Modeling Advanced Avalanche Effects for Bipolar Transistor Circuit Design

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***Abstract*—As the demands for high operating frequency and high output power of modern bipolar transistor circuits increase, designers are trying to exploit transistor operating regions where they would be able satisfy both conditions, namely working within an avalanche region. For such applications, compact models have to be at their best, so the designers could have a full overview of the device behaviour and possibilities. In order to accomplish that, there should be an adequate way in characterization of avalanche in the RF regime, as well as in verification of the devices against some figures of merit. This paper gives an insight on possible RF avalanche characterization techniques. Repercussions of working in the avalanche regime on some important transistor properties like unilateral power gain, the maximum avaliable gain and the stability factor is demonstrated. Measurements of modern industrial devices, as well as simulations using the world standard bipolar compact model Mextram are presented in a context of working in AC avalanche regime.**

Keywords: Dynamic Avalanche, Bipolar Transistor, Modeling, Compact Models, Transistor Avalanche Characterization.

I. INTRODUCTION

The low breakdown voltage and high current carrying capability of advanced high speed bipolar transistors are forcing designers to exploit the possibility of controlling the transistor operation above the breakdown voltage limits. To this end, it is important to know the maximum usable transistor output voltage and its dependence on driving conditions, as well as the repercussions of working in the avalanche regime on other transistor parameters like, for example, various measures of power gain. Modeling of the avalanche breakdown behaviour is therefore becoming a central problem in the design of high-speed Si and SiGe bipolar circuits.

The avalanche related phenomena have been so far mainly studied only under DC conditions. In general, avalanche in bipolar transistors can be studied in three practically different cases, depending on in which region the device is biased and by which signal type it is driven. One is the static, DC case, which is well-known [1] and for which there are models [2] [3] [4] that well describe device behaviour in the, so called, weak avalanche regime, where carriers generated in a process of impact ionization do not generate extra carriers. The second case is small signal AC, where the device is biased in the avalanche regime and a small AC signal is applied, on which this paper focuses. In third case device is biased outside avalanche regime but the applied AC signal is large enough to put the device into avalanche regime producing alternating periods where the device is in the avalanche regime and periods where the impact ionization does not take place.

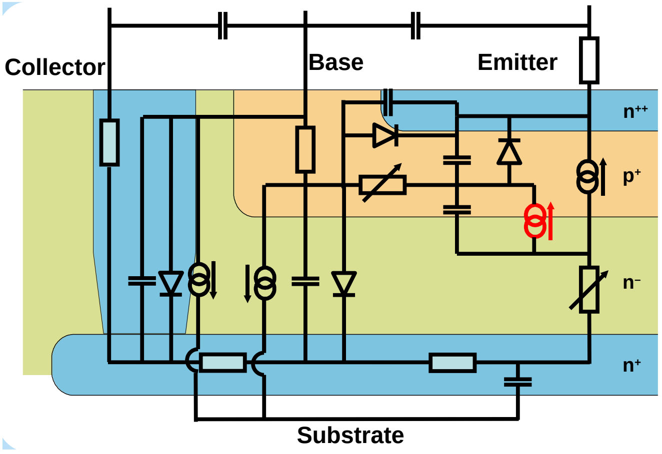

Fig. 1. Mextram 504.7: full equivalent large signal circuit schematics. Avalanche current source is highlighted in red.

Integrated circuit designers use circuit simulations to verify the electrical behaviour of their design. Compact models, which describe accurately the behaviour of transistors in a mathematical way are essential in these simulations. This work presents a study on a way of observing and characterizing avalanche in the small signal AC regime, as well as the effects of avalanche on intrinsic transistor properties like unilateral power gain, the stability factor and the maximum available power gain on basis of application of the world standard bipolar compact model Mextram [4].

