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A Novel High Performance of GaN-Based HEMT with Two Channel Layers of GaN/InAlGaN

Reza Karami[1], Massoud Sabaghi[2]*, Massoud Masoumi[1]

[1]Department of Electrical Engineering, Islamshahr Branch, Islamic Azad University, Tehran, Iran
[2]Laser and Optics Research School, Nuclear Science and Technology Research Institute (NSTRI), Tehran, Iran
Email: *msabaghi@aeoi.org.ir

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Abstract

The potential impact of GaN-based high electron mobility transistor (HEMT) with two channel layers of GaN/InAlGaN is reported. Using two-dimensional and two-carrier device simulations, we investigate the device performance focusing on the electrical potential, electron concentration, breakdown voltage and transconductance (gm). Also, the results have been compared with structure of AlGaN/GaN HEMT. Our simulation results reveal that the proposed structure increases electron concentration, breakdown voltage and transconductance; and reduces the leakage current. Also, the mole fraction of aluminum in the InAlGaN has been optimized to create the best performing device.

Keywords

Mole Fraction, GaN/InAlGaN, Breakdown Voltage, High Electron Mobility Transistor (HEMT)

1. Introduction

In recent decades, GaN is considered an outstanding material for high frequency and high power devices due to its superior intrinsic physical properties including wide bandgap, high breakdown electric field, high electron saturation velocity and high density carriers in the form of two-dimensional electron gas with high mobility [1]-[8]. Wide bandgap semiconductor power devices offer great performance improvements and can work in harsh environments where silicon power devices cannot function. One of the main advantages of III-nitride materials such as gallium nitride is the ability to form a heterojunction with a ternary alloy made from another III-nitride semiconductor material such as aluminium gallium nitride [9]-[14]. The high electric breakdown field of GaN is a result of the wide bandgap of 3.44 eV at room temperature of the material and enables

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the application of high supply voltages on GaN-based devices, which is one of the two requirements for high power device performance. Therefore, these material properties clearly indicate why GaN is a serious candidate for next generation microwave high power and high temperature applications [7] [11] [12] [13] [14].

In recent years, GaN-based high electron mobility transistor (HEMT) has attracted considerable attentions and shown excellent performance in high power and high frequency microwave applications because of wide band-gap, superior carrier saturation velocity, large breakdown field strength and strong spontaneous and piezoelectric polarization [1] [2] [15] [16] [17] [18]. Due to the its unique characteristic and excellent performance in high power operations, AlGaN/GaN HEMTs are emerging as the promising candidates for next generation radio frequency power amplifiers [18]-[27].

In this paper, the potential impact of GaN-based HEMT with two channel layers of GaN/InAlGaN is studied using a two dimensional device simulator. The unique features of the HEMT with two channel layers of GaN/ InAlGaN are explored and compared with those of AlGaN/GaN and AlGaN/InGaN HEMTs in terms of the drain current, electrical potential, breakdown voltage and transconductance (gm).

