A Comparative Study of DC and Microwave Characteristics of Lattice-Matched InP HBTs and Metamorphic HBTs Grown by MBE

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Abstract

We have demonstrated comparable DC and RF characteristics for both lattice-matched InP based heterojunction bipolar transistors (LM-HBTs) and Metamorphic HBTs (M-HBTs) of identical design but grown on a GaAs substrate using MBE technology. The cut-off frequencies f_T and f_{MAX} are 75GHz and 45GHz, respectively for both LM-DHBTs and M-DHBTs with 5×10μm^2 emitters. To our knowledge, this f_T is the highest recorded for a M-HBT. This result is another step in the required process to demonstrate that high-performance InP HBTs can be manufactured on the more cost effective GaAs substrate.

INTRODUCTION

InP HBTs offer significant improvements in performance over GaAs based HBTs in terms of higher operating frequency, reduced power consumption, and improved noise characteristics. However, issues associated with substrate size (maximum 4" in diameter), material cost per square inch, and brittleness of InP substrates represent roadblocks to high volume commercialization of InP HBTs. The metamorphic approach to growing InP-like HBT structures on GaAs substrates represents a potential solution to realizing high volume, low cost, high performance InP-like HBTs. An additional benefit of the metamorphic approach is the increased degree of freedom in bandgap engineering, since the lattice constant of the active layers is not restricted to that of InP. However, the primary technical challenge for the metamorphic buffer (M-buffer) to overcome is the large lattice mismatch between the substrate and the active layers that can potentially cause a high density of threading dislocations and the associated minority carrier lifetime degradation.

In this paper we present comparative DC results for both single heterojunction bipolar transistor (SHBT) and double heterojunction bipolar transistor (DHBT) with 500 Å InGaAs base layers C-doped to 4e19 cm^{-3}. Both M-DHBTs and LM-DHBTs with 5×10μm^2 emitters exhibit effectively the same f_T (~75GHz) and f_{max} (~45GHz). To our knowledge, this f_T is the highest recorded for a M-HBT.

EXPERIMENTAL

The epitaxial structures were grown on 3" SI InP and GaAs substrates in a Varian GEN-II reactor configured with solid sources. The C-doping source is carbon tetrabromide (CBr_4). Metamorphic HBTs with identical LM-HBT design were grown on GaAs substrates with a linearly graded InAlAs buffer layer and an inverse graded step. The M-buffer design was used previously for M-HEMT growth [1]. The generic HBT structures discussed in this work have a 500Å InGaAs base layer carbon doped at 4×10^{19} cm^{-3}. The SHBT structures incorporate an InP emitter with abrupt base-emitter junction and a 4000Å InGaAs collector layer doped at 1×10^{17} cm^{-3}. The DHBT structures have InAlAs emitters and 3000Å InP collector layers doped at 1.5×10^{16} cm^{-3}. Digital gradings at the base-emitter and base-collector junctions were used to improve carrier injection and to suppress current blocking.

A "quick turn around process" was employed to enable rapid DC measurements on large area devices (base-emitter junction dimensions of 110×110μm^2). H_2SO_4:H_2O_2:H_2O and HCl:H_2O_2 etchants were used to selectively etch InGaAs and InP layers, respectively, to form the emitter mesa and to expose the sub-collector layer for contacting. Ti/Au metals were deposited to form both n- and p- type Ohmic contacts. For RF measurement, small area devices were fabricated using a self-aligned process. Gold-electroplated air-bridges for interconnection combined with Ti/Pt/Au ohmic metallization yield a very low thermal resistance for device operation [2]. The base-emitter junction dimensions of the small area devices are 5×10μm^2.

DEVICE PERFORMANCE AND DISCUSSION

DC Characteristics

On-wafer DC characteristics from large area devices ($110\times110\mu m^2$ emitters) were measured with a HP4155B semiconductor parameter analyzer using a Karl-Suss PM5 manual probe station. Fig. 1 shows typical common-emitter DC characteristics for the LM-SHBT, M-SHBT, LM-DHBT and M-DHBT devices. In Fig. 2 are the Gummel plots, and Tables 1 and 2 list the DC characteristics for SHBTs and DHBTs.

