Microwave Noise and Power Performance of Metamorphic InP Heterojunction Bipolar Transistors

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***Abstract*—For the first time, microwave noise and power performance of metamorphic InP heterojunction bipolar transistors (MM–HBTs) grown on GaAs substrates are reported. We find that microwave performance of MM–HBTs is comparable to that of lattice-matched InP heterojunction bipolar transistors of identical design. The preliminary results imply that the superior performance of InP heterojunction bipolor transistors can be confidently exploited with the more mature manufacturing technology of GaAs.**

***Index Terms*—Heterojunction bipolar transistors, heterojunctions, microwave transistors.**

I. Introduction

THE purpose of this paper is to assess the viability of InP metamorphic InP heterojunction bipolar transistors (MM–HBTs) that are fabricated on a GaAs substrate. We report, for the first time, microwave noise and power performance of InP MM–HBTs grown on a GaAs substrate. We find the performance of InP MM–HBTs is comparable to that of lattice-matched InP heterojunction bipolar transistors (LM–HBTs) of identical design, but fabricated on an InP substrate. This finding implies that high-performance InP heterojunction bipolar transistors (HBTs) can be manufactured at lower cost and higher volume by the better established GaAs foundries.

HBTs lattice matched (LM) to InP (i.e., LM–HBTs) have demonstrated superior microwave noise and power performance [1], [2] to that of GaAs HBTs. However, the brittle nature, small size, and high cost of InP substrates hinder high-volume and low-cost manufacturing. These limitations can be alleviated by growing the InP structure metamorphically on a GaAs substrate. Metamorphic (MM) high electron-mobility transistors (HEMTs) have already exhibited excellent performance and reliability [3], [4]. By contrast, little has been reported on MM HBTs. The following is the first comprehensive comparison of microwave noise and power performance of MM–HBTs with that of LM–HBTs.

Manuscript received March 21, 2001; revised August 18, 2001. This work was supported by the National Science and Technology Board of Singapore (EMT/99/011) under the Monolithic Microwave Integrated Circuit Program Phase 2.

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Publisher Item Identifier S 0018-9480(01)10450-3.

TABLE I
LAYER STRUCTURE OF MM–HBT

Layers	Composition	Doping cm^{-3}	Thickness nm
Cap	InGaAs	$2x10^{19}$ Si	100
	InP	$2x10^{19}$ Si	60
Emitter	InP	$3x10^{17}$ Si	90
Base	InGaAs	$2x10^{19}$ Be	47
Collector	InGaAs	$5x10^{15}$ Si	40
	InGaAs	$1x10^{18}$ Be	10
	InP	$1x10^{18}$ Si	10
	InP	$5x10^{15}$ Si	290
	InP	$5x10^{18}$ Si	8
	InGaAs	$5x10^{18}$ Si	450
Buffer	InP		50
	$In_{0.48}Ga_{0.52}P \rightarrow InP$		1500
	GaAs		100
GaAs (100) S.I. Substrate			

II. Device Description

Table I lists the HBT layer structure that was grown metamorphically on a GaAs substrate by using solid-source molecular beam epitaxy (MBE). The structure includes an InP emitter, an $In_{0.53}Ga_{0.47}As$ base, and an $In_{0.53}Ga_{0.47}As$–InP composite collector. A linearly graded $In_xGa_{1-x}P$ ($x = 0.48$ to 1) buffer layer is used to relieve the strain between GaAs and InP. The InGaAs/InP composite collector structure is used to avoid current blocking. A dipole doping is employed at the InGaAs/InP interface in the composite collector to further reduce the current blocking effect [5]. Device fabrication is essentially the same as that for the LM–HBTs, which employs a standard mesa isolation process. Details of the fabrication technique are reported in [6].

Fig. 1 shows typical collector characteristics of an MM–HBT with an emitter area of $5 \times 5\ \mu m^2$. The common-emitter current gain β of the MM–HBT peaks at 40, while that of an LM–HBT of comparable size peaks at 180. Detailed analysis shows that the lower current gain is probably due to a rougher base–emitter interface, as well as increased bulk recombination in the base. The open-base breakdown voltage BV_{CEO} is greater than 9 V

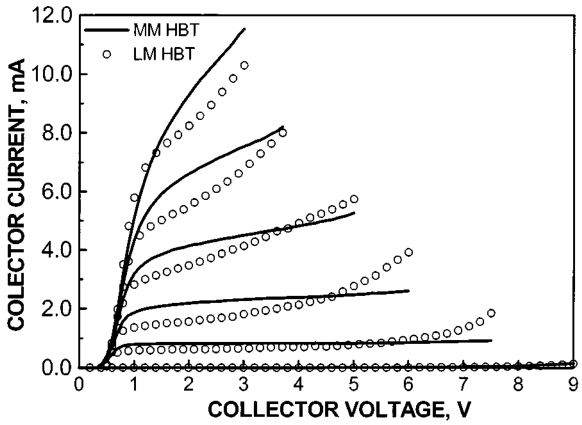

Fig. 1. Collector characteristics of an MM–HBT and an LM–HBT with a $5 \times 5\ \mu m^2$ emitter. $I_B = 0, 50 \ldots 250\ \mu A$ for the MM–HBT and $I_B = 0, 10 \ldots 50\ \mu A$ for the LM–HBT, bottom up.

