High-Performance Microwave AlGaAs–InGaAs Pnp HBT with High-DC Current Gain

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***Abstract*— A Pnp heterojunction bipolar transistor, which had among the highest reported values of $f_T(\sim 23\text{ GHz})$ and $f_{\max}(\sim 40\text{ GHz})$, employed a heavily doped InGaAs pseudomorphic base. However, this HBT had very low values of dc current gain (≤ 4). Pnp microwave HBT's with a modified base design are reported, which not only achieve similar high-frequency performance, but also attain dramatically higher current gain values ~ 90.**

Pnp HETEROJUNCTION bipolar transistors (HBT's) have recently attracted much attention because of their applications to monolithic complementary HBT technologies. Due to the low-hole mobility in GaAs, the base layer of Pnp microwave HBT's must be carefully designed to reduce the base transit time. Typical base layer designs involve narrowing the base layer to below 500 Å [1], or establishing a base electric field by grading the base dopant concentration[2] or the indium composition of an InGaAs base [3 (Note a typo in the Fig. 1 of this reference; the base doping should have been 2×10^{19}/cm^3)], [4]. Among these approaches, high f_T ($\sim$ 23 GHz) and $f_{\max}$ ($\sim$ 40 GHz) values have been obtained for the InGaAs base HBT's [3], [4]. However, the base layer of these HBT's was heavily doped at a designed value of 2×10^{19}/cm^3 and low-dc current gain values of 4 were obtained. In general, for digital applications such as A/D conversion functions, both good high-frequency performance and high-dc current gain values of 50–100 are required [5].

In this letter, Pnp HBT's with a similar InGaAs base layer design are fabricated. However, in contrast to the previous control design which used heavy base doping (wafer 1803) [3], [4], this design (wafer 1805) has a moderate base doping of 5×10^{18}/cm^3. In addition, the base thickness is increased from 300 Å to 500 Å to facilitate device fabrication. Measured dc current gain, $\beta = I_c/I_b$, of 90 and incremental current gain, $H_{fe} = \Delta I_c/\Delta I_b$, of 110 are obtained for microwave devices with an emitter area equal to 2×8 μm^2. The measured cutoff frequency, f_T, and maximum oscillation frequency, $f_{\max}$, at a collector current density of 5×10^4A/cm^2 are 22 GHz, and 40 GHz, respectively. While these high-frequency results are comparable to those of the previous design that used heavy base doping, the dc current gain in this design increases dramatically ($\sim$ 20-fold) from the previous design [3], [4].

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TABLE I
THE PNP HBT EPITAXIAL LAYER STRUCTURE UNDER INVESTIGATION

Layer	x	Doping (cm^{-3})	Thickness (Å)
p-GaAs		1×10^{20}	200
p-GaAs		1×10^{18}	200
p-GaAs		5×10^{17}	1000
P-$Al_xGa_{1-x}As$	0.3→0	5×10^{17}	200
P-$Al_xGa_{1-x}As$	0.3	5×10^{17}	200
P-$Al_xGa_{1-x}As$	0→0.3	5×10^{17}	300
n-$In_xGa_{1-x}As$	0.15→0	5×10^{18}	500
p-$In_xGa_{1-x}As$	0.15	5×10^{16}	100
p-$In_xGa_{1-x}As$	0→0.15	5×10^{16}	150
p-GaAs		5×10^{16}	2500
p-GaAs		4×10^{19}	12 000
S. I. GaAs Substrate			

The aluminum grading in the 300 Å $Al_xGa_{1-x}As$ is parabolic. All other gradings are linear.

Table I shows the schematic diagram for epitaxial layers of the Pnp HBT's under this investigation. The epitaxial growth was by molecular beam epitaxy, and the growth conditions were identical to those in [3]. The indium composition in the InGaAs base was linearly graded from 15% at the collector edge to 0% at the emitter edge. This grading establishes a base quasielectric field of approximately 3.3×10^4 V/cm which reduces the base transit time of the devices. The base layer thickness of 500 Å is well within the critical layer thickness for the given indium composition [6], thus preventing base minority carrier lifetime from being significantly reduced by the misfit dislocations of a nonpseudomorphic InGaAs layer. Most importantly, a moderate base doping of 5×10^{18}/cm^3 (compared to 2×10^{19}/cm^3 in the previous design) is designed to increase the current gain. When the base doping is high, the base transport factor decreases due to lowered base minority carrier lifetime [7]. Moreover, for a Pnp HBT with degenerate base, the injection efficiency is expected to decrease from band-filling, especially when the emitter aluminum composition is less than 40% [8].

