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Effects of a Compositionally Graded $In_xGa_{1-x}As$ Base in Abrupt-Emitter InP/InGaAs HBTs

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We report the role a compositionally-graded $In_xGa_{1-x}As$ base plays in upgrading the performance of abrupt-emitter InP/InGaAs HBTs. The built-in field in the base enables a more than 50% improvement in current gains, compared to a uniform-base structure. The peak f_T for the graded-base HBT is 143 GHz versus 121 GHz for the uniform-base HBT. Furthermore, the graded-base structure exhibits an f_{max} over 200 GHz even at V_{CE} as low as 1 V.

1. Introduction

In InP/InGaAs and InAlAs/InGaAs HBTs, hot electron injection from the abrupt emitter-base junction provides quasiballistic transport across the p^+ base region[1-3] and is expected to reduce the base transit delay markedly. However, a recent theoretical study[4] shows that a small amount of large-angle scattering in the base degrades electron transport properties by building up the steady-state population of energy-relaxed electrons. The average electron velocity is decreased over the whole base region as a result of the backward diffusive motion of the relaxed electrons.[5] To take full advantage of the nonequilibrium electron transport, therefore, the built-in field in the base is indispensable in terms of sweeping the energy-relaxed electrons out towards the collector. In this study, we describe a new hybrid base structure[5] that consists of an abrupt emitter-base junction and a compositionally graded $In_xGa_{1-x}As$ base, and show how the proposed structure can improve the DC and RF performance of InP/InGaAs HBTs.

2. Layer Structure

The graded-base HBTs (hereafter referred to as GB-HBTs) were grown on 2-inch-diameter semi-insulating (001) InP substrate by low-pressure MOVPE. Microwave transistors with emitter metal size of 1.2×5 μm^2 were fabricated using the self-aligned process reported elsewhere[6]. Schematic band diagram and layer structure parameters are shown in Fig. 1 and Table I, respectively. The base is 650-Å thick and doped to $p = 4 \times 10^{19}$ cm^{-3} with Zn. The InAs fraction in the pseudomorphic $In_xGa_{1-x}As$ base is linearly decreased from $x = 0.53$ to 0.46 towards the emitter-base junction. The potential drop across the graded layer is 40 meV (corresponding to the built-in field of 6 kV/cm), which was calculated taking the strain-induced bandgap change into consideration. The $In_{0.53}Ga_{0.47}As$ collector is 3000-Å thick and is not intentionally doped. For reference, we also grew conventional uniform-base HBTs (UB-HBTs) that had the same abrupt-emitter and undoped-collector structures.

In order to investigate the band-edge offsets at the $InP/In_xGa_{1-x}As$ heterointerface, we measured the turn-on voltages of 50×50 μm^2 emitter-base diodes fabricated on the same epi-wafers. As a result, there was no appreciable change in the turn-on voltage between the two devices. It is thus speculated that the

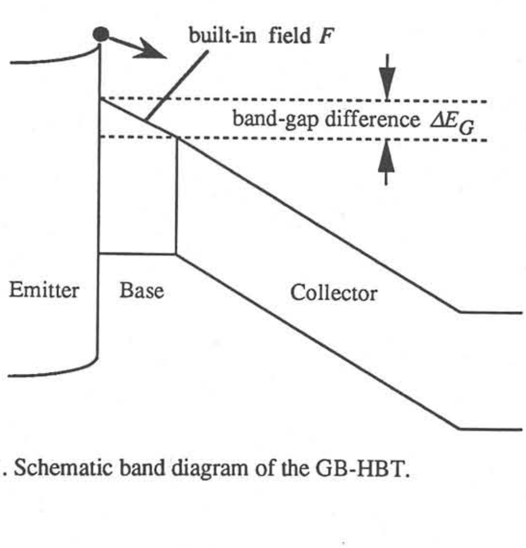

Fig. 1. Schematic band diagram of the GB-HBT.

Table I. Layer structure parameters of the GB-HBT.

Layer	Material	Doping (cm^{-3})	Thick. (Å)
cap	$In_{0.53}Ga_{0.47}As$	$n = 3 \times 10^{19}$	700
cap	InP	$n = 2 \times 10^{19}$	300
emitter	InP	$n = 4 \times 10^{17}$	700
spacer	$In_{0.46}Ga_{0.54}As$	—	50
base	$In_xGa_{1-x}As$	$p = 4 \times 10^{19}$	650
collector	$In_{0.53}Ga_{0.47}As$	—	3000
buffer	$In_{0.53}Ga_{0.47}As$	$n = 5 \times 10^{18}$	5000
graded base: $x = 0.53$ to 0.46 ($\Delta E_G \approx 40$ meV)			

bandgap change due to the compositional grading is mainly ascribed to the change in the conduction-band offset with no significant change in the valence-band offset.

