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Analytic Estimation of Two-Dimensional Electron Gas Density and Current-Voltage Characteristic in AlGaN/GaN HEMT's

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ABSTRACT

This paper is mainly dedicated to understand the phenomena governing the formation of two-dimensional electron gas (2DEG) confined in the quantum well which hold the role of the channel in the high electron density transistors (HEMT) based on AlGaN / GaN heterojunction. The theory takes into account: the crystal structure, the spontaneous and piezoelectric polarization concept, the formation mechanism of two-dimensional electron gas at the AlGaN / GaN interface, the approximate resolution of the Poisson and Schrödinger equations to determine the density of Two-dimensional electron gas after the analytical formula of the current-voltage characteristic is established. Our study is also concerned with the dependence of the two-dimensional electron gas density on the following technological parameters: Aluminum molare fraction, AlGaN layer thickness and AlGaN layer doping, In order to control the influence of these parameters on the device performance. Finally, the current-voltage characteristic which reflects the variation of the drain-source current as a function of the modulation of the gate voltage has been discussed.

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1. INTRODUCTION

The area of microelectronics has been marked by an increase in the demand for components which can operate in frequency increasingly higher [1-3]. Emerging needs in this area are not only related to the telecommunications market, but in other areas of application such as embedded electronics at bound for the automotive and aeronautic. The largest concerns in semiconductor integrated circuits are high-speed operation and low power consumption [4]. Since the 90s, a new generation of semiconductor components (HEMT) is under study and evaluation thanks to the advent of wide band gap materials such as GaN [5], GaN based devices are very useful for high frequency high temperature microwave applications such as radar systems [6]. Transistors AlGaN / GaN HEMTs results are very promising for power electronics and high frequency due to their two-dimensional electron gas 2DEG high density and high mobility as well as to their high breakdown field [7].

To develop a reliable model of HEMT, an accurate estimate of the two-dimensional electron gas density at AlGaN / GaN interface is of considerable importance. A number of charge control models for HEMTs have been developed to characterize the 2-DEG concentration. These models are useful as they provide an insight into the physical operation of the device, but they generally require simplifying assumptions for the 2DEG density. Some models assume a linear dependency of 2DEG density at the gate bias, but the values of 2DEG density are underestimated near the threshold [8], [9]. Other models offer a

nonlinear dependence, but have used many fitting parameters that are of little physical importance [10], [11] or use iterative techniques that are unsuitable for circuit simulation [12], [13]. Therefore, to provide a better physical understanding of the device operation, an analytical approach to model the 2-DEG density of AlGaN / GaN HEMTs is highly desirable.

This work is mainly devoted to formally present all the features necessary for understanding high electron density transistors based on AlGaN / GaN heterojunction, The crystal structure of GaN and the concepts of spontaneous and piezoelectric polarizations, The mechanism of the formation of the 2DEG at the AlGaN / GaN interface then solving Poisson and Schrödinger equations to determine the 2DEG density and finally deduce the current i_{ds}.

2. RESEARCH METHOD

2.1. Spontaneous and Piezoelectric Polarization

The III-V materials crystallographic arrangement studied in this work will be Wurtzite, as seen this crystalline form is the most stable phase and it provides remarkable physical properties [14]. The combination of both gallium and nitrogen elements of different electronegativities causes a charge transfer of the element with a high electronegativity to the element having a low electronegativity. This phenomenon is the cause of the spontaneous polarization, which is the first characteristic of the gallium nitride. The spontaneous polarization field of ternary compounds can be calculated by applying Vergard's law [15].

$$P_{sp}\left(A_m B_{1-m} C\right) = P_{sp}\left(BC\right) + m\left(P_{sp}\left(AC\right) - P_{sp}\left(BC\right)\right) \quad (1)$$

The GaN is often developed on sapphire, SiC or silicon. The lattice mismatch between GaN and the substrate imposes a strain (expansion or compression) in the base plane of GaN layers. The deformation of the lattice GaN entrains a charge barycenter displacement, hence a change in the spontaneous polarization. This effect is the second characteristic of the gallium nitride called: piezoelectric polarization, which strengthens or weakens the spontaneous polarization. The piezoelectric polarization field is given by [16]:

$$P_{pzAlGaN}(m) = 2\frac{a(0)-a(m)}{a(0)}\left[e_{31}(m) - \frac{e_{33}(m)C_{13}(m)}{C_{33}(m)}\right] \quad (2)$$

