We have fabricated high-speed InGaP/GaAs HBT’s using a wet-etched self-aligned base metal (SABM) technique to reduce the base resistance ($R_B$). Citric acid based etchant was newly developed for emitter etching process, which is proved to be very controllable and repeatable. The newly developed SABM process can be applied to the emitter width of below 2um and the fabricated device with 2x20um$^2$ emitter has a $f_T$ of 75GHz and $f_{max}$ of 150GHz. This performance is one of the best-reported results among the similar structure HBTs. In this paper, we present the newly developed emitter etching process for SABM and show the fabricated devices performances.
I. INTRODUCTION

Recently, InGaP/GaAs heterojunction bipolar transistors (HBT’s) have been attentioned as a promising alternative of AlGaAs/GaAs HBT’s because of their superior device performances and material properties such as good reliability, low frequency noise, high linearity, near ideal current-voltage(I-V) characteristics and manufacturability[1]-[3]. The manufacturability is enhanced by the selective etching nature of InGaP/GaAs epi-layer[4]-[5] and could be the most important reason that InGaP/GaAs HBT’s could replace AlGaAs/GaAs HBT’s. In this paper, we present the Postech’s SABM process for InGaP/GaAs HBT fabrication, which can effectively reduce the extrinsic base resistance to deliver a high speed. To take advantage of selective etching nature, the emitter etching for SABM is performed using the wet-etching process. The employed wet etching process should be controllable, repeatable and stable. But commonly used H2SO4 or H3PO4 based etchant could not satisfy these required conditions and we have developed a new etching solution based on citric acid/H2O2 composition. The composition of citric acid/H2O2 and etching temperature were experimentally optimized. The fabricated HBT’s(emitter size 2x20um²) using the wet-etched SABM process achieved a $f_T$ of 75GHz and $f_{max}$ of 150GHz. The yield, even under the university fabrication environment, was over 90%. This result indicates that the SABM process using the citric acid is well suited for high speed InGaP/GaAs HBT manufacturing.
II. DESIGN AND FABICATION

1. Design of High speed InGaP/GaAs HBT

The epitaxial structure shown in Table 1 was grown by metal organic vapor deposition (MOCVD). To obtain the sufficient current gain and high frequency performance, the thickness of active emitter InGaP layer is optimized at 400Å and doped with Si(n=3x10^{17}cm^{-3}). Indium (In) mole fraction of InGaP layer is selected as 0.49 to make ordered heterostructure with base layer. The 750 Å base layer is doped with carbon (p=4x10^{19}cm^{-3}), so high-speed electron transit time and low base sheet resistance can be obtained simultaneously. The collector thickness is selected to 7000 Å for high maximum oscillation frequency and BV_{CEO}. The collector is doped at 3x10^{17} to increase the kirk-current level.

The figure 1 shows the designed device layout. Emitter size 2x20um^2 is selected for sufficient power and high frequency performance. To reduce the extrinsic base resistance which critically affects the maximum oscillation frequency, SABM(self-aligned base metal) technique is used. To reduce the parasitic base/collector junction capacitance, the base metal width is tightly controlled to 1um. The used emitter widening metal makes the post-air bridge process easier and reduces the parasitic capacitance. Non-alloyed Ti/Pt/Au emitter and Pt/Ti/Pt/Au base metal systems are used and alloyed Au/Ge/Ni/Au metal system is used for collector contact.

Table 1

Fig.1
2. Fabrication of High speed InGaP/GaAs HBT

After non-alloyed Ti/Pt/Au emitter metal is deposited, InGaAs and GaAs emitter cap layers are etched using the citric acid based etchant (citric acid: H2O2=15:1) at 28 °C. The emitter undercut process relies on the highly selective etches in InGaP/GaAs system: InGaAs/GaAs emitter etching using citric acid naturally stops at a InGaP active emitter layer and it is possible to form a wanted emitter lateral undercut depth by adjusting the etching time. The optimized citric acid is proved that it is more controllable, repeatable and stable than the H2SO4 or H3PO4 based etchant. Furthermore, lateral etching problem between the emitter metal and InGaAs layer, which is happened when H2SO4 or H3PO4 base etchant is used, is completely disappear.

The InGaP active emitter layer is etched using the HCl based etchant (HCl: H2O=3:1). The HCl based etchant etches the InGaP emitter layer only to the vertical direction not to the lateral direction and stops at the GaAs base layer.

Fig.1 shows the cross sections of 2um size stripe pattern and real finger of HBTs after base metal evaporation. According to the InGaAs/GaAs etching time interval of 20 seconds, the difference of lateral etching depth 2000Å is formed, which shows that lateral etching depth control according to the etching time is possible.

Fig. 2

After self-aligned base metal Pt/Ti/Pt/Au is deposited, emitter widening metal
process is followed. Next, base-collector and sub-collector layer is etched using H2SO₄ based etchant and Au/Ge/Ni/Au collector metal is deposited. The annealing process is performed at the 425°C furnace. Table 2 shows the contact metal resistance after annealing process, which is measured by TLM method. The specific contact resistivity of base and collector shows 3.9x10⁻⁷ Ω-cm² and 1x10⁻⁶ Ω-cm², respectively. These low specific contact resistivities show that the annealing condition is well optimized.

Table 2

After annealing process, devices are passivated using Si₃N₄ and then emitter and base metals are connected to pad metals using Au-air bridge. Photolithography was performed using contact aligner, and lift-off technique is used for each metalization process.

