MICROWAVE PERFORMANCES OF npn AND pnp AlGaAs/GaAs HETEROJUNCTION BIPOLAR TRANSISTORS

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ABSTRACT

The performances of MOCVD grown npn and pnp AlGaAs/GaAs HBTs were compared at microwave frequencies to identify relative merits of each type of device. F_t and f_{max} values of devices with 100 nm thick bases were 22 and 40 GHz for npn transistors and 19 and 25 GHz for pnp transistors, respectively. An accurate device model was developed using the measured S-parameter data. The base resistance of the pnp transistors, as determined from the model, was about five times lower than identical size npn device. A theoretical comparison of the two types indicated that similar performances may be obtained from both if the base layer thickness of pnp transistor is half that of the npn device. Large signal characterization was carried out at 10 GHz.

INTRODUCTION

Heterojunction bipolar transistors (HBT) based on GaAs are gaining acceptance as high power microwave amplifiers. Power densities as high as 2.5 W/mm of emitter periphery was demonstrated at 10 GHz[1-3] under CW conditions. Devices operating under pulsed conditions produced even higher power densities (5.4 W/mm)[3]. These power densities are a factor of two to four higher than GaAs FETs operating under similar conditions at this frequency. HBTs are also important for microwave applications for their low phase noise characteristics. At 4 GHz, it was shown that HBT oscillator noise characteristics are similar to that of Si bipolar transistors and superior to that of GaAs FETs[4]. These performance advantages coupled with the fact that HBT fabrication can be accomplished with optical lithography (minimum linewidth >1 µm) for frequencies at least up to 40 GHz continue to encourage the development of this device for microwave applications.

All high performance (microwave and digital) HBTs to date are of npn type to take advantage of high electon mobility in III-V compound semiconductors. The npn configuration is chosen by most designers because of the low series resistance that can be obtained in the emitter and collector regions. Also, the minority carrier mobility in the base is kept high. These advantages are offset by the high resistance of the thin p-type base. It is important to keep the resistance of this layer low, especially for high frequency operation. Pnp transistors, on the other hand, can have low base resistances at the expense of increased emitter and collector resistances. Although the mobility of holes in the collector is low, carriers are travelling at their saturated velocities through most of this layer owing to the large electric fields that must be sustained for power generation. Therefore, the collector transit time delay is not much higher than in npn counterparts. The only significant time delay encountered in pnp structures is the delay due to the diffusion of holes through the base layer. This is about a factor of five higher than in npn structures of similar dimensions. Of course, pnp transistors can have narrower bases for a given base sheet resistance, which reduces this difference somewhat. Pnp HBTs, therefore, can be considered for high performance microwave applications. More importantly, the availability of pnp transistors enables the implementation of microwave complementary circuits which have not so far been possible with GaAs.

The performance potential of pnp HBTs was analyzed recently[5,6] and the performance potential was compared to that of npn transistors[7]. Findings of these studies suggest that both types of devices will operate at similar speeds, provided that each is optimized in its own unique ways. In this paper we have made an experimental comparison of the performances of npn and pnp HBTs with similar structures. The aim of the study was to determine relative merits of each type of transistor to act as a base for future optimization studies.

DESIGN AND FABRICATION

The vertical structures of the transistors are shown in Figure 1. All epitaxial layers were grown by MOCVD on a (100) surface of an undoped semi-insulating (SI) substrate. Si and Zn were used as the dopants for n- and p-layers, respectively. The emitter was made of $Al_xGa_{1-x}As$ in both cases with x=0.4. The thicknesses of emitter, base, and collector were kept the same in both structures but the doping concentrations in the base were different. An acceptor level of $1x10^{19}$ cm^{-3} was used for the base of npn structures whereas the donor concentration of the base for the pnp structure was $3x10^{18}$ cm^{-3}. These doping levels represent the highest levels that could be obtained at the typical growth temperature of 750°C. No intentional spacer layers or band-gap grading were employed in these structures. It is, however, reasonable to assume that the heterointerface between the emitter and the base is exponentially graded over a distance of about 10 nm due to the temperature and growth rates employed in typical MOCVD runs. The structures shown in Figure 1 yielded devices with base-collector breakdown voltage of about 20 V.

Layer	Thickness (µm)	Doping (cm^{-3}) npn		Doping (cm^{-3}) pnp	
Emitter Contact	0.2	(n+)	3E18	(p+)	1E19
$Al_{0.4}Ga_{0.6}A$	0.2	(n)	2E17	(p)	2E17
Base	0.1	(p+)	1E19	(n+)	3E18
Collector	1.0	(n)	3E16	(p)	3E16
Collector Contact	1.0	(n+)	3E18	(p+)	1E19
SI Substrate	500		--		---

Figure 1. The vertical structure for npn and pnp HBTs.

