Effect of Temperature on the Electronic Current of AlGaN/GaN High Electron Mobility Transistors (HEMT)

Rajab Yahyazadeh and Zahra Hashempour
Department of Physics, Islamic Azad University of Khoy Branch, Khoy, Iran 58135/175

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Abstract: An analytical-numerical model for the electronic current of two dimensional quantum well AlGaN/GaN in high electron mobility transistors has been developed in this paper that is capable of accurately predicting the effect of temperature on the electronic current of two dimensional quantum well. Salient futures of the model are incorporated of fully and partially occupied sub-bunds in the interface quantum well. In addition temperature dependent of band gap, quantum well electron density, threshold voltage, mobility of electron, dielectric constant, polarization induce charge density in the device are also taken into account. The calculated model results are in very good agreement with existing experimental data for high electron mobility transistors device.

Key words: AlGaN/GaN, mobility, threshold voltage, temperature.

1. Introduction

Over the past few years, AlGaN/GaN high electron mobility transistors have emerged strongly as attractive candidates for high-power, high temperature, high speed applications at frequencies well into the microwave region. The presence of strong spontaneous and strain-induced polarization fields due to lattice mismatch between AlGaN/GaN is the important characteristic of the AlGaN/GaN material system. These polarization fields have been attributed to the reduced symmetry of the wurtzite crystal structure and the polar bonding nature of GaN and its alloy [1]. The AlGaN/GaN material system is unique in that extremely high two-dimensional electron gas concentrations (>10¹³ cm⁻²) are readily generated without modulation doping. The high breakdown fields (3×10⁶ V/cm) resulting from the wide band gaps of GaN and AlGaN enable the use of much higher drain biases than can typically be used in the AlGaAs/GaAs system [2-4]. Together with these high field properties, the high saturated electron drift velocity (~10⁷ cm/s) in GaN can be exploited for superior high frequency performance. More recently, high performance GaN-based transistors such as high electron mobility transistors have been fabricated and reported by several group [5, 6]. The effect of temperature on the electronic current of two dimensional quantum well was previously observed and was related on electron threshold voltage without including optical phonon scattering [7, 8]. In the present work, a new model for electronic current of two dimensional quantum well is presented. This is achieved by (1) using a self consistent solution to the Schrödinger and Poisson equations in order to obtain the Fermi level (EFI) specified relative to the bottom of triangular well, and band bending of GaN (EB), (2) taking into account the temperature dependent quantum well width, (3) taking into account analytical relation for electronic current and charge density in two dimensional quantum well, (4) using a more accurate model for mobility, (5) using the electron traps effects in the surface, interface and
buffer layers, and (6) incorporating a simple, realistic model for the ungated area in the AlGaN/GaN high electron mobility transistors device.

2. Model Description

In order to obtain accurate values for the Fermi energy, the energies of quantized levels within the two dimensional electron gas (2DEG), the occupancy of the various sub-bands, the intrasub-band and intersub-band coupling coefficients ($H_{mn}$) for the two dimensional electron gas in AlGaN/GaN heterostructures; both the Schrödinger and Poisson equations must be solved self-consistently. This has been achieved by solving Schrödinger’s equation and simultaneously taking into account the electrostatic potential obtained from Poisson’s equation, as well as the image and exchange-correlation potentials using Numerov’s numerical method.

In the self-consistent calculation, the nonlinear formulism of the polarization-induced field as a function of Al mole fraction in Al$_{x}$Ga$_{1-x}$N/GaN heterostructures has been assumed, as well as taking into account all fully and partially-occupied sub-bands within the interface two dimensional electron gas potential well [9, 10]. Using such an approach, it is possible to calculate the two dimensional electron mobility taking into account the combined contributions from each of the individual electron scattering mechanisms.

