

Modelling and Simulation of Self Heating in GaN Based High Electron Mobility Transistors (HEMTs)

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Abstract: In this paper we present the numerical simulation and characterization of GaN based high electron mobility transistors (HEMTs) using commercial device simulation software ATLAS from Silvaco international. Device has been characterized in terms of its electrical and thermal behavior by simulating its transfer and output characteristics without self-heating and with self-heating. Also we simulated the distribution of lattice temperature inside the device for thermal characterization of the device. For electrical characterization the fundamental equations responsible for charge transport of charge carriers have been solved using finite element method. For thermal characterization fundamental equations of charge transport and heat flow equations have been solved self consistently.

Keywords: GaN, HEMTs, Self heating, Numerical simulation, Drift diffusion model.

INTRODUCTION

Over the past four decades, the AlGaIn/GaN high electron mobility transistor (HEMT) has become a promising candidate for high power [1-47], high breakdown voltage, high frequency and high temperature applications due the superior material properties of GaN [1-47]. For achieving higher frequency performance of the transistors, the operating quiescent point of transistor is shifted to higher current densities resulting in self-heating effect. Therefore the temperature of active device increases and due to this effect device exhibits larger thermal resistances (R_{th}) and large value of device junction temperature (T_j). The thermal resistance (R_{th}) depends on material properties as well as the physical device structure; therefore modeling and simulation of self heating in GaN based HEMTs continue to be a topic of increasing interest. As need to understand basic device operation, to optimize device structures, and to consider novel device structures grows, the importance of numerical device simulation is rising as well [1-47]. Since cost of systematic experimental study is high and it takes a lot of time, technology computer aided design (TCAD) is used for experimentation on virtual fabrication lab provided through TCAD tools by Silvaco Inc [1-47].

In this work we created physical structure of the GaN based HEMTs using commercial technology computer aided design (TCAD) tool ATLAS from Silvaco International. Further we performed the modeling and simulation of the electrical and thermal behavior of the GaN based HEMTs. For simulating the

electro-thermal characteristics of the device fundamental equations (like Poisson's equation, current continuity equation for electrons and holes and drift diffusion model for electrons and holes) responsible for charge transport were solved using finite element method. For simulating the self-heating behavior of the GaN HEMT heat flow equation has been solved along with the fundamental equations responsible for charge transport in the device.

MATERIAL PROPERTIES OF GAN

GaN is an excellent material for power transistors. Due to its wide bandgap [1-12] and high electron saturation velocity [1-12], GaN devices are able to operate at high voltage and speeds, respectively. Its high thermal conductivity [1-12], which is essential for high power devices, allows the devices to efficiently dissipate heat easily. The GaN is a binary III-V compound material with wurtzite (hexagonal) crystal structure, wide band gap of 3.4 eV (direct) and high thermal conductivity. Selected properties at 300K are shown in following table.

Table 1: Properties of GaN at 300K

| Property | GaN |
|-------------------------------|-------------|
| Band gap (ev) | 3.4 [1-12] |
| Relative permittivity | 9-10 [1-12] |
| Breakdown field (MV/cm) | 3 [1-12] |
| Thermal Conductivity (W/K/cm) | 1.3 [1-12] |

SEMICONDUCTOR DEVICE MODELING EQUATIONS

The models developed to simulate the operation of semiconductor devices consists of equations derived

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from Maxwell's laws, Poisson's equation, the continuity equations and the drift-diffusion transport equations [14-40]. The method in which the above equations will be solved is a prime when developing a device model in ATLAS™. Several different numerical methods can be used for calculating the solutions to various device structures. Different solution methods are employed depending on the situation. The model developed in this paper incorporated the lattice heating parameter simulated through GIGA™. When the lattice heating model is added to drift-diffusion equations an extra equation is added. The BLOCK algorithm solves the three drift diffusion equations as a Newton solution and follows this with a decoupled solution of the heat flow equations [14-40]. The NEWTON algorithm solves all four equations in a coupled manner. NEWTON is preferred once the temperature is high, however BLOCK is quicker for low temperature gradients. The combination utilized for this paper was: METHOD BLOCK NEWTON.

