Model of AlGaN/GaN based on High Electron Mobility Transistors using SILVACO ATLAS™

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Abstract. Since the introduction of semiconductors, the world has undergone numerous profound transformations during the past few decades. With advancements in technology, semiconductor products' performance requirements keep rising. Research on novel materials and device structures is required to meet the criteria. This research presents a novel GaN HEMT construction. The components of an AlGaN/GaN heterojunction HEMT are the drain, source and gate electrode. Since M. Asif Khan and his colleagues published the first AlGaN/GaN HEMT in 1993, a lot of HEMT structures have been reported by researchers; nevertheless, none of them contain three electrodes on distinct sides of the device. In this study, we constructed a 2DEG GaN HEMT and observed its features, including its drain current characteristics curves, Ion/Ioff ratio, and transconductance characteristics curves. Which were acquired from simulations carried out with Silvaco ATLAS™.

Keywords: AlGaN/GaN HEMT, 2-DEG, drain current characteristics, transconductance, T-CAD SILVACO.

1. INTRODUCTION

Semiconductors based on group III-V nitride have been crucial components for high power and high frequency applications in electronic devices. Numerous semiconductors from the group III-V have been used in these kinds of applications over the years. High power and radio frequency applications have been demonstrated to benefit greatly from the unique properties of gallium nitride high electron mobility transistors (HEMTs) [1]. Because of the aforementioned characteristics of group III-nitrides, such as strong breakdown field and high velocity saturation, they are employed to construct high mobility devices, including aluminum nitride (AlN), gallium nitride (GaN), and indium nitride (InN). [2] Provides the bound charge of sheet charge strength of nitride materials on GaN, InN, and AlN alloys.

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The next generation of RF and microwave power amplifiers is the AlGaN/GaN HEMT, which is able to handle huge power at higher frequencies. A hetero-structure device is the HEMT. In general, heterostructure devices meet the requirements for high power and frequency. HEMT is commonly used in applications where very high- frequencies are appropriate. The production of 2-DEG is one of the primary advantages of the HEMT heterostructure that makes it appropriate for high-speed applications [3–6].

The heterostructure that forms the 2DEG is the result of the interfacing of low bandgap (undoped) and wide bandgap (doped) materials, which increases the electron mobility of the device [7,8]. The polarization effects that arise in the hetero-junction are the cause of 2DEG. Polarization results from lattice mismatch and simulated variation during hetero-structure creation. Due to differences in their band energy, the lattice structure of doped (wide band-gap) and undoped (narrow band-gap) materials tends to adapt to each other's atomic structures [9].

Due to its material characteristics, AlGaN is a strong candidate for high-speed applications. The primary purpose of the InGaN layer is to increase the electron mobility found in 2DEG. The InGaN layer helps to improve the concentration of 2-DEG in the hetero-junction and reduces disorderly scattering of alloys [10,11]. Owing to its growing concentration property and carrier mobility, high power applications employ it.

The features assessed in the AlGaN/InGaN/GaN hetero-structure are contrasted with the AlGaN/GaN structure that is currently in place. The structure of AlGaN/GaN is wurtzite. The carrier concentration of the interface is greatly increased by strain-induced piezoelectric polarization, which may occur five times more frequently in the top layer than in a typical AlGaAs/GaAs device [12]. The inclusion of an InGaN layer results in a higher piezoelectric polarization than AlGaN/GaN. It is possible to evaluate the total polarization generated charge density by summing the piezoelectric and spontaneous polarization [13]. Piezoelectric polarization is created when tensile and compressive strains are applied to a hetero layer, replacing the preexisting one. The value of InGaN's lattice parameter determines the stress [14].

An AlGaN/GaN/InGaN/GaN double-heterojunction HEMT (DH-HEMT) with reduced buffer leakage and high mobility 2DEG was reported in [15]. Compared to traditional AlGaN/GaN HEMT, the electron mobility obtained in this device is 30% greater. It is recommended in [16]to replace the AlGaN barrier layer in AlGaN/GaN HEMT with an InAlN layer with different Indium mole fractions. Using Sentaurus TCAD simulation, the n++GaN/InAlN/AlN/GaN HEMT by influence of bulk and interface traps is explored in [17]. Their findings showed how acceptor traps affected the concentration of free carriers in the channel.

