Thermal Stability of Beryllium Doped InP/InGaAs Single and Double HBTs Grown by Solid Source Molecular Beam Epitaxy

James Sexton and Mohammed Missous

UMIST, Department of Electrical Engineering and Electronics
Sackville Street, Manchester M60 1QD, England, UK, Phone: + 44 161 200 4782
(Email: j.sexton-2@postgrad.umist.ac.uk and missous@umist.ac.uk)

Abstract — Heavily beryllium doped (~1.5×10^{19}cm^{-3}) InP/InGaAs single heterojunction bipolar transistors (SHBTs) and double heterojunction bipolar transistors (DHBTs) have been successfully grown by solid source molecular beam epitaxy (SSMBE). The epitaxial growth was performed on a VG 90H MBE system with 100mm wafer growth capability. The novelty of this process was the use of dimeric phosphorus generated from a gallium phosphide (GaP) decomposition source which permitted growth at fairly low temperature (420°C) while conserving extremely high quality materials. Thermal stability studies were then performed on the heavily doped HBTs using postgrowth annealing in an N$_2$ ambient. The devices were annealed over a temperature range of 350-550°C for 15 minutes prior to fabrication. The relatively low growth temperature of ~420°C and the use of stoichiometric conditions for both the arsenides and phosphide materials produced remarkably thermally stable, high-gain SHBTs and DHBTs up to annealing temperatures of 550°C.

I. Introduction

InP/InGaAs heterojunction bipolar transistors (HBTs) have shown excellent characteristics that make them extremely attractive for high frequency applications [1], [2]. The high frequency performance of InP-based HBTs is primarily due to the low bandgap InGaAs used in the base layer that has a high electron mobility and results in shorter transit times for electrons traversing the base.

The reduction of both the base resistance and base width in HBTs is necessary in order to increase both the maximum frequency of oscillation $f_{\max}$ and the unity gain cut-off frequency f_T. Hence, optimum performance is achieved when the base width is minimised, whilst at the same time maximising the doping concentration.

Traditionally, zinc (Zn) and beryllium (Be) are used as the base dopants for InP/InGaAs HBTs. However, the high diffusivity of the zinc dopants can cause severe problems in terms of device processing and reliability [3]. Also, the requirement for the doping to be maximised whilst being confined to the small base region is difficult to achieve. The uses of both low growth temperature and increasing the V/III ratio during MBE growth can dramatically increase performance [4], [5].

In recent studies [6], [7], carbon was used as a p-type dopant for InGaAs material due to its very low diffusion coefficient. However, it was clear from these studies that using carbon as the dopant had serious implications on the performance of the HBTs. This was especially severe when using metalorganic chemical vapour deposition (MOCVD) to grow the structure [6], due to the low temperatures used (by MOCVD standards) to confine the carbon dopants.

In this study, the MBE growth process relied upon two key developments. Firstly, the use of dimeric phosphorus generated from a GaP decomposition source made it possible to grow high quality phosphorus compounds at the relatively low temperature of ~420°C [8] and secondly, the use of stoichiometric growth conditions [9]. This has led to extremely thermally stable, high gain InP/InGaAs SHBTs and DHBTs up to annealing temperatures of 550°C.

II. Material Growth and Fabrication

Standard Npn HBT and NpN DHBT layer structures were used in this study. The profile includes a base thickness of 860 Å for the SHBT doped to 1.5×10^{19}cm^{-3} and 1000 Å for the DHBT doped to 1.0×10^{19}cm^{-3}. The use of a composite collector and dipole doping in the DHBT were used to reduce the current blocking effect at the base-collector interface [10]-[12]. A complete description of the structure was reported in [13].

The epitaxial growth was performed on a VG 90H MBE system that utilised a ultra high vacuum (UHV) chamber with a base pressure of <10^{-10} Torr. Pyrolitic boron-nitride crucibles were used for the evaporation of gallium, arsenic, indium, silicon and beryllium. Phosphorus was generated from a GaP decomposition source whose operational aspects were described in [8]. The growth was performed at the relatively low temperature of ~420°C and used stoichiometric conditions for both the arsenide and phosphide materials. This had the added beneficial effects of confining the high concentration Be-dopant used in the structures. The base regions were Be doped to ~1.5×10^{19}cm^{-3} and calibration layers using the same doping profiles gave a room temperature hole mobility of ~90cm^2/Vs. Thermal stability studies were then performed on the heavily Be doped HBTs using postgrowth annealing in an N$_2$ ambient. The samples were annealed over a temperature range of 350-550°C for 15 minutes prior to fabrication.

