NONLINEAR MODELLING OF SIGE HBTS UP TO 50 GHZ

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ABSTRACT

A new large-signal model for SiGe HBTs is presented that includes nonideal leakage currents, Kirk-effect, and thermal behavior. The parameters are extracted from measurements using a special procedure. The model yields excellent accuracy for DC and S parameters up to 50 GHz. It proved its usefulness in MMIC oscillator design.

INTRODUCTION

Recent developments in the area of Si/SiGe/Si Heterostructure Bipolar Transistors (HBTs) led to f_{max} and f_t values of 160 GHz and 116 GHz, respectively [1, 2]. This qualifies the HBT as a key component in the development of microwave Si-based MMICs. The most critical issue in MMIC design is the accurate modelling of the active devices. This is true particularly for highly nonlinear circuits such as oscillators.

Compared with the MESFET, large-signal HBT modelling is still in its infancy. Due to the more complicated equivalent-circuit topology, determination of the elements from measurements requires highly-sophisticated extraction procedures. On the other hand, the common bipolar large-signal descriptions need to be extended to cover the microwave transistor structures. Most commercial and AlGaAs HBT models [3, 4, 5] do not consider the Kirk effect. For an accurate modelling of a double-heterojunction HBT (e.g. SiGe-HBT), however, this phenomenon has to be taken into account, because the additional heterojunction at the base-collector interface leads to a pronounced Kirk effect.

In this paper, a novel model is presented. Its special features are

- A full implementation of the Kirk effect
- Temperature-dependent DC characteristics
- Nonideal leakage currents (saturation)
- Reliable extraction of extrinsic elements by means of a field-theoretical approach.

DC Modelling and Technology

The nonlinear model (Fig. 1) is based on the well-known Gummel-Poon (GP) integral base-charge bipolar model [6]. Enhancements regarding the temperature behavior are implemented [5]. Optimum operating conditions for HBTs are at high current densities ($J_C > 10^5$ A/cm^2) [7]. This makes it necessary to

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take the Kirk effect into account. In the standard bipolar-junction transistor (BJT) model only high injection is considered. Because of the extremely high base doping ($N_A > 10^{20}$ cm^3) this effect can hardly occur in SiGe-HBTs but, on the other hand, the Kirk-effect gains more influence. At high current densities and low base-collector voltages, the electrons cannot drift fast enough over the base-collector space-charge region and, therefore, partially neutralize the ionized donors in this region. As a result, the neutral base width of the device is increased, which leads to an increased transit-time τ_f. This causes the unwanted base pushout and a drop-off in current gain. We include this effect by modifying the integral over the base charge. Because in a HBT the Kirk effect starts more abrupt than in the BJT the well-known equations [6, 8] need to be modified.

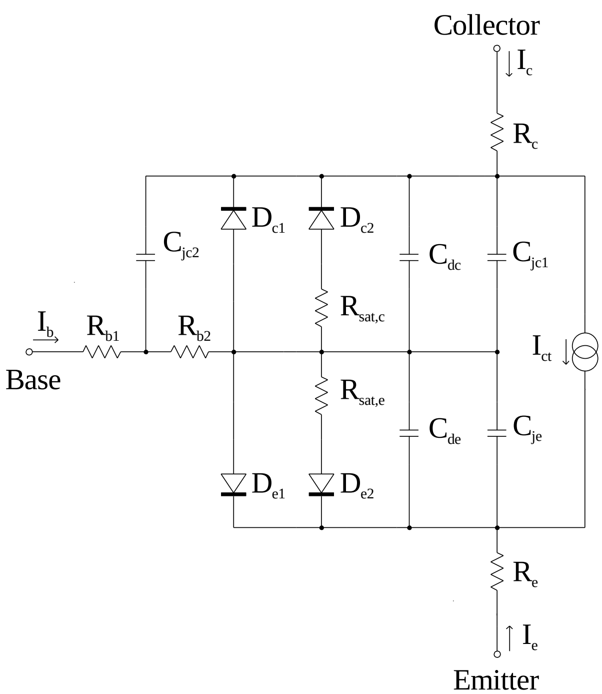

Figure 1: Extended intrinsic Gummel-Poon Model for the SiGe HBT

The HBT type under investigation relies on the double-heterojunction SiGe-base approach with inversion of the doping levels ($N_{base} > N_{emitter}$). Due to the high base-doping level the base sheet resistance is as low as 550 Ω/☐. Transistors with six 1×10 μm^2 emitter fingers achieve f_{max} values of about 85 GHz (MAG).

Figs. 2 and 3 present simulated and measured data for output characteristics and Gummel plot.

