A 160-GHz f_T and 140-GHz f_{MAX} Submicrometer InP DHBT in MBE Regrown-Emitter Technology

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***Abstract*—We report a 0.7 $\times$8 μm^2 InAlAs–InGaAs–InP double heterojunction bipolar transistor, fabricated in a molecular-beam epitaxy (MBE) regrown-emitter technology, exhibiting 160 GHz f_T and 140 GHz f_{MAX}. These initial results are the first known RF results for a nonselective regrown-emitter heterojunction bipolar transistor, and the fastest ever reported using a regrown base–emitter heterojunction. The maximum current density is $\mathrm{J_E} = 8 \times 10^5$ A/cm^2 and the collector breakdown voltage $\mathrm{V_{CEO}}$ is 6 V for a 1500-Å collector. In this technology, the dimension of base–emitter junction has been scaled to an area as low as 0.3 $\times$4 μm^2 while a larger-area extrinsic emitter maintains lower emitter access resistance. Furthermore, the application of a refractory metal (Ti–W) base contact beneath the extrinsic emitter regrowth achieves a fully self-aligned device topology.**

***Index Terms*—Double heterojunction bipolar transistor (DHBT), molecular-beam epitaxy (MBE).**

I. INTRODUCTION

HIGH BREAKDOWN heterojunction bipolar transistors (HBTs) with f_T greater than 300 GHz are required for analog and digital systems operating at clock rate of 80–160 GHz. To achieve high f_T and f_{MAX} in III–V HBT technology, the base and collector thickness are often thinned to reduce the base and collector transit time. Simultaneous lateral scaling is also required to reduce the value of the capacitive charging term in the equation of f_T [1]. SiGe HBT technology using regrowth by chemical vapor deposition and diffusion to form the base–emitter junction generates a low-resistance, deep-submicrometer base–emitter structure. Reports for 0.12 $\times$2.5 μm^2 junctions demonstrate a f_T of 350 GHz in the SiGe technology [2]. Given the higher carrier mobility and stronger heterojunction advantages of III–V compound semiconductors, much larger 0.4 $\times$8 μm^2 InP HBTs have been reported exhibiting comparable $f_T = 370$ GHz [3]. The base–emitter junctions of contemporary III–V HBTs with wide bandwidth ($f_T > 300$ GHz) are generally fabricated by wet/dry etching [3], [4]. We have found that these processes result in low yield and inhibit deep submicron scaling. Furthermore, deep submicron scaling in III–V HBTs results in excess emitter resistance arising from the reduced emitter contact area. In SiGe HBTs, an enlarged emitter contact area is formed by the deposition of a highly doped-polycrystalline extrinsic emitter.

The regrown-emitter concept has been previously demonstrated in III–V HBTs. GaAs-based single heterojunction bipolar transistors (SHBTs) have been reported using selective emitter regrowth through a submicron aperture formed by dielectric deposited on a base–collector template [5]–[7]. In these works a maximum f_T of 75 GHz and f_{MAX} of 46 GHz was reported on a device with a base–emitter junction area of 1.4 $\times$11 μm^2 [5]. Although the reported motivation for these efforts was to laterally scale the transistors, the nature of selective regrowth limits the ability to create a wide extrinsic emitter contact.

In this letter, we report InAlAs–InGaAs–InP DHBTs utilizing nonselective MBE regrown base–emitter junctions with extrinsic emitter areas much wider than the base–emitter junction. We have previously reported the dc performance of large area devices characterizing this regrown layer structure [8] and MBE regrown polycrystalline InAs with low bulk resistivity and low contact resistance with a Ti–Pt–Au metal stack [9]. In this nonselective emitter regrowth technology, the base–emitter junction is formed by MBE regrowth onto a SiN$_X$ patterned base–collector template. A thick InAs layer is then used to cap the emitter regrowth forming a continuous layer over both the SiN$_X$ dielectric and the epitaxial emitter regrowth. This nonselective growth over the epitaxial emitter and SiN$_X$ dielectric are used to form an emitter contact area larger than the base–emitter junction. In this technology, the intrinsic base can be thinned for low transient time while an extrinsic base can be used to maintain low base resistance. A refractory base contact was also employed to achieve a fully self-aligned base–emitter junction. The base contact width is determined by the base contact transfer length and, therefore, base–collector parasitic capacitance can be reduced substantially. We report a regrown emitter III–V HBT with base–emitter junction dimensions of 0.3 $\times$4 μm^2 demonstrating a common-emitter current gain of 20 under dc measurement. A maximum f_T of 160 GHz and f_{MAX} of 140 GHz are exhibited by a device with emitter junction area of 0.7 $\times$8 μm^2. For all devices, the maximum current density is $\mathrm{J_E} = 8 \times 10^5$ A/cm^2, and the collector breakdown voltage $\mathrm{V_{CEO}}$ is 6 V.