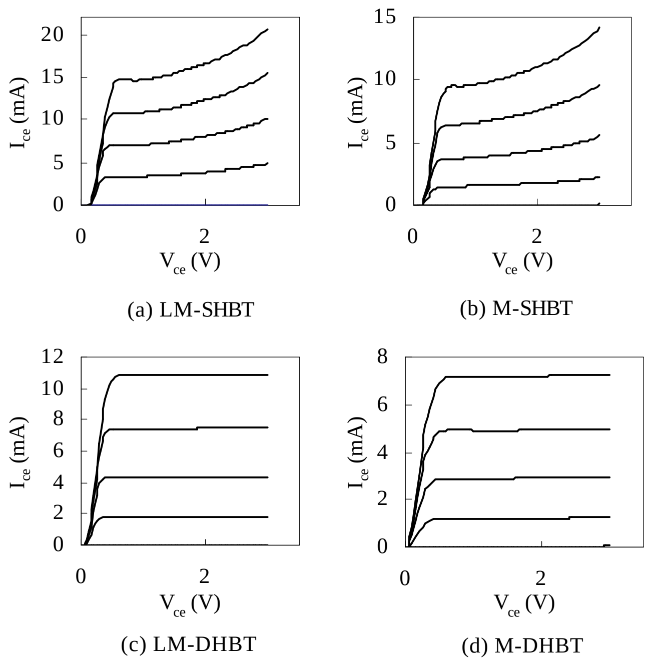

Figure 1. Common emitter characteristics of (a) LM-SHBT, (b) M-SHBT, (c) LM-DHBT and (d) M-DHBT (I_b=50µA/step)

The DC characteristics of M-HBTs, including current gain, base-emitter and base-collector ideality factors, were found previously [3] to be strongly correlated with both the surface roughness and the residual dislocations in the base region. Note in Table 1, the LM-SHBTs and M-SHBTs exhibited common-emitter current gains of 49 and 47, respectively with BV_{ceo}=4.0V. The ideality factors for the collector and base currents are comparable, with no indication of p-n junction degradation. The offset voltages, B-E, and B-C junction characteristics are very comparable. The M-DHBT shows some degradation in the DC current gain (31 vs. 41 for LM-DHBT as indicated in Table 2), but the breakdown voltages are essentially the same as the reference LM-DHBT. No current blocking effect was observed for either LM-DHBT or M-DHBT. Both LM-DHBT and M-DHBT exhibit the same collector ideality factor of n_c=1.00. M-DHBT has a lower base ideality factor (n_b=1.33) than that measured for LM-DHBT (n_b=1.43), which is consistent with lower gain for M-DHBT. This means the bulk recombination current in M-DHBT is higher than that in LM-DHBT.

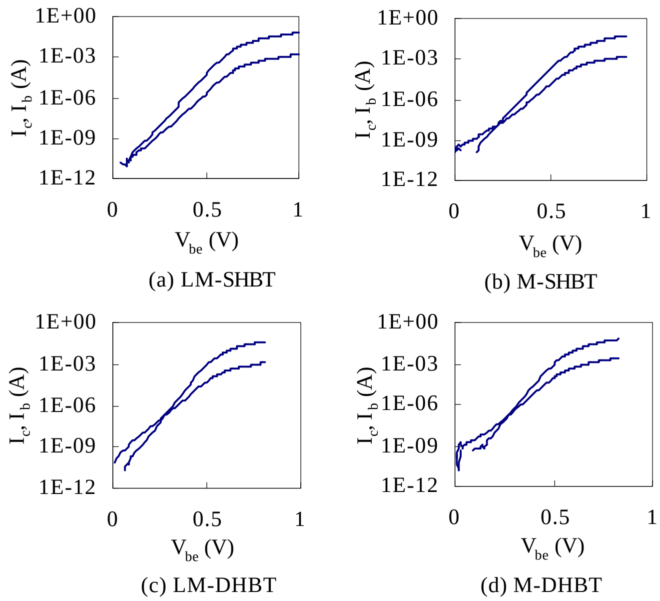

Figure 2. Gummel plots of (a) LM-SHBT, (b) M-SHBT, (c) LM-DHBT and (d) M-DHBT

TABLE I
Summary of Large-Area Device Results for LM-SHBT and M-SHBT

Structure	LM-SHBT:C (on InP)	M-SHBT:C (on GaAs)
Current gain, β @I_c=80mA	49	47
V_{offset} (V)	0.13	0.13
BV_{ceo} (V)	4.0	4.0
B-E junction V_f/V_r (V@0.5 mA)	0.55/4.6	0.54/4.2
B-C junction V_f/V_r (V@0.5 mA)	0.42/5.4	0.41/5.2
Ideality factors (n_c/n_b)	1.08/1.37	1.09/1.41

