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1.5V Low-Voltage Microwave Power Performance of InAlAs/InGaAs Double Heterojunction Bipolar Transistors

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Abstract - We report the first demonstration of microwave power performance at an extremely low operation voltage of 1.5 V using InAlAs/InGaAs double heterojunction bipolar transistors(DHBTs). In order to obtain a high output power, Pout at a low operation voltage, we reduced the offset voltage, $V_{CE,offset}$ by using DHBTs. The collector of our DHBTs does not have thick layers in order to avoid the degradation of high-speed performance which is another advantage of InGaAs-based HBTs. We obtained a $V_{CE,offset}$ of 50 mV, a f_T of 76 GHz and a f_{max} of 157 GHz. Due to the low $V_{CE,offset}$, we obtained a P_{out} of 20.6 dBm with a power added efficiency, η_{add}, of 36.6% and a power gain, G_a, of 8.5 dB biased for class B operation at 1.9 GHz and a low operation voltage of 1.5 V.

1. Introduction

A recent requirement has been to reduce the operation voltage of semiconductor devices for microwave and logic IC applications. InGaAs-based HBTs have a higher-speed performance than conventional GaAs-based HBTs because of their higher electron mobility. They also have lower turn-on voltages because of their smaller bandgap. This enables us to reduce the operation voltage. For digital ICs, two-stacked gating ECL circuits using InGaAs-based HBTs with a low supply voltage of 3.5 V have been reported[1]. However for microwave power amplifiers, low-voltage operation, which requires a low $V_{CE,offset}$, has not yet been reported.

With the decrease in the operation voltage, $V_{CE,offset}$ becomes the dominant factor which degrades power performance. $V_{CE,offset}$ is caused by the difference in the conduction band discontinuity between the emitter-base and the collector-base. The double hetero structure reduces the difference in the conduction band discontinuity. In other words, it decreases $V_{CE,offset}$. Therefore, DHBTs give a high Pout and also a high η_{add} at a low operation voltage, and the power performance does not require a high breakdown voltage. Hence a thick collector, which degrades high-speed performance, is not needed. InGaAs-based DHBTs are promising devices both for their power performance at low-voltage operation and their high speed.

2. Experiments

To compare the dependence of the power performance on the collector structure, we fabricated DHBTs and also single heterojunction bipolar transistors(SHBTs). Both epitaxial structures are given in Table 1. In order to obtain a high Pout at a low operation voltage, a large collector current is needed. The collector structure is required to suppress the Kirk effect and carrier accumulation. The SHBT has a 300 nm n-InGaAs layer ($n = 3 \times 10^{16}$ cm^{-3}) to suppress the Kirk effect. The DHBT has a 100 nm undoped InGaAs layer, 25 nm 4-step graded and 100 nm InAlGaAs layers ($n = 3 \times 10^{16}$ cm^{-3}) to suppress the Kirk effect and the carrier accumulation at the conduction band spikes. Both base layers are 70 nm Be-doped p^+-InGaAs. An n-InAlAs is used as a wide-gap emitter and a heavily-doped n^+-InGaAs is used as a cap layer.

Devices were fabricated using our self-alignment triple-mesa process. A cross-sectional illustration of our device is shown in Figure 1. The main feature of this process is to reduce the area of the base-mesa. The base-mesa was formed in self-alignment with the emitter using a large side-wall as an etching mask to reduce the capacitance of the base-collector junction, C_{BC}[2]. The reduction of C_{BC} improves the high-speed performance and stability of power operation. Ti/Pt/Au and WSi were used for the emitter ohmic contacts for the DHBT and SHBT, respectively. Pt/Ti/Pt/Au was used for

	SHBT			DHBT		
	Material	Thickness (nm)	Doping (cm^{-3})	Material	Thickness (nm)	Doping (cm^{-3})
Cap	n^+-InGaAs	150	5×10^{19}	n^+-InGaAs	150	5×10^{19}
	n^+-InAlGaAs	50	1×10^{19}	n^+-InAlGaAs	50	1×10^{19}
Emitter	n-InAlAs	130	1×10^{18}	n-InAlAs	130	1×10^{18}
	n-InAlGaAs	40	1×10^{18}	n-InAlGaAs	40	1×10^{18}
Base	i-InGaAs	10	—	i-InGaAs	10	—
	p^+-InGaAs	70	2×10^{19}	p^+-InGaAs	70	2×10^{19}
Collector	n-InGaAs	300	3×10^{16}	i-InGaAs	100	—
				n-InAlGaAs	25 X 4	3×10^{16}
				n-InAlGaAs	100	3×10^{16}
Sub-collector	n^+-InGaAs	350	5×10^{18}	n^+-InAlGaAs	50	5×10^{18}
				n^+-InGaAs	300	5×10^{18}

Table 1. Epitaxial layer structures.

the base ohmic contact and Ti/Pt/Au was used for the collector ohmic contact. The device mesa structure was planarized by polyimide.

