S-Parameter Simulation of HBTs on Gallium-Arsenide

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Abstract

We present two-dimensional simulations of one-finger power Heterojunction Bipolar Transistors (HBTs) on GaAs. Several important physical models are discussed. We demonstrate good agreement of simulations of four different types of devices with measured data in a wide temperature range. In addition, we were able by accounting properly for self-heating to simulate correctly the output device characteristics. Finally, we simulated S-parameters with our two-dimensional device simulator at 5 GHz and calculated them for the range from 0 to 20 Ghz using T-like eight element small signal equivalent circuit. A comparison of simulated and measured S-parameters is presented in the paper.

1. INTRODUCTION

Heterojunction Bipolar Transistors (HBTs) on GaAs are of significant importance for mobile telecommunication systems applications. Due to their ability to handle high current densities they are quite suitable for use in power amplifiers [1]. Accurate simulation of the electrical behavior of HBTs gives deeper understanding of the underlying device physics and aims to save expensive technological efforts while improving the device performance.The two-dimensional device simulator MINIMOS-NT [2] is extended to deal with different complex materials and structures, such as binary and ternary semiconductor III-V alloys with arbitrary material composition profiles. Various important physical effects, such as band gap narrowing, surface recombination, and self-heating, are taken into account. Our simulations of one-finger power HBTs on GaAs [4] deliver results which are in good agreement with experimental data for several device structures in a wide temperature range.
Recently, we extended our work with S-parameter simulation next to the DC simulations. Our approach is similar to the one used in [5] where it has been successfully applied to RF-High Electron Mobility Transistors (HEMTs). We found that the physics-based calculation of Y- and S-parameters with MINIMOS-NT by a small signal approach delivers results in good agreement with measurements for the respective HBTs.

2. PHYSICAL MODELS

We have developed a new physically-based analytical band gap narrowing model [6], applicable to compound semiconductors, which accounts for the semiconductor material, the dopant species, and the lattice temperature. However, this well-known phenomenon in the silicon world is widely neglected in III-V simulations, even though it is well-pronounced, especially in the case of p-doped materials.
As the minority carrier mobility is of considerable importance for bipolar transistors, a new universal low field mobility model has been implemented in MINIMOS-NT [7]. It is based on Monte-Carlo simulation results and distinguishes between majority and minority electron mobilities. We found that neglecting this effect can result in underestimation few times of the electron mobility in the GaAs base of our HBTs and therefore result in significant overestimation of the extracted base resistance.

3. HETEROINTERFACES AND SELF-HEATING

Considering the nature of the simulated devices (including abrupt InGaP/GaAs and AlGaAs/InGaP heterointerfaces) and the rising high carrier temperatures we use sophisticated thermionic-field emission interface models [8]. At the other (homogeneous or graded) interfaces constant quasi-Fermi levels were assumed. To account for self-heating effects the lattice heat flow equation is solved self-consistently with the energy transport equations (system of six partial differential equations). The thermal conductivity and the specific heat are expressed as functions of the lattice temperature and in the case of semiconductor alloys of the material composition.