The detailed fabrication procedure for these HBT's was described elsewhere [3], [9]. In brief, a dual proton implantation was used to isolate the active device area, and a dual selective etching technique was used to etch to the thin base layer. The dual selective etching technique consists of a hydrogen peroxide/ ammonium hydroxide solution to selectively etch the GaAs contact layer and a ferric-ferro cyanide solution

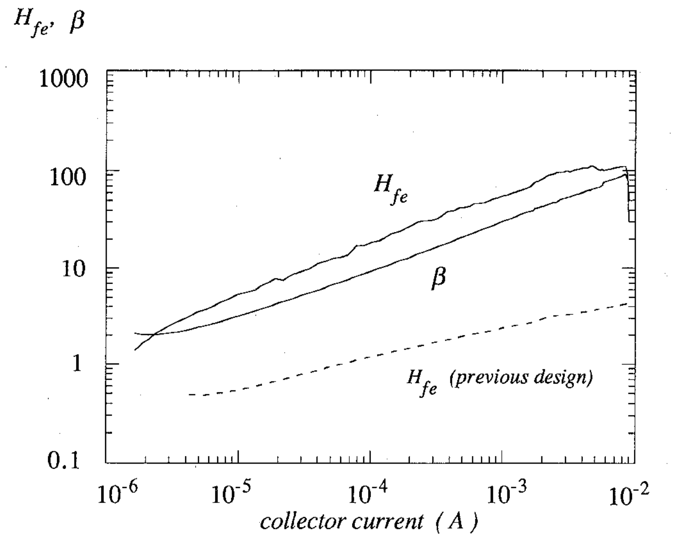

Fig. 1. Measured current gain, $\beta = I_c/I_b$, and incremental current gain, $H_{fe} = \Delta I_c/\Delta I_b$, as a function of collector current (solid lines). Dashed line represents the H_{fe} in HBT's of the previous design [3], [4]. All devices have an emitter area of 2×8 μm^2.

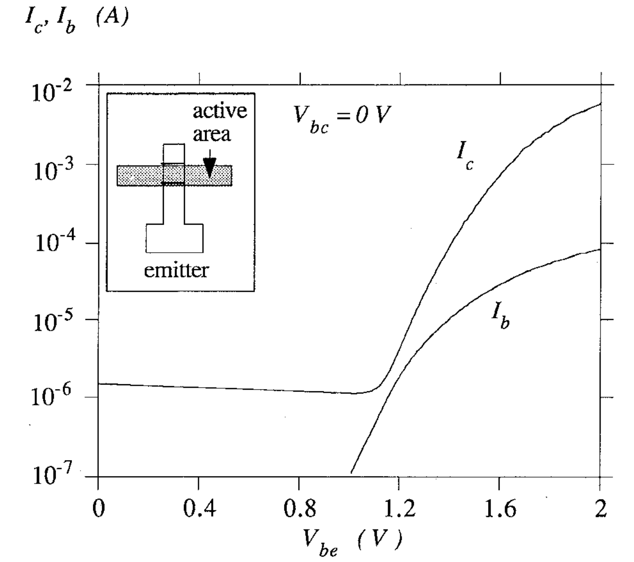

Fig. 2. Measured Gummel plot at a base-collector bias of 0 V. Inset shows the layout of the active area mask and emitter mask. Boldfaced lines indicate the recombination surfaces.

to selectively etch the AlGaAs emitter layer and stop at the graded $In_xGa_{1-x}As$ base layer when x reaches 5% (Table I) [10]. A nonalloyed contact of Ti–Pt–Au was used to contact the base layer. DC characterization was done with a HP 4145 parameter analyzer. All devices have an emitter area of 2×8 mm^2. The measured common-emitter I–V characteristics show that the emitter-collector offset voltage is 0.4 V and the emitter-collector breakdown voltage, BV_{CEo}, is 6.8 V. This BV_{CEo} value is expected for these measured HBT's whose collector thickness is only 2500 Å, even though the base-collector junction contains a portion of the lower-bandgap InGaAs material.

