Reliability of GaN HEMTs: Current Degradation in GaN/AlGaN/AlN/GaN HEMT

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Abstract— **Electrical reliability of the AlGaN/GaN material system in both the on and off state regimes is a fundamental problem to be solved before the widespread use of this technology. The two major reliability concerns in this technology is electric field induced strain degradation also known as electromechanical coupling and current collapse mechanism. In the present work, an electro thermal particle based device simulator has been developed to address these two issues. It consists of a Monte Carlo-Poisson solver that is self-consistently coupled with a thermal solver for both the acoustic and the optical phonon baths. This simulator has been used to understand the physics behind these mechanisms that lead to reliability concerns.**

Keywords - modeling, GaN HEMTs, Self-heating effects, reliability, electromechanical coupling, current colapse

I. INTRODUCTION

GaN technology has been emerging as a strong candidate for high power, high temperature and high frequency applications [1, 2]. Large band gaps, high peak velocity, large saturation velocity and high thermal stability make them the ideal material for microwave power devices. When used in a heterostructure technology, nitride semiconductors achieve very high two dimensional electron gas densities owing to their strong piezoelectric characteristics [3].

However, electrical reliability in both the on and the off state regimes has been a fundamental problem in this device technology. One of the reliability concerns is the output current degradation due to electric-field induced strain relaxation [4] or alternatively called electromechanical coupling. GaN material being strongly piezoelectric in nature has large spontaneous and piezoelectric polarization charge density that leads to formation of inversion channel in these devices. The piezoelectric polarization charge depends on the strain state of the layers in the device which has been experimentally proved to vary with the electric field profile in the device. This degradation of strain changes the piezoelectric polarization charge density and thus varies the output current in these devices.

The second reliability concern is self heating in the HEMT technology which also degrades the output characteristics of the device. The self heating is also responsible for mechanical reliability concerns at the hot spot region near the gate to drain edge of the device [5].

The paper is organized as follows. In Section II, the details of the simulator developed to explain electromechanical coupling and self heating is described briefly. Simulation results are presented in Section III. These results illustrate the importance of reliability mechanisms and their impact on the output current. Conclusions from this work are presented in Section IV.

II. DEVICE SIMULATOR

A. Electromechanical Coupling

In the previous work [6] a theoretical model was developed to estimate the gate voltage dependence of the piezoelectric polarization charge in GaN HEMT devices using

$$P_{PE}^{\alpha} = 2\Xi_x^{\alpha}\left(e_{31}^{\alpha} - \frac{c_{13}^{\alpha}}{c_{33}^{\alpha}} e_{33}^{\alpha}\right) + E_z^{\alpha} \frac{{e_{33}^{\alpha}}^2}{c_{33}^{\alpha}}, \tag{1}$$

where α represents the layers, E_z represents the electric field normal to the layer, e_{31} and e_{33} are the piezoelectric constants, c_{31} and c_{33} are the elastic constants and E_x represents the strain at the surface.

In the present work, this model has been implemented into a particle based Monte Carlo device simulator for a GaN/AlGaN/AlN/GaN HEMT device. The simulator consists of a Poisson kernel self consistently coupled to a Monte Carlo kernel to solve for potential and electron distribution respectively as shown in Figure 1.

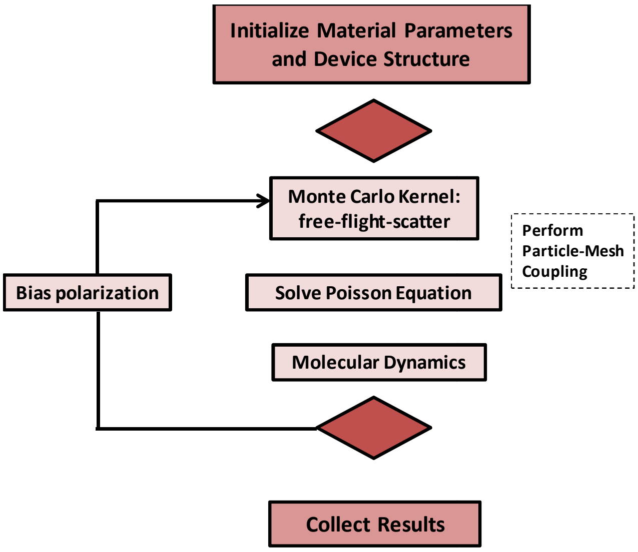

Figure 1. Flow chart of particle-based device simulator that in the self consistent manner takes into account the bias polarization charge.

B. *Self-Heating*

To model the current collapse mechanism due to self-heating in GaN technology, an electro-thermal device simulator has been developed. It consists of a Monte Carlo-Poisson equation solver that is self-consistently coupled with an energy balance solver for both the acoustic phonons and optical phonon baths as shown in Figure 2. The nature of heat transfer in the device requires separate treatment of both acoustic and optical phonon baths.