Sample	Temperature (°C)	n_B (±2%)	n_C (±2%)	Gain (β) (±1%)	R_{sh} (Ω/)	Percentage increase in R_{sh} (%)	Breakdown voltage (V) (±1%)
SHBT (#1444)	As Grown	1.12	1.11	100	580		5.0
	350	1.17	1.10	103	618	7	5.0
	450	1.22	1.12	103	655	13	4.5
	500	1.25	1.14	100	746	29	5.0
	550	1.4	1.90	<1	783	35	19.0
DHBT (#1450)	As Grown	1.03	1.05	90	802		12.5
	350	1.00	1.02	97	818	2	11.0
	450	1.01	1.03	91	833	4	8.0
	500	1.02	1.03	94	852	6	12.5
	550	1.08	1.11	104	868	8	12.5

TABLE I
BERYLLIUM OUT-DIFFUSION RESULTS FOR SHBT AND DHBT

Devices were fabricated using a conventional wet etch approach. First, the emitter contact was formed by lift-off, and selective wet etching of the InGaAs cap layer was carried out with H_3PO_4:H_2O_2:H_2O (3:1:50) using the emitter contact as a mask. The InP emitter was then etched using HCl:H_2O (1:1), exposing the base layer. To define the base and collector mesas, a photoresist mask was used followed by an etch in H_3PO_4:H_2O_2:H_2O. The DHBT sample followed a similar processing approach, and once fabricated, the devices were tested using a HP4145B Semiconductor Parameter Analyser.

The transistors were configured in the common-emitter configuration and current-voltage (I-V) characteristics were measured. The idealities, gain, turn-on and breakdown voltages were compared and any change in base sheet resistance was also calculated using TLM of the base region.

III. RESULTS AND DISCUSSION

The (I-V) characteristics of typical SHBT and DHBT samples are shown in Fig. 1 and 2 respectively. As observed, the current gain of the SHBT is ≈100 and that of the DHBT is ≈90 and are as expected from the base thickness and doping concentrations used. The offset voltage is also extremely low, at approximately 0.05V, indicating little difference in the turn-on voltages of the base-emitter and base-collector junctions.

Characteristics of the SHBT and DHBT samples are shown in Table 1 and highlights the large gain and only marginally affected properties throughout the entire annealing temperature range studied. The base current idealities for the SHBT show relatively small changes with increasing anneal temperature and only once annealed at 550°C does catastrophic failure occur. At this temperature, the gain reduced to <1 and resulted in poor junctions, causing a 25% increase in n_B and 71% increase in n_c. However, the results for the DHBT are excellent in comparison, and are virtually independent of temperature. In fact, at 550°C, the junction quality is maintained despite the high annealing temperature, with only a minor increase in n_B of 5% and 6% in n_c.

To determine the major impact of annealing the samples prior to fabrication, the base-emitter and base-collector diode, turn-on voltages were studied. It was found that annealing had negligible affect on the base-collector diode maintaining a constant turn-on voltage of 0.33V (see Table 2). It can, therefore, be concluded that

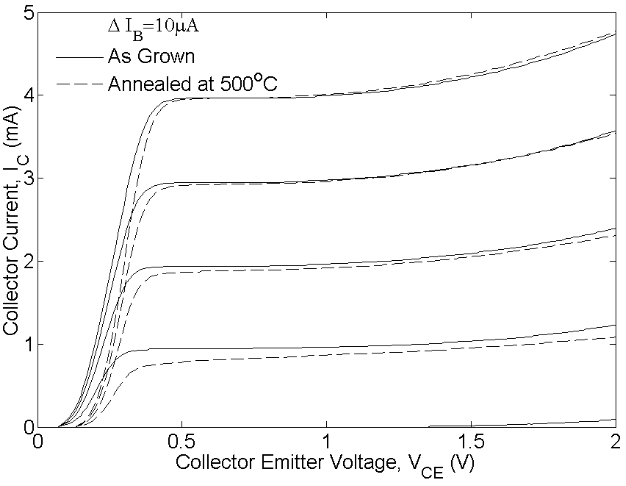

Fig. 1. DC Characteristics of SHBT Sample as Grown (Solid line) and Annealed at 500°C (Dashed)

