Characterization and Modeling of InP DHBTs

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InP DHBTs have been characterized and their large signal model has been developed. The devices showed excellent DC characteristics without current blocking up to very high current levels. The peak f_T is 160GHz and peak f_{max} reaches 190GHz. Compared to InGaP HBTs, the extent of thermal resistance improvement in InP DHBT strongly depends on the area of the B-C junction. To take advantage of the low thermal resistivity of InP material, proper layout designs need to be implemented. Extracted large signal model exhibited excellent fitting with measurements. Based on this model, simulated and measured circuit performance showed excellent agreement.

INTRODUCTION

While GaAs based InGaP heterojunction bipolar transistor (HBT) technology plays an important role in building components, such as power amplifiers, for wireless applications, InP double heterojunction bipolar transistors (DHBT) have been considered as an enabling technology for the next generation broadband applications at speed of 40Gb/s and beyond. Among numerous advantages of InP DHBTs over other competing technologies, the high frequency and high-speed performance together with high breakdown and low operation voltages is the most attractive combination to many circuit designers. To meet the future needs and to embrace the most advanced technology for higher speed communication, we developed high performance InP DHBTs by leveraging our existing high yield and high performance InGaP HBT production experience (Sun *et al* (1)). To facilitate the use of our InP DHBTs and to fully utilize their advantages, device electrical and thermal properties have been characterized and the large signal transistor model has been developed. This paper describes the device characteristics and model development of our InP DHBTs.

DEVICE ELECTRICAL CHARACTERISTICS

Properly designed base-collector junction is crucial to achieve superior device performance for InP DHBTs. Improperly constructed collector structure introduces an excess electron barrier at the base-collector junction, which blocks electron transport to the collector and leads to an increase in electron charge storage in the base. This current blocking effect degrades both DC and high frequency performance because of increased base recombination and base-collector charging time. This effect becomes more severe as the current level increases.

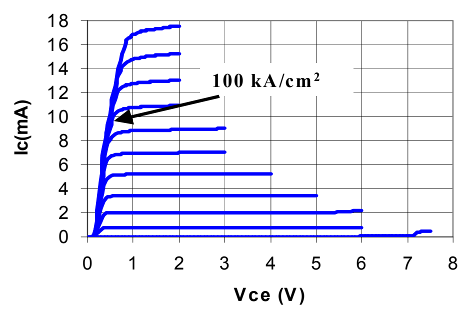

Figure 1 Typical common-emitter I-V curves of a 1.2x8μm² InP DHBT

In our design we used compositionally graded collector structure to remove the conduction band spike at the base-collector heterojunction and effectively avoided the current blocking effect up to very high current levels. Figure 1 shows typical common-emitter I-V family curves of a 1.2x8μm² InP DHBT, where the current blocking is not seen even the current density is beyond 100 kA/cm². Besides the treatment of the collector compositional structure, properly tailored thickness and

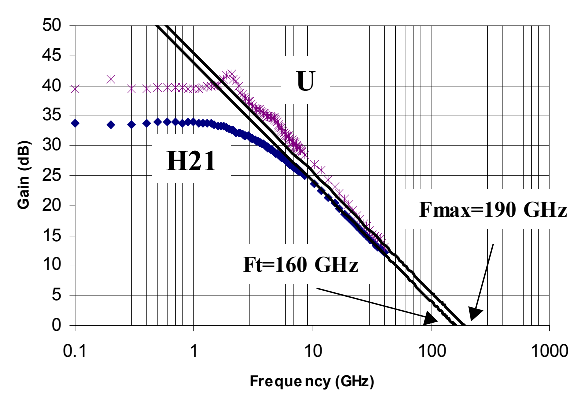

Figure 2. Frequency Response of a 1.2x8 μm² InP DHBT

doping concentrations of the base and collector epi-layers ensure good high frequency performance with good breakdown characteristics. Figure 2 and figure 3 depict

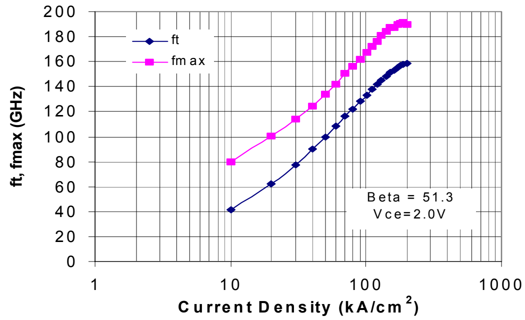

Figure 3. Current density dependence of f_T and f_{max} for a 1.2x8 μm² InP DHBT

the high frequency performance of a 1.2x8 μm² transistor. The peak cutoff frequency, f_T, is 160GHz and peak maximum oscillation frequency, f_{MAX}, reaches 190 GHz, with a breakdown voltage BVCEO of larger than 7V.

