

ANALYTICAL- NUMERICAL MODEL FOR SHEET RESISTIVITY OF $\text{Al}_x\text{Ga}_{1-x}\text{N}$ / GaN HIGH-ELECTRON-MOBILITY TRANSISTORS

R. YAHYAZADEH*

Department of Physics, Khoy Branch, Islamic Azad University, Khoy, Iran

An analytical-numerical model for the sheet carrier concentration and mobility based high electron mobility transistors has been developed that is capable to predict accurately the effects of Al composition on the 2DEG resistivity in one sub-band, multi sub-band and depletion layer model. Salient features of the model are incorporated of fully and partially occupied sub-bands in the interface quantum well, combined with a self-consistent solution of the Schrödinger and Poisson equations and including the three-dimensional electron gas mobility in the barrier of AlGa_N. The calculated model results are in very good agreement with existing experimental data for high electron mobility transistors device.

(Received April 10, 2018; Accepted June 8, 2018)

Keywords: sheet resistivity, mobility, AlGa_N

1. Introduction

III-nitride materials based heterostructures are very suitable materials for optoelectronic devices at the high temperatures because of their wide band gap, high thermal and mechanical stability, the great piezoelectric constant, the low sensitivity to ionized radiation. One of the high-performance electronic devices based on III-nitride heterostructures is the high electron mobility transistors (HEMTs). The key to the enhanced performance of HEMTs is improved charge confinement and carrier gas sheet charge density with concomitant high mobility. The two-dimensional electron gases in AlGa_N/GaN-based heterostructure HEMTs which are induced by strong polarization effects, are sensitive to a large number of different physical properties such as polarity, alloy composition, the width of the depletion layer in AlGa_N barrier [1-4]. These devices emerged as strong candidates for wireless base-station amplifiers power electronic circuits radars operating in extreme environments and fully integrated wireless sensors for industrial process monitoring and control. Low intrinsic carrier generation with the increase of temperature and high breakdown field due to wide band gap energy make GaN the right material for high-power and high-temperature systems in comparison with other broadly researched wide bandgap materials (except Diamond), GaN has higher electron mobility which leads to high-frequency operation of GaN-based HEMTs devices. Larger sheet carrier density along with high saturation velocity allows the AlGa_N/GaN HEMTs devices to operate with higher current density. Compared to silicon carbide (SiC) FETs, GaN HEMTs have lower specific on-resistance because of the high-density 2D electron gas (2DEG) (10^{13} cm^{-2}) and high electron mobility ($>1500 \text{ cm}^2/\text{Vs}$) [5]. GaN devices are also suitable for high-frequency microwave applications due to the high saturation velocity in the GaN channel [6]. The total mobility of these transistors was previously calculated without including depletion layer effects [7]. In the present work, a new analytical- numerical model for the total mobility and sheet carrier concentration is presented. That is capable of determining effects of Al composition on the 2DEG resistivity in multi sub-band and depletion layer model. This is achieved by (i) using a self-consistent solution of the Schrödinger and Poisson equations in order to obtain both two-dimensional electron gas density, Fermi level (E_F) specified relative to the bottom of a triangular well, and band bending of GaN (E_B), (ii) take into account the current in the AlGa_N barrier, (iii) take into account the two-dimensional electron gas channel temperature, (iv) take into account the occupancy of the various sub-bands, the intrasub-band and intersub-band coupling coefficients (H_{mn}).

*Corresponding author: yahyazadehs@gmail.com

2. Model description

In order to obtain accurate values for mobility and the sheet carrier concentration of the two-dimensional electron gas in AlGaIn/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 formalism of the polarization-induced field as a function of Al mole fraction in $\text{Al}_m\text{Ga}_{1-m}\text{N}/\text{GaN}$ heterostructures has been assumed, as well as taking into account intersub-band coupling coefficients (H_{mn}) and all fully and partially-occupied sub-bands within the interface 2DEG potential well.