Table 1. Physical parameters of InN, AlN and GaN

	InN	AlN	GaN
a0 ((Å	3.585	3.110	3.189
e31 (C/m^2)	-0.57	-0.50	-0.35
e33 (C/m^2)	0.97	1.79	1.27
c13 (GPa)	92	108	106
c33 (GPa)	224	373	398
Psp (C/m^2)	-0.042	-0.09	-0.034

Table 1 shows the values for relevant physical parameters of AlN and GaN [17-19]. To calculate the effects of polarization in $Al_mGa_{1-m}N$ alloy we need the lattice constant, piezoelectric constants and elastic constants of $Al_mGa_{1-m}N$ which can be calculated by analogously applying Vergard's law. To amount of the polarization induced charge density is given by:

$$\sigma^{+} = \left[P_{sp} + P_{pz}\right]_{AlGaN} - P_{spGaN} \quad (3)$$

2.2. Calculating the Electronic Density at the Interface

We are particularly interested by the heterojunction AlGaN / GaN, basic element of the barrier layer and the channel of the transistor studied. The principle of the heterojunction based on contacting of two semiconductor materials with different bandgap, such as one has a large bandgap, the other has a low bandgap. Depending on the model of Anderson which is supported on the approximation of Schokley [8], bringing into contact of these materials, in the case of thermodynamic equilibrium, causes the alignment of the Fermi level and the transfer of electrons of the wide bandgap material to the low bandgap material. An electric field is generated at the interface and a band of curvature appears in its vicinity. A potential well is

created at low bandgap semiconductor side; hence an accumulation of electrons forms at the interface. In a HEMT structure, the electrons accumulated in the potential will form a two-dimensional electron gas. Understanding the physical phenomena governing the operation of the HEMT and the formation of a 2DEG requires solving the Schrödinger's equation. With the first two quantum states occupied, the total 2DEG density in the accumulation layer is given by [20]:

$$n_s(E_F) = \frac{m_e^*}{\pi\hbar^2} kT \ln\left[\left(1+\exp\left(\frac{E_F - E_0}{kT}\right)\right)\times\left(1+\exp\left(\frac{E_F - E_1}{kT}\right)\right)\right] \quad (4)$$

Where E_F is the Fermi level, E_1 and E_2 are quantum state occupied. We establish a first equation of 2DEG density noted n_s (E_F) that binds the electrons density at the interface AlGaN/GaN, to the Fermi level. A second relation of the type n_s (V_{gs}, E_F) can be established by integrating the Poisson equation. We obtain

$$n_s(V_{gs}, E_F) = \frac{\varepsilon}{qd}\left(V_{gs} - \frac{E_F}{q} - V_{th}\right) \quad (5)$$

With ε is GaN dielectric constant. Hence the equation governing the evolution of the threshold voltage

$$V_{th} = \frac{\varphi_b}{q} - \frac{\Delta E_c}{q} - \frac{qN_D}{2\varepsilon} d^2 - \frac{\sigma^+}{\varepsilon} d \quad (6)$$

Where φ_b is the Schottky barrier height, ΔE_c is the conduction band discontinuity between AlGaN and GaN, N_D AlGaN layer doping and d is AlGaN layer thickness. Solving the system of Equations (4) and (5) allows the evolution of carrier concentration ns in the well as a function of V_{gs}. We can obtain approximate solutions in three specific bias ranges: weak inversion, moderate inversion and strong inversion.