RF power characteristics are also important to circuit designers. Without optimising the high speed InP DHBT epitaxial structure, power measurements and two-tone characterization of a 2x2x20 μm² device were performed and showed power density of 2.22 W/mm and IP3/Pdc of 15.1 at 1.9GHz. Further improvements can be expected from an optimised power epi-structure. The InP DHBT technology shows great potentials for low voltage and high linearity power applications in addition to high speed/high frequency applications with some tailoring in collector doping and thickness.

THERMAL RESISTANCES AND TEMPERATURE DEPENDENCE

One of the advantages of InP DHBT is the lower thermal resistivity of the InP substrate. Compared to GaAs, the thermal resistivity of InP is about 29% lower (1.47 C*cm/W for InP vs. 2.08 C*cm/W for GaAs). To

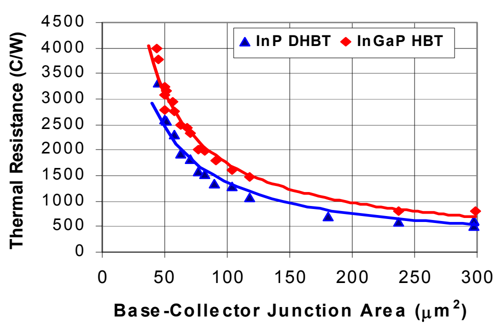

Figure 4 BC junction area dependence of thermal resistance.

Table 1 Thermal resistance comparison

A_{BC} (μm²)	Rth (C/W) (InGaP HBT)	Rth(C/W) (InP DHBT)	Improvement
298	815	603	26%
118	1432	1093	23.7%
104	1570	1206	23%
90.4	1725	1347	21.9%
76.8	2017	1594	21%
63.2	2478	1968	20.6%
49.9	2781	2288	17.7%
49.6	3083	2602	15.6%

determine how this better thermal property of InP is reflected in device, thermal resistances were electrically measured and calculated for HBTs with different base-collector geometries, following the approach given by Dawson *et al* (2). The dependence of the thermal resistance on the base-collector junction area is shown in figure 4. The comparison between InP DHBTs and InGaP HBTs shows that the thermal resistances of InP DHBTs are in a range of 15% to 26% lower than those of InGaP HBTs, depending on the base-collector junction area. Table 1 gives a one-to-one comparison between InGaP HBTs and InP DHBTs with the same layout style but different BC junction areas. From Table 1., it can be seen that the improvement in thermal resistance of InP DHBTs drops from 26% to 15.6% as the BC junction area decreases from 298 μm² to 49.6 μm². This indicates that the percentage of the heat flow from the junction through the substrate decreases as the junction area decreases. In other words, the role of the substrate for heat conduction is less important in small dimension transistors.

Although the thermal resistance in InP DHBTs is lower than that in GaAs based InGaP HBTs, self-heating effect in an InP DHBT is still important and needs to be carefully considered in device modelling. The junction temperature rise induced by self-heating leads to the increase of the reverse hole injection from base to emitter and the reduction of the emitter junction built-in potential. The former lowers the emitter efficiency and the latter causes the runaway in collector current under fixed Vbe conditions (Zhang *et al* (3)). In InP DHBTs, it is observed that, while the current gain is not sensitive to self-heating effect indicated by the lack of obvious negative resistance in the Ib driven I-V characteristics (Figure 1), the collector current still tends to run away as the DC power rises under constant Vbe driving conditions as shown in Figure 8 in the next section. The lack of negative resistance in InP HBTs can be attributed to the insensitivity of current gain to temperature. Figure 5 shows InP DHBT I-V curves measured at 25, 100 and 150 °C. It can be seen that the collector current does not change much with temperature. Compared with GaInP/GaAs HBTs (see also Figure 6), the current gain of InP DHBT is much less sensitive to temperature. The common emitter current gain, β, can be expressed as (Liu (4)) by ignoring surface recombination and other secondary effects

$$\frac{1}{\beta} = \frac{1}{\beta_0} + f_1 \exp\frac{-\Delta E_V}{kT} \qquad (1)$$

where ΔE_v is the valence band discontinuity, f_1 is a function of doping and thickness of the emitter and base layers and β_0 is determined by base transport factor which is temperature insensitive. The second term on the RHS of (1) is determined by the emitter efficiency, which