At high temperature ($T \geq 300$ K), inelastic polar optical phonon scattering dominates over all other scattering mechanisms. In the linearized Boltzmann equation, the different scattering rates can be separated into two types: (1) elastic scattering due to acoustic and piezoelectric phonons, ionized impurities and interface roughness, etc., and (2) inelastic scattering due to polar optical phonons in order to take into consideration all scattering mechanisms in the mobility calculation, it is solve numerically using an iterative technique [11].

The field effect transistors model used in calculations is shown schematically in Fig. 1, where the x-direction is along the two dimensional electron gas channel, the z-direction is along the growth direction, and the region I and III represent the ungated channel portions of the field effect transistors, and region II represents the gated area of the device.

In the model, it has been assumed that the voltage varies linearly with x in the ungated regions, so the voltage is given by the following relation [12]:

$$V_{GS}(x) = \begin{cases} I: & \left(\frac{V_{GS}}{L_{SG}}\right)x \\ II: & V_{GS} \\ III: & \left(\frac{V_{GS}}{L_{GD}}\right)(x - L_{G} - L_{SG}) + V_{GS} \end{cases}$$

Where $x$ is the distance along the channel from the source, $V_{GS}$ and $V_{DS}$ are the applied gate and drain voltage with respect to the grounded source, so that $L_{SG}$, $L_{G}$ and $L_{GD}$ are the length of the ungated distance between source and gate, the gate length and the ungated distance between gate and drain, respectively.

The drain-source current within 2DEG channel ($I_{2DEG}$), in linear and saturation regimes are given by the following relations [5, 13]:

**Linear Regime,**

$$I_{2DEG} = \left(-A_{1} + \left(B_{1}^{2} - 4A_{1}C_{1}\right)^{1/2}/2A_{1}\right)$$

**Saturation regime,**

$$I_{2DEG} = \left(-B_{1} + \left(B_{1}^{2} - 4A_{1}C_{2}\right)^{1/2}/2A_{1}\right)$$

where

$$A_{1} = (\lambda/2)(R_{o} + 2R_{i} + 2R_{p}) + (\Psi E_{c})(2R_{i} + R_{p})$$

$$B_{1} = \lambda V_{DS}(R_{o} + R_{p}) + \gamma(2R_{i} + R_{p}) - (L_{GD} + L_{SG} + L_{G})$$

$$\Psi E_{c} = V_{DS} - \lambda(2R_{i} + R_{p})$$
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\[ C_1 = \lambda V_O V_{DS} - (\lambda/2)V_{DS}^2 - \gamma V_{DS} \]

\[ B_2 = \lambda V_O (R_s + R_o) + \gamma (2R_s + R_o) - (L_s + L_{SG} + L_{GD}) - \]

\[ \left(\frac{1}{2}E_C V_{DS} - \lambda V_O - \lambda (2R_s + R_D) \right) \]

\[ C_2 = \left(\lambda V_O^2/2\right) - \gamma V_O \]

with

\[ V_O = V_{GS} + V_{VG} - V_T, \quad \gamma = \frac{k_B}{q} T, \quad \lambda = \mu(T) C \] (4)

where \( R_S \) and \( R_D \) are the source and drain contact resistance respectively, \( V_{VG} \) is the virtual gate which formed between gate-drain and near the gate because of the reduction in the amount of net positive charge on surface, \( E_C \) is the electric field in the saturation regime, \( k_B \) is Boltzmann constant, \( \mu(T) \) is the two dimensional electron mobility as a function of temperature and \( C \) is capacitance. The capacitance, \( C \), is equivalent capacitance for the capacitances of AlGaN barrier (\( C_{AlGaN} \)) [5], band bending in GaN (\( C_{GaN} \)) [13], interface traps (\( C_s \)) [14], spacer layer [15] and two dimensional electron gas (\( C_{2D} \)). In the model, effective width of 2DEG depends on the density of electron at that point and temperature. This has been achieved by solving Schrödinger’s and Poisson’s equations.

For the energy levels corresponding to the two dimensional electron gas, we assumed the presence of five sub-bands within the interface single-well.

