280 GHz f_T InP DHBT with 1.2 μm^2 base-emitter junction area in MBE Regrown-Emitter Technology

Yun Wei, Dennis W. Scott, Yingda Dong, Arthur C. Gossard, and Mark J. Rodwell
Department of Electrical and Computer Engineering, University of California, Santa Barbara, CA 93106
yunwei@ece.ucsb.edu, 805-893-3543

We report an InP/InGaAs/InP double heterojunction bipolar transistor (DHBT) with a 0.3 μm × 4 μm regrown base-emitter junction. The HBT exhibits 280 GHz current gain cutoff frequency (f_τ) and 148 GHz power gain cutoff frequency ($f_{\max}$). This DHBT was fabricated in a molecular beam epitaxy (MBE) regrown-emitter technology [1] [2] and has the highest f_τ yet reported for a III-V regrown-emitter HBT. The device has $V_{CE,sat}$ < 0.9 V even at $J_E = 11\ \text{mA}/\mu\text{m}^2$, peak AC current gain h_{21} =30, and 5 V collector breakdown voltage V_{CEO}. In this technology, the area of base-emitter junction has been scaled to as small as 1.2 μm^2 while a larger-area extrinsic emitter contact maintains a low 11 Ω emitter access resistance.

Regrown-emitter DHBTs address key limits in HBT scaling [3]. A doubling of HBT bandwidth in a general circuit requires a 2:1 reduction of all HBT transit delays and capacitances, while maintaining constant the bias current and all resistances. In addition to reducing τ_c by 2:1, a 2:1 reduction in collector depletion-layer thickness permits 4:1 increased J_E and consequently reduces by 2:1 the collector capacitance charging time $C_{cb}\Delta V_{\text{logic}}/I_C$. To maintain constant emitter resistance, the emitter resistance normalized to a unit area, ρ_{ex}, must be reduced 4:1. To reduce C_{cb} by 2:1 while maintaining R_{bb} constant, the emitter and collector junction widths must be reduced 4:1. A 2:1 reduction in τ_b requires a $\sim 0.7:1$ reduction in base thickness. Emitter width (W_E) and ρ_{ex} are key scaling challenges; an HBT technology suitable for 250 GHz clock rate operation [4] requires W_E ~0.3 μm and $\rho_{ex} < 5\ \Omega-\mu\text{m}^2$. At W_E = 0.3 μm, it is difficult to maintain emitter junction width control or high-yield base contact liftoff in standard self-aligned mesa-etched InP emitter-base fabrication processes, while $\rho_{ex} < 5\ \Omega-\mu\text{m}^2$ is difficult to obtain in submicron InP emitters. The emitter regrowth process we here report addresses these key scaling limits. Submicron emitters are formed by patterned MBE growth, not by mesa-etching, self-aligned base contacts are formed without liftoff, and the emitter contact is ~3:1 larger than the emitter junction to reduce R_{ex}

Regrown emitters are standard in SiGe. Rieh reported a 0.12 × 2.5 μm^2 emitter HBT with 350 GHz f_τ, employing chemical vapor deposition (CVD) regrowth and diffusion to form the base-emitter junction [5]. The highly-doped polycrystalline extrinsic emitter provides an emitter contact area much larger than the intrinsic base-emitter junction, greatly reducing R_{ex}. A thin intrinsic base reduces τ_b, while a thick extrinsic base reduces R_{bb}. Other process features reduce C_{cb}. These superior process and scaling features of SiGe HBT offset the substantially superior electron transport of InP, and hence InP HBTs only obtain moderately higher digital clock rates than SiGe, albeit at larger lithographic feature size [6]

Drawing from the SiGe emitter-base device structure, we here report InP DHBTs utilizing non-selective-area MBE regrown base-emitter junctions. The base-emitter junction is formed by MBE regrowth onto a SiN_X patterned base-collector template. A thick continuous N++ InAs layer caps the emitter regrowth layer over both the SiN_X dielectric and the epitaxial emitter to form an emitter contact area larger than the base-emitter junction (Figure 1). The intrinsic base is thinned for low τ_b and a thick, heavily-doped extrinsic base maintains low R_{bb} ($\rho_{s,base}$ ~230 Ω) The process incorporates self-aligned sputtered W/Ti/W refractory base Ohmic contacts. Initial results [2] revealed high emitter access resistance, resulting from formation of growth facets and consequently discontinuous film formation during emitter epitaxial regrowth. To suppress such faceting, the abrupt InP emitter is oriented at 60 degree to [110] and an InGaAs layer is inserted between InP emitter and InAs cap to suppress indium migration on the regrowth facets. PECVD SiN_X contains hydrogen, which then passivates carbon dopant during high temperature MBE regrowth and increases base sheet resistance more than *tenfold*. The HBTs reported here use sputter-deposited hydrogen-free SiN_X, although partial H passivation remains due to our present use of PECVD SiN_X sidewalls.

