Simulation of InAlAs/InGaAs High Electron Mobility Transistors with a Single Set of Physical Parameters

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Abstract– Simulation results of InAlAs/InGaAs High Electron Mobility Transistors based on both GaAs and InP substrates are presented using the two-dimensional device simulator MINIMOS-NT. Three different HEMT technologies are evaluated by simulation and a single set of physical parameters is verified. The critical interaction of self-heating, impact ionization, SiN surface effects, and material composition is incorporated, which renders the simulation results suitable for the evaluation of device reliability issues. Starting from the analysis of gate-currents the simulation model can quantitatively support the basic understanding of this advanced material system.

INTRODUCTION

InAlAs/InGaAs Heterostructure Field Effect Transistors (HFETs) and Heterostructure Bipolar Transistors (HBTs) are the fastest three-terminal devices existing (1). Data communication systems are being developed beyond 40 Gbit/s and High Electron Mobility Transistor (HEMT) based analogue circuits have been demonstrated beyond 200 GHz (2). The development and verification of device simulation tools for these high speed devices has become desirable, especially for process control in comparison to statistically analyzed measured data. The recent progress in the development of metamorphic HEMT technologies on GaAs substrate gives further rise to the development (3). For industrial application of simulation it is necessary to develop a technology independent set of simulation parameters, as has been demonstrated for pseudomorphic AlGaAs/InGaAs/GaAs HEMTs (4,5).

SIMULATION

Hydrodynamic simulations of InAlAs/InGaAs HEMTs lattice matched to InP substrates and metamorphic HEMTs on GaAs substrate are presented. The physical models are implemented in the two-dimensional device simulator MINIMOS-NT (4) and are demonstrated for gate-lengths between l_g= 100 nm and 200 nm. The $In_yAl_{1-y}As/In_xGa_{1-x}As$ material system is considered for the whole range between x= 0 and x= 1, and for the $In_yAl_{1-y}As$ barrier. All relevant material parameters are modeled composition dependent to allow simulations of pseudomorphic $In_xGa_{1-x}As$ contents with $x \neq 0.53$ in the channel. The parameters are found both by Monte Carlo simulations and process analysis. High field effects especially relevant to $In_yAl_{1-y}As/In_xGa_{1-x}As$ HEMTs are modeled using carrier temperature dependent energy relaxation times and a non-local impact ionization model. For the InAlAs/InGaAs interface description a thermionic field emission model is applied. A complete description of high field effects of holes is included in the simulation. An advanced Schottky contact model is capable of simulating the thermionic field effects dominating at certain V_{GS} voltages. Lattice temperature dependence as well as self-heating effects are included which are found crucial for the understanding of the breakdown behavior, as it is shown below. The impact ionization model uses a second order polynomial for the incorporation of self-heating effects into the generation rate. For the InAlAs/SiN interface Fermi-level pinning is accounted for both by interface charges and recombination on surface states. The quaternary buffer is modeled composition dependent as a function of the ternary constituents in the metamorphic structures. No adjustments of the transport parameters are necessary for modeling metamorphic devices in agreement with material analysis.

DC RESULTS

Fig. 1 shows the simulated and measured extrinsic transfer characteristics for a 2×60 μm composite channel $In_{0.52}Al_{0.48}As/In_{0.68}Ga_{0.32}As/In_{0.53}Ga_{0.47}As$ HEMT for two different substrate temperatures T_{sub} at V_{DS} = 0.75 V. The simulations account for self-heating effects. A close agreement between measurement and simulation can be observed. The increase of the substrate temperature at this bias leads to a reduction of the maximum drain current and further a reduction of the transconductance with rising temperature. The extrinsic maximum transconductance $g_{m\ max}$ amounts to 970 mS/mm at T_{sub} = 300 K and the given bias.

Fig. 2 shows the simulated and measured output characteristics of a 2×30 μm composite channel HEMT with l_g = 150 nm gate-length at T_{sub} = 300 K including self-heating. Note the agreement with measured data, especially for the output conductance. Although suppressed by device design a slight kink effect is visible which is correctly described by the model. In agreement with (6-7), the occurrence of the kink effect is based on the interplay of the pinned Fermi-level at the SiN/InAlAs interface, the length of the source side ledge, and the generation processes in the drain side high field zone due to impact ionization. The latter leads to a recombination-generation equilibrium at the source side, which again is influenced by the trap concentration in the InAlAs barrier and at the SiN surface. With rising lattice temperature, a reduction of the kink is observed. For the transient behavior of the kink, technology specific transient trap information is obtained by *1/f* noise measurements.

