Measurement and Modelling of Static and Dynamic Breakdowns of Power GaInP/GaAs HBTs

Sylvain Heckmann*, Jean-Michel Nébus*, Raymond Quéré*
Jean-Claude Jacquet**, Didier Floriot**, Philippe Auxemery***

* IRCOM, University of Limoges (France)
** Thales Research and Technology, rd 128, 91404 Orsay Cedex (France)
*** United Monolithic Semiconductors (UMS), rd 128, 91404 Orsay Cedex (France)

Abstract – **The breakdown value of GaInP/GaAs HBTs have been strongly increased, keeping constant RF performances. A 67 V common base breakdown voltage (BVcb0) is obtained associated to a 37 V of collector emitter breakdown value (BVce0). Such devices have great potentialities to be used in base station as power amplifiers where 10 W (linear) and 100 W (compressed) output powers are needed. For such powers, transistors work close to the breakdown limit. Therefore an accurate modelling of both static and dynamic breakdown phenomena becomes important for the optimum design of reliable amplifiers. This is the purpose of this paper. The base-collector breakdown of a 16 fingers HBT transistor have been characterised in the cases of constant base current and constant base voltage biasing conditions. A HBT model accounting for breakdown is presented and large signal load pull measurements reported.**

I. INTRODUCTION

The power HBT technologies offers many ways to address all the needs in term of power, efficiency high reliability for applications ranging from L to Ku bands [1].

Having high breakdown voltage transistors offers the way to provide high power amplifiers by deriving benefit from large output voltage swings. Furthermore, high load impedances make easier the design of output matching circuits. For base stations applications, the Breakdown value of GaInP/GaAs HBTs have been strongly increased, keeping constant RF performances [2]. To achieve this result, the collector thickness and the collector doping have been optimised to obtain the best trade-off between high breakdown and high current standing values. Thus, in comparison to previous published results or manufactured devices, the maximum operating collector voltage is increased by a factor three. Such devices will be able to address third-generation cellular base station where LDMOS and Si-BJT are dominant for the moment. Due to their high power density, HBTs will be also great candidates for modern S Band and X Band radar applications. For operating at high collector voltage, circuits designers need to know accurately the limitations due to breakdown. Several papers have been published on this topic : Physically based models in which electric field and electron impact ionisation coefficients are fitted [3], numerical calculations which solve Poisson and continuity equations [4]. In this paper, we have chosen a non linear circuit based model compatible with commercial CAD packages.

II. BREAKDOWN MECHANISM

A high collector voltage generates electron-hole pairs by ionisation. Holes drift towards base because of the high electric field and contribute to the decreasing of the base current by recombining with the electrons coming from the emitter. The value for which the current becomes negative is related to the definition of BVce0 (Ib=0). The avalanche current is located in the base-collector depletion region [5].

If the external base current is forced by a (high impedance) current source, the continuous (DC) part of the base-collector breakdown current feeds back the base-emitter junction. Therefore the base-emitter voltage increases. More electrons are injected from the base to the collector creating more hole-electron pairs. Irreversible breakdown occurs until the device failure (cumulative effect).

In the case of an external base-emitter voltage source (low impedance), the DC part of the base-collector breakdown current is shunted by the external base biasing circuit (no more cumulative effect). A negative base current is observed and irreversible BC breakdown occurs at a higher dynamic collector voltage compared to the previous case (constant DC base current control).

This phenomena, commonly known as $BVce_{open}$ and $BVce_{short}$ in bipolar transistors has been reported as static (DC) breakdown conditions, supporting the use of common base topology for power amplification.

In comparison to the common base topology, the common emitter topology presents the advantage to exhibit an higher input impedance making easier the design of input matching circuit.

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In the following paper we point out that the static common emitter breakdown voltage is too much conservative. Under dynamic (RF) operation mode, the collector voltage swing can go beyond the static limitation without damaging the transistor.

Furthermore, as far as the DC base bias conditions are carefully controlled, a common-emitter configuration of HBT can be used for very large power amplification at microwave frequencies.

III BREAKDOWN MEASUREMENTS

In order to characterise and model the breakdown effect in GaInP/GaAs HBTs, we used a quasi isothermal pulsed I-V measurement methodology and capabilities. Pulse width and periodicity were set respectively to 500 ns and 6 μs. A schematic of the test bench is given in figure 1. A 16 fingers of $2x70\mu m^2$ HBT was used. To validate the test configurations, these first samples present a 3μm thick collector.

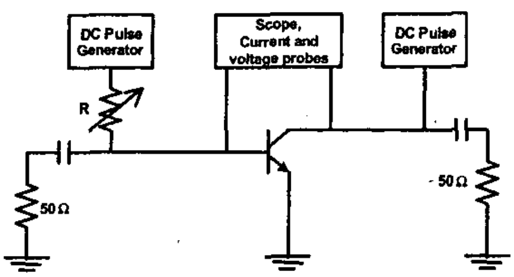

Fig. 1. Pulse measurement set up
Equivalent impedance of the base supply is monitored by R

In the Ic (Vce) plan, we scanned the CB breakdown area for two different conditions.

