Modeling of Current-gain Collapse in Multi-finger HBT's

Akhil Garlapati and Sheila Prasad
Dept. of Electrical and Computer Eng., 418 Dana Research Center,
Northeastern University, 360 Huntington Avenue, Boston, MA 02115, USA.
Ph. No. 617-373-3010, Fax No. 617-373-8970, e-mail : prasad@ece.neu.edu

July 6, 2000

Abstract

This paper presents an equivalent circuit model for common-emitter current-gain collapse in multi-finger HBTs. The collapse of current-gain is an undesirable phenomenon, which occurs in multi-finger HBTs when they are operated at high power density. The collapse manifests itself by a distinct abrupt decrease of collector current in the output characteristics of the HBT. Until now, there hasn't been an equivalent circuit model to simulate the current collapse behavior of multi-finger HBTs. In this paper, for the first time, the large-signal Ebers-Moll model is modified to include the effect of current-gain collapse. Hence, the model presented here is a big step towards predicting the behavior of multi-finger HBTs under high power and high frequency operating conditions. Also, the self-heating effect which gives rise to the negative output resistance is included in the equivalent circuit without the use of an external thermal feedback circuit. Hence, the equivalent circuit is much simpler to implement and easier to analyze. Moreover, it includes the phenomenon of current-gain collapse. The model is applied to an InGaAs/GaAs multi-finger heterojunction bipolar transistor (HBT) and the simulated and the measured characteristics are compared in order to validate the model. Both the small signal and large signal models are implemented as user-defined models in the commercial circuit simulator, LIBRA.

1 Introduction

Thermal stability is a very important design criterion for commercial applications where HBT's are operated at high power densities [1]. Under such conditions, thermal considerations become very important for multiple-emitter-finger HBT's [2]. At low collector current, the device has the usual I-V thermal droop and breakdown. However, at higher levels a sharp drop in current is observed with increasing voltage. The reason for this is suggested to be the current hogging by a localized hot spot region in one emitter finger with the turn-on voltage being controlled by the energy gap rather than the emitter resistance. As a result, there is an overall current reduction in the other emitter fingers. Emitter ballast resistors are used in HBT's to maintain more uniform emitter-base turn-on voltages for multiple emitters and to increase the threshold for thermal runaway. However, this sacrifices the performance of the HBT's and increases the cost of fabrication.

In order to understand the current collapse phenomenon and to design circuits which are resistant to this phenomenon, a model for the HBT including the current collapse phenomenon is required. Until now there is no equivalent circuit model to simulate the current collapse behavior of HBTs. For the first time, an attempt is made to develop a unified model for both single and multi-finger HBTs including the self-heating effect and the current collapse phenomenon. Several a approaches that include the self-heating effect in the large signal model have been reported in the past [3,4,5]. These methods involve a complex analysis of the coupling between the electrical and thermal circuits [6].

This paper presents a simple unified analytical large signal model, including the self-heatin effect and the current collapse phenomenon, for an InGaAs/GaAs heterojunction bipolar transistor (HBT). The model that is presented avoids the complex analysis of the coupling between the electrical and thermal circuits by implementing the self-heating effect and current collapse as two different feedbacks from the collector-current to the base with current-controlled voltage sources. A partially analytical approach is used for the extraction of the small-signal model parameters. The combination of analytical and numerical optimization procedures is exploited to accurately extract the model parameters. The large signal model is based on the measured forward Gummel plot and is built over the small-signal model. The overview of the paper follows.

Section 2 presents the small-signal model of the HBT. Section 3 presents the large signal model with an emphasis on the implementation of the self-heating effect and current collapse. Section 4 presents the verification of the model by comparing the simulated and measured characteristics.

2 Small signal model

The small signal equivalent circuit of the HBT used in the present work is shown in Fig. 1. The lumped elements that are added to the intrinsic HBT circuit, as seen in Fig. 1, serve to characterize the frequency response of the HBT's more accurately.

All the parameters of the small-signal model given above are extracted using a partially analytical approach. The parasitic capacitances are extracted from the S-parameters of the HBT under reverse operation. These capacitances are de-embedded from the equivalent circuit and the corresponding Z-parameters are used to extract the remaining elements. The extrinsic and intrinsic base resistances, and the base-collector capacitance are extracted by optimizing the error between the simulated and measured S-parameters.

