

# **Fabrication of High-Speed InGaP/GaAs HBT's Using a Wet-etched SABM Technique**

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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 2 $\mu$ m and the fabricated device with 2x20 $\mu$ m<sup>2</sup> 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.

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## 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 H<sub>2</sub>SO<sub>4</sub> or H<sub>3</sub>PO<sub>4</sub> based etchant could not satisfy these required conditions and we have developed a new etching solution based on citric acid/H<sub>2</sub>O<sub>2</sub> composition. The composition of citric acid/H<sub>2</sub>O<sub>2</sub> and etching temperature were experimentally optimized. The fabricated HBT's(emitter size 2x20um<sup>2</sup>) 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 Hgh 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( $n=3 \times 10^{17} \text{cm}^{-3}$ ). 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 ( $p=4 \times 10^{19} \text{cm}^{-3}$ ), 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  $BV_{CE0}$ . The collector is doped at  $3 \times 10^{17}$  to increase the kirk-current level.

The figure 1 shows the designed device layout. Emitter size  $2 \times 20 \mu\text{m}^2$  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 1 $\mu\text{m}$ . 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: H<sub>2</sub>O<sub>2</sub>=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 H<sub>2</sub>SO<sub>4</sub> or H<sub>3</sub>PO<sub>4</sub> based etchant. Furthermore, lateral etching problem between the emitter metal and InGaAs layer, which is happened when H<sub>2</sub>SO<sub>4</sub> or H<sub>3</sub>PO<sub>4</sub> base etchant is used, is completely disappear.

The InGaP active emitter layer is etched using the HCl based etchant (HCl: H<sub>2</sub>O=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 2μm 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 H<sub>2</sub>SO<sub>4</sub> 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  $3.9 \times 10^{-7} \Omega\text{-cm}^2$  and  $1 \times 10^{-6} \Omega\text{-cm}^2$ , respectively. These low specific contact resistivities show that the annealing condition is well optimized.

**Table. 2**

After annealing process, devices are passivated using Si<sub>3</sub>N<sub>4</sub> 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  $90 \text{KA/cm}^2$ , and  $\eta_B$  and  $\eta_C$  are 1.3 and 1.0 respectively. The collector current ideality factor  $\eta_C=1.0$  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 ( $\Delta E_c \approx 0.13 \text{eV}$ ) and large valence band discontinuity ( $\Delta E_v \approx 0.31 \text{eV}$ ). 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  $100 \text{kA/cm}^2$ , and common emitter breakdown voltage

( $BV_{ceo}$ ) is 19.9V.

**Fig. 3**

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  $V_{ce}=1.5V$  and  $I_c=25mA$ .  $H_{21}$  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  $2 \times 20 \mu m^2$  single emitter finger HBT.

**Fig. 4**

**Fig. 5**

## 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  $2 \times 20 \mu\text{m}^2$  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

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## 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 2 $\mu$ m stripe and real finger

Fig. 3. DC Characteristics of a InGaP/GaAs HBT (2x20 $\mu$ m<sup>2</sup>)

Fig. 4. The measured  $U$ , MSG/MAG and  $H_{21}$  of a InGaP/GaAs HBT (2x20 $\mu$ m<sup>2</sup>)

Fig. 5. The output power of a InGaP/GaAs HBT (2x20 $\mu$ m<sup>2</sup>)



Composition	Thickness(um)	Conc.	Dopant	Type
In <sub>0.6</sub> Ga <sub>0.4</sub> As	0.02	>1x10 <sup>19</sup>	Te	N
In <sub>y</sub> Ga <sub>1-y</sub> As (y=0.6→0)	0.02	>1x10 <sup>19</sup>	Te	N
GaAs	0.1	5x10 <sup>18</sup>	Si	N
GaAs	0.05	5x10 <sup>17</sup>	Si	N
In <sub>0.49</sub> Ga <sub>0.51</sub> P	0.04	3x10 <sup>17</sup>	Si	N
GaAs	0.075	4x10 <sup>19</sup>	C	P
GaAs	0.7	3x10 <sup>16</sup>	Si	N
GaAs	0.6	5x10 <sup>18</sup>	Si	N
Semi-insulating GaAs substrate				

TABLE 1  
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	<b>Emitter</b>	<b>Base</b>	<b>Collector</b>
<b>Doping Concentration</b> [cm <sup>-3</sup> ]	1x10 <sup>19</sup>	4x10 <sup>19</sup>	5x10 <sup>18</sup>
<b>Metal System</b>	Ti/Pt/Au	Pt/Ti/Pt/Au	Au/Ge/Ni/Au
<b>Rsc[Ω-Cm<sup>2</sup>]</b>	1.7x10 <sup>-7</sup>	3.9x10 <sup>-7</sup>	1x10 <sup>-6</sup>

