Development, implementation and verification of a physics-based Si/SiGe HBT model for millimeter-wave non-linear circuit simulations.

S. Bruce, A. Rydberg*,
H. Schumacher, U. Erben**,
J-F. Luy***,
M. Karlsteen, M. Willander****.

*Circuits and Systems Group,
Department of Technology,
University of Uppsala, Box 534,
S-751 21 Uppsala, Sweden

**Department of Electron Devices and Circuits,
University of Ulm, D-89069 Ulm, Germany

***Daimler-Benz Research Center,
P. O. Box 2360, D-89081 Ulm, Germany

****Linköping Institute of Technology,
Department of Physics and Measurements
Technology, S-581 83 Linköping, Sweden

Abstract

A physics-based large-signal model including thermal dependence has been developed for Si/SiGe HBTs. The model takes into account several effects that are important for the operation of Si/SiGe HBTs and is directly related to the parameters in the fabrication process. Using extraction procedures for only a few parameters that inherently are difficult to predict, either due to uncertainties in the fabrication process or due to complex physical relations, a good agreement is found between the model and measurements. The model has been implemented using a commercial CAD-system facilitating design of non-linear Si/SiGe HBT applications. Thus the model has been used to design and predict the behaviour of a doubler circuit operating at 55 GHz with good accuracy.

Introduction

The recent progress in SiGe technology which has yielded HBTs with f_{max} of 160 GHz [1], making it possible to design circuits for the important frequency range used in automotive applications. For analysis and implementation of Si/SiGe HBTs in non-linear microwave applications, the access to an accurate physics-based large-signal model with parameters directly related to the fabrication process and describing the physical properties of SiGe is of great importance. The thermal properties of the Si/SiGe HBT which plays an important part in power applications has also to be taken into account in a model. Such model has been developed and it is now used for the design and optimization of Si/SiGe HBT millimeter-wave frequency doublers operating at 55 GHz.

Model

A modified Ebers-Moll model, having transit time delay added to the current generator, can be shown to sufficiently model HBT transistors at microwave frequencies [2]. The model has the benefit of taking into account the physical properties of the transistor and of having only a moderate amount of components. Also of importance is that variation of the technological parameters can be accounted for.

The implementation of the model has been done in a SPICE-like simulator using MDS from Hewlett Packard. A special feature called SDD (Symbolically Defined Device) has been used for modelling the intrinsic part of the transistor (the shaded part in Fig. 1a shows a schematic of the modelling). Embedding the intrisic part is a shell composed of lumped circuit elements which accounts for the extrinsic transistor (elements outside shaded part in Fig. 1a) and also for pad parasitics.

By utilizing the ability to control the current inside the SDD via equations, it is possible to mathematically create a discrete analogy to the processes occuring. Thanks to this, the ideal electron and hole injection currents in each junction are treated separately which makes the modelling of the heterojunctions straightforward. Furthermore, the common base amplification factor can be decomposed. The factors α_F and α_R no longer need to account for the emitter injection efficiency, but only for base transport factor and a possible bulk breakdown in the space charge regions.

The current generators I_{LCB} and I_{LBE} have been added to empirically model high injection effects and the surface currents occurring on a mesa device structure. The capacitances C_{BE} and C_{BC} have been calculated using the SPICE model for junction depletion capacitances taking into account charge compensation in the collector space charge region which occurs at high collector currents for the base-collector capacitance C_{BC} [3].

Thermal modelling has been accomplished by creating a versatile interface via the SDD. Thanks to this, it is possible to use different complexities in the thermal model; from a lumped thermal resistance to non-linear models derived from FEM-simulations, see Fig 1b.

Parameter Extraction and Verification of Model

The analytical expressions which the model parameters are based on are useful for a first estimation of transistor behaviour. Starting values for the parameters are calculated from given device geometries, layer structure and known semiconductor properties. Due to the complexity in the physical relations governing the semiconductor and to uncertainties in the fabrication process, some of these parameters that are used in the calculations inherently contain errors. Measurements are therefore needed to adjust certain parameters and to verify the accuracy of the calculations.

