An InGaAs/InP DHBT With Simultaneous $f_T/f_{\text{max}}$ 404/901 GHz and 4.3 V Breakdown Voltage

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ABSTRACT We report an InP/InGaAs/InP double heterojunction bipolar transistor fabricated in a triple-mesa structure, exhibiting simultaneous 404 GHz $f_T$ and 901 GHz $f_{\text{max}}$. The emitter and base contacts were defined by electron beam lithography with better than 10 nm resolution and smaller than 20 nm alignment error. The base-collector junction has been passivated by depositing a SiNx layer prior to benzocyclobutene planarization, improving the open-base breakdown voltage $BV_{CEO}$ from 3.7 to 4.3 V.

INDEX TERMS HBT, InGaAs/InP DHBT, THz device.

I. INTRODUCTION

The demand for submm-wave radio systems [1], high data rate communication systems [2] and high performance signal processing systems [3], [4] drives the development of high bandwidth transistors. Key to increasing RF performance is scaling [5]: transit delays are reduced by thinning epitaxial base and collector layers. Concurrently, $RC$ charging delays are lowered by lithographically narrowing emitter and base/collector widths while maintaining constant parasitic resistances $R_{ex}$, $R_{bb}$, device current $I_e$ and transconductance $g_m$. Scaling challenges involve achieving low ohmic contact resistivities to emitter and base, fabricating narrow and well aligned emitter and base/collector junctions as well as sustaining high device current densities.

We report a self-aligned triple-mesa InP/InGaAs/InP DHBT with $f_T = 404$ GHz and simultaneous $f_{\text{max}} = 901$ GHz at 180 nm x 2.7 µm emitter area, operating without failure at current and power densities in excess of 23 mA/µm² and 42 mW/µm², respectively. Under different biasing conditions, $f_T = 424$ GHz and simultaneous $f_{\text{max}} = 831$ GHz have been exhibited. Although the $f_{\text{max}}$ obtained here is ≈10 % below previous results [6] due to process variations (emitter end undercut, contact resistivity) and lower than [7], it exceeds that of other reported HBTs, including those of recent publications [8], [9]. The usable range of transistor operation [10] is extended by increasing the breakdown voltage $BV_{CEO} = 4.3$ V by means of passivating the base/collector semiconductor with conformal PECVD SiNx prior to BCB planarization. A device identical in epitaxial structure and similar in fabrication except with BCB junction passivation exhibited $BV_{CEO} = 3.7$ V [6].

II. DESIGN AND FABRICATION

The DHBT wafer has been grown by solid source molecular beam epitaxy on a 4” InP substrate by IQE. The n-In$_{0.53}$Ga$_{0.47}$As emitter cap is highly doped for low emitter resistance $R_{ex}$. The 30 nm thick base is doping-graded from 9–5 × 10$^{19}$ cm$^{-3}$, resulting in 55 mV conduction band slope. The 100 nm thick collector is comprised of a 13.5 nm setback, a 16.5 nm chirped superlattice InGaAs/InAlAs grade and a 67 nm drift collector region (Table 1).

The 500 nm tall composite Mo/W/TiW emitter metal stack is fabricated in a dry etch process [11]. After forming dielectric SiNx sidewalls on the emitter metal, the emitter semiconductor is removed in a selective wet etch. Self-aligned
TABLE 1. Epitaxial structure design.

<table>
<thead>
<tr>
<th>T (nm)</th>
<th>Material</th>
<th>Doping (cm⁻³)</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>In₀.₅₃Ga₀.₄₇As</td>
<td>8 x 10¹³</td>
<td>Emitter Cap</td>
</tr>
<tr>
<td>20</td>
<td>InP</td>
<td>5 x 10¹⁴</td>
<td>Emitter</td>
</tr>
<tr>
<td>15</td>
<td>InP</td>
<td>2 x 10¹⁸</td>
<td>Emitter</td>
</tr>
<tr>
<td>30</td>
<td>In₀.₅₀Ga₀.₅₀As</td>
<td>9 x 10¹⁹</td>
<td>Base</td>
</tr>
<tr>
<td>13.5</td>
<td>In₀.₅₃Ga₀.₄₇As</td>
<td>5 x 10¹⁶</td>
<td>Setback</td>
</tr>
<tr>
<td>16.5</td>
<td>InGaAs/InAlAs</td>
<td>5 x 10¹⁶</td>
<td>B-C Grade</td>
</tr>
<tr>
<td>3</td>
<td>InP</td>
<td>3.6 x 10¹⁸</td>
<td>Pulse Doping</td>
</tr>
<tr>
<td>67</td>
<td>InP</td>
<td>5 x 10¹⁶</td>
<td>Drift Collector</td>
</tr>
<tr>
<td>7.5</td>
<td>InP</td>
<td>2 x 10¹⁸</td>
<td>Sub-Collector</td>
</tr>
<tr>
<td>5</td>
<td>In₀.₅₃Ga₀.₄₇As</td>
<td>4 x 10¹⁹</td>
<td>Sub-Collector</td>
</tr>
<tr>
<td>300</td>
<td>InP</td>
<td>1 x 10¹⁹</td>
<td>Sub-Collector</td>
</tr>
<tr>
<td>5</td>
<td>In₀.₅₃Ga₀.₄₇As</td>
<td></td>
<td>NID Etch Stop</td>
</tr>
<tr>
<td>≈ 625k</td>
<td>Si InP</td>
<td></td>
<td>Substrate</td>
</tr>
</tbody>
</table>