From the definition of the drift mobility we obtain [8]:

$$\mu_{2DEG}(T, E) = \frac{e}{m^*} \langle \tau_{total}(T, E) \rangle \quad (1)$$

The term τ_{total} is given by the following relation:

$$\frac{1}{\tau_{total}(T, E)} = \frac{1}{\tau_{rou}(T, E)} + \frac{1}{\tau_{dis}(E)} + \frac{1}{\tau_{acou}(T, E)} + \frac{1}{\tau_{res}(E)} + \frac{1}{\tau_{alloy}(E)} + \frac{1}{\tau_{opt}(T, E)} \quad (2)$$

Where τ_{rou} , τ_{dis} , τ_{acou} , τ_{res} , τ_{opt} and τ_{alloy} are relaxation times associated with interface roughness, dislocation, acoustic phonon (both piezoelectric and deformation potential), residual impurity, optical phonon and alloy disorder scattering, respectively so that these relaxation times have been calculated using the methods described in Refs [5, 7 and 9]. Also, the different scattering rates can be separated into two types: (i) elastic scattering due to acoustic and piezoelectric phonons, ionized impurities and interface roughness, etc., and (ii) inelastic scattering due to polar optical phonons. In order to take into consideration all scattering mechanisms in the mobility calculation, it is necessary to include all such mechanism in the linearized Boltzmann equation and to solve it numerically using an iterative technique [9]. It should be noted that in the linearized Boltzmann equation, $\Phi(E, T)$ is the perturbation function so that to obtain the $\Phi(E, T)$ needs to take into account the contribution of all occupied sub-bands by means of following relation [7]:

$$\frac{1}{\Phi(E, T)} = \sum_m \sum_n \frac{N_m}{N_{2DEG}} \frac{1}{\Phi_{mn}} \quad (3)$$

Equation (3) indicated that all occupied states contribute to the total mobility of the two-dimensional electron gases. This equation also shows that the contribution of each sub-band depends on its occupation number (that is relative concentration N_m/N_{2DEG}) such that the most significant contribution comes from the first sub-band, which has the highest occupation number. Using such an approach, it is possible to calculate the 2D-electron mobility taking into account the combined contributions from each of the individual electron scattering mechanisms. Effective mobility in AlGaIn barrier is given by the equation [10, 11]:

$$\frac{1}{\mu_{AlGaIn}} = \frac{\int \frac{N_{AlGaIn}(z, T, m, V_{GS})}{\mu(z)} dz}{\int N_{AlGaIn}(z, T, m, V_{GS}) dz} \quad (4)$$

$$z = d_{AlGaIn} - d_2$$

$$\frac{1}{\mu(z)} = \frac{1}{\mu_{op}(z)} + \frac{1}{\mu_{alloy}(z)} + \frac{1}{\mu_{def}(z)} + \frac{1}{\mu_{dis}(z)}$$

Here, $\mu(z)$ is the mobility for a three-dimensional electron gas (3DEG) of density N_{AlGaN} , so that in the present work we, therefore, take into account alloy, optical phonon, deformation potential and dislocation mobility in the AlGaN barrier. The total mobility can be obtained as [12]

$$\mu_{total} = \begin{cases} \frac{\mu_{2DEG} N_{2DEG}(T, m, d_2, T_{ch}) + \mu_{AlGaN} N_{AlGaN}}{N_{2DEG}(T, m, d_2, T_{ch}) + N_{AlGaN}} & \text{for } d_2 < \text{barrier thickness} \\ \mu_{2DEG} & \text{for } d_2 \geq \text{barrier thickness} \end{cases} \quad (5)$$

Where d_{AlGaN} , d_2 are the AlGaN barrier thickness and depletion distance at the gate edge near the drain side of the AlGaN/GaN high electron mobility transistors respectively. Analytical-numerical model analysis steps is shown in Fig. 1. The total sheet carrier concentration in the depletion approximation ($d_{AlGaN} = d_2$) is given by the following relation [4,13]:

$$N_{2DEG}(T, m, d_{AlGaN}, T_{ch}) = N_{total} \quad \text{for } d_2 = d_{AlGaN}$$

$$N_{2DEG}(T, m, d_{AlGaN}, T_{ch}) = \frac{\varepsilon_{AlGaN}(T, m)}{(d_{AlGaN}(T, V_{GS}) + d_i + \Delta d(T, m))} \times (V_{GS} - V_T(T, m, d_{AlGaN}) - E_F(T, m) - V_{ch}(x, T_{ch}, T)) \quad (6)$$

$$N_{2DEG}(T, m, d_2, T_{ch}) = \frac{\varepsilon_{AlGaN}(T, m)}{(d_2 + d_i + \Delta d(T, m))} \times (V_{GS} - V_T(T, m) - E_F(T, m) - V_{ch}(x, T_{ch}, T)) \quad \text{for } d_2 < d_{AlGaN} \quad (7)$$

So that N_{AlGaN} is the density of electron real space transfer from the two-dimensional electron gas channel to three-dimensional electron gas channel state (in AlGaN barrier) which can be obtained as:

$$N_{AlGaN} = N_{2DEG}(T, m, d_{AlGaN}, T_{ch}) - N_{2DEG}(T, m, d_2, T_{ch}) \quad (8)$$