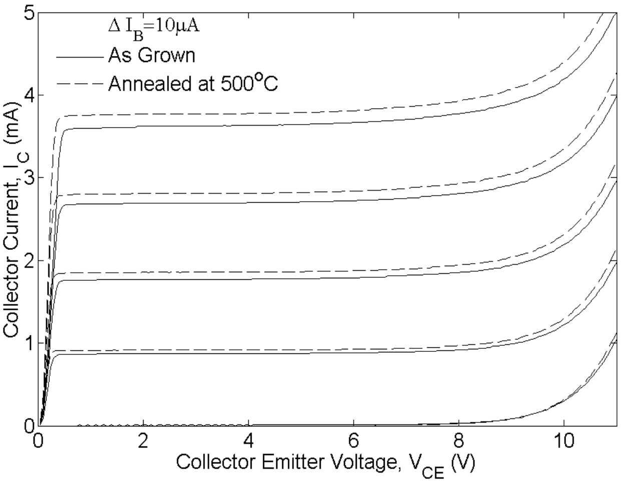

Fig. 2. DC Characteristics of DHBT Sample as Grown (Solid line) and Annealed at 500°C (Dashed)

Temperature (°C)	Emitter-Base Diode Turn-on (V)		Collector-Base Diode Turn-on (V)		Offset Voltage (V)	
	#1444 (SHBT)	#1450 (DHBT)	#1444 (SHBT)	#1450 (DHBT)	#1444 (SHBT)	#1450 (DHBT)
As Grown	0.39	0.36	0.33	0.33	0.07	0.04
350	0.42	0.36	0.33	0.33	0.07	0.04
450	0.41	0.36	0.32	0.32	0.10	0.05
500	0.48	0.37	0.37	0.34	0.13	0.04
550	0.65	0.41	0.32	0.34	0.38	0.09

TABLE 2
TURN-ON VOLTAGES FOR EMITTER-BASE AND BASE-COLLECTOR DIODES WITH ANNEAL TEMPERATURE

the diffusion of dopants from the base into the collector is not apparent in these samples. However, the base-emitter diode showed extensive change in turn-on voltage for both samples 1444 and 1450, increasing by 65% for the SHBT and 14% for the DHBT. Hence, it can be assumed that most of the dopants diffuse towards the spacer region in the emitter and result in an increased turn-on voltage of the base-emitter diode. The gummel plot shown in Fig. 3 of the SHBT and Fig. 4 of the DHBT further illustrates this point. The negligible change in gain is also a further indication that diffusion is limited to the emitter-base region. If diffusion did occur in the base-collector, it would effectively increase the base width, reducing the gain as reported in [12].

When studying the TLM results for the base in Table 1, the striking feature is the dramatic difference between the performance of the SHBT and DHBT. The SHBT can be seen to have the lowest sheet resistance of 580Ω/ , equating to a doping level of approximately $1.5\times10^{19}cm^{-3}$. The sheet resistance increases by 35% to 783Ω/ at 550°C. On the other hand the DHBT has a relatively high sheet resistance of 802Ω/ increasing by 8% to 868Ω/ at 550°C. Although excellent performance is achieved, the doping level of the DHBT is calculated at approximately $1.0\times10^{19}cm^{-3}$ (around 50% less than the SHBT). Thus, the reason for this increased performance, especially in terms of the emitter-base diode, is most probably due, in part, to the lower doping used in the base of the DHBT compared to the SHBT.

Comparing the DC characteristics of both our SHBT and DHBT samples to similar carbon doped devices, the results can be seen to differ widely. In the study produced by Cui et al [6] whose samples were grown by MOCVD, both our devices show far superior improvement. This was mainly due to the requirement for a low (MOCVD) temperature step of 450°C during growth and low V/III ratio of ~2 in order to maximise the carbon doping concentration. As stated in [6], this temperature produced the best trade-off between p-type doping concentration and good surface morphology. However this approach resulted in extremely poor junction qualities, producing idealities for the base and collector current of 2.2 and 1.6 respectively. Also, due to the low diffusion of carbon, the spacer region remains undoped and thus affects the ohmic contact resulting in a large contact resistance (33.7Ω). Hence, these compromises produced HBTs that had a gain as low 16 and high sheet resistance of 828Ω/ (43% higher than ours). Only when the devices were grown by GSMBE and MOMBE [7] without a spacer region do the junctions exhibit much improvement in quality and are comparable to the quality of our devices. In the study produced by Kuo et al [7], the idealities for the base and collector current were 1.17-1.2 and 1.03-1.08 respectively. Our SHBT devices produced base current idealities of 1.12 and collector current idealities 1.11, of which compare favourably with [7]. However, it is interesting to note that our base sheet resistance is almost equal to that of [7] despite the fact that the doping level is approximately 2.6 times lower. This could indicate the

