LARGE-SIGNAL MODELING OF SELF-HEATING AND RF-BREAKDOWN EFFECTS IN POWER HBTS

C. J. Wei and J. C. M. Hwang
Lehigh University, 5 E Packer Av, Bethlehem PA 18015
W. J. Ho and J. A. Higgins
Rockwell International, 1049 Camino Dos Rios, Thousand Oaks, CA 91360

***Abstract*—A large-signal HBT model including both self-heating and RF-breakdown effects was developed. The model was verified through RF waveform measurements. Using the model, the competing effects of open-base and open-emitter breakdown were analyzed.**

I. INTRODUCTION

Typically, the performance and reliability of power transistors is limited by either by either self-heating or electrical-breakdown effect. Therefore, large-signal power transistor models must properly account for both effects. To date, many large-signal HBT models have included self-heating [1-8], but not the breakdown effect. This is because the breakdown effect is difficult to characterize due to the tendency of the HBT to burn out under dc breakdown conditions and the lack of correlation between dc and RF breakdown characteristics.

Using an RF waveform measurement technique, we have modeled the HBT large-signal characteristics under real operating conditions [9]. In this paper we extend, for the first time, the model to include both self-heating and RF-breakdown effects. The RF breakdown effect will be more critical as improvements are made to reduce the HBT thermal resistance and nonuniformity, so that RF breakdown becomes the limiting factor for HBT performance and reliability [10].

II. MODELING TECHNIQUES

The HBT under test is similar to that in [9]. The emitter area was approximately 360 μm^2. Under a common-emitter configuration, the cut-off frequency and the maximum frequency of oscillation were measured to be 40 and 32 GHz, respectively. The output power was greater than 1 W with a greater than 57% power-added efficiency. Other RF parameters were measured using the waveform characterization technique described in [9]. For RF breakdown, a 2 GHz signal was applied to either the base with the HBT in forward operation, or to the collector with the HBT in reverse operation. In both cases, the opposite electrode was terminated in either 50 Ω or a tuner. As a reference, the dc breakdown characteristics were measured to be BV_{CEO} = 12 V; BV_{CBO} = 19 V; n_B = 6.2. The thermal parameters were obtained from pulsed *I-V* characteristics.

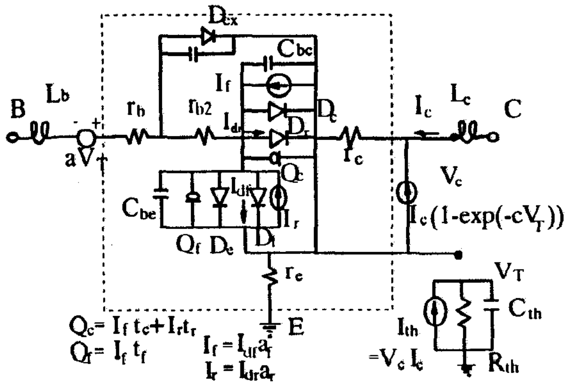

Fig. 1 Present large-signal HBT model.

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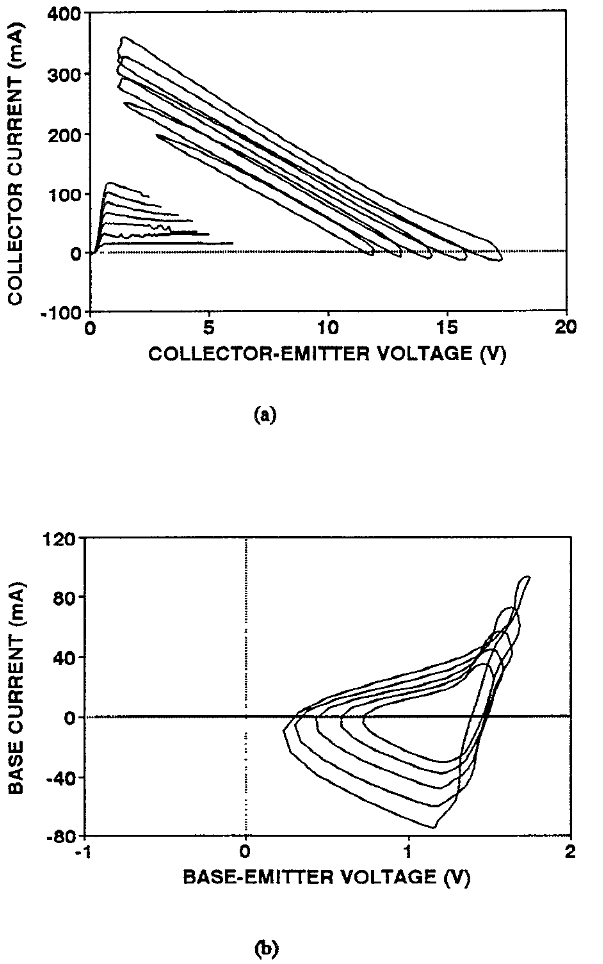


Fig. 2 Measured dynamic (a) load and (b) drive lines at the collector and base, respectively. V_{BE0} = 1.3 V. V_{CE0} = 8 V. P_{IN} = 11, 13, ... 19 dBm @ 2 GHz. The measured dc I-V characteristics are superimposed in (a).