All material parameters used in the calculation throughout this article have been taken from Refs. [4-6] and are listed in Table 1.

To calculate the exact electrical properties in high electron mobility transistors, one need to include the electron traps effects such as interface and surface traps, and GaN barrier trap in calculation. As a result of lattice mismatch between AlGaN and GaN, and possibly compositional non-uniformity caused by alloy clustering, there could be considerable amount of trap states at the AlGaN/GaN interface. The electrical behavior of the interface trap states can be modeled as a capacitive (\( C_s \)) and a conductive (\( G_s \)), where \( G_s \) is negligible at the model biases.

It should be mentioned that the solution obtained holds for \( V_{DS} \) in the range \( 0 \leq V_{DS} \leq V_0 \). \( V_{DS} = V_0 \) the channel concentration \( N_s \) is zero at the drain side and drain current is pinch off.

In order to obtain accurately calculated mobility and electric field in the saturation regime, it is necessary to determine the channel temperature, because it is different from the temperature of the device. This has been achieved using self-heating model [15, 16].

The threshold voltage \( (V_T) \) is given by the following relation [17, 18]:

\[ V_T(T,m) = \Phi_B - \Delta E_C(T,m) - \frac{\sigma_{ple}(m)d_{AlGaN}}{2\epsilon_{AlGaN}(T,m)} \]

\[ \Delta E_C(T,m) = 0.75(E_g^{AlGaN}(T,m) - E_g^{GaN}(T,m)) \] (6)

where \( \Phi_B \) is the Schottky barrier at metal/AlGaN in interface, \( \sigma(m)/q \) is the polarization induced charge density at heterostructure interface, \( N_D \) is the donor density in AlGaN and \( \Delta E_C \) is the conduction band discontinuity between AlGaN and GaN [19, 20]. This discontinuity dependent on the band gaps of GaN \( \left(E_g^{GaN}(T,m)\right) \) and AlGaN \( \left(E_g^{AlGaN}(T,m)\right) \). In the model, analytical relations (temperature dependent) of these band gaps were taken into account [18].

Temperature dependent of analytical relation for two dimensional electron gas density is given by the following relation[8]:

\[ N_s(T,m) = \frac{\epsilon_{AlGaN}(T,m)}{d_{AlGaN} + d_s + \Delta d(T,m)} \]

\[ (V_{GS} - V_T(T,m) + E_f(T,m)) \] (7)

where \( E_f(T,m), d_s \) are the Fermi level (specified relative to the bottom of triangular well) and spacer layer ( in AlGaN barrier thickness) respectively.

3. Results and Discussion

To assess the validity of this combined analytical-numerical model for the effect of temperature on the electronic current of two
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dimensional quantum well, a comparative study has been undertaken comparing theoretically obtained $I-V$, $N_s$, $\mu$ and $V_T$ curves with experimental results from Refs. 6, 8, 12 17 for AlGaN/GaN based HEMT. The material and device details are presented in Table 1 and all other material parameters have been taken from Refs. [4-6]. The results presented in Fig. 2 show the mobility at sheet carrier concentrations as a function of temperature. As shown in Fig. 2, the mobility decrease monotonically with increasing temperature for ranging 200 to 500 K; this behavior suggests that phonon scattering is the dominant scattering mechanism at high temperature, in agreement with number of previous studies [21, 22]. The reduce dependence of mobility on temperature for lower carrier concentration suggests that scattering by

Table 1  The material and device parameters used in the model calculations.

