High Bandwidth and Low-Leakage Current InP–$In_{0.53}Ga_{0.47}As$–InP DBHTs on GaAs Substrates

Y. M. Kim, Z. Griffith, M. J. W. Rodwell, and A. C. Gossard

***Abstract*—InP–$In_{0.53}Ga_{0.47}As$–InP double heterojunction bipolar transistors (DHBTs) were grown on GaAs substrates. A 284-GHz power-gain cutoff frequency $f_{\max}$ and a 216-GHz current-gain cutoff frequency f_τ were obtained, presently the highest reported values for metamorphic HBTs. The breakdown voltage BV_{CEO} was > 5 V while the dc current gain β was 21. High thermal conductivity InP metamorphic buffer layers were employed in order to minimize the device thermal resistance.**

***Index Terms*—Heterojunction bipolar transistor (HBT), indium phosphide, metamorphic growth, molecular beam epitaxy (MBE).**

I. INTRODUCTION

DOUBLE heterojunction bipolar transistors (DHBTs) have applications in high-frequency communications and radar [1], [2]. Though InP-based DHBTs presently show the best high-frequency performance, the high cost and the low breaking strength of InP substrates are major disadvantages in manufacturing. For those reasons, InP-based DHBTs grown metamorphically on GaAs substrates is an active topic of research [3], [4]. We had earlier reported [5] metamorphic HBTs (MHBTs) with 200-GHz f_τ and 200-GHz $f_{\max}$ using $4 \cdot 10^{19}/\mathrm{cm}^3$ Be base doping. We here report MHBTs with substantially improved $f_{\max}$ resulting from high carbon-base doping graded from 8 to $5{\cdot}10^{19}/\mathrm{cm}^3$. We obtained 284-GHz $f_{\max}$ and 216-GHz f_τ. Despite the potential for defects associated with metamorphic growth, the HBTs show a base–collector leakage current $I_{\mathrm{cbo}} = 1.2$ nA at $V_{\mathrm{CB}} = 0.3$ V, comparable to the 1.8 nA I_{cbo} for similar lattice matched DHBTs fabricated in our laboratory.

To minimize C/I charging times in $\sim 100 -$ GHzclock-rate logic [6], HBT emitter current densities must be $\sim$ 4–10 mA/μm^2, and hence for a 40 °C junction-ambient temperature rise at $V_{\mathrm{CE}} = 1$ V, the HBT thermal resistance normalized to the emitter junction area must be low at $\sim$ 4–10 K $\cdot$ μm^2/mW. As reported earlier [3], [7] the buffer layer thermal conductivity has a large impact upon the device thermal resistance. We therefore use InP metamorphic buffer layers ($\sim$ 35 W/m-K measured thermal conductivity), as for these we have observed substantially higher thermal conductivity than for InAlAs (10.5 W/m-K) or AlAsSb (8.4 W/m-K) buffers.

TABLE I
LAYER STRUCTURE OF THE MBE-GROWN INP–$In_{0.53}Ga_{0.47}As$–INP METAMORPHIC DHBT. THE BASE DOPING VARIES FROM $8 \cdot 10^{19}/\mathrm{cm}^3$ ADJACENT TO THE EMITTER TO $5 \cdot 10^{19}/\mathrm{cm}^3$ ADJACENT TO THE COLLECTOR. THE BASE-COLLECTOR SUPERLATTICE GRADE HAS A 15 Å PERIOD

