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Solid-State Electronics 46 (2002) 1541–1544

SOLID-STATE ELECTRONICS

www.elsevier.com/locate/sse

$InP/In_{0.53}Ga_{0.47}As/InP$ double heterojunction bipolar transistors on GaAs substrates using InP metamorphic buffer layer

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Received 11 December 2001; accepted 17 January 2002

Abstract

$InP/In_{0.53}Ga_{0.47}As/InP$ double heterojunction bipolar transistors were grown on GaAs substrates. A 92 GHz power-gain cutoff frequency f_{max} and a 165 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 27. In order to minimize the transistor operating junction temperature, high-thermal-conductivity InP metamorphic buffer layers were employed.

Keywords: Metamorphic growth; Heterojunction bipolar transistor; Indium phosphide

1. Introduction

Double heterojunction bipolar transistors [1–3] (DHBTs) have applications in high-frequency communications and radar. HBTs using InGaAs or GaAsSb epitaxial base layers and InGaAs or InP epitaxial collector layers—lattice-matched to InP—currently exhibit significantly higher current-gain and power-gain cutoff frequencies than GaAs-based HBTs. However, InP substrates are expensive and are available only in smaller diameters than GaAs substrates are. Additionally, 100-mm-diameter InP substrates are fragile and are readily broken during semiconductor manufacturing. This has motivated the investigation of metamorphic growth of InP-based DHBTs on GaAs substrates [4]. To date, reported metamorphic growths have used AlGaAsSb or InAlAs buffer layers, which have very low thermal conductivities, approximately 5–10 $W K^{-1} m^{-1}$ as measured for layers grown in our laboratory. When the HBT is operated at high ($\sim 10^5$ A/cm^2) bias current density, which is required for high-transistor bandwidth, such low-thermal-conductivity epitaxial layers beneath the transistor will increase the junction temperature substantially relative to that of an HBT grown on a lattice-matched InP substrate [5], with a consequent reduction in HBT reliability [6]. Here we report metamorphic InP-based HBTs with greatly improved performance. A 92 GHz power-gain cutoff frequency f_{max} and a 165 GHz current-gain cutoff frequency f_τ were obtained in a device with a 5 V common-emitter breakdown voltage BV_{CEO}. In order to minimize the transistor operating junction temperature, InP metamorphic buffer layer was employed. This has a measured thermal conductivity of 16.1 $W K^{-1} m^{-1}$.

2. 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. After oxide desorption, 1000 Å

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0038-1101/02/$ - see front matter
PII: S0038-1101(02)00102-8

undoped GaAs buffer layer was grown at 600 °C, forming a smooth surface prior to metamorphic growth. The substrate temperature was then reduced to 480 °C and the 1.5 μm undoped InP metamorphic buffer layer was grown directly on the GaAs substrate. During buffer layer growth, the reflection high-energy electron diffraction (RHEED) pattern showed strong streaks, indicating two-dimensional growth, although the RHEED pattern intensity was slightly weaker than that observed during lattice-matched growth. The remaining HBT layers were then grown. Key features of the layer structure (Table 1) include an InP emitter, a 400-Å-thick InGaAs base with 52 meV band gap grading for base transit time reduction, a 200-Å InGaAs/InAlAs base–collector heterojunction grade, and a 1700-Å InP collector. The heterojunction between the $In_{0.53}Ga_{0.47}As$ base and the InP collector is a 200-Å-thick $In_{0.53}Ga_{0.47}As/In_{0.52}Al_{0.48}As$ chirped superlattice whose composition adjacent to the collector is $In_{0.53}Ga_{0.26}Al_{0.21}As$, chosen so as to eliminate discontinuities in the conduction-band energy at the interface. A similar superlattice grade is employed in the emitter–base junction. A 1.4×10^{12} cm^{-2} N-type pulse-doped layer below the base–collector grade, which has a larger doping than that required to counteract the quasi-field associated with the grade, produces an accelerating field in the base–collector grade. A significant Be base dopant migration into the base–collector grade would produce an energy barrier in the conduction band, partially suppressing electron transport from base to collector, and thereby increasing the base transit time. For this reason, a 100 Å undoped $In_{0.53}Ga_{0.47}As$ setback layer was introduced between the base and the base–collector grade. The total collector–base depletion region thickness is therefore 2000 Å.