The measurements, performed at a known ambient temperature, result in Gummel, I-V-plots and S-parameter curves at different bias. Desirable is to measure the S-parameters at low and high I_C and at least one intermediate value to get information of transistor behaviour at the most important bias levels.

The fitting of parameters is then done in a two-step process where initially only the technological parameters are allowed to vary within limits known from the fabrication process. Following this, elements in the equivalent circuit that do not directly relate to the intrinsic transistor are varied to further improve the accuracy.In order to verify the model, parameters fora 1µm×20µm emitter-area HBT with device geometry and layer structure described in ref. [4] were calculated and further tuned for accuracy using the approach described above.

Using the same analytical expressions that were used for calculating the model parameters, the IV-characteristics and S-parameters are also simulated, see Fig. 2 and 3. As can be seen in Fig. 2 and 3, the simulated results agree with both the DC and RF measurements. The slightly sharper kink for simulated IV-characteristics in Fig. 2 at low V_{CE} and high I_C compared to the measured data is likely caused by the Kirk-effect [5]. The typical decrease in β at high I_C with increasing V_{CE} is caused by the self heating effect [3].

The model has also been used to design an active frequency doubler [6] and a comparison between measured and simulated data for this component can be seen in Fig. 4. The doubler is operating at a frequency of 55 GHz. This is a higher frequency than the transistor has been characterised to. Still, the extrapolated data show good agreement with measurements.

Conclusions

We have presented a physics-based large-signal Si/SiGe HBT model which uses data given from the fabrication process for finding the model parameters. With fitting of a few parameters it is possible to accurately model the large signal behavior up to millimeterwave frequencies.

Acknowledgement

The authors wishes to thank U. Spitzberg for help with measurements, M. Birk and R. Schnitzer for technical assistance, J. Schneider for useful discussions, K.M. Strohm for continuous technological support, H. Kibbel for layer growth, A. Schüppen and A. Gruhle for essential comments regarding the HBT process and D. Eisbrenner for technical support. The Swedish Board for Industrial and Technological Development (NUTEK) and the ISS90 foundation are acknowledged for financial support.

References

[1]: A. Schüppen, U. Erben, A. Gruhle, H. Kibbel, H. Schumacher, and U. König, “Enhanced SiGe Heterojunction Bipolar Transistors with 160 GHz-f_{max},” IEEE Intl. Electron Devices Meeting (IEDM ‘95) Tech. Dig., pp. 30.4.1-30.4.4, 1995.

[2] D. A. Teeter, J. R. East, R. K. Mains, and G. I. Haddad, "Large-signal numerical and analytical HBT models," IEEE Trans. Electron Devices, vol. 40, no. 5, pp. 837-845, May 1993.

[3] Q. M. Zhang, J. Hu, J. Sitch, R. K. Surridge, and J. M. Xu, "A new large signal HBT model," in 1994 IEEE MTT-S Int. Microwave Symp. Dig., San Diego, California, May 1994, pp 1253-1256.

[4] A. Gruhle, H. Kibbel, U. König, U. Erben, and E. Kasper, "MBE-grown Si/SiGe HBTs with high β, ft, and fmax," IEEE Electron Device. Lett., vol. 13, pp 206-208, 1992.

[5] S. M. Sze, "Physics of semiconductor devices," 2nd ed., p. 145, John Wiley and Sons, 1981.

[6] S. Bruce, M. Kim, A. Rydberg, K. M. Strohm, and F. Beiβwanger, "On the design of a 55 GHz Si/SiGe HBT frequency doubler operating close to F_{max}," submitted for presentation at EuMC, Prague, Czech Republic, 1996.

