Improved High Frequency Performance by Composite Emitter AlGaAs/GaInP Heterojunction Bipolar Transistors Fabricated using Chemical Beam Epitaxy

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Abstract. A new emitter design based on composite AlGaAs/GaInP approach is described which allows significant reduction of C_{BE} and improved high frequency performance. Self-aligned composite AlGaAs/GaInP and traditional emitter design HBTs were fabricated on CBE layers grown with TBA/TBP precursors. C_{BE} of composite emitter HBTs is significantly lower than for traditional designs and does not show significant variation with collector current. This leads to enhanced f_T characteristics for composite emitter HBT designs and confirms the theoretical expectations. The C_{BE} achieved with the new designs was by at least 4 times lower than that of conventional transistors and resulted in 20% enhancement of cutoff frequency.

1. Introduction

GaInP/GaAs Heterojunction Bipolar Transistors (HBTs) offer significant advantages over AlGaAs/GaAs devices such as large valence band discontinuity and excellent etching selectivity as demonstrated by the authors[1] and other laboratories [2], [3]. Excellent microwave properties have been obtained using GaInP HBTs [3] and Chemical Beam Epitaxy (CBE) using TBA/TBP precursors has been reported for material growth of such devices [4]. A common limitation in high speed performance of HBTs has been their relatively large base-emitter capacitance(C_{BE}) which is limited by mobile carrier transport in the emitter region [5]. Mobile carrier transport takes place in traditional HBT designs by diffusion and results in charge accumulation in the emitter and thus increased C_{BE}. To reduce the impact of this effect, a composite AlGaAs/GaInP emitter design was employed. A compositionally graded AlGaAs layer forms an electron launcher at the interface with the GaInP layer which injects the electrons at a high kinetic energy towards the remaining part of the emitter, thus resulting in lower free carrier concentration and smaller C_{BE}, especially at high current drive(J_C). Although the dynamic resistance of the HBT also increases with J_C, the C_{BE} increase in traditional designs plays a predominant role, dominating therefore the emitter time constant (τ_E). This paper addresses experimentally the new emitter design based on the earlier reported composite AlGaAs/GaInP approach [5] which allows significant reduction of C_{BE} and thus improved high frequency performance.

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2. Layer Structure and Device Fabrication

The new emitter HBT design consists of a compositionally graded $5x10^{17}cm^{-3}$, 380Å thick AlGaAs (Al : 0 → 0.22) layer followed by undoped 100Å thick GaInP which serves in reducing the spike created in the conduction band of the AlGaAs/GaInP heterointerface. A $5x10^{16}$ cm^{-3}, 400Å thick emitter layer is used below the undoped GaInP and the p-doped base. To better evaluate the advantages of the new emitter design and validate the proposed approach, an abrupt junction GaInP/GaAs traditional HBT was also fabricated for comparison. The emitter design of the traditional HBT consists starting from the emitter cap, of an n+ ($1x10^{19}cm^{-3}$) GaInP, 700Å thick layer followed by n ($3x10^{17}$ cm^{-3}), 2000Å thick GaInP. A common design feature of the two HBT structures is a GaInP etch stop layer between the GaAs collector and subcolllector. This can be used to form a laterally etched undercut and leads to reduction of the C_{BC} capacitance and thus cutoff frequency enhancement. The GaInP/GaAs HBT layers were grown by CBE. Group III atoms were provided by TEGa and TMIn. Precracked tertiarybuthylarsine and phosphine (TBA,TBP) and uncracked trisdimethylaminoarsine (tDMAAs) were employed as Group V sources. Uncracked hydrogen sulfide (H_2S) and TMGa were used for n- and p- doping respectively. The employed growth approach resulted in very high level of reproducibility of growth parameters and very low defect densities as expected earlier on by the authors [6]. Self-aligned HBTs with single $2x30\mu m^2$ emitter fingers were fabricated on the above layers. The key process features are as follows; Ti/Pt/Au non-alloyed emitter and collector ohmic contacts; Pt/Ti/Pt/Au non-alloyed base contacts, GaInP emitter etch by HCl and pillar/airbridge fabrication using Ti/Al/Ti/Au. GaAs collector undercut as necessary for C_{BC} was achieved by a wet etching solution consisting of $NH_4OH : H_2O_2 : H_2O$. Fig. 1 shows the cross-section of a completed HBT with laterally etched undercut.