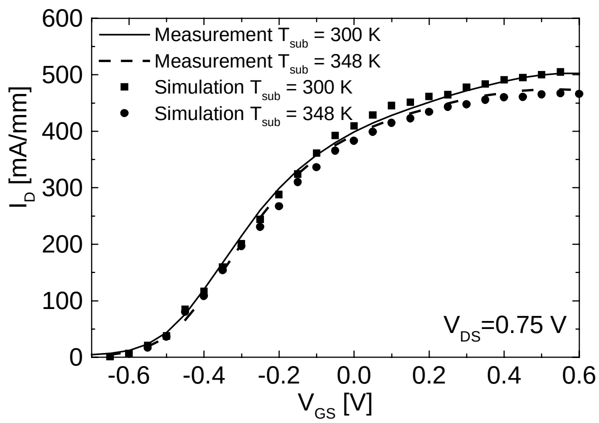

Fig.1: Set of transfer characteristics of a composite channel $In_{0.52}Al_{0.48}As/In_{0.68}Ga_{0.32}As/In_{0.53}Ga_{0.47}As$ HEMT as a function of substrate temperature.

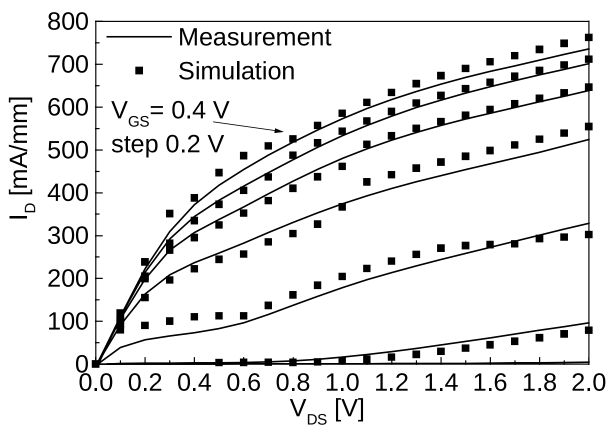

Fig.2: Output characteristics of an $In_{0.52}Al_{0.48}As/In_{0.68}Ga_{0.32}As/In_{0.53}Ga_{0.47}As$ HEMT for T_{sub} = 300 K.

Fig. 3 shows the simulated and measured transfer characteristics of an $In_{0.52}Al_{0.48}As/In_{0.53}Ga_{0.47}As$ metamorphic depletion HEMT for two different substrate temperatures T_{sub}. Gate-length is l_g = 150 nm, gate-width amounts to 4×60 μm. Again good agreement is obtained between simulation and measurements.

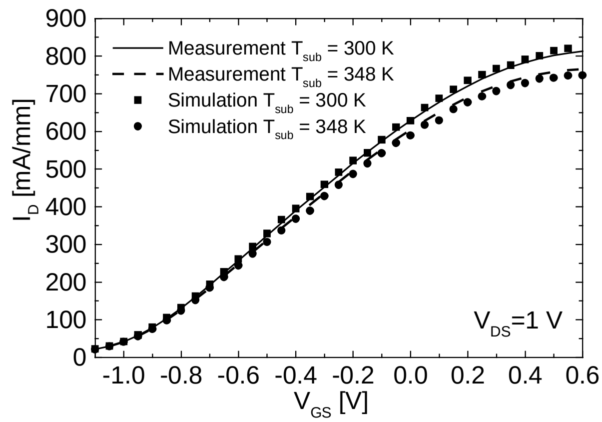

Fig.3: Transfer characteristics of a depletion metamorphic HEMT at two substrate temperatures.

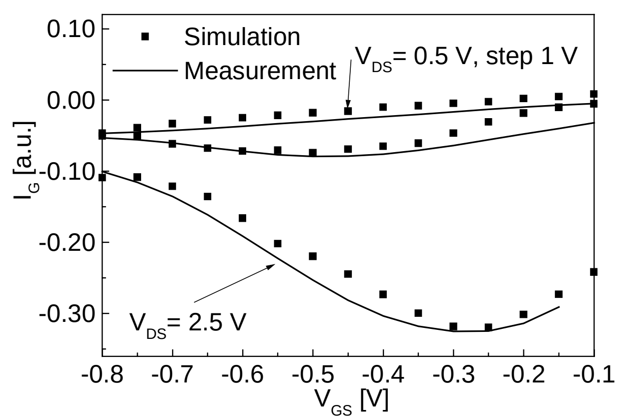

Fig.4: Simulated gate currents I_G and comparison to measurements at T_{sub} = 300 K.

Fig. 4 shows the input characteristics including self-heating at a substrate temperature of T_{sub} = 300 K. A bell shaped behavior of the gate current I_G can be seen as a function of V_{GS} voltage due to the generation of holes by impact ionization in both simulation and measurement. The thermionic field emission Schottky contact model and the impact ionization model give the correct gate currents also in the simulation. I_G measurements for several devices and corresponding simulations as a function of bias and temperature allow to obtain HEMT specific impact ionization coefficients, similar to a procedure known in MOSFETs from substrate currents. We stress the strong influence of the self-heating and the lattice temperature on the results obtained, which renders necessary the inclusion of temperature dependence of the impact ionization coefficients in the simulations.