A self-aligned fabrication technique[1] was used to place the base contact as close to the emitter as possible. The emitter and base finger widths were kept constant at 2 µm in all devices. The emitter periphery (2 X emitter length + 2 X emitter width) was 60 µm. AuGe/Ni and TiPtAu alloys were used as the contacts for n- and p-type layers, respectively. TiPtAu does not form an ohmic contact to p-type GaAs, but the doping levels used in these layers are high enough to yield acceptable contact properties. In the device model described below, contacts to p-type layers were characterized as Schottky contacts. Although AuZn based alloys produced better contact properties, they were found unsuitable for realibility of these essentialy nonplanar devices. Mesa isolation was used to seperate device active areas. All contact pads were fabricated on the surface of the SI GaAs substrate as shown in Figure 2.

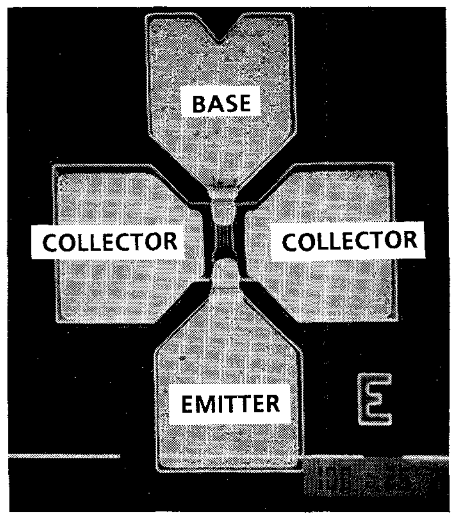


Figure 2. SEM picture of the 60 µm emitter periphery device.

RESULTS AND DISCUSSION

Figure 3 shows the dc characteristics of the devices fabricated. In both cases β values in excess of 50 could be obtained. Important differences between the characteristics of npn and pnp transistors can be identified as an increased emitter/collector series resistance in pnp devices as evidenced by the slope of the linear portion if the I-V curves, an increased offset voltage of 0.5 V in pnp devices compared with 0.2 V observed with npn, and a lower Early voltage with pnp transistors.

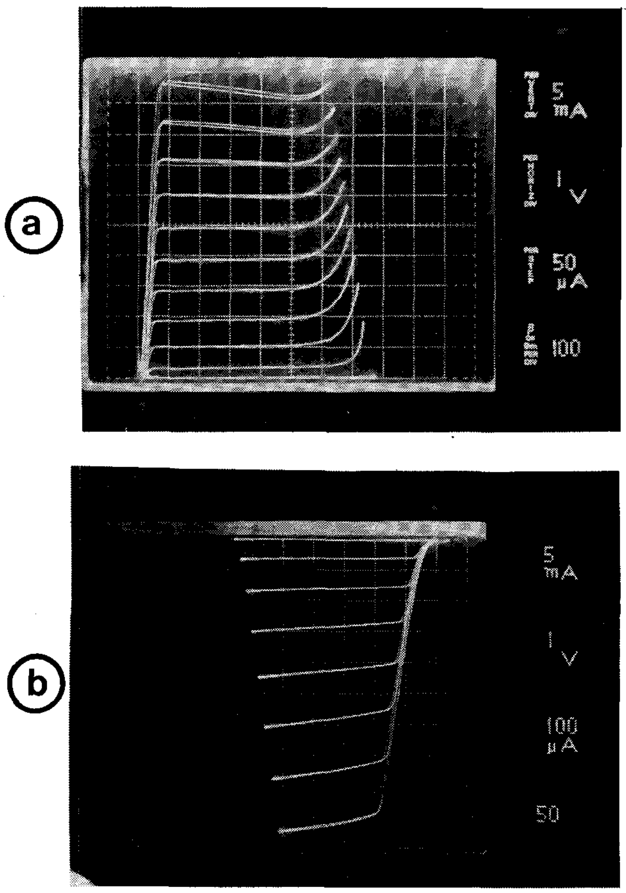
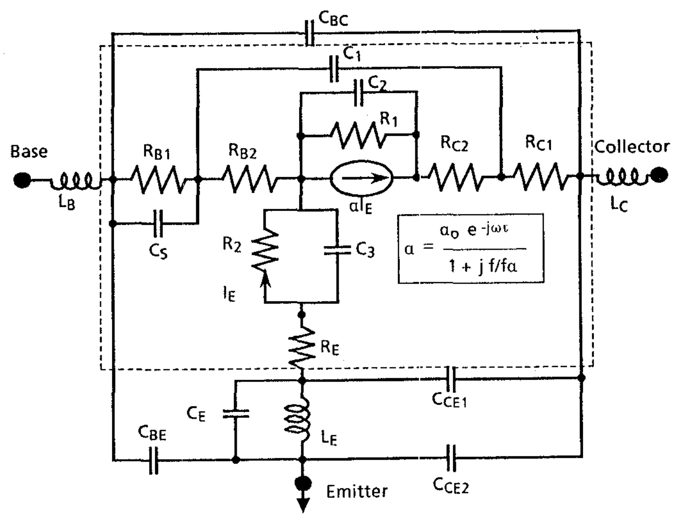


