Reliability Concerns due to Self-Heating Effects in GaN HEMTs

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ABSTRACT

Current collapse phenomenon that occurs in GaN HEMTs under a moderately large DC bias stress, poses serious problems for usage of GaN technology in high-power high-frequency applications from a reliability standpoint. Additional problem in these devices operated at high biases is the appearance of self-heating effects that degrade device characteristics and, as shown in this work further amplify the problem of current collapse by changing the device electrostatics.

Index Terms: GaN HEMTs, self-heating, current collapse

I. INTRODUCTION

Nitride semiconductors have emerged as a strong candidate for high power, high temperature and high frequency applications in the recent years [1-3]. The motivation for using this material system is clearly illustrated in Figure 1 below. It is important to emphasize that the strongest feature of the III-V materials is the heterostructure technology it can support - quantum well, modulation-doped hetero interface, and heterojunction structure can all be made in this material system.

Two dimensional electron densities on the order of 10^{13} cm^{-2} or higher can be achieved in GaN HEMTs owing to its large piezoelectric polarization charge that arises due to strain of the top layers. The piezoelectric polarization charge in these devices is about five times larger in comparison to GaAs HEMT structures.

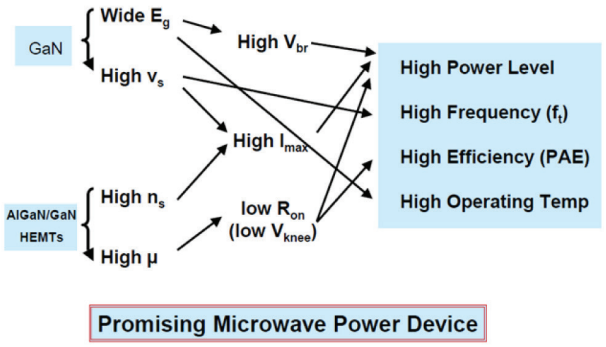

Figure 1. Applications for GaN bulk materials and AlGaN/GaN HEMTs.

In addition, the spontaneous polarization, which is an inherent property of the material, is very high for GaN and AlN material systems. The electric fields produced by these charges are on the order of 2-5 MV/cm. These high electric fields are responsible for the very high two-dimensional electron densities in these devices [4].

The major problem in GaN technology is the current collapse phenomenon [5]. The trapping of charge at the gate-drain surface leads to increase in the drain access resistance. This, in turn, leads to increase in conduction losses in high power switching applications. Significant amount of work, both experimental and theoretical, has been done to shed more light on the current collapse phenomena [6]. However, the role of self-heating effects on the gate edge electric field has not been examined. The goal of the present work is to evaluate the influence of self-heating towards the current collapse phenomenon in GaN HEMTs.

II. THEORETICAL MODEL AND SIMULATION FRAMEWORK

Proper treatment of self-heating effects in nanoscale devices within the semi-classical limits necessitates the solution of the Boltzmann transport equation for the electrons and phonons simultaneously. This, in general is a difficult task and approximations to the problem usually made. The coupling of the electron Boltzmann transport equation solver (via Monte Car-

lo Method) with a 2D-3D Poisson equation solver is nowadays routinely done by various groups and there exist particle-based device simulators in different forms and shapes (from non-parabolic band models with analytical phonon dispersions [7] to full-band models with full phonon dispersions [8]. However, not very many of these solvers assume that phonons are out of equilibrium. Few years ago at Arizona State University we developed electro-thermal particle-based device simulator to model self-heating effects in FD SOI devices [9] and GaN HEMTs [10]. To get insight into the self-heating problems in these two technologies, instead of solving directly the phonon Boltzmann transport equation self-consistently with the Poisson solver and with the electron Boltzmann transport equation, solver we solve the energy balance equations for the acoustic and optical phonon bath that are easily derived by taking moments of the phonon Boltzmann transport equation. The two energy balance equations that we solve are of the form [11]:

$$C_{LO}\frac{\partial T_{LO}}{\partial t} = \frac{3nk_B}{2}\left(\frac{T_e - T_L}{\tau_{e-LO}}\right) + \frac{nm^* v_d^2}{2\tau_{e-LO}} - C_{LO}\left(\frac{T_{LO} - T_A}{\tau_{LO-A}}\right) \quad (1)$$

$$C_A\frac{\partial T_A}{\partial t} = \nabla.(\kappa_A \nabla T_A) + C_{LO}\left(\frac{T_{LO} - T_A}{\tau_{LO-A}}\right) + \frac{3nk_B}{2}\left(\frac{T_e - T_L}{\tau_{e-L}}\right) \quad (2)$$