The analytical threshold voltage (V_T) is given by the following relation [14-16]:

$$V_T(T, m, d_{AlGaN}) = V_{BI} - \Delta E_c(T, m) - \frac{\sigma_{pz}(T, m) d_{AlGaN}}{\varepsilon_{AlGaN}(T, m)} - \frac{q N_d d_{AlGaN}^2}{2 \varepsilon_{AlGaN}(T, m)} \quad (9)$$

$$\Delta E_c(T, m) = 0.75(E_g^{AlGaN}(T, m) - E_g^{GaN}(T, m)) \quad (10)$$

Where $E_F(T, m)$, q , m , V_{gs} and $\sigma(m, T)/q$ are the Fermi level, electron charge, Al mole fraction in AlGaN barrier, the gate to source voltage and the polarization induced charge density at the heterostructure interfaces. So that discontinuity (ΔE_c) dependent on the band gaps of GaN ($E_g^{GaN}(T, m)$) and AlGaN ($E_g^{AlGaN}(T, m)$) respectively also Δd is the effective thickness of two the dimensional electron gases. Knowing the maximum sheet carrier concentration

$N_{2DEG}(m, T, d_2, T_{ch})$ at the interface of undoped AlGaIn/GaN structures, one can estimate the minimum sheet resistivity to (16,17):

$$\rho_{total}(x, T) = \frac{1}{qN_{2DEG}(m, T, d_2, T_{ch})\mu_{total}(m, T, d_2, T_{ch})} \quad (11)$$

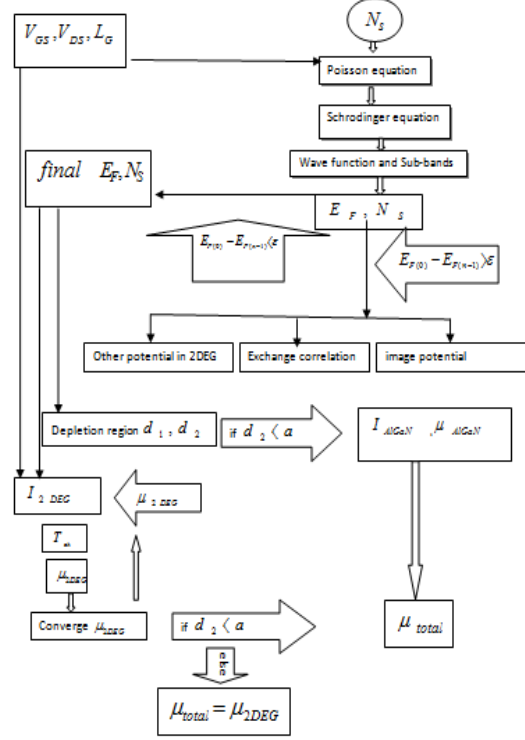


Fig. 1. Flowchat of Analytical-numerical model analysis steps.

3. Results and discussion

To assess the validity of this combined analytical–numerical model for the 2DEG sheet resistance a comparative study has been undertaken to compare theoretically obtained, N_s , μ and ρ_{total} curves with experimental results from Refs. 12, 18, and 19 for AlGaIn/GaN-based HEMT. The material and device details and all other material parameters have been taken from these Refs. Analysis of Fig. 2 shows that as the percentage of aluminum alloy increases, the absolute value of the threshold voltage increases (it leans towards negative voltage).

Furthermore, the trend of changes in N_s relative to the applied voltage, V_g , changes slightly with the change in aluminum alloy percentage, and the value of N_s increases. The reason for this may be that in structures with high aluminum alloy percentage, the energy band gap is large and, as a result, discontinuity in the conductivity band between AlGaIn and GaN increases, and polarity effects also increase. This increase in polarity effects causes an increase in the value of N_s .

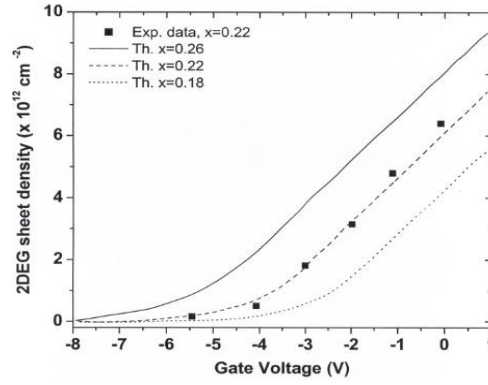


Fig. 2. Total sheet carrier concentration verse gate-source bias at 300K based HEMT in depletion approximation in comparison with existing experimental data (circles) from Ref. [12].