4. SIMULATION RESULTS

Four different types of HBTs have been analyzed to obtain one concise set of model parameters, used in all simulations. Starting with the traditional AlGaAs/GaAs HBT (see Fig.1), later on referred to as Dev. 1, continuing with the next ingredienting InGaP layers (Dev. 2 and Dev. 3), and concluding with state-of-the-art InGaP/GaAs HBTs (Dev. 4). The devices vary in layer thickness and doping. At the first stage Gummel plots have been obtained, e.g. see Fig.2 and Fig.3 where the results for Dev.2 and Dev.4 are shown. Furthermore, very good agreement for the reverse Gummel plots has been achieved, e.g. the comparison with measured data for Dev.3 shown in Fig.4.
However, in the case of simulation of the output HBT characteristics one meets severe problems to achieve realistic results, especially in the case of power devices, which in fact is the case with the HBTs considered in this work. Note the significant disagreement between simulation without self-heating and the measured results depicted in Fig.5. Nevertheless, we achieved good agreement in the simulation with self-heating. In Fig.6 we present the intrinsic temperature in the device depending on the collector to emitter voltage Vce. In the particular case (Dev.3) demonstrated here it reaches as far as 400 K for thermal resistance of about 400 K/W [3] at the substrate thermal contact. As we already stated in previous work ([4]) such lattice temperatures significantly change the material properties of the device and, therefore, it's electrical characteristics. This confirms the necessity of exact DC-simulations at several high ambient temperatures before including self-heating effects. As shown in Fig.1 excellent agreement between experimental data and simulation has been achieved up to 380 K.
Considering our ability to reproduce correctly the thermal device behavior our work has been extended with RF-simulation to connect DC- and high-frequency device operation. Our approach is similar to the one used in [5] where it has been successfully applied to RF-High Electron Mobility Transistors (HEMTs). By applying small signals to the device terminals calculations of Y- and S-parameters with MINIMOS-NT have been performed. The frequency of 5 GHz has been applied, which ensures extraction close to the operating frequency. The smith/polar charts in Fig. 7 show the comparison of simulated and measured S-parameters of a 90 μm^2 HBT at V_{CE} = 3 V and $I_C \doteq$ 22 mA for the frequency range between 0 and 20 GHz. The calculation is based on a T-like eight-element equivalent circuit model as shown in [9]. It has to be stated that using a conventional modeling of the measured parameters using this eight-element extraction, of S_{22} turned out to be difficult to obtain for the given device. For the extrinsic parasitics for the extrinsic S-parameter calculation by MINIMOS-NT typical values for the technology [10] have been used.
As expected the deviations of measured and simulated S-parameters using MINIMOS-NT are more pronounced than for unipolar devices given the bias point is a typical operation regime of a power device. Since we apply no fitting, but use the deviations to obtain information about the modeling of the HBT, a good coincidence was not expected. Using the extraction above it was found that the physical background of some crucial elements has to be correctly modeled. These are the the small signal elements base resistance R_b and the emitter junction capacity C_{je}, which showed significant deviations on the first approach. E.g., as mentioned in a previous section, the base resistance has been initially overestimated due to the higher majority electron mobility in the base has not been considered. After including the respective mobility model better agreement has been achieved (see the second smith chart of Fig. 7).
For S_{11} good agreement with the measurements has been obtained. The underestimation of the magnitude of S_{21} is partly due to the missing hydrodynamic simulation. S_{22} as expected cannot be modeled perfectly because of limitations from the equivalent circuit chosen. For S_{12} reasonable agreement for this kind of extraction has been achieved.

We have to note that two different approaches in the RF-simulation have been applied. One considers self-heating effects when the small signal is applied. Thus, transient self-heating effects are accounted for into the result. These can be neglected by the second approach when the average device temperature (see Fig.5) is evaluated for a given point of the output device characteristic. The RF-simulations are performed without considering self-heating, but at higher ambient temperature corresponding to the respective calculated intrinsic device temperature. We found the second approach appropriate for RF-simulation as the applied signal is at a frequency high enough not to have influence on the lattice temperature.

5. CONCLUSION

We have presented simulations of power HBTs on GaAs. Several sophisticated models have been used not only for achieving good agreement with experimental DC-results, but to get an insight of high-frequency device behavior based on understanding of the underlying physics. The simulations are of practical interest to aid low-cost improvement of the device performance.

Acknowledgment

The authors acknowledge the support of Dr. W. Kellner, CPR 3, Infineon Technologies AG.

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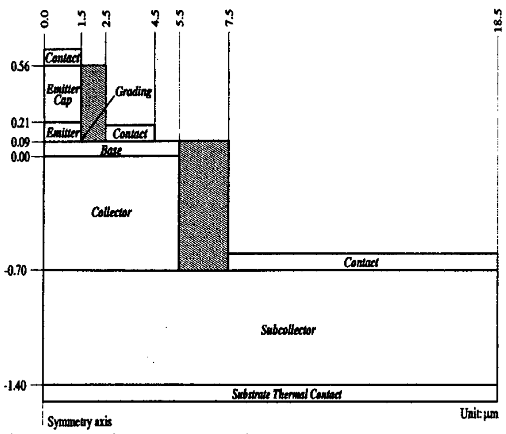


Figure 1: Simulated device structure Dev. 1. In Dev. 2 and Dev. 3 the grading, and in Dev. 4 the emitter consist of InGaP.

