

Heavily Doped InP-based HBTs for New Wireless and Fiber-optic Telecommunication Applications

D. Lubyshev,* Y. Wu, X.-M. Fang, T. Yurasits, W. K. Liu and A. B. Cornfeld

IQE, Inc. 119 Technology Drive, Bethlehem, PA 18015, USA
Phone: 610-861-6930, Fax: 610-861-5273, Email:dloubychev@iqep.com

ABSTRACT

IQE Inc. has developed a manufacturable MBE process for growing SHBT and DHBT structures lattice-matched to 3" and 4" diameter InP substrates. The high base doping of $4 \times 10^{19} \text{ cm}^{-3}$ and small base thickness of 500 Å were chosen to support the frequency response required for new wireless and 40 Gb/s fiber-optic telecommunication products. Both beryllium and carbon were used for base doping, and produced similar DC characteristics for large-area devices. In addition to the traditional approach of lattice-matched growth on InP substrates, HBT structures were grown on GaAs substrates with metamorphic buffer layers. DC characteristics of M-HBTs was found to compare favorably with that of LM-HBTs.

INTRODUCTION

InP-based single and double heterojunction bipolar transistors (SHBT and DHBT) are prime candidates for new wireless and 40 Gb/s fiber-optic telecommunication applications. The combination of superior electronic properties of InP, InGaAs, and InAlAs, a thin low resistivity base layer, and precise control of alloy grading afforded by molecular beam epitaxy (MBE) enable the realization of HBTs with f_t of over 200 GHz.

InP-based HBTs with heavily doped beryllium (Be) base suffer from the risk of Be diffusing towards the base-emitter junction and the resulting degradation in current gain and device reliability. Devices fabricated from structures using the low-diffusivity *p*-type dopant carbon (C) frequently exhibit lower current gain [1] due to auto-compensation in the InGaAs base and carbon precursor transients in the growth chamber. In this work, we present comparative data on C- and Be-doped SHBTs and DHBTs with base doping around $4 \times 10^{19} \text{ cm}^{-3}$ grown on InP. Preliminary results for HBT structures grown on GaAs substrates with metamorphic buffer layers will also be discussed.

EXPERIMENT

All lattice-matched HBT (LM-HBT) structures were grown on Varian GEN-II and Applied Epi GEN-III MBE

reactors using all solid groups III and V sources and 3" and 4" InP substrates. The dopant sources for the base were a standard effusion cell for Be and a gas injector for C with carbon tetrabromide (CBr_4) as the precursor. Bulk InGaAs layers doped with Be and C at $4 \times 10^{19} \text{ cm}^{-3}$ exhibit similar carrier transport properties, with room temperature mobilities between 60 and 65 $\text{cm}^2/\text{V}\cdot\text{s}$. Growth parameters for Be-doped structures were optimized to minimize Be diffusion towards the base-emitter junction, and evaluated by SIMS and turn-on voltage measurements. The generic SHBT structure used has a 500 Å InGaAs base, an InP emitter and an abrupt B-E junction was used. The generic DHBT structure has a 500 Å InGaAs base, an InP collector and an InAlAs emitter. Digital gradings were used at both heterojunctions to improve carrier injection and to suppress current blocking.

Metamorphic HBTs (M-HBTs) were grown on GaAs substrates with a linearly graded InGaAlAs buffer layer and an inverse graded step. The M-buffer design was used previously for M-HEMT growth.[2] The residual dislocation density, plastic relaxations in the buffer and surface roughness data were described elsewhere.[3,4]

Material evaluation consisted of DC measurements performed on large-area devices with base-emitter junction dimensions of $60 \times 60 \mu\text{m}^2$. The same quick turn around process was employed to characterize M-HBT structures.

LM-SHBTs

The major DC parameters of large-area devices obtained from our initial set of LM-SHBTs samples are summarized in Table I. The corresponding Gummel plots are shown in Fig. 1.

TABLE I
SUMMARY OF LARGE-AREA SHBT DEVICE RESULTS

Structure	SHBT:Be	SHBT:C
Current gain, β	50-65	35-40
Base R_{sh} (Ω/sq) TLM	615	488
V_{offset} (V)	0.10	0.12
BV_{ceo} (V)	3.5	4.0
B-E junc. V_f/V_r (V/0.5 mA)	0.55/5.0	0.60/4.6
B-C junc. V_f/V_r (V/0.5 mA)	0.43/5.2	0.40/5.4
Ideality factors (n_c/n_b)	1.10/1.39	1.08/1.37

The difference in the current gain is related to the difference in the actual base doping concentration as reflected by the sheet resistance (R_{sh}) values. For this initial set of SHBTs, we observed a slightly higher turn-on voltage of approximately 40 mV for the Be-doped devices, possibly due to slight Be diffusion towards the B-E junction.