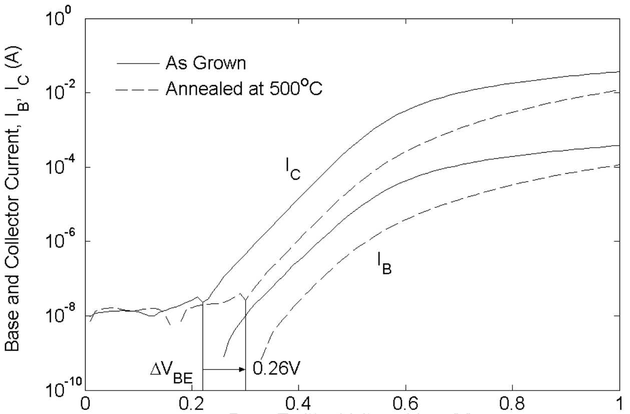

Fig. 3. DC Characteristics of SHBT Sample as Grown (Solid line) and Annealed at 500°C (Dashed)

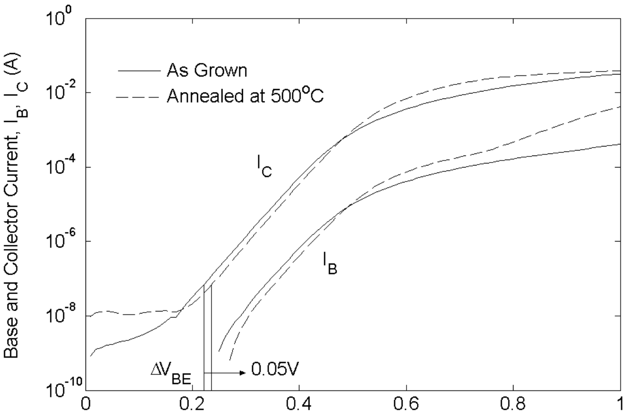

Fig. 4. DC Characteristics of DHBT Sample as Grown (Solid line) and Annealed at 500°C (Dashed)

mobility of carbon shown in Fig. 1 in [7] is less than expected, and result in an increased sheet resistance (605Ω/ instead of 300Ω/). An additional indication to this problem is the low gain of 27 that is a direct consequence of the high doping and low mobility.

The high-quality properties of these devices are shown on further examination of Fig. 1 in [7] and Fig. 4 in [6]. They both show that the room temperature hole mobility of beryllium at a doping of $1.5\times10^{19}cm^{-3}$ is ~$75cm^2/Vs$ even though they are grown by different methods (MBE vs MOCVD). Our hall effect measurements produced a mobility of ~$90cm^2/Vs$ of which is a clear indication of the benefits of using this growth method detailed in [12].

Although, once annealed the differences between our devices and those published by Kuo et al become more pronounced. The base current idealities in [7] increased from 1.2 to 1.3 for the as grown transistors annealed at 500°C. Our SHBT samples annealed over the same temperature range produced marginally improved performance with values for base current ideality ranging from 1.1-1.25. At the high anneal temperature of 550°C both ours and those fabricated by Kuo et al resulted in devices with no substantial gain (<1). However, the base current ideliaties of our devices, which give an indication of the junction quality, produced substantially improved results of 1.4 compared to those produced in [7] of 1.9. In comparison, the DHBT produced the most exciting results, showed negligible degradation in both current gain and idealities, even up to the highest anneal temperature tested (550°C).

VI. CONCLUSIONS

We have fabricated and tested heavily beryllium doped SHBT and DHBT grown by SSMBE. These were shown to be extremely thermally stable, high gain transistors operating with little degradation up to an anneal temperature of 500°C. This inherent stability is a direct result of the relatively low growth temperature of 420°C, and the use of dimeric phosphorus generated from a gallium phosphide (GaP) decomposition source.

When these transistors were compared to similar carbon-doped devices, it was seen that good quality devices could not easily be fabricated using MOCVD [6]. This was due to the requirement of low V/III ratio of ~2 and very low temperature growth of 450°C instead of the optimum 570°C. This was necessary to increase the carbon-doping whilst maintaining a good surface morphology. Only once grown by similar methods [7] do our results show striking similarities with carbon-doped devices. This is especially true in the case of the SHBT, resulting in the same degradation in terms of current idealities, and the failure at 550°C.

The results for the DHBT show very little out diffusion from the base, producing a constant current gain, idealities and breakdown voltages at different annealing temperatures. The excellent nature of this device indicates that given the correct structure design, beryllium doped HBTs can produce high gain, high speed and very thermally stable microwave devices.

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