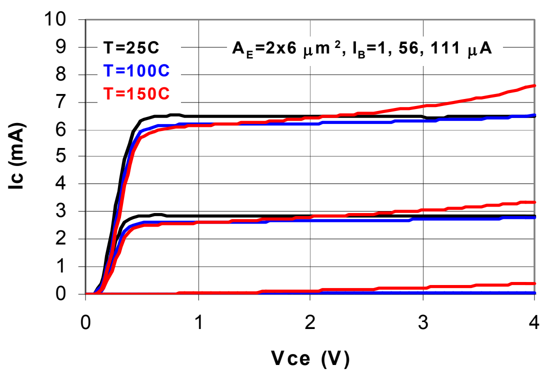

Figure 5. I-V curves measured from a 12 μm² InP DHBT at different temperatures.

is temperature dependent through exponential relation to ΔE_v. Equation (1) tells us that a large ΔE_v and high neutral base recombination will result in a temperature insensitive current gain since the temperature sensitive second term on the RHS is negligible. Since both InP/InGaAs and InGaP/GaAs base-emitter heterojunctions have a large valence band discontinuity

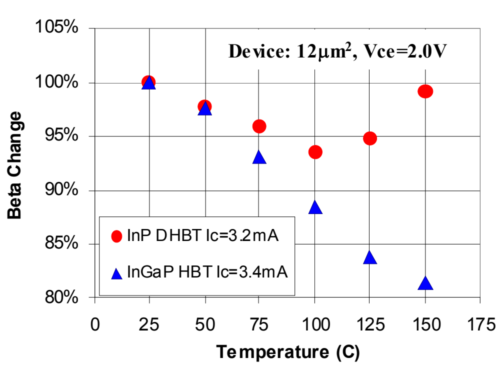

Figure 6. Temperature dependence of current gain

(0.38eV in InGaP/GaAs and 0.37eV in InP/InGaAs), the temperature insensitive current gain of InP DHBTs is a result of the high recombination in the neutral InGaAs base. As a matter of fact, with similar base doping and thickness, a typical common emitter current gain of an InP DHBT is much lower than an InGaP HBT, which is a clear indication of high base recombination in InGaAs base.

TRANSISTOR MODELLING

After the device electrical and thermal properties were characterized, a large signal model was developed for InP DHBTs following our successful modelling approach for GaAs-based InGaP HBTs. This model modifies the standard Gummel-Poon model by including the self-heating effect and some unique effects for HBTs. It takes a similar form of equivalent circuit topology as used in our InGaP HBTs (Ho *et al* (5)) and can be readily implemented in popular commercial circuit simulators such as SPICE and ADS.

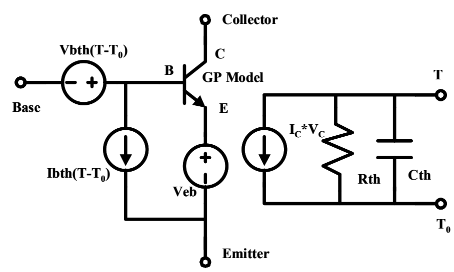

Figure 7. Simplified Model topology with incorporation of self-heating feedback elements.

Figure 7 presents the simplified transistor model schematic. The model makes use of the standard GP model and adds a thermal equivalent sub-circuit and temperature feedback elements to model the self-heating effect. In the schematic, the temperature controlled voltage source Vbth(T-T_0) accounts for the reduction of electron barrier at the E-B junction due to junction temperature rise, $\Delta T = T - T_0$, caused by self-heating. The temperature controlled current source Ibth(T-T_0) presents the increase in backward hole injection which results in the deterioration of the emitter efficiency due to ΔT. The thermal equivalent circuit converts the DC power dissipation (Ic*Vc) to junction temperature rise ΔT and dynamically controls Vbth and Ibth. Since the developed large signal model treats the two physical mechanisms, namely, the emitter efficiency degradation and Vbe reduction, separately when self-heating occurs, it achieves accurate modelling results which are in excellent agreement with the measurements in both Ib driven and Vbe driven I-V characteristics as shown in Figure 8 and 9. Besides the self-heating issue, the model also includes the effect of the potential barrier variation at the E-B junction by adding a Vbe dependent voltage source (Veb). Additionally if the current blocking in the base-collector junction is significant, the barrier effect in the B-C junction of a DHBT should be modelled