The resulted large-signal model is in the form of an extended Ebers-Moll model as shown in Fig. 1. In addition to the leakage and breakdown parameters, an unique feature of the model as represented by Q_C which accounts for the collector transit time effect which has been discussed in [9]. The self-heating effect is represented by a thermal equivalent circuit which calculates the temperature rise ΔT according to the instantaneous power dissipation $I_C V_C$ and the thermal time constant τ_{TH}. In turn, the reductions in base-emitter voltage and collector current are calculated according to $\Delta V_{BE} = -a\Delta T$ and $\Delta I_C = I_C[1-\exp(-c\Delta T)]$, respectively, a and c being proportional constants. To facilitate large-signal simulation, this model has been incorporated in *LIBRA* [11] in terms of a user-defined element.

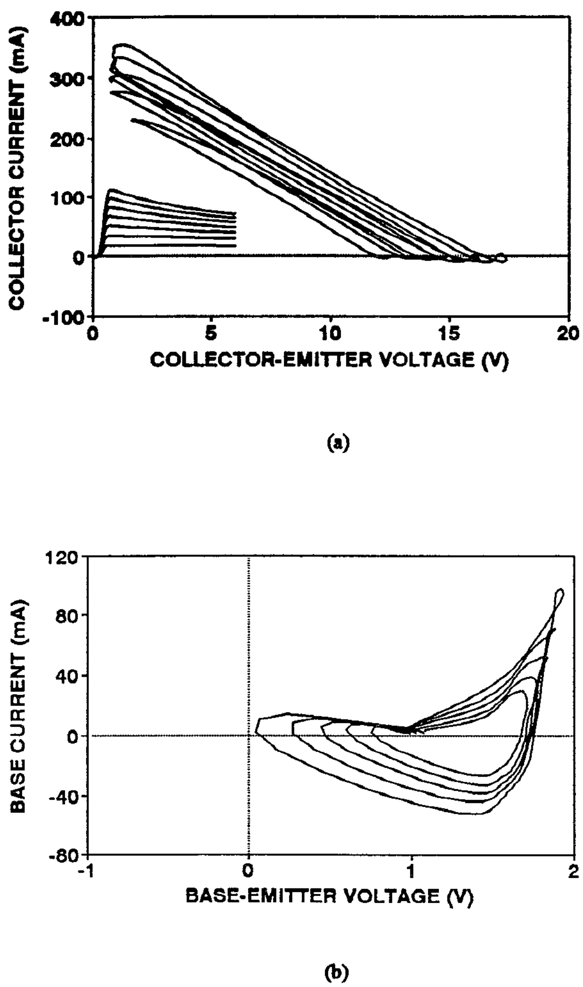


Fig. 3 Modeled dynamic (a) load and (b) drive lines at the collector and base, respectively. V_{BE0} = 1.3 V. V_{CE0} = 8 V. P_{IN} = 11, 13, ... 19 dBm @ 2 GHz. The modeled dc I-V characteristics are superimposed in (a).

III. Results and Discussion

Figs. 2a and 2b show the measured dynamic load and drive lines (contours) at the collector and base, respectively, when the input power was stepped from 11 to 19 dBm or 5 dB compression. The measured dc collector characteristics are superimposed on Fig. 2a. In comparison, the range covered by dc characteristics is rather limited in order to avoid strong thermal effect. Figs. 3a and 3b show the modeled load and drive lines, respectively, as well as modeled dc collector characteristics. In general, they are in good agreement with the measured characteristics of Fig. 2.

Fig. 4 shows the RF breakdown characteristics measured with the HBT under reverse operation in which the dc bias conditions were such that I_{B0} = 0 and V_{CE0} = 9 V. This places the quiescent point right at where breakdown can be probed with minimal dc and RF power thereby avoiding burning out the HBT. The resulted RF breakdown characteristics are consistent with dc BV_{CEO} and the emitter minority-carrier injection mechanism.

