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2-D Theoretical Model for Current-Voltage Characteristics in AlGaN/GaN HEMT's

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ABSTRACT

A threshold-voltage-based 2-D theoretical model for the Current-Voltage characteristics of the AlGaN/GaN high electron mobility transistors (HEMT's) is developed. The present work proposes an improved charge-control model by employing the Robin boundary condition when introduced the solution of the 2-D Poisson's equation in the density of charge depleted in the AlGaN layer. The dependence of 2-DEG sheet carrier concentration on the aluminum composition and AlGaN layer thickness has been investigated in detail. Current-voltage characteristics developed from the 2-DEG model in order to take into account the impact of gate lengths. The relation between the kink effect and existing deep centers has also been confirmed by using an electrical approach, which can allow to adjust some of electron transport parameters in order to optimize the output current.

Keywords: AlGaN/GaN; High Electron Mobility Transistors; Two-Dimensional Electron Gas Sheet Charge Density; Current-Voltage Characteristics; Kink Effect

1. Introduction

Attracting a lot of attention in recent years are the III-nitride wide band-gap semiconductors (GaN, AlN, …) and their alloys, has become the basis of an advanced, microwave-power-device technology for several reasons. Indeed GaN has a breakdown field of 20 MV/cm [1], which is larger than that of GaAs (4 MV/cm) and Si (3 MV/cm), and a high peak electron velocity [2] of 3×10^7 cm/s as compared to 2×10^7 cm/s of GaAs and Si. A peculiar feature of GaN-based transistors with the wurtzite crystal structure is the formation of a two-dimensional electron gas (2DEG) at the AlGaN/GaN heterointerface, due, mainly to spontaneous and piezoelectric polarizations, high sheet carrier concentrations (n_s) of 10^{13} cm^{-2} have been obtained in AlGaN/GaN HEMT's, which make them meet the demands of high-power devices [3,4]. High saturation velocity obtained in the GaN channel has shown promising performance for the high-frequency microwave applications. AlGaN/GaN high electron mobility transistors (HEMTs), have received much attention for high-power and high frequencies applications because of a high breakdown field in the wide-band gap semiconductors are capable of the high temperature applications [5,6]. In addition to that, a large conduction band discontinuity between GaN and AlGaN and the presence of polarization fields allow a large two-dimensional electron gas (2-DEG) concentration to be confined [7,8]. On the other hand, the improvement of these performances is still subject to the crucial problem is how to achieve simultaneously a high electron transport in a transistor device based on doped AlGaN/GaN structures. However, similarly to other III-V transistors, the AlGaN/GaN HEMT's are limited by some anomalies like kink effect as has been found in I_{ds}-V_{ds} output characteristics [9,10]. This parasitic effect is characterized by a sharp increase in the drain-source current I_{ds} at a certain drain-source voltage ($V_{ds} = V_{kink}$). So that, it is required to understand the origin of the kink effect in order to overcome its degrading limitations. For that, reliable and predictive theoretical models are needed along with the fast development of GaN-based devices.

The aim of the work is to present a threshold-voltage-based 2-D theoretical model for the I-V characteristics of AlGaN/GaN HEMTs. We have used the conventional charge-control model in order to simulate the I_{ds}-V_{ds} transport characteristics of AlGaN/GaN HEMT structures. The 2DEG sheet carrier concentration has been explored according to the thickness d_d of the AlGaN donor layer and Al composition when considered. Also, Current-voltage characteristics developed from the 2-DEG

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model in order to take into account the impact of gate lengths. An improvement and accurate analytical model for the I-V characteristics of kink effect on AlGaN/GaN high electron mobility transistors is presented. Thus remain to simulate and confirm the relation between the kink effect and defects.

2. Theoretical Considerations and Results

2.1. Model Description

Figure 1 Shows the cross-sectional view of an AlGaN/GaN HEMT. The layer sequence is, from top to bottom, metal/n-AlGaN/undoped-AlGaN/undoped-GaN with a 2-DEG formed at the unintentionally doped (UID)-AlGaN/GaN interface.

