Simulation of AlGaN/GaN-HFETs including spontaneous and piezoelectric polarization charges

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Abstract. The influence of spontaneous and piezoelectric polarization charges on static and dynamic device characteristics of AlGaN/GaN-HFETs has been studied by numerical simulations. For the simulation a 2D-microscopic/macroscopic algorithm was used which consists of the solution of the effective mass Schrodinger equation together with the Poisson equation and a self-consistent coupling of the macroscopic transport and continuity equations. The polarization effects are included by a positive interlayer charge at the heterojunction interface, a negative surface charge and a negative interlayer charge at the AlN/GaN buffer heterojunction.

1. Introduction

Significant progress has been made in the last few years in the development of GaN-based heterojunction field-effect transistors (HFETs) for high-speed, high-power and high-temperature applications. The large interest comes from the unique material properties of the group-III-nitrides. The presence of internal strain in the commonly used wurtzite phase of GaN may lead to the generation of large piezoelectric polarization fields. In addition the spontaneous polarization (at zero strain) is very large in wurtzite group-III-nitrides [1],[2]. The spontaneous and piezoelectric polarization causes additional sheet charges at the heterojunction interfaces of the structures. Numerical simulations have been carried out to study the influence of these effects on carrier distributions and on static and dynamic device characteristics of AlGaN/GaN-HFETs. Comparisons with experimental results demonstrate the importance of the consideration of polarization charges in the design and analysis of nitride-based HFET structures.

2. Simulation model

For the simulation we used a 2D-microscopic/macroscopic algorithm as described in [3] which consists of the solution of the effective mass Schrodinger equation

$$-\frac{\hbar^2}{2}\nabla\cdot\left(\frac{1}{m^*}\nabla\psi\right)+(V-E)\psi=0 \qquad (1)$$

(m* effective electron mass, E discrete energy levels, ψ wavefunctions, V potential energy)

together with the Poisson equation

$$\nabla\cdot(\varepsilon\nabla\varphi)=-e\left(p-n+N_D^+-N_A^-+N_P\right) \qquad (2)$$

(N_D^+, N_A^- ionized donor and acceptor density, N_P polarization charge)

to calculate the exact electron density within the two-dimensional electron gas (2DEG) channel. The macroscopic continuity and transport equations for electrons and holes are coupled self-consistently to get the device characteristics at different bias conditions. For further information about the 2D/3D device simulator SIMBA see http://www.iee.et.tu-dresden.de/~klix/simba.

3. Results

The calculated $Al_{0.15}GaN$-GaN-HFET-structure [4] is represented in Fig. 1. The GaN buffer as well as the AlGaN barrier- and cap-layer are unintentionally doped ($10^{16}cm^{-3}$ assumed). The supply layer is Si-doped ($2\cdot10^{19}cm^{-3}$). The effects of spontaneous and piezoelectric polarization are included by a positive interlayer charge σ_i at the heterojunction interface, a negative surface charge σ_s and a negative interlayer charge σ_b at the AlN/GaN heterojunction. The AlN layer is inserted between sapphire substrate and GaN buffer and was neglected at the simulation.

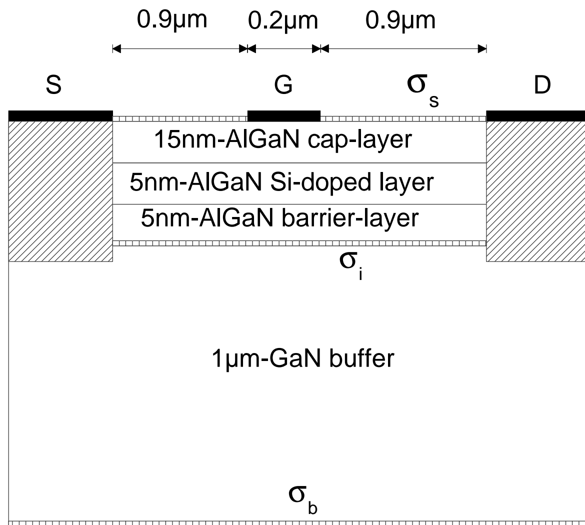

Fig.1. AlGaN/GaN-HFET structure ($\sigma_i = 2\cdot10^{12}$ cm^{-2}, $\sigma_s = -0.3\cdot10^{12}$ cm^{-2}, $\sigma_b = -1.7\cdot10^{12}$cm^{-2})