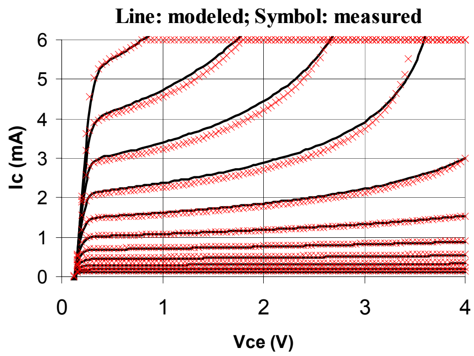

Figure 8. Comparison between measured and modelled I-V curves with constant Vbe driving. Device: 1.2x8 μm^2

properly in order to achieve a good accuracy across the full bias range of operation. Fortunately, the proper design of the collector structure of our InP DHBT avoided the current blocking effect and makes the special modelling treatment unnecessary. High frequency parameters of the model are extracted following similar approach reported previously (Zhang *et al* (3)).

With the help of the developed InP DHBT model, some

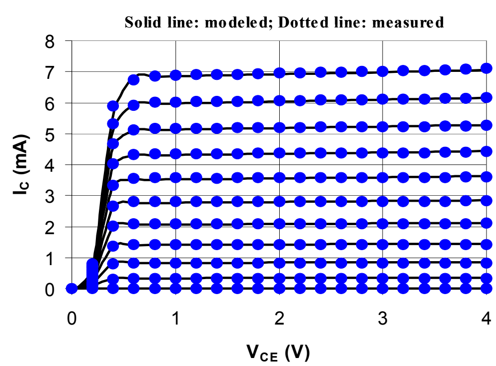

Figure 9. Comparison between modelled and measured I-V curves with constant Ib driving. Device: 1.2x8 μm^2

exploring circuits have been designed and fabricated using our InP DHBT technology (Sun *et al* (1)). An example is shown in Figure 10, where simulated and measured transimpedances for a transimpedance amplifier (TIA) are compared, the simulation predicts the circuit high frequency performance as well as DC bias conditions with excellent accuracy. The success in model development largely reduces new product development cycle.

CONCLUSIONS

Our InP DHBTs have been characterized. Measured peak f_T is 160GHz and f_{max} reaches 190GHz with good DC characteristics and no current blocking effect up to very

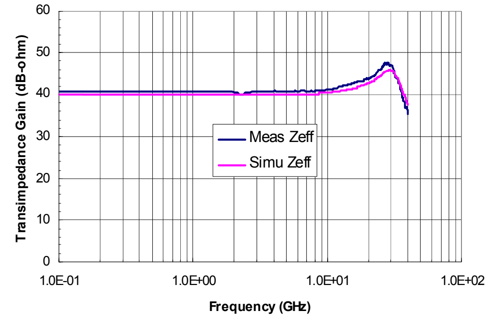

Figure 10.Comparison between measured and designed TIA Transimpedence

high current levels. The thermal resistance and temperature dependence of InP DHBTs were measured and compared with InGaP HBTs. The BC junction area dependence of thermal resistance shows that larger area InP DHBTs have more improvement in thermal resistance, likely due to dominant heat spread path through more thermally conductive InP substrate in larger devices. A large signal model has been developed and good modelling results were achieved and demonstrated in circuit applications.

ACKNOWLEDGEMENT

The authors would like to express the appreciation to Euvis Inc. for technical discussions and characterization data of TIA for this paper.

REFERENCES

(1) Mike Sun, Juntao Hu, Wu-Jing Ho, Gary Hu, Jiang Li, Vicki Weng, Wei-Ming Xu, June Nguyen, Chang-Hwang Hua and Ding Day, *A Non-Self Aligned InP HBT Production Process,* Mantech, 2002.

(2) Dale E. Dawson, Aditya K. Gupta and Mike L. Salib, *CW Measurement of HBT Thermal Resistance*, IEEE Tran. On Electron Devices, Vol.39, No.10, Oct. 1992

(3) Q.M. Zhang, Juntao Hu, John Sitch, R.K. Surridge and Jimmy Xu, *A New Large Signal HBT Model,* IEEE Trans. On Microwave Theory and Technologies, Vol.44, No.11, Nov. 1996, pp.2001-2009.

(4) William Liu, *handbook of III-V Heterojunction Bipolar Transistors*1

(5) Wu-Jing Ho, Mike Sun, Juntao Hu, Chang-Hwang Hua, Ding Day, Steve Sprinkle, Pat Reginella, Joe Gering and Paul DiCarlo., *Manufacturing HBTs for Wireless and Broadband Applications,* CSMAX Conference, Boston, MA 2001