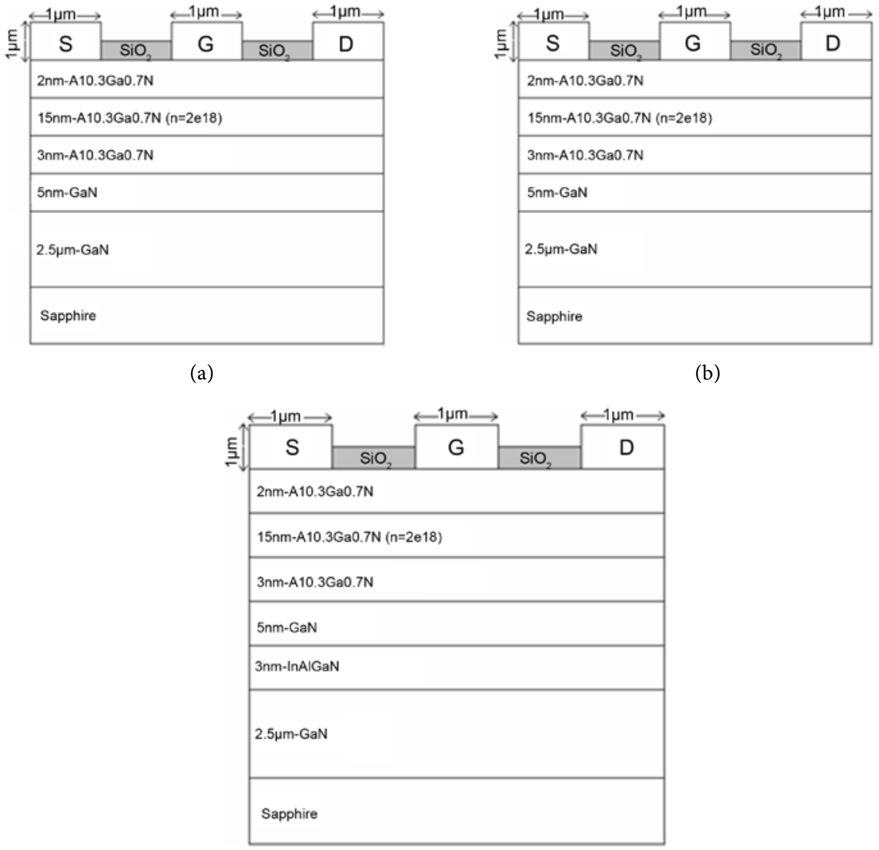
In the next section, the proposed structure dimensions and the physical models used in the 2-D simulation are described in detail. In the third section, we explain how the presence of the two channel layers of GaN/InAlGaN will enhance performance of GaN-based HEMT. Also, in this section, the effect of these layers on the electrical potential, electron concentration, breakdown voltage and transconductance are studied and compared with that in structure of AlGaN/GaN HEMT in details.

2. Device Structure

Figures 1(a)-(c) show the schematic cross section of AlGaN/GaN, AlGaN/InGaN and GaN-based HEMT with two channel layers of GaN/InAlGaN, respectively. The dimensions of the structures are as follows: gate length of 1 µm, gate-drain spacing of 1 µm, gate-source spacing of 1 µm. Barrier layer and two channel thicknesses of GaN/InAlGaN are 3 nm, 5 nm and 3 mm, respectively. The spacer layer is an n-type heavily doped $Al_{0.3}Ga_{0.7}N$ thicknesses of 3 nm. Also, the p-layer in the barrier is a p-type heavily doped $Al_{0.3}Ga_{0.7}N$ with doping concentration of $2e^{18}$. The work function of gate is 5.1 eV for the gate schottky contact. The devices are simulated using two dimensional SILVACO software [28]. The several models are activated in order to achieve more realistic results in simulations that including the SRH, Conmob, Fldmob and Fermi Dirac models for Shockley-Read-Hall recombination, standard concentration dependent mobility, parallel electric field-dependent mobility and statistics [28].

3. Results and Discussion

At first, we optimized the mole fraction of aluminum in the InAlGaN to create



(a) (b)

(c)

Figure 1. Schematic cross section of (a) AlGaN/GaN; (b) AlGaN/InGaN and (c) GaN-based HEMT with two channel layers of GaN/InAlGaN.

the best performing device. Table 1 show the different structure parameters of InAlGaN layer with various mole fraction including polarization charge, band gap, conduction band and critical electric field. As seen, the polarization charge increases with lower mole fraction of aluminum that causes higher electron consternation. However, the higher mole fraction of aluminum causes higher critical electric field. Therefore, the best of mole fraction of aluminum is value that has the most polarization charge and the critical electric field greater than critical electric field of GaN. Figure 2 and Figure 3 show the potential and electron concentration in the channel below at gate voltage of zero, respectively. The concentration is normalized to $N_0 = 1\times10^{18}$ cm^{-3}. Also, the energy axis in this figure is normalized to 25 meV. As can be seen from these figures, the structure with $In_{0.15}Al_{0.2}GaN$ layer has higher potential barrier and electron concentration than the other two structures. Therefore, structure with $In_{0.15}Al_{0.2}GaN$ layer has higher transconductance as can be shown in Figure 4.