FIGURES

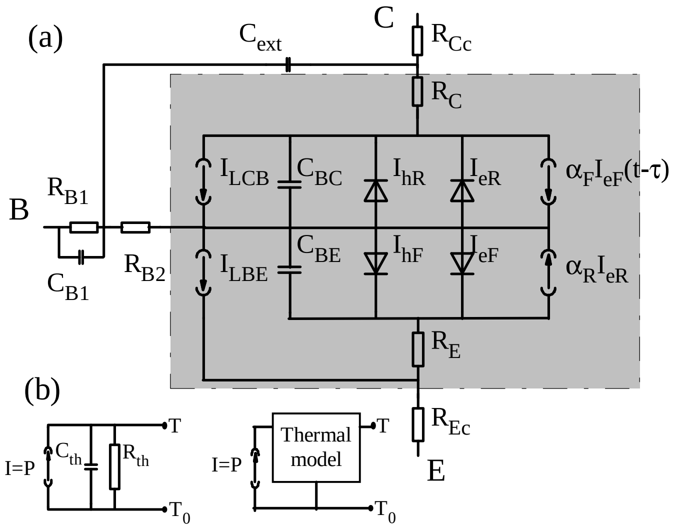

Fig. 1. Large signal HBT model: (a) electrical model, (b) examples of thermal equivalents for the circuit.

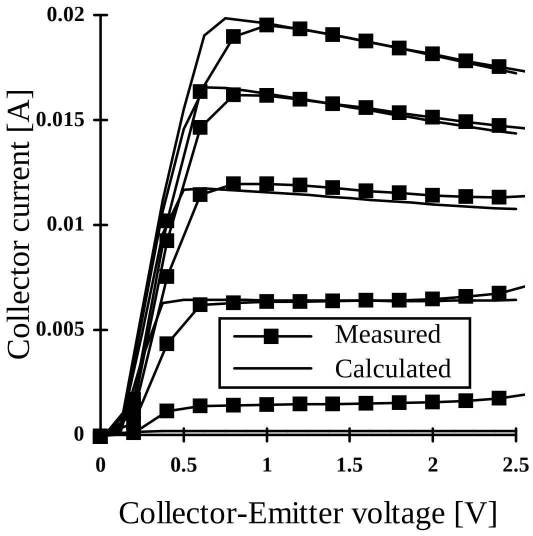

Fig. 2. Measured and calculated I-V characteristics varying I_B from 50 to 250 µA.

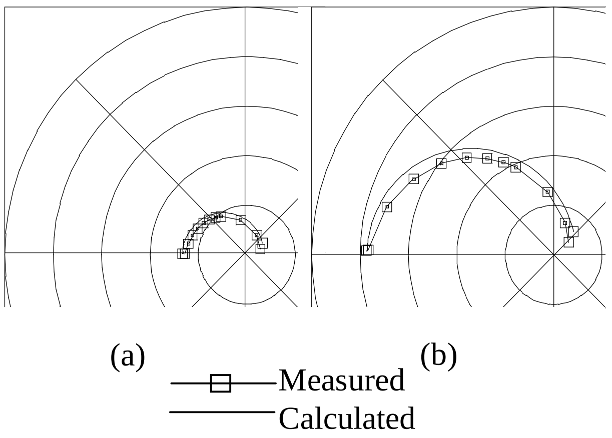

Fig. 3. Measured and simulated S_{21} from 45 MHz to 50 GHz. DC-bias is 3V, 1mA (a) and 3V, 10mA (b). Full scale of the plot is 10.

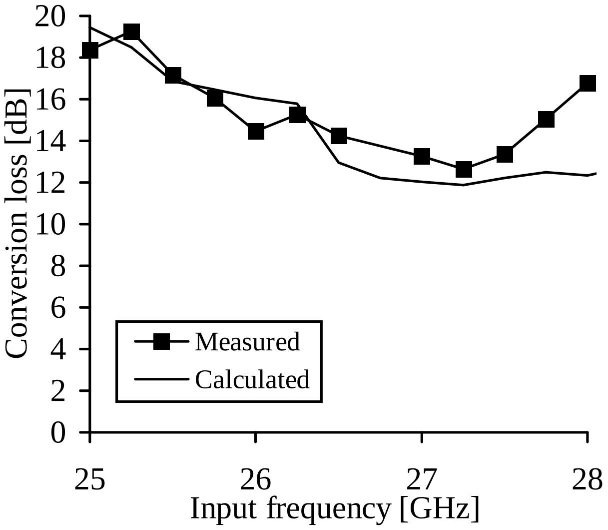

Fig. 4. Conversion loss for an active frequency multiplier.