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A compact C–V model for 120 nm AlGaN/GaN HEMT with modified field dependent mobility for high frequency applications

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Abstract

We present a theoretical model of AlGaN/GaN high electron mobility transistor (HEMT) that includes the effect of spontaneous and piezoelectric polarization. Present model also incorporates the effect of mole fraction dependent mobility, saturation velocity and the accurate 2-DEG density in HEMT as a function of gate voltage in subthreshold, linear and saturation regimes. This paper reports a detailed 2-D analysis of capacitance–voltage (C–V) characteristics. The contribution of various capacitances including fringing field capacitance on the performance of the device is also shown. The model further predicts the transconductance, drain conductance and frequency of operation and is in close proximity with the experimental data which confirms the validity of proposed model.

Keywords: Heterostructure; AlGaN/GaN MODFET; Drain current; Transconductance; Cutoff frequency

1. Introduction

High electron mobility transistors (HEMTs) are extremely promising devices in the area of high speed ICs [1,2] for optical communication systems, and in microwave analog circuits for mobile communication systems [3,4] owing to their very high switching speed and low-power consumption. AlGaN/GaN HEMTs have shown outstanding potential for high-power, high temperature, high voltage microwave electronic applications and for opto-electronic device application. AlGaN/GaN HEMTs have large energy band gap (3.4 eV) and high saturation drift velocity combined with large conduction band discontinuities and high thermal stability [5–7]. GaN has a high breakdown field (~3MV/cm) which is much larger than that of GaAs.

Further, the presence of strong spontaneous and strain induced piezoelectric polarization due to lattice mismatch between AlGaN/GaN results in very high free carrier concentration within the channel region of HEMTs which is not achieved by modulation doping alone [8–10]. The strain induced polarization can induce electric fields which in turn alter the band bending resulting in greatly increased free carrier concentration within the channel region. The Al mole fraction of the AlGaN layer has been identified as one of the major factors in determining the properties of AlGaN/GaN HEMTs as it directly affects the polarization induced charge density. So to obtain an accurate device model, all the parameters that are affected by Al mole fraction needs to be taken into account.

In this paper we present a compact analytical model using accurate charge control relation to characterize the dc performance of AlGaN/GaN HEMT. The model takes into account the highly dominant spontaneous and piezo-electric polarization effects to predict the 2-DEG sheet charge density at the heterointerface. In short channel devices source and drain are very close to each other and the charges are confined in very small region so 2-D analysis has been carried out in the saturation region of the device to calculate gate to source capacitance and gate to drain capacitance which are then used to estimate the cutoff frequency of the device. The model includes the effect of various fringing field capacitances arising due to

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the small geometry and high field. The internal device capacitances, both gate drain and gate-source play a vital role in determining the performance of the HEMT. The capacitances have been calculated simply from the charge variations in different regions. Cutoff frequency of the order of 55.5 GHz is achieved. The analytical results so obtained have shown a good agreement with the experimental data thus proving the validity of the model.

2. Model formulation

The basic structure of AlGaN/GaN HEMT considered in the present analysis is shown in Fig. 1.

2.1. Charge-control model

The basic charge-control equation for 2-DEG sheet charge density formed at the $Al_mGa_{1-m}N$/GaN hetero-interface (Fig. 1) is obtained as [11]

$$n_s(x) = n_{s0}\left(\frac{V_{gs} - V_{th}(m) - V_c(x)}{\left(v_0^4 + \left(V_{gs} - V_{th}(m)\right)\right)^{1/4}}\right) \approx n_{s0}\left(\frac{V_{gs} - V_{th}(m) - V_c(x)}{v_0}\right), \quad (1)$$

where q is the electron charge, m is the Al mole fraction in $Al_mGa_{1-m}N$, $V_c(x)$ is the channel potential at x due to the drain voltage, V_{gs} is the applied gate to source voltage, n_{s0} is the value at which $n_s(x)$ saturates and $V_{th}(m)$ is the device threshold voltage which is strongly dependent on mole fraction and polarization charge density and is given by [9]

$$V_{th}(m) = \phi(m) - \Delta E_c(m) - \frac{q(n_d)d_d^2}{2\varepsilon(m)} - \frac{\sigma(m)}{\varepsilon(m)}(d_d + d_i), \quad (2)$$

where $\phi(m)$the Schottky barrier height, n_d the doping density of AlGaN layer, $\sigma(m)$ the total polarization induced charge density. $\Delta E_c(m)$ is the conduction band discontinuity at the AlGaN/GaN interface,$\varepsilon(m)$ is polarization dependent dielectric constant of $Al_mGa_{1-m}N$, d_d is the doped AlGaN layer thickness, d_i is the spacer layer thickness and v_0 is a constant which is given as [12]

$$v_0 = \frac{q(d_d + d_i + \Delta d)n_{s0}}{\varepsilon(m)}, \quad (3)$$

where Δd is the effective thickness of 2-DEG.