Figure 5 and Figure 6 show the comparison of electron concentration and transconductane values between GaN-based HEMT with two channel layers of GaN/InAlGaN and of AlGaN/GaN HEMT. It is evident that GaN-based HEMT with two channel layers of GaN/InAlGaN has a high potential barrier before the channel. It causes that leakage current decreases. On the other hand, Figure 5

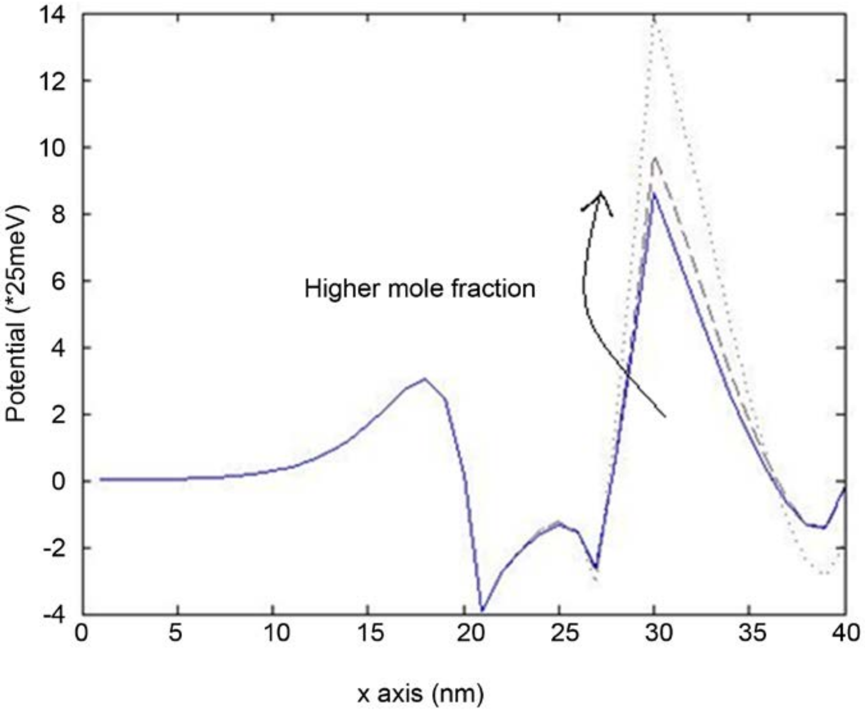


Figure 2. The Potential of GaN-based HEMT with two channel layers of GaN/InAlGaN in the channel below at gate voltage of zero.