II. AC AVALANCHE REGIME CHARACTERIZATION

In proceeding further, the first question to be answered is how avalanche effects are observed in the small signal AC regime. In developing a method of observation, the Mextram model is used as the basis. The Mextram version 504.7 full equivalent circuit schematics is shown in figure 1. The avalanche current source is highlighted in red. For AC analysis of interest, a linearized network is used. The linearized equivalent circuit at certain bias point (with neglected substrate

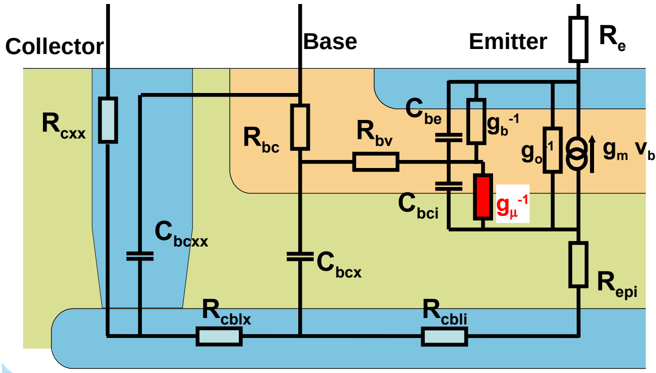

Fig. 2. Mextram 504.7: linearized equivalent circuit used in small signal analysis with neglected substrate coupling.

coupling) of the Mextram 504.7 model is shown in figure 2. If now admittance parameters (y-parameters) are derived for a two port network representation of such circuit, and attention is drawn to y_{12} admittance parameter, it yields equations (1) and (2) for its imaginary and real part, respectively. Neglecting effects caused by parasitics and second order effects, the imaginary part of the y_{12} admittance parameter can be used to measure and extract the total collector-base depletion capacitance, $c_\mu(I_C, V_{CE})$, which is a function of bias, where I_C is a DC collector current and V_{CE} the DC collector-emitter voltage,

$$-\Im\{y_{12}\} = \omega c_\mu + O(\omega^2) \qquad (1)$$

where ω is angular frequency. The collector-base depletion capacitance is charged by the intrinsic transistor avalanche current, meaning that $\Im\{y_{12}\}$ encompasses avalanche generated charge. Analogously, a method to measure avalanche conductance, $g_\mu(I_C, V_{CE}, \omega)$, which is *de facto* the value that characterizes avalanche in AC small signal regime, is based on observing the real part of the same admittance parameter.

$$-\Re\{y_{12}\} = g_\mu + O(\omega^2) \qquad (2)$$

Due to its properties, y_{12} admittance parameter is the simplest quantity which allows direct observation of the avalanche effects in AC regime. Example of the real part of the negative value of the y_{12} parameter are shown in figure 3. It can be observed that, in the medium current region, $O(\omega^2)$ effects are responsible for the global slight increase of the value of the admittance parameter, while in the same current region impact ionization and avalanche are responsible for the complete change in trend. These and all other measurements in this work are performed on a modern QUBiC4X [5] BNX-type SiGe heterojunction bipolar transistor (HBT) with emitter dimensions $0,4 \times 1,0\mu\text{m}^2$, at an ambient temperature of $25\,^\circ\text{C}$. All AC measurements are done at fixed measurement frequency of $5,337$GHz, while base-emitter and collector-emitter bias voltages are swept. For all simulations Mextram 504.7 is used.

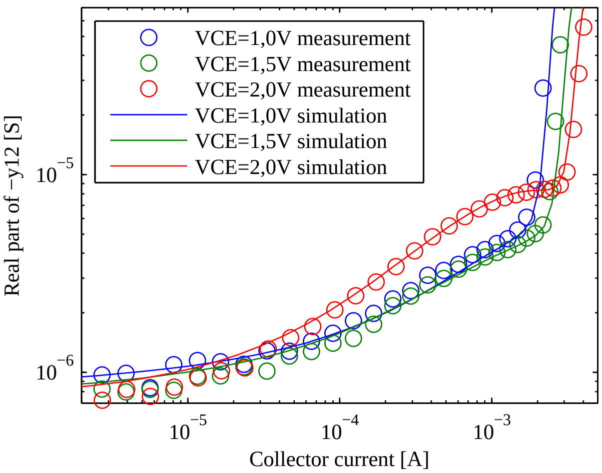

Fig. 3. Measured and simulated real part of $-y12$ parameter as a function of collector current, for three values of the collector-emitter bias voltage. In the medium current values region complete change in trend (2,0V line overcrosses 1,0V and 1,5V lines) caused by avalanche is observed on the plot.

