

# High Efficiency and High Ruggedness InGaP/GaAs HBT EPI Design

Rei-Bin Chiou, Ta-Chuan Kuo, Cheng-Kuo Lin, Shu-Hsiao Tsai, Shin-Yi Ho, Tung-Yao Chou, Dennis Williams, and Yu-Chi Wang

WIN Semiconductors Corp. Kuei Shan Hsiang, Tao Yuan Shien, 333, Taiwan

E-mail: [reibinc@winfoundry.com](mailto:reibinc@winfoundry.com), [tachuank@winfoundry.com](mailto:tachuank@winfoundry.com)

**Keywords:** Heterojunction bipolar transistor (HBT), epitaxial, collector, capacitance, InGaP, High Efficiency, Ruggedness

## Abstract

InGaP/GaAs HBT has been widely used in GSM/WCDMA/LTE power amplifier (PA) design because of its high efficiency. On the other hand, another important characteristic for PA is the superior HBT ruggedness, which can guarantee the same performance after the stress of high voltage standing wave ratio (VSWR) mismatch. However, there is a well known trade-off between the efficiency and ruggedness.

In this work, we provide a newly developed Technology Computer Aided Design (TCAD) simulation technique for InGaP/GaAs HBT to overcome the above predicament. With the high precision TCAD simulation, we can efficiently study the collector structures without spending large manufacturing time and without consuming additional fabrication resource. Thus we can successfully achieve a good time-to-market solution. In this paper, we present an outstanding HBT technology which can deliver remarkable PAE as 74.6% at saturated power and can also pass the stringent ruggedness test under 5V~10.5V  $V_{CE}$  and 10:1 VSWR.

## INTRODUCTION

The InGaP/GaAs HBT power amplifier (PA) device has been widely applied in the mobile handset equipments for GSM/WCDMA/LTE communication networks. The efficiency and ruggedness are both the most important characteristics to evaluate PA performance. The higher efficiency could extend battery's life. On the other hand, the higher ruggedness means that the PA could survive with high VSWR conditions in stringent environment. In previous study [1]~[3], the methodologies of improving ruggedness have been widely discussed. The authors adopt step-doped collector structure, which is one of the most effective way to improve on-state breakdown voltage. Once the breakdown voltage is improved, the ruggedness is also boosted. However, the improved ruggedness is proved to be accompanied with the suffered power-add-efficiency (PAE). The mechanism is similar to the well-known trade-off between cut-off frequency and breakdown voltage. The step-doped contains a lightly doped first collector, and the highly doped second collector. The role of the first collector is to sustain the off-state breakdown voltage, but it will causes higher on-resistance and leads to worse RF performance and PAE. Reference paper [4] shows the positive correlation

between Kirk effect and PAE. In this paper, we utilize TCAD simulation to study the possible step-doped collector profile which can improve Kirk effect, hence improve PAE. After more than 30 different structure trials, we successfully demonstrate the optimized collector epitaxial structures through complete electrical verification by DC, RF, 1-tone load-pull, and ruggedness performance.

## TCAD SIMULATION VERIFICATION

In this section, we demonstrate the measurement and TCAD simulation information. The error rate between the TCAD simulation and measurement data can be successfully controlled within only 1~2%, which is our evaluating criterion for high qualitative prediction. In the following figures, we demonstrate the simulation and measurement comparison of Gummel plots, I-V characteristics, C-V curves, and S-parameter, respectively. The test device size is 3um x 40um x 3 emitter fingers with current gain of 75. Fig.1 shows the fitting results of Gummel plot. For the HBT's characteristics, the typical turn-on voltage is around 1.265 V, and the typical power amplifier operation voltage is around 1.3 V of  $V_{BE}$ . The error rate between simulation and measurement can be controlled within 1% from 0.8V to near 1.4V. The I-V characteristics are shown in Fig. 2. The knee region can achieve the error rate less than 1%, where is thought to be the most important region. Furthermore, the error rate of the thermal sensitive region (the high voltage and high current) is also less than 2%.

