700	2.00E+18
Base Layer	*n* InGaAsN	1000	3.00E+18
Collector Layer	p^- GaAs	5000	3.00E+16
	p^+ GaAs	7500	2.00E+19
Substrate	S. I. GaAs		

Both devices have been fabricated using a triple mesa process with emitter area of $3\times25\mu m^2$. All three mesa etching processes were performed by wet etching using H_3PO_4:H_2O_2:H_2O as the etchant. Sputtered WSi served as the emitter metal, while evaporated PdGeAu and TiPtAu were used as the base and collector contact, respectively. A 4000 Å thick layer of SiO_XN_Y was deposited by ECR for device passivation. The devices are then tested by HP-4145 for device D. C. characteristics, and HP-8510 for device R. F. characteristics.

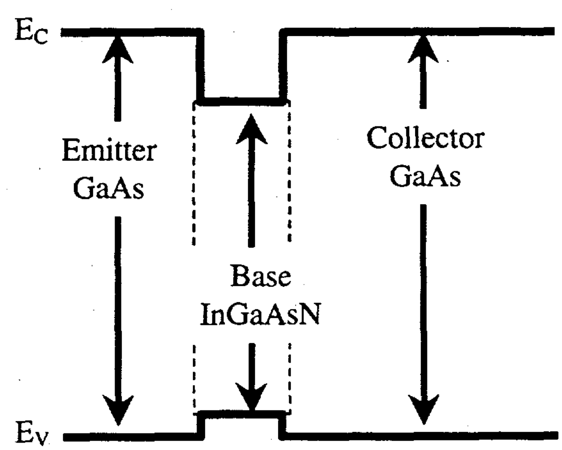

Figure 2 : The band diagram of the P-n-PGaAs/InGaAsN/GaAs

Results

The GaAs/InGaAsN/GaAs DHBT has a functional current gain (β) that is greater than 45, and the device has nearly ideal IV

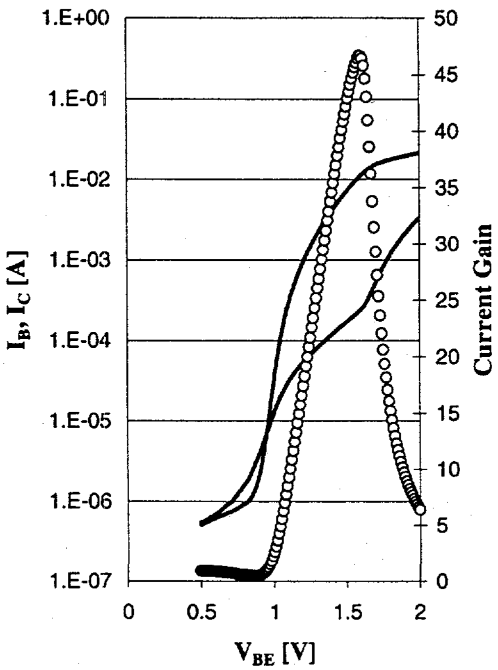

Figure 3 : The Gummel plot of the 3×25 μm^2 P-n-P GaAs/InGaAsN/GaAs HBT. The B bias is set at 0 V.

characteristics as shown in Figures 3 and 4. Compared to the P-n-p AlGaAs/GaAs HBT, we have observed a significantly reduced β, which has a β of 130. The β reduction is expected because the GaAs/InGaAsN BE junction does has a reduced ΔE_C compared to AlGaAs/GaAs, in addition, despite recent advance in the InGaAsN material, the crystal quality of the InGaAsN base is still inferior to that of a GaAs base. However, as shown in Figure 5, the V_{ON} of the novel InGaAsN DHBT is about 0.27 V lower than in the comparable GaAs HBT, and even slightly lower than the 0.25 V for a comparable AlGaAs/InGaAsN HBT reported previously[5]. The resulting offset voltage (V_{offset}) of 0.06 V is also significantly lower than the 0.13 V observed in the GaAs HBT. The low-power characteristics are what is expected from the reduced E_G in the base material, and from the near-ideal band alignment of the BE and BC junctions.

The f_T of the P-n-P GaAs/InGaAsN/GaAs DHBT is about 12 GHz, comparable to that of a similar AlGaAs/GaAs P-n-p HBT. The f_{MAX} of about 12 GHz observed in the InGaAsN device, however, is almost 2 GHz higher than in a similar GaAs based P-n-p HBT. The R. F. characteristics of these devices are compared in Figure 6. These are excellent results considering that they are either comparable to better than in the comparable AlGaAs/GaAs device. The comparable f_T values are expected considering that the base layer constitute only a small portion of the total HBT structure, while the GaAs

