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Implementation of a Large-Signal HBT Model in Libra^{TM}

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Abstract

This paper describes novel techniques for the implementation of a practical large-signal HBT model into the popular commercial microwave CAD package, Libra^{TM}. These techniques are applied to a modified Gummel-Poon (GP) SPICE HBT model described in [1]. The model takes into account the well known self-heating and transit-time effects present in HBTs [1-5]. In particular, the excess phase factor (PTF) has been added to the built-in GP model of Libra^{TM} (Series IV, V. 6.0) using an ideal delay. Furthermore, only built-in linear and nonlinear Libra^{TM} elements are utilized to account for various physical phenomena described by the model. Simulated and measured results are compared for a 6.5x3μm^2 GaInP/GaAs HBT under DC, small-signal from 1 to 40GHz, and large-signal conditions at 12GHz in order to assess the accuracy of the model.

Introduction

HBTs have been shown to be attractive in many microwave and millimeter-wave applications [7]. As a result, there is an ever-increasing demand for a practical and accurate nonlinear model which can be accessed through commercial CAD packages. Although this model has already been incorporated in SPICE, it is more practical for microwave circuit design to use a harmonic balance (HB) based simulator such as HP-EEsof's Libra^{TM}. This is due to faster simulation times using HB compared to transient analysis and the availability of a large library of accurate frequency domain models for distributed elements such as microstrip. Furthermore, designers can take advantage of very accurate electromagnetic (EM) simulators for passive elements and include the results in the overall simulation.

One of the more popular microwave CAD packages is HP-EEsof's Libra^{TM}. Although new user-defined models can be incorporated into Libra^{TM}, this requires entering the equation for the current at each node in the model as well as the charge and its derivative as a function of the applied voltages. This information must be coded in ANSI C and then linked into the Series IV environment which can be a very complicated and time consuming procedure. This paper presents techniques that allow the implementation of a nonlinear SPICE HBT model directly into Libra^{TM} using only built-in elements and avoiding the aforementioned difficulties.

Model Description

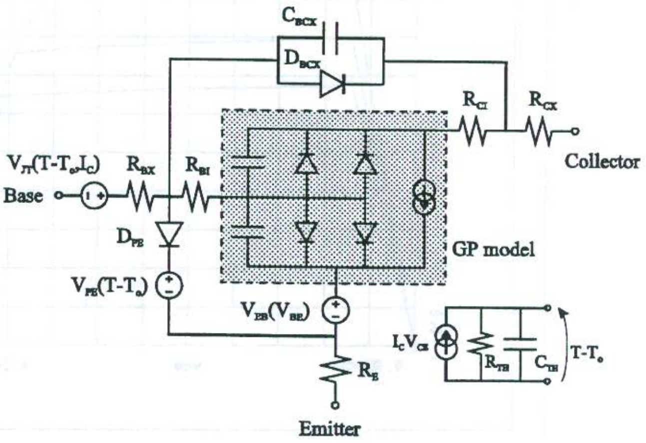

Fig. 1 Modified GP HBT model

This model is a modified GP model as shown in Fig. 1 [1]. It includes the following features which must be incorporated into Libra^{TM}:

1) *Thermal sub-circuit*:

GaAs based HBTs have been shown to exhibit self-heating due to the low thermal conductivity of the GaAs substrate and the high current densities under which the devices can be operated [6]. This self-heating effect is most observable in the static DC I-V curve where the collector current, I_C, as a function of collector emitter voltage, V_{CE}, exhibits a negative slope.

To take this effect into account, a thermal sub-circuit is used to relate the instantaneous power applied to the device with the corresponding rise in junction temperature. This information is then updated to all temperature-dependent sources in the model. To implement this circuit in Libra^{TM}, two linear voltage controlled voltage sources were used to sample V_{CE} and I_C. The nonlinear voltage multiplier (VMULT) was then used to multiply I_C and V_{CE} to obtain the power [8]. A resistor and capacitor are used to simulate the thermal resistance and thermal delay, respectively [1-3].

2) *Transit-time effect*:

The SPICE HBT model incorporates transit-time effects through the use of the GP parameter *PTF*. This parameter is currently not implemented in the Libra^{TM} Series IV V. 6.0 GP model [8]. In general, *PTF* represents the excess phase at the unity current gain frequency and is given by:

$$PTF = excess\ phase\ at\ f = \frac{1}{2\pi \cdot TF} \tag{1}$$

where *TF* is a SPICE GP parameter corresponding to the ideal forward transit time, and *f* is the frequency [9]. In SPICE AC analysis this phase shift is implemented by adding the appropriate delay to the forward transconductance term of the linearized GP model. For SPICE transient analysis, the excess phase is modeled by a second order Bessel function which requires solving a differential equation for the forward collector current in the time domain [9]. To include the effect of *PTF* in the Libra^{TM} model, a delay term given by :

$$TAU = \frac{\pi}{180} \cdot PTF \cdot TF \tag{2}$$

can be added to the forward collector current source, I_{CC}, of the built-in GP model. This can be accomplished by canceling out I_{CC} and replacing it with a delayed version of itself, i.e. $I_{CC}(t\text{-}TAU)$. The following procedure was used to accomplish this task:

I_{CC} of the GP model is given by (3):

$$I_{CC} = I_S\left[\exp(qV_{BE} / (N_F KT)) - 1\right] \tag{3}$$

where I_S is the saturation current and N_F is the collector ideality factor. This current source is located between the internal collector and emitter nodes of the GP model. It has the same form as the current through a diode. In order to cancel it out, all resistors in the built in GP model are set to zero so that the internal base emitter voltage, V_{BE}, can be accessed. The sampled V_{BE} is then connected across the terminals of a diode with the same N_F and I_S as in (3), but with the polarity opposite to I_{CC}. The same diode current is also passed through a linear current controlled current source between collector and emitter terminals with parameter *TAU* equal to the required time delay given by (2). This diode current (with the delay term added) now effectively replaces I_{CC} of the built in GP model. The result is a new GP model which possesses the delay parameter. This is illustrated in Fig. 2.

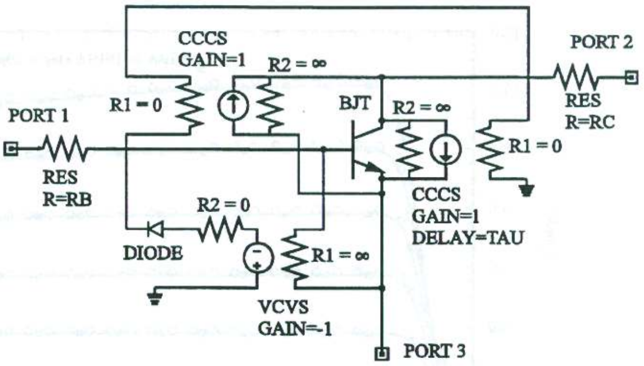

Fig. 2 Circuit used to implement forward delay term.

3) *Nonlinear controlled sources:*

As illustrated in Fig. 1 the model contains three nonlinear voltages sources, V_{JT}, V_{EB}, and V_{PE}. V_{JT} models the decrease in emitter built-in potential as a function of temperature [1,2]. V_{PE} along with D_{PE} model the increase in back hole injection into the emitter with temperature [1]. Finally V_{EB} models the emitter barrier effect [1,2]. These sources were included in the model by using the built-in linear and nonlinear controlled source elements available in Libra^{TM}. A limitation of these sources however is that the controlling equation must be in the form of a polynomial and be a function of only one voltage or current. In order to conform to the elements available, sources not in the form of a polynomial were approximated by a Taylor series. Sources which were controlled by more than one voltage or current were accommodated by making use of the nonlinear voltage multiplier element, VMULT, and separating the function into the sum of two functions in the form of a polynomial. Two controlled sources were then connected in series in order to implement the overall function. All of the above features were implemented in Libra Series IV V.6.0^{TM} to complete the model.

Simulated and Measured Results

In order to verify that the model was implemented correctly into Libra^{TM}, SPICE and Libra^{TM} simulations were compared. The simulated response was also compared with measured results for a 6.5x3μm^2 GaInP/GaAs HBT. The simulated and measured DC-IV characteristic are shown in Fig. 3.

As can be been seen, the Libra and SPICE simulations are identical and the agreement with measurement is very good up to the rated current for this device which was 10mA.

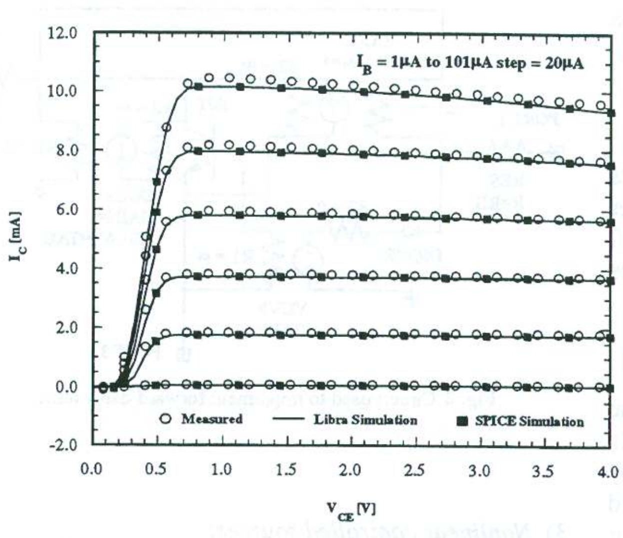

Fig. 3 DC IV curve showing Libra and SPICE simulations as well as the measured response.

Small signal scattering parameters for this device were also measured on wafer from 1 to 40GHz. The simulated and measured results are shown in Fig. 4 at a bias of I_B=78.4μA and V_{CE}=1.5V. Good agreement between simulation and measurement was obtained.