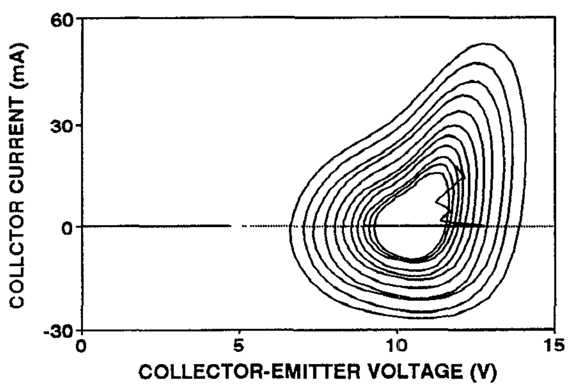
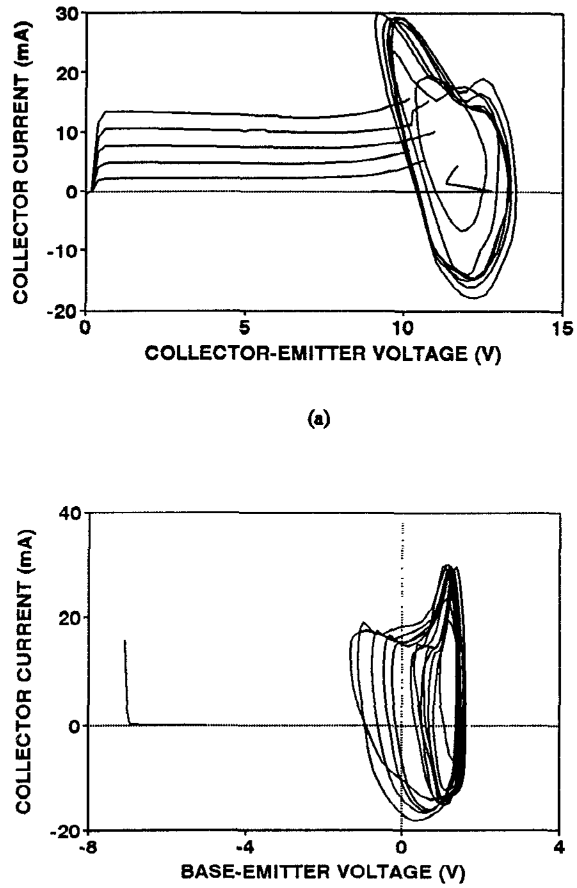


Fig. 4 RF breakdown characteristics with the HBT in reverse operation. I_B = 0. V_{CE0} = 9 V. P_{IN} = 2, 4, ... 14 dBm @ 2 GHz. The dc breakdown characteristics is also included which resembles a zigzag line.

Figs. 5a and 5b show the RF breakdown characteristics at the collector and base, respectively, with the HBT under forward operation in which I_{B0} = 0.2 mA and V_{CE0} = 12 V. Input powers between 8 and 15 dBm were applied to the base while a tuner was connected to the collector. The tuning resulted in nearly vertical load contours which again allowed breakdown to be probed without burning out the HBT.



(b)

Fig. 5 RF (a) collector and (b) base breakdown characteristics with the HBT in forward operation. I_{B0} = 0.2 mA. V_{CE0} = 12 V. P_{IN} = 8, 10, 12, 14 and 15 dBm. The dc collector and base characteristics are superimposed in (a) and (b), respectively.

Both the contours in Fig. 5a and Fig. 5b contain two peaks. By examining the phase relationship of the measured waveforms, it was found that the smaller peak of Fig. 5a at higher collector-emitter voltages corresponds to the smaller peak of Fig. 5b at lower base-emitter voltages. Thus, while the larger peak is apparently caused by the open-base minority-carrier injection as in the case of Fig. 4, the smaller peak is caused by open-emitter base-collector reverse breakdown. However, under such an RF condition, BV_{CBO} = 15 V which is significantly lower than the dc value. Therefore, a large-signal model based on dc breakdown characteristics will significantly underestimate the breakdown current while overestimating the power performance. In addition, the open-base and open-emitter breakdown mechanisms tend to have opposite temperature dependence. Hence, their relative importance will change as the junction temperature rises. This further underscores the importance of incorporating both the self-heating and RF breakdown effects in the large-signal model.

IV. CONCLUSION

In summary, a large-signal HBT model including both self-heating and breakdown effects was developed. The model was verified through RF waveform measurements. Using the model, the competing effect of open-base vs. open-emitter breakdown was analyzed. Such a large-signal model will be critical when the thermal resistance and nonuniformity of HBT is reduced so that RF breakdown becomes the limiting factor for HBT performance and reliability.

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