Layer	Material	Doping	Thickness (Å)
Emitter cap	$In_{0.53}Ga_{0.47}As$	3×10^{19} cm^{-3}: Si	400
N$^+$ emitter	InP	3×10^{19} cm^{-3}: Si	800
N emitter	InP	8×10^{17} cm^{-3}: Si	100
N$^-$ emitter	InP	3×10^{17} cm^{-3}: Si	300
Base	$In_{0.53}Ga_{0.47}As$	8×10^{19} cm^{-3} 5×10^{19} cm^{-3} : C	300
Setback	$In_{0.53}Ga_{0.47}As$	2×10^{16} cm^{-3}: Si	200
Base-collector grade	$In_{0.53}Ga_{0.47}As$ to $In_{0.53}Ga_{0.26}Al_{0.21}As$	2×10^{16} cm^{-3}: Si	240
Pulse doping	InP	3×10^{18} cm^{-3}: Si	30
Collector	InP	2×10^{16} cm^{-3}: Si	1,700
Subcollector	InP	1.5×10^{19} cm^{-3}: Si	500
Subcollector	$In_{0.53}Ga_{0.47}As$	2×10^{19} cm^{-3}: Si	500
Subcollector	InP	3×10^{19} cm^{-3}: Si	2000
Buffer	InP	undoped	200
Leakage blocking layer	$In_{0.52}Al_{0.48}As$	undoped	200
Buffer	InP	undoped	15,000
GaAs (100) semi-insulating substrate			

II. GROWTH

InP–$In_{0.53}Ga_{0.47}As$–InP DHBTs were grown on a GaAs substrate using a Varian Gen II molecular beam epitaxy (MBE) system. Growth was initiated with a 1000-Å undoped GaAs buffer layer, followed by growth at 470 °C of a 1.5-μm undoped InP metamorphic buffer layer. The remaining HBT layers were then grown. The layer structure (Table I) is similar to lattice-matched DHBTs we had earlier reported [8], with an InP emitter, a 300-Å InGaAs base with carbon doping graded from $8{\cdot}10^{19}/\mathrm{cm}^3$ to $5{\cdot}10^{19}/\mathrm{cm}^3$ for reduced base transit time and increased current gain, a 200-Å undoped $In_{0.53}Ga_{0.47}As$ setback layer, a 240 Å $In_{0.53}Ga_{0.47}As/In_{0.52}Ga_{0.48}As$ chirped superlattice base–collector heterojunction grade, and a 1700 Å N-InP collector. The total collector–base depletion region thickness at greater than $\sim$ 0.5 V reverse bias is 2170 Å.

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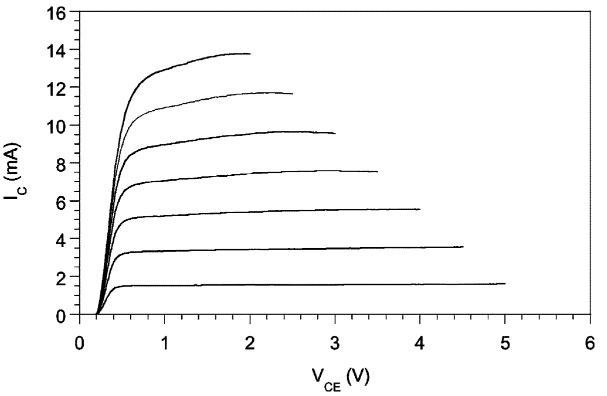

Fig. 1. Common–emitter dc characteristics of a 0.6 × 8 μm emitter device. The base current steps are 100 μA.

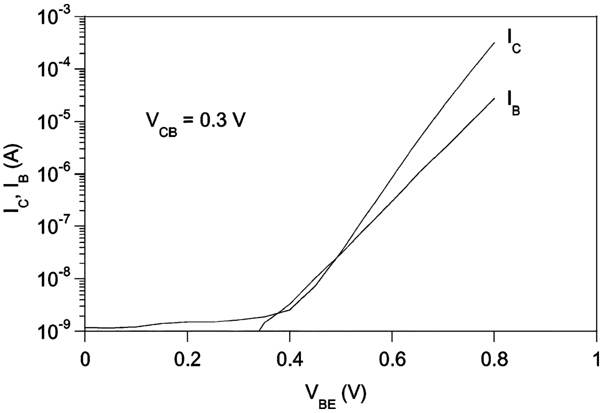

Fig. 2. MHBT Gummel characteristics of an HBT with a 0.6 ×8 μm emitter–base junction and a 2.7 × 11 μm base–collector junction.