3. Fabrication and measurement

HBTs were fabricated in a triple-mesa process using optical projection lithography and selective wet chemical etching. Use of narrow emitter–base and collector–base junctions reduces both the base resistance and the collector–base capacitance [7]. While the emitter contact metal is 0.7 μm × 8 μm, lateral undercutting during the HCl-based etch of the InP emitter forms an emitter–base junction whose dimensions are approximately 0.4 μm × 8 μm. Collector–base capacitance is reduced by employing narrow base Ohmic contacts of 0.25 μm width on either side of the emitter stripe, producing a small 1.2 μm × 11 μm base–collector junction area. Polyimide is used both for passivation and for mesa planarization prior to interconnect deposition.

Fig. 1 shows the common-emitter characteristics. The measured peak small-signal DC current gain is approximately 27, while the common-emitter open-circuit breakdown voltage BV_{CEO} is 5 V at 2 mA bias. Fig. 2 shows the Gummel characteristics, again indicating $\beta \cong 23$ and a base ideality factor of 2.0. We observe a similar DC current gain and base ideality factor in lattice-matched InP/InGaAs/InP DHBTs with submicron emitter dimensions [8], effects we attribute to electron conduction on the exposed InGaAs base surface between the emitter heterojunction and the base Ohmic contact. I–V measurements of the collector–base junction (with open emitter) indicate 0.7 μA collector–base leakage I_{cbo} at 0.3 V reverse bias on the collector–base junction.

Fig. 2 also shows Gummel characteristics measured on a large-area HBT (60 μm × 60 μm emitter–base and 100 μm × 130 μm base–collector junctions) fabricated from the same epitaxial material. Despite the large col-

Table 1
Layer structure of the MBE-grown $InP/In_{0.53}Ga_{0.47}As/InP$ metamorphic DHBT (GaAs (1 0 0) semi-insulating substrate)

Layer	Material	Doping	Thickness (Å)
Emitter cap	$In_{0.53}Ga_{0.47}As$	2×10^{19} cm^{-3}: Si	1000
Grade	$In_{0.53}Ga_{0.47}As$ to $In_{0.53}Ga_{0.26}Al_{0.21}As$	2×10^{19} cm^{-3}: Si	200
N^+ emitter	InP	2×10^{19} cm^{-3}: Si	900
N^- emitter	InP	3×10^{18} cm^{-3}: Si	300
Emitter–base grade	$In_{0.53}Ga_{0.26}Al_{0.21}As$ to	8×10^{17} cm^{-3}: Si	233
	$In_{0.455}Ga_{0.545}As$	8×10^{17} cm^{-3}: Be	67
Graded base	$In_{0.455}Ga_{0.545}As$ to $In_{0.53}Ga_{0.47}As$	4×10^{19} cm^{-3}: Be	400
Setback	$In_{0.53}Ga_{0.47}As$	Undoped	100
Base–collector grade	$In_{0.53}Ga_{0.47}As$ to $In_{0.53}Ga_{0.26}Al_{0.21}As$	1×10^{16} cm^{-3}: Si	200
Pulse doping	InP	7×10^{18} cm^{-3}: Si	20
Collector	InP	2×10^{16} cm^{-3}: Si	1700
Subcollector	$In_{0.53}Ga_{0.47}As$	1×10^{19} cm^{-3}: Si	250
Subcollector	InP	2×10^{19} cm^{-3}: Si	750
Buffer	InP	undoped	15 000

All graded layers are $In_{0.53}Ga_{0.47}As/In_{0.52}Al_{0.48}As$ digital alloy grades, except the base, which is an $In_xGa_{1-x}As$ linear compositional grade.

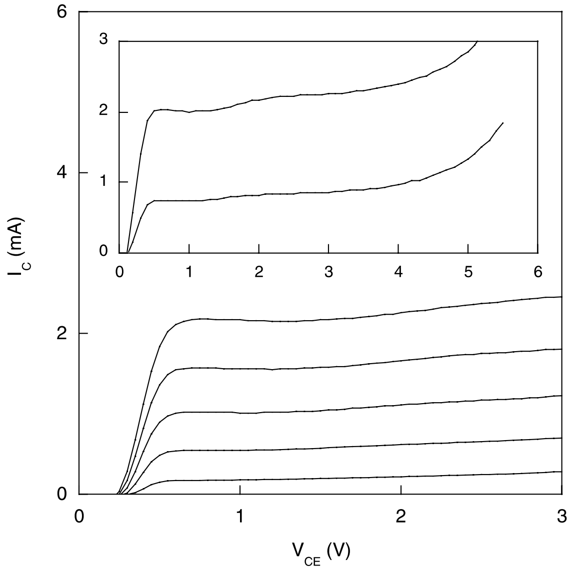

Fig. 1. Common-emitter DC characteristics of 0.4 μm × 8 μm emitter device. The base current steps are 20 μA. The plot inset, over an expanded voltage range and with 50 μA base current steps, shows a 5 V common-emitter breakdown voltage.

