International Journal of Engineering and Advanced Technology (IJEAT)
ISSN: 2249 – 8958, Volume-8, Issue-2S2, January 2019

DC Characteristics of AlN Spacer Based $Al_XGa_{(1-X)}N$/GaN HEMT for High Power Applications

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ABSTRACT--- *We report the DC characteristics of 0.3µm gate length, 4X75 µm width , AlN spacer layer based* $Al_XGa_{(1-X)}N$*/GaN HEMT devices for two different Al mole fraction x=0.30 and x=0.27 in the barrier layer. The proposed device exhibits a maximum drain current* I_{DS} *of 1210 mA/mm, highest sheet carrier density (*n_s*) of* $1.39x10^{13}$ cm^{-2} *, mobility (µ) of 1643* cm^2 */ V-s and transconductance (*g_m*) of 288 mS/mm for x=0.30 . The proposed HEMT structure is simulated using Synopsys TCAD tool and results are verified with experimental data. This excellent DC characteristics obtained from this HEMT device have helped us propose that III-N compound semiconductors with higher 2DEG sheet carrier density are ideal for future high power applications.*

KEYWORDS *2DEG, Sheet charge density, HEMT, transconductance, polarization, DC characteristics.*

1. INTRODUCTION

GaN based HEMTs have been attractive semiconductor devices for high power and high frequency applications for the past two decades. GaN based compound semiconductor devices are prominent nano electron devices for high speed and high power application in the area of power electronic devices, High power amplifiers and opto electronic devices because of their higher band gap of 3.4 eV, higher saturation velocity $2.5x10^7$cm/s, peak electric field of 150 kV/cm and higher electron mobility of 1000 cm^2/V-s [1-3].

Existence of alloy disorder scattering in conventional AlGaN/GaN limits the mobility of electron in 2DEG .The higher band gap AlN spacer layer between the AlGaN/GaN reduces the wave penetration in 2DEG which tends to enhance the electron mobility and the sheet charge carrier density also improves [1].

Existence of spontaneous and piezoelectric polarization at AlGaN/GaN interface, the device achieves high electron density in the 2DEG region.

In this research article, we propose a new HEMT structure by introducing a 1nm AlN space layer between the barrier and channel layer. The wide bandgap of AlN (6.1 eV) spacer layer induces high electron density in 2DEG region and we are used 50 nm Si_3N_4 passivation to protect the device from surrounding. A very thin 1nm GaN cap layer was used, which reduced the leakage current and also it prevented the devices from oxidation. Moreover, a 115 nm AlN layer was added between the GaN buffer and SiC substrate to reduce the strain induced because of lattice mismatch between them. The proposed device structure takes care of leakage current minimization with enhanced thermal conductivity. Therefore the proposed AlN spacer based HEMT device shows excellent DC characteristic with Drain current of I_{ds}=1210 mS/mm, transconductance of (gm) 288mS/mm with breakdown voltage of 14V for Al mole fraction of 0.30 in the barrier layer.

The proposed AlN based spacer layer $Al_XGa_{(1-X)}N$/GaN HEMT device structure is simulated for two different Al mole fraction (x=0.30, 0.27). A peak drain current density of 1210 mA/mm and 288 mS/mm of transconductance achieved for Al mole fraction x=0.30. The device with Al mole fraction of x=0.27 exhibits 710 mA/mm of peak drain current density and 217 mS/mm of transconductance.

2. ALGAN/ALN/GAN HEMT DEVICE STRUCTURE

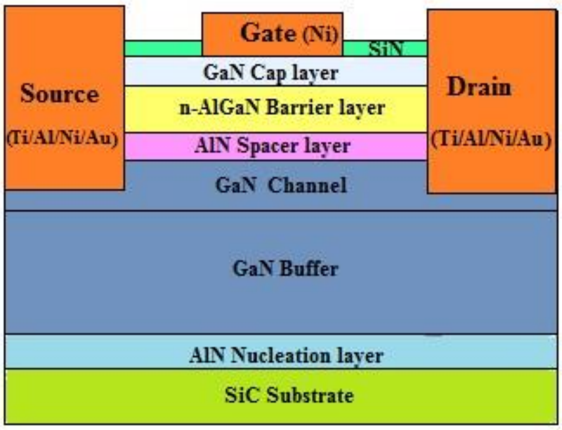

Figure.1. 0.3µm gate length, 4x75µm width of AlN spacer based HEMT

The schematic view of 300nm $Al_XGa_{(1-X)}N$/SiN/GaN shown in Fig.1. A very thin GaN cap layer is deposited over the barrier layer to reduce leakage current in the devices and also prevent the device surface from oxidation.

