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Reduction of Turn-on Voltage in GaInNAs and InGaAs Base Double Heterojunction Bipolar Transistors

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1. Introduction

Heterojunction bipolar transistors (HBTs) are important devices that have been extensively used as the power amplifiers in mobile handsets. To achieve high performance DHBTs, it is necessary to reduce the turn-on voltage and power consumption. InP-based HBTs have shown great potential in such applications due to its small bandgap energy. However, InP-based devices are much more expensive, as compared to GaAs-based devices. Strained InGaAs on GaAs is another approach. However, the bandgap energy of InGaAs on GaAs will increase slightly due to the compressive strain. Thus, turn-on voltage of InGaAs/GaAs-HBTs will also become higher. Another approach is to use GaInNAs as the base layer. By incorporating suitable amount of indium (In) and nitrogen (N) into GaAs, we could achieve a quaternary compound, which is lattice-matched to GaAs substrates [1-2]. We could also significantly reduce the bandgap energy of GaInNAs base layer and to achieve a low HBT turn-on voltage due to the large bowing factor of this particular material [3-6]. In this paper, we report the fabrication of GaAs-based double heterojunction bipolar transistors (DHBTs) with different base layers, which include GaInNAs, InGaAs and GaAs. The turn-on voltages of these DHBTs will also be compared.

2. Experiment

The DHBT structures used in this work were all grown by metalorganic chemical vapor deposition (MOCVD), as shown in Table I.

Table I Structures of the DHBTs used in this work

	Material	Thickness (nm)	Carrier concentration (cm^{-3})
Contact Layer	n^+ InGaAs	100	$1\times10^{+19}$
	n^+ GaAs	120	$5\times10^{+18}$
Emitter Layer	n InGaP	35	$3\times10^{+17}$
Base Layer	p^+ GaInNAs or GaAs or InGaAs	50	$4\times10^{+19}$
Collector Layer	n^- GaAs	550	$1\times10^{+16}$
Subcollector	n^+ GaAs	500	$5\times10^{+18}$
Substrate		S. I. GaAs	

The carrier concentration in each layer was determined by Hall measurement. The basic DHBT structure consists of a 35nm n-InGaP emitter followed by a 50nm p^+-GaInNAs (InGaAs or GaAs) base and a 550nm n-GaAs collector and a n^+-GaAs sub-collector. The DHBT devices were fabricated using a triple mesa process. We used $1H_2SO_4$:$4H_2O_2$:$45H_2O$ to etch GaAs, InGaAs and GaInNAs. $1H_3PO_4$:$1H_2Cl$ was used to etch the InGaP emitter layer. AuGeNi was then deposited and annealed at 420°C for 1.5 min to serve as the emitter and collector contacts. On the other hand, AuZn without annealing was used as the ohmic contact for the p-type base layer. The final devices have an emitter size of $2\times6\mu m^2$. The fabricated devices were then characterized by an Agilent 4155B and an Agilent 8510C for DC and up to 40.05GHz RF measurements, respectively.

3. Results and Discussion

Five samples with five different base layers were fabricated, as shown in Table II. The compositions of these base layers were calibrated by using photoluminescence measurement and x-ray diffraction. Fig. 1 shows collector current (I_C) as functions of base-emitter voltage (V_{BE}) of these five DHBTs. As indicated by the dot-dash line, we defined the V_{BE} turn-on voltage as the operation voltage when I_C equals 1μA.

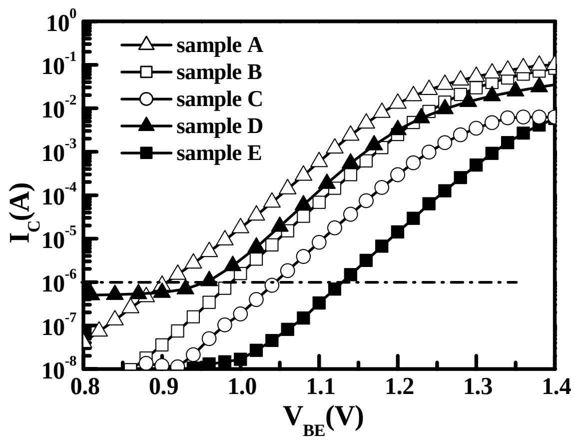

Fig. 1 I_C vs V_{BE} characteristic of the N-P-N DHBTs with different base layers.