2.3. Weak Inversion

For low electrons densities at the interface: the Fermi level is located beyond the first energy sub-band. Exhibitors appearing in Equation (4) are negative and limited development type ln (1 + ε) = ε of this equation allows giving:

$$n_s = \frac{m_e^*}{\pi\hbar^2} kT \exp\left(\frac{E_F}{kT}\right)\left[\exp\left(\frac{-E_0}{kT}\right) + \exp\left(\frac{-E_1}{kT}\right)\right] \quad (7)$$

For this electric polarization regime, E_0 and E_1 are less than KT so that

$$n_s = 2\frac{m_e^*}{\pi\hbar^2} kT \exp\left(\frac{E_F}{kT}\right) \quad (8)$$

As well the Fermi energy E_F is bonded to the electron density by the relation

$$E_F = kT \ln\left(\frac{n_s \pi\hbar^2}{2m_e^* kT}\right) \quad (9)$$

By postponing this expression in the Equation (4) and supposing that the density is weak compared to the density of states associated with the both first sub-bands, we get:

$$n_s = 2\frac{m_e^*}{\pi\hbar^2} kT \exp\left(\frac{q\left(V_{gs} - V_{th}(m)\right)}{kT}\right) \quad (10)$$

Note that in weak inversion regime, the potential well is quite large and not too deep, it results that the quantization of electronic states is low and that the structure has an offset relative to a two-dimensional electron gas.

2.4. Moderate Inversion

In this regime, the Fermi level is at the bottom of the potential well, just a few kT above the conduction band. The structure then operates near to the threshold. As well we can rewrite the equation:

$$n_s = n_{s0}\left[\frac{E_F}{kT}\right] \cong n_{s0}\left[1+\frac{E_F}{kT}\right] \tag{11}$$

By combining the two equations Equation (4) and Equation (11), we find that:

$$E_F = \frac{q\varepsilon(m)kT\left(V_{gs}-V_{th}(m)-\frac{qdn_{s0}}{\varepsilon(m)}\right)}{q^2dn_{s0}+\varepsilon(m)kT} \tag{12}$$

Finally, we get the relation linking n_s to V_{gs} in moderate inversion regime:

$$n_s = n_{s0}\exp\left[\frac{q\varepsilon(m)kT\left(V_{gs}-V_{th}(m)-\frac{qdn_{s0}}{\varepsilon(m)}\right)}{q^2dn_{s0}+\varepsilon(m)kT}\right] \tag{13}$$

With n_{s0} as the equilibrium sheet carrier density at E_F=0.

2.5. Strong Inversion

The electron density in the channel becomes sufficiently important, that the Fermi level goes above the bottom of the second sub-band E_1. The exponentials terms in Equation (4) then become much higher than 1 and we can write approximated as:

$$n_s = \frac{m_e^*}{\pi\hbar^2}\left(2E_F - E_0 - E_1\right) \tag{14}$$

Hence the expression of E_F can be deduced

$$E_F = \frac{E_0+E_1}{2} + \frac{\pi\hbar^2}{m_e^*}n_s \tag{15}$$

Explicit the terms of E_0 and E_1 is obtained

$$E_F = \frac{\gamma_0+\gamma_1}{2}n_s^{\frac{2}{3}} + \frac{\pi\hbar^2}{m_e^*}n_s \tag{16}$$

By postponing this expression in the Equation (5), we get

$$n_s\left(1+\frac{\varepsilon(m)\pi\hbar^2}{2q^2dm_e^*}\right)+\frac{\varepsilon(m)\left(\gamma_0+\gamma\right)_1}{2q^2d}n_s^{\frac{2}{3}} = \frac{\varepsilon(m)}{2d}\left(V_{gs}-V_{th}\right) \tag{17}$$

In strong inversion regime, the linear term is dominant in n_s, so that the electron density follows an approximately linear law, therefore is given by

$$n_s = \frac{2q\varepsilon(m)m_e^*}{2dq^2m_e^* + \varepsilon(m)\pi\hbar^2}\left(V_{gs} + V_{th}\right) \tag{18}$$

The HEMT AlGaN/GaN mainly operate in the strong inversion region, the current in this region actually determines the performance of AlGaN / GaN HEMT for high power applications.