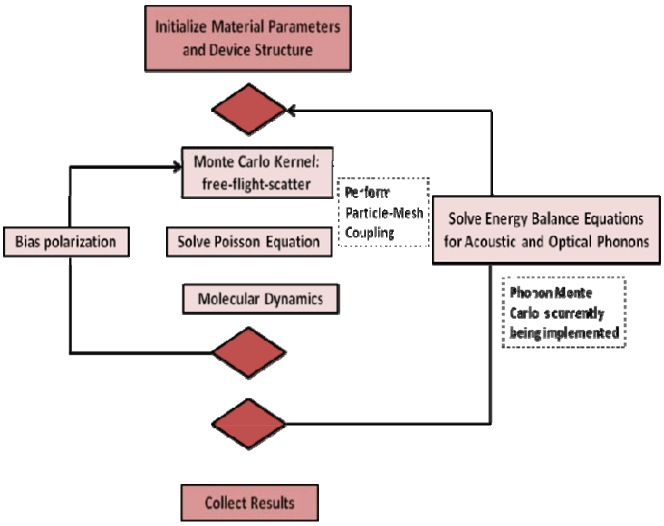

Figure 2. Flow chart of particle-based device simulator that in the self consistent manner takes into account the self-heating.

The energy transfer between the electrons, optical and acoustic phonons takes place at different time scales as shown in Figure 3. The energy of the electrons gained from the electric field is quickly transferred to the optical phonons and some part of the energy to the acoustic phonons. Optical phonons are very poor carriers of the heat as they have almost negligible group velocity. They transfer the energy to the acoustic phonons which propagate the heat in the device.

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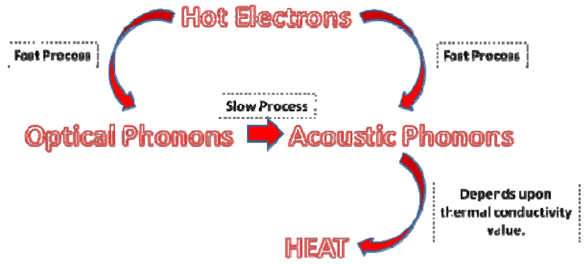


Figure 3. Transport of energy in the electron-phonon system

III. SIMULATION RESULTS

The structure investigated in the present work is shown schematically in Figure 4. It consists of a GaN substrate on top of which a 1nm AlN layer, a 16nm AlGaN buffer layer and a 3 nm GaN cap layer are grown.

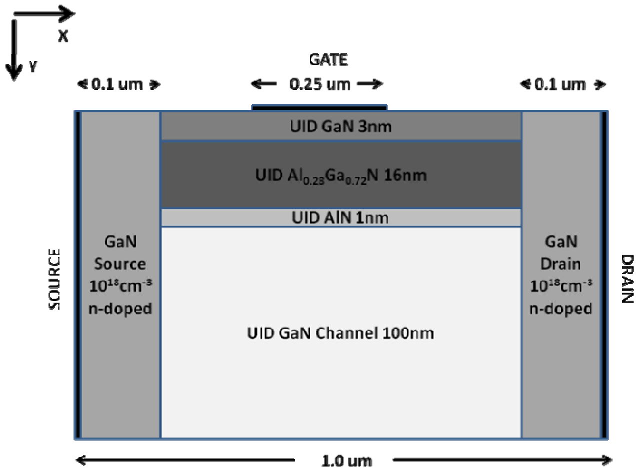


Figure 4. GaN HEMT device structure.

The Schottky gate length is 0.25 um and is made of gold. The source and drain regions are doped to 10^{18} cm^{-3}. The other layers are unintentionally doped.

A. *Electromechanical Coupling*

The transfer characteristic of the device is shown in Figure 5. We clearly see that with the inclusion of electromechanical coupling (or coupled formulation), the output current degrades. The degradation varies from 2 to 18%, depending on the gate voltage as seen in Figure 6. This degradation in current depends on the vertical electric field in the various layers. When the gate voltage is near the threshold voltage of the device, the channel is devoid of charges and the electric field in the layer is highest causing the maximum degradation in output current. Conversely, as the gate voltage increases, the channel region is formed and the electric field in the layers reduces.

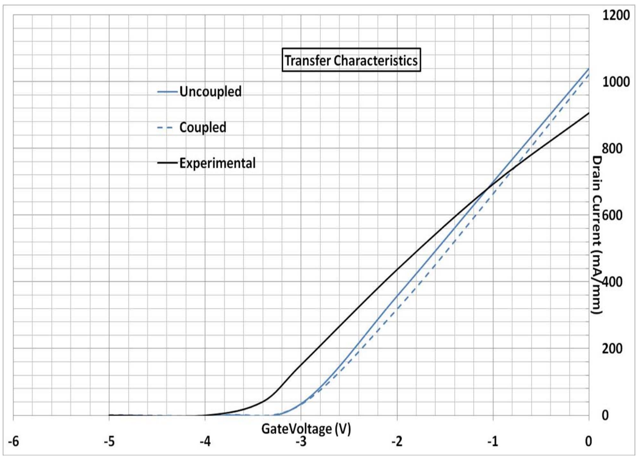


Figure 5. Transfer Characteristics.