III. RESULTS

Avalanche, if present, affects all four parameters of the two port transistor representation, independent of which parameters are into consideration. Avalanche has a profound effect on unilateral power gain and stability factor k, and by that on all figures of merit dependent on k, including there maximum available power gain. As shall be demonstrated, avalanche influence on admittance parameters is accurately modeled by Mextram.

1) Unilateral and Maximum Available Power Gains:

Unilateral power gain [6] [7] is a central concept in two-port characterization, because it is an invariant and hence an intrinsic device property. Unilateral power gain is expressed in terms of two-port network parameters by the following expression:

$$G_U = \frac{|\gamma_{21} - \gamma_{12}|^2}{4(\Re\{\gamma_{11}\}\Re\{\gamma_{22}\} - \Re\{\gamma_{12}\}\Re\{\gamma_{21}\})} \qquad (3)$$

where each γ can be replaced by impedance (z), admittance (y), hybrid (h) or inverse hybrid (g) corresponding two port parameter. This is a property of invariants. Forward Early measurements, from which avalanche parameters are extracted, are shown in figure 4. On the same figure simulation with correctly extracted parameters is plotted. With such avalanche parameters simulations beside the measurements of the unilateral power gain are plotted on figure 5. Here, unilateral power gain collapse is clearly visable when avalanche plays significant role. In order to evolve this, avalanche is intentionally neglected, as demonstrated on forward Early measurement in figure 6. If the model with such avalanche parameters (all other parameters remained unchanged in respect to previous example) is used for unilateral gain simulation, figure 7 arises. In particular, gain collapse does not happen and value of the unilateral power gain is dramatically overestimated. From the

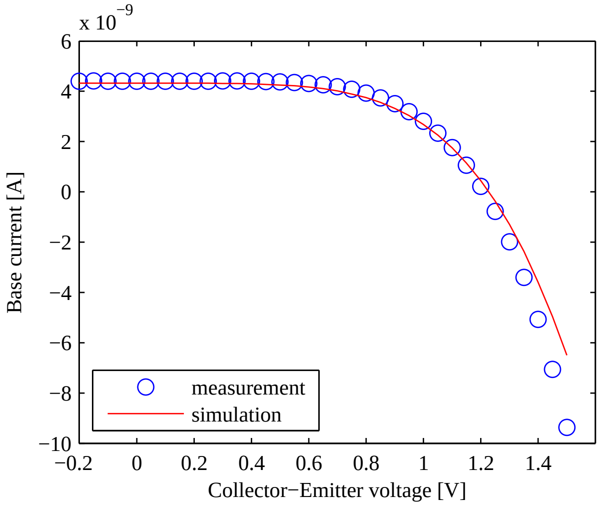

Fig. 4. Measured and simulated base current as a function of collector-emitter voltage. Avalanche is modeled well in the week avalanche region.

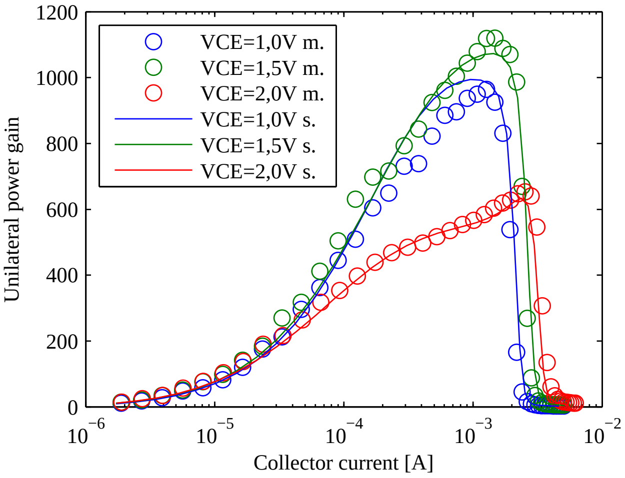

Fig. 5. Measured and simulated unilateral power gain as a function of collector current, for three values of the collector-emitter bias voltage.

previous four figures, the following can be concluded. Good forward Early measurement fit, from which avalanche model parameters are extracted, is a necessity (but not enough) for a good prediction on behaviour of unilateral gain. It is demonstrated that good avalanche model is crucial for prediction of the values of unilateral gain. Avalanche is responsible for the change in trend, and, practically, for the collapse of the value of the unilateral power gain with increase of collector-emitter bias voltage. Underestimation of avalanche can lead to overestimation of unilateral power gain which can further lead to a non-functional design.