3 Large signal model

The traditional Ebers-Moll model [3] is modified to incorporate the self-heating effect [7] and the current collapse. This is to avoid the complex analysis of coupling between the electrical and thermal circuits. The advantage of this model is that the analysis of the large signal behavior of an HBT is reduced to a single circuit. The modified circuit is shown in Fig. 2. It is implemented in a commercial circuit simulator, LIBRA.

3.1 Self-heating Effect

The self-heating is included in the model as the first feedback from the collector current to the base with a current-controlled voltage source. The transfer resistance of the dependent source is a variable equal to the applied collector voltage. This feedback reduces the effective base-emitter voltage at high-power consumption, thereby introducing a droop in the collector current as expected at high temperatures. But, the amount of feedback depends on the thermal resistance of the device, and also on the variation of V_{BE} with base-emitter junction temperature under constant collector current. This is implemented in the model by using the resistances R_1 and R_2. The ratio of these two resistances controls the amount of feedback from the collector to the base. The ratio of R_1 and R_2 is given by

$$\frac{R_1}{R_2} = \phi R_{th} \tag{1}$$

where ϕ is a factor representing the variation of V_{BE} with base-emitter junction temperature under constant collector current, and has a range of 1 mV/K to 2 mV/K. R_{th} is the thermal resistance of the device.

3.2 Current Collapse

The current-gain collapse is also simulated by introducing a feedback from the collector current to the base-emitter voltage. From Fig. 2, it is seen that there are two different feedbacks from the collector to the base. This is to allow independent control of current-collapse and self-heating effects. Both the feedbacks from the collector current to the base are comprised of a current-controlled voltage source. The transfer resistance of the dependent source is the difference between the two feedbacks. For the first feedback, the transfer resistance of the dependent source is a variable equal to the applied collector voltage. This is used to simulate the self-heating effect.

The second feedback is used to simulate the current-collapse phenomenon. The transfer resistance for the second feedback is a function of the power dissipated in the device and is given by

$$F_2 = \frac{e^{(V_{ce} * I_c - P_0)}}{1 + e^{(V_{ce} * I_c - P_1)}} \tag{2}$$

Current-collapse occurs under high power operation. However, the bias beyond which the current-collapse occurs follows an almost constant power profile. Hence, an offset equal to this power is given in the feedback transfer resistance of the dependent source and is referred to as the 'offset-power'. Since the feedback is exponential, once the power dissipation level in the device crosses the offset-power in the transfer resistance, the droop in the collector current increases exponentially leading to the simulation of current collapse.

The distributed base-collector junction is modeled by the split base-collector capacitance. The transit time is included in the current gain of the Ebers-Moll model. The various parameters involved in the large-signal equivalent circuit are extracted from the forward Gummel plot, measured using a Semiconductor Parameter Analyzer (HP4145B).

4 Results and Conclusion

The small signal model is verified by comparing the simulated and measured small-signal S-parameters, given in Figs. 3 and 4. It can be seen that there is a good match between the simulated and measured S-parameters.

Figure 5 presents the simulated and measured Gummel-Poon plots and it can be seen that they are an excellent match. The Gummel-Poon plots are plotted for the HBT operating in the low power region. This verifies that the large signal model for DC operation is accurate in the low power region. Figure 6 presents the simulated and measured DC I-V characteristics of the InGaAs/GaAs HBT. It can be seen that there are three regions of operation for the device. In the low power region, the transistor operates normally. The second region of operation is the high current region but below the offset-power level. In this region, the HBT exhibits the negative output resistance behavior. It can be seen from Fig. 6, that the simulated and measured characteristics have an excellent match. This shows that the feedback used to simulate the self-heating effect is accurate. The third region of operation is the current-collapse region. This is the region where the power dissipated in the device is greater than the offset-power. It can be seen that the model accurately predicts the critical collector-current beyond which the current-collapse occurs. It is evident that the measured collector current decreases abruptly in the collapse region and also that the simulated characteristics follow this behavior with an excellent match. This shows that the model accurately predicts the large-signal behavior of the multi-finger HBT in all the regions of operation. The main advantage of the model is that a single circuit is used to predict the behavior of the transistor in all the regions of operation thus avoiding the complex analysis involved in analyzing the interaction between the electrical and thermal circuits as is done in the existing models. Also, this is first time, an equivalent circuit model is used to simulate the current-collapse phenomenon that occurs in multi-finger HBTs.