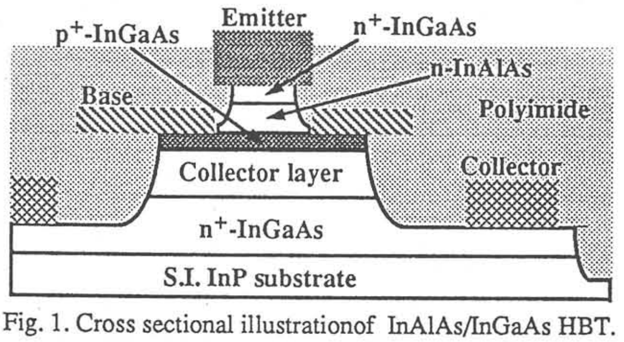

Fig. 1. Cross sectional illustrationof InAlAs/InGaAs HBT.

3. Results and Discussion

A. Common-emitter I-V characteristics

The common-emitter I-V characteristics of the DHBT and SHBT are shown in Figure 2. Both emitter sizes are 1.5 X 20.0 µm. The DC current gains were 10 for the SHBT and 20 for the DHBT, and the breakdown voltages at an open base were 3 V for the SHBT and 7 V for the DHBT. Both current gains did not fall off at a high collector current density of 1×10^5 A/cm^2 because of suppression of the Kirk effect and carrier accumulation.

Due to the decreased difference in the conduction band discontinuity between the emitter-base and the collector-base, a much lower $V_{CE,offset}$ of 50 mV could be obtained for the DHBT compared with 300 mV for the SHBT.

B. Small signal characteristics

On the wafer, we performed microwave S-parameter measurements between 400 MHz and 40 GHz. The dependence of the unity cut-off

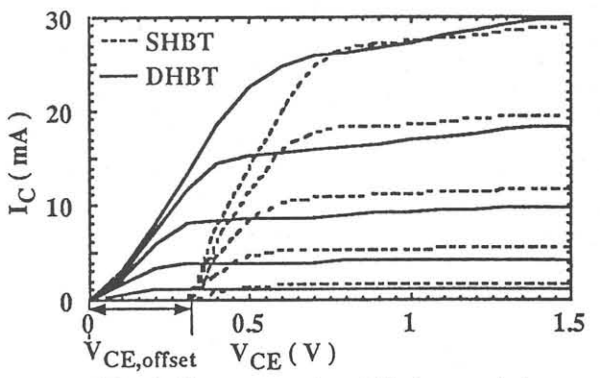

Fig. 2. Common-emitter I-V characteristics.

frequency, f_T, and the maximum oscillation frequency, f_{max}, on the collector currents for both the SHBT and DHBT are shown in Figure 3. Both f_T and f_{max} increased with the increase in current density up to 1×10^5 A/cm^2 because of suppression of the Kirk effect and carrier accumulation. The peak f_T and f_{max} were 94 GHz and 134 GHz for the SHBT, and were 76 GHz and 157 GHz for the DHBT. This high performance could not be obtained using a thick collector, due to the large collector transit time.

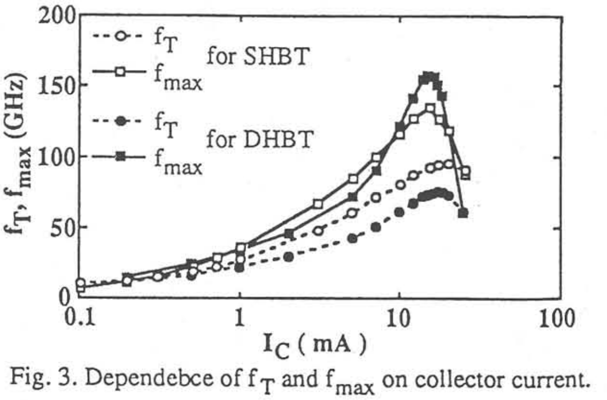

Fig. 3. Dependebce of f_T and f_{max} on collector current.