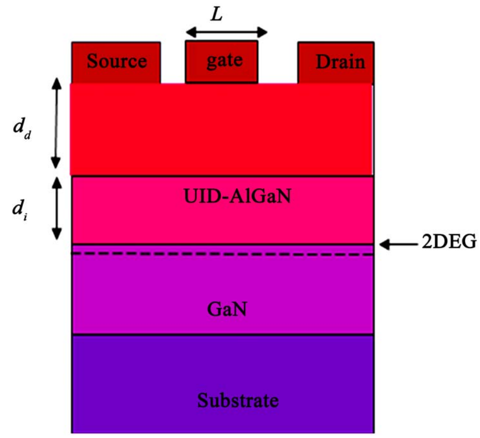

Figure 1. Cross-section view of an AlGaN/GaN HEMTs with gate length *L*, n-AlGaN layer thickness d_d, and spacer layer thickness d_i

2.2. Charge-Control Model

As established above, the AlGaN/GaN HEMTs simulated shows only the first two subbands occupied at $T = 300$ K. Thus, the total density of the 2-DEG accumulated in the channel can be approximately expressed as: (Equation (1), see the bottom of this page)

$$n_s = D\cdot K_B\cdot T\ln\left(\left(1+\exp\left(\frac{E_F-E_0}{K_B\cdot T}\right)\right)\times\left(\left(1+\exp\left(\frac{E_F-E_1}{K_B\cdot T}\right)\right)\right)\right) \quad (1)$$

where K_B, $\hbar$, and E_F are the Boltzmann constant, Planck constant and the Fermi energy constant respectively.

Under total depletion approximation, the density of charge depleted in the AlGaN layer is obtained using the assumption of total depletion by solving Poisson's equation [11,12]:

$$n_s(m) = \frac{e(m)}{q(d_d+d_i)}\left(V_{gs}-V_{th}-\frac{E_F}{q}\right) \quad (2)$$

where q is the electron charge, ε and $d = d_d + d_i$ are the permittivity and the total thickness of the AlGaN layer, respectively, E_F is the Fermi level with respect to the bottom of the conduction band in the GaN layer, and V_{th} is the threshold voltage of the HEMT given by:

$$V_{th} = \phi_{eff}^b - \Delta E_c - \frac{qN_s d_{\text{AlGaN}}^2}{2\cdot\varepsilon_{\text{AlGaN}}} - \sigma\frac{d_{\text{AlGaN}}}{\varepsilon_{\text{AlGaN}}} \quad (3)$$

where ϕ_{eff}^b is the effective barrier height of the Schottky gate, ΔE_c is the discontinuity of the conduction band at the interface between the UID-AlGaN and the GaN layers. $\frac{qN_s d_{\text{AlGaN}}^2}{2\cdot\varepsilon_{\text{AlGaN}}}$ is the doping concentration in n-AlGaN layer, and σ is the polarization induced charge density at the interface. Equations (1) and (2) have to be solved simultaneously and the interfacial sheet electron concentration in the strong inversion regime is given by [11]:

$$n_s(m) = \frac{2e^2 m_e^* d}{2e^2 d m_e^* + \varepsilon(m)\pi\hbar^2}\left[\left(V_{gs}-V_{th}\right)\frac{\varepsilon(m)}{ed} + \frac{m_e^*}{\pi\hbar^2}\left(E_1+E_2\right)\right] - \frac{m_e^*}{\pi\hbar^2}\left(E_1+E_2\right) \quad (4)$$

where E_1 and E_2 are the subband energies.

Calculations were carried out in order to study the impact of gate voltage on the 2-DEG density. We wanted to show the influence of different Al composition and the barrier thickness on the characteristic $N_s = f(V_{gs})$. **Figure 2** shows the variation of 2-DEG sheet density versus the gate voltage V_{gs} calculated for different AlGaN layer thickness and reveals that: 1) When the thickness d_d of the AlGaN donor layer increase, the concentration of 2-DEG increases with V_{gs}. 2) The threshold voltage of the transistor shifts toward increasingly in absolute value with increased d_d. 3) The increase of the electron density is due to the increased effect of the piezoelectric and spontaneous polarization. 4) The slope of the N_s-V_{gs} plots corresponds to the gate capacitance of the structure, which is linked directly to the separation between the gate and 2-DEG, more precisely to the thickness d_d, the latter is growing more capacities decreases and beyond the threshold voltage decreases it induces the reduction in the gate capacity, this is demonstrated for $d_d = 20$ nm, the slope is 2.1×10^{12} $\text{cm}^{-2}\cdot\text{V}^{-1}$, while that for $d_d = 26$ nm, the slope is 1.4×10^{12} $\text{cm}^{-2}\cdot\text{V}^{-1}$. This shows that high values of the barrier width are favorable to achieving significant electronic density and to obtain low gate capacitance values. The calculations were carried out by using the parameters: a composition of aluminum equal to 0.23, doping density order to 10^{18} cm^{-3}, and a spacer width 30 Å.