1/ Keeping constant the base emitter voltage at 0 V, we measured the pulsed collector current versus the pulsed collector emitter voltage.

2/ The same measurements are performed keeping constant a very low base current.

The results are focused on breakdown area and depicted in figures 2a and 2b.

In case 1/, voltage source close to 0 V, the breakdown occurs at collector emitter voltage of 55 V. Note that the base current has a negative value. It is thus experimentally demonstrated that the breakdown current generated in the base-collector junction can be collected in the base biasing circuit, if the impedance presented at the base bias port is small enough in comparison to the impedance presented by the base-emitter junction. Therefore the base-emitter voltage doesn't increase and the maximum value of the collector emitter voltage for which an irreversible breakdown occurs is much higher.

In case 2/, current source close to 0 mA, the breakdown occurs at 34 V of collector emitter voltage.

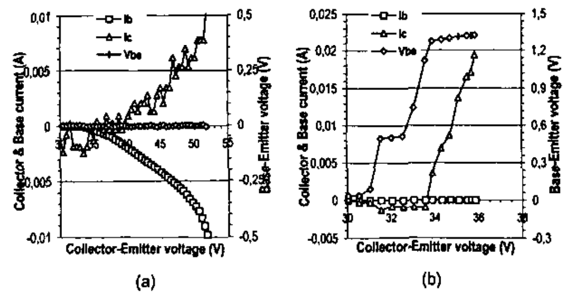

Fig. 2. Breakdown measurement:
(a) monitoring at constant base voltage
(b) monitoring at constant base current

Figure 3 shows time domain pulse waveforms in the case of an external constant base emitter voltage (set to 0 V in this case).

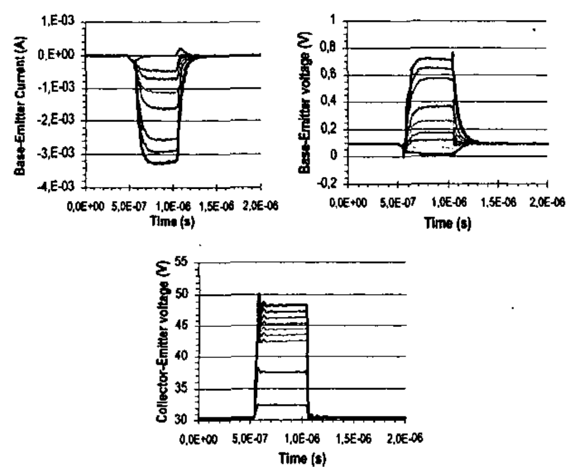

Fig. 3. Time domain pulse waveform during breakdown measurement when base-emitter voltage is set to 0V for different collector emitter pulse level.

IV MODELLING

The model used in this work is a conventional T-shape derived from the Ebers-Moll equations.

The current sources I_C and I_E include the leakage current part and the self heating. The equations of the different non-linear capacitors have already been published [6].

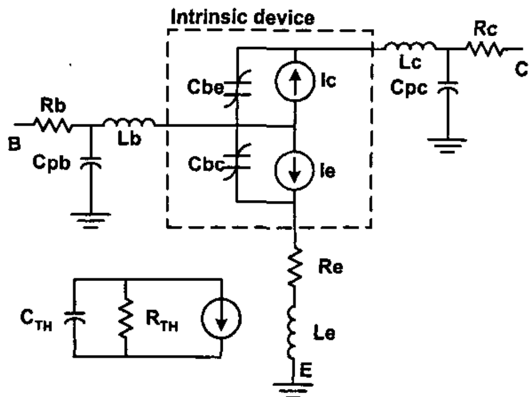

Fig. 4. Large signal HBT model including self-heating.

Here we explain how the model has been modified to include the breakdown behaviour.

$$I_C = I_{SC}(T_j)\left(\exp^{\frac{q.Vbc}{Nc.k.Tj}}-1\right)-I_{SE}(T_j)\left(\exp^{\frac{q.Vbe}{Ne.k.Tj}}-1\right)\alpha_F^{*} + I_{SFC}(T_j)\left(\exp^{\frac{q.Vbc}{Nfc.k.Tj}}-1\right) \quad (1)$$

The dominant part of this current is the term depending of V_{BE}.

$$I_E=I_{SE}(T_j)\left(\exp^{\frac{q.Vbe}{Ne.k.Tj}}-1\right)-I_{SC}(T_j)\left(\exp^{\frac{q.Vbc}{Nc.k.Tj}}-1\right)\alpha_R + I_{SFE}(T_j)\left(\exp^{\frac{q.Vbe}{Nfe.k.Tj}}-1\right) \quad (2)$$

Where the common base current gain is defined by the following equation [7]:

$$\alpha_F^{*}=\alpha_F.M \quad (3)$$

And the multiplication factor by :

$$M=\frac{1}{1-\left(\frac{V_{CB}}{BV_{CB0}}\right)^{n}} \quad (4)$$

With this approach the breakdown limit depends on the base biasing conditions (figure 5).

Because of the influence of the multiplication factor (M) on common base current gain, it could be possible to differentiate common base and common emitter breakdown voltages.