TABLE II
COMPARISON OF DC AND RF CHARACTERISTIC FOR MM–HBT AND LM–HBT WITH $5 \times 5\ \mu m^2$ EMITTER AREA

	β @ I_C=10mA	BV_{CE0} (V)	Peak f_T (GHz)	Peak f_{max}(GHz)
MM HBT	40	9.8	48	42
LM HBT	180	9.2	73	52

and is comparable between MM- and LM–HBTs (Table II). As shown in Fig. 2, the cutoff frequencies f_T and $f_{\rm MAX}$ of the MM–HBT are 48 and 42 GHz, respectively. f_T and $f_{\rm MAX}$ of the LM–HBT are higher at 70 and 50 GHz, respectively. Detailed analysis suggests that the lower f_T and $f_{\rm MAX}$ values of the MM–HBT are due to higher base and collector transit time $\tau_{\rm B}$ and $\tau_{\rm C}$ rather than the base–collector capacitance ($C_{\rm BC}$) and base–emitter capacitance ($C_{\rm BE}$) and resistances, as they are found to be the same for both types of devices.

III. MICROWAVE NOISE PERFORMANCE

For evaluation of microwave noise performance, several $5 \times 5\ \mu m^2$ devices have been measured using an ATN NP5 automated noise–pull measurement system. Fig. 3 compares the minimum noise figure $F_{\rm MIN}$ and associated gain (G_A) at 2 GHz and different collector current. As expected, $F_{\rm MIN}$ decreases linearly with lower collector current for both types of devices and reaches a minimum and then rises again at very low collector current ($I_{\rm C} < 1$ mA). $F_{\rm MIN}$ reaches as low as 2 dB for MM–HBTs, whereas the same approaches 1.0 dB for LM–HBTs, which is comparable to reported results [1]. With $I_{\rm C} = 2.1$ mA, the MM–HBT exhibits an $F_{\rm MIN}$ of 2.7 dB and G_A of 18 dB. In comparison, the LM–HBT has both lower $F_{\rm MIN}$ and lower G_A. The lower $F_{\rm MIN}$ is probably due to lower bulk recombination in the LM–HBT. These results are typical of more than ten HBTs of each type. It is worth noting that one particular LM–HBT with a lower β (45) and, presumably, higher bulk recombination, performs similarly to the MM–HBT with an $F_{\rm MIN}$ of 2.3 dB and a G_A of 18 dB at $I_{\rm C} = 2.1$ mA. As seen in Fig. 4, the $F_{\rm MIN}$ increases with frequency, contrary to the reported results [1], presumably because of lower f_T values of these devices.

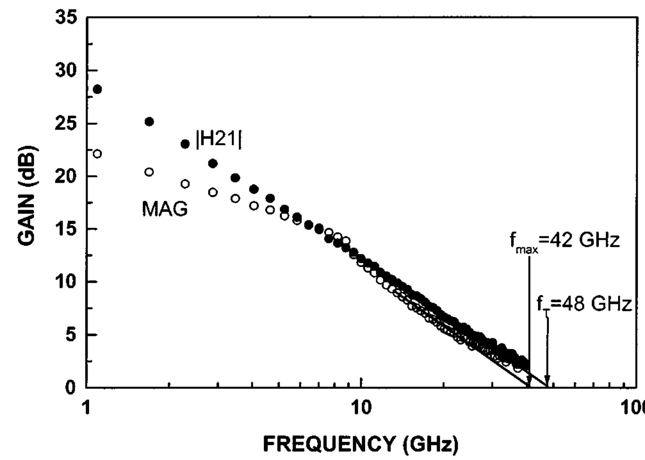

Fig. 2. Maximum available gain (MAG) and current gain (|h12|) showing f_T and f_{max} for a $5 \times 5\ \mu m^2$ MM–HBT.

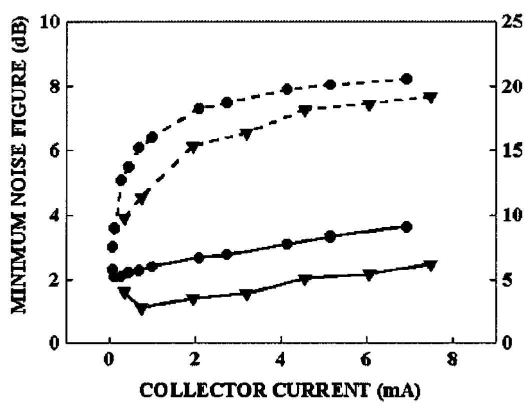

Fig. 3. Comparison at 2 GHz of (—) minimum noise figure and (- - -) associated gain between (●) an MM–HBT and (▼) an LM–HBT. In both cases, the emitter area = $5 \times 5\ \mu m^2$ and $V_{\rm CE} = 1.5$ V.