Figure 3 shows the variation of 2-DEG density Ns versus the gate voltage V_{gs} calculated for different Al composition and reveals that: 1) When the Al mole fractions in AlGaN/GaN HEMTs increase the electron density increases as well for the threshold voltage which exhibits shifts toward increasingly in absolute value as a function Al composition. 2) The variation in the Al mole fractions shown will also vary considerably the threshold voltage (−4 to −6 V), however, this variation does not influence on the slope of the N_s-V_{gs} characteristics.

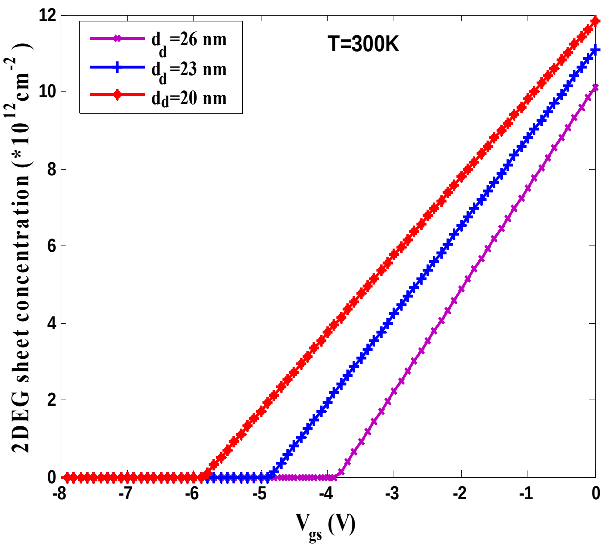

Figure 2. The 2D sheet charge density in AlGaN/GaN HEMTs as calculated versus the gate bias for different AlGaN layer thicknesses.

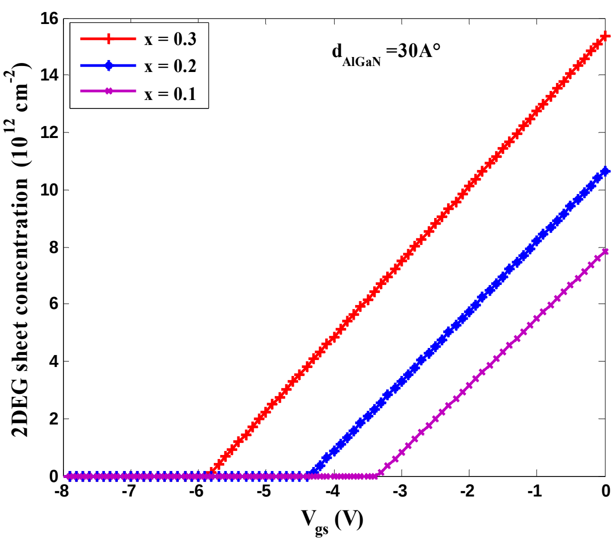

Figure 3. The 2D sheet charge density in AlGaN/GaN HEMTs as calculated versus the gate bias for different Al compositions.