2. DEVICE STRUCTURE

This section's figures and curves were all created using TONYPLOTTM, a potent tool for displaying mesh structures and plot log files. Additionally, we have utilized TONYPLOTTM's overlay feature to view several curves from several log files on a single graph. To improve visibility and readability of the output figures and graphs, we experimented with various scale factors, typefaces, line widths, colors, and other design elements.

The goal of this work is to investigate the potential of Silvaco TCAD [18](Technology Computer Aided Design) for power transistor physical simulation using AlGaN/GaN heterostructures. The fundamental simulation structure made with the ATLAS software package is displayed in Fig. 1. This structure is made up of an undoped GaN channel layer, an AlGaN-barrier layer (with a 25% Al mole fraction), a Si3N4 passivation layer, and a GaN buffer layer produced on a silicon substrate.

A computation mesh must be constructed in order to perform the simulation routine. Mesh spacing decreases to improve computation accuracy and convergence in the AlGaN/GaN heterojunction area, under the gate, and around the edges of the source and drain contacts. A built mesh HEMT structure based on GaN is depicted in Fig. 2.

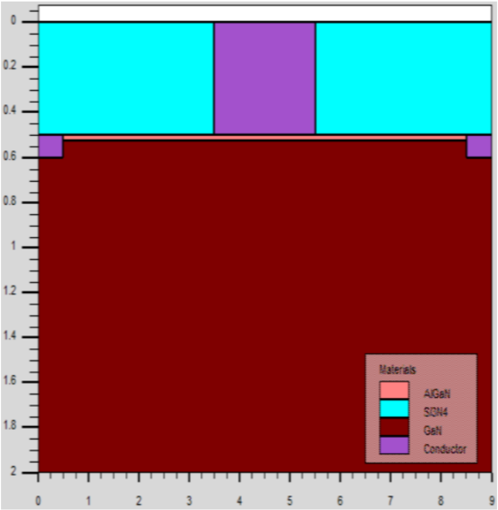


Figure 1. 2DEG structure of a Gallium Nitride HEMT

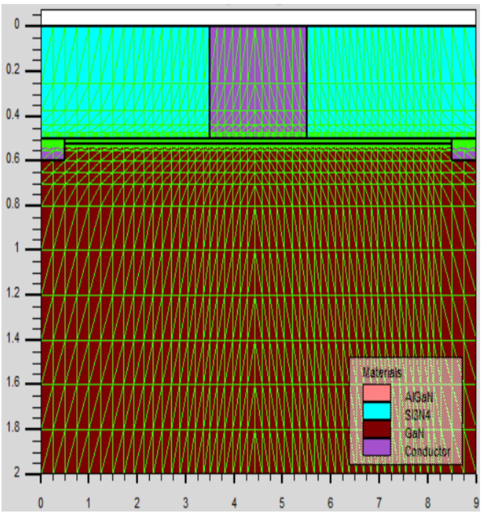


Figure 2. Mesh of AlGaN/GaN based HEMT simulation structure

Table 1 lists the parameters of the device construction during simulation process, together with the material and meshing of each component of the simulated device. The real gadget serves as the basis for the structural specifications. Assuring consistency between simulation and experiment [19], the source and drain electrodes in the simulation structure are carved into the GaN buffer layer so that the electrodes can be in direct contact with the 2-DEG. The simulation's dependability is guaranteed by the findings, which demonstrate that the device's features closely resemble those of the real thing.

Table 1. Parameters of the device construction during simulation.

Parameters of GaN Material	Values
Thickness of AlGaN barrier /nm	25
Thickness of GaN barrier /nm	1475
Width of gate /nm	500
Length of gate /um	0.5

3. RESULTS AND ANALYSIS

The simulation result of the AlGaN/GaN heterostructure band diagrams obtained at zero gate voltage is displayed in Fig. 3. At the AlGaN/GaN heterojunction, the bands discontinuity occurs.