At low temperatures, the dominating scattering mechanisms (the effect of interface roughness, alloy defects, etc.) are strongly dependent on aluminum alloys (x), whereas they have a weak dependence on the number of occupied sub-bands.

For further clarification of this issue (the dependence of the dispersions at various composition on the number of occupied sub-band), electronic stimulations at two temperatures of 10K and 400K, in the single- sub-bands and the multi sub-bands cases, are compared in Fig. 3. At lower temperatures, there is no difference between the single sub-bands and the multi- sub-bands cases, for small alloys, since there is only one occupied sub-bands. Therefore, the multi sub-bands model is converted to the single sub-bands model. Whereas for $x > 0.5$, as x increases, the number of occupied and semi-occupied bands increases, and as a result, a difference between the single sub-bands model and the multi sub-bands model arises. At higher temperatures, there is a difference between the single sub-bands model and the multi sub-bands model from the beginning, since electrons are stimulated and moved to higher sub-bands. Therefore, in this case, there are a number of semi-occupied sub-bands, even for small alloys. Consideration of inter-band dispersion (which is not considered for low temperatures and its dominating mechanisms) causes this difference. By increasing aluminum alloy percentage, the difference between the single- sub-bands model and the multi sub-bands model is maximized, due to the increase in the number of occupied sub-bands.

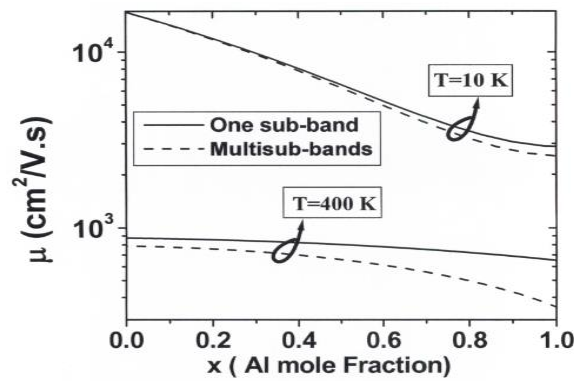


Fig. 3. Total mobility versus Alloy composition of Al for AlGa_N / Ga_N based HEMT.

The mobility limits associated with each scattering mechanism are shown in Fig. 4, the mobility in AlGa_N/Ga_N devices take into account the carrier scattering. The different scattering mechanism in the figure labeled as (a) polar optical phonon, (b) interface roughness, (c) acoustic

phonon (deformation potential and piezoelectric), (d) dislocation, (e) residual impurity and (f) alloy disorder respectively.

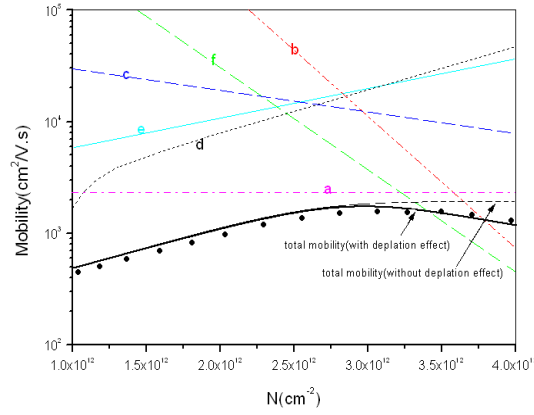


Fig. 4. The total mobility verse total sheet carrier concentration at 300K for $Al_{0.15}Ga_{0.85}N/GaN$ based HEMT.in comparison with existing experimental data (circles) from Ref. [12]. The different scattering mechanisms in the figure are labeled as (a) polar optical phonon, (b) interface roughness, (c) acoustic phonon (deformation potential and piezoelectric), (d) dislocation, (e) residual impurity and (f) alloy disorder, respectively.

Fig. 5 shows that as the percentage of aluminum alloy increases, the sheet resistance in three model decreases. By increasing aluminum alloy percentage, the difference between the single- sub-bands model, multi sub-bands model, and depletion layer effects is maximized, due to the increase in the number of occupied sub-bands, discontinuity in the conduction band between AlGa_N and GaN and three-dimensional channel in AlGa_N barrier. The results show that sheet resistivity is generated by multi subband and depletion layer effects are in good agreement between the model and experimental data.