2.6. Current-voltage Characteristic

The drain-source current i_{ds} can be obtained from the relation between the current intensity and the electric charge accumulated in the electron gas [19]:

$$i_{ds} = wqn_s v(x) \tag{19}$$

Where w is the gate width, v(x) is the velocity of the electrons in the channel at the abscissa x. The gate voltage replaced by the effective gate voltage (V_{gs}-V(x)) at the position x, the electron gas density in the channel can be expressed as:

$$n_s = \frac{2q\varepsilon(m)m_e^*}{2dq^2m_e^* + \varepsilon(m)\pi\hbar^2}\left(V_{gs} - V(x) + V_{th}\right) \tag{20}$$

With

$$v(x) = \begin{cases} \dfrac{\mu_0 E(x)}{1 + \dfrac{E(x)}{E_1}}, E(x) \le E_c \\ v_{sat}, E(x) \ge E_c \end{cases} \tag{21}$$

and

$$E(x) = \frac{dV(x)}{dx} \tag{22}$$

Using the Equations (19), (20), (21) and (22), we obtain

$$i_{ds}\left(1 + \frac{1}{E_1}\frac{dV(x)}{dx}\right) = wq\frac{2q\varepsilon(m)m_e^*}{2dq^2m_e^* + \varepsilon(m)\pi\hbar^2}\left(V_{gs} - V(x) + V_{th}\right)\frac{dV(x)}{dx} \tag{23}$$

The integration of equation along the channel length with the following boundary conditions $V(x)_{x=0} = I_{ds}R_s$ and $V(x)_{x=L_g} = V_{ds} - i_{ds}(R_s + R_d)$allows reaching the relation i_{ds} (V_{ds})

$$i_{ds} = \frac{-\alpha_2 + \sqrt{\alpha_2^2 - 4\alpha_1\alpha_3}}{2\alpha_1} \tag{24}$$

Where

$$\begin{cases} \alpha_1 = \dfrac{2q^2\mu_0 w\varepsilon(x)m_e^*}{2dq^2m_e^* + \varepsilon(x)\pi\hbar^2}(R_d^2 + 2R_sR_d) - \dfrac{2R_s + R_d}{E_1} \\ \alpha_2 = L_g + \dfrac{V_{ds}}{E_1} + \dfrac{4q^2\mu_0 w\varepsilon(x)m_e^*}{2dq^2m_e^* + \varepsilon(x)\pi\hbar^2}((V_{gs} - V_{Th})(2R_s + R_d) - V_{ds}(R_s + R_d)) \\ \alpha_3 = \dfrac{4q^2\mu_0 w\varepsilon(x)m_e^*}{2dq^2m_e^* + \varepsilon(x)\pi\hbar^2}(\dfrac{V_{ds}^2}{2} - V_{ds}(V_{gs} - V_{Th})) \end{cases} \quad (25)$$

3. RESULTS AND ANALYSIS

We calculate the characteristics of AlGaN/GaN HEMT for Lg = 200nm and Wg = 1µm, the value of the aluminum molar fraction is chosen in the range of [0.2; 0.3], which allows to have a piezoelectric polarization beneficial for the accumulation of the two-dimensonal electron gas in the quantum well. The theory mentioned above shows that the density of electrons transferred to the potential well depends on the Aluminum molar fraction content, the AlGaN layer thikness and AlGaN layer doping. Figure 1 shows the variations of the 2DEG density as a function of the gate voltage for different values of aluminum molar fraction. The 2DEG density increases with the aluminum content. This result can be explained by the theory discussed above. Thus increasing the conduction band discontinuity of AlGaN / GaN heterojunction, makes it possible to improve the confinement of 2DEG in the quantum well as well as the presence of strong piezoelectric and spontaneous polarizations at the interface, Which are directly dependent on the aluminum molar fraction. On the other hand the threshold voltage increases in absolute value with the aluminum molar fraction.