Table 1

Layer	*Specifications*
Si_3N_4 Passivation	50nm

Revised Manuscript Received on December 22, 2018.

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GaN cap	1 nm
Al$_X$Ga$_{(1-X)}$N Barrier	25 nm
AlN spacer	1 nm
GaN channel /Buffer	1.5 µm
AlN Nucleation	115 nm
SiC substrate	0.8 µm

The band gap of the Al$_X$Ga$_{(1-X)}$N barrier layer is to be calculated from the expression;

$$Eg(x) = xEg(AlN) + (1-x)Eg(GaN) - bx(1-x) \quad (1)$$

From equation (1) , by increasing the thickness and Al mole fraction in the barrier layer the band gap is increased which causes the higher density of sheet carrier in 2DEG . A 1 nm AlN spacer layer between the barrier and channel layer reduces the alloy disorder scattering and the interface roughness scattering. A very thin layer of AlN is preferred to reduce the coulomb scattering in 2DEG.

The high resistive Unintentionally doped lower band gap GaN material is used as buffer layer to achieve higher electron mobility and sheet carrier density in 2DEG .

To minimize the strain induced effects at the interface of GaN buffer and SiC substrate due to lattice mismatch, a very thin AlN layer used as nucleation layer. SiC is one of the suitable substrate materials for GaN based HEMT s because of it superior thermal conductivity.

2.1 Energy band gap and Polarization of AlN spacer based AlGaN/GaN HEMTs

Band gap structure of proposed device structure is displayed in Fig.2.

Lattice mismatch between the layers causes a mechanical perturbation (strain) at the interface, this leads to piezoelectric polarization.

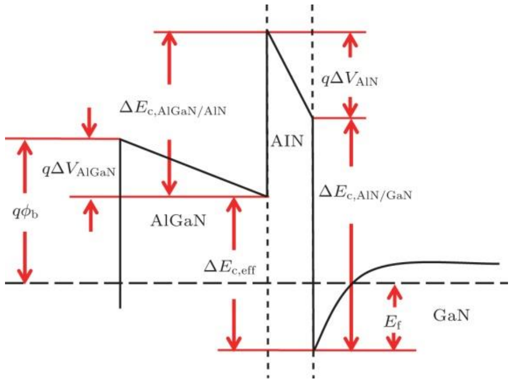

Figure.2. The conduction band offset diagram of AlGaN/AlN/GaN

The sheet charge density at the AlN/GaN interface due to spontaneous and piezoelectric polarization as:

$$\sigma = -\left(P_{AlN}^{total} - P_{GaN}^{total}\right)C/m^2 \quad (2)$$

Where P_{AlN}^{total} and P_{GaN}^{total} are total polarization charges in the AlN and the GaN layer respectively.

2.2 Drain to Source current (I_{DS})

The drain source current is expressed by,

$$I_{DS} = k(V_{DS})k'_n \frac{W}{L}\left[(V_{GS} - V_t)V_{DSAT} - \frac{V_{DS}^2}{2}\right] \quad (3)$$

Where $V_{DS} \le V_{GS} - V_t$

$$I_{DSAT} = k(V_{DSAT})k'_n \frac{W}{L}\left[(V_{GS} - V_t)V_{DSAT} - \frac{V_{DS}^2}{2}\right] \quad (4)$$

Where $V_{DS} = V_{DSAT} \ge (V_{GS} - V_t)$

Where k'_n is the proportionality constant which give the measure of mobility.