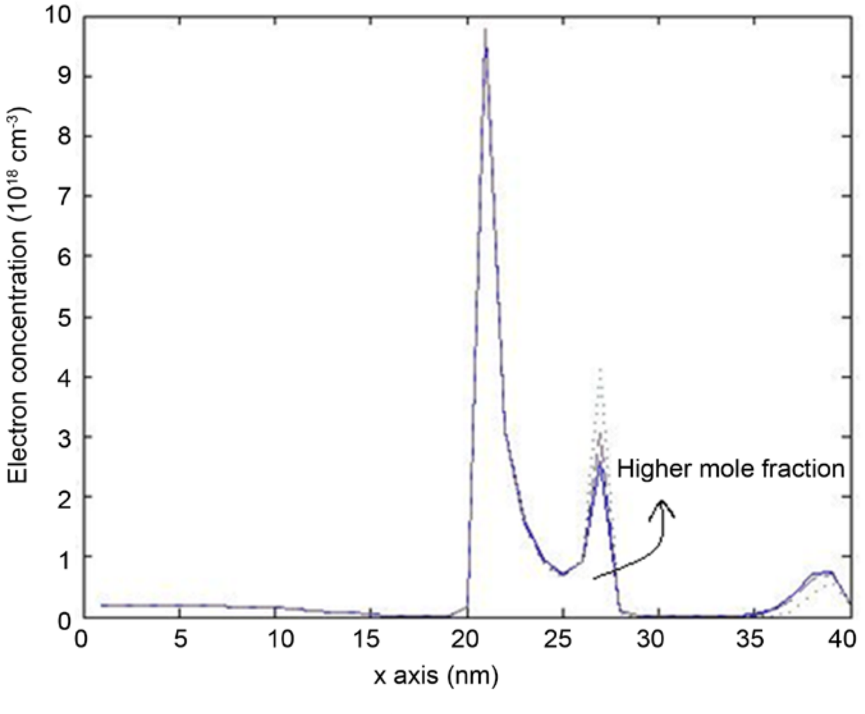


Figure 3. The Electron concentration of GaN-based HEMT with two channel layers of GaN/InAlGaN in the channel below at gate voltage of zero.

shows that electron concentration for GaN/InAlGaN structure, which have two channel layers, is higher than the AlGaN/GaN HEMT. The GaN/InAlGaN structure have two channel layers which causes more total electron mobility in

Table 1. The structure parameters of InAlGaN layer with various mole fraction including polarization charge, band gap, conduction band and critical electric field.

Material	Polarization Charge	Band Gap(ev)	Conduction Band(ev)	Ecrit(Mv/Cm)
$In_{0.1}GaN$	1.25E26	3.026	−0.248	1.75
$In_{0.1}Al_{0.13}GaN$	8.09E25	3.3	−0.074	2.01
$In_{0.1}Al_{0.15}GaN$	7.35E25	3.347	−0.046	2.016
$In_{0.15}Al_{0.2}GaN$	1.09E26	3.26	−0.099	2.06

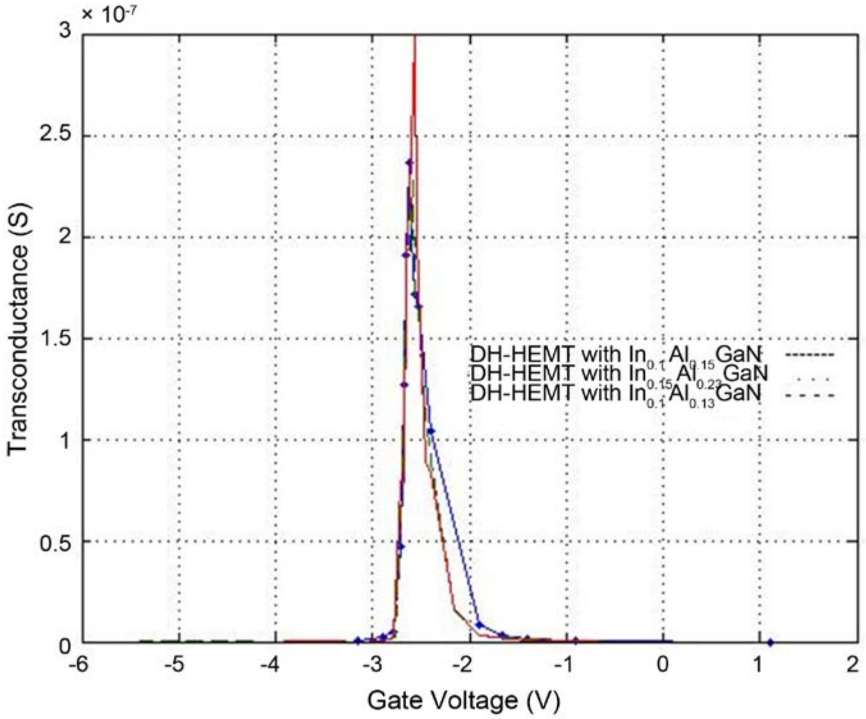


Figure 4. The Comparison of Transconductane values of GaN/InAlGaN HEMT with different mole fraction of aluminum.