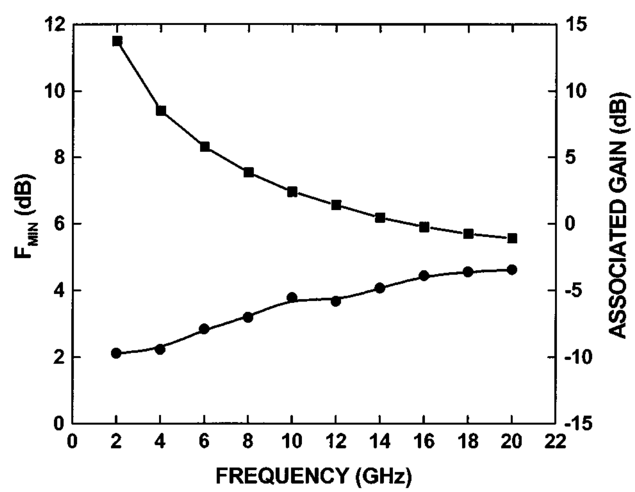

Fig. 4. Frequency versus $F_{\rm MIN}$(●) and associated gain (■) for a $5 \times 5\ \mu m^2$ emitter area MM–HBT at $I_{\rm C} = 1$ mA, $V_{\rm CE} = 2$ V.

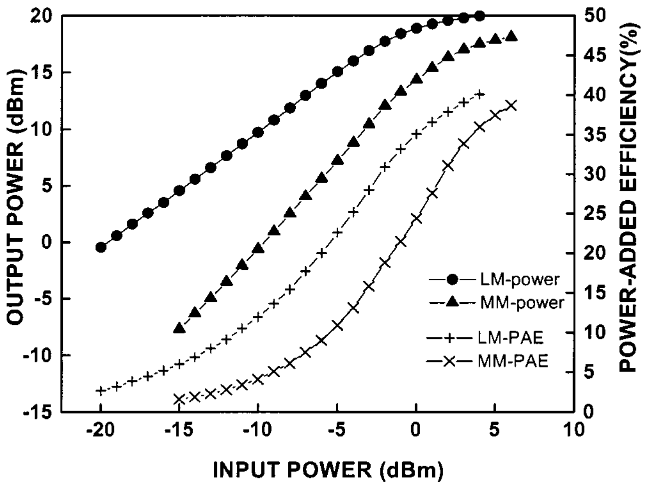

Fig. 5. Output power and PAE between an MM–HBT and LM–HBT at 2.5 GHz $V_{CE} = 4$ V, $I_C \cong 2$ mA emitter area 5×20 μm^2.

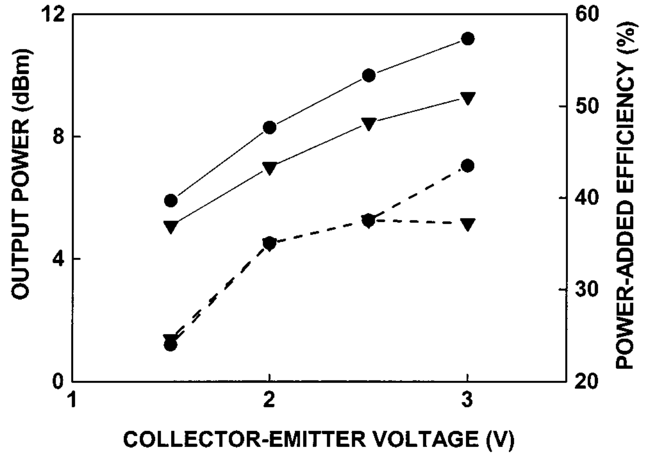

Fig. 6. Comparison at 7.5 GHz of (—) maximum output power and (- - -) PAE between (●) an MM–HBT and (▼) an LM–HBT at different collector voltages. $I_C \cong 7$ mA emitter area = 5×20 μm^2.