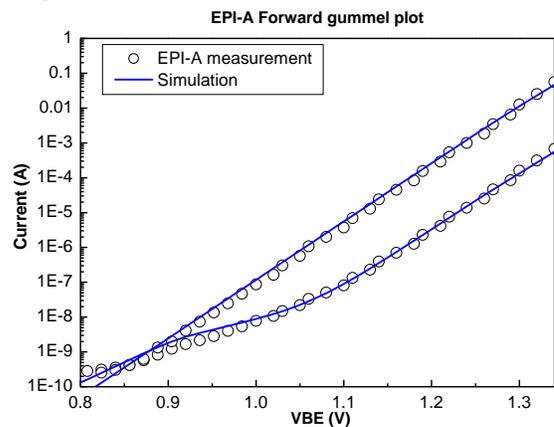


Fig.1 The Gummel-Plots characteristics comparison of measurement (symbol-line) and TCAD simulation results (solid-line)

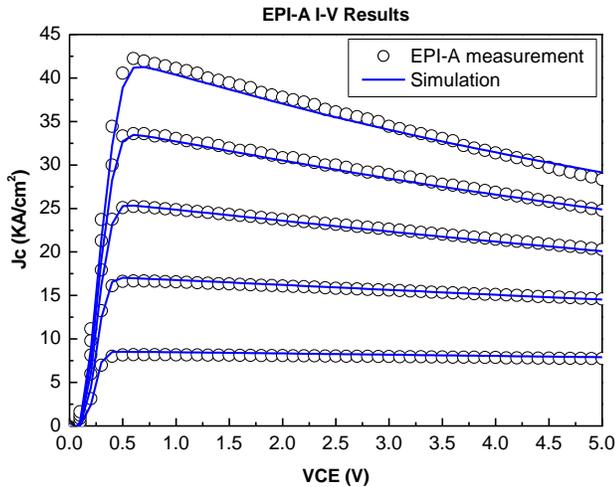


Fig.2 The I-V Curves characteristics comparison of measurement (symbol-line) and TCAD simulation results (solid-line)

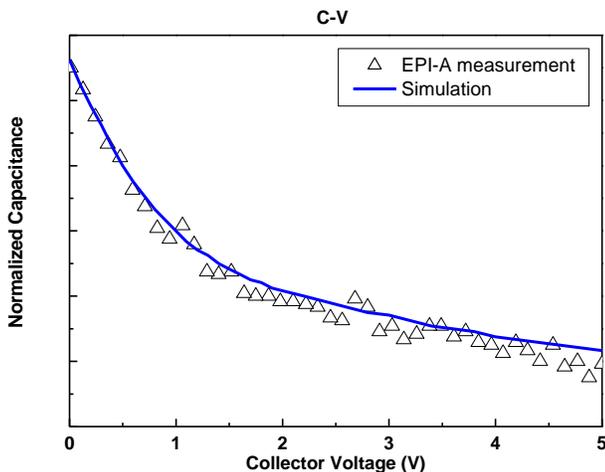


Fig.3 The C-V characteristics comparison of measurement (symbol -line) and TCAD simulation results (solid line)

Fig.3 plots the C-V curves. The collector capacitance is related to the collector thickness and doping profile. The power gain is strongly related to the collector capacitance. Therefore collector capacitance is always one of the key parameter to analyze device performance. The error rate is also controlled within 2%. S-parameter comparison is shown in Fig.4 with frequency range from 0.1GHz to 20GHz. The condition is at  $V_{CE} = 3.6V$ , and  $I_c = 10mA$ , which is the typical operation quiescent current of power amplifier. The result shows that the simulation fits the measurement results quite well.

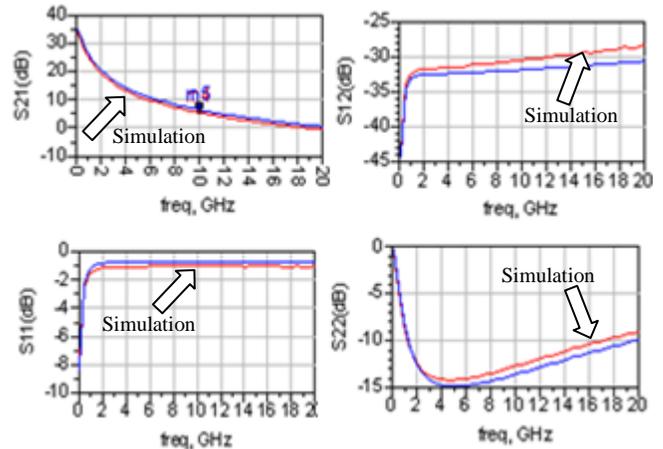


Fig.4 The S-parameter characteristics comparison of measurement and TCAD simulation results .

#### EPITAXIAL DESIGN

As we mentioned in the introduction, the previous study [1]-[3] adopt step-doped collector structures to improve ruggedness. Fig.1 shows the step-doped illustration plots. Collector structure consists of lightly doped first layer and highly doped second layer. The lowly doped layer is designed for better off-state breakdown. However, when collector current increases at high collector voltage, the electron charge compensate the electric field in the collector, thus the electric field will shift to sub-collector soon, which is the well-known Kirk-effect. The increased second collector layer doping concentration can avoid the electric field transfer too fast to the sub-collector junction, thus can suppress Kirk-effect. Finally it can enhance the on-state breakdown. In conclusion, the step-doped collector structure is an indispensable approach to design a HBT structure with sufficient off-state and on-state breakdown voltage, which can guarantee the good ruggedness results.