We summarized the measured turn-on voltage and DC current gain of these five samples in Table II. It can be seen that turn-on voltage decreases as the nitrogen content in the base layer increases. With a 0.5% nitrogen content, it was found that turn-on voltage of sample A was only 904.6 meV, which is much lower than the 1129.3 meV turn-on voltage of the conventional GaAs-based DHBT (i.e. sample E). Furthermore, it was found that turn-on voltage of sample A was also 50 meV smaller than that of sample D, although indium content in sample A's base layer was much lower. Such a result indicates that we can indeed achieve a smaller turn-on voltage by using GaInNAs to replace InGaAs and/or GaAs as the DHBT base layer.

Fig. 2 shows Gummel plots of samples A and D. DC current gain as a function of V_{BE} for sample A was also plotted in the same figure. It was found that we could achieve a maximum DC current gain of about 85, which was also larger than the maximum DC current gain of 65 observed from sample D. From the Gummel plots, it was found that the ideality factors of I_C and I_B were 1.2 and 1.25, respectively, for sample A. On the other hand, the ideality factors of I_C and I_B were 1.09 and 1.18, respectively, for sample D. The values suggest that quality of these two samples were both reasonably good.

Table II Characteristics Comparisons of the N-P-N DHBTs for Different Bases Materials

Samples	Material of Base	Current gain	Turn-on Voltage (meV)
A	$GaIn_{0.015}N_{0.005}As$	83.8	904.6
B	$GaIn_{0.015}N_{0.0045}As$	53	988.1
C	$GaIn_{0.015}N_{0.004}As$	68.4	1044.3
D	$In_{0.03}GaAs$	56	954.6
E	GaAs	162	1129.3

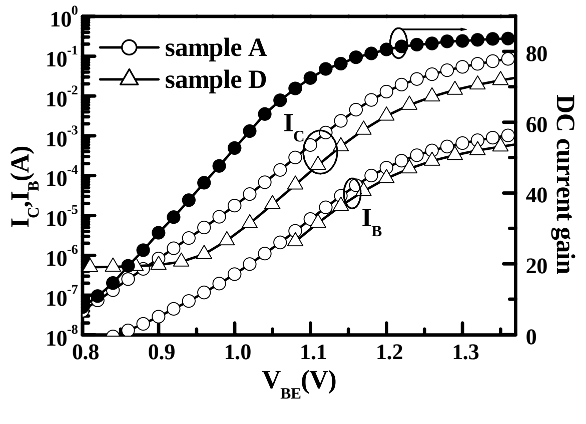

Fig. 2 Gummel plots of NPN InGaP/$In_{0.3}GaAs$/GaAs DHBT and InGaP/$GaIn_{0.015}N_{0.005}As$/GaAs DHBT.

Fig. 3 shows RF characteristics of sample A with a small active emitter area of 2×6 μm^2. It can be seen that we could achieve a high cut-off frequency f_T and a high maximum oscillation frequency f_{MAX}, which were both higher than 40GHz from this particular DHBT with a $GaIn_{0.015}$ $N_{0.005}As$ base layer.

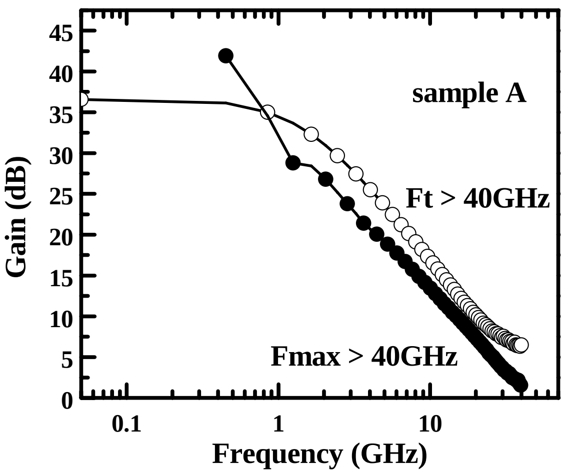

Fig. 3 Small-signal gain h_{21} and unilateral power gain U of 2×6 μm^2 InGaP/ $GaIn_{0.015}$ $N_{0.005}As$ HBT

4. Conclusions

In conclusion, GaAs-based DHBTs with GaInNAs, InGaAs, and GaAs base layers were successfully fabricated. With 0.5% nitrogen content, it was found that turn-on voltages of DHBTs with $GaIn_{0.015}N_{0.005}As$, $In_{0.03}GaAs$, and GaAs base layers were 904.6 meV, 954.6 meV and 1129.3 meV. The maximum DC current gain of 85 observed from the InGaP/$GaIn_{0.015}N_{0.005}As$/GaAs DHBT was also much larger than that observed from the conventional InGaP/InGaAs/GaAs DHBT. Furthermore, it was found that f_T and f_{MAX} of the fabricated InGaP/$GaIn_{0.015}N_{0.005}As$/GaAs DHBT were both higher than 40GHz.

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