FIGURE 1. Transmission electron micrograph of a fabricated device. Emitter junction width \( w_e = 240 \) nm, single-sided base metal width \( w_{bm} = 220 \) nm, single-sided base mesa undercut \( w_{bmu} = 125 \) nm, and emitter-base contact spacing \( w_{Gap} \approx 12 \) nm.

FIGURE 2. Common emitter characteristics for an HBT with 180 nm × 2.7 μm emitter junction area.

FIGURE 3. Collector-emitter breakdown measurement with floating base \( BV_{CEO} \) for an HBT with 180 nm × 2.7 μm emitter junction area.

FIGURE 4. Gummel characteristics for an HBT with 180 nm × 2.7 μm emitter junction area.

FIGURE 5. Measured RF gains for an HBT with 180 nm × 2.7 μm emitter junction area and 310 nm base-collector mesa width using off-wafer LRRM structures and on-wafer pad open/short de-embedding. Single-pole fit to the measured data yields \( f_\tau \approx 404 \) GHz, \( f_{\text{max}} \approx 901 \) GHz.

Sub-20 nm alignment tolerance between emitter and base has been attained in electron beam lithography. Such alignment tolerance is necessary given that the base metal-semiconductor contacts are only 105 nm wide (Fig. 1).

III. RESULTS

Electrical yield throughout the sample is approximately 80%, exceeding previous experiments by 30%. Extractions from transmission line model measurements show base and collector contact resistivity \( \rho_{\text{base}} \approx 9 \) Ω·μm² and \( \rho_{\text{coll}} \approx 55 \) Ω·μm². The sheet resistance of unpinched and pinched base TLM structures is estimated at 1200 and 810 Ω/□ [12], indicating process damage to the extrinsic base regions. FIB/TEM analysis reveals that the base metallization interdiffuses with \( \approx 6 \) nm of InGaAs (Fig. 1).
A total emitter access resistivity $\rho_{em} \approx 3.3 \, \Omega \cdot \text{mm}^2$ was extracted from RF data. A peak DC current gain $\beta = 25$ was observed on HBTs with emitter area $A_e = 3.7 \cdot 0.24 \, \mu \text{m}^2$, i.e., on the largest emitter width devices on the sample that have the smallest perimeter-to-area ratio. Figs. 2 and 4 show common-emitter and Gummel characteristics for a transistor with $A_e = 2.7 \cdot 0.18 \, \mu \text{m}^2$. The common-emitter breakdown voltage $BV_{CEO} = 4.3 \, \text{V}$ for $I_e = 10 \, \text{kA/cm}^2$ is observed for the same transistor (Fig. 3). We suspect that the conformal SiN$_x$ layer improves surface passivation of the base-collector junction, thereby reducing the surface trap density [13], [14] and enhancing the surface electric field distribution.

RF measurements from 1-67 GHz were carried out using an Agilent E8361A PNA. The reference plane was brought to the probe tips using LRRM calibration on an impedance standard. The device parameters have been de-embedded from measurements of on-wafer open and short pad structures [15]. Fig. 5 shows peak $f_{\text{max}}$ performance at $I_e = 11.3 \, \text{mA}$, $V_{ce} = 1.8 \, \text{V}$, $V_{cb} = 0.89 \, \text{V}$, and $J_e = 23.7 \, \text{mA/\mu m}^2$. The Kirk effect is observed at $J_e = 25 \, \text{mA/\mu m}^2$ when $f_t$ falls to 95% of its peak value (Fig. 6). A small signal equivalent hybrid-$\pi$ circuit has been developed from RF measurements (Fig. 7) exhibiting good agreement between measured and simulated S parameters (Fig. 8).

**IV. CONCLUSION**

InP/InGaAs DHBTs with simultaneous $f_t = 404 \, \text{GHz}$ and $f_{\text{max}} = 901 \, \text{GHz}$ at $v_{ce} = 180 \, \text{nm}$, 310 nm base-collector mesa width and emitter current density $J_e > 23 \, \text{mA/\mu m}^2$ have been demonstrated. Sub-20 nm alignment between emitter and base has been achieved using electron beam lithography. The breakdown voltage $BV_{CEO} = 4.3 \, \text{V}$ has been increased by passivating the base/collector mesa with PECVD SiN$_x$.

High base and collector contact resistivities limit $f_{\text{max}}$ performance. TEM analysis revealed interdiffusion of Pt base metal with InGaAs. Moreover, the extrinsic base semiconductor has been damaged during processing. Future work will pursue reduction in access resistivities while narrowing base contact widths to improve device performance.

**REFERENCES**


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Authors’ photographs and biographies not available at the time of publication.