Novel Analytical model for current-voltage characteristics and transconductance of undoped AlGaN/GaN MISHFETs and performance comparison with different high-k dielectrics

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Abstract. In this paper an improved charge controlled model of undoped, lattice mismatched AlGaN / GaN MISHFET is presented. This model gives an accurate estimation of the 2-DEG sheet carrier concentration at the interface contributed entirely by spontaneous and piezoelectric polarization. The dependence of this sheet carrier density on Al composition and the insulator thickness is investigated in detail. Based on these developments an analytical current - voltage model incorporating Source/Drain parasitic resistance is presented. Also, the non-linear behavior of saturated Drain current is properly formulated and computation of transconductance is carried out for the same. Even without any intentional doping the proposed model exhibits fairly encouraging values of output current and conductance.

1. Introduction

With the impulsive rise of mobile computing and communication sector, high power RF devices are destined to play significant role in consumer electronics. Wide band gap semiconductors such as GaN are strong contender for high power electronic and optoelectronic circuits. Larger direct band gap (3.4 eV), as compared to Silicon (1.1 eV) and GaAs (1.4 eV) leads to higher values of critical fields and breakdown voltages. Recently GaN/AlGaN based heterostructure devices are grabbing much attention of
both material and device community due to excellent electron transport properties and high sheet carrier densities. In GaN/AlGaN based systems a significant amount of charge concentration is found to originate at the interface without any intentional doping in the AlGaN layer. This carrier charge confinement results from both piezoelectric and spontaneous polarization in the GaN/AlGaN layers. The omission of delta doping in the AlGaN layer leads to simpler and economic fabrication technologies. But such HFETs are susceptible to high gate leakage due to the moderate Schottky barrier height of the gate metal (Au/Ni). For this purpose nowadays the device structure further modified, as an insulator layer with high permittivity is grown between the gate metal and the AlGaN layer [1, 2]. This ensures lower gate leakage in terms of body currents which in turn reduces low power loss in OFF state and also serves the purpose of passivating the AlGaN layer. Now reliable and predictive analytical models of such metal-insulator-semiconductor heterostructure FETs are needed along with their fast development in circuit implementation. But till date only a few of such models have been developed and there exists a great void to be filled.

In this paper we present a threshold voltage based analytical model to compute the I-V characteristics of undoped AlGaN/GaN MISHFET structures. In our model we take into account the nonlinear relationship of carrier concentration with Fermi level. As natural continuation of our earlier work we have formulated the drain current in the saturation region also with non zero sloped behaviour. Therefore this present model accurately predicts the current in weak, moderate and strong inversion regions. Transconductance, which effectively determines the device cut-off frequency, is also found out analytically. All the calculations are repeated for different dielectric materials for device performance optimization.

2. Compact MISHFET Model

![Figure 1. Schematic of an undoped AlGaN/GaN MISHFET](image_url)

In an undoped MISHFET structure the free charge concentration at the AlGaN/GaN interface is entirely comprised of those originating from polarization (both
spontaneous & piezoelectric). A generalized layered structure of the same is as shown in Figure 1. The active GaN mono layers are grown on stress reliving buffer layers of the same material. For a metamorphic growth of this nature, the substrate chosen is generally Sic owing to its high thermal conductivity for high temperature application. Up on this layers of undoped Al$_x$Ga$_{1-x}$N (strained), insulator and the Schottky gate metal are grown respectively. For a n-channel device the Source and Drain are heavily doped.