This paper presents a unified analytical large-signal model, including the self-heating effect and current-gain collapse, for an InGaAs/GaAs heterojunction bipolar transistor (HBT). The self-heating effect and the current collapse in the HBT are simulated as two different feedbacks from the collector to the base with current-controlled voltage sources. This is the first time an attempt is made to model current-gain collapse using an equivalent circuit model. The main advantage of the circuit presented here is that an additional analysis of the coupling between electrical and thermal circuits is not required as is the case with the existing models. The coupling is built into the circuit itself making the analysis less cumbersome compared to the models proposed previously [6]. Both the small-signal and large-signal models are implemented in the commercial circuit simulator, LIBRA, and verified by a comparison of the simulated and measured characteristics of the HBT.

Acknowledgement

This research was supported in part by the National Science foundation under Grant ECS-9529643. The authors wish to thank Professor C. G. Fonstad of the Massachusetts Institute of Technology, Cambridge Massachusetts, USA for providing the laboratory facilities and Rockwell Semiconductors Inc., USA for providing the devices.

References

[1] M. E. Kim, A. K. Oki, G. M. Gorman, D. K. Umemoto, and J. B. Camou, "GaAs heterojunction bipolar transistor device and IC technology for high-performance analog and microwave application," *IEEE Trans. Microwave Theory Tech.,* vol. MTT-37, pp. 1286-1303, 1989.

[2] B. Bayraktaroglou, J. Barrette, L. Kehias, C.I.Huang, R.Fitch, and R.Scherer, “Very high-power-density CW operation of GaAs/A1GaAs microwave heterojunction bipolar transistors,” *IEEE Electron Device Lett.,* vol. EDL-14, pp. 493-495, 1993.

[3] P. C. Grossman and J. Choma, “Large signal modeling of HBT’s including self-heating and transit time effects,” *IEEE Trans. Microwave Theory Tech.,* vol. MTT-40, pp. 449-464, 1992.

[4] L. L. Liou and J. L. Ebel, “Thermal effects on the characteristic of A1GaAs/GaAs heterojunction bipolar transistor using two-dimensional numerical simulation,” *IEEE Trans. Electron Devices,* vol. ED-40, pp. 35-43, 1993.

[5] L. L. Liou, B. Bayraktaroglu, and C. I. Huang, “Theoretical thermal runaway analysis of heterojunction bipolar transistors: junction temperature rise threshold,” *Solid State Electron.,* vol. 39, pp.165-172, 1996.

[6] B. Li, S. Prasad, L. W. Yang and S. C. Wang, “Large signal characterization of A1GaAs/GaAs HBTs,” *IEEE Trans. Microwave Theory Tech.,* vol. MTT-47, Sept., 1999.

[7] A. Garlapati and S. Prasad, “Large Signal Characterization of HBTs for Microwave Applications, including Self-Heating Effects,” *29th European Microwave Conference,* Munich, Germany, 4-8 October 1999.