2.3 Transconductance

The current driving capability of a transistor depends on the transconductance of the device which is also a very important parameter to high frequency operation of the HEMT device.

$$g_m = \frac{\partial I_{DS}}{\partial V_{GS}} \text{ at constant } V_{DS}$$

3. RESULT AND DISCUSSION

The proposed device structure is simulated by Synosys TCAD tool. Fig.3. shows the variation of sheet charge density for different Al mole fraction the barrier channel. The carrier density is linearly increasing with the Al content. The calculated sheet charge densities (n_S) for Al$_{0.30}$Ga$_{0.70}$N and Al$_{0.27}$Ga$_{0.73}$N are 1.39x10^{13} cm^{-2} and 1.26x10^{13} cm^{-2} respectively.

The electron mobility dependence on Al mole fraction is displayed in Fig.4. The electron mobility of 1643 cm^2 / V-s and 1506 cm^2 / V-s obtained for (Al$_{0.30}$Ga$_{0.70}$N and Al$_{0.27}$Ga$_{0.73}$N respectively.

The DC characteristics of proposed device structure are shown in Fig.5 and Fig.6 for different gate source voltages starting from 1 V to -5 V. The peak drain current density of 1210 mA/mm and 710 mA/mm obtained for 0.27 and 0.3 Al mole fraction respectively. and the results are validated with the experimental data [1].

Fig.7. displays the transconductance (gm) for different Al mole fraction in barrier layer. The peak transconductance of 288 mS/mm and 217 mS/mm is achieved 0.3 and 0.27 Al mole fraction.

The transfer characteristics of HEMT structure is shown in Fig.8. for Al$_{0.30}$Ga$_{0.70}$N and Al$_{0.27}$Ga$_{0.73}$N barrier layer. The maximum gate current of 1210 mA/mm is achieved for Al$_{0.30}$Ga$_{0.70}$N barrier layer.

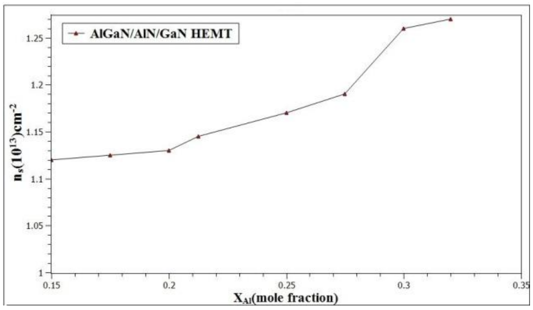

Figure 3. Sheet charge carrier density variation with Al mole fraction.

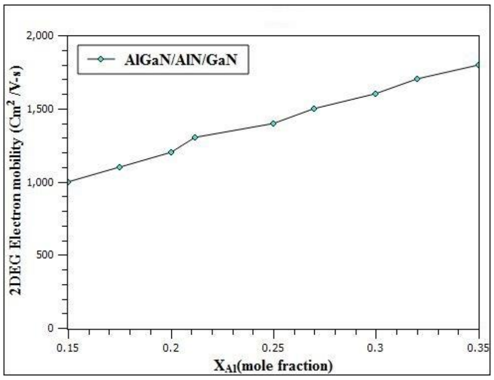

Figure 4. Electron mobility variation with Al mole fraction.

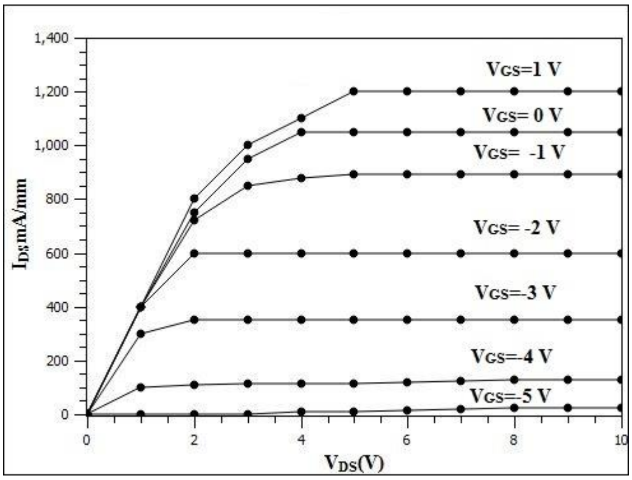

Figure 5. Dependences of Drain-source current (I_{DS}) for different gate voltages (V_{GS}) With different V_{GS} from 1V to -6V for each step down by 1V