Other important invariants, especially usefull in circuit design, are so called the stability factor, k,

$$k = \frac{2\Re\{\gamma_{11}\}\Re\{\gamma_{22}\} - \Re\{\gamma_{12}\gamma_{21}\}}{|\gamma_{12}\gamma_{21}|} \tag{4}$$

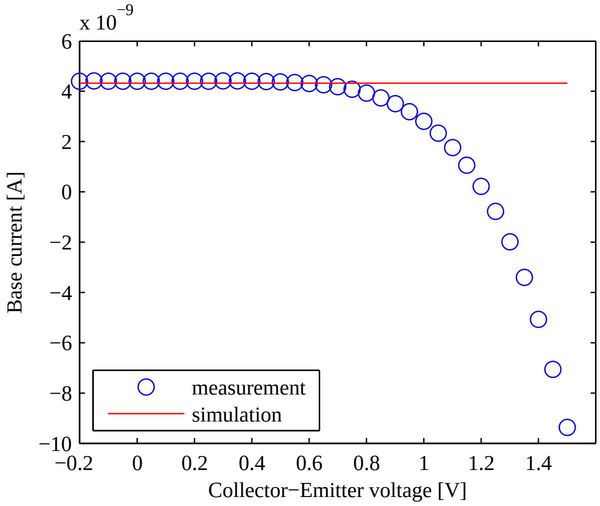

Fig. 6. Measured and simulated base current as a function of collector-emitter voltage. Avalanche model is intentionally completely neglected.

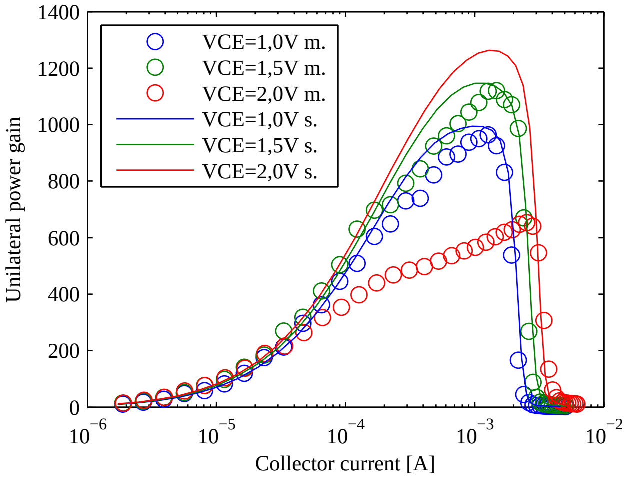

Fig. 7. Measured and simulated unilateral power gain as a function of collector current, for three values of the collector-emitter bias voltage, when avalanche in the model is completely neglected. The repercussion is gain overestimation in the region where avalanche would play a role when modeled.

and the maximum available power gain, G_{MA},

$$G_{MA} = \left|\frac{\gamma_{21}}{\gamma_{12}}\right|(k - \sqrt{k^2 - 1}) \tag{5}$$

where each γ can be replaced by impedance (z), admittance (y), hybrid (h) or inverse hybrid (g) corresponding two port parameter. The influence of avalanche on maximum available gain is similar as its influence on unilateral power gain. In fact, when avalanche influence is underrated, the maximum avaliable gain is overvalued, which can lead to severe mistakes in design.

2) Mextram EXAVL flag: Quasi-saturation has a subtle effect on avalanche. Due to extra carriers that are injected from the base into the collector region, the electrical field is modulated in such a way that its maximum is shifted from

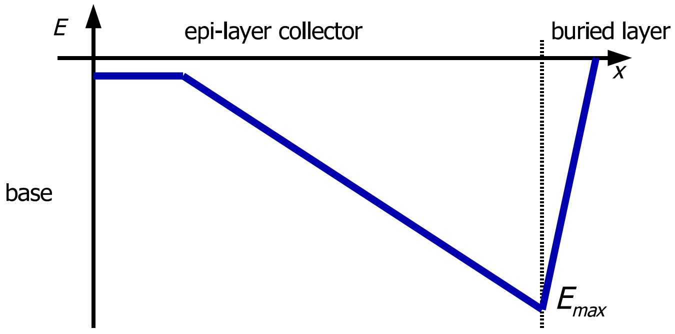

Fig. 8. Collector electric field distribution when base push-out effect is present. The maximum of the field is modulated towards buried layer.