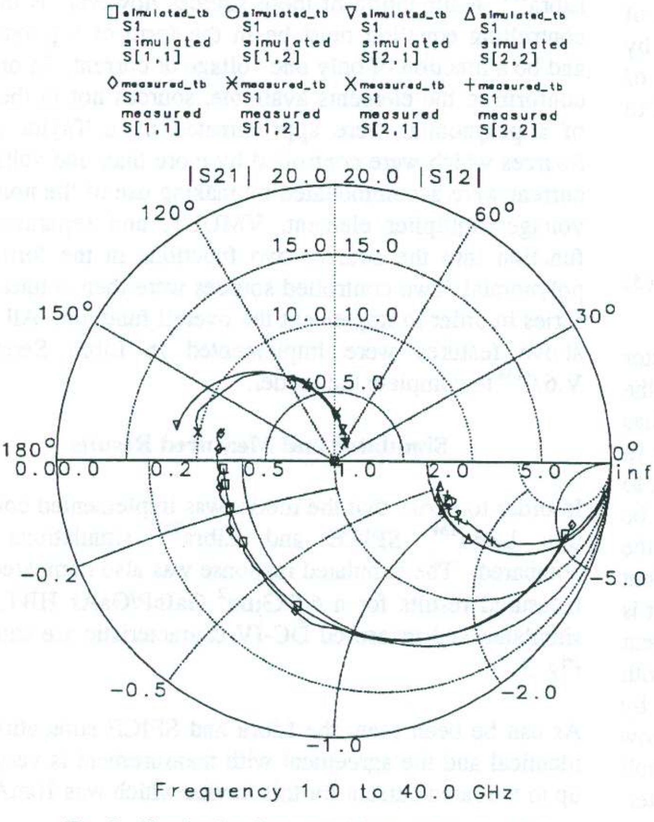

Fig. 4 Simulated and measured S-parameters. I_B=78.4μA, V_{CE}=1.5V.

Further evaluation of the model was carried out by measuring a typical device under large-signal stimulus. A 6.5 x 3μm² HBT was mounted in a carrier with bond wires used to connect the base and collector to 50Ω input and output microstrip lines. The device was biased at the rated current and near cutoff and compression curves were generated. The measured and simulated results for the two bias points are shown in Fig. 5 and Fig. 6. The two results agree very well.

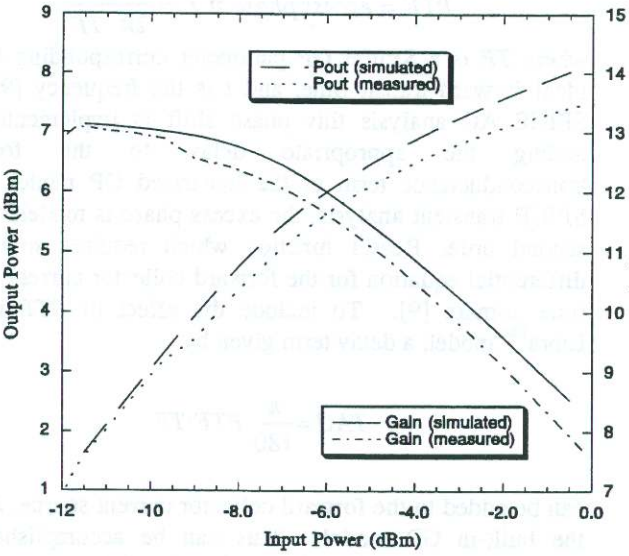

Fig. 5 Simulated and measured P_{out} versus P_{in} at 12GHz biased at the rated current (I_B=100μA and V_{CE}=3.0V).

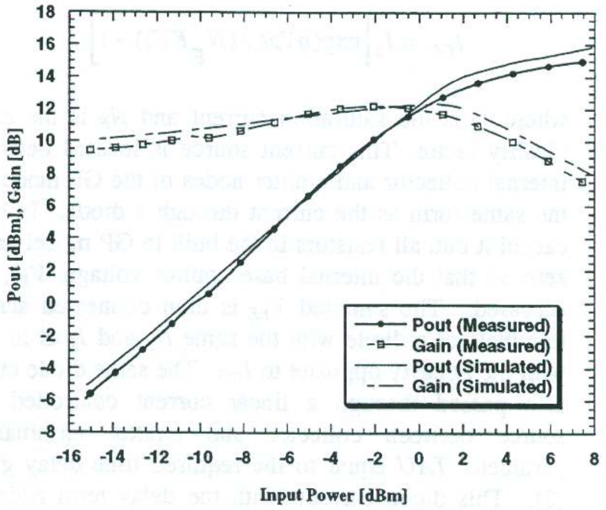

Fig. 6 Simulated and measured P_{out} versus P_{in} at 12GHz biased near cutoff (V_{BE}=1.331V, V_{CE}=3.0V).

Conclusion

A procedure used to implement a nonlinear SPICE HBT model into Libra Series IV^{TM} using only built-in elements has been demonstrated. The model has been compared with measured results under DC, small-signal S-parameter and large-signal (at 12GHz) excitation. Good agreement in all cases has been obtained.

This model provides the user the opportunity to design microwave circuits in a powerful CAD environment. Using Series IV, the circuit designer has the following advantages: convenience and speed of the HB engine, a large library of distributed passive elements, and the ability to incorporate simulated results for passive structures from EM simulators.

Acknowledgments

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