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RF performance of a novel all ternary InAlAs/InGaAs DHBT

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Abstract

All ternary $\text{In}_{0.52}\text{Al}_{0.48}\text{As}$ – $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$ – $\text{In}_{0.52}\text{Al}_{0.48}\text{As}$ double-heterojunction bipolar transistors (DHBTs) have been grown using solid-source molecular-beam epitaxy. The development of these DHBTs required epitaxial design trade-offs which culminated in an optimum structure achieving high-breakdown (5.5 V), and RF performance demonstrating unity cutoff frequency (f_t) and maximum oscillation frequency (f_{max}) of 140 GHz and 95 GHz at relatively relaxed emitter dimensions of $\sim 1 \times 5 \mu\text{m}^2$. This is the highest reported cutoff frequency for an all ternary $\text{In}_{0.52}\text{Al}_{0.48}\text{As}$ – $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$ – $\text{In}_{0.52}\text{Al}_{0.48}\text{As}$ DHBT. The demonstration of the frequency performance at relaxed emitter dimensions shows potential for this material type.

1. Introduction

The operation frequency of InP-based single- and double-heterojunction bipolar transistors (SHBTs) and (DHBTs) has been pushed steadily higher as the demand for high-speed communication and high power microwave applications increases.

$\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$ – $\text{In}_{0.52}\text{Al}_{0.48}\text{As}$ SHBTs are well established in high-speed communication applications with reported high cutoff frequencies (f_t) of 550 GHz [1] and f_{max} of 687 GHz [2] using 0.25 μm emitter technology. However SHBTs suffer from low breakdown characteristics because of higher avalanche multiplication factors of the low band gap collector material.

Ideally, high-power microwave or precision mixed-signal applications require a large breakdown and/or higher early voltage. These characteristics are readily achievable by utilizing a double-heterojunction structure in which a large band-gap material is placed within the collector. This region effectively prevents the early breakdown characteristics inherent to SHBTs by reducing the detrimental effect of impact ionization at the base–collector interface. These improvements have, to a large extent been implemented in the InP–InGaAs DHBT. InP/InGaAs DHBTs research by the Northrop Grumman Company (NGC), HRL laboratories and the University of California Santa Barbara (UCSB) generally supported by DARPA are leading the way in producing high-

speed III V semiconductors with the highest reported f_t of 560 GHz [3] and f_{max} 859 GHz [4] using device geometries of $0.25 \times 4 \mu\text{m}^2$ achieved either by deep-uv photo or e-beam lithography.

It is clear from dc characteristics, such as breakdown voltage BV_{ceo} and current density, that leading InP DHBTs over the last five years are producing similar results. Breakdown voltages are always in the region of 4 to 4.5 V. The current-handling of these small devices is impressive, the highest reported current density being 20 $\text{mA } \mu\text{m}^{-1}$ but most range from 5 to 15 $\text{mA } \mu\text{m}^{-1}$ [3–11].

NGC and UCSB have proven their technology by reporting frequency divider performance. UCSB have demonstrated a 300 GHz dynamic frequency divider [4] and a 204.8 GHz static divide by 8 frequency divider [11]. NGC has reported a 200 GHz divide by 2 frequency divider in 2010 [5].

Research into ternary InAlAs–InGaAs DHBTs has to date been very limited. A reason for this is that the $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$ – $\text{In}_{0.52}\text{Al}_{0.48}\text{As}$ base–collector interface suffers from a large discontinuity ΔE_c compared to that of InP. The discontinuity causes a problem known as current blocking. Research into current blocking [12, 13] has demonstrated that the use of quaternary InAlGaAs collector, super-lattice and/or compositional grading at the hetero-junction yields improvements. In most cases the current blocking can only be eliminated via the use of quaternary alloys, which invariably compromises the breakdown characteristics. Quaternary and

graded collector InAlAs DHBTs have shown promise in device performance and have shown f_i and $f_{\max}$ of 76 and 157 GHz, respectively, and BV_{ceo} of 3 V for a device size of $1 \times 20 \mu\text{m}^2$ [12, 14].

Cowles and Farley [15, 16] have demonstrated devices with no current blocking and BV_{ceo} of 7.5 V. However the poor f_i of 30 GHz achieved was surmised to be a consequence of the relatively low electron saturation velocity in the ternary InAlAs compared with InP. McAlister *et al* [17] and other authors [18, 19] have used a combination of dipole doping [20] and setback layer in DHBTs to reduce current blocking with various degrees of success. However, no high-frequency data has been reported.