II. DEVICE STUCTURE AND FABRICATION

Fig. 1 shows the schematic cross-section of the regrown-emitter DHBT fabrication with self-aligned refractory base metal buried beneath the emitter regrowth. An expanded process flow is depicted in [8]. The device is fabricated using

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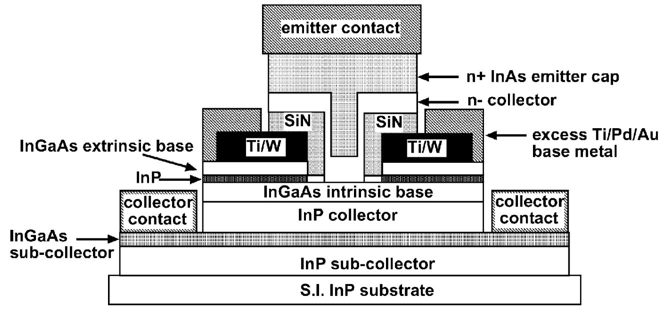

Fig. 1. Cross-sectional schematic of the fully fabricated regrown-emitter DHBT.

a patterned base–collector template onto which the emitter and cap layers are regrown. The base–collector template is grown on a semi-insulating (100) InP substrate. The epitaxial structure consists of 3100 Å InGaAs–InP n+ subcollector, 1100 Å n- InP collector, 400 Å n- grade and undoped setback, 400 Å p+ InGaAs base, 20 Å InP p+ etch stop, and 500 Å InGaAs base contact layer. The two InGaAs base layers are carbon doped and the InP etch stop is beryllium doped.

A Ti–W metal stack is sputtered onto the base–collector template, patterned, and dry etched to form refractory base contacts. The 1000 Å of plasma-enhanced chemical vapor deposition (PECVD) SiN_X is then deposited over the entire wafer. The emitter-etch windows are then lithographically defined in the centers of the refractory base contacts. The etch windows vary in widths of 0.5, 0.7, and 0.9 μm and lengths of 4 and 8 μm. The emitter lengths are oriented perpendicular to the [011] direction. The SiN_X and Ti–W metal stack are then reactive ion etched (REI) from the emitter regrowth areas using the single lithography as an etch mask. The exposed extrinsic base in the emitter regrowth window is then selectively etched using a citric-based etchant. A second 1000-Å PECVD SiN_X is deposited over the entire wafer to create an insulating layer in the emitter regrowth window that will become the emitter sidewall. RIE etchback is used to form vertical SiN_X sidewalls in the emitter window. A 0.1-μm sidewall spacer is thus formed between the intrinsic emitter and the extrinsic base contact region. After removal of the 20-Å InP etch stop by HCl-based etching, nonselective MBE regrowth is used to deposit a 275 Å base–emitter superlattice grade, 600-Å n- InAlAs emitter, 500-Å n+ InAlAs, 500-Å InGaAs and 1500-Å heavily doped InAs. The regrown epitaxy in the exposed intrinsic base region is crystalline while that on SiN_X is polycrystalline. A Ti–Pt–Au–Pt metal stack is deposited over the emitter regrowth windows to form the emitter contact. The excess regrown-emitter material over the entire wafer with SiN_X underneath is dry-etched by ICP and RIE, respectively, using the emitter metal as an etch mask. Because the Ti–W base refractory metal has a low electrical conductivity, a self-aligned Ti–Pd–Au metal is evaporated over the exposed refractory contacts to reduce the feed metal resistance. Remaining processes include collector contact deposition and device isolation typical of mesa HBTs. Polyimide is used as an insulating material and Au forms the coplanar waveguide wiring. The base–emitter junction is not defined by an etch process and is passivated by the SiN_X sidewalls. The polyimide is used as an insulative and protective material, and not as a passivation material for the junction.

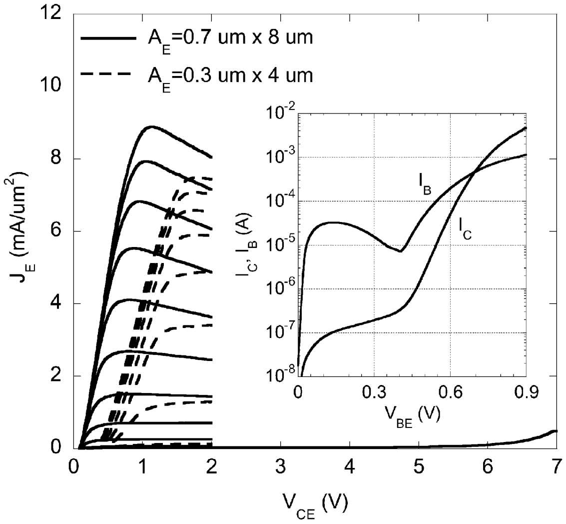

Fig. 2. Common emitter *I–V* curve for regrown-emitter DHBTs with $\mathrm{A_E} = 0.7 \times 8\ \mu\mathrm{m}^2$ ($\mathrm{I_{Bstep}} = 200\ \mu\mathrm{A}, \beta = 15$) and $\mathrm{A_E} = 0.3 \times 4\ \mu\mathrm{m}^2$ ($\mathrm{I_{Bstep}} = 100\ \mu\mathrm{A}, \beta = 20$); inset of Gummel plot for $\mathrm{A_E} = 0.7 \times 8\ \mu\mathrm{m}^2$ device.