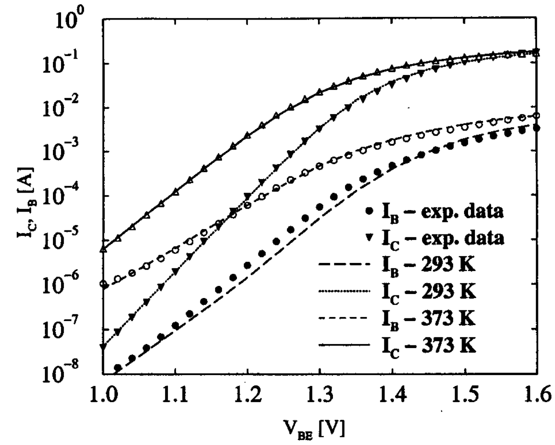


Figure 2: Forward Gummel plots at $V_{CB} = 0$ V. Comparison with measurement data at 293 K and 376 K.

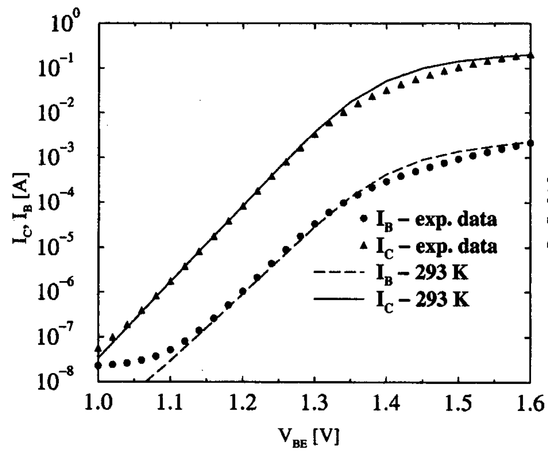


Figure 3: Forward Gummel plots at $V_{CB} = 0$ V. Comparison with measurement data at 293 K and 376 K.

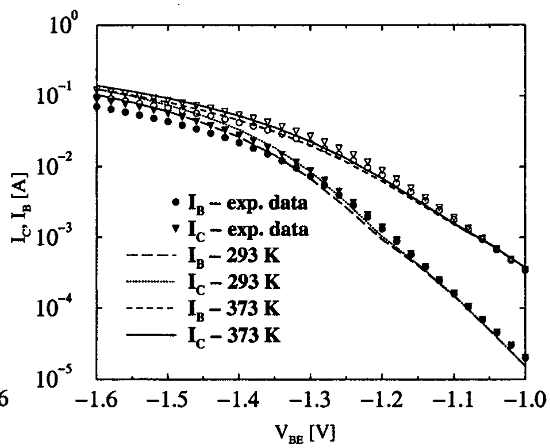


Figure 4: Reverse Gummel plots at $V_{CB} = 0$ V. Comparison with measurement data at 293 K and 376 K.

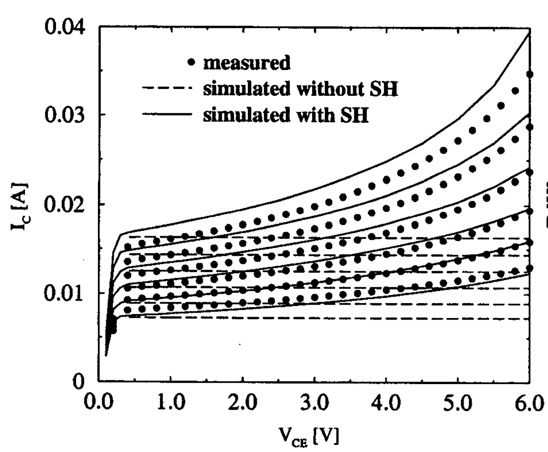


Figure 5: Output characteristics. Simulation with and without self-heating compared to measurement data.