| Parameters                               | Value  | Unit   |
|------------------------------------------|--------|--------|
| Gate Width                               | 100    | $\mu$m |
| Gate length                              | 0.2    | $\mu$m |
| Drain gate & gate source distance        | 1.7    | $\mu$m |
| AlGaN Si doping density                  | $1 \times 10^{18}$ | $cm^{-3}$ |
| AlGaN unintentional doping Density       | $2 \times 10^{18}$ | $cm^{-3}$ |
| GaN barrier thickness                    | 200    | Å      |
| Low field mobility                       | 0.075  | $m^2V^{-1}S^{-1}$ |
| Maximum sheet charge density             | $1 \times 10^{17}$ | $cm^{-2}$ |
| Drain series resistance                  | 23     | $\Omega$ |
| Source series resistance                 | 10     | $\Omega$ |
| Zero-bias threshold voltage              | -4.7   | V      |
| Deformation potential                    | 8.5    | eV     |
| Dislocation charge density               | $1 \times 10^{10}$ | $cm^{-2}$ |
| Saturation drift velocity                | $2.5 \times 10^7$ | $cm/s$ |
| Electron effective mass                  | 0.25$m+0.228$ | $m_0$ |
| Static dielectric constant               | -0.3$m+10.4$ | $\varepsilon_0$ |
| Ni Schottky barrier (m)                  | 1.3$m+0.85$ | eV     |
| Piezoelectric constant $h_d$             | $4.28 \times 10^{-9}$ | V/m |
| Elastic constant $C_e$                   | $2.66 \times 10^{11}$ | N/m² |
| $C_T$                                    | $0.62 \times 10^{11}$ | N/m² |
| Interfacial layer                        | 5      | Å      |
| Virtual gate in from gate                | 0.2 $\mu$m | $V$ |
| Interface trap density                   | $10^{-2}$ | $cm^2eV^{-2}$ |
| LO-phonon energy                         | 90.5   | meV    |

Fig. 2 shows The mobility at sheet carrier concentrations of $5 \times 10^{10}, 8 \times 10^{11}, 2.6 \times 10^{10} cm^{-2}$ as a function of temperature in comparison with existence experimental data from Ref. [12].

dislocations and defect is more significant for lower carrier concentration. Fig. 3 shows the sheet carrier concentrations and threshold voltage of two dimensional electron gases as a function of temperature. As shown in Fig. 3, the absolute of threshold voltage $V_T$ (voltage that to require for formation of two dimensional quantum well in interface AlGaN/GaN) decrease with the increase of temperature as a results decrease of depth and Fermi level in quantum well. With decreasing in depth of quantum well, decrease the discontinuity in band gaps and occupancy of the various sub-bands (sheet carrier concentrations). The result shows that change in threshold voltage $-0.2$ and sheet carrier concentrations $0.3 \times 10^{12} cm^{-2}$ of device with increase in temperature from 200 K to 600 K.

As a result, to calculate an exact current –voltage (I-V) curve to see temperature effects in AlGaN/GaN based HEMTs for applied gate bias and high drain voltage, one needs to include the temperature effects of band gaps, quantum well electron density, threshold voltage, mobility of electron, dielectric constant, polarization induce charge density in the device thus Fig. 4 shows the variation of drain current versus drain-source voltage with including theses effects in comparison with existence experimental data in literature. As evident from this figure there is a good agreement between the model calculations and experimental data.
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Fig. 3 The sheet carrier concentrations and threshold voltage of two dimensional electron gas as a function of temperature in comparison with existence experimental data from Refs. [6, 8].

Fig. 4 The variation of drain current versus drain-source voltage in comparison with existence experimental data from Refs. [6, 17]. Temperature is stepped in 100 K from 200 K to 500 K.

4. Conclusions

An accurate analytical-numerical model for the effect of temperature on the electronic current of two dimensional quantum well has been developed the AlGaN/GaN high electron mobility transistors. This model is able to accurately predict the drain-source electronic current of two dimensional quantum well in high drain voltage. The model incorporates by including temperature effects on the quantum well electron density, threshold voltage, mobility of electron, dielectric constant and polarization induce charge density in the device. Evidence for the applicability of the developed model is provided by the fact that the current-voltage characteristics calculated for dependent temperature shows good agreement with published experimental data.

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