TABLE 2  
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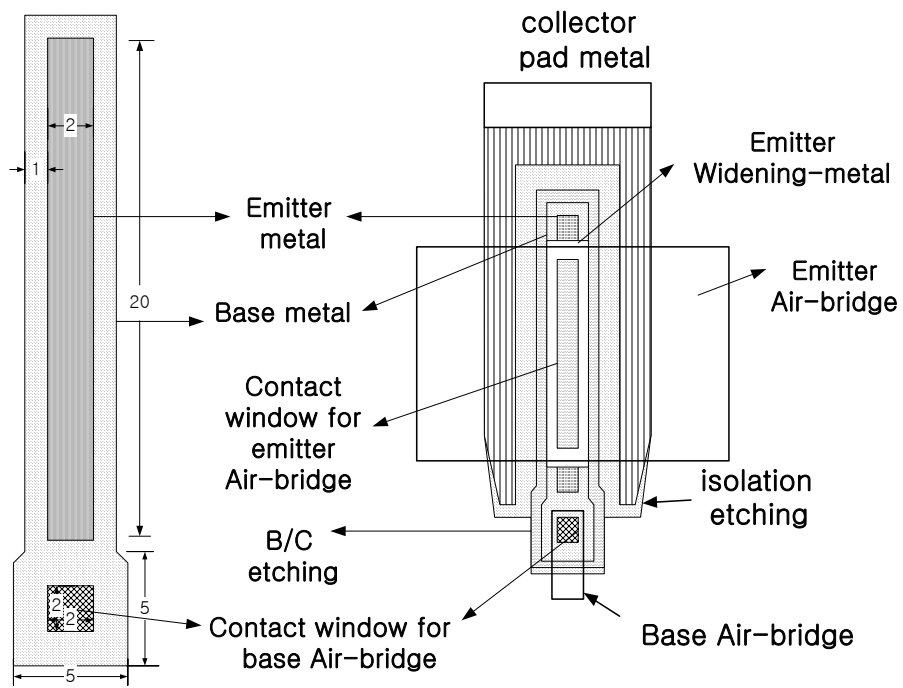


FIGURE 1  
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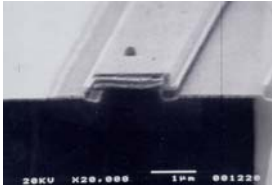


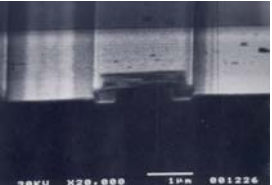
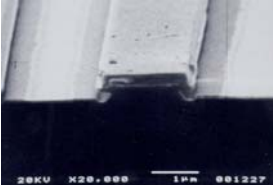
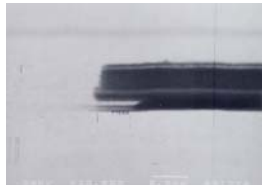
	Minor(stripe)	Major(stripe)	Major(finger)
<b>1min 40sec</b>			
<b>2min</b>			

FIGURE 2  
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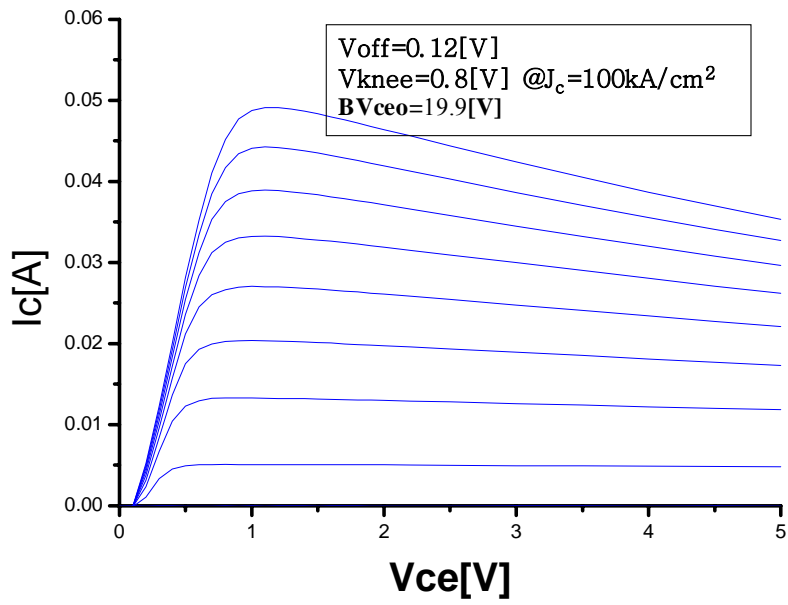
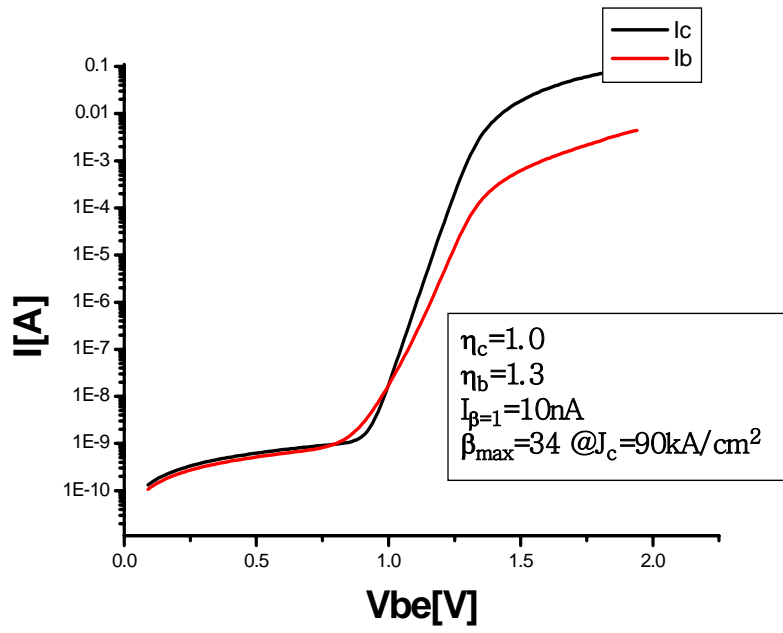