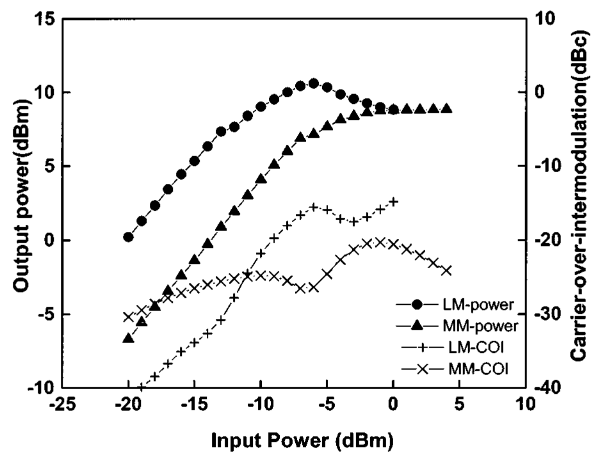

Fig. 7. Comparison at 2.5 GHz of the COI between an MM–HBT and LM–HBT at quiescent bias of $V_{CE} = 3.5$ V. $I_C \cong 2$ mA emitter area = 5×20 μm^2.

IV. Microwave Power Performance

Microwave power measurements on these HBTs were carried out using an ATN LP1 load–pull system. Fig. 5 compares the power performance of an MM–HBT and LM–HBT. The devices were driven by a constant voltage source in series with a resistor at the base to facilitate a self-biasing current. A resistance of 1 KΩ for LM–HBT and 750 Ω for MM–HBT were found to be adequate to deliver high power. Both HBTs have an emitter area of 5×20 μm^2 and are biased for class-AB operation. All the measurements were carried out on an un-thinned wafer without any heat-sinking mechanism in place.

When tuned for maximum power, the MM HBT delivered 18 dBm (64 mW) and 40% power-added efficiency (PAE) at 2.5 GHz, whereas the LM–HBT exhibited 20 dBm (100 mW or 1 mW/um^2) and 42% PAE at the same frequency and bias conditions ($V_{CE} = 4.0$ V) (Fig. 5). When tuned for maximum efficiency, the same MM device offered 59% PAE with saturated output power of 14.5 dBm (30 mW), whereas the LM device exhibited 60% PAE with 15.5-dBm output power. No harmonic tuning was employed. In comparison, the LM–HBT exhibits the power comparable to the benchmark [2], but somewhat reduced power performance of MM–HBTs may be attributed to the self-heating mechanism due to poorer thermal conductivity of the GaAs substrate. The power performance is expected to increase by thinning the wafer and by providing adequate heat-sinking arrangements.

The load reflection coefficients for the maximum power-tuned condition were 0.24° ∠ 153° for LM devices and 0.44° ∠ 99° for MM devices. The source reflection coefficients for the same were 0.61° ∠ 74° and 0.32° ∠ 18° for LM and MM devices, respectively. Both source and load conditions reflect existence of much higher capacitance (charges) in MM devices compared to LM devices, which need to be improved in order to achieve greater power, efficiency, and high speed.

At an upper frequency of 7.5 GHz, the 5×20 μm^2 MM–HBTs maintains marginally lower power performance of 17 dBm (50 mW) with lower PAE of 23% and small-signal gain of 5 dB. The LM device exhibits 18.5 dBm (72 mW) with 34% PAE and small-signal gain of 9.5 dB. Under constant current source at the base, Fig. 6 shows that both MM- and LM–HBTs exhibit adequate power performance when the collector voltage is reduced from 3 to 2 V. On the other hand, higher bias voltage or current was not possible due to on-state breakdown. This implies that better power performance can be achieved by increasing the collector thickness beyond the present 3500 Å.

V. Distortion Performance

A tow-tone third-order distortion measurement was performed using an ATN LP1 load–pull system at 2.5 GHz in order to evaluate the nonlinear performance of these devices. The load and source impedance were tuned for maximum efficiency and the third-order intermodulation (IM3) products were measured by a spectrum analyzer. Fig. 7 depicts the two-tone fundamental power and the carrier-over-intermodulation (COI) ratio versus input power. Under small-signal operation, the LM device exhibits a greater COI ratio of 40 dBc compared to MM devices (30 dBc). The distortion products for MM device do not increase as rapidly as that of an LM device and, at higher power and IM3, products for MM devices are lower than that of LM devices. This signifies that the MM devices may have a higher degree of capacitive nonlinearity, cancelling out the resistive nonlinearity resulting in lower distortion products at higher power levels [7].

VI. CONCLUSION

In conclusion, MM–HBTs and LM–HBTs exhibited comparable microwave performance, with MM–HBTs lower in power and noise performance. The difference in performance can be attributed to interface roughness and base layer quality in addition to lower thermal conductivity of the GaAs substrate. With continued improvement in the MM growth technique and proper heat dissipation mechanism, the performance of MM–HBTs is expected to be on par with that of LM–HBTs. These encouraging preliminary results imply that the superior performance of InP HBTs can be exploited with the more mature manufacturing technology of GaAs.

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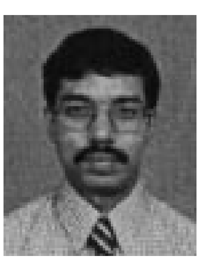

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