2.1. Current-Voltage Characteristics

The threshold voltage of the undoped MISHFET structure is given by [3]:

$$V_{th} = \Phi_b - \frac{\Delta E_c}{q} - \frac{\sigma_{pz}(m)}{s}(da + \frac{\xi_{stn}}{m}) + \frac{E_f}{q} + k1$$  \hspace{1cm} (1)

Where $\sigma_{pz}(m)$ is the charge induced due to spontaneous and piezoelectric polarization, $E_c$ is the conduction band discontinuity of the heterostructure, $E_f$ is the fermi level distance from the bottom of the conduction band. It is to be noted $E_f$ and charge density $N_s$ are interrelated and have to solved simultaneously. Now for mobility in GaN we follow the model given by [4] and proceed as per [5]. Before saturation the boundary conditions are

- at Source end
  $$V_S = I_D R_S$$  \hspace{1cm} (2)

- at Drain end
  $$V_L = V_D S - I_D R_D$$  \hspace{1cm} (3)

by appropriate substitution we get

$$\frac{I_D}{\lambda E_C} (1 + pe_0 + e_0^4) = (e_0 + qe_0^4)(V_G S - V_{TH} - I_D R_S)$$  \hspace{1cm} (4)

$$\frac{I_D}{\lambda E_C} (1 + pe_L + e_L^4) = (e_L + qe_L^4)(V_G S - V_{TH} - V_D S - I_D R_D)$$  \hspace{1cm} (5)

$$\frac{I_D}{\lambda E_C} \left( \frac{e_L}{2e_0} + \frac{e_0}{2e_L} + p(e_L - e_0) \right) = (V_G S - V_{TH})(e_L - e_0) + e_0(V_D S - I_D R_D) - e_L I_D R_S - e_0 e_L E_C L$$  \hspace{1cm} (6)

Where $\lambda$ is the body effect factor, $ex = E(x)/E_c$, $E_c$ being the critical electrical field. By simultaneously solving the above equations, we obtain current in the linear region. In the saturation region if l be the point of pinch off then.

$$V_l = V_{DSSAT}$$  \hspace{1cm} (7)

$$V_L = V_D S - I_{DSAT} R_D$$  \hspace{1cm} (8)

Hence we acquire the following relations

$$\frac{I_{DSAT}}{\lambda E_C} (1 + pe_0 + e_0^4) = (e_0 + qe_0^4)(V_G S - V_{TH} - I_{DSAT} R_S)$$  \hspace{1cm} (9)
\[ \frac{I_{DSAT}}{\lambda E_C} (2 + p) = (1 + q)(V_{GS} - V_{TH} - V_{DS} - I_{DSAT}R_D) \]  
\[ = (V_{GS} - V_{TH})(1 - e_0) + e_0(V_{DS} - I_{DSAT}R_D) - I_{DSAT}R_S - e_0E_CL \]  
\[ V_I + \Psi E_C \sinh(L - \frac{Ll}{\Psi}) = V_{DS} - I_{DSAT}R_D \]

Similarly by solving the above we get current in saturation region.

2.2. Transconductance

Differentiating saturation drain current with respect to gate to source voltage, the transconductance in the saturation region can be computed.

3. Results & Discussion

The present model evaluates both the d.c current-voltage characteristics and small signal gain of undoped AlGaN/GaN MISHFET.

![Figure 2](image)

(a)

Figure 2. Variation of 2-DEG density with Fermi level for Al mole fraction of (a) 0.15 and (b) 0.3 in a V_{GS} sweep of -2 to 2V

The variation of sheet carrier density with Fermi level is plotted in Figure 2. From these graphs we obtain a comparative analysis by changing the aluminium content. Evidently an increment in the aluminium mole fraction induces higher polarized charges. Figure 3.(a) & (b) shows the variation of drain current with drain to source voltage for different gate to source biases. As the Gate overdrive voltage increases so does the current. From the figures it is clear that the present analysis correctly incorporates the channel length modulation effect in the saturation region. An observed increase in the drain current is which obviously originates from a higher value of sheet carrier density.
Figure 3. Variation of drain current with drain to source bias for SiO2 as the gate insulator for Al mole fraction of (a).15 and (b).3. Variation of transconductance with gate to source voltage for different insulators is plotted in (c).

4. Conclusion

The proposed model gives a fair representation of undoped MISHFETs. It can be concluded that even without any intentional doping such structures can operate under normal biases and may be considered as a substitute of doped structures.

References

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