Recent work at the University of Manchester (UoM), involving molecular-beam epitaxy (MBE) growth of a large number of all ternary DHBT wafers and with different combinations of composite collector and doping interface dipole have successfully achieved optimum combination to eliminate current blocking in pure ternary $\text{In}_{0.52}\text{Al}_{0.48}\text{As}$ – $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$ – $\text{In}_{0.52}\text{Al}_{0.48}\text{As}$ DHBT up to a current density of $2 \text{ mA } \mu\text{m}^{-2}$ [21]. Following this work further $1 \times 5 \mu\text{m}^{-2}$ devices have been fabricated and these showed excellent performances with $f_i/f_{\max}$ 110 GHz/90 GHz, respectively, for a pure ternary DHBT [22].

This paper reports further improvements to the pure ternary $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$ – $\text{In}_{0.52}\text{Al}_{0.48}\text{As}$ DHBT epitaxial design to yield devices where f_i exceeds 140 GHz on a $1 \mu\text{m}$ optically fabricated DHBT process.

2. Growth and device structure

2.1. Wafer growth

The optimized wafer used in this work was grown on a RIBER V90H solid source MBE system on $3''$ Fe-doped semi-insulating (100) InP substrates. The system utilized an ultra high vacuum (UHV) chamber with a base pressure of $<10^{-10}$ Torr. Pyrolytic boron-nitride crucibles were used for the evaporation of gallium, arsenic, indium, silicon and beryllium. The growth was performed at the relatively low growth temperature of $\sim 420^\circ\text{C}$ in order to confine the high-concentration Be-base dopant. The entire epitaxial structure comprises of $\text{In}_{0.52}\text{Al}_{0.48}\text{As}$ and $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$ lattice-matched layers to the InP substrate unless otherwise stated; no quaternary alloys are used.

2.2. Device structure

Table 1 illustrates the epitaxy of the reported wafer. The Epitaxy design has a 281 Å thick highly Be doped (4.2×10^{19}) base and a 500 Å non-intentionally doped (nid) collector spacer layer. The high base doping provides a sheet resistance of $750 \Omega/\square$. This structure is similar to that reported by Mohiuddin *et al* [21]. The base also has a base grading of 13%, the base Indium composition varying from a value 53% at the base–collector junction to a value of 46% at the emitter–base junction.

The sample was fabricated using a triple mesa, optical lithography, self-aligned emitter and base process reported

Table 1. Epitaxial structures of the $\text{In}_{0.52}\text{Al}_{0.48}\text{As}$ – $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$ – $\text{In}_{0.52}\text{Al}_{0.48}\text{As}$ DHBT.

Layer	Material	Thickness (Å)	Doping (cm^{-3})
Cap	$\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$	800	2×10^{19} (n)
Emitter 1	$\text{In}_{0.52}\text{Al}_{0.48}\text{As}$	800	2×10^{19} (n)
Emitter 2	$\text{In}_{0.52}\text{Al}_{0.48}\text{As}$	500	5×10^{17} (n)
Spacer	$\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$	100	nid
Base	$\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$	281	4.2×10^{19} (p)
Spacer	$\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$	500	nid
p-n dipole doping	$\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$ - $\text{In}_{0.52}\text{Al}_{0.48}\text{As}$	2×100	5×10^{18} (pn)
Collector	$\text{In}_{0.52}\text{Al}_{0.48}\text{As}$	1000	nid
Collector 2	$\text{In}_{0.52}\text{Al}_{0.48}\text{As}$	500	1×10^{19} (n)
Sub-collector	$\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$	4500	1×10^{19} (n)
Buffer	$\text{In}_{0.52}\text{Al}_{0.48}\text{As}$	300	nid
Substrate	InP		Semi-insulating

nid = no intentional doping.

earlier [23]. The Ohmic contacts for emitter, base and collector used Pd/Ti/Pd/Au metallization and all interconnects used non-alloyed Ti/Au deposited by thermal evaporation.

3. Fabrication

The emitter was etched in two stages starting with the cap layer then the emitter. Orthophosphoric ($\text{H}_2\text{O}_2:\text{H}_2\text{O}:\text{H}_3\text{PO}_4$) chemical wet etch in the ratio of (1:50:3) and with an average etch rate of 800 Å min^{-1} was used to remove the InGaAs cap layer. The InAlAs emitter was removed in a solution of $\text{HCl}:\text{H}_2\text{O}$ (3:1) chemical wet etch. The InGaAs layer below the emitter acts as an etch stop layer to the $\text{HCl}:\text{H}_2\text{O}$ (3:1) chemical. This etch stop layer ensures minimal over etch occurs into the base and allows for excellent emitter definition leading to a relatively simple process technology for the all ternary DHBT.