1. Poisson's Equation

Poisson's equation is a well-known partial differential equation that has functions in electrostatics and theoretical physics. In semiconductor modeling it often serves as the starting point in obtaining quantitative solutions for electrostatic variables [12-40]. In electrostatics, Poisson's equation relates the electrostatic potential to the space charge density and is given by [12-40]:

$$\text{div}(\epsilon \nabla \psi) = -\rho \quad (1)$$

2. Carrier Continuity Equations

The carrier continuity equations for electrons and holes are defined by [12-40]:

$$\frac{\partial n}{\partial t} = \frac{1}{q} \nabla \cdot J_n + G_n - R_n \quad (2)$$

$$\frac{\partial p}{\partial t} = -\frac{1}{q} \nabla \cdot J_p + G_p - R_p \quad (3)$$

where n and p are the electron and hole concentration, J_n and J_p are the electron and hole current densities, G_n and G_p are the generation rates for electrons and holes, R_n and R_p are the recombination rates for electrons and holes and q is the magnitude of the charge on the electron. It is possible to solve for only the holes or electrons in the equations, and the model presented in this paper solves the equations for electrons only. Hole transport in the HEMT is insignificant.

3. Transport Equations

Electrons in thermal equilibrium at temperature T_L within a semiconductor lattice obey Fermi-Dirac statistics. That is the probability $f(E)$ that an available electron state with energy E is occupied by an electron is given by [1-12]:

$$f(E) = \frac{1}{1 + \exp\left(\frac{E - E_F}{K_B T_L}\right)} \quad (4)$$

Where K_B is Boltzmann constant and E_F is Fermi energy level.

The Current density equations are obtained by using the "drift-diffusion" charge transport model. The reason for this choice lies in the inherent simplicity and the limitation of the number of independent variables to just three, ψ , n and p . The accuracy of this model is excellent for all technologically feasible feature sizes. The drift-diffusion model is described as follows

$$J_n = qn\mu_n E_n + qD_n \nabla n \quad (5)$$

$$J_p = qp\mu_p E_p - qD_p \nabla p \quad (6)$$

where μ_n and μ_p are the electron and hole mobilities, D_n and D_p are the electron and hole diffusion constants, E_n and E_p are the local electric fields for electrons and holes, respectively, and ∇n and ∇p are the three dimensional spatial gradient of n and p .

4. Heat Flow Equation

Giga adds the heat flow equations to primary equations that are solved by ATLAS. The heat flow equations have the form:

$$c \frac{\partial T_L}{\partial t} = \nabla \cdot (k \nabla T_L) + H$$

Where: C is the heat capacity per unit volume k is thermal conductivity. H is the heat generation, T_L is the local lattice temperature.

Working

The large spontaneous and piezoelectric polarizations in the AlGaIn/GaN HEMT form the polarization induced charges at the AlGaIn surface, AlGaIn/GaN interface and GaN/substrate interfaces. The polarity of the charges at the AlGaIn surface and AlGaIn/GaN interface are opposite. The presence of

these polarization induced charges alone is insufficient to form the two-dimensional electron gas (2DEG) at the AlGaIn/GaN interface. Therefore, it is necessary that a positive sheet charge exists at the AlGaIn surface so that 2DEG can be formed at the AlGaIn/GaN interface [1-40].

Giga adds the heat flow equation to the primary equations that are solved by Atlas. Due to electron collision this heat is generated in the lattice is called the lattice temperature distribution. Further this heat is localized at the junction because the heat is trapped due to lattice structure that does not allows heat to escape easily. Electrical and thermal behavior of the device has been simulated by solving fundamental equations responsible for charge transport and heat flow equation responsible for thermal effect using finite element method with the help of device simulation software ATLAS.

RESULTS AND DISCUSSIONS

In this work physical structure of GaN HEMT has been created using commercial technology computer aided design (TCAD) tool ATLAS from Silvaco international. Electrical and thermal behavior of the device has been simulated by solving fundamental equations responsible for charge transport and heat flow equation responsible for thermal effect using finite element method with the help of device simulation software ATLAS. Id-Vg and Id-Vd characteristics has been simulated without self-heating and Id-Vd characteristics has also been simulated by incorporating models for self-heating effect in the device. Lattice temperature distribution inside the device has been predicted using 2D TCAD simulation.

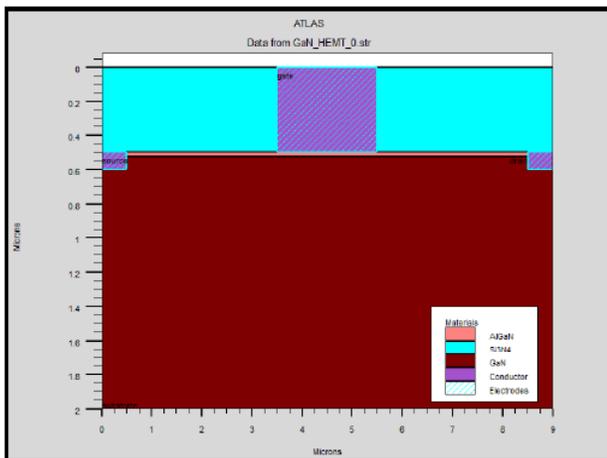


Figure 1: GaN based HEMT device structure.