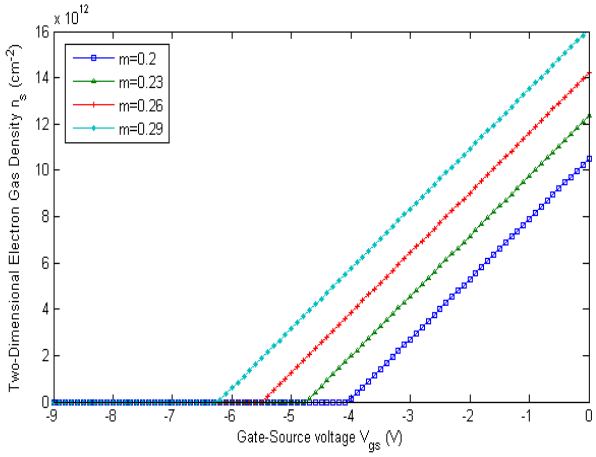

Figure 1. Variations of the 2-DEG density as function of the gate voltage for different values of aluminum molar fraction

Figure 2 and Figure 3 show the influence of the AlGaN layer thickness on the calculated 2DEG density as a function of the voltage applied to the gate, for two structures $Al_{0.2}Ga_{0.8}N$/ GaN and $Al_{0.26}Ga_{0.74}N$/ GaN. The variation of the AlGaN layer thickness from 20 nm to 26 nm is associated with an increase in the 2DEG density for the both structure. An increase in the absolute value of the threshold voltage of the HEMT transistor is also observed. That shows more the AlGaN layer thickness is high, higher the threshold voltage to be applied to deplete the 2DEG must be raised in reverse polarization. The values of the 2DEG density are attributed to the presence of the charges induced by the total polarization at the interface of the AlGaN / GaN heterojunction, as the theory indique. The slope of the plot ns (Vgs) allows us to find the gate capacitance value of the structure, which is related to the thickness of the AlGaN layer; the latter is growing more capacities decreases, this is demonstrated for d=20nm the slope is $2.6*10^{12}cm^{-2}V^{-1}$, while that for d=26nm the slope is $1.99*10^{12}cm^{-2}V^{-1}$for the firt structure; the same is observed for the second structure, we obtain $2.59*10^{12}cm^{-2}V^{-1}$ and $1.98*10^{12}cm^{-2}V^{-1}$ for 20nm and 26nm respectively. It is also observed that the gate capacitance is more sensitive to the variation in the AlGaN layer thickness than to the variation in the

aluminum molar fraction. This shows that high values of AlGaN layer thickness are favorable to achieve significant 2DEG density and to obtain low gate capacitance values.

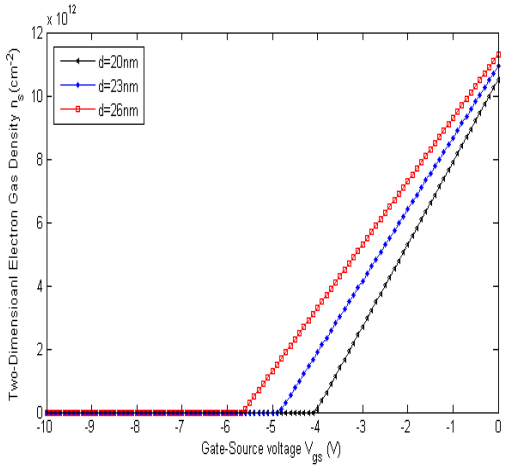

Figure 2. Variations of the 2DEG density for different values of the AlGaN layer thikness and for m=0.2

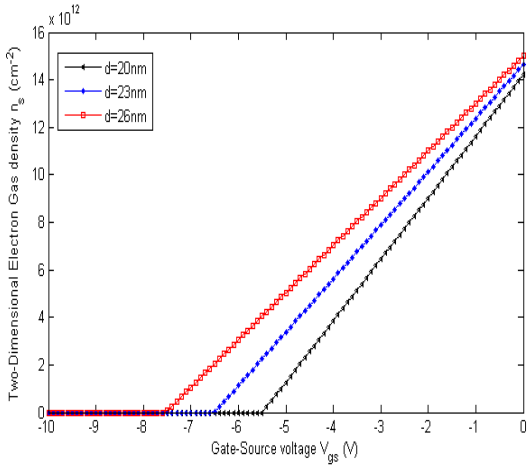

Figure 3. Variations of the 2DEG density for different values of the AlGaN layer thikness and for m=0.26