FIGURE 3  
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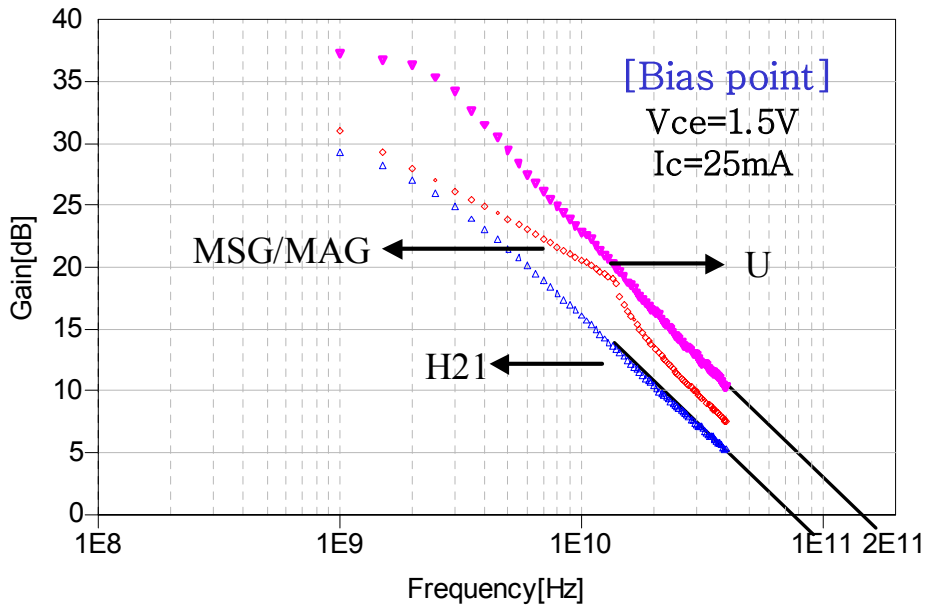


FIGURE 4  
 Jongchan Kang  
 JKPS

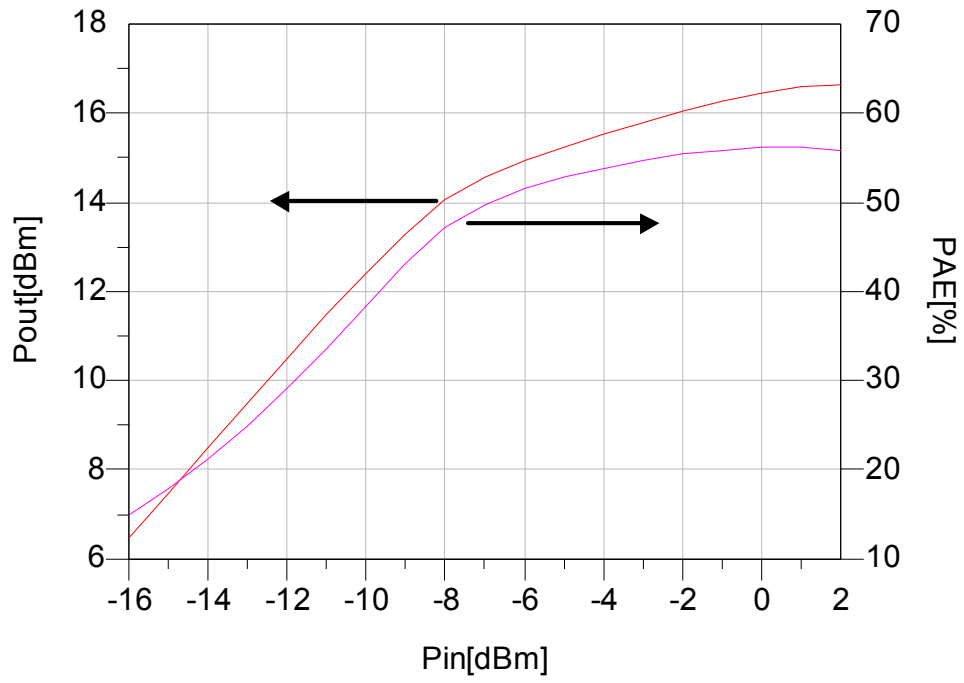


FIGURE 5  
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