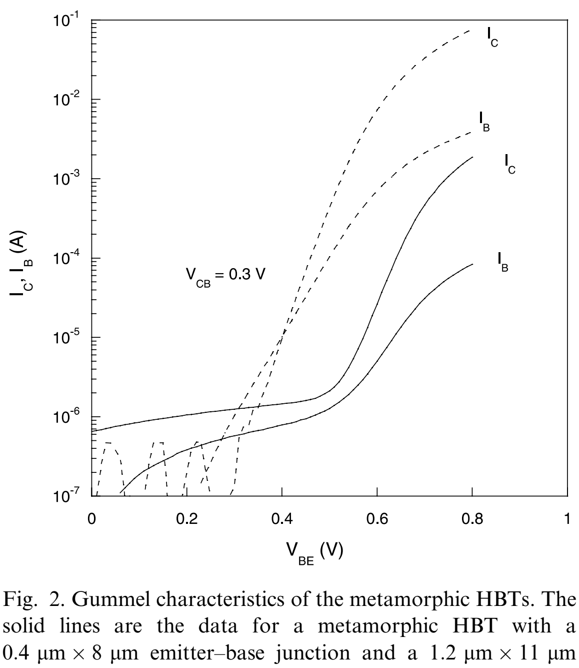

Fig. 2. Gummel characteristics of the metamorphic HBTs. The solid lines are the data for a metamorphic HBT with a 0.4 μm × 8 μm emitter–base junction and a 1.2 μm × 11 μm base–collector junction, while the dotted lines are for a metamorphic HBT with a 60 μm × 60 μm emitter–base junction and a 100 μm × 130 μm base–collector junction.

lector–base junction area, the Gummel characteristics indicate that I_{cbo} of the large-area HBT is below 0.5 μA. If associated with defects arising from metamorphic growth, the observed collector–base leakage current would be proportional to the collector–base junction area. Given the low I_{cbo} associated with the large-area HBT, the data suggests that I_{cbo} of the small-area HBT most probably results from inadequate collector–base junction surface passivation.

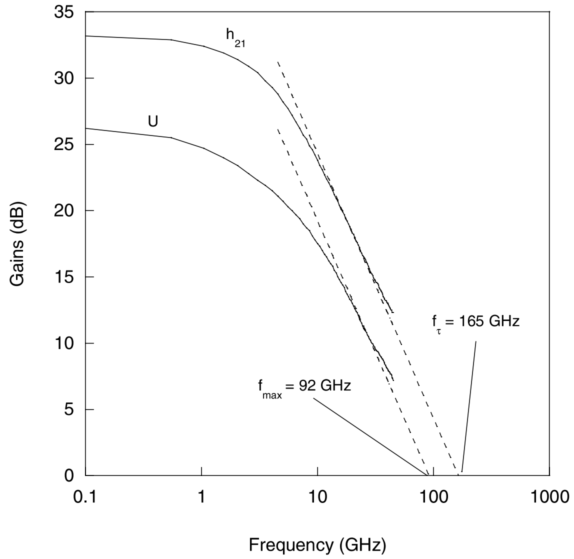

Fig. 3. Measured short-circuit current gain h_{21} and Mason unilateral power-gain U vs. frequency for an HBT with a 0.4 μm × 8 μm emitter–base junction and a 1.2 μm × 11 μm base–collector junction ($I_C = 7.0$ mA and $V_{CE} = 1.5$ V).

Fig. 3 shows the current gain (h_{21}) and unilateral power-gain (U) of the small-area HBT, computed from the measured 0.045–45 GHz S-parameters. A 165 GHz f_τ and a 92 GHz f_{max} were measured at ($I_C = 7.0$ mA (3.3×10^5 A/cm^2) and $V_{CE} = 1.5$ V, as determined by a −20 dB/decade extrapolation. These are the highest values reported for metamorphic HBTs.

Acknowledgements

This work was supported by the ONR under grant number N00014-01-1-0065.

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