Electro-Thermo-Mechanical Simulation of AlGaN/GaN HEMTs

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INTRODUCTION

During the last years AlGaN/GaN HEMTs have been studied extensively for the use in high power microwave applications. The reliability of GaN-based HEMTs, however, still remains a major issue, which is usually assumed to be associated with strain- and temperature-related effects. Simulation models including these effects are therefore of high interest for the understanding of device reliability.

Traditionally, simulation of GaN-based HEMTs has been based on the drift-diffusion or hydrodynamic model coupled to a thermal model, usually based on the Fourier model. More recently, non-equilibrium thermal transport has been considered [1]. Several coupled electro-mechanical simulation models for HEMTs have been proposed in the last years, too [2], [3]. A coupled electro-thermo-mechanical model has been reported in [4] and is based on a matlab-implemented strain calculation following a self-consistent thermoelectric TCAD simulation.

In this work we present a fully selfconsistent, coupled electro-thermo-mechanical simulation model implemented in a single simulation software, tiberCAD (http://www.tibercad.org).

SIMULATION MODEL

Our simulation model is based on the self-consistent solution of (1) the equations of linear elasticity, (2) the drift-diffusion/Poisson equations and (3) the Fourier model for the lattice temperature. The three models are mutually coupled in the following way. The strain ϵ_{jk} obtained from the linear elasticity model induces a piezoelectric polarization field $P_i = e_{ijk}\epsilon_{jk}$ that enters in the Poisson equation. The electric field E_i in turn induces a mechanical stress $\sigma_{jk} = e_{ijk}E_i$ due to converse piezoelectric effect. The transport model provides the heat source for the thermal model due to Joule and Thompson effect, whereas the temperature profile enters in the transport model by means of temperature dependent parameters and the Seebeck effect. The temperature profile also enters in the mechanical model due to the thermal expansion of the semiconductor lattice. The three models are solved iteratively until appropriate convergence criteria are reached.

EXAMPLE

We apply the model to a GaN/Al$_{0.18}$Ga$_{0.82}$N/GaN HEMT (Fig. 1), comparing the results of selfconsistent electro-thermal (in this case strain is calculated for each bias point without changing the strain and polarization field entering in the drift-diffusion model), electro-mechanical and electro-thermo-mechanical simulations. Strain has been simulated on a restricted domain excluding the SiN passivation. Fig. 2 shows the transfer and output characteristics for the different cases. The strongest effect on electrical behaviour can be seen to be due to converse piezoelectric effect, causing a slight shift of threshold voltage since the selfconsistent polarization field is smaller. Fig. 3 shows the self-consistent temperature map for a power dissipation of $\sim$ 7 W/mm. Fig. 4 and 5 present the elastic energy density along the x-direction at the top end of the AlGaN barrier, where electric field and strain are highest, in off and on state. In the off state (V$_g$ = -2 V), only converse piezoelectric effect is relevant, causing an increase in energy density for increasing negative gate bias. At V$_g$ = 0 V, however, the local device heating leads to a strain relaxation, which results in a decrease of elastic

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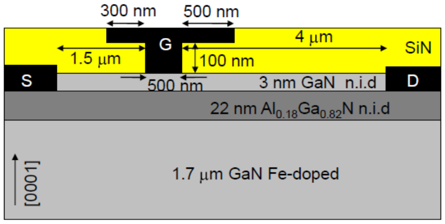

Fig. 1. The simulated GaN/$Al_{0.18}Ga_{0.82}$N/GaN HEMT.

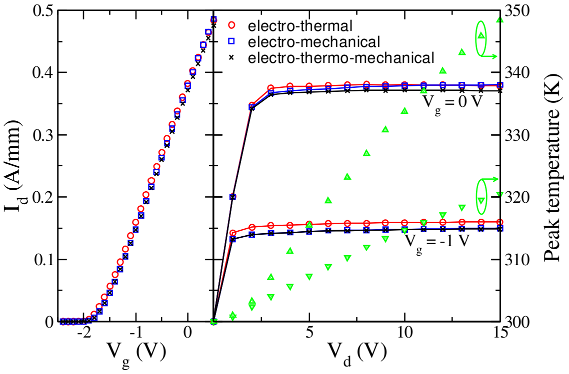

Fig. 2. Transfer and output characteristics for the different simulation models.

energy density (Fig. 5). The simulations also show that the impact on elastic energy of thermal stress and converse piezoelectric effect are of the same order of magnitude. Even though their effect is not very strong in the considered device, in particular piezoelectric effect will increase significantly for increasing Al content.

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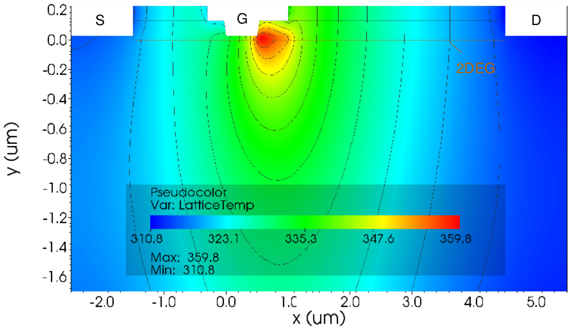

Fig. 3. Temperature map at V_d = 20 V, V_g = 0 V, P_{diss} = 7 W/mm.

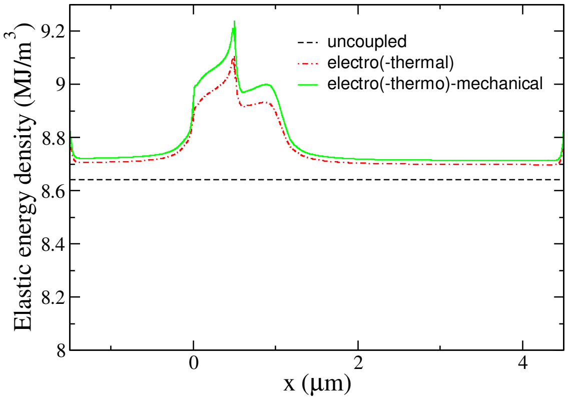

Fig. 4. Elastic energy density at V_d = 20 V, V_g = -2 V. Note that in this case there is no device heating.

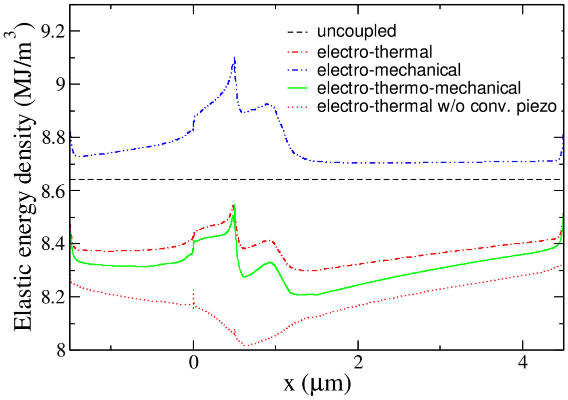

Fig. 5. Elastic energy density at V_d = 20 V, V_g = 0 V.