The base metal layer patterned a self-aligned air bridge structure. The base/collector and isolation steps undercut the metal reducing the base–collector area thus minimizing the base–collector capacitance of the device.

For the interconnection, Ti-Au metal is deposited on a passivation layer of BCB, which is subsequently plasma etched with CF_4 and O_2 in a ratio of 1:4 to expose the emitter, base and collector [24].

4. Results and discussion

Figure 1 shows the common emitter I – V plot of the sample with an emitter area of $1 \times 5 \mu\text{m}^2$ at a stepped base current (i_b) of $15 \mu\text{A}$. The device shows a current gain (I_c/I_b) of 42, an offset voltage of 350 mV, power handling capability of 10 mW and current density of $1 \text{ mA } \mu\text{m}^{-1}$. The overlapped graph in figure 1 displays the break down voltage BV_{ceo} at an I_C current of 100 μA . The breakdown voltage for $1 \times 5 \mu\text{m}^2$ devices is 5.5 V. Figure 2 shows the forward Gummel plots of a $1 \times 5 \mu\text{m}^2$ device. The base and collector ideality factors are $n_B = 1.54$ and $n_C = 1.44$, respectively, and the $1 \times 5 \mu\text{m}^2$ device is showing a current gain of 42.

Figure 1. Common emitter I - V plot of a $1 \times 5 \mu\text{m}^2$ device and over-laid breakdown plot BV_{ceo} at $100 \mu\text{A}$.

Figure 2. Forward Gummel plot and current gain (β) of a $1 \times 5 \mu\text{m}^2$ device.

To test the high-frequency characteristics of the samples an Agilent 8510C VNA 40 GHz vector network analyser using 100 μm pitch probes was used. The system was calibrated using a standard LRRM calibration substrate and the devices were de-embedded using open, short and through structures. Peak RF performance was achieved at an $I_c = 4.2 \text{ mA}$ and a $V_{\text{ce}} = 2 \text{ V}$. The extrapolated f_t and f_{max} was obtained by a -20 dB/decade rolloff. Figure 3 shows the unity gain cutoff frequency ($H_{2,1}$) and Mason's unit literal gain (U) to be 140 and 95 GHz, respectively. Figure 4 shows the extrapolated f_t and f_{max} against collector currents I_c biased at a $V_{\text{ce}} = 2 \text{ V}$. The peak high-frequency performance ($f_t = 140 \text{ GHz}$ and $f_{\text{max}} = 95 \text{ GHz}$) is achieved at a current density $J_c = 1 \text{ mA } \mu\text{m}^{-2}$.

Table 2 shows a comparison of different InP and GaAs 1–2 μm emitter width DHBTs, which are commercially available. The reported InAlAs/InGaAs DHBT high-frequency performance does not exceed the current commercially available InP 1 μm emitter width DHBTs but it is comparable. However, relative to InP and GaAs DHBTs the research into all ternary InAlAs/InGaAs DHBT technology is limited. With further epitaxial design work and investment to reduce device geometries, this material system may prove to have RF performance useful for high-frequency power applications.

Figure 3. Extracted RF gains $h_{2,1}$ and U for a $1 \times 5 \mu\text{m}^2$ device biased at $I_c = 4.2 \text{ mA}$ and $V_{\text{ce}} = 2 \text{ V}$.

Figure 4. Extrapolated f_t/f_{max} from S-parameters against collector current I_c for $1 \times 5 \mu\text{m}^2$ device.

Table 2. Commercially available InP and GaAs DHBTs [25–28].

Company	Type	Emitter width (μm)	f_t (GHz)	f_{max} (GHz)	BV_{ceo} (V)
Ommic	InP	1.5	180	220	7
GCS	InP	1	150	150	7
Triquint	GaAs	2	40	60	14
WIN	GaAs	1	65	80	9
UoM	InP	1	140	95	5.5

This novel all ternary InAlAs/InGaAs DHBT is the fastest reported device in this material type to the best of the authors' knowledge. The reported DHBT is the start of a UoM InAlAs/InGaAs BiFET and MMIC fabrication process.

5. Conclusion

The demonstration of the frequency performance whilst achieving large breakdown voltage of 5.5 V coupled with the ease of processing makes the reported all ternary InGaAs–

InAlAs DHBTs attractive candidates for a number of high-power MMICs and BiFET applications.

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