HIGH POWER PERFORMANCE USING InAlAs/InGaAs SINGLE HETEROJUNCTION BIPOLAR TRANSISTORS

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Abstract

The power performance of InP based single HBTs has been mediocre compared with their double HBTs counterparts due to their inherently low breakdown voltage. [1] For power amplifiers requiring moderate output power levels, single HBTs are more cost effective due to their simplicity of fabrication and design. InP-based single HBTs have demonstrated power performance at 10GHz of 1.37mW/μm^2, 11dB gain and 33.9% power-added-efficiency [2]. In this work, a graded InAlAs/InGaAs emitter base junction and a low-doped thick collector was employed to lower the turn-on voltage and increase the breakdown voltage respectively. InAlAs/InGaAs single HBTs were subsequently fabricated with undercut collectors for reduced base-collector capacitance. A 4-finger 2x10 μm^2 HBT unit cell exhibited 22.5 dBm continuous wave (CW) output power (2.23mW/μm^2 power density), 35% power-added-efficiency and an associated gain of 10.5dB at 10GHz. To our knowledge, this is the best output power density performance for InP based single HBTs.

I. Introduction

InP-based heterojunction bipolar transistors (HBTs) have demonstrated excellent frequency performance and power handling ability. While operation at higher current densities and with higher breakdown voltages gives HBTs the advantage for power amplifiers over their HEMTs counterparts, the power performance of InP based single HBTs has not been well investigated due to their inherently low breakdown voltage. The narrow bandgap for InGaAs collectors in these single HBTs limits the breakdown voltage and therefore the maximum collector-emitter voltage (V_{CE}) applied while conducting appreciable collector current. Generally, InP collectors are employed in double HBTs to increase the breakdown voltage and thus the output voltage swing. To minimize the current blocking effect of the conduction-band spike at the base-collector heterojunction [3], different designs can be employed [4,5,6,7]. A BV_{CEO} as high as 32 V was reported for such double HBTs with a special designed superlattice to eliminate the heterojunction spike at the base collector junction. [8]. A record 3.6mW/μm^2 output power density with PAE of 56% at 9GHz was achieved using DHBTs. [8].

While the low breakdown voltage of InP-based single HBTs limits the output swing voltage, output power levels up to 1.37mW/μm^2 at 10GHz have been reported [2]. The breakdown voltage increases with the collector thickness; however, the latter also increases the collector delay time and hence degrades the cut-off frequency f_T. In addition, very thick collectors are difficult to fully deplete with minimal available collector doping concentrations. A BV_{CEO} of 11V has been reported for InP-based single HBTs with a 7000Å/5x10^{15}cm^{-3} InGaAs collector, and the device f_T was 45GHz [4].

II. Device Design and Fabrication

In this work, InAlAs/InGaAs single HBTs have been designed to increase the breakdown voltage by employing a thick 7000Å low-doped collector. The layer structure is summarized in Table 1. It consists of a 4300Å sub-collector, a 7000Å collector, an 800Å beryllium-doped base, a graded InAlGaAs transition layer, InAlAs emitter layers and InGaAs emitter cap layer. The thick collector and low collector doping concentration allow pronounced depletion of the collector and lead in a reduction of the electric field density in this region and thus high breakdown voltage. A graded InAlGaAs layer was also used to reduce the turn-on voltage by eliminating the emitter-base conduction band spike.

It is noticed that a thicker base (800Å versus 600Å) was used in this design than the previous study [2] so that the base resistance can be reduced. Moreover, a low-doped, thicker collector (7000Å versus 5000Å) was used in order to reduce the base-collector capacitance. Both design features will enhance the maximum frequency of oscillation f_{max}. The thicker low-doped collector design is also expected to increase the breakdown voltage.

The all wet etch-based process developed at the University of Michigan was employed in the fabrication to create trenches and isolation mesas. The base contacts were self-

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aligned to the emitters to reduce the base parasitic resistance. The emitters were protected and the wafers were then etched to the sub-collector layer using the base contact as etch mask after base metallization. The resulting collector undercut led in reduction of the base-collector capacitance and thus enhanced f_{max} performance.