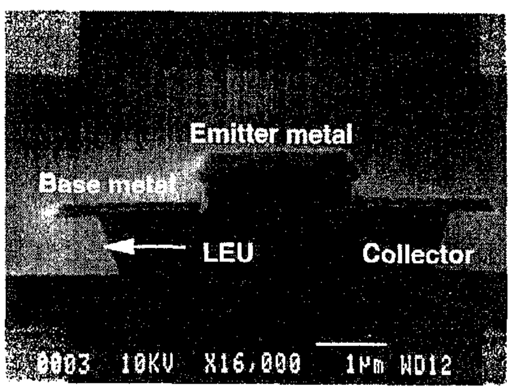
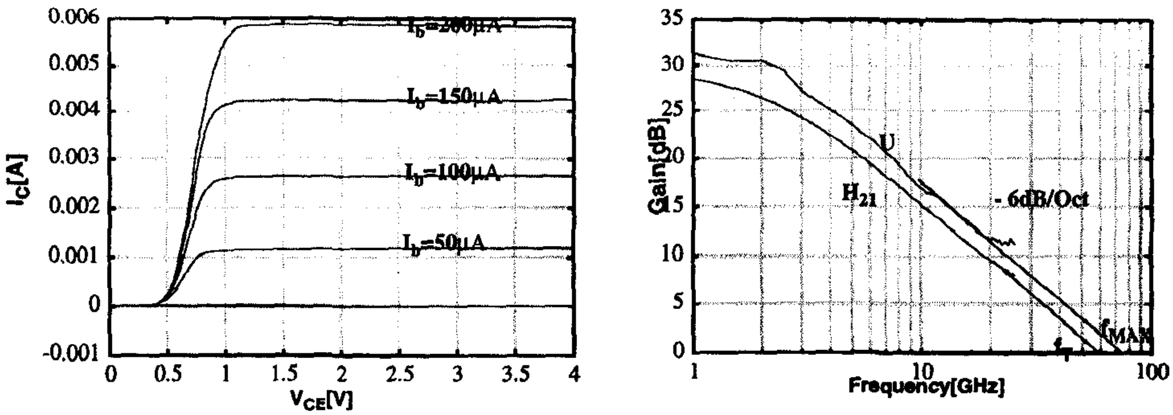


Fig. 1. Cross-section of the device profile with laterally etched collector.

3. DC and Microwave Performance

Typical DC characteristics of the composite emitter and the traditional emitter device are presented in Fig. 2(a). DC gain of 30 and 28, base ideality factors of 1.72, 2.26 and collector ideality factors of 1.26, 1.27 and a collector-emitter breakdown voltage of above 13.5V are obtained for the composite emitter and traditional emitter device respectively. The offset voltage (V_{offset}) of both devices was about same (0.15V). The microwave properties of HBTs were measured in common-emitter configuration using on wafer tests and an HP8510B network analyzer. The power and current gain versus frequency characteristics of the composite emitter HBT are shown in Fig. 2(b). The current gain cutoff frequency (f_T) extrapolated from the measured $|H_{21}|$ using a -6dB/Oct slope rule was 60GHz for the composite emitter design HBT, and 43GHz for the traditional emitter design HBT. The maximum oscillation frequency (f_{max}) from Mason's U was 75GHz for the composite design, and 60GHz for the traditional design at V_{CE}=2V, I_C=18.1mA and V_{CE}=2V, I_C=16.5mA for the composite and traditional designs respectively.