The first two terms on the right hand side (RHS) of Eq. (1) describe the energy gained by the electrons, where n is the electron density and v_d is the drift velocity, while the last term in Eq. (1) is the energy loss to the acoustic phonons. This term appears as a gain term on the RHS of Eq. (2). The first term on the RHS of Eq. (2) accounts for the heat diffusion and the last term must be excluded if electron-acoustic phonon interaction is treated elastic. In this term, the lattice temperature T_L is estimated as equivalent to T_A. C_{LO} and represent the heat capacity of optical and acoustic phonons, respectively, and K_A is the thermal conductivity. The electron temperature T_E, the electron density n and the electron drift velocity v_d, appearing in Eqs. (1-2) are obtained from the Ensemble Monte Carlo averages.

It is important to note that the solution of the energy balance equations for the acoustic and the optical phonon bath is a must because of the nature of the processes taking place in the structure. Namely, high drain biases mean that highly energetic electrons exist in the structure which, in collisions with the lattice, will give most of their energy very quickly to the optical phonon bath and some energy to the acoustic phonon bath (as depicted in Figure 2). The optical phonons involved in the process are typically zone center phonons that have negligible group velocity and as a result of this the heat is localized and a hot spot forms. It takes two orders of magnitude more time that for the optical phonons, through anharmonic processes to decay into acoustic phonons, and therefore transport the heat from the hot spot.

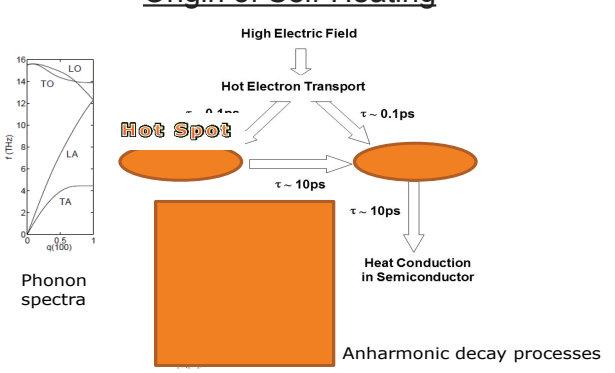

Figure 2. Transfer of energy from the electron system to the acoustic and optical phonon baths.

In addition to self-heating effects, in our theoretical model used to describe the operation of this structure we have also incorporated electromechanical coupling following the methodology described in Ref. [13,14].

III. RESULTS AND DISCUSSION

The structure analysed in for this study is shown in Figure 3. It consists of a GaN substrate, 1 nm AlN layer (to prevent the electrons in the channel to move into the AlGaN layer) followed by a 16 nm AlGaN layer and a GaN cap layer on the top. All the layers are unintentionally doped. The Schottky gate contact is made out of gold and the source and drain are doped to 10^{18} cm^{-3}. The geometry and the experimental data for this device structure are provided to us by J. del Alamo from MIT. More details about the structure can be found in Ref. [15].

An important parameter related to the reliability of GaN HEMTs is the lattice temperature profile shown in Figure 4. It is evident from the figure that the hot-spot is near the drain end of the channel where the electron temperature is the highest (Figure 5), and is shifted slightly towards the drain contact (Figure 4) due to the finite group velocity of the acoustic phonons.

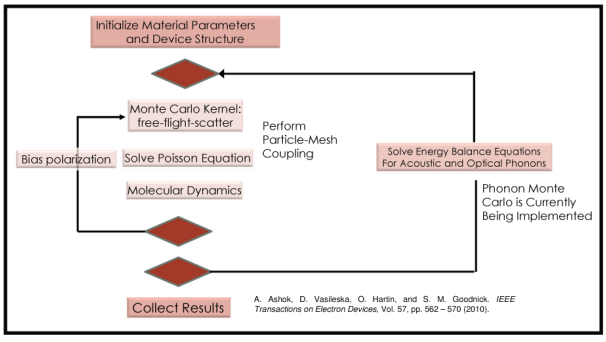

Figure 3. GaN/AlGaN/AlN/GaN HEMT structure.