RF RESULTS

Physics based S-parameters are calculated within MINIMOS-NT and shown for V_{GS} at $g_{m\ max}$ in Fig. 5 for InP based HEMT of l_g = 150 nm. The same parasitics are used for simulations and measurement for correct comparison of extrinsic S-parameters. Fig. 6 shows the current gain cut-off frequency f_T as a function of V_{DS} bias, both simulation and measurement. A maximum f_T = 155 GHz is found both by simulation and measurement and the slope of the decrease of the f_T values with rising V_{DS} voltage is modeled correctly.

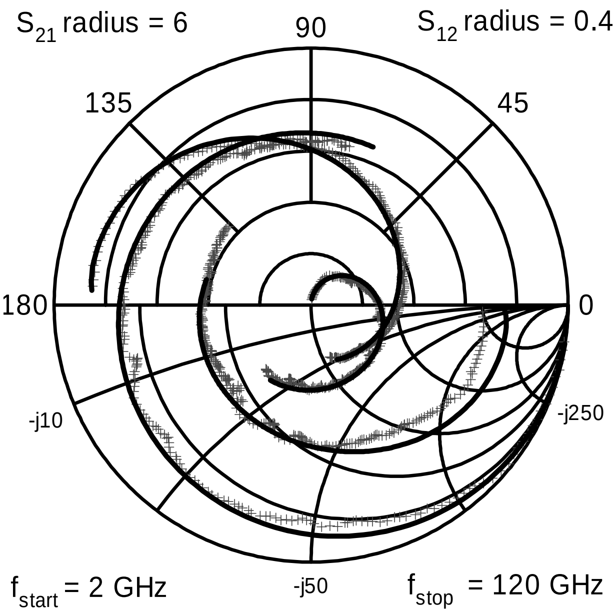

Fig.5: Simulated (-) and measured (+) S-parameters at T_{sub} = 300 K of an InP-based HEMT of l_g = 150 nm.

For the simulation of the bias dependence of the small-signal equivalent circuit elements, the hydrodynamic simulation and the non-constant energy relaxation times are found to be the basis for the agreement.

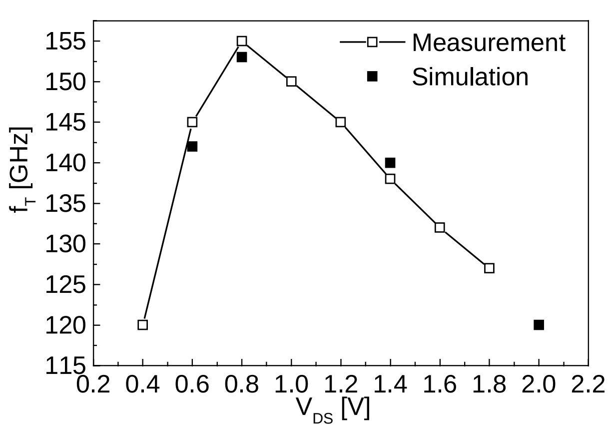

Fig.6: f_T of a 2×50 µm composite channel HEMT as a function of V_{DS} bias.

Special care is taken to model the geometrical gate shape and the exact shape of the SiN-passivation coating the gate contact, which is obtained by SEM images. The small-signal equivalent elements based on physical transient simulation are found in overall good agreement with measurements for various bias. Fig. 7 shows the physically simulated and measured S-parameters for a third technology. A 2×50 µm enhancement $In_{0.52}Al_{0.48}As/In_{0.53}Ga_{0.47}As$ HEMT of l_g = 200 nm from a metamorphic technology is shown. Also for this technology good agreement is achieved both for DC and RF quantities.

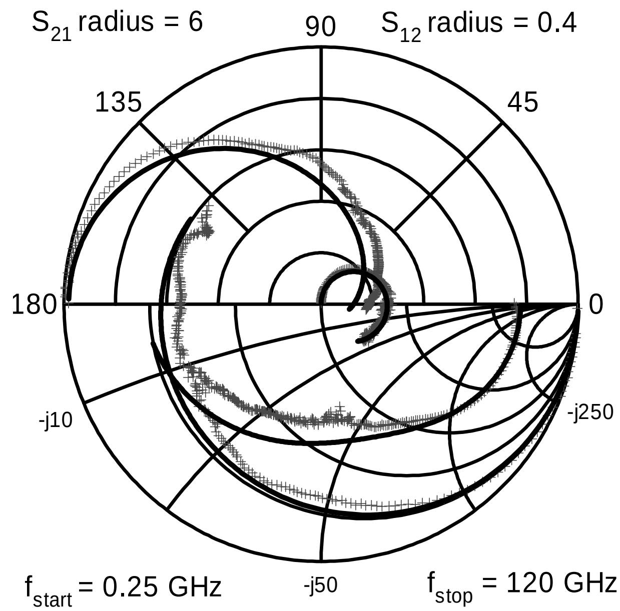

Fig.7: Simulated (-) and measured (+) S-parameters of an enhancement metamorphic HEMT of l_g = 200 nm.