InGaAs	750	n^+	Emitter cap
InAlAs	450	N^+	Emitter cap
InAlAs	1000	N	Emitter
InAlGaAs	450	N	Grade
InGaAs	800	p^+	Base
InGaAs	7000	n^-	Collector
InGaAs	4300	n^+	Subcollector
InP Substrate			

Table 1: Layer Structure of the InAlAs/InGaAs Single HBT

III. DC and Small-Signal Microwave Results

The common-emitter I_c-V_{ce} characteristics for a 5x10 μm^2 InAlAs/InGaAs HBT are shown in Fig. 1. The measured offset voltage was 0.15V. The reduction of the offset voltage from previously-reported HBTs [2] is due to the presence of the InAlGaAs transition layer, which eliminates the conduction spike at the base-emitter junction. The knee voltage for these devices was found to be around 0.4V and the breakdown voltage BV_{CEO} was larger than 8.5 volts at I_B=0 as a result of the thick low-doped collector design. The low knee voltage combined with the high breakdown voltage contributed by the larger collector thickness and low collector doping concentration design suggests the possibility of improved power performance for these HBTs compared with previously reported results on InP-based single HBTs [2].

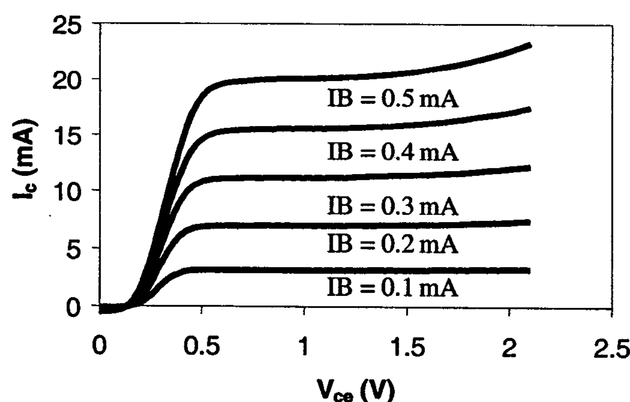

Fig. 1. Common-emitter I_c-V_{CE} characteristics for 5x10 μm^2 InAlAs/InGaAs HBT

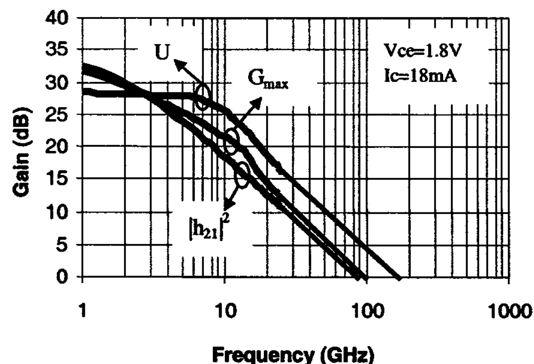

Fig. 2. High-frequency performance of a 5x10 μm^2 HBT at I_C=18mA and V_{CE}=1.8V. f_T=90 GHz and f_{max}=105GHz.

The small signal S-parameters of InAlAs/InGaAs HBT were measured by using an HP8510B network analyzer from 0.5GHz to 25.5 GHz. The current gain $|h_{21}|^2$, maximum power gain G_{max} and unilateral power gain (Mason's gain) were calculated from the measured S-parameters and plotted in Fig. 2 for a 5x10μm^2 HBT. The thick collector design of 7000Å used in this work versus 5000Å reported earlier [2], should lead to longer collector delays and hence degradation of the cut-off frequency.

However, the fabricated InAlAs/InGaAs single HBTs showed good microwave characteristics. A 5x10 μm^2 HBT was measured at a bias condition of VCE=1.8V and Ic=18mA. As shown in Fig. 2, the InAlAs/InGaAs single HBT shows a f_T and f_{max} of 90GHz and 105GHz respectively (see Figure 3). The extrapolated f_{max} value from U exceeds 150GHz. This is partially due to the collector-undercut technique, leading to the reduction of base-collector capacitance and hence the improvement of HBT microwave performance.

IV. Power Characterization

On wafer measurements were performed at 10GHz by using in-house developed load-pull system. Focus electromechanical tuners were used on both the source and the load.