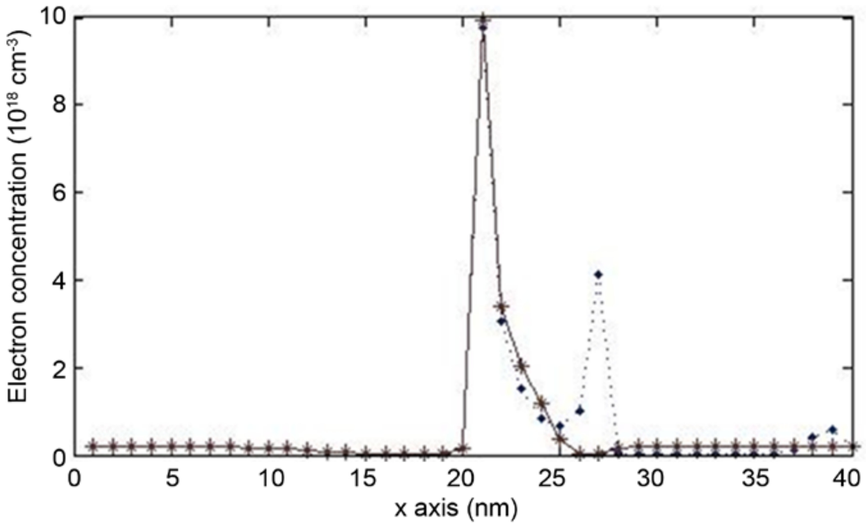


Figure 5. The comparison of electron concentration values between GaN-based HEMT with two channel layers of GaN/InAlGaN and of AlGaN/GaN HEMT.

the two channels and as a result more transconductance, as can be seen in Figure 6.

Generally, the breakdown in HEMTs can occur because of different effects including impact ionization, tunneling or surface states that it is important to find the dominant effect in order to control the breakdown of HEMTs. The off-state breakdown occurs at a drain-source voltage when the applied gate voltage causes that channel is pinched off [10] [29]. In this way, the maximum electric field occurs at the edge of gate in drain side and then the impact ionization is dominant effect of the breakdown. Figure 7 shows the electric field in x axis of GaN-based HEMT with two channel layers of GaN/InAlGaN. Since the InAlGaN material has higher critical field in comparing with that of AlGaN/GaN, the breakdown voltage of GaN-based HEMT with two channel layers of GaN/InAlGaN is larger. As can be seen from Figure 7, the electric field has critical in drain voltage of −130 V compared with 90 V of the conventional HEMT and structure has in off-state breakdown.

4. Conclusion

To improve the electrical potential, electron concentration, breakdown voltage and transconductance, we have proposed a novel GaN-based HEMT that has two channel layers of GaN/InAlGaN. This new structure increases electron concentration, breakdown voltage and transconductance; and reduces the leakage current. The breakdown voltage of 130 V is obtained for the GaN/InAlGaN com-