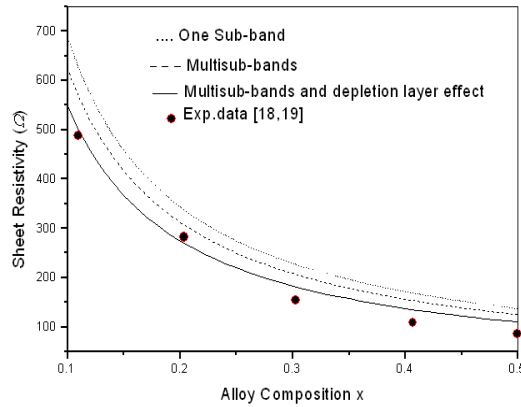


Fig. 5. The sheet resistivity verse Alloy composition of Al at 300K for $Al_{0.15}Ga_{0.85}N/GaN$ based HEMT for one sub-band, multi sub-band and depletion layer effect In comparison with existing experimental data [18,19].

4. Conclusions

An analytical-numerical model for the sheet resistance of AlGa_N/Ga_N high electron mobility transistors is reported. With increasing Al, the mobility is decreasing so that by increasing aluminum alloy percentage, the difference between the single- sub-bands and the multi sub-bands

effects is maximized, due to the increase in the number of occupied sub-bands. Electrons within non-depleted three-dimensional channel of AlGa_N barrier in depletion layer model can cause decrease sheet carrier density and 2DEG mobility in well. The reason for decrease sheet carrier may be that in structures with small aluminum alloy percentage, the energy band gap is small and, as a result, discontinuity in the conductivity band between AlGa_N and Ga_N decreases, and polarity effects also decreases. This decreases in polarity effects cause a decrease in the value of N_s and increases of sheet resistivity. There is a good agreement between the multi sub-band depletion layer model and experimental data.

References

- [1] H. Tokuda, J. Yamazaki, M. Kuzuhara, Journal of Applied Physics **108**, 104409 (2010).
- [2] A. Asgari, L. Faraone, Applied Physics Letters **100**, 122106 (2012).
- [3] R. Jun, Y. T. Jun, J. C. Yu, T. R. Chun, W. Z. Guo, Z. G. Yi, Chinese Physics Letters **26**, 087802 (2009).
- [4] R. Yahyazadeh, A. Asgari, M. Kalafi, Physica E **33**, 77 (2006).
- [5] D. Jena, A. C. Gossard, U. K. Mishra, Appl. Phys. Lett. **76**, 1707 (2000).
- [6] L. Hsu, W. Walukiewicz, J. Appl. Phys. **89**, 1783 (2001).
- [7] A. Asgari, M. Kalafi, L. Faraone, J. Appl. Phys. **95**, 1185 (2004).
- [8] T. Kawamura, S. D. Sarma, Physical Review B, **45** (1992).
- [9] S. Yamakawa, H. Ueno, K. Taniguchi, C. Hamaguchi, K. Miyatsuji, K. Masaki, U. Ravaioli, J. Appl. Phys. **79** (1996).
- [10] S. Rajan, S. P. Denbaars, U. K. Mishra, Appl. Phys. Lett. **88**, 042103 (2006).
- [11] J. Simon, A. Wang, Hexing, Appl. Phys. Lett. **88**, (2006).
- [12] X. Z. Dang, P. M. Asbeck, E. T. Yu, G. J. Sullivan, M. Y. Chan, B. T. McDermott, et al., Appl. Phys. Lett. **74**, 3890 (1999).
- [13] M. A. Huque, S. A. Eliza, T. Rahman, H. F. Huq, S. K. Islam, Solid State Electronics **53**, 341 (2009).
- [14] P. Gangwani, S. Pandey, S. Halder, M. Gupta, R. S. Gupta, Microelectronic Journal **38**, (2007).
- [15] R. Yahyazadeh, Z. Hashempour, Journal of Material Science and Engineering **5** (2011).
- [16] Z. Hashempour, A. Asgari, S. Nikipar, M. R. Abolhasani, M. Kalafi, Physica E **41**, 1517 (2009).
- [17] J. Deng, R. Gaska, M. S. Shur, M. A. Khan, J. W. Yang, Materials Research Society Symposium-Proceedings, **V595**, w 4.5.1 (2000).
- [18] O. Ambache, J. Smart, J. R. Shealy, N. G. Weimann, K. Chu, M. Murphy, W. J. Schaff, L. F. Eastman, Journal of Applied Physics **85**, 3233 (1999).
- [19] C. Y. Chang, T. J. Anderson, F. Ren, S. J. Pearton, A. M. Dabiran, A. M. Wowchak, B. Cui, P. P. Chow, CS MANTECH Conference, May 18th-21st, 2009, Tampa, Florida, USA.