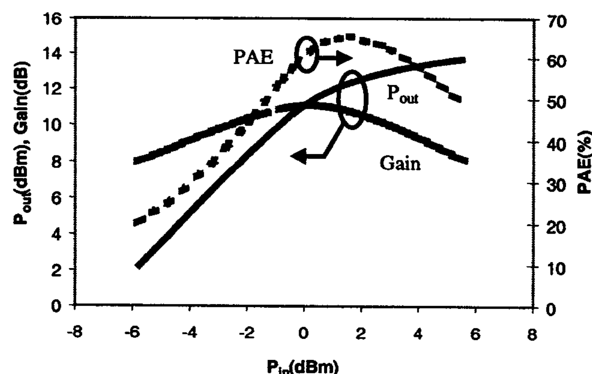

Fig. 3. Power characteristics of 5x10μm^2 InAlAs/InGaAs HBT optimized for PAE

Source and load electromechanical tuners were adjusted for different optimization purposes, such as maximum power-added-efficiency, output power and gain. The power characteristics of a 5x10 μm^2 InAlAs/InGaAs HBTs were measured under class AB conditions. Power characteristics optimized for power-added-efficiency (PAE) by adjusting source and load impedance are shown in Fig. 3. The measured InAlAs/InGaAs single HBT was biased at V_{CE} = 4.0V and I_C=4mA. As shown in Fig. 3, a power-added-efficiency of 65.5% was measured at 10 GHz for this HBT (5x10μm^2) when the source and load terminations were optimized for this purpose. The associated output power and gain was 13.7dBm and 11dB respectively.

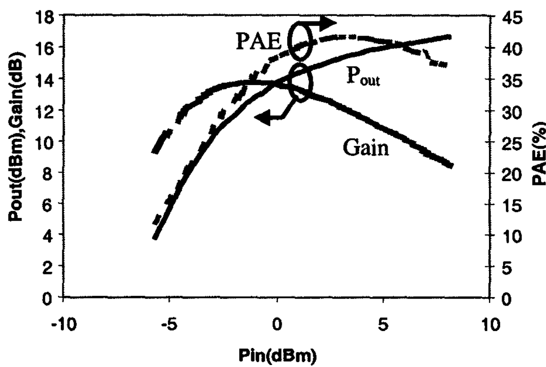

Fig. 4. Power characteristics for 5x10 μm^2 InAlAs/InGaAs HBT optimized for best compromise of power performance

The same 5x10 μm^2 InAlAs/InGaAs single HBT was measured when the source and load terminations were optimized for best compromise of power performance, namely, output power, power-added-efficiency and gain. The measurement results are shown in Fig. 4. As can be seen, an improvement of more than 3dB compared with P_{out} under optimum PAE (14-17.5dBm) was observed at 10GHz. The measured InAlAs/InGaAs single HBT still showed a good power added efficiency of 42% under a collector bias of 4 volts.

Fig. 5 shows the DC bias dependence of power characteristics of 5x10 μm^2 InAlAs/InGaAs HBT optimized for maximum PAE. It shows that the PAE first increases as the bias voltage increases and saturates at certain bias level due to gain reduction at high bias voltage. It also shows that the HBT presents good power-added-efficiency (37%) even at 2.0 volts V_{CE} collector bias voltage. This is an indication of low knee voltage provided by the graded base-emitter junction design, where a 450Å InGaAlAs layer was employed. The power-added-efficiency increases from 37% at 10 GHz with 2 volts V_{CE} bias voltage to 65.5% with a bias voltage of 4 volts. It is also noticed that the power-added efficiency was almost the same at V_{CE}=4.5 volts as V_{CE}=4 volts, which is due to gain reduction at high bias level.

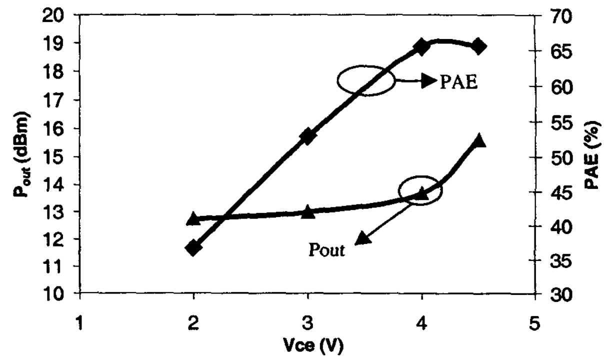

Fig. 5. DC bias dependence of power characteristics of 5x10 μm^2 InAlAs/InGaAs HBT optimized for maximum PAE