BREAKDOWN ANALYSIS

For the small band gap materials necessary for mm-wave applications it is very desirable to evaluate the mechanisms of device failure quantitatively with respect to the given technology. As stated e.g. in (8) in HEMT transistors a balance of on-state (impact ionization) and off-state breakdown (thermionic field emission) effects prevails. Thus, the exact behavior of the gate currents needs to be modeled to explain DC and RF properties (9). Fig. 4 shows that the model incorporates the transition between thermionic field emission effects and impact ionization correctly when increasing the V_{GS} voltage for the InAlAs/InGaAs material system. Fig. 8 shows the simulated and measured gate currents I_G for a given V_{DS} voltage in an InP based high speed HEMT which is not optimized for power applications (8). The impact of an increase of the substrate temperature by 48 K on the gate current can be observed and is described by the model correctly. This stresses the importance of the lattice temperature

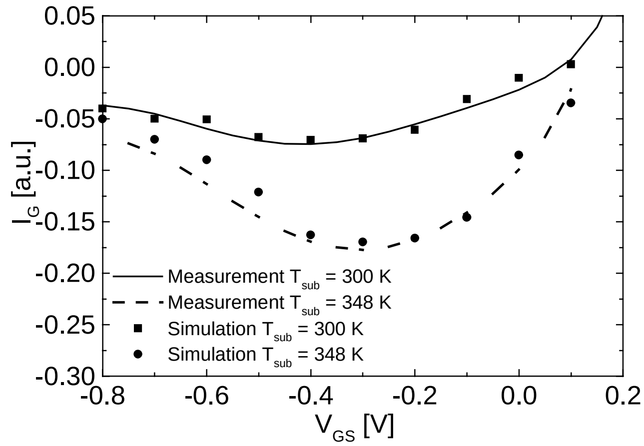

Fig.8: Comparison of the simulated and measured gate current I_G as a function of substrate temperature T_{sub}.

and the control of self-heating effects for reliability reasons. In order to evaluate the on-state breakdown limiting the InAlAs/InGaAs HEMTs devices in (10) a method is suggested to measure gate currents to compare the on state breakdown voltage BV_{DS} of different transistors. Thus, for a metamorphic transistor Fig. 9 shows a comparison of the simulated BV_{DS} at 1 mA/mm and a drain current of 100 mA/mm using MINIMOS-NT. The comparison is made for different channel and barrier material compositions for the same transistor changing only x in $In_xAl_{1-x}As/In_xGa_{1-x}As$. Gate length is l_g = 150 nm. As expected the simulated breakdown voltage BV_{DS} increases for lower In content. The magnitude of BV_{DS} is found realistic for the device. Furthermore, the model describes correctly a general tendency observed, e.g. (11), to reduce the In content in the $In_xAl_{1-x}As/In_xGa_{1-x}As$ HEMTs for RF power applications.

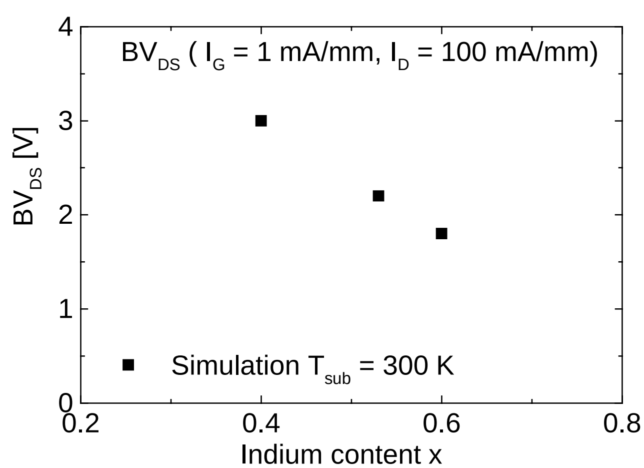

Fig.9: Comparison of the simulated breakdown voltage BV_{DS} at I_G = 1 mA/mm and I_D = 100 mA/mm as a function of In content.

Conclusions

We developed a two-dimensional model that allows precise simulations for the InAlAs/InGaAs material system suitable for process control. It has been verified for several HEMT devices from three different technologies for gate-lengths below 200 nm. Several issues, such as self-heating, the simulation of high field effects and generation processes and their interaction are successfully demonstrated in good agreement with measurements. These features allow reliability estimates for the InAlAs/InGaAs material system.

Acknowledgment

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