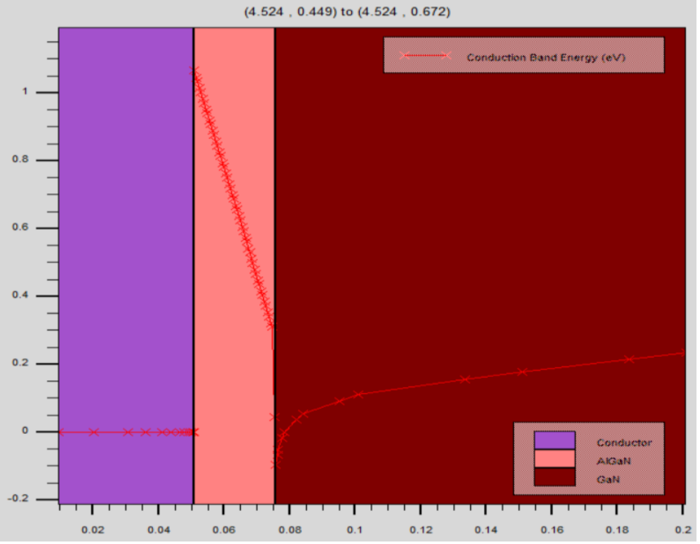
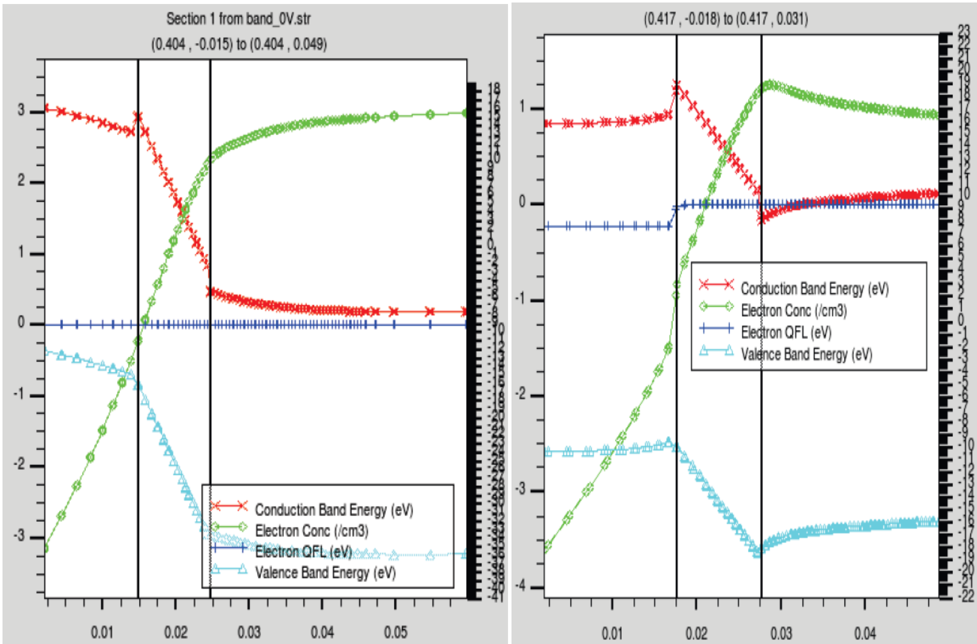


FIGURE 3. Conduction band diagrams at zero gate voltage of AlGaN/GaN heterostructure.

Next, a triangular quantum well forms, where the majority of charge carriers gather. Fermi level is below the GaN conduction band, as seen in Fig. 4a, meaning that no 2DEG forms in the channel. The distribution of carrier concentration (Fig. 4a) is $2 * 10^{15}\text{cm}^{-2}$and the sheet concentration is $4{,}2 * 10^{9}\text{cm}^{-2}$. These bulk and sheet concentration values line up with the off-state scenario. As illustrated in Fig. 4b, under positive gate voltage, the value of carrier concentration rises to $1 * 10^{20}\text{cm}^{-3}$ (sheet concentration equals $3{,}1 * 10^{12}\text{cm}^{-2}$. In this instance, electrons accumulating at the heterointerface form 2-DEG, and the Fermi level is above the GaN conduction band. This is consistent with the on-state situation. The obtained results enable the conclusion that the physical processes occurring in the real transistor are properly described by the provided model.



(a) (b)

FIGURE 4. Band diagrams showing the AlGaN/GaN heterostructure at both zero (a) and positive gate voltages (b).

Figure 5, which displays the Id-Vgs curve HEMT, reveals that the model's Vth (threshold voltage) is roughly -6V. The output characteristic for various gate-source voltages is displayed in Figure 6 as the drain Current-voltage characteristics Ids-Vgs for several values of gate Voltage for AlGaN/GaN HEMT. While the gate-voltage was swept from 0 V to -6 V, the drain source bias changed from 0 V to 40 V.