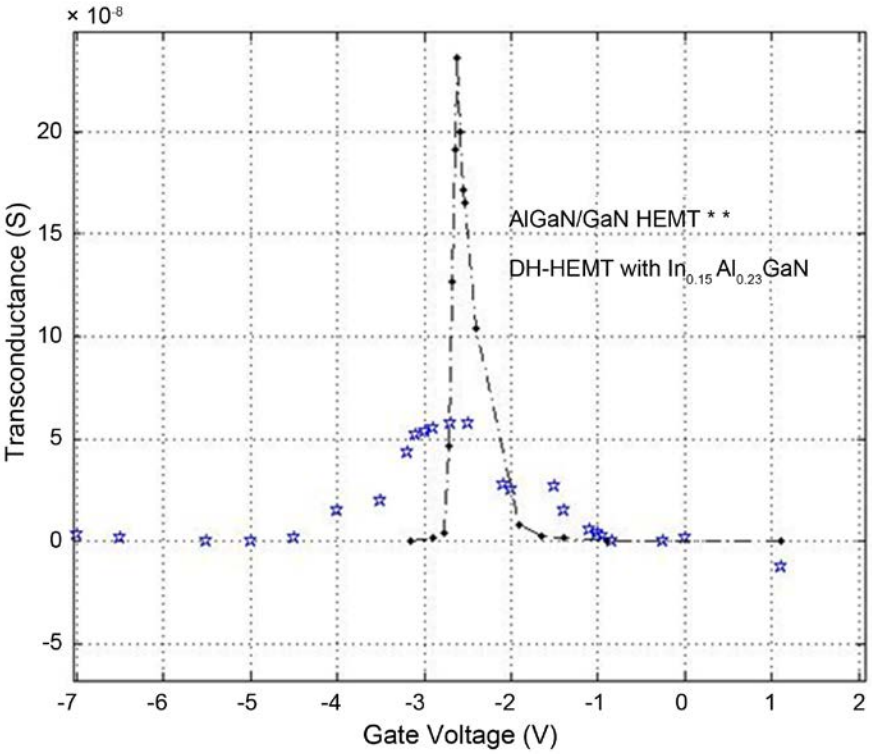


Figure 6. The comparison of transconductane values between GaN-based HEMT with two channel layers of GaN/InAlGaN and of AlGaN/GaN HEMT.

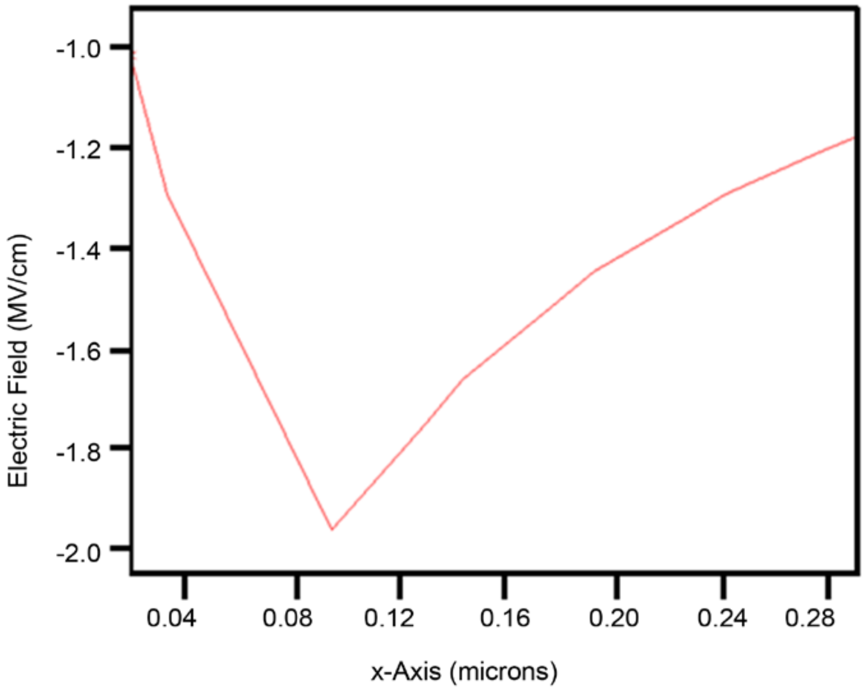


Figure 7. The Electric Field in x Axis of GaN-based HEMT with two channel layers of GaN/InAlGaN.

pared with 90 V of the conventional HEMT. Also, the mole fraction of aluminum in the InAlGaN has been optimized to create the best performing device.

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