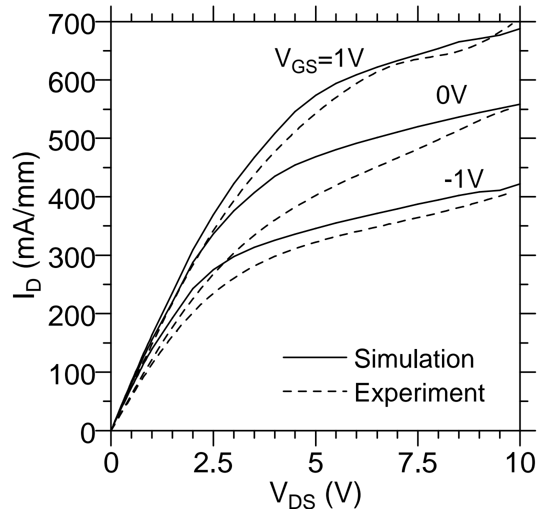

Fig. 2. Comparison of simulated and experimental output characteristics

The total sheet charge density for $Al_{15}GaN/GaN$ is in the range of $2\text{-}4\cdot10^{12}\ cm^{-2}$ [1],[2]. We assumed $\sigma_i + \sigma_b + \sigma_s = 0$ and found $\sigma_i = 2\cdot10^{12}\ cm^{-2}$, $\sigma_s = -0.3\cdot10^{12}\ cm^{-2}$, $\sigma_b = -1.7\cdot10^{12}\ cm^{-2}$ by comparison with experimental results. The calculated output and transfer characteristics and the transconductance as well as the experimental results are represented in Fig. 2 - 4. The differences in Fig. 2 result from additional contact resistances. In Fig. 3 and Fig. 4 the simulation results without polarization charges show the necessity of considering these charges for getting correct values.

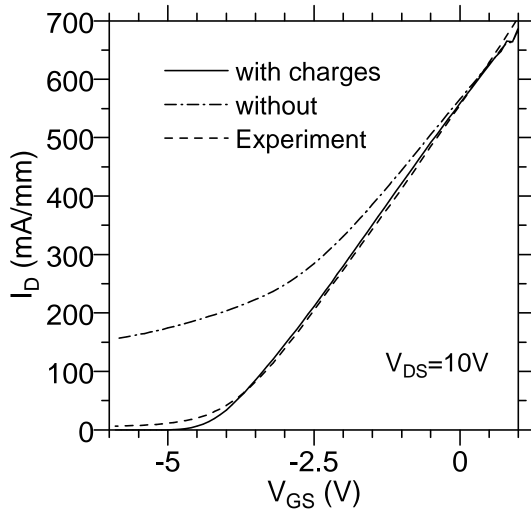

Fig. 3. Transfer characteristics with and without polarization charges in comparison with experimental results

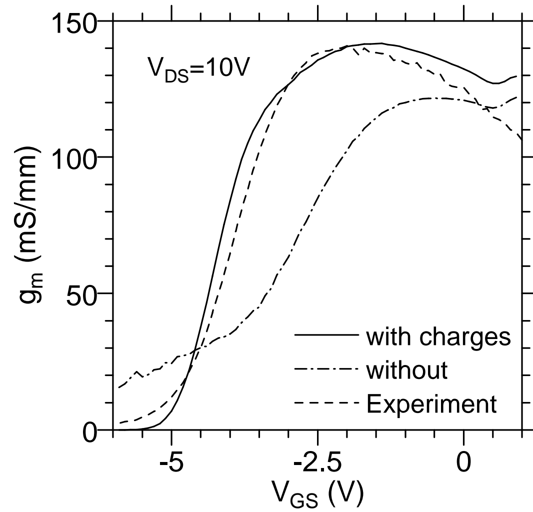

Fig. 4. Transconductance with and without polarization charges in comparison with experimental results

The calculated RF gains of the HFET are represented in Fig. 5. The cut-off frequencies $f_t = 50$ GHz and $f_{max} = 100$ GHz agree with the experimental results if the influence of extrinsic pad capacities and terminal resistances which are not included in the simulation are taken into account.