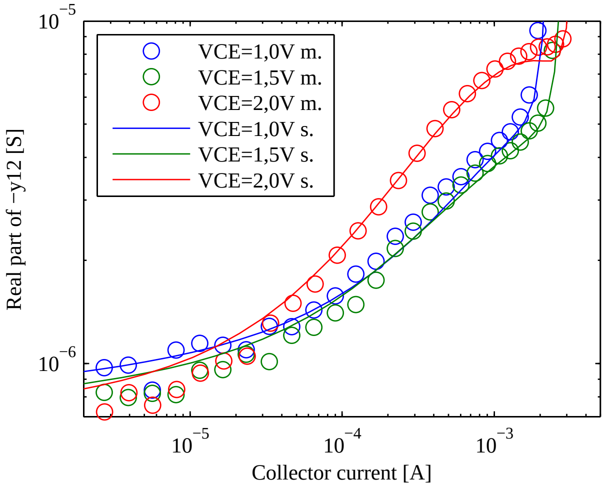

Fig. 9. Measured and simulated real part of $-y12$ parameter as a function of collector current, for three values of the collector-emitter bias when voltage when extended avalanche flag EXAVL=0.

base-collector junction to the buried layer. This is sketched on figure 8. This effect is taken into account by Mextram, when EXAVL flag is set to 1. The effect of EXAVL flag on $-\Re\{y_{12}\}$ is simulated and shown in figure 9, EXAVL flag equals 0, and in figure 9, when EXAVL flag is 1. A subtle effect in the high current region ($\approx 1,5$mA) on $2,0$V simulation curve can be noted.

IV. CONCLUSION

The motivation for pushing a bipolar transistor to work into an avalanche region is stated at the beginning. In order to enable designers to have confidence in their design, models have to be accurate enough to model complex AC device physics occurring in the region where impact ionization plays an important role. In order to verify models, AC characterization technique is developed. It is based on quantifying avalanche conductance, g_μ. Complex influences of combining avalanche breakdown and AC signals have its repercussions on unilateral power gain, the stability factor and the maximum available gain. Namely, value of the unilateral power gain and the maximum available gain can drastically collapse when the device enters avalanche region. This effect is strongly dependent on the operating frequency, though it occurs in all sorts of bipolar transistor devices. Measurements of the modern industrial devices were presented. It is shown that the Mextram 504.7 model successfully models all types of characteristics when various effects are combined. In that sense Mextram's extended avalanche flag which combines influences of avalanche and quasi-saturation is demonstrated.

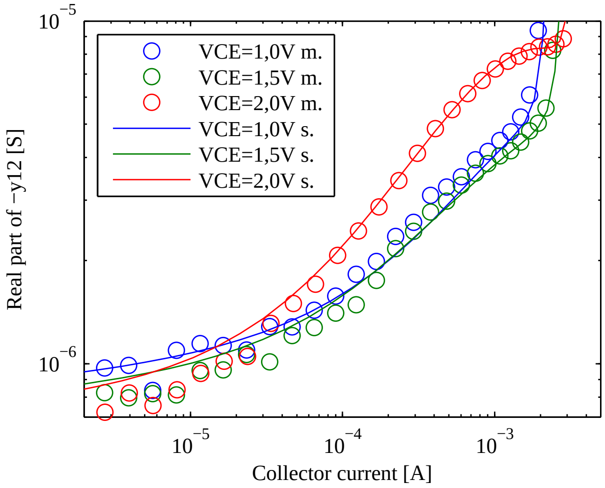

Fig. 10. Measured and simulated real part of $-y12$ parameter as a function of collector current, for three values of the collector-emitter bias voltage when extended avalanche flag EXAVL=1.

ACKNOWLEDGEMENT

The authors would like to thank the Semiconductor Research Corporation (SRC) and Texas Instruments Inc. on supporting the RID-1335 project.

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