III. FABRICATION

HBTs were fabricated in a triple-mesa process using optical projection lithography and selective wet chemical etching. The junctions are narrow [9] for reduced $R_{bb}C_{\mathrm{CB}}$. The emitter contact metal is 0.7 × 8 μm and base contacts extend 1.0 μm on each side of the emitter stripe, producing a small 2.7 × 11 μm base–collector junction area. Due to undercut during emitter etching, the emitter junction area is approximately 0.6 × 8 μm. Pd(30 Å)–Ti(200 Å)–Pd(200 Å)–Au(400 Å) base Ohmic contacts a provide specific contact resistance below 10^{-6} $\Omega\mathrm{cm}^2$. The emitter and collector contacts are Ti–Pt–Au and all the metal contacts are annealed at 300 C. Polyimide is used both for passivation and for mesa planarization prior to interconnect deposition.

IV. RESULTS

Fig. 1 shows the common–emitter characteristics, measured from 0–14 mA. The measured dc current gain is approximately 21, the common-emitter open-circuit breakdown voltage at low current $\mathrm{BV}_{\mathrm{CEO}}$ is greater than 5 V, while $V_{\mathrm{CE,SAT}}$ is low (0.5 V) at 10 mA ($\sim$ 2.5 mA/μm^2), indicating correct design of the base–collector junction grade. Fig. 2 shows the HBT Gummel ($\log\{I_C, I_B\}$ versus V_{CE}) characteristics, indicating a collector current ideality factor of 1.26 and a base current ideality factor of 1.71. The characteristics are measured with nonzero (0.3 V) reverse bias applied to the collector–base junction, so that base–collector junction leakage, if present, will be observed. The base–collector leakage current I_{cbo} is 1.2 nA (40 pA/μm^2) at $V_{\mathrm{CB}} = 0.3$ V. This leakage is comparable to 1.8 nA I_{cbo} (61 pA/μm^2) for similar lattice-matched InP DHBTs in our laboratory, and is 10:1 smaller than we had previously reported [5] for MHBTs. We ascribe this variation to variations in the success of the polyimide passivation procedure. Gummel characteristics of large-area HBTs (60 × 60 μm emitter–base and 100 × 130 μm base–collector junctions) fabricated from the same epitaxial material (Fig. 3) shows 0.1 μA I_{cbo} (7.7 pA/μm^2), as compared to 5 nA (0.39 pA/μm^2) for similar large-area lattice-matched HBTs, with the larger leakage current most probably arising from thermal generation associated with bulk defects arising from metamorphic growth. The leakage current I_{cbo} per unit collector–base junction area measured with 2.7 × 11 μm base–collector junction area MHBTs is 5.2:1 larger than that of the large-area test devices, suggesting that in the small devices I_{cbo} is dominated by surface leakage, not defect-associated thermal generation in the bulk collector depletion region. Supporting this hypothesis, small-area metamorphic DHBTs with improved benzocyclobutene (BCB) passivation and having 1.5 × 10 μm base–collector junction area exhibited 100 pA I_{cbo} (6.7 pA/μm^2), a leakage current density similar to that of the large-area metamorphic samples.