2.3. Current-Voltage Characteristics

The Current-Voltage is related to the density variation for the 2DEG density under the influence of a gate-source voltage applied of the component. In fact, any action on the gate voltage V_{gs} has the effect to modify the electronic population of the channel which varies the electrons density n_s. Several authors have developed models in order to account for the I_{ds}-V_{ds} characteristics electrical behavior of HEMTs [13,14]. First, we started to introduce conventional expression of the drain-source current I_{ds} according to the voltage drain-source V_{ds} in order to determine ideal characteristics I_{ds}-V_{ds} for different values of V_{gs}. The current I_{ds} is proportional to the density of electrons in the channel n_s which is expressed as follows [11,12]:

$$I_{ds} = Z\mu q n_s(x)\frac{\mathrm{d}V(x)}{\mathrm{d}x} \tag{5}$$

where Z is the channel width and μ is the mobility of carriers. In deriving I_{ds}, we have neglected the diffusion current and the dependence of μ as a function of the built-in electric field. The drain-source current is obtained by integrating I_{ds} along the channel. The boundary conditions are: $V(x = 0) = R_s \cdot I_{ds}$ and $V(x = L) = V_{ds} - (R_s + R_d) \cdot I_{ds}$ where R_s and R_d are the source and drain contact resistances and V_{ds} is the bias voltage applied to the drain with respect to the source. In the linear regime, the voltage drops across source and drain resistance accesses can be neglected. Therefore, the drain-source current is expressed according to [12]:

$$I_{ds} = \frac{Z\mu\beta e}{L}\left(V_{gs} - V_{th} - \frac{V_{ds}}{2}\right)V_{ds} \tag{6}$$

In saturation regime, the channel current tends to saturate and ceases to increase with the drain-source voltage. It is straight forward to establish at the drain gate ($x = L$):

$$I_{dsat} = Z\mu e\beta\left(V_{gs} - V_{th} - V_{ds,sat}\right)F_s \tag{7}$$

Here, F_s represents the critical electric field for velocity saturation. According to Equations (4) and (5), V_{dsat} as well as I_{dsat} are given by:

$$V_{dsat} = \left(V_{gs} - V_{th} + F_s L\right) - \sqrt{\left(V_{gs} - V_{th}\right)^2 + F_s^2 L^2} \tag{8}$$

and

$$I_{dsat} = \beta e\mu F_s\left(\sqrt{\left(V_{gs} - V_{th}\right)^2 + F_s^2 L^2} - F_s L\right)$$

We simulate the I_{ds}-V_{ds} characteristics by a Matlab program using the above relations for several values of V_{gs}. **Figure 4** shows the Current-Voltage characteristics for different gate voltage V_{gs} ranging from −4 V to 0 V. These characteristics correspond to an ideal HEMT structure, *i.e.* without considering the anomalies may be present in this type of component. It appears clearly that the saturated drain current increases when increasing gate voltage.

However, the drain current increase is influenced by gate lengeth. An example is given to 300 K for the V_{gs} = 0 V are shown in **Figure 5**. As can be seen the variation of saturated drain-current as a function of drain voltage at different gate lengths. The plots reveal enhanced drain current in decreasing gate lengths. It should be, however, noted that the use of short gate lengths seem to be an appropriate way to achieve improved electron transport in AlGaN-related HEMTs.

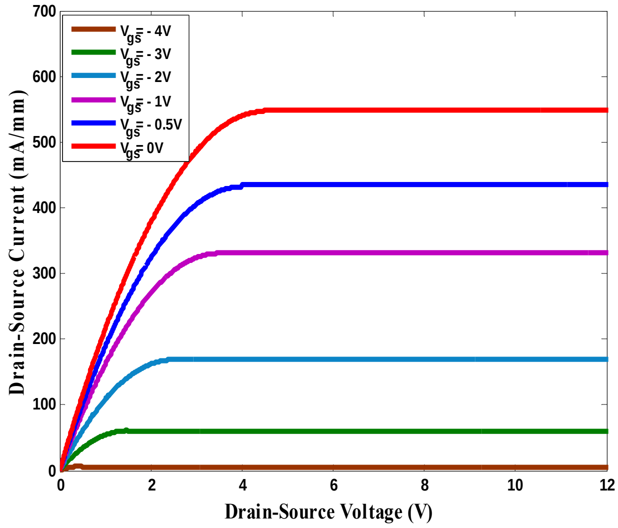

Figure 4. Theoretical ideal characteristics I_{ds}-V_{ds} for an AlGaN/GaN at different gate Voltage.