(a) (b)

Fig. 2. DC (a) and Microwave (b) characteristics of the composite emitter HBTs, V_{ce}=2V, I_C=18.1mA.(Emitter size : 2x30μm^2)

The HBT equivalent circuit parameters were extracted from S parameter data using our previously reported analytic approach [7]. The total delay time (τ_d) and forward transit time ($\tau_F = \tau_B + \tau_C$) were calculated analytically from the impedance block elements of the HBT equivalent circuit. The relations below summarize the approach used [7], [8]:

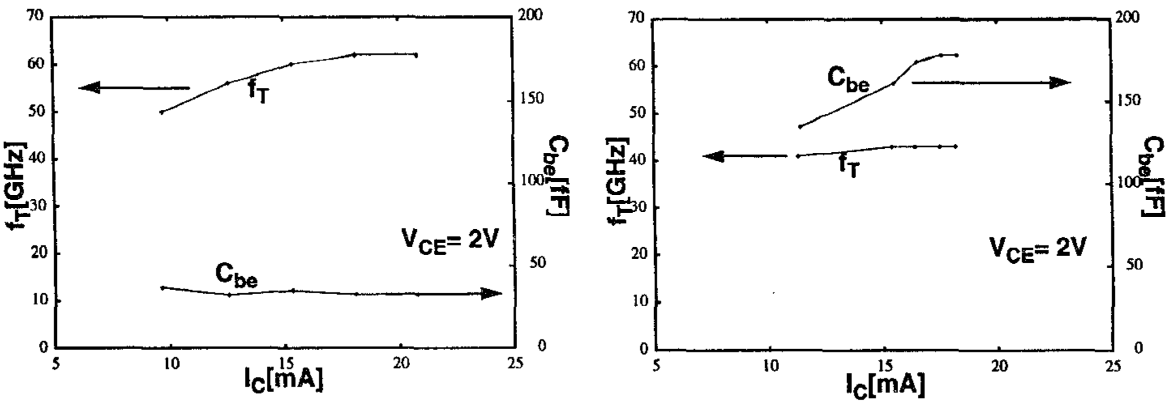
$$\tau_d = \tau_E + \tau_B + \tau_C + \tau_C' = \arg([Z_{12}-Z_{21}]/[Z_{22}-Z_{21}]) \quad (1)$$

$$\tau_F = \tau_B + \tau_C = -\tan^{-1}(Re[\alpha Z_{BC}]/ Im[\alpha Z_{BC}]) \quad (2)$$

where $\tau_E \sim C_{BE}R_{BE}$, $\tau_C' = C_{BC}R_C$

The calculated τ_d, τ_F as function of frequency from the extracted small signal parameters were as follows; In case of the composite emitter design, a τ_d of 2.33psec, a τ_F of 2.2psec were achieved which leads to an emitter delay time($\tau_E = \tau_d - \tau_F - \tau_C'$) of only 0.071psec; $\tau_C' = C_{BC}R_C$ was in this case 0.059psec. On the other hand, the total delay time (τ_d) of the traditional design was 3psec while its forward transit time (τ_F) was 1.66psec. The resulting emitter delay time (τ_E) for the traditional design was consequently 0.485psec. These results indicate that the emitter delay time of the composite design is much shorter than that of traditional design HBTs. Thus the composite design leads to enhancement of cutoff frequency which in the case of the tested devices is of the order of 20%. The C_{BE} and f_T

dependence on J_C manifests distinct features for composite and traditional emitter designs as shown in Fig. 3 for a 2x30μm^2 single emitter device. In particular, the C_{BE} of composite emitter HBTs is significantly lower than that of traditional designs and presents a weak J_C dependence. This feature is representative of the new design and as expected from theory leads to enhanced f_T performance. Best microwave performance for composite emitter HBTs was f_T=60GHz and f_{max}=75GHz for a 2x30μm^2 emitter geometry. In summary, we have applied CBE growth technology using TBA/TBP precursors to the demonstration of self-aligned composite emitter AlGaAs/GaInP designs and showed the superior properties of such designs for reduced emitter-base capacitance and enhanced f_T performance.



(a) (b)

Fig. 3. Comparison of C_{BE} and f_T of the composite emitter design (a) and the traditional emitter Design (b) HBTs.

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