Effect of Gate Length on the Electrical Characteristics of Nanoelectronic AlGaN/GaN High Electron Mobility Transistors to Fabricate the Biomedical Sensors in Nanoelectronics

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In this work, the drain current is optimised and achieved up to 589 mA with respect to the gate length, aluminium mole fraction, drain voltage and gate voltage in nanoelectronic single-heterojunction AlGaN/GaN high electron mobility transistors (HEMTs). The effect of gate length on drain characteristics in these HEMTs is one novelty of this work. Also, the above investigations in HEMTs of nanoelectronic dimensions is another novelty of this work from the aspect of geometrical dimensions according to a strong and updated literature survey. According to this work, the drain current is larger at higher aluminium mole fraction. Also, the drain current is higher at lower gate length with a fixed source to gate distance. All simulation results are obtained by SILVACO-ATLAS software tool with a verification by MATLAB programs. This simulation work is completely supported by the previously derived mathematical formulation according to the theoretical analysis on band gap discontinuity. This work will be useful to experimentally fabricate the sensors in nanoelectronics using these nanoelectronic HEMTs.

Keywords: Single Heterojunction, Gate Length, Aluminium Mole Fraction, Drain Current, Band Gap Discontinuity.

1. INTRODUCTION
Charfeddine et al. have investigated a two-dimensional theoretical model of electrical characteristics in microelectronic AlGaN/GaN high electron mobility transistors (HEMTs) by the proposition of a charge-control model involving the Robin boundary condition. The dependence of two-dimensional electron gas (2-DEG) sheet carrier concentration on aluminium mole fraction and on AlGaN thickness is investigated. According to their designs, the top to bottom layers are metal, n-AlGaN, undoped-AlGaN, undoped-GaN, with a 2-DEG formed at the unintentionally doped (UID) AlGaN/GaN interface.

Many models are demonstrated to theoretically analyse the microelectronic HEMTs, for example, thermal model including self-heating effect and non-linear polarization. Luo et al. presented a model to increase the breakdown voltage in AlGaN/GaN HEMTs using double buried p-type layers. To investigate the electrical characteristics for maximum drain current in nanoelectronic AlGaN/GaN HEMTs is still a challenging research-area. AlGaN/GaN HEMTs in microelectronic dimensions are useful to fabricate the wireless hydrogen sensor networks and biosensors. Successful designs and fabrication of Nanoelectronic HEMTs will be useful for the miniaturization of sensor networks.

In this work, the effect of gate length on drain current is investigated in nanoelectronic single-heterojunction AlGaN/GaN HEMTs. Also, the effect of aluminium mole fraction on drain current is studied in these nanoelectronic HEMTs. Finally, the formation of 2-DEG in quantum well at the AlGaN/GaN interface in nanoelectronic HEMTs is demonstrated by computer simulation. This simulation work is completely supported by the previously derived mathematical formulation according to the theoretical analysis on band gap discontinuity. This simulation work will be helpful to fabricate the nanoelectronic sensors in multifarious applications in nanoelectronics.
2. DESIGNS OF SIMULATED STRUCTURES IN THIS WORK

In this work, a representative cross-sectional view of the Nanoelectronic HEMT structures is shown in Figure 1. The cross-sectional dimensions of different portions of these designed Nanoelectronic HEMT-structures are given below: (A) source dimensions are 250 nm (length) \times 30 nm (height); (B) drain dimensions are 250 nm (length) \times 30 nm (height); (C) gate dimensions are \( L_G \) (length) \times 40 nm (height); (D) total horizontal length of the device is 1750 nm; (E) GaN thickness is 60 nm; (F) sapphire thickness is 100 nm; and (G) source to gate fixed distance is 250 nm. In this work, the gate length \( (L_G) \) is varied with the following lengths as 0.25, 0.50, and 0.75 micron. With the variation in gate length, the source to gate distance is fixed (250 nm) but the gate to drain distance is variable. GaN and sapphire are chosen as the materials to design the Nanoelectronic HEMTs according to the comparative material properties.\(^{11, 12}\) Above the GaN nano-layer, one intrinsic AlGaN nano-layer of 5 nm thickness is structured. Above this nano-layer, one \( n \)-type AlGaN nano-layer of 10 nm thickness is structured in the middle. Finally, a top intrinsic AlGaN nano-layer of 5 nm thickness is structured. Doping concentration of the \( n \)-type AlGaN nano-layer is \( 1 \times 10^{18} \) cm\(^{-3}\). The chosen aluminium mole fractions \( (x) \) are 0.30 and 0.20. These structures are simulated by the SILVACO-ATLAS software tool. All the simulation results are verified by MATLAB programs.