The base contact resistivities measured by transmission line method were 0.45 $\mu\Omega cm^2$ for the GB-HBT and 1.0 $\mu\Omega cm^2$ for the UB-HBT, while the base sheet resistance was around 500 Ω/sq for both kinds of structures. The lower contact resistivity of the GB-HBT is presumably due to the higher Zn incorporation in the vicinity of the emitter-base junction, which is related to the larger GaAs fraction in the graded-base structure. This low contact resistivity of the GB-HBT is expected to provide 20% reduction in the base resistance, compared to that of the UB-HBT.

3. Device Performance

Figure 2 shows typical common-emitter I_C-V_{CE} characteristics for the fabricated transistors. The GB-HBT exhibits a small-signal current gain of 50 at $I_C = 5$ mA (current density of $J_C \approx 125$ kA/cm^2), which is 1.5 times as large as that of the UB-HBT. At lower current-injection levels, such gain enhancement due to the graded layer is more significant, as shown in Fig. 3, where the current gains are plotted as a function of collector injection current. Consequently, the built-in field in the base is effective for reducing the base transit time as well as in suppressing the recombination currents at the emitter-base junction and in the external base region.

In Fig. 2, the GB-HBT shows small but noticeable gain-reduction behavior at high-I_C and low-V_{CE} bias region while the output conductance of the UB-HBT gradually increases with collector bias voltage. This difference suggests that the strained $In_xGa_{1-x}As$ base has nonradiative-recombination centers that are large enough to degrade the minority-carrier lifetime with device self-heating. It should be noted that the GB-HBT provides higher current gains in spite of having the larger recombination centers.

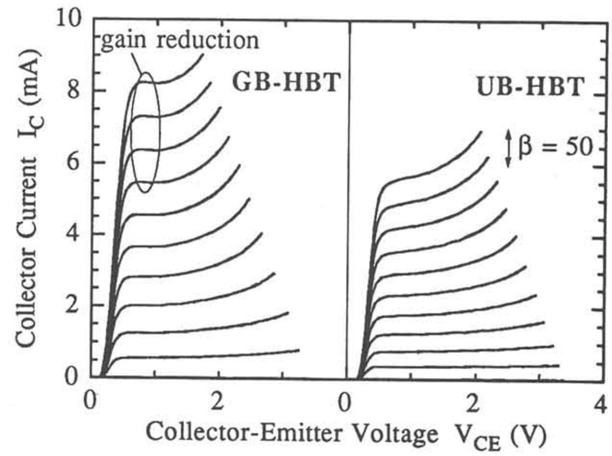

Fig. 2. Common-emitter I_C-V_{CE} characteristics for the GB-HBT and UB-HBT. Curves are taken in steps of 20 μA of base current.

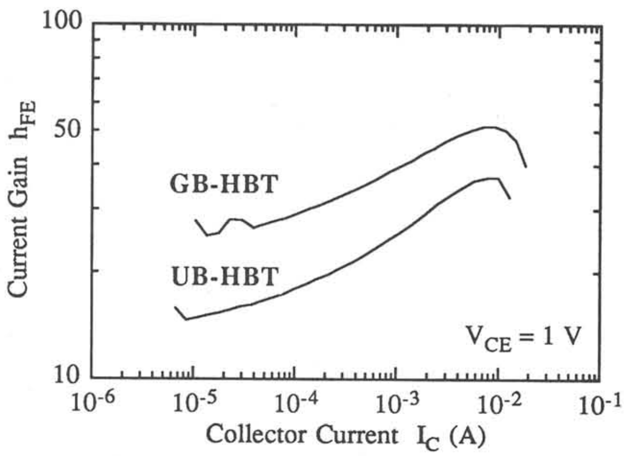

Fig. 3. Dependencies of small-signal current gain h_{FE} on I_C.

To obtain more detailed information on base transport properties, on-wafer S-parameter measurement was performed in the frequency range of 0.5-50 GHz under various collector bias conditions. The S-parameters of open and short pads on the same epi-wafers were also measured to remove the parasitic effects between the pad and the substrate. The f_T and f_{max} values were respectively determined by extrapolation of $|h_{21}|^2$ and Mason's unilateral power gain UG to unity with a -20 dB/decade slope line. Shown in Fig. 4 are f_T and f_{max} plotted as a function of collector current at V_{CE} of 1.3 V. The GB-HBT obtains a peak f_T of 143 GHz at $I_C = 8$ mA ($J_C \approx 200$ kA/cm^2), while the peak f_T for the UB-HBT is 121 GHz. The intrinsic delay times extracted using measured device parameters were 0.71 ps for the GB-HBT and 0.93 ps for the UB-HBT; thus, there is a 0.22 ps reduction in the base transit time in the proposed graded-base structure. If we assume the collector transit time of 0.4 ps, which is a typical value for a 3000-Å-thick InGaAs