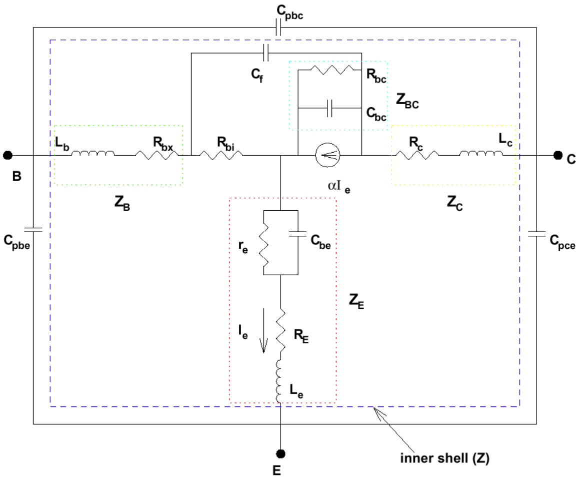

Figure 1: Equivalent circuit for the small signal model

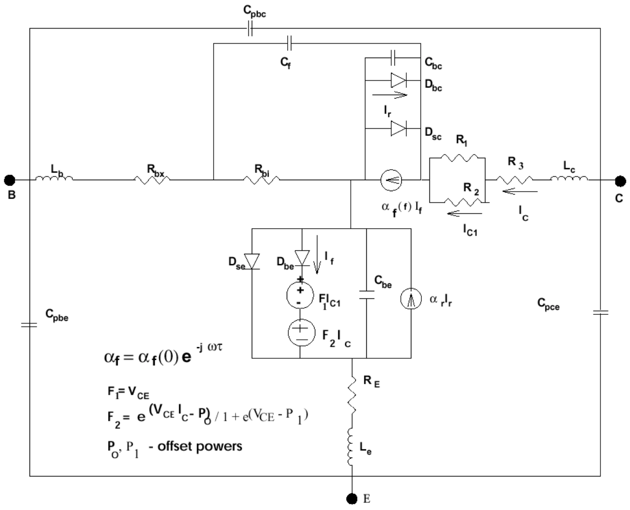

Figure 2: The schematic of the HBT's large signal model

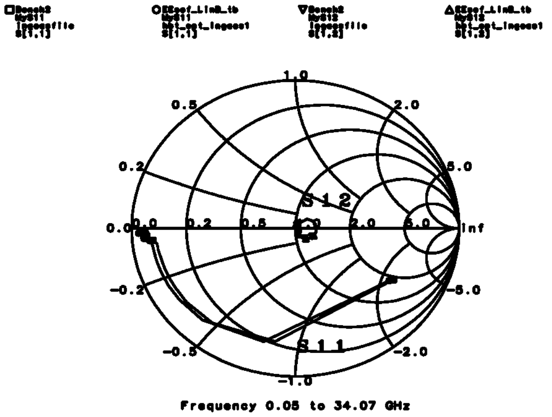

Figure 3: Simulated and measured S-parameters

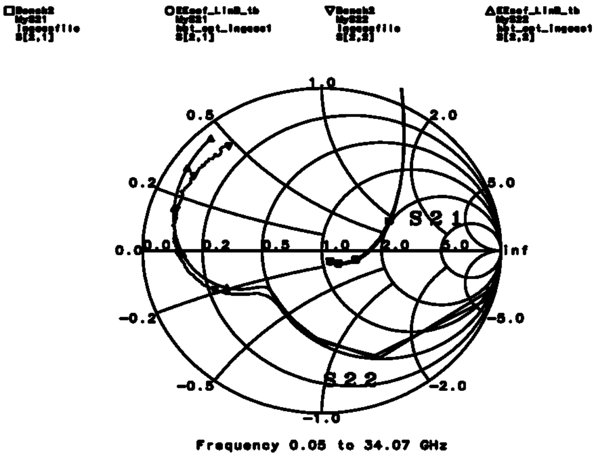

Figure 4: Simulated and measured S-parameters

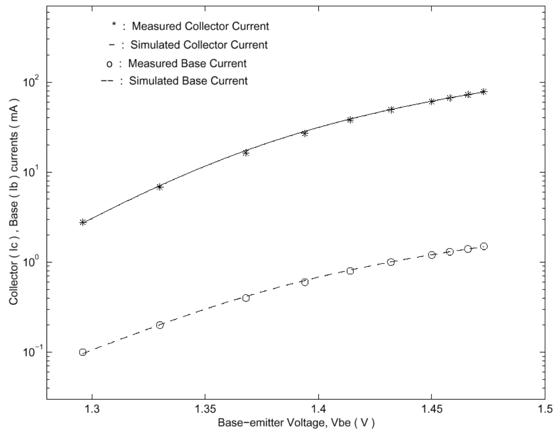

Figure 5: Gummel Plot

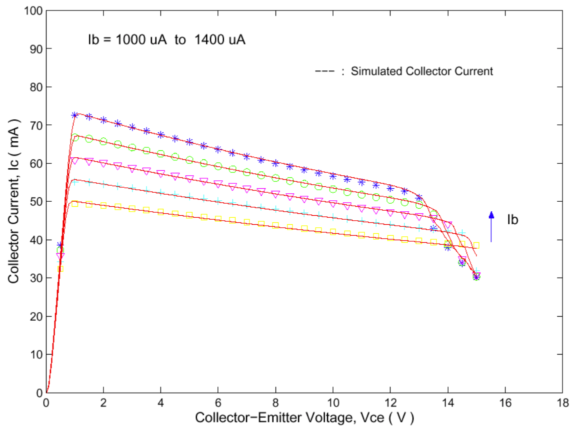

Figure 6: Simulated and measured DC I-V characteristics