On the other hand, the previous study [4] mentioned that the PAE has positive correlation with Kirk effect. In our point of view, in order to improve PAE, the Kirk effect needs to be suppressed around 3-5V collector voltage which is the typical PA operation range. The depletion region at relatively lower collector voltage is shorter than that of the higher ones. Therefore, the first collector design is more critical to affect the PAE when the collector voltage is relatively lower. Kirk effect improving is not as easy as alternative reducing thickness or increasing doping concentration. The first collector design needs to consider both factors at the same time. After we simulated more than 30 collector epitaxial structures, we found a particular structure which can overcome the trade-off between PAE and ruggedness. In the following section, we will show the performance comparison of three typical epitaxial structures

design: EPI-A, EPI-B, and EPI-C. We take EPI-A as our standard reference, which is based on WIN's mature product technology. EPI-B is exclusively designed for superior ruggedness performance. EPI-C is designed for both PAE and ruggedness requirement.

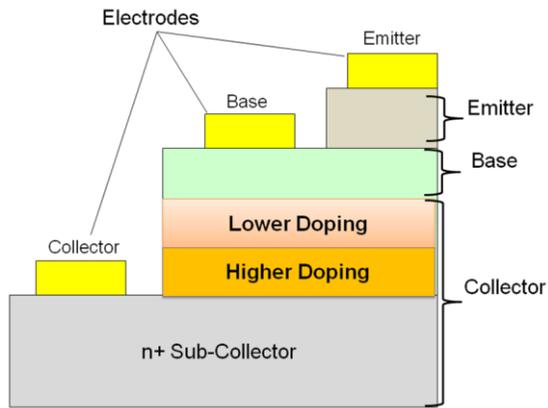


Fig.5 The HBT step-doped collector epitaxial structure illustration Plot

DEVICE RF AND SOA PERFORMANCE

Fig.6 shows the cut-off frequency versus collector current density of a unit-cell with size of  $3\mu\text{m} \times 40\mu\text{m} \times 3\text{ fingers}$  at  $V_{CE} = 3.6\text{ V}$ . There are three curves of EPI-A, EPI-B, and EPI-C. The maximum cut-off frequencies are around 28GHz, 26GHz, and 32GHz respectively. The lower cut-off frequency of EPI-B is due to the lightly doped first collector layer for the benefit of high off-state-breakdown. The higher cut-off frequency of EPI-C is because of the proper first collector doping and thickness for reducing Kirk-effect.

Fig.7 shows the safe-operation region (SOA) plots of EPI-A, EPI-B, and EPI-C of a unit cell with  $3\mu\text{m} \times 40\mu\text{m} \times 3\text{ fingers}$ . As the collector current density is lower than  $5\text{ kA/cm}^2$ , all of the three epitaxial structure show compatible breakdown voltage. EPI-A as a mutual technology has been applied for the high efficiency mobile phone application. It is regarded as high ruggedness epitaxial structure. EPI-B shows further improvement over EPI-A at the on-state region. EPI-B has mainly applied to infrastructure application with high ruggedness requirement. Additionally, EPI-C shows a remarkable enhancement of on-state breakdown voltage. The EPI-C is successfully overcome the trade-off between cut-off frequency and breakdown voltage.

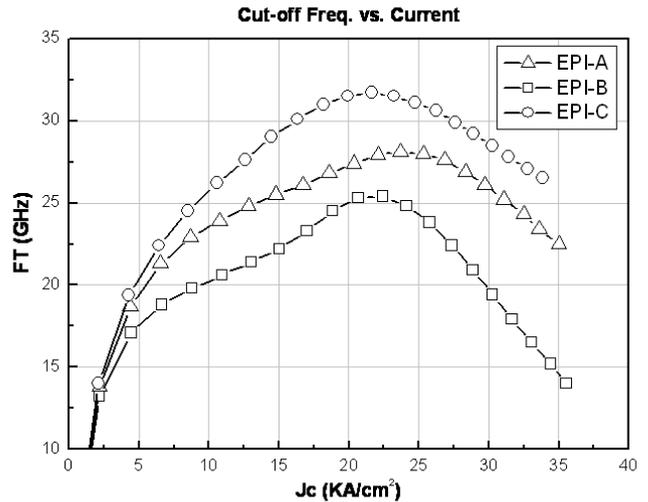


Fig.6 The comparison of EPI-A, EPI-B, and EPI-C of cut-off frequency characteristics.