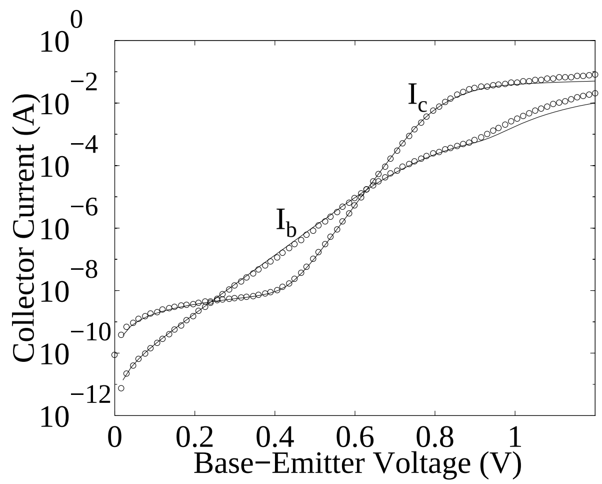

Figure 2: Measured (○) and modelled (-) Gummel plot of the SiGe HBT

In comparison with the standard BJT one observes significant deviations in the high collector-current regime as well as in the low base-current region. Due to the low-temperature passivation process in conjunction with the double mesa surface relatively high leakage currents occur, which are dominated by the current flow over the surface. Fig. 1 shows the complete large-signal model. Additionally to the GP model, two resistors $R_{sat,c}$ and $R_{sat,e}$ are included to model the saturation of the leakage currents. Without these resistors satisfying agreement of the DC curves cannot be achieved. Therefore, the Diodes D_{c2} and D_{e2} together with the Resistors $R_{sat,c}$ and $R_{sat,e}$ describe the nonideal behavior of the space-charge region and surface recombination current.

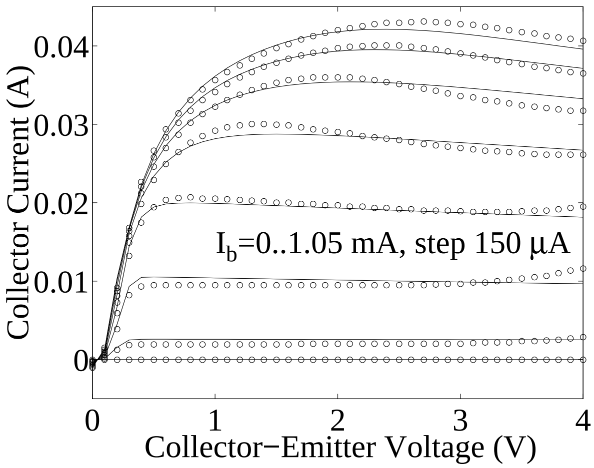

Figure 3: Measured (○) and modelled (-) I-V characteristics of the SiGe HBT

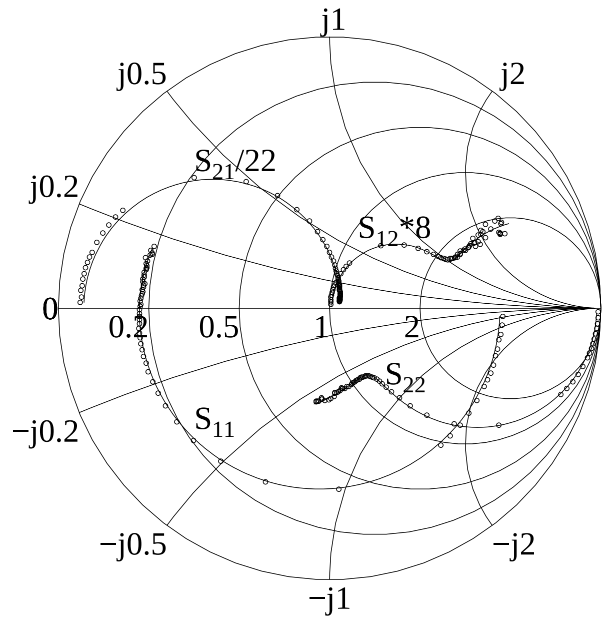

Figure 4: Measured (○) and modelled (-) S parameters (f = 0.05…50 GHz) of the SiGe HBT

RF MODELLING

The values of the RF-relevant elements were found using small-signal extraction by analytical methods. Additional open-collector and cut-off measurements are performed. One important issue is the accurate determination of the extrinsic elements. Deviations at this point cannot be corrected elsewhere and lead to non-physical intrinsic elements. For the SiGe-HBT studied here, some values of the extrinsic and intrinsic elements are rather small, which causes the Z/S/Y matrices that are required for the deembedding procedure of the model to be ill-conditioned. Therefore, in addition to the common measurements field-oriented simulations of the transistor periphery were performed. This enables one to obtain reliable values for the extrinsic elements and to estimate the influence of passivation, the depth of etching etc.. Multi-bias measurements at 100 bias points were performed. The extracted values could be directly implemented in the large-signal model. Fig. 4 shows the measured and simulated S parameters for a typical operating-point (I_b = 450 µA, I_c = 26 mA). Excellent agreement is found.

RESULTS

Using the new model in conjunction with large-signal simulations, we designed a monolithically integrated LC-oscillator [9]. For fabrication, the Daimler-Benz SiGe process was used. The nominal value for the oscillating frequency was 38.25 GHz. Five oscillators on the same wafer were measured. The maximum output power was 2 dBm. Apart from the fact that the output power is not yet satisfying the agreement regarding frequency is excellent. Maximum relative deviation from the nominal frequency is 1.1% (37.818 GHz to 38.680 GHz). This proves usefulness and accuracy of our model.

CONCLUSIONS

The results demonstrate that the standard nonlinear BJT model can be modified to describe also the microwave HBT case. For SiGe HBTs, non-ideal diodes, Kirk effect, and temperature dependence need to be accounted for. A special procedure is applied to extract the small-signal equivalent-circuit parameters. The new model yields excellent accuracy in RF-behavior for frequencies up to 50 GHz. It can be implemented in the common non-linear microwave CAD tools and software and was successfully employed with MMIC oscillator design.

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