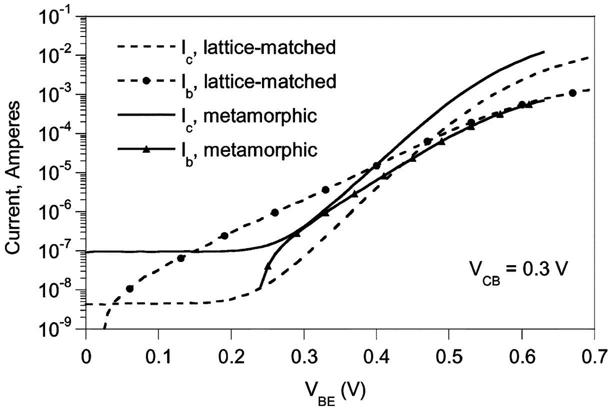

Fig. 3. Large-area Gummel characteristics (I_C) of MHBT and LM-HBT with a 60 × 11 μm emitter–base junction and a 100 × 130 μm base–collector junction. The solid line is for MHBT and dotted line is for LM-HBT.

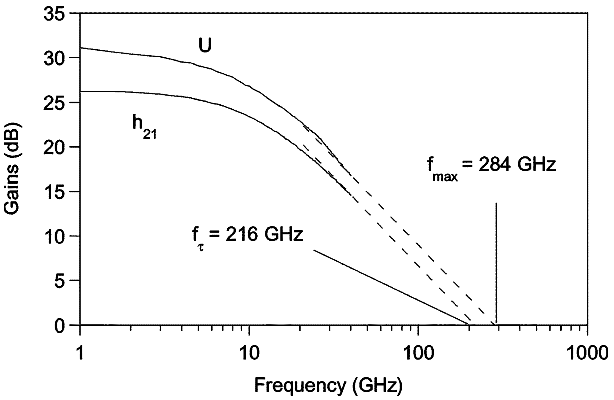

Fig. 4. Measured short-circuit current gain h_{21} and Mason,s unilateral power gain U versus frequency for an HBT with a 0.6 μm× 8 μm emitter–base junction and a 2.7 μm× 11 μm base–collector junction. $I_C = 14.0$ mA and $V_{\mathrm{CE}} = 1.5$ V.

Fig. 4 shows the current gain (h_{21}) and unilateral power gain (U) of the small-area HBT, computed from the measured 5–40

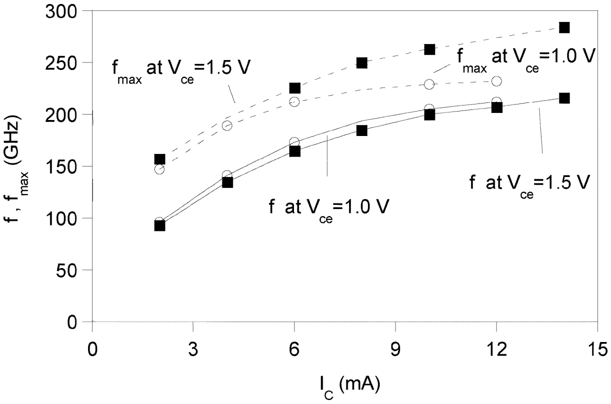

Fig. 5. Measured current-gain cutoff frequency f_τ and power-gain cutoff frequency $f_{\max}$ versus current at $V_{\rm CE} = 1.0$ V and $V_{\rm CE} = 1.5$ V.

GHz S-parameters. A 216 GHz f_τ and a 284 GHz $f_{\max}$ were measured at $I_C = 14.0$ mA and $V_{\rm CE} = 1.5$ V, as determined by a -20 $\rm dB/decade$ extrapolation. These are the highest values reported for MHBTs. Lattice-matched DHBTs with similar material design and junction dimensions [8] exhibited 282 GHz f_τ and > 400 GHz $f_{\max}$. Because f_τ and $f_{\max}$ are greatly influenced by emitter and base Ohmic contact resistivities and by the degree of base–collector junction undercut, we do not believe that the difference between lattice-matched and MHBT bandwidth can be fully ascribed to differences in material quality. Fig. 5 shows the variation of f_τ and $f_{\max}$ with collector current, as measured at $V_{\rm CE} = 1.0$ V and $V_{\rm CE} = 1.5$ V. The increased $f_{\max}$ compared to prior results [5] results from increased base doping and reduced base Ohmic contact resistivity.

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