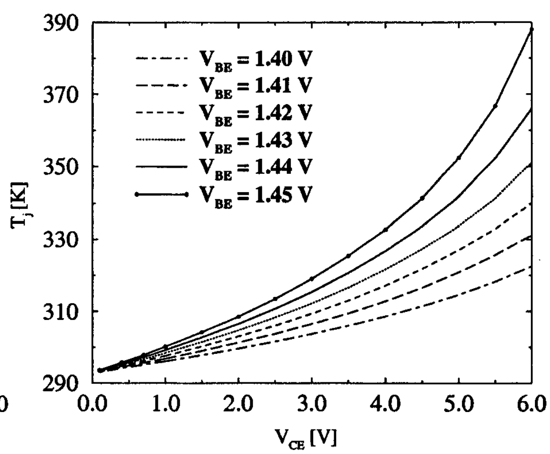
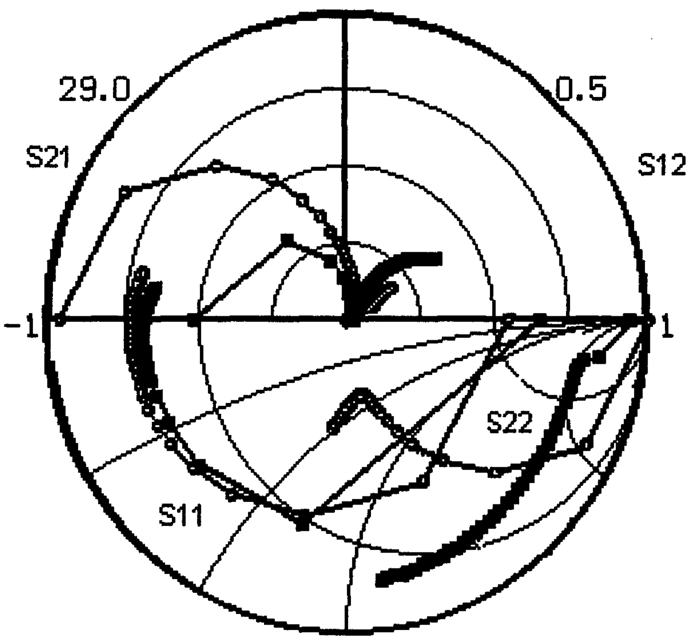


Figure 6: Intrinsic device temperature vs. V_{CE}. Used as ambient temperature for RF-simulation without self-heating.



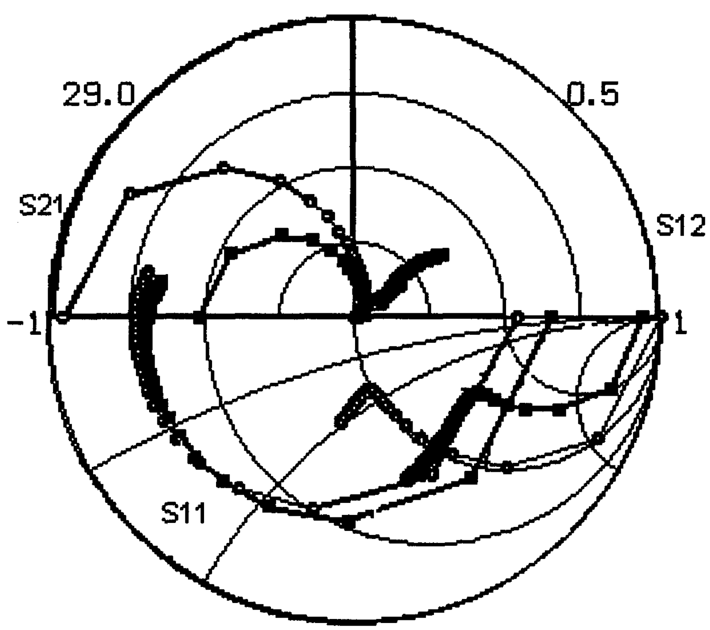


Figure 7: S-parameters in a combined Smith chart (S_{11} and S_{22}) and a polar graph (S_{21} and S_{12}) from 0 to 20 Ghz at V_{CE} = 3 V, I_C = 22 mA. Simulated S-parameters (filled squares) are compared to measured ones (empty circles).