TABLE II
Summary of Large-Area Device Results for LM-DHBT and M-DHBT

Structure	LM-DHBT:C (on InP)	M-DHBT:C (on GaAs)
Current gain, β @I_c=80mA	41	31
V_{offset} (V)	0.07	0.07
BV_{ceo} (V)	8.9	8.9
B-E junction V_f/V_r (V@0.5 mA)	0.50/1.6	0.49/1.6
B-C junction V_f/V_r (V@0.5 mA)	0.43/12.0	0.42/10.8
Ideality factors (n_c/n_b)	1.00/1.43	1.00/1.33

RF Characteristics

On-wafer S-parameters were measured with an HP8510B network analyzer and a Cascade microwave probe station from 1 to 40GHz for DHBTs with a relatively large emitter size (5×10μm^2). The current gain ($|H_{21}|$) and the maximum stable gain (MSG) are extrapolated at –20dB/ decade to obtain the two figures of merit, f_T, the unity current gain cutoff frequency and f_{max}, the maximum oscillation frequency. At a collector to emitter (V_{CE}) bias of 1.5V and a collector current (I_c) of 15mA, M-DHBT exhibits an f_T=75GHz and an f_{max}=45GHz as shown in Fig. 3. Likewise, LM-DHBT exhibits the same f_T=75GHz and f_{max}=45GHz as indicated in Fig. 4. To our knowledge, this f_T is the highest recorded for a M-HBT. The low f_{max} is mainly due to the relaxed design rule (5 ìm emitter) and the large collector to emitter area ratio causing a non-optimum base/collector capacitance. The comparable microwave results for the M-DHBT and LM-DHBT indicate the effective equivalence for base and collector transit times in each structure.

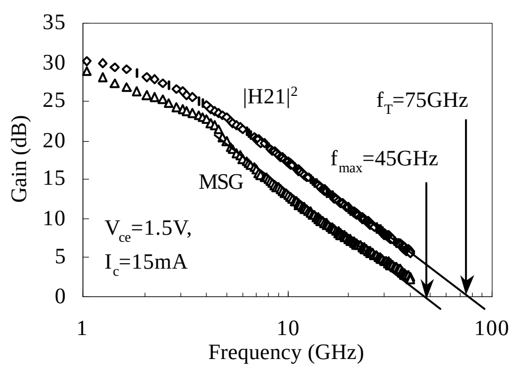

Figure 3. RF gains for a M-DHBT with 5×10μm^2 emitter

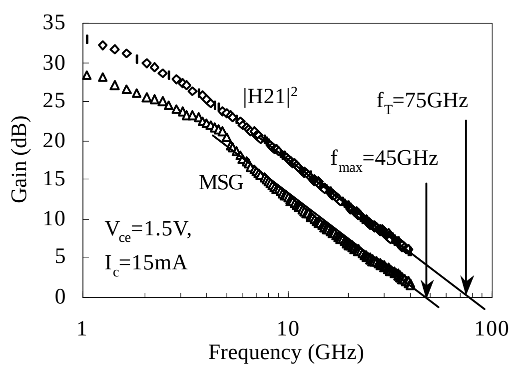

Figure 4. RF gains for a LM-DHBT with 5×10μm^2 emitter

Conclusions

We have demonstrated comparable DC and RF characteristics for both LM-HBTs and M-HBTs. A M-DHBT device with 5×10μm^2 emitter area exhibited a f_T=75GHz and a f_{max}=45GHz which are the same values measured for the LM-DHBT device. The 75GHz cutoff frequency is the highest recorded for M-HBTs. These DC and RF results strongly suggest that M-HBTs should be evaluated with regard to their reliability to clarify whether the metamorphic approach to InP based HBT growth is indeed a viable technology.

References

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ACRONYMS

MBE: Molecular Beam Epitaxy
LM-HBT: Lattice Matched Heterojunction Bipolar Transistor
M-HBT: Metamorphic Heterojunction Bipolar Transistor
SHBT: Single Heterojunction Bipolar Transistor
DHBT: Double Heterojunction Bipolar Transistor