The device layer structure is shown in Table 1. Figure 2 shows common emitter characteristics for an HBT with 0.3 × 4 μm^2 emitter junction area. At $J_E = 11\ \text{mA}/\mu\text{m}^2$, $V_{CE,sat}$ <0.9 V, V_{CEO} =5V and h_{21} =30. The emitter contact width is 0.9 μm and the refractory base contacts extend 0.6 μm on each side of the emitter. R_{ex} =11 Ω is determined from both DC fly-back and microwave measurements. Figure 3 shows the Gummel plot with base and collector ideality factors η_B=3.2 and η_C=1.2 respectively. The microwave characteristics (Figure 4) exhibit 280 GHz peak f_τ and 148 GHz $f_{\max}$. The f_τ is presently limited by large collector junction dimensions associated with a process development mask set. Orientation of the regrown emitter at 30 degree to [110] is expected to further reduce R_{ex}. Base sheet resistance on the present wafer remains high due to the PECVD SiN_X

sidewall; a sputtered SiN_X sidewall process, in development, is expected to eliminate hydrogen passivation and hence increase $f_{\max}$.

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Layer	Material	Doping (cm^{-3})	Thickness (Å)
Emitter cap	InAs	3e19 Si	800
Cap grade	$InGa_XAs_{1-X}$	3e19 Si	500
N+ Emitter	InP	3e19 Si	800
N- Emitter	InP	8e17 Si	100
N-- Emitter	InP	3e17 Si	300
Extrinsic base *	InGaAs	1~2e20 C	500
Etch stop	InP	~4e19 Be	20
Intrinsic base	InGaAs	4e19 C	400
Set-back	InGaAs	2e16 Si	200
Grade	InGaAlAs	2e16 Si	240
Delta doping	InP	3e18 Si	30
Collector	InP	2e16 Si	1030
Subcollector 1	InGaAs	2e19 Si	100
Subcollector 2	InP	2e19 Si	3000

Table 1. Layer structure of regrown-emitter InP HBT

**Extrinsic base remains only under base contact.*

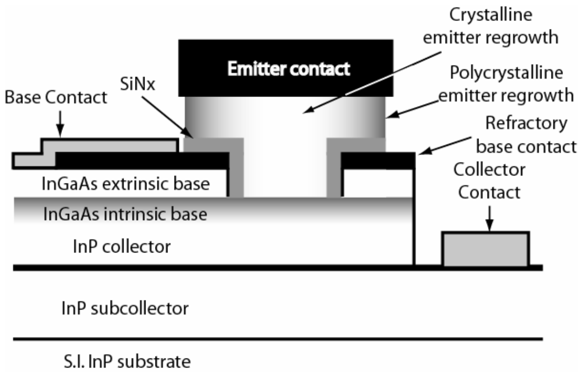

Figure 1: Device cross-section

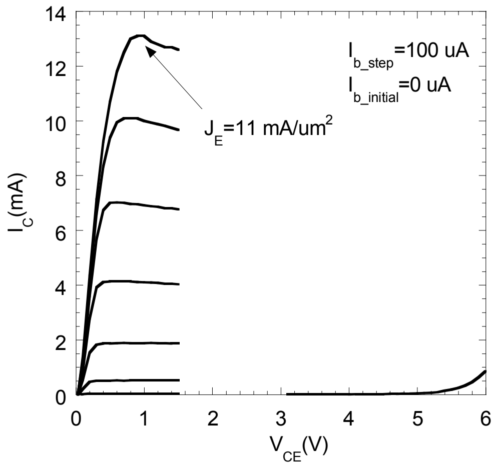

Figure 2: Common-emitter characteristics

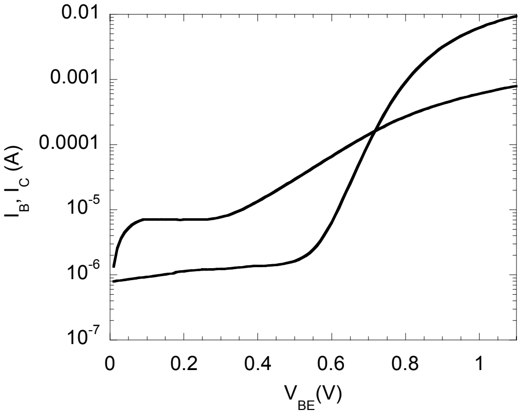

Figure 3: Gummel plot at V_{cb}=0.3 V

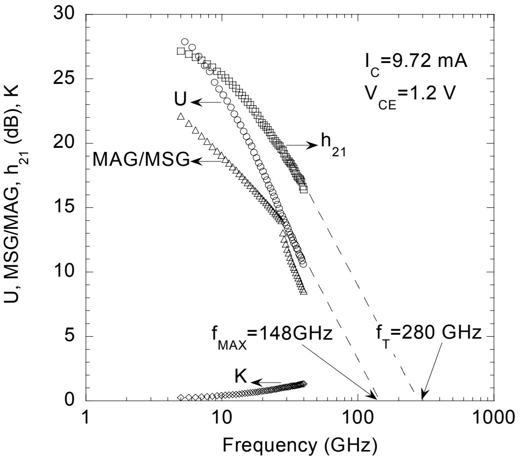

Figure 4: Microwave gains and stability factor