III. DEVICE PERFORMANCES AND DISCUSSIONS

Fig. 3 shows the measured DC characteristics. As shown in Gummel-plot, the maximum current gain is 34 at a collector current density 90KA/cm², and η₈ and η₉ are 1.3 and 1.0 respectively. The collector current ideality factor η₉=1.0 can be interpreted as a high emitter injection efficiency. This is resulted from the ordered or partially disordered InGaP emitter layer, which has a small conduction band discontinuity (ΔEc≈0.13eV) and large valence band discontinuity (ΔEv≈0.31eV). The low offset voltage of DC-IV curve also shows such a band-gap alignment. Knee-voltage was 0.8V at the collector current density of 100kA/cm², and common emitter breakdown voltage
(BV_{ceo}) is 19.9V.

For microwave performances, s-parameters are measured on wafer using HP 8510B parameter analyzer. The measured frequency range is from 0.5GHz to 45GHz and the U, MSG/MAG and H_{21} are extracted from the data. Fig. 4 shows the results at a bias point of Vce=1.5V and Ic=25mA. H_{21} curve has a slope of about −20dB/decade and the extrapolated $f_T$ of 75GHz. The unilateral power gain, U has the extrapolated $f_{max}$ of 150GHz. We extract a large signal model of the fabricated HBT’s. The model shows that this high $f_{max}=\sqrt{f_T/(8\pi R_B C_{bc})}$ is resulted from a small $R_B$ and the small $R_B$ is partially due to the well defined SABM using the citric acid based etchant. Fig 5 shows the output power at class A operation. Maximum PAE (power added efficiency) is 53.6% and $P_{1dB}$ (1dB gain compression point) is 15dBm from a 2x20um^{2} single emitter finger HBT.

**IV. CONCLUSIONS**

High-speed InGaP/GaAs HBT’s were fabricated. For the SABM technique, we have developed citric acid based etchant and establish the wet-etching condition. From the SEM picture and device performance, the newly developed SABM technique was
proved to be very controllable, repeatable and stable. The yield was over 90%, and the fabricated HBT’s with 2x20um\(^2\) emitter finger achieved a \(f_T\) of 75GHz and \(f_{\text{max}}\) of 150GHz. This performance is one of the best-reported results among the similar structure HBT’s and shows that the newly developed SABM process is well suited for high speed InGaP/GaAs HBT manufacturing.

ACKNOWLEDGEMENT

This work was supported in part by Ministry of Commerce, Industry and Energy, Ministry of Education through BK21 program, and ADD in Korea. The author would like to thank president H. S. Park of EPIPLUS Ltd. for his devoted assistance

REFERENCES


**TABLE CAPTIONS**

Table 1: Epitaxial structure of InGaP/GaAs HBT’s

Table 2: Resistances of contact metals after 425°C, 1 minute 10 seconds annealing.

**FIGURE CAPTIONS**

Fig. 1. Device layout of high-speed InGaP,GaAs HBT

Fig. 2. The SEM cross-sectional picture of 2um stripe and real finger

Fig. 3. DC Characteristics of a InGaP/GaAs HBT (2x20um²)

Fig. 4. The measured U, MSG/MAG and H21 of a InGaP/GaAs HBT (2x20cm²)

Fig. 5. The output power of a InGaP/GaAs HBT (2x20um²)
<table>
<thead>
<tr>
<th>Composition</th>
<th>Thickness(um)</th>
<th>Conc.</th>
<th>Dopant</th>
<th>Type</th>
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<tr>
<td>In$<em>{0.4}$Ga$</em>{0.6}$As</td>
<td>0.02</td>
<td>$&gt;1\times10^{19}$</td>
<td>Te</td>
<td>N</td>
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<tr>
<td>In$<em>{y}$Ga$</em>{1-y}$As (y=0.6 $\rightarrow$ 0)</td>
<td>0.02</td>
<td>$&gt;1\times10^{19}$</td>
<td>Te</td>
<td>N</td>
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<td>GaAs</td>
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<td>$5\times10^{18}$</td>
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<td>N</td>
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<td>P</td>
</tr>
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<td>N</td>
</tr>
<tr>
<td>GaAs</td>
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<td>$5\times10^{18}$</td>
<td>Si</td>
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</tbody>
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Semi-insulating GaAs substrate

TABLE 1
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<table>
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<tr>
<th></th>
<th>Emitter</th>
<th>Base</th>
<th>Collector</th>
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<tr>
<td><strong>Doping Concentration ([cm^{-3}])</strong></td>
<td>1x10(^{19})</td>
<td>4x10(^{19})</td>
<td>5x10(^{18})</td>
</tr>
<tr>
<td><strong>Metal System</strong></td>
<td>Ti/Pt/Au</td>
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<tr>
<td><strong>Rsc[(\Omega-Cm^2)]</strong></td>
<td>1.7x10(^{-7})</td>
<td>3.9x10(^{-7})</td>
<td>1x10(^{-6})</td>
</tr>
</tbody>
</table>

**TABLE 2**

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<table>
<thead>
<tr>
<th>Time</th>
<th>Minor(stripe)</th>
<th>Major(stripe)</th>
<th>Major(finger)</th>
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<tr>
<td>1min 40sec</td>
<td><img src="image1" alt="Image" /></td>
<td><img src="image2" alt="Image" /></td>
<td><img src="image3" alt="Image" /></td>
</tr>
<tr>
<td>2min</td>
<td><img src="image4" alt="Image" /></td>
<td><img src="image5" alt="Image" /></td>
<td><img src="image6" alt="Image" /></td>
</tr>
</tbody>
</table>

FIGURE 2
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$\eta_c = 1.0$
$\eta_b = 1.3$
$I_b = 10\text{nA}$
$\beta_{max} = 34 \quad @J_c = 90\text{kA/cm}^2$

$V_{off} = 0.12\text{[V]}$
$V_{knee} = 0.8\text{[V]} \quad @J_c = 100\text{kA/cm}^2$
$BV_{CEO} = 19.9\text{[V]}$
FIGURE 4
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FIGURE 5
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