Figure 1 shows the physical structure of the device under consideration which is created using ATLAS. In this structure GaN acts as channel of the device. Figure 2 shows the device structure showing the mesh for finite element based simulation.

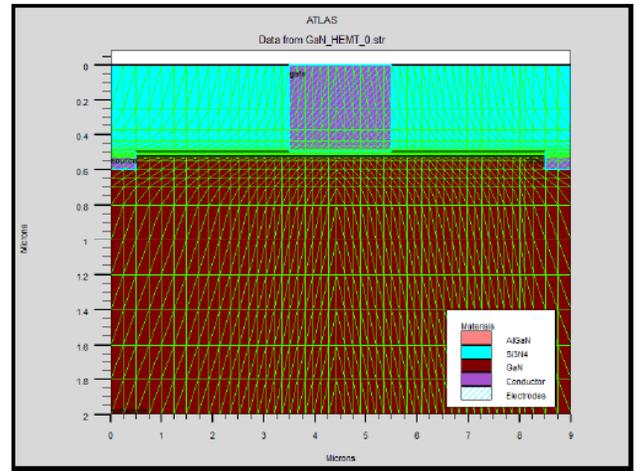


Figure 2: Device structure showing mesh.

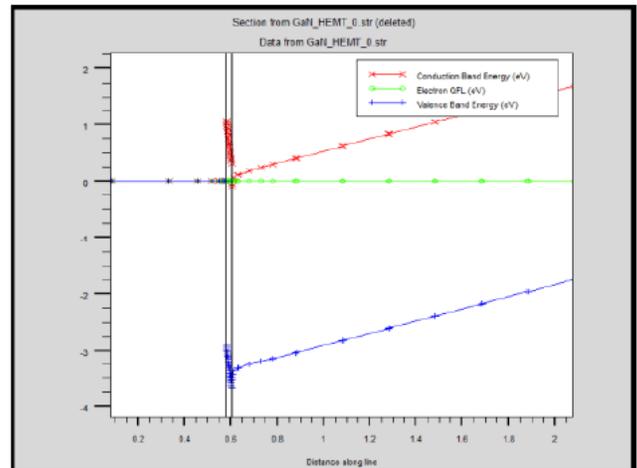


Figure 3: Energy band diagram.

Figure 3 is the full view of the energy band diagram showing the conduction band in red, the Fermi level in blue and the valence band in green. The bandgap of the simulated structure was measured and found to be 3.42eV. The value of this figure is that it shows the structure design is correct and that the 2DEG is formed on the GaN side of the heterojunction.

TRANSFER CHARACTERIZATION

The Id-Vg plot gives the transfer characteristics of the device as shown in Figure 4. This shows that in reverse bias the -6V of potential is enough to on the transistor. It means the device under consideration is

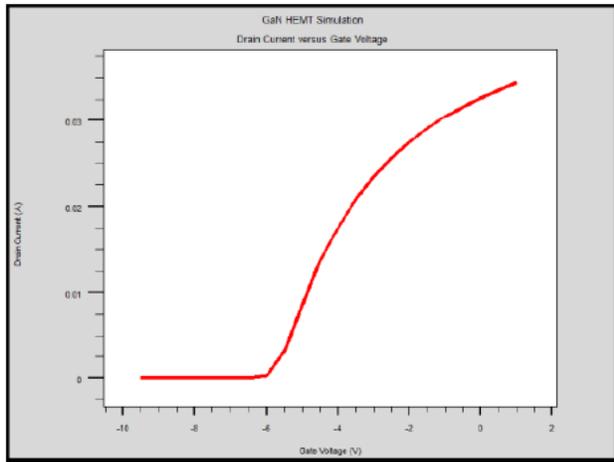


Figure 4: simulated transfer characteristics of HEMT device.

normally on and this is why it acts as depletion type transistor and its pinch off voltage $V_P = -6V$.

Lattice temperature distribution inside the device

Due to electron collision this heat is generated in the lattice is called the lattice temperature distribution.

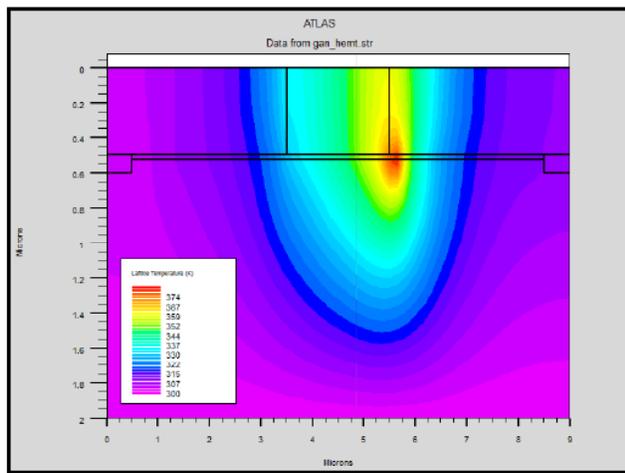


Figure 5: Output Characteristics (I_d - V_d Curves).