The $\sigma_{pz}(m)$ is the polarization induced sheet charge density given as [13]

$$\left|\sigma_{pz}(m)\right| = \left|2\left(\frac{a(0) - a(m)}{a(m)}\right) \times \left(e_{31}(m) - e_{33}(m)\frac{C_{13}(m)}{C_{33}(m)} + P_{sp}(m) - P_{sp}(0)\right)\right|, \quad (4)$$

where $a(0)$ and $a(m)$ are the lattice constants, $e_{31}(m)$ and $e_{33}(m)$ are the piezoelectric constants, $C_{13}(m)$ and $C_{33}(m)$ are the elastic constants and $P_{sp}(0)$and $P_{sp}(m)$ are the spontaneous polarization. The various Al mole fraction dependent parameters have been calculated [13], and listed in Table 1.

The mole fraction dependent mobility is given as

$$\mu(x) = \frac{\mu_o}{1 + \frac{1}{E_1}\frac{\partial V_c(x)}{\partial x}}, \quad (5)$$

where

$$\mu_0 = \mu_1 + \frac{\mu_2}{1 + \left(\frac{N}{N_\mu}\right)^\alpha}, \quad (6)$$

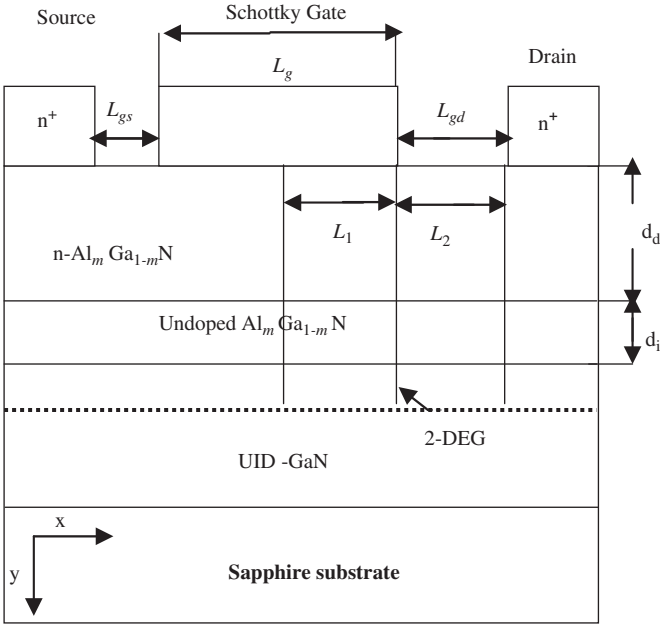

Fig. 1. Cross-sectional view of AlGaN/GaN MODFET. L_g is the gate length, d_d is the n-AlGaN layer thickness and d_i is the spacer layer thickness.

Table 1
Parameters for $Al_mGa_{1-m}N$/GaN MODFET

N_d	$2 \times 10^{24}\,m^{-3}$
E_c	$190 \times 10^5\,V/m$
ΔE_c	0.1953 V
Φ_m	1.035 V
ε_a	$8.345 \times 10^{-11}\,C/m\,V$
d_d	370 Å
d_i	30 Å
Δd	100 Å
a	$3.177 \times 10^{-10}\,m$
a_0	$3.189 \times 10^{-10}\,m$
e_{31}	$-0.506\,C/m^2$
e_{33}	$0.84\,C/m^2$
C_{13}	103.75 GPa
C_{33}	400.2 GPa
P_{sp}	$-0.037\,C/m^2$
N_t	$5 \times 10^{22}\,m^{-3}$
σ_{pz}	$0.013\,C/m^2$
L_g	0.12 μm