Fig. 1 shows β and H_{fe} vs. collector current for a microwave device. As shown the current gain continues to increase with collector current, and reaches a maximum value of 90 before it suddenly decreases. The observation that the current gain never saturates at a constant value indicates that the base-emitter space charge recombination current, rather than the base bulk recombination current, is a main base current component [11], [12]. This is expected from a HBT whose base-emitter junction is graded rather than abrupt. The large space charge recombination current most likely results from the fact that the depletion region adjacent to the base layer, in which most recombination events take place, is made of narrow bandgap GaAs. Therefore, the larger thermal carrier concentration associated with narrow bandgap material leads to a higher recombination current than expected from abrupt HBT's [11]. In contrast, the base bulk recombination current is small because both a base quasielectric field and a moderate base doping are used. Typical H_{fe} values of 100–150 are measured across the wafer, and it is 110 for a device whose characteristics is shown in Fig. 1.

Fig. 2 illustrates the Gummel plot of the same microwave device, demonstrating that its β is limited by two factors at low to moderate current levels. First, the material quality of the AlGaAs emitter grown on the pseudomorphic InGaAs base layer may not be optimum. The AlGaAs quality, together with the graded base-emitter junction used, result in a high base-emitter space charge recombination current as mentioned. This is evidenced by the relatively high ideality factor of 2.75 for the base current. Second, at low current levels, β is lowered by the parasitic leakage current passing through the interfaces of the base-emitter space charge region and the proton isolated region. These interfaces are marked as boldfaced lines in the inset figure of Fig. 2. Because the emitter stripe overlaps the proton implantation defined active device area, the recombination interfaces still remain after the emitter mesa etching. For the present devices, the implant energy and dose of the dual proton implantation ($8 \times 10^{15}/cm^2$ @ 200 KeV followed by $2 \times 10^{15}/cm^2$ @ 70 KeV) have not been optimized to minimize carrier recombination occurring at or in the implant damaged region. From Fig. 2, one observes that the leakage current of $1 \sim 1.4$ μA dominates the collector current for base-emitter voltages smaller than 1 V. Measured leakage currents between two collector contacts separated by a 10–μm gap range from 250 nA to 500 nA at 1 V.

Fig. 3 shows the magnitudes of current gain, h_{21}, and unilateral power gain, U, as a function of frequency. Both values were calculated from S-parameters measured with a HP 8510 network analyzer, showing that the cutoff frequency is 22 GHz and the maximum oscillation frequency is ~ 40 GHz. The base specific contact resistance and base sheet resistance measured from a transmission line pattern are 1×10^{-3} $\Omega \cdot cm^2$ and 130 Ω/square, respectively. It should be noted that, because there exists intrinsically a shunting capacitance associated with the nonalloyed base contacts, the base contact impedance at high frequency can be much lower than its dc values [13]. Furthermore, these high-frequency results are very close to the published values for those HBT's with very low β [3], [4]. Hence, with a lighter designed base doping level, these HBT's under investigation enjoy having dramatically higher β without sacrificing the high-frequency performance.

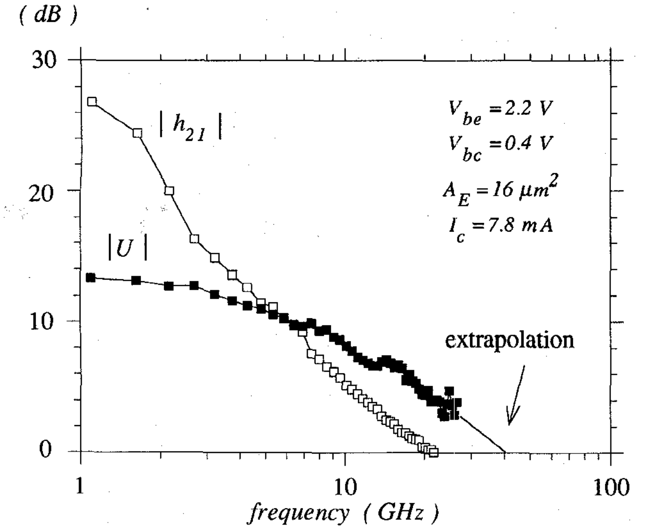

Fig. 3. Measured high-frequency response with a reverse base-collector voltage of 1 V and a collector current of 7.8 mA. Base-emitter bias was 2.2 V.

In summary, microwave Pnp HBT's with high-frequency performance of $f_T \sim$ 22 GHz and $f_{\max} \sim$ 40 GHz have been fabricated. This HBT design differs from a previously published design, which also attains relatively the same f_T and $f_{\max}$ values, but with a very low current gain of 4. In this design, the base doping level is lowered, and high current gain of 90 is obtained without sacrificing its high-frequency performance.

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