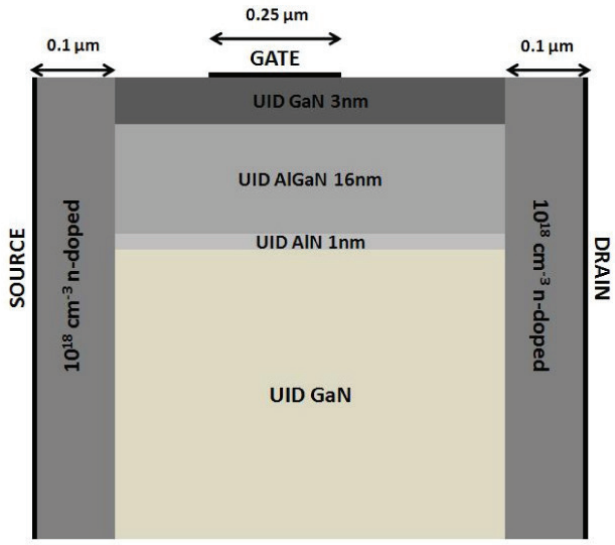

Figure 4. GaN/AlGaN/AlN/GaN HEMT structure

More importantly, the hot spot extends both towards the gate and towards the channel. The substrate used in the simulation is GaN with the back surface being one of the thermal boundary conditions and the gate electrode being the other. Therefore, in our analysis we do not incorporate the role of the substrate on the amount of self-heating present in the structure.

The peak lattice and electron temperature variation with the electron to optical phonon relaxation time has been plotted in Figure 6. It is observed that with the increase in relaxation time, the peak lattice temperature decreases and the peak electron temperature increases. This is due to the reduction of scattering of the electron near the drain with the increase in electron-phonon relaxation time.

The modification of the electrostatics when self-heating effects are accounted for modifies the magnitude of the electric field. This is clearly shown in Figure 7 where we plot the y-component (along the growth direction) of the difference of the electric field for the case when self-heating effects are accounted for and for the case when self-heating effects are not accounted for (isothermal case).

We observe from the results presented in Figure 7 that the net field difference is positive near the gate-drain extension thus contributing to a larger probability that the channel electrons are being accelerated towards the surface and increasing the occupancy or hot carrier generation of surface states. Since the whole device has to be charge neutral, holes will accumulate at the drain extension which, in turn, reduces the magnitude of the on-current (current collapse). Simulated transfer and outpout characteristics of the dealong with from Figure 4, for the isothermal and thermal case, along with experimental data are shown in Figures 9 and 10 respectively. We see excellent agreement between the non-isothermal case and the experimental data in particular in the saturation region. We also see

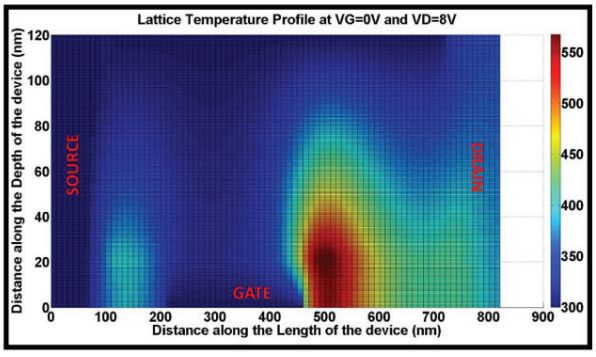

Figure 5 . Lattice Temperature Profile

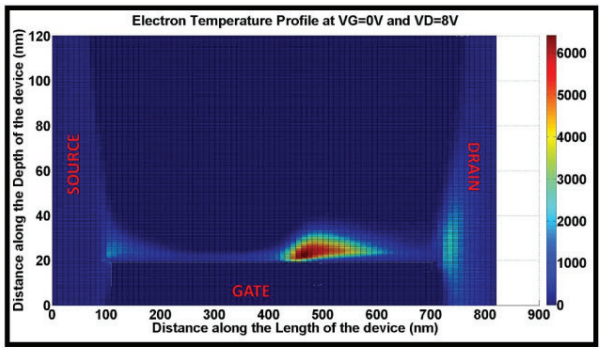

Figure 6 . Electron Temperature Profile

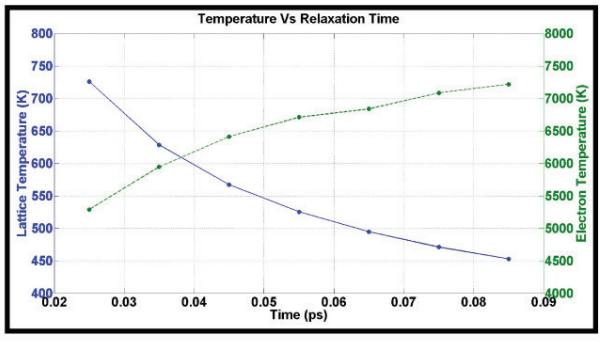

Figure 7 . Maximum Lattice and Electron Temperature vs. Phonon relaxation time ($V_G = 0V$ and $V_D = 8V$).