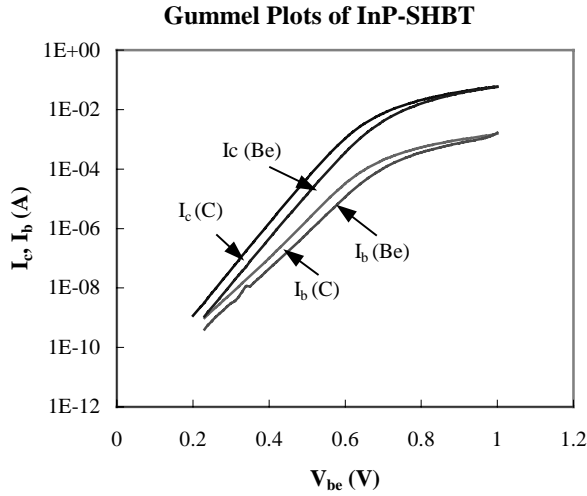


Fig.1 Gummel plots of Be- and C-doped SHBTs.

LM-DHBTs

Further optimization of the growth process focused on the suppression of Be diffusion and improvement of gas manifold and injector design to reduce CBr_4 transients. The generic DHBT structure was used for testing. Optimization of the growth procedure and hardware configuration led to the narrowing of the current gain difference (50 and 45, respectively) and turn-on voltage difference (10 mV) between Be- and C-doped DHBTs. The DC characteristics of these DHBTs are shown in Table II and the Gummels plot in Fig. 2.

TABLE II

SUMMARY OF LARGE AREA DHBT DEVICE RESULTS

Structure	DHBT:Be	DHBT:C
Current gain, β	27–50	28–45
Base R_{sh} (Ω) TLM	565	565
V_{offset} (V)	0.07	0.07
BV_{ceo} (V)	10.0	10.0
B-E junc: V_f/V_r (V/0.5 mA)	0.52/2.2	0.50/1.6
B-C junc V_f/V_r (V/0.5 mA)	0.50/12.5	0.40/12.0
Ideality factors (n_c/n_b)	1.00/1.41	1.00/1.43

The use of a thin InP collector layer was found to increase the device collector-emitter breakdown voltage to

10 V (Fig. 3). SIMS analysis data (not shown here) showed no sign of Be diffusion.

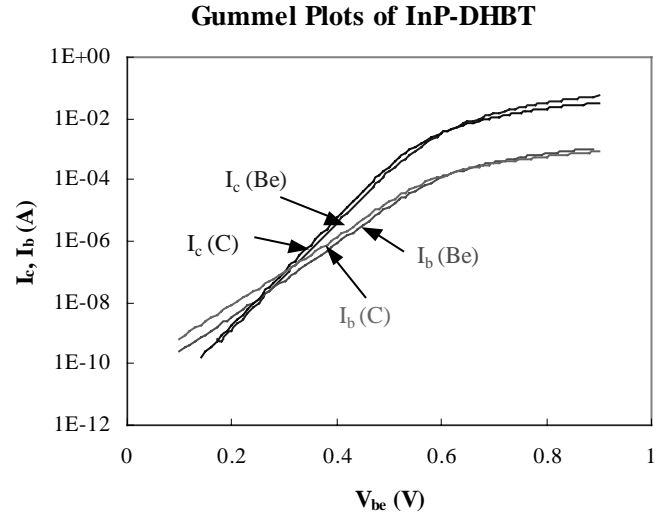


Fig. 2 Gummel plots of Be- and C-doped DHBTs.

InP-DHBT Common Emitter I_c vs. V_{ce} Curves

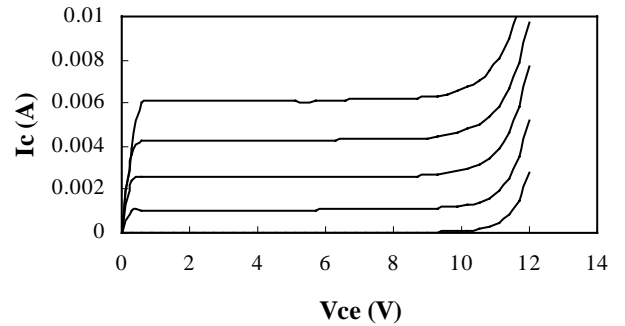


Fig. 3 Common emitter characteristics of DHBT:Be.

M-SHBTs

The design and growth procedures for the metamorphic buffer are optimized for smooth surface morphology and complete strain relaxation. Current gain, base-emitter and base-collector ideality factors of M-HBTs were found to be strongly influenced by both the surface roughness and the residual dislocations in the base region. In general, the surface roughness of metamorphic epilayers scales as a function of total layer thickness. Since HBT structures are

typically thicker than HEMT structures, M-HBT growth is more challenging than the corresponding M-HEMT growth.