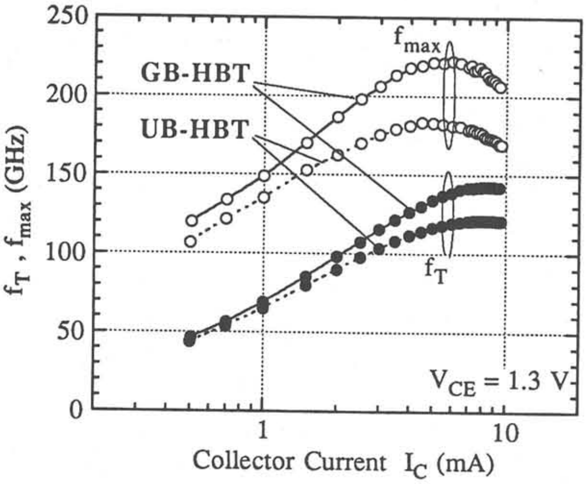

Fig. 4. f_T and f_{max} plotted as a function of I_C at V_{CE} = 1.3 V.

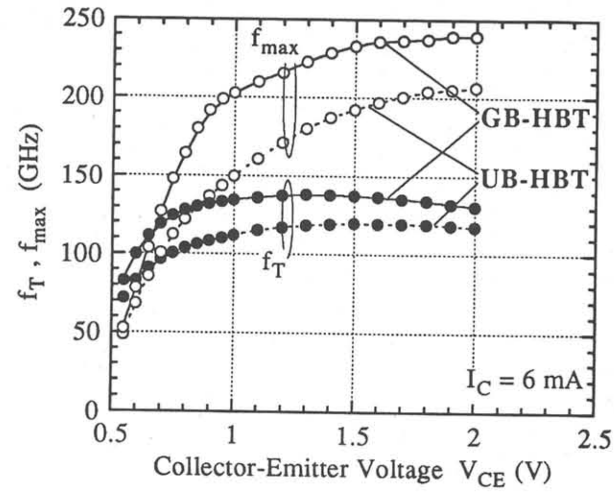

Fig. 5. Collector bias dependencies of f_T and f_{max} at I_C = 6 mA.

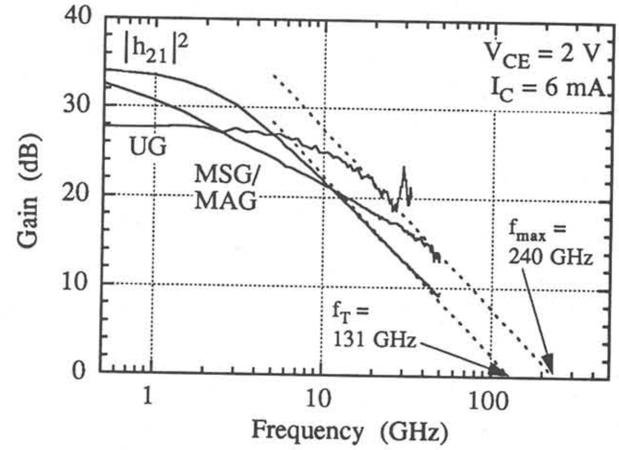

Fig. 6. Frequency dependencies of $|h_{21}|^2$, UG, maximum stable/available gains MSG/MAG of the GB-HBTs. The collector bias conditions are V_{CE} = 2 V and I_C = 6 mA.

collector calculated using the Monte Carlo simulation[5], average electron velocities in the base are 2.3×10^7 cm/s for the GB-HBT and 1.3×10^7 cm/s for the UB-HBT.

In addition to reducing the base transit delay, the graded-base structure is also found to suppress the base widening effect under high-I_C and low-V_{CE} bias conditions. The built-in field in the base accelerates low-speed energy-relaxed electrons into the collector, which minimizes the accumulation of space charges near the base-collector junction. Figure 5 shows collector bias dependencies of f_T and f_{max} at I_C = 6 mA (J_C = 150 kA/cm^2). At $V_{CE} < 1$ V, the cutoff frequencies of the GB-HBT rapidly increase with increasing collector bias voltage. As a result, the GB-HBT provides f_{max} of 203 GHz and f_T of 134 GHz even at V_{CE} as low as 1 V. Besides this impressive turn-on behavior, an f_{max} of 240 GHz is successfully obtained at V_{CE} = 2 V, as shown in Fig. 6.

4. Conclusion

By comparing the DC and RF characteristics of graded- and uniform-base HBTs, we have presented clear evidence that the built-in field in the base markedly improves the electron transport properties in the abrupt-emitter InP/InGaAs HBTs. The proposed structure is also effective for minimizing the base widening effect under high-I_C and low-V_{CE} bias conditions. The suppressed base widening effect, combined with small base resistance, permits an f_{max} as high as 200 GHz even at V_{CE} of 1 V.

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