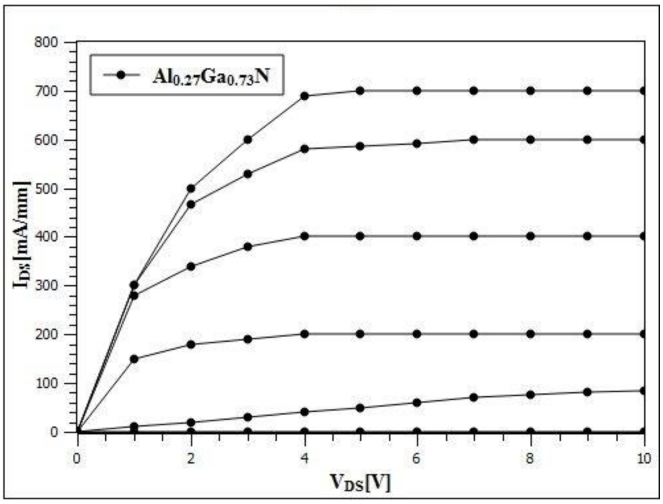

Figure 6. Drain-Source current (I_{DS}) variation with Drain –Source voltages (V_{DS}) With different V_{GS} from 1V to -4V for each step down by 1V.

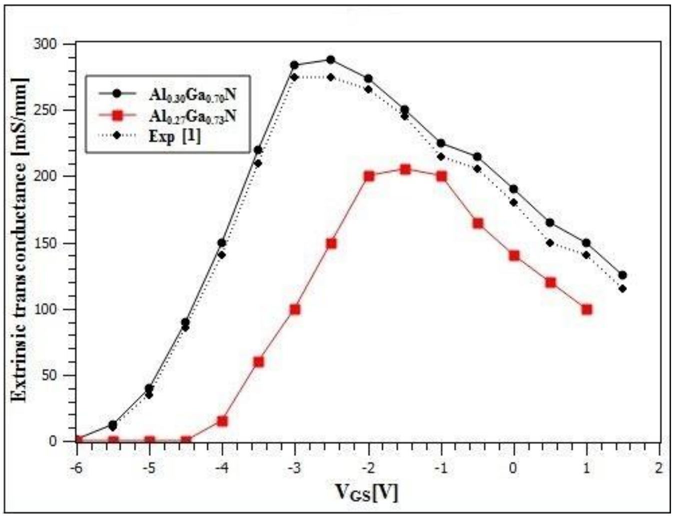

Figure .7. Transconductance variation with Gate source voltage (V_{GS})

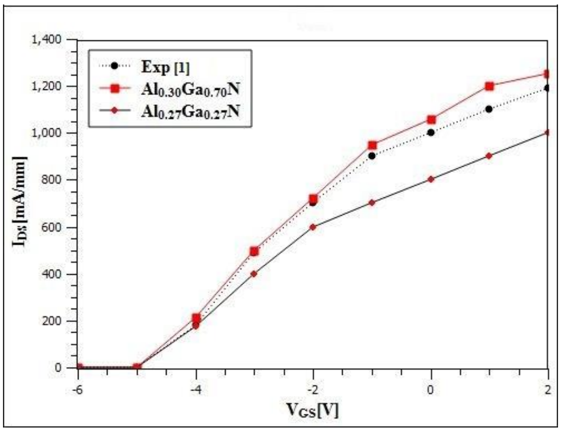

Figure .8. Transfer characteristics

4. CONCLUSION

The DC characteristics of AlGaN/GaN HEMT with AlN spacer layer is presented in this research article. The proposed device structure is simulated for two different Al mole(0.27, 0.3) fractions. The peak drain current density of of 1210 mA/mm, highest sheet carrier density ($n_{s)}$ of $1.39\text{x}10^{13}$ cm^{-2} , mobility (µ) of 1643 cm^2 / V-s and transconductance (g_m) of 288 mS/mm for $Al_{0.30}Ga_{0.70}N$/AlN/GaN HEMT. The superior DC characteristics of the proposed HEMT are suitable candidate for high speed and high power electronics applications.

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