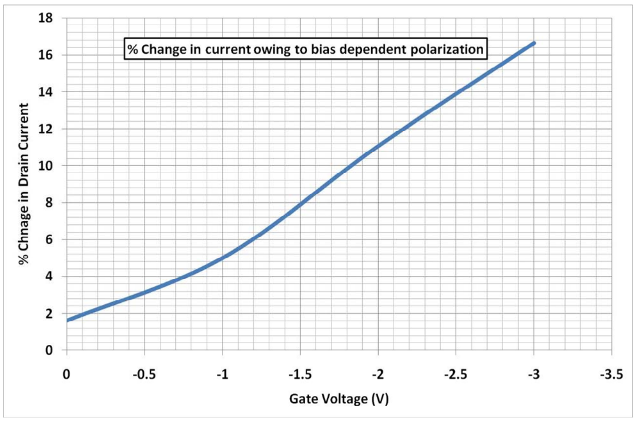


Figure 6. % change in drain current.

The output characteristics of the device as shown in Figure 7 also follow the same trend as the transfer characteristics. The amount of degradation in the output current at various gate voltages varies.

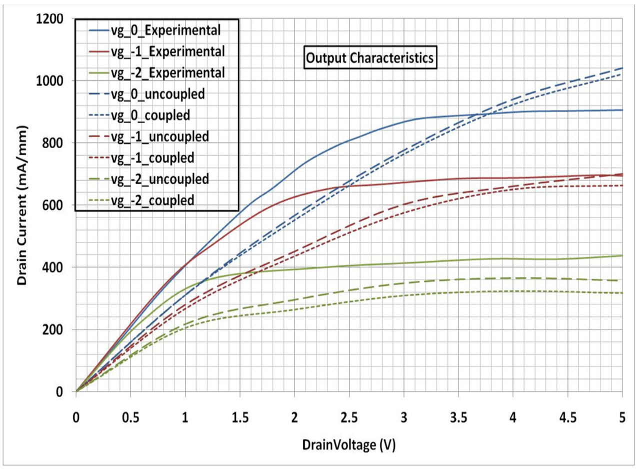


Figure 7. Output Characteristics.

More work is currently being done to better match the simulations with the experimental curve by accounting for partial relaxation of the lattice and better tuned polarization charges at various interfaces.

B. *Self-Heating*

Simulations were run using the electro-thermal device simulator described in Section II and diagrammatically illustrated in Figure 4. The Monte Carlo simulations were run for 10ps and coupled with the energy balance equations for acoustic and optical phonons. This comprises one Gummel cycle. It takes several Gummel cycles for this self consistent solution to converge.

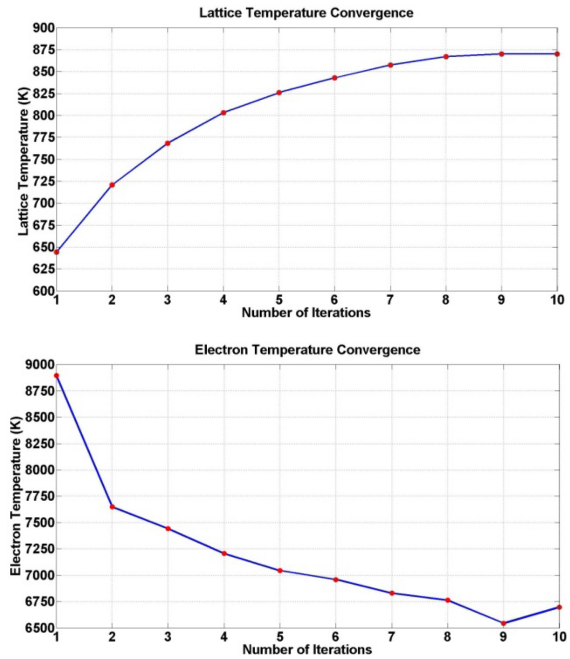


Figure 8. Lattice Temperature (Top) and Electron Temperature (Bottom) vs. Gummel cycles for VG = 0V and VD = 9V for phonon relaxation time of 0.025 ps.

The temperature in the device structure is strongly dependent on the phonon relaxation time as shown in Figure 9. As the phonon relaxation time is increased the peak lattice temperature reduces and the peak electron temperature increases.