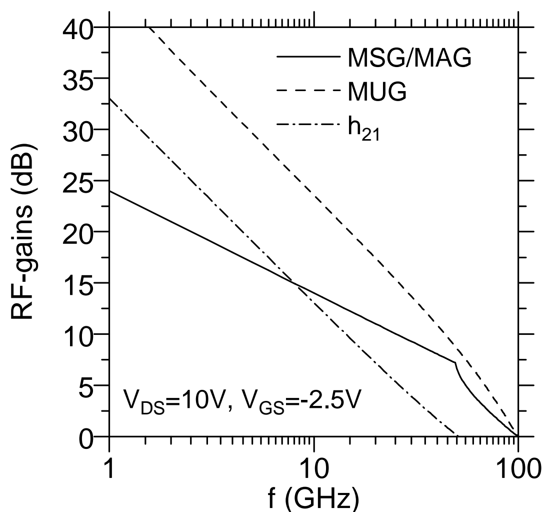

Fig. 5. Simulated RF-gains of the HFET ($f_{max} = 100$ GHz, $f_t = 50$ GHz)

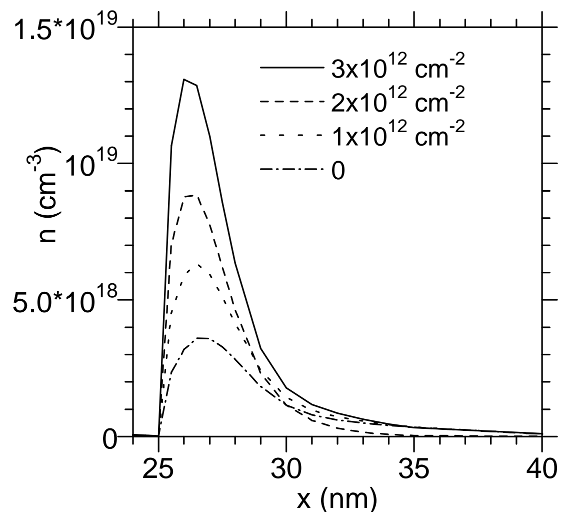

Fig. 6. Electron density in the 2DEG-channel for different interface charges σ_i

To study the device behaviour at different polarization charges extensive variations of the charge distribution have been made. In Fig. 6 the electron density within the channel are plotted for different heterojunction interface charges σ_i. The corresponding transfer characteristics and transconductances are represented in Fig. 7 and Fig. 8. The AlGaN/GaN heterojunction interface charge has a strong influence on drain current and on transconductance. Larger interface charges improve the transconductance but worsen the pinch-off behaviour of the HFET.

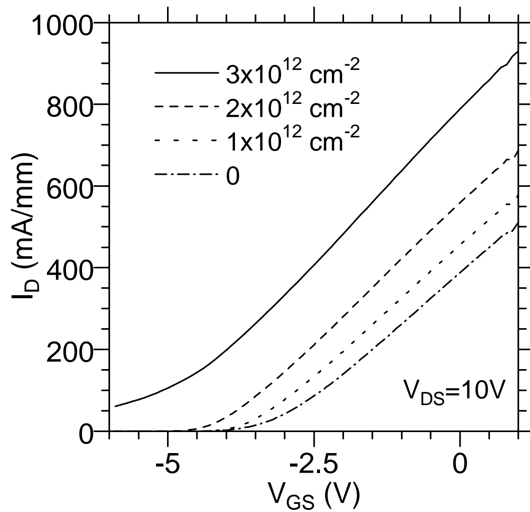

Fig. 7. Transfer characteristics for different interface charges σ_i

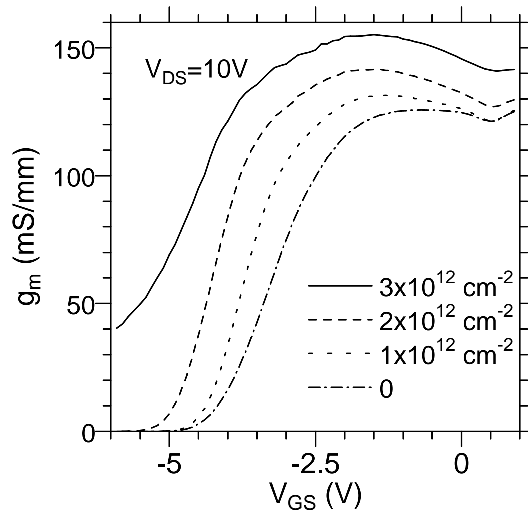

Fig. 8. Transconductance for different interface charges σ_i

4. Conclusions

Numerical 2D-simulations of AlGaN/GaN-HFETs have been carried out. The effects of piezoelectric and spontaneous polarization are included by additional sheet charges at the AlGaN/GaN and at the GaN/AlN heterojunction as well as at the device surface. HFETs with 0.2 µm gate length are simulated and the static and dynamic device characteristics are evaluated. The variation of the polarization charges shows the strong dependence of the device performance on these charges. The comparison with experimental results demonstrates the necessity of considering polarization charges for getting correct values.

References

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