Further this heat is localized at the junction because the heat is trapped due to lattice structure that does not allows heat to escape easily. Figure 5 shows the lattice temperature distribution of GAN HEMT.

Once the model was complete and analyzed, a subroutine in ATLAS™ was created to generate the I_d s vs. V_{ds} (I - V) curves. Figure 6 shows the I_d - V_d characteristic of the HEMT device without self heating into consideration. Figure 7 shows the I_d - V_d characteristic of the GaN HEMT when self heating is taken into consideration.

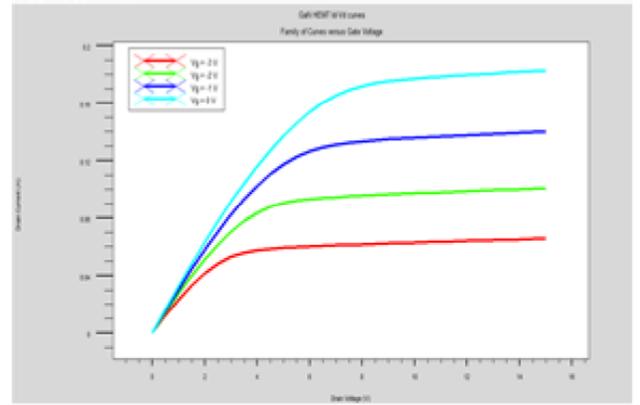


Figure 6: I_d - V_d -plot without self heating.

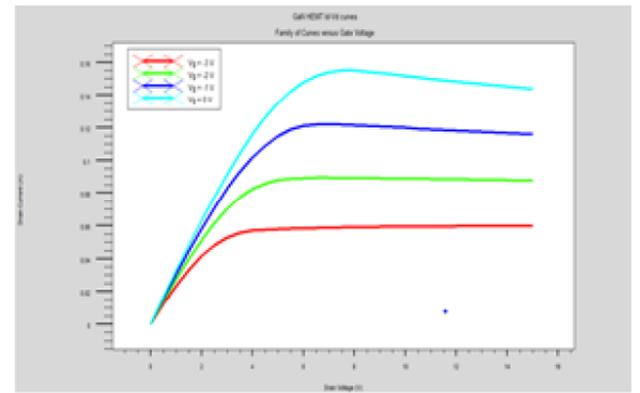


Figure 7: I_d - V_d plot with self-heating.

Figure 8 shows the I_d - V_d characteristics of the device with and without self heating. It is observed that self-heating reduces the effective drain current and degrades the performance of the device.

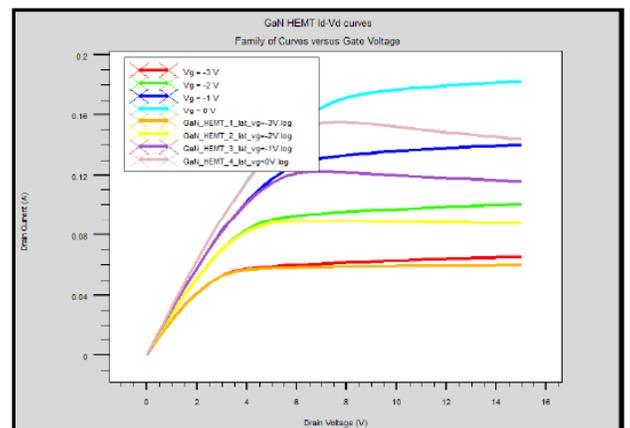


Figure 8: Combined I_d - V_d plot with and without self-heating.

CONCLUSION

In this work we created the physical structure of the GaN HEMT using commercial device simulation

software ATLAS and its electrical and thermal behavior has been investigated. For the investigation of electrical behavior of the device fundamental equations (like Poisson's equation, current continuity equation for electrons and holes and drift diffusion model for electrons and holes) responsible for charge transport were solved using finite element method. For simulating the self-heating behavior of the GaN HEMT heat flow equation has been solved along with the fundamental equations responsible for charge transport in the device. This shows that the drain current is lowered due to self-heating which is due to power dissipation at high current densities. The lattice temperature increases at alarming levels which could damage the device. This temperature can be reduced by using diamond substrate. Thus, we can conclude thermal effect is an important factor for device operation and its temperature should be reduced with various techniques. Many techniques should be employed for lowering the device temperature in order to give best results.

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