Comparative Study Between AlGaN/GaN and AlInN/GaN High Electron Mobility Transistors

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Abstract—Different characteristics of AlGaN/GaN and AlInN/GaN high electron mobility transistors (HEMTs) are compared in this paper. For two dimensional electron gas (2DEG) density calculation of AlGaN/GaN HEMT, we used AlGaN barrier with different Al composition on GaN substrate with thickness varying from 20nm to 30nm. For AlInN/GaN HEMT, we used AlInN barrier with different In composition on GaN substrate with thickness varying from 5nm to 10nm. Threshold voltage calculation for alloy composition of $0.1 \leq x \leq 0.45$ for AlGaN/GaN HEMT and $0.08 \leq x \leq 0.26$ for AlInN/GaN HEMT were performed. Variations of sheet carrier concentration in 2DEG with gate voltages at different alloy composition and with alloy composition at different barrier thickness for both systems are observed. The lattice matched AlInN/GaN HEMT always exhibits larger sheet carrier density and less strain than that of the AlGaN/GaN HEMT. By comparing different parametric variations it is concluded that the usage of AlInN/GaN HEMT is much more convenient for future devices.

Keywords—HEMT, 2DEG, Threshold voltage, AlGaN/GaN, AlInN/GaN

I. Introduction

The III-Nitride based wide band gap materials (GaN, InN, AlN) and their alloy AlGaInN have drawn much attentions in recent years in the field of high power and high frequency applications [1,2]. The polarization effect at the hetero interface produces two dimensional electrons gas (2DEG) which exhibits unique characteristics of III-Nitride based High Electron Mobility Transistors (HEMT). The high value of sheet charge density (n_s) near 10^{13} cm^{-2} meets the demand of high power devices and high peak electron velocity in GaN of 3×10^7 cm/s as compared to 2×10^7 cm/s of GaAs and Si in the channel gives promising performance for high frequency microwave applications [3,4].

The new material system $In_{0.17}Al_{0.83}N$ with lattice matched growth on GaN leads to potential structure device which overcomes all the surface related instabilities and exhibits higher sheet charge density over the conventional $Al_{0.3}Ga_{0.7}N$ HEMT [5]. In $In_xAl_{1-x}N$ based technology, for tensile strain (at the alloy composition of In, $x<0.17$) the piezoelectric field in the barrier layer is beneficial for electron accumulation in the quantum well which produces charge density more than 2.5×10^{13} cm^{-2} for a barrier thickness of 15nm at zero gate voltage. On the other hand, the compressive strain at $x > 0.17$ in the barrier layer reduces the sheet charge density but yet at x=0.26, the expected sheet charge density is around 1.8×10^{13} cm^{-2} which is still more than the corresponding value of conventional AlGaN/GaN structure [6].

The aim of this paper is to present a comparison between the conventional AlGaN/GaN material system and novel InAlN/GaN material system for HEMT applications. We have used conventional models in order to calculate threshold voltage, sheet charge density at different alloy compositions, thickness and gate voltage. Section II represents the device structure and polarization data. Section III represents