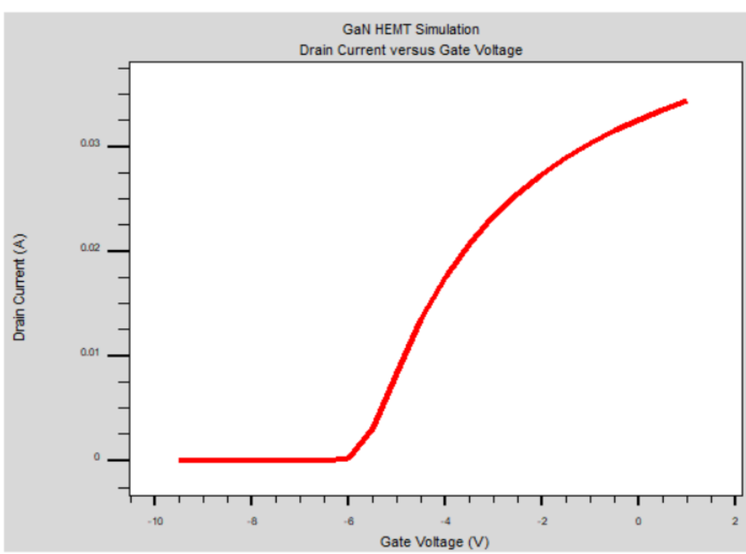


FIGURE 5. 2DEG HEMT transfer curve (Ids vs Vgs).

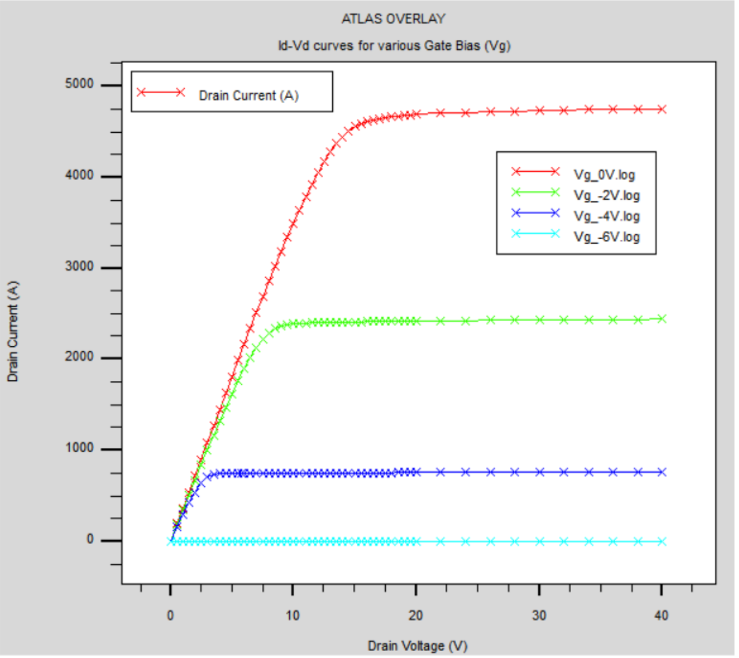


FIGURE 6. Current-voltage characteristics Ids-Vgs for several values of gate Voltage for AlGaN/GaN HEMT

In this study, we constructed a 2DEG GaN HEMT and examined its features, including the current voltage characteristics I-V curve, and Ion/Ioff ratio. Given that the 2DEG HEMT model's Vth is equal to -6V, our suggested model is expected to switch more quickly than [19,20] because its threshold voltage is lower. For our 2DEG HEMT, we obtained a lower drain current in the simulation Current-voltage characteristics Ids-Vgs for AlGaN/GaN HEMT when compared to [22] for the same Vgs. Additionally, the Ion/Ioff ratio characteristics value is 1.05457 A.
The simulation results presented in this research paper will all contribute to a deeper understanding of GaN HEMTs. The results are shown in Table 2.

Table 2. Results of GaN HEMT structures

Parameter	Values
Vth (in V)	-6
Ion(in A)	0.0344802
Ioff (in A)	0.0326959
Ion/ Ioff ratio	1.05457

The polarization charge at the AlGaN-GaN interface, which causes the creation of a 2-DEG, is the fundamental idea of an AlGaN/GaN HEMT. The polarization parameter on the model statement specifies which built-in models in the simulator are used to calculate the total polarization charges.
Firstly, the initial solution (with zero bias) was derived together with the 2D Electron Gas (2DEG) sheet density calculation. Next, for a few chosen Vds voltages, the Id-Vg transfer characteristics are calculated (Figure 7), from which the transconductance gm-Vg characteristics are derived (Figure 8).