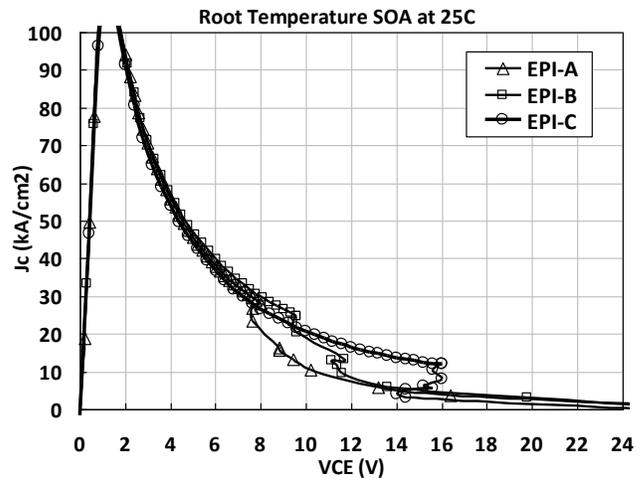


Fig.7 The Comparison of EPI-A, EPI-B, and EPI-C of Self-operation region characteristics.

DEVICE POWER AND RUGGEDNESS PERFORMANCE

As Fig.8 shown, the same test vehicle of SOA measurement of emitter size ( $3\mu\text{m} \times 40\mu\text{m} \times 3\text{ fingers}$ ) is chosen for the load-pull measurement under 900MHz. DUT was attached on an evaluation board and the power performance was measured via a Focus load pull system. The device was biased at  $V_{CE}$  of 3.6V and collector quiescent current was 10mA. The device was well-tuned the load impedance for the maximum PAE performance. Linear power gain is around 19 dB, and P1dB is around 19.3 dBm of all three structures. The power added efficiency (PAE) is around 68%, 71.1%, and 74.6% at saturated power of EPI-A, EPI-B, and EPI-C respectively. Fig.8(b) shows the comparison of the PAE at output power 0~22 dBm. EPI-C always shows higher PAE over all the output power region. Its maximum PAE is around 3.5% higher than EPI-A and also 6.5% higher than EPI-B.

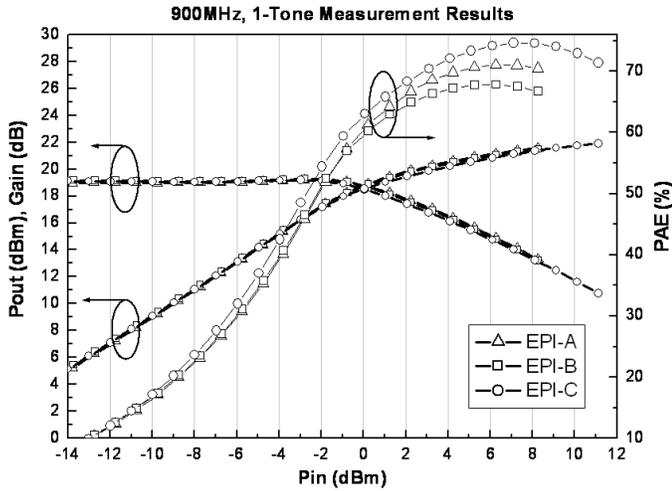


Fig.8(a) The comparison of EPI-A, EPI-B, and EPI-C of 1-tone load-pull at 900MHz characteristics.

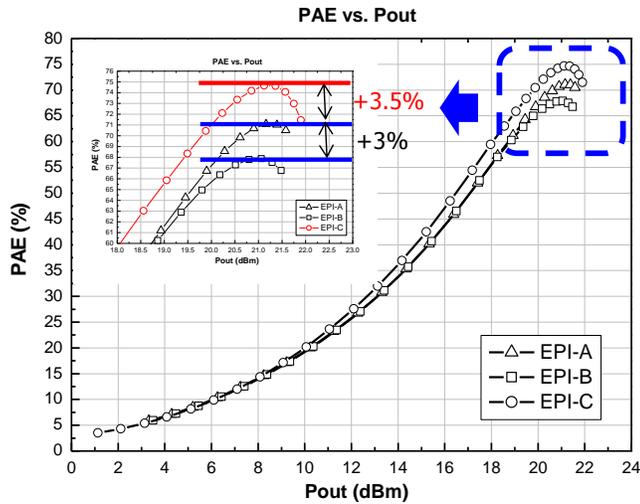


Fig.8(b) The comparison of EPI-A, EPI-B, and EPI-C of 1-tone load-pull at 900MHz characteristics.