The dependency of two-dimensional electron gaz to AlGaN layer doping for m=0.26 is giving by Figure 4. As the thickness and doping of AlGaN layer increase, the 2DEG density also increases. The sensitivity of 2DEG to the thickness of the AlGaN layer is greater with a high doping concentration. Also, the AlGaN layer doping has a larger impact on the 2DEG density at large values of layer thiknes; For AlGaN layer thickness varie from 10nm to 20nm, we notice that 2DEG slitghly increase with AlGaN layer doping, thus we observe that 2DEG became more influenced by doping when AlGaN layer thickness are over than 20nm. This result can be explain that the AlGaN layer doping widens the bandgap of the AlGaN semiconductor, which influences the conduction band discontinuity of AlGaN / GaN heterojunction, that implies an increase in the 2DEG confinement in the quantum well. Therefore, it is evident that obtaining high densities of 2DEG requires either a high doping or a higher AlGaN layer thickness.

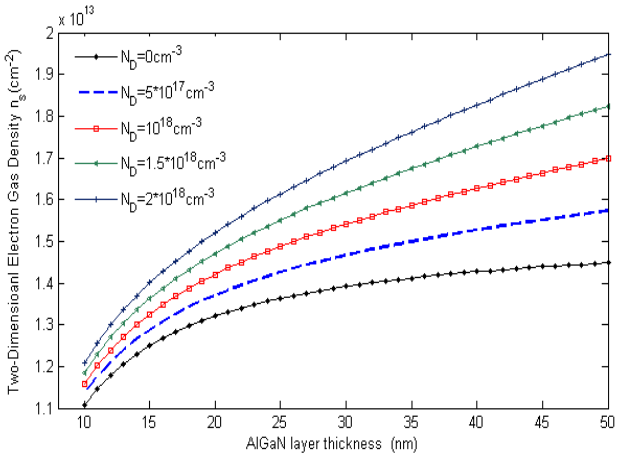

Figure 4. Variations of the 2DEG density for different values of the AlGaN layer doping

The correctness of the current-voltage model depends on the accuracy of the model for the 2DEG concentration as a function of gate voltage, since it directly affects the electric field in the AlGaN layer. Figure 5 shows the current-voltage characteristic as a function of the drain-source voltage for different gate-source voltage values ranging from -8V to 0V. These characteristics correspond to an ideal HEMT structure. High currents are attributed to very high 2DEG density, resulting from large conduction band discontinuity and strong polarization effects. The saturation current increases with the gate voltage.

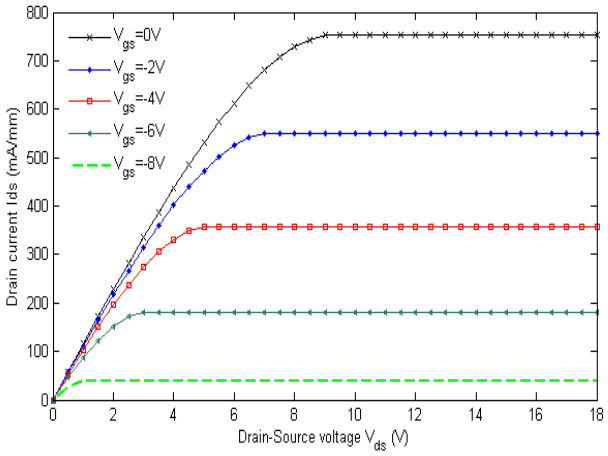

Figure 5. Current-voltage characteristic Ids-Vds for AlGaN/GaN HEMT for different values of Gate voltage

4. CONCLUSION

In this paper, we have analytically estimated the 2DEG density in AlGaN/GaN HEMT, the most important parameter in characterizing and evaluating the performance of AlGaN/GaN HEMT. First, the phenomena responsible for formalizing the two-dimensional electron gas have been presented. Also, the expression of the 2DEG density at the AlGaN / GaN interface and the expression of the current-voltage characteristic have been established. Second, In order to have a favorable confinement of 2DEG in the quantum well, the dependency of 2DEG on the Aluminum content, doping and the thickness of the AlGaN layer has been discussed. The characteristic current-voltage has been presented. High currents are attributed to very high 2DEG density.

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