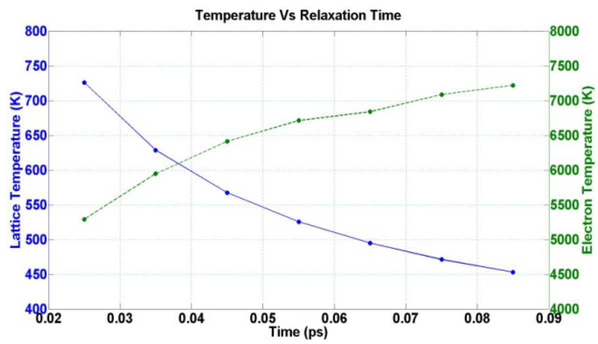
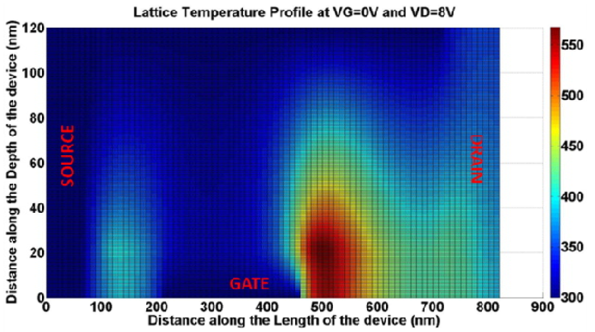


Figure 9. Maximum temperature vs. phonon relaxation time for VG=0V and VD=8V.

The typical lattice temperature and electron temperature profile in the device structure is shown in Figure 10. We see that the hot spot in the device is near the critical gate drain edge since the electron velocity is the highest in this region. The lattice temperature is slightly shifted more to the drain end of the structure compared to electron temperature due to finite group velocity of acoustic phonons. The substrate and the gate constitute the thermal boundary conditions and are at room temperature (300K).



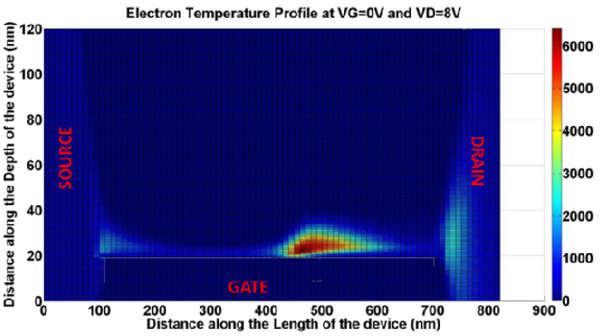


Figure 10. Lattice Temperature (Top) and Electron Temperature (Bottom) profile for VG= 0V and VD = 8V and phonon relaxation time of 0.045ps.

The self- heating changes the electrostatics in the device and modifies the electric field profile as shown in Figure 11. The fields near the gate drain edge increase which may cause the electrons in the channel to accelerate to the surface state and cause further collapse of the current.

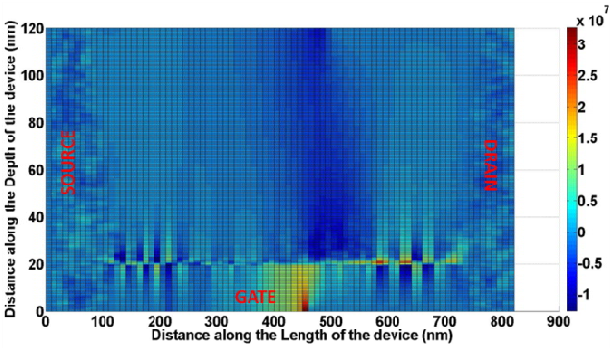


Figure 11. Vertical electric field componenet increase due to self heating effects.

The degradation in the output current characteristic due to self heating effect is shown in Figure 12.

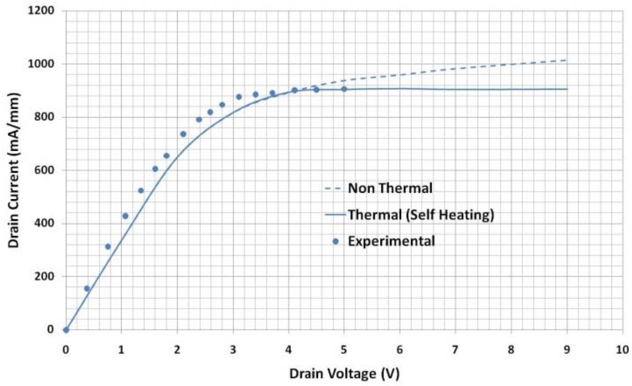


Figure 12. Output Characteristics including self heating effects

IV. CONCLUSION

A particle based device simulator has been developed to model and understand the physics behind the reliability issues in GaN HEMT technology. The major reliability concerns are electromechanical coupling and self heating effects. The current degradation due to these effects have been simulated and correlated with experimental values.

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