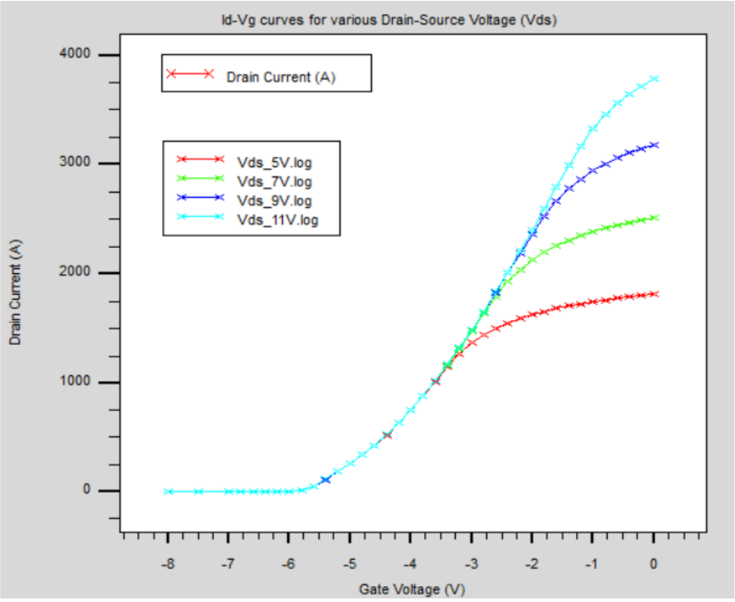


FIGURE 7. Characteristics of drain current for several Vds voltages Id-Vds.

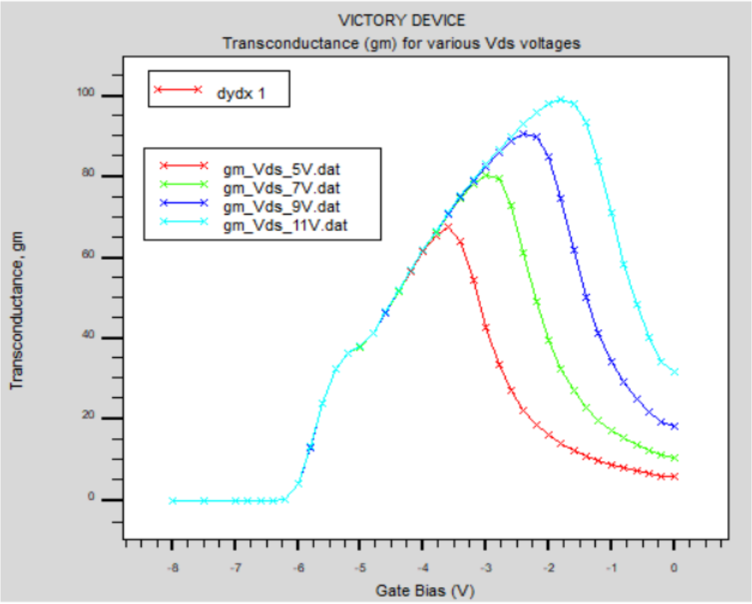


FIGURE 8. Transconductance gm-Vg characteristics,extracted from Id-Vg.

However, subsequent research on the 2DEG model of GaN HEMT has resulted in several sophisticated designs, such as GaN HEMT with InGaN back barriers [23]. GaN HEMTs have numerous useful applications in the fields of high power [24]and high frequency[25], making them a ground-breaking development in contemporary electronics.

4. CONCLUSION

Consequently, the band diagram of the power transistor's AlGaN/GaN heterostructure was constructed, considering the polarization processes. It was determined what the carrier concentrations were in 2DEG at both positive and zero gate voltage. In order to determine the carrier concentration while accounting for quantum effects, the self-consistent Schrödinger–Poisson equation was solved. In addition, the matching subbands and wave functions of the electrons in the transistor channel in the 2-DEG were constructed.
Therefore, it can be said that a good model of nitride-based heterojunction transistors may be developed through simulation using the Silvaco TCAD, videlicet ATLAS device modelling framework. This would also enable the prediction of actual device behaviour and cut down on the time and financial expenses related to the expensive technological process.

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