C. Power characteristics

We measured the power characteristics with on-wafer probes. Figure 4 shows the power performances of both the SHBT and DHBT with an emitter size of 1.5 X 20 µm when the load was tuned to the maximum output power. The frequency was 1.9 GHz. The bias conditions were a V_{CE} of 1.5 V and class-B operation. A higher P_{out} of 12.6 dBm with an η_{add} of 32.4% and a power gain, G_a, of 12.6 dB was obtained compared with a P_{out} of 9.3 dBm with an η_{add} of 25.5% and a power gain of 7.3 dB for the SHBT. The superior performance of the DHBT is evidently attributed to its lower $V_{CE,offset}$.

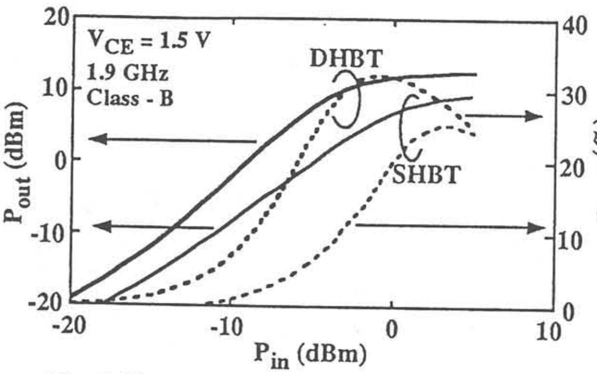

Fig. 4. Output power and power added efficiency of a 1.5 X 20.0 µm emitter.

Figure 5 shows the dependence of P_{out} and η_{add} for the DHBT with an emitter size of 1.5 X 20 µm on the operation voltage when the load was tuned to the maximum P_{out} at 1.5 V. With the decrease in the operation voltage, η_{add} did not decrease drastically, even at 1.0 V. This result indicates that InGaAs-based DHBTs have the advantage of low voltage operation.

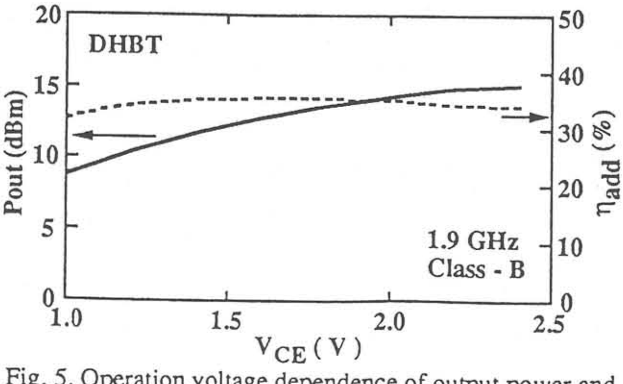

Fig. 5. Operation voltage dependence of output power and power added efficiency of a 1.5 X 20.0 µm emitter.

Preliminarily, we measured the power performance of an 8-emitter finger of 1.5 X 20 µm DHBT biased for class-B at 1.9 GHz. As shown in Figure 6, when the load was tuned to the maximum P_{out}, a P_{out} of 20.6 dBm with an η_{add} of 36.6% and a G_a of 8.5 dB was obtained at the low operation voltage of 1.5 V. We also obtained an η_{add} of 49.5% when the load was tuned to the maximum efficiency.

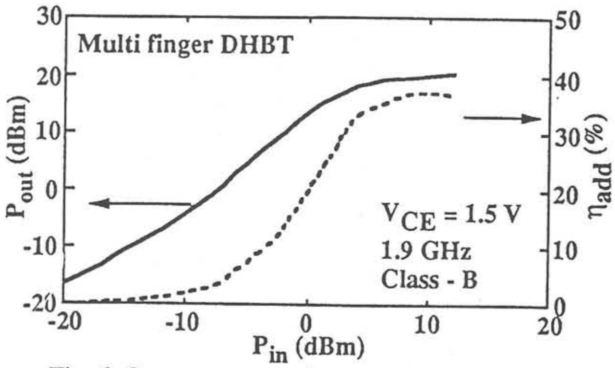

Fig. 6. Output power and power added efficiency of 8 X 1.5 X 20.0 µm emitter.

4. Conclusion

We demonstrated power performance with low-voltage operation and high-speed performance for the InAlAs/InGaAs DHBTs. In terms of power performance, a Pout of 20.6 dBm with an η_{add} of 36.6% was obtained at the low operation voltage of 1.5V and a frequency of 1.9 GHz. In terms of high-speed performance, the peak f_T of 76 GHz and the peak f_{max} of 157 GHz were obtained.

Our results show that InGaAs-based DHBTs with only one epitaxial structure are feasible both for practical power and high-speed applications with low-voltage operation.

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References

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