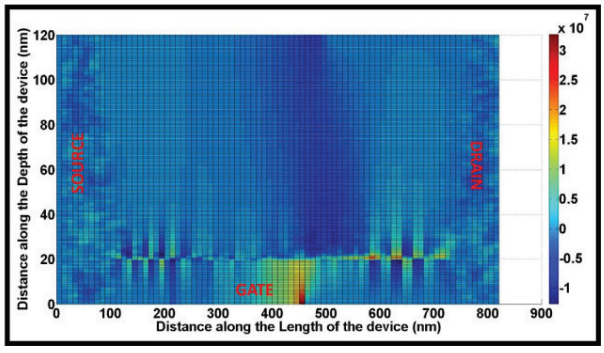

Figure 8. Difference between the vertical component of electric field in the simulation including self-heating effects and excluding the same.

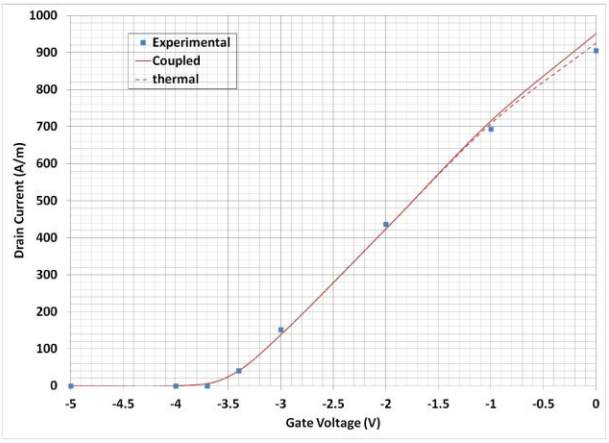

Figure 9. Simulated transfer characteristic of the device for VD = 5 V. Also shown here are available experimental data.

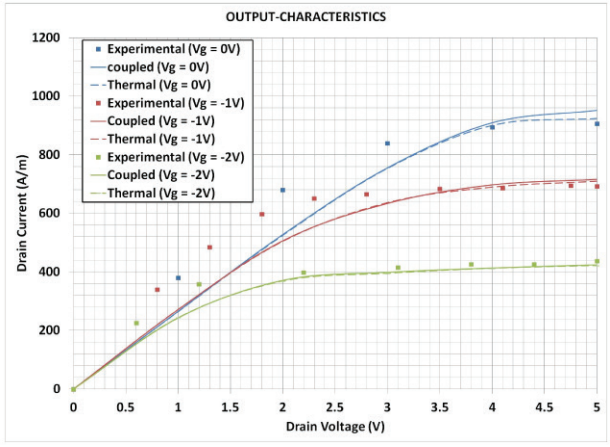

Figure 10. Simulated output characteristics of the device from Fig. 4 together with experimental data (symbols)

that for Vd = 5V, self-heating leads to current degradation of around 5%. Larger current degradations are expected for higher drain biases. The temperature increase is localized in the drain end of the channel and not the entire channel and the amount of degradation correlates to this factor.

IV. CONCLUSIONS

An electro-thermal particle based device simulator consisting of a Monte Carlo-Poisson equation solver that is self consistently coupled with an energy balance solver for both the acoustic and optical phonon baths has been developed to understand the physics behind the self-heating phenomenon in these devices. An output current degradation of around 5.5% at Vds = 5V and Vgs = 0V has been observed in simulations. We demonstrate that the electrostatics in the device is modified with the inclusion of the self-heating effects. The electric field near the gate-drain edge is modified in a direction to accelerate the electrons from the channel towards the surface states of the device. The trapping de-trapping of these defects can lead to further degradation in the performance of these devices. This study has also proved that the electrostatics near the gate-drain edge governs the reliability of these devices.

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