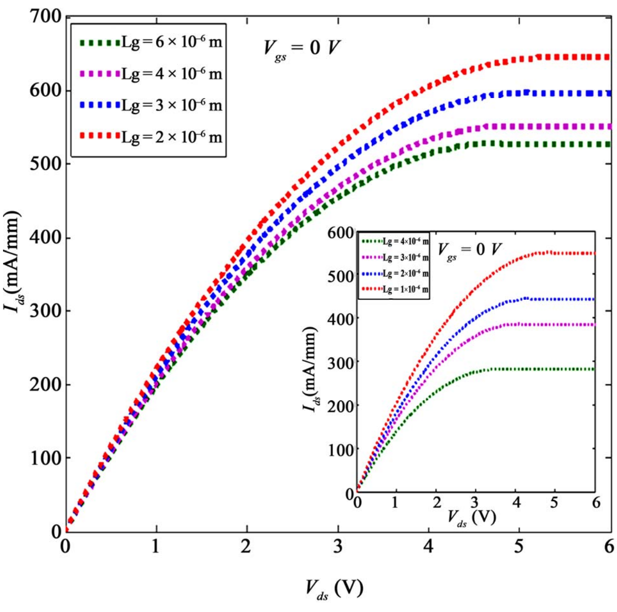

Figure 5. Output characteristics of AlGaN/GaN/Si HEMTs at different gate lengths.

Experimental studies have been reported on the gate length effect in output characteristics I-V [15]. These studies demonstrated that reducing the gate length resulting in a higher drain current. This is coherent because the drain current of HEMTs is directly proportional to the drift velocity. When the gate length decreases the effects of excess speed are more pronounced induced an increase of the drift velocity in order to optimize the output current in the kind of transistors.

2.4. Kink Effect in AlGaN/GaN HEMTs

Kink effect is a detrimental phenomenon for the FET performance. It leads to an output-conductance increase, a transconductance decrease, a drain current drop and a dispersion between DC and RF characteristics. Many studies of the kink effect have been reported [16,17], but due to its complex behaviour, the origin of this effect is still a subject of controversy. Theoretically, the kink effect was coarsely described in various kind of FETs, like Si MOSFETs, GaAs MESFETs and AlGaN/GaN high electron mobility transistors (HEMT's) [18,19]. Many research experiences are directed toward understanding and eliminating these parasitic effects and minimizing the trapping effects [20,21]. In this part, we will report the parasitic effects, observed in output characteristics I_{ds}-V_{ds} namely kink effect of GaN-based HEMT. Some authors have performed two-dimensional (2-D) numerical simulations. However, there are only few analytical study which explained the origin of this effect. Consequently, for further improvement of AlGaN/GaN HEMTs it is crucial to investigate the impact of the kink effect on transport properties of the AlGaN/GaN HEMT's. Many studies have correlated kink effect with defects on AlGaN/GaN transistors [22]. For this reason we developed an analytical current-voltage model for AlGaN/GaN power HEMT that incorporates the expression of concentration N_T^+. Assuming that only a single deep trap is present in the host lattice with a concentration N_T and based on the balance equilibrium, the proportion of ionized traps is expressed as:

$$N_T^+ = -\frac{1}{2}\left(N_D + \frac{N_C}{2}e^{\left(\frac{E_c-E_T}{KT}\right)}\right) + \frac{1}{2}\sqrt{\left(\frac{N_C}{2}e^{\left(\frac{E_c-E_T}{KT}\right)} + N_D\right)^2 + 2N_C N_T e^{\left(\frac{E_c-E_T}{KT}\right)}} \quad (9)$$

where N_D represents the density of residual donor impurities, $(E_c - E_T)$ is the binding energy of the trap, N_c is the density of states in the conduction-band and T is the local lattice temperature. By taking into account the ionized electron traps, the electron sheet concentration in the channel will be given by the extended relationship:

$$n_s(m) = N_T^+ L + \beta\left(V_{gs} - V_{th} - V(x)\right) \quad (10)$$

As a direct consequence, activated electrons from deep traps can participate noticeably to the conductive channel current. For V_{ds} larger than the pre-kink bias, the drain-source voltage and the drain current should have both the following forms:

$$V'_{dsat} = \left(V_{gs} + \frac{N_T^+ L}{\beta} - V_{th} + F_s L\right) - \sqrt{\left(V_{gs} + \frac{N_T^+ L}{\beta} - V_{th}\right)^2 + F_s^2 L^2} \quad (11)$$

and

$$I'_{dsat} = \beta e \mu F_s \left(\sqrt{\left(V_{gs} + \frac{N_T^+ L}{\beta} - V_{th}\right)^2 + F_s^2 L^2} - F_s L\right)$$

By introducing the modified term using Equation (9), we achieve the new characteristics I_{ds}-V_{ds} (**Figure 6**) showing the apparition of a kink effect at a certain drain-voltage called kink voltage (V_{kink}).