III. Results and Discussion

Fig. 2 shows common emitter current–voltage (*I–V*) curves for the fabricated devices with base–emitter junction areas of $0.7 \times 8\ \mu\mathrm{m}^2$ and $0.3 \times 4\ \mu\mathrm{m}^2$. The emitter contact extends an additional 0.3 μm to each side of the junction and the refractory base has a width of 0.6 μm on each side of the emitter. The 2.7-μm collector contacts are located on each side of the base mesa with 0.5-μm spacing. The base–collector layer structure is similarly designed as [3] enabling a maximum emitter current density of $8 \times 10^5\ \mathrm{A/cm^2}$ and a V_{CEO} of 6 V. The inset of Fig. 2 shows the Gummel plot for the $0.7 \times 8\ \mu\mathrm{m}^2$ device. The collector ideality factor η_C is 1.2, and the base ideality factor η_B is 2.2. Although the base ideality factor is not ideal, it is not unexpected given the nature and the maturity of the device technology. The base current at low bias also shows an unexpected leakage behavior. We suspect that this characteristic may be due to unintended contact between regrown InAs emitter contact material and the base layers. This scenario may be possible if there is partial failure of the SiN_X sidewall prior to regrowth or incomplete coverage by the emitter ternary layers during regrowth.

The microwave performance of the device was characterized by on-wafer S-parameter measurements from 5 to 40 GHz using an HP8510C network analyzer. A peak f_T of 160 GHz and a simultaneous f_{MAX} of 140 GHz are extracted using $-20\ \mathrm{dB/decade}$ extrapolation from the plots of h_{21} and Mason's gain, as shown in Fig. 3. The RF measurement in Fig. 3 was obtained at bias current density of $4 \times 10^5\ \mathrm{A/cm^2}$ and collector voltage of 1.3 V. Fig. 3 also shows curves for the maximum stable/available power gain and the stability factor (K).

Both the dc flyback measurement and a hybrid-π model extraction demonstrate an emitter contact resistance of $80\ \Omega \cdot \mu\mathrm{m}^2$. This excess emitter resistance substantially degrades the device bandwidth and is beyond the expected value calculated from the polycrystalline InAs transmission-line measurements

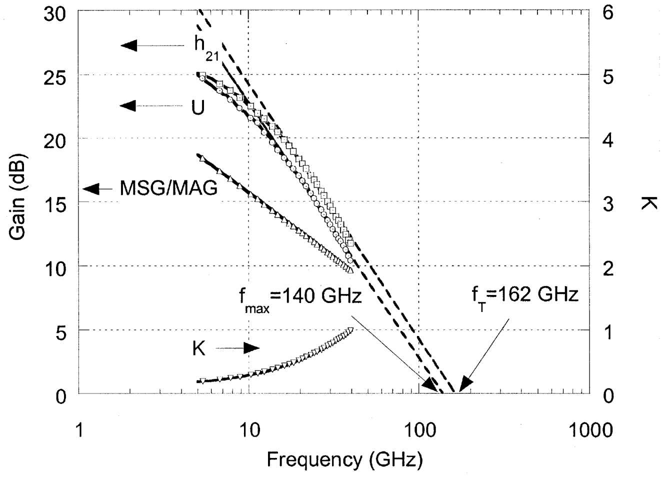

Fig. 3. RF gains and stability factor.

(TLM) [9]. We attribute the excess emitter resistance to surface states on the intrinsic base caused by the pre-regrowth processing. This hypothesis has been recently tested by a series of emitter regrowth experiments on large-area dc transistors. New pre-regrowth surface treatments and processing are being developed to improve the emitter resistance numbers. In addition, on-wafer TLM measurements show a base sheet resistance of 1200 Ω/□. We believe that this anomalously high resistance is a result of hydrogen passivation of the carbon-doped base layers and substantially degrades f_{MAX}. We are currently working to address this problem and several other known growth and processing issues in the device technology.

In summary, small-area device results of MBE-regrown emitter DHBT technology is presented for the first time. A 160 GHz f_T and 140 GHz f_{MAX} is exhibited for a $0.7 \times 8\ \mu\mathrm{m}^2$ device with maximum current density of $8 \times 10^5\ \mathrm{A/cm}^2$ and collector breakdown voltage of 6 V. These initial RF results are the fastest known for a regrown-emitter HBT.

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