3. RESULTS AND DISCUSSION

3.1. Investigations on Drain Characteristics

Figure 2(a) corresponds to the gate length \( (L_G) \) of 0.25 micron and aluminium mole fraction \( (x) \) of 0.30. In Figure 2(a), the drain current is lower at more negative gate voltage \( (V_G) \). This happens due to the \( n \)-type AlGaN nano-layer of 10 nm thickness at the middle. According to the comparison between this present work and our previously performed extensive simulation work, the drain current increases remarkably by the use of top and bottom intrinsic AlGaN nano-layers having 5 nm thickness for each.\(^{13, 14}\)
Figure 2(b) corresponds to the gate length \((L_G)\) of 0.50 micron and aluminium mole fraction \((x)\) of 0.30. Again, the drain current is lower at more negative gate voltage \((V_G)\). Similar electrical behavior is observed in Figure 2(c) corresponding to the gate length \((L_G)\) of 0.75 micron and aluminium mole fraction of 0.30. According to the Figures 2(a)–(c), the drain current is lower due to higher gate length. The probable reason of this gate length dependence is higher channel resistance related to larger gate length.

Figures 3(a)–(c) show the drain current dependence on gate length \((L_G)\) at the aluminium mole fraction \((x)\) of 0.20. In brief, the drain current is higher related to lower gate length \((L_G)\) at the aluminium mole fraction \((x)\) of 0.20. Also, according to this work, the drain current is higher at the larger aluminium mole fraction \((x)\) maintaining fixed structural dimensions. Figures 4(a) shows the quantum well at the AlGaN/GaN heterojunction corresponding to the gate length \((L_G)\) of 0.25 micron with aluminium mole fraction \((x)\) of 0.20. Figure 4(b) shows similar quantum well corresponding to the gate length \((L_G)\) of 0.50 micron with aluminium mole fraction \((x)\) of 0.20. The two-dimensional electron gas (2-DEG) is formed at the AlGaN/GaN heterojunction interface due to this quantum well. Hence, this simulation work is a direct demonstration of the formation of 2-DEG in quantum well transistors. Drain currents flow in the high electron mobility transistors due to this 2-DEG formation. In each figure...
of this work showing the drain characteristics, the linear region and saturation region are prominent.

3.2. Investigations on Conduction Band Engineering

In this section, the conduction band engineering is investigated by theoretical calculations. The aluminium mole fraction (m) is represented by ‘m’ according to the previously deduced theory.3–6 The mathematical expression of band gap discontinuity (ΔE_g) at the AlGaN/GaN interface is given as follows:

\[ \delta E_g(T, m) = E_g^{AlGaN}(T, m) - E_g^{GaN}(T) \]  

(1)

The non-linear temperature dependence of band gap by Bose-Einstein expression is given as follows [for 2k ≤ T ≤ 580 K and 0 ≤ m ≤ 0.65]:

\[ E_g^{AlGaN}(T, m) = E_g^{AlGaN}(RT, m) + \frac{2E_g^{GaN}}{\exp(S_B^{GaN}/T - 1)} \]  

(2)

The composition dependent band gap of Al_xGa_{1-x}N at room temperature is given as follows:

\[ E_g^{AlGaN}(RT, m) = 6.13m + 3.42(1-m) - m(1-m) \]  

(3)

The band gap of GaN is expressed as follows [for 2K ≤ T ≤ 580 K]:

\[ E_g^{GaN}(T) = E_g^{GaN}(T = 0) - \frac{2E_g^{GaN}}{\exp(S_B^{GaN}/T - 1)} \]  

(4)

According to the Eqs. (1) to (4), the calculated band gap discontinuity (ΔE_g) is 0.381 eV corresponding to the aluminium mole fraction (m) of 0.2 (Fig. 5). According to the Figures 4(a) to (b), the measured band gap discontinuity (ΔE_g) is 0.383 eV corresponding to the aluminium mole fraction (m) of 0.2. This ΔE_g is measured by the SILVACO-ATLAS software tool. Therefore, the theoretical investigations of this work are completely supported by the previously derived mathematical formulation.

3.3. Application of This Work into Future Design and Fabrication of Biomedical Sensors

Besides the use in wireless hydrogen sensor network related to wireless transceiver, AlGaN/GaN HEMTs are applicable in biomedical sensors.7–10 AlGaN/GaN HEMT based biosensors are highly useful to detect the C-reactive protein (CRP) related to the antigen-antibody interactions on the gate surface.4 The AlGaN/GaN HEMT based biosensor can be used to detect gases, ions, pH values, proteins and DNA.9 Therefore, the next phase of our present work is to experimentally develop the AlGaN/GaN HEMT based biosensor with the investigations on material compatibility for any specific bioengineering application. The optimization of device structures to achieve maximum drain current in this work will be helpful to design and fabricate the AlGaN/GaN HEMT based biosensors in the next phase.

4. CONCLUSIONS

In this work, the drain current is lower due to more negative gate voltage for the presence of the n-type AlGaN layer of 10 nm thickness at the middle. The drain current is higher due to smaller gate length. The drain current is higher due to larger aluminium mole fraction. According to the direct demonstration in this work, the formation of 2-DEG at the AlGaN/GaN heterojunction interface is responsible to generate the drain current in the channel of high electron mobility transistors as quantum well devices. This simulation work is completely supported by the previously derived mathematical formulation according to the theoretical analysis on band gap discontinuity. This work will be helpful to fabricate the nanoelectronic sensor networks in future for different applications in nanoelectronics.

References and Notes

6. M. K. Chattopadhyay and S. Tokekar, Analytical model for the transconductance of microwave Al_xGa_{1-x}N/GaN HEMTs including nonlinear macroscopic polarization and parasitic