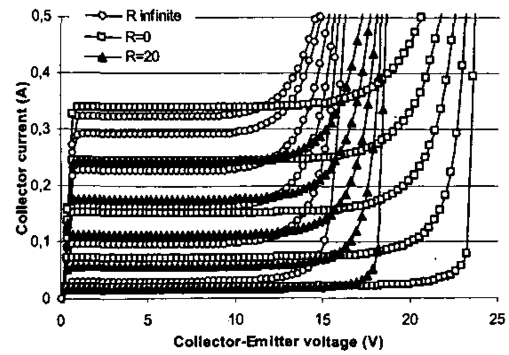

Fig. 5 Isothermal I-V characteristics simulated in three cases: constant base bias voltage (box, R=0), constant DC base voltage supply with 20Ω serie base resistor (triangle, R=20Ω self bias condition) and last with constant base current (circle).

IV LOAD PULL MEASUREMENTS

Load pull measurements were performed at 2GHz on a second set of transistors with a collector layer close to 1 μm. For this last value, the devices have 16V of BVce0 (Ib=0.1 μA). A 6 fingers of 2x30μm² HBT was used in the measurement coming from the HB20P process developed by UMS. During the large signal measurements, the transistor was biased with a constant DC base emitter voltage Vbe = 0 V, corresponding to a class C operation mode.

The Input / Output power characteristics and the DC base and collector currents were recorded for different values of the collector emitter bias voltage (from V_{CE} = 10V until 15V). For each value, the load impedance was tuned looking for a maximum output power. At high output power, the maximum collector current was with respect to Kirk effect.

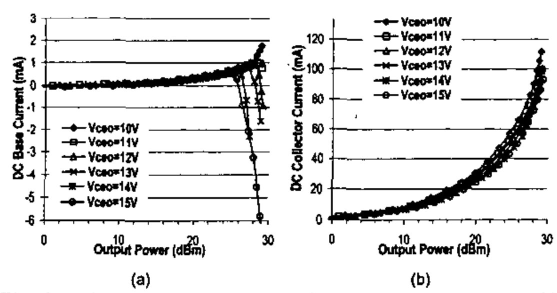

Fig. 6 Average base current (a) and collector current (b) versus output power during load-pull measurement at various collector voltage Vce0 at 2 GHz.

Figure 6 shows the DC base and collector currents versus the output power. The negative value of the base current shows that the RF signal goes beyond the BVce0 voltage and swings in the BC avalanche area. This trend demonstrates the ability of HBTs to operate at very high collector voltage without failure as far as the base biasing is carefully controlled.

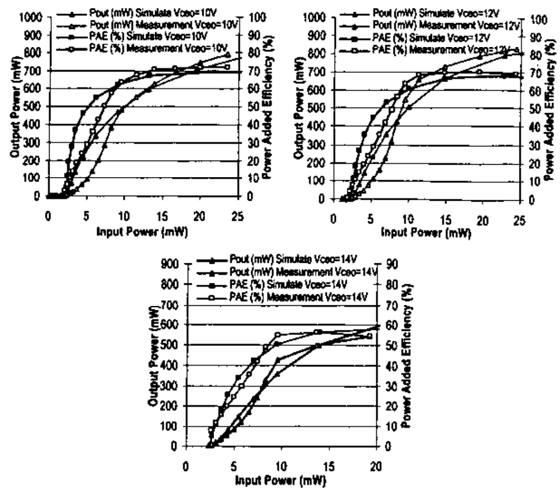

Fig. 7. Output Power and Power Added Efficiency versus Input Power measured and simulated on C-Class (Vbeo=0V) at 2GHz for various collector bias voltage (10V, 12V, 14V). Load was modified between each measurement for maximum output power.

Figure 7 shows power measurements. Figure 8 gives comparisons between measurements and simulations. The model presented in this paper claims its ability to fit the breakdown behaviour of HBTs.

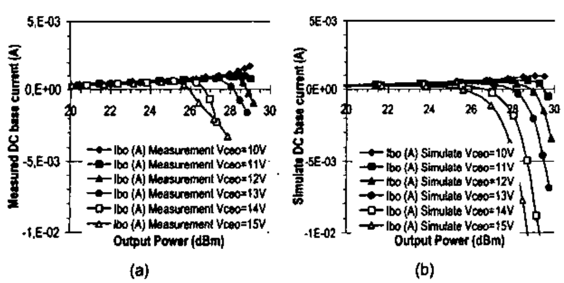

Fig. 8. Comparison between average base current versus output power measured (a) and simulated (b).

V Conclusion

A lot of experiences confirm the ability of the HBTs to operate above the $BVce_{open}$ breakdown voltage. The influence of such operating mode on DC is established and a new non-linear HBT model taking into account this effect is proposed. It is assessed that the DC current variations are useful to detect if the transistor work in the breakdown area during load-pull measurement. Negative base current over 10 mA was got without any damage of the device.

Measurements and modelling of the HBT under high RF swing was made and gave excellent results assessing the model accuracy. Furthermore, because of slight thermal dependence of the breakdown behaviour on thermal effect, such an effect could be included in the breakdown modelling by the way of the factor n.

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