



<b>Title</b>	<b>Integration of GaInP/GaAs heterojunction bipolar transistors and high electron mobility transistors</b>
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# Integration of GaInP/GaAs Heterojunction Bipolar Transistors and High Electron Mobility Transistors

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**Abstract**—Integration of carbon-doped GaInP/GaAs heterojunction bipolar transistors (HBT's) and high electron mobility transistors (HEMT's) is demonstrated by growing an HBT on the top of a HEMT. A current gain of 60, a cutoff frequency of 59 GHz and a maximum oscillation frequency of 68 GHz were obtained for a  $5 \times 15 \mu\text{m}^2$  self-aligned HBT. The HEMT with a gate length of  $1.5 \mu\text{m}$  has a transconductance of 210 mS/mm, a cutoff frequency of 9 GHz and a maximum oscillation frequency of 22 GHz. It is shown that the GaInP/GaAs HBT on the HEMT is a simple Bi-FET technology suitable for microwave and mixed signal applications.

## I. INTRODUCTION

THE integration of a GaAs heterojunction bipolar transistor (HBT) and a field effect transistor (FET) is very attractive for making digital, analog, mixed signal and microwave circuits. Several successful technologies of the integration of AlGaAs/GaAs HBT's and FET's have been reported [1]–[5]. For example, an FET is fabricated on an HBT emitter using the emitter cap layer as the channel [1], [2]. The layer structure of this technology is the same as that of a single HBT without any additional epitaxial layers. However, the parasitic effects of the base layer under the FET degrade the FET performance. The integration of the high electron mobility transistor (HEMT) and HBT has been obtained with the two growth steps by selective MBE [3], [4]. Because the HBT and the HEMT are grown separately and in different locations, the device performance can be individually optimized. It has also been shown that an HBT may be grown on the top of a HEMT with a single growth step [5].

We have found that the lattice matched GaInP/GaAs material system offers a favorable band lineup [6], highly etching selectivity and few DX centers in GaInP layer [7], which are very suitable for making HBT's [6], [8] and HEMT's [9], [10]. In addition, carbon does not form p-type dopant in GaInP layer making the HBT performance more reliable. In this paper, we demonstrate the integration of GaInP/GaAs HBT's and HEMT's grown by MOCVD. It is shown that both HBT and HEMT have good performance.

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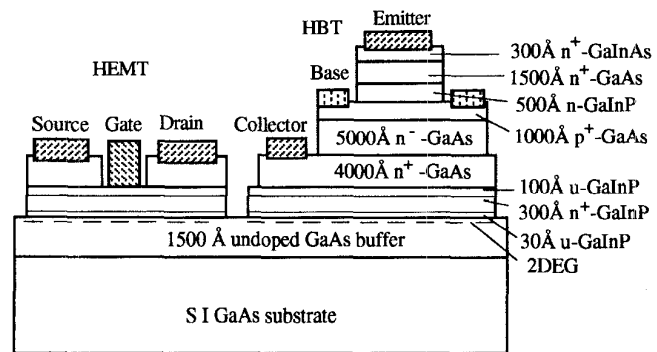
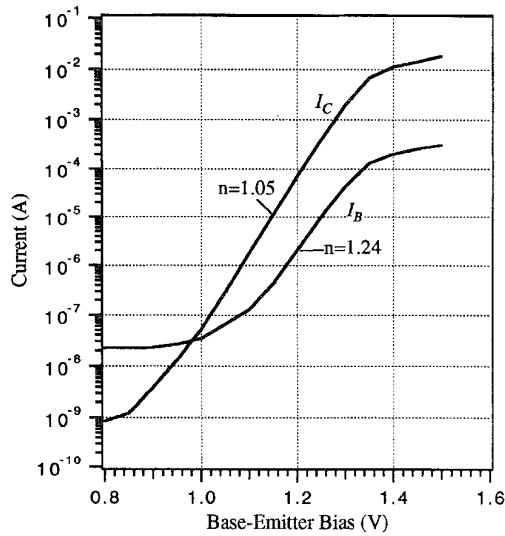


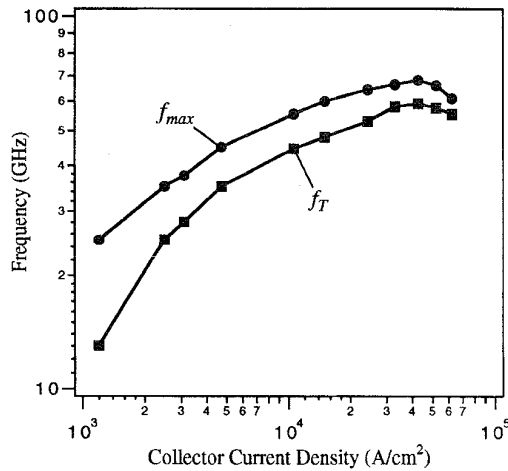
Fig. 1. The cross section with layer structure of the integrated GaInP/GaAs HBT and HEMT.

## II. DEVICE FABRICATION

The GaInP/GaAs HBT and HEMT structures were grown by MOCVD on a semi-insulating GaAs substrate. Epitaxial growth conditions were similar to those reported in [11]. Carbon and silicon were used as p- and n-type dopants. The device cross section with the layer structure is shown in Fig. 1. A thin buffer layer of 1500 Å was used so that the total thickness of the epitaxial layer was similar to that of a normal HBT. Both HBT and HEMT devices were fabricated using the mesa structure. Standard photolithographic and chemical wet selective etching techniques were used in the device processing. The GaInP layer was etched using a solution of dilute HCl and the GaInAs and GaAs layers were etched with  $\text{H}_3\text{PO}_4 : \text{H}_2\text{O}_2 : \text{H}_2\text{O}$ . The processing began with the formation of the emitter mesa by selectively etching the InGaAs and GaAs cap layer and GaInP emitter layers. The self-aligned base contact metal of AuZn/Au was then deposited using the emitter mesa photoresist as a mask. After the base mesa was defined, the base metal, the base layer and the collector layer were etched, respectively. Then, the HBT collector mesa and the HEMT mesa were defined and formed by etching the n<sup>+</sup>-GaAs subcollector layer and the HEMT structure layer to provide device isolation. The n-type ohmic contact metal of AuGeNi/Au for the HBT emitter and collector as well as the HEMT drain and source were deposited and liftoff followed by alloying at 400°C for 10 s. The gate was defined and recessed by etching the n<sup>+</sup>-GaAs layer. Al was deposited as the gate metal. Finally, polyimide was used as an isolation layer and via hole was opened followed by the deposition of Au for the electrode pads. Due to the high etching selectivity, the emitter mesa and gate recess were



(a)



(b)

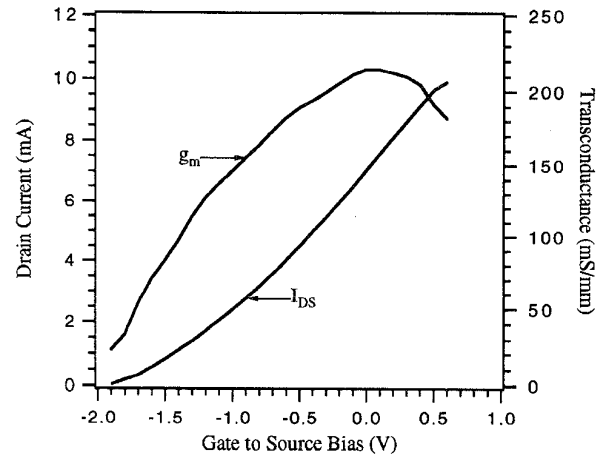
Fig. 2. (a) Gummel plot and (b) cutoff frequency and maximum oscillation frequency as a function of collector current density at  $V_{ce}$  of 1.6 V for a GaInP/GaAs HBT with an emitter area of  $5 \times 15 \mu\text{m}^2$ .

easily processed without suffering overetch. The HBT has an emitter area of  $5 \times 15 \mu\text{m}^2$  and the HEMT has a gate length and width of  $1.5 \times 25 \mu\text{m}^2$ .