This effect appears for high drain-to-source voltage V_{ds} increasingly in order to pinch off the channel. The results are shown in **Figure 6**. We can easy notice the variation of the kink current ΔI_{kink} simulated as a function of defects concentration for different gate-to-source voltages (V_{gs}).

These results are in a good agreement with this approach which confirms the influence of deep defects, present in AlGaN/GaN HEMT transistors. However, the drain-source current continues to increase even in the saturation region for such V_{gs} values which tends towards zero and for decreasingly high values of concentration traps.

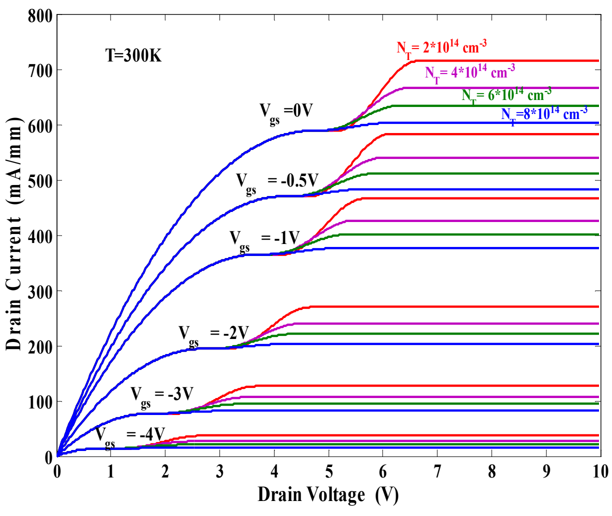

Figure 6. Theoretical spectra I_{ds}-V_{ds} at T = 300 K reveal the kink effect. Defects are clearly shown.

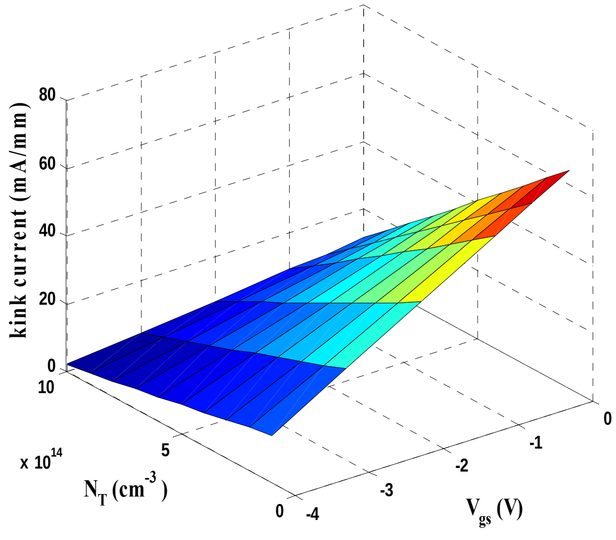

Figure 7. Variations of the kink current ΔI_{kink} at T = 300 K as a function of defects concentration and at different gate voltage.

The result is illustrate in the tridimensional plot in **Figure 7**, in order to represent $\Delta I_{\text{kink}}(N_T, V_{gs})$. This last plot represents the value of kink current (ΔI_{kink}) increases as the gate voltage tends to 0 V and the defects concentration decreases.

3. Conclusion

A 2-D analytical model has been calculated for the Current-Voltage characteristics in AlGaN/GaN High Electron Mobility Transistors (HEMT's). At first, we have developed the conventional charge-control model for the current-voltage characteristics of AlGaN/GaN HEMTs without considering any defect in order to take into account the impact of gate lengths. In a second step, we have calculated the kink current versus the defect concentration. In this simulation, the kink effect is mainly due to deep lying defects. In the paper, both kink effect and existing deep centers has also been confirmed by using an electrical approach, which can allow to adjust some of electron transport parameters in order to optimize the output current.

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