Nevertheless, M-HBT structures grown under optimal conditions exhibit root-mean-square roughness of only 1.6 nm as measured by AFM using a scan size of $5\ \mu\text{m} \times 5\ \mu\text{m}$. This value compares very favorably with those published for M-HEMT structures and is lower than the 2.0 nm figure for merit for gauging device reliability.[2–5] On the other hand, the crosshatch patterns on M-BHTs are generally more well developed and are clearly visible in the SEM micrograph of the large-area devices shown in Fig. 4.

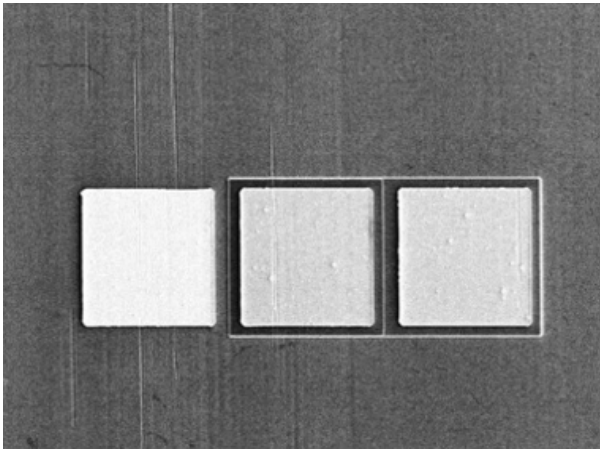


Fig. 4 SEM image of large-area ($60 \times 60\ \mu\text{m}^2$) M-HBT devices revealing well developed crosshatching patterns.

The DC characteristics of M-HBT structures grown on GaAs substrates were compared to that of baseline LM-HBT structures grown on InP substrates. A SHBT test structure with a thin InGaAs collector, a $1000\ \text{\AA}$ base doped at $1 \times 10^{19}\ \text{cm}^{-3}$, and an InAlAs emitter was used. Large-area device results are listed in Table III below. The difference in the current gain to base sheet resistance ratio of the M-HBT and LM-HBT is less than 5%.

TABLE III
SUMMARY OF LARGE-AREA M- AND LM-SHBT DEVICE RESULTS

Structure	M-SHBT (on GaAs)	LM-SHBT (on InP)
Current gain, β	220–320	250–360
Base R_{sh} (Ω/sq) TLM	909	985
V_{offset} (V)	0.18	0.15
BV_{ceo} (V)	3.4	4.0
B-E junc: V_f/V_r (V/0.5 mA)	0.6/3.6	0.6/3.8
B-C junc V_f/V_r (V/0.5 mA)	0.4/14.4	0.4/15.0
Ideality factors (n_c/n_b)	1.39/1.67	1.31/1.46

Gummel plots for the M-HBT and LM-HBT devices also exhibit very similar characteristics (Fig. 5). There is no indication of p-n junction degradation due to interfacial roughness or Be diffusion. These preliminary results suggested that the metamorphic approach for HBT growth is viable for producing large diameter and potentially lower cost wafers for wireless and 40 Gb/s fiber-optic telecommunication applications.

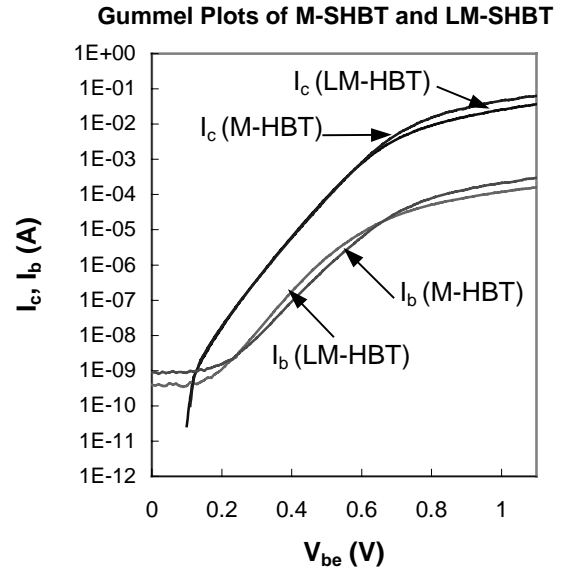


Fig. 5 Gummel plots for large-area M-SHBT and LM-SHBT devices.

CONCLUSIONS

We have developed MBE growth processes for large diameter InP-based HBT structures with base region heavily doped with Be and C that are attractive for new wireless and optoelectronic device applications. Growth parameters were optimized to effectively suppress Be diffusion with base doping level up to $4 \times 10^{19}\ \text{cm}^{-3}$. Both Be- and C-doped devices exhibit good linearity and DC current gain. The use of an InP collector and an effective base-collector grading help increase device breakdown voltage and eliminate current blocking.

M-HBTs grown on GaAs substrates exhibit DC characteristics comparable to their LM counterparts grown on InP substrates. No degradation in DC current gain was observed. These preliminary results demonstrate the potential of M-HBT as a low cost alternative to HBT devices grown on InP substrates.

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