The ruggedness test of  $3\mu\text{m} \times 40\mu\text{m} \times 3\text{ fingers}$  unit cell device is shown as Fig.9. The DUT was partially matched on an evaluation board and it can deliver 21.5 dBm output power at 900 MHz. VSWR is set for 10:1 at all phase rotation during ruggedness test, and gradually increase  $V_{CE}$  from 3.6V until device burn out. This work shows the excellent ruggedness performance of EPI-C which can pass under VSWR 10:1 at  $V_{CE}$  10.5V. Table.1 shows the summary of all three epitaxial structures. EPI-A could pass VSWR 10:1 under  $V_{CE}$  7V. EPI-B could pass VSWR 10:1 under  $V_{CE}$  9V. EPI-C shows the best performance among all three structures.

Table 1

Ruggedness test results under VSWR 10:1 for EPI-A, EPI-B, and EPI-C . Device size is  $3\mu\text{m} \times 40\mu\text{m} \times 3\text{ fingers}$ .

VCE	5V	7V	8V	9V	10.5V	11V
EPI-A	Passed	Passed	Failed			
EPI-B	Passed	Passed	Passed	Passed	Failed	
EPI-C	Passed	Passed	Passed	Passed	Passed	Failed

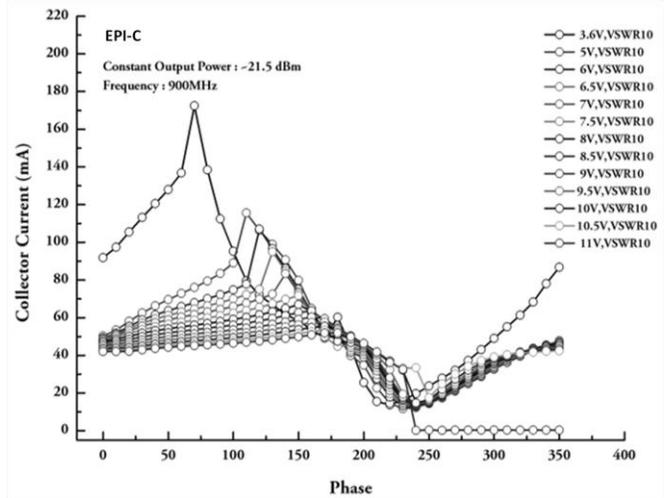


Fig.9 The Ruggedness test results of EPI-C at 900MHz, VSWR 10:1

## CONCLUSIONS

This paper provides a new HBT collector structure, which can deliver a superior PAE and maintain an outstanding ruggedness. This particular collector structure is done by newly developed TCAD simulation tools. We successfully achieve the error rate within 1~2 % between our TCAD simulation and the real measurement. We lift the cut-off frequency from 28GHz to 32GHz and boost the PAE to be around 3.5% better than WIN's current mature HBT technology. Meanwhile, the ruggedness could pass 10:1 VSWR under 5V~10.5V  $V_{CE}$ . Therefore, it can be applied to current GSM/WCDMA/LTE PA market. This new technology is expected to be favorable for global PA designers.

## ACKNOWLEDGEMENTS

The authors would like to thank the people that supported the measurements and wafer processing of WIN's device characterization team and manufacturing team respectively.

## REFERENCES

- [1] Chien-Ping Lee, et al., *The Safe Operating Area of GaAs-Based Heterojunction Bipolar Transistors*, IEEE Trans. Electron Devices, vol. 53, no. 11, pp. 2681-2688, Nov. 2006.
- [2] M. Pfof et al., *Optimization of the collector profile of InGaP/GaAs HBTs for increased robustness*, IEEE GaAs Digest, pp.115-118, 2003.
- [3] T. Niwa et al., *A composite-collector InGaP/GaAs HBT with high ruggedness for GSM power amplifiers*, IEEE MTT-S Digest, pp.711-714, 2003
- [4] Mikhail S. Shirokov, et al., *Large-Signal Modeling and Characterization of High-Current Effects in InGaP/GaAs HBTs*, IEEE Trans. Microwave Theory Tech., vol. 50, no. 4, pp. 1084-1094, APRIL 2002

## ACRONYMS

- HBT: Heterojunction Bipolar Transistor
- SOA: Safe-Operation Region
- PA: Power Amplifier
- FOM: Figure of Merit
- TCAD: Technology Computer Aided Design
- VSWR: Voltage Standing Wave Ratio