The good DC characteristics of InAlAs/InGaAs HBTs, namely high breakdown and low knee voltage are contributed to the thick collector and low collector doping design and can lead in the improvement of the power characteristics of SHBTs over previously reported designs. [2]. The power characteristics of a 4 finger 2x10 μm^2 HBT were measured at 10 GHz using again our in-house load-pull measurement system directly on 630-μm unthinned InP substrates and are shown in Figure 6. The source and load impedance of the device was optimized for maximum output power. The device was biased at class AB and the collector biasing voltage and current were 4.5 V and 4 mA respectively. At 10 GHz, the device generated an output power of 22.5dBm, corresponding to a power density of 2.23 mW/μm^2. This is a record power density performance for InP based single HBTs. The power-added-efficiency (PAE) of the devices was 35% and the associated gain was 10.5dB at 10GHz.

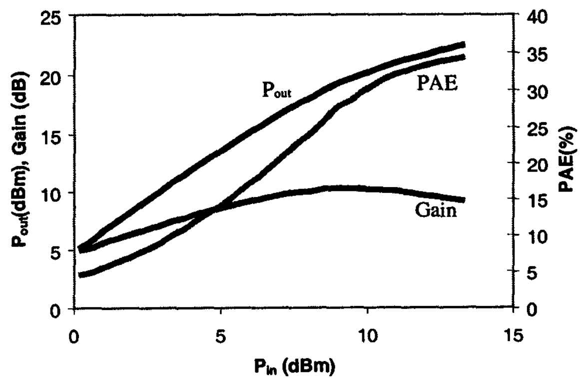

Fig. 6. Power characteristics of a 4x(2x10μm^2) InAlAs/InGaAs HBT under class AB bias with V_{CE}=4.5V. I_c=4mA. Maximum P_{out}=2.23 mW/μm^2 and PAE=35%

V. Discussion

The InAlAs/InGaAs HBTs fabricated and measured above present significant improvement in terms of power

performance over results presented in previous study of InP/InGaAs single HBTs. An output power density of 2.23mW/μm^2 was achieved compared with 1.37mW/μm^2 measured in the previous study for HBTs with same geometry (4 finger 2x10μm^2). Improved power-added-efficiency was also achieved for the InAlAs/InGaAs single HBT and an power-added-efficiency achieved at 10 GHz with a collector-emitter bias voltage of 4 volts was found to be 65.6%.

Compared with previous designs, a thicker (800Å versus 600Å) base was employed to reduce the base resistance R_b. While a thicker collector design leads to the longer collector delays, it reduces the base-collector capacitance. Both reduction of R_b and C_{BC} leads to the improvement of f_{max}. Moreover, a collector-undercut technique was used in the fabrication reported here which also leads to the improvement of HBT performance.

It is also noticed that the previous design utilized InP as emitter layer while this study employed InAlAs. An abrupt InP/InGaAs emitter-base junction has a bandgap discontinuity $\Delta E_C/\Delta E_V$ of 0.25/0.34eV while an abrupt InAlAs/InGaAs emitter-base junction has a bandgap discontinuity $\Delta E_C/\Delta E_V$ of 0.48/0.24eV, leading to a 0.23V larger turn-on voltage. The graded InAlAs/InGaAs emitter-base junction used here eliminates the conduction spike and reduces the turn-on voltage, which reduced the offset voltage from 0.4v to 0.15 volts.

Finally, a thicker low doped collector (7000Å versus 5000Å) allowed improvement of the breakdown voltage over the previous design as the collector could be further depleted. Therefore the electric field density in the collector region could be reduced leading to an increase of the breakdown voltage.

Conclusion

Overall, InAlAs/InGaAs single HBTs with thick, low-doped collector were fabricated and the DC, small signal and power performance is reported at 10 GHz. Despite the thicker collector design, f_T and f_{max} of 90 GHz and 150 GHz (U) were achieved by using a lateral-collector-undercut technique. Power-added-efficiency of 65.5% were measured at V_{CE}=4 V when the load-pull measurements were optimized for PAE. A record output power density of 2.23 mW/μm^2 was achieved for 4 finger 2x10 μm^2 InAlAs/InGaAs single HBTs compared with 1.37mW/μm^2 demonstrated by a previous study. These results demonstrate very promising performance for application of InP based single HBTs in high power amplifier circuits.

Acknowledgements

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