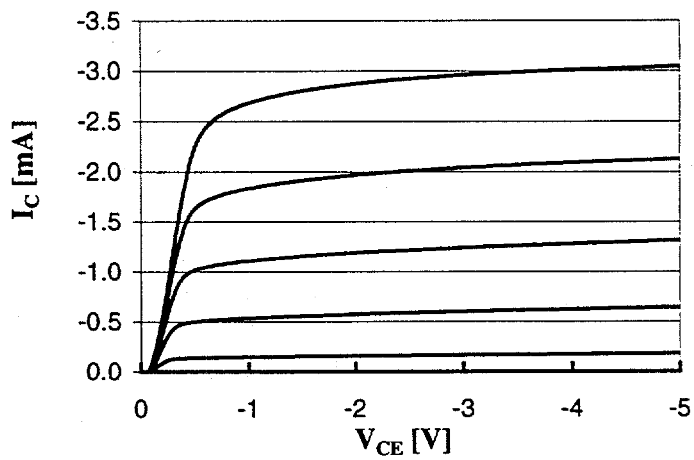

Figure 4 : The common emitter IV characteristics of the 3×25 μm^2 P-n-P GaAs/InGaAsN/GaAs HBT. The base current varies from 20 μA to 100 μA at 20

emitter actually provides better hole transport properties than in a AlGaAs emitter, thus the total transit time required for transport a hole through the HBT structure is not significantly affected. The improved f_{MAX} value, however, is a pleasant surprise probably due to the advantage of GaAs over AlGaAs, and an improved BE junction.

Conclusion

In conclusion, we have demonstrated a GaAs/InGaAsN/GaAs P-n-P DHBT that has shown near-ideal D. C. characteristics with a function β of 45, while its R. F. Characteristics are comparable or better than in a

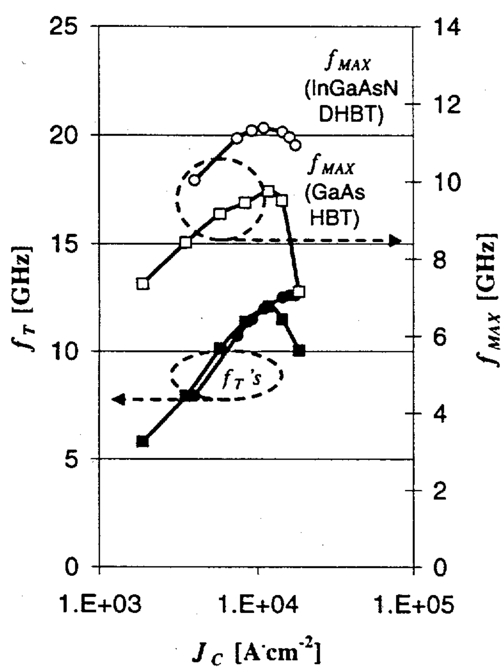

Figure 6 : The f_T and f_{MAX} of the GaAs/InGaAsN/GaAs P-n-P HBT, and of the AlGaAs/GaAs P-n-p HBT.

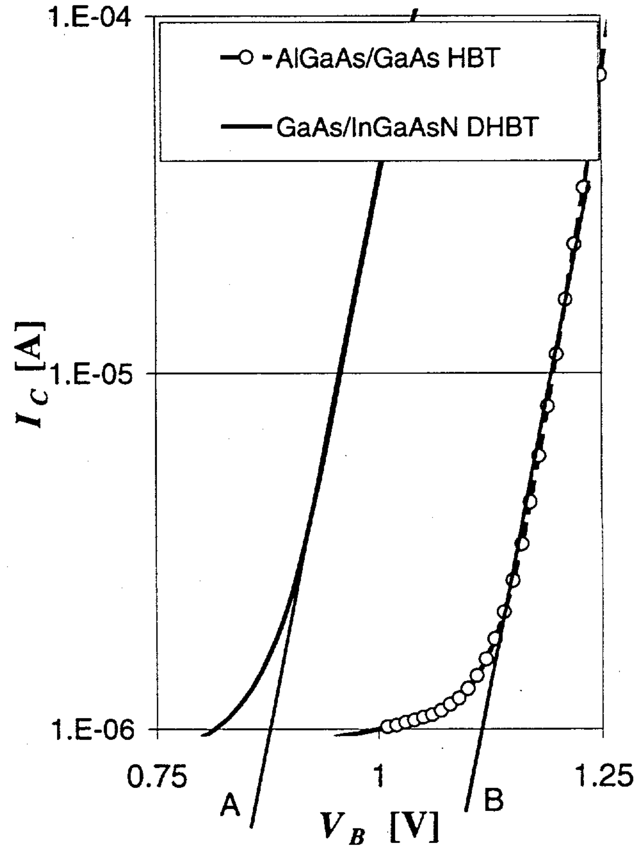

Figure 5 : The V_{ON} of the GaAs/InGaAsN/GaAs P-n-P HBT (curve A), the AlGaAs/InGaAsN/GaAs PnP HBT (curve B), and that of the AlGaAs/GaAs Pnp HBT (curve C).

similar AlGaAs/GaAs HBT. The GaAs emitter in this design eliminates the problems associated with AlGaAs emitters. And the reduced V_{ON} of 0.27 V makes it very useful for low-voltage complementary electronics that can take advantage of the maturing GaAs foundries.

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