Figure 3. *Dc characteristics: a) npn, b)pnp*

Small-signal characteristics of the devices were determined using HP 8510 automatic network analyzer in the frequency range of 0.25 to 26.5 GHz. From these measurements, figure of merit numbers f_t, common emitter current gain cut-off frequency, and f_{max}, maximum frequency of oscillation, were determined for each type of transistor. F_t and f_{max} values were, 22 and 40 GHz for npn devices and 19 and 25 GHz for pnp devices, respectively. On the basis of these measurements we can state that the microwave performances of both types of devices are quite similar. A theoretical analysis using the approach described in Reference[7] showed that f_t and f_{max} values of the pnp transistors will increase to 25 and 50 GHz if the base thickness is reduced to 50 nm without any other change in the device structure. The performance of 100 nm thick base npn HBT is therefore more closely matched by the performance of 50 nm pnp device.

An equivalent circuit model was developed by computer fitting of the measured S-parameters data to the circuit element values. The results are shown in Figure 4. It can be seen that the capacitive elements are almost the same for both devices whereas some noteworthy differences exist in the resistive elements. The most important difference is in the base resistance. Pnp transistor has a base resistance about a factor of five lower than that of npn conterpart. On the other hand, the collector series resistance is a factor of seven higher in pnp transistors. Emitter resistors appear to be comparable in both case. These observations are consistent with the lower mobility of p-type layers in each type device.



Para-meter	NPN	PNP	Para-meter	NPN	PNP
f_t	22 GHz	19 GHz	C_s	1.34 pF	0
f_{max}	40 GHz	25 GHz	R_{C1}	1 Ω	7.4Ω
α_o	.93	.96	R_{C2}	4Ω	3.3Ω
τ	2 ps	4 ps	R_E	8.5Ω	7.0Ω
$f\alpha$	65 GHz	35 GHz	C_{BC}	.012 pF	.012 pF
C_1	.06 pF	.04 pF	C_{BE}	.022 pF	.022 pF
C_2	.01 pF	.1 pF	C_{CE1}	.012 pF	.012 pF
C_3	.4 pF	.3 pF	C_{CE2}	.06 pF	.08 pF
R_1	1E6Ω	1E6Ω	C_E	.022 pF	.03 pFR
R_w	10Ω	6.8Ω	L_B	.165 nH	.26 nH
R_{B1}	17Ω	3.0Ω	L_E	.032 nH	.09 nH
R_{B2}	27.5Ω	4.4Ω	L_C	.06 nH	.134 nH

Figure 4. ***The equivalent circuit model and parameter values for 60 µm emitter periphery npn and pnp HBTs.***

Large signal characteristics were determined by operating devices as amplifiers in common-base configuration at 10 GHz. Both CW and pulsed mode of operations were investigated. Table 1 lists the results obtained. It is seen that pnp HBTs produce approximately half the power density of npn HBTs. The power-added-efficiencies are also about half that of npn devices. There are some similarities in the large signal characteristics, however. The power densities in both devices almost double going from CW to pulsed mode of operation.

Table 1. Large signal performances of 60 µm emitter periphery npn and pnp HBTs at 10GHz.

Device Type	Operation Mode	Output Power (mW)	Power Density (W/mm)	Gain (dB)	Power Added Eff.
npn	CW	120	2.0	6	40%
pnp	Pulsed	300	5.0	8	50%
pnp	CW	70	1.15	4	21%
pnp	Pulsed	120	2.0	5	25%

A comparison of the small and large signal results indicate that the speed of pnp devices is similar to npn, but the power output and efficiencies are lower. This can be explained as a result of larger collector series resistances encountered in pnp devices. Since this resistor is on the output side of the device, it has significant effect on the power performance. A reduction in this parasitic resistor can be achived by the use of thicker sub-collector layers and lower resistivity ohmic contacts.

CONCLUSIONS

Microwave performances of npn and pnp AlGaAs/GaAs HBTs with 100 nm thick bases were compared. Although the small signal characteristics were found to be similar, the power output of pnp devices were about half those obtained from npn devices. Further optimization of the pnp structure will probably reduce this difference making both types of devices comparable in performance. The availability of high performance npn and pnp HBTs will make it possible to implement complementary microwave (or high speed digital) circuits.

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