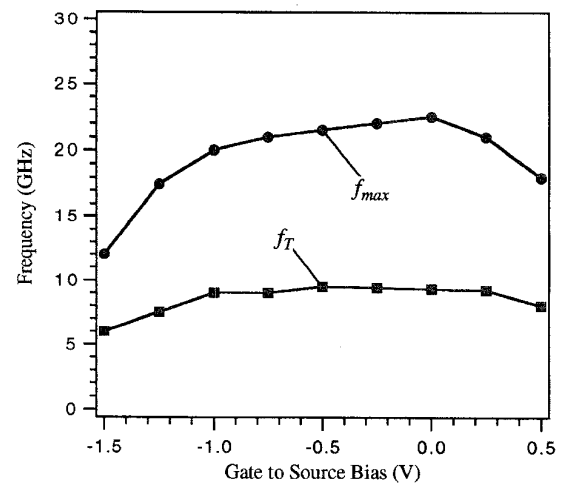
### III. RESULTS AND DISCUSSION

DC characteristics were measured with an HP4145B semiconductor parameter analyzer. Microwave measurements were made with an HP8510B network analyzer and cascade microwave probes in the frequency range from 100 MHz–20 GHz. The cutoff frequency ( $f_T$ ) and the maximum oscillation frequency ( $f_{max}$ ) were extrapolated from current gain and unilateral power gain by using a  $-20$  dB/decade slope.

The typical Gummel plot and RF characteristics for a  $5 \times 15 \mu\text{m}^2$  HBT are shown in Fig. 2. A gain of more than 60



(a)



(b)

Fig. 3. (a) Transfer characteristics and transconductance as a function of gate to source bias. (b) Cutoff frequency and maximum oscillation frequency versus the gate to source bias for a GaInP/GaAs HEMT at a drain source bias of 3.0 V.

is obtained at a high collector current density. The breakdown voltage  $BV_{ceo}$  is 6 V (not shown in the figure). As shown in Fig. 2(a), ideality factors for the collector and base currents are 1.05 and 1.24, respectively. A large base leakage current in the low current regime is shown in the Gummel plot. This is because the extrinsic base surface was not passivated by a GaInP layer. A peak  $f_T$  of 59 GHz and a peak  $f_{max}$  of 68 GHz are obtained at collector current density of  $4.2 \times 10^4 \text{ A/cm}^2$ .

Fig. 3 shows transfer characteristics and RF performance for a  $1.5 \mu\text{m}$  HEMT. A transconductance of 210 mS/mm and a maximum channel current of 400 mA/mm are obtained. The pinch-off voltage is  $-1.9$  V. The peak  $f_T$  and peak  $f_{max}$  are 9 and 22 GHz, respectively. It can be seen that the RF performance does not change much in the bias range between  $-1.0$ – $0.2$  V. Although a thin buffer layer is used to minimize the total epitaxial layer thickness, the HEMT DC and RF performance of our devices is comparable to that of the

GaInP/GaAs HEMT with similar gate length but thicker buffer layers [9], [10]. The HEMT performance can be improved by reducing the gate length.

#### IV. CONCLUSION

The GaInP/GaAs HBT grown on the top of the HEMT provides an alternative and simple technology of the HBT-HEMT integration. GaInP/GaAs material system is easy to process. It is particularly attractive because of the freedom of choices of growing any kind of HEMT structure under the HBT. It is demonstrated that with a reduced buffer layer for the HEMT, the total epitaxial layer thickness is similar to that of a normal HBT, while the performance of the HEMT is comparable to that of a normal HEMT. The performance of both GaInP/GaAs HBT and HEMT is attractive for microwave and mixed signal applications.

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