Development of Manufacturable Commercial 6-inch InP HBT

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Fig. 1. (a) SEM image of fabricated InP HBT of size 0.5x4μm2 (b) cross-sectional SEM image of emitter mesa with self-aligned base metal (c) base metal air-bridge design

## **Abstract**

**A foundry-ready service in 6-inch InP HBT technology has been developed for mass production in this work. Good uniformity of device performance over 6-inch wafer is obtained. Delicate EPI design with trade-off between cut-off frequency (Ft) and breakdown voltage (BVceo) are devoted to satisfy varieties of demands. We achieved Ft of 175GHz with BVceo of 6.6V and Ft of 100GHz with BVceo of 16V to fulfill the requirements in optical communication and RF power amplifier applications. An advanced sub-micron process is introduced to enhance RF performance for further demands in higher frequency region.**

## Introduction

InP-based Heterojunction Bipolar Transistors (HBT) have long been regarded as a technology of choice for optical communication systems and high frequency applications toward the terahertz domain, due to its superior high frequency response. With the soaring demands of 5G, its high frequency response over GaAs and SiGe makes it a high potential approach. However, the InP activities in the market have been stagnant for few years. Access of InP-based process technology has been very limited to exclusive R&D institutions. In addition to the high price of substrate, lack of massive production foundry service and relevant supply chains are the major concerns. Some foundries have been devoted to this field for a long time but all the achievements were obtained on 4-inch InP substrate [1-3]. Recently availability of high-quality 6-inch InP substrate together with the supports of pure-play epitaxy vendors have enabled development of InP device technology for massive commercial manufacturers. WIN Semiconductors, the global leading compound semiconductor foundry, is in duty bound to this field. In this work, process development of 6-inch InP HBT and corresponding EPI solutions will be reported.

## EPI DESIGN AND DEVICE FABRICATION

The InP Double HBT (DHBT) epi wafers were grown by Molecular Beam Epitaxy (MBE) and the structures consist of, from top to bottom, a highly-doped n-InGaAs emitter-cap layer, an n-InP emitter layer, a carbon-doped InGaAs base layer, an n-InP collector structure with an n-InGaAs/InAsGaAs grading transition layer between base and collector to eliminate electron blocking and an n-InP sub-collector layer. To provide optimum performance for specific applications, epi structures were designed to compromise the tradeoffs between cut-off frequency (Ft) and the collector-emitter breakdown (BVceo). Optical communication and digital circuits pursue higher operation frequency. In contrast, breakdown voltage is the dominating factor in RF power amplifiers (PA). Collector thickness is of great influence on BVceo [3]. Given that, two structures (EPI-1 and EPI-2) with different collector thickness were designed for these two purposes. Between them, EPI-1 has similar epi structure with EPI-2 but with thinner collector thickness.

Leveraging from our production-ready InGaP/GaAs 6-inch GaAs HBT line, we have developed InP HBT baseline process taking complete advantages of the mature process modules, including photolithography, thin film deposition, mesa etching, and etc. To pursue better performance in extremely high frequency operation region, advanced sub-micron process was introduced into active fabrication. The key features include self-aligned emitter metal/emitter mesa, self-aligned base metal, and air-bridge base metal design. A combination of selective chemical wet etching and dry etching was implemented to define emitter mesa dimension. With emitter mesa undercut inside emitter metal, self-aligned base metal can be achieved. Furthermore, exclusively chemical wet etching was employed to form base air-bridge between base post and active area which played a key role to drastically reduce effective base mesa. The processing of HBT was completed by collector metal deposition and mesa fabrication. Devices with emitter widths ranging from 0.5 to 2μm were fabricated. Top-view SEM image of fabricated InP HBT of size 0.5x4μm2 is displayed in Figure 1(a). Figure 1(b) shows the cross sectional SEM image of emitter mesa where self-aligned base metal forms with 0.15μm emitter to base metal spacing. Decent base metal air-bridge design can be achieved, and the SEM image is shown in Figure 1(c).

For the following metal interconnection processes, metal posts were introduced on base and collector metals to make their heights aligned with emitter metal. The devices were then planarized and encapsulated with benzocyclobutene (BCB). An etch-back process is employed to ensure emitter, base and collector posts well exposed for the first-level metal to access those contacts. BCB is also used as low-loss dielectric between first and second interconnection metals. TaN thin film resistor and SiN MIM capacitors are used as passive components for monolithic integration. For the back-end-of-line (BEOL) process, Cu pillar bump is adopted for high power handling PA requirements and the additional third connecting metal is provided for high frequency circuits demands acting as thin film micro strip line. Robust and reliable interlayer connections are achieved through etched BCB via opening with plating metal, which provide good process controllability. Figure 2 exhibits the SEM images of a 0.5x4μm2 InP HBT (a) prior to BCB capsulation and (b) after etch-back process. The cross-sectional SEM image of BEOL is displayed in Figure 2(c).

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Fig. 4. 6-inch wafer map of normalized current gain for an InP HBT with size of 2x10μm2

## DEVICE PERFORMANCE

Gummel plot characteristics of 2x4μm2 InP HBTs with EPI-1 are shown in Fig. 3. The collector and base ideality factors *η*c and *η*b are 1.07 and 1.65. For the dc current gain, β, is 30 at *J*C= 100kA/cm2, which are relatively reasonable value. Generally, high β value in InP HBT is difficult to obtain since the base layer should be carefully designed. Considering the better RF performance, a compromise in β is unavoidable.

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Fig. 3. Gummel plot characteristics of 2x4μm2 InP HBTs with EPI-1

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Fig. 2. SEM images of a 0.5x4μm2 InP HBT (a) prior to BCB capsulation and (b) after etch-back process. (c) cross-sectional SEM image of BEOL

Yield is always the first priority for mass production. Figure 4 exhibits a 6-inch wafer map of normalized current gain distribution for an InP HBT with size of 2x10μm2. The uniformity in current gain over 6-inch wafer is decent and comparable to that in WIN’s 6-inch GaAs products.

Typical common-emitter I-V characteristics of 2x4μm2 InP HBTs are shown in Fig. 5. For EPI-1, the VCE offset voltage of 0.15V and the low knee voltage of 0.7V at JC=300kA/cm2 indicates that the current blocking effect in the base-collector heterojunction should be negligible. Slightly higher VCE offset voltage and on-resistance in EPI-2 can be attributed to thicker collector. BVceo for EPI-1 and EPI-2 are 6.6 and 16V at JC=1kA/cm2, respectively. On-wafer small-signal RF measurements were performed with vector network analyzer in the frequency range from 1 to 50GHz. Figure 6 shows Ft versus Jc at VCE=2V of 2x4μm2 InP HBT with two EPIs. Peak Ft of 175GHz at JC=300kA/cm2 was achieved in EPI-1 and EPI-2 reached its peak Ft of 100GHz at JC=100kA/cm2. Using conventional Ft · BVceo as the figure of merit to evaluate EPI-1 and EPI-2, the performances are comparable to other works [3].

To fulfill further performance requirements in higher frequency, advanced sub-micron process was applied in EPI-1. Figure 7 shows maximum available gain (MAG) versus frequency of a 2x4μm2 EPI-1 InP HBT with advanced sub-micron process. The devices were biased at VCE=2V with JC=300kA/cm2. With self-aligned base metal, MAG can increase 2dB. Another 2dB improvement in MAG can be obtained in the case with additional air-bridge base metal. The enhanced MAG performance can be attributed to the shrinkage of effective base mesa area. One thing worthy to mention is no sacrifice was observed in MAG rolled-off frequency.

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Fig. 7. MAG versus frequency of a 2x4μm2 EPI-1 InP HBT with advanced sub-micron process

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Fig. 5. Typical common-emitter I-V characteristics of 2x4μm2 InP HBTs with EPI-1 and EPI-2

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Fig. 6. Ft versus Jc at VCE=2V of 2x4μm2 InP HBT with EPI-1 and EPI-2

## Conclusions

In summary, we have developed a manufacturable 6-inch InP HBT technology for commercial foundry service. Good uniformity of device performance over 6-inch wafer is obtained. Two EPI structures with trade-off between Ft and BVceo are available in this technology. Ft of 175GHz with BVceo of 6.6V in EPI-1 can meet demands of optical communication and digital circuits. EPI-2 has achieved Ft of 100GHz with BVceo of 16V, which is of great potential for RF PA applications. Enhanced RF performance using advanced sub-micron process can satisfy applications with further requirements in higher frequency.

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Acronyms

HBT: Heterojunction Bipolar Transistor

PA: Power Amplifier

BCB: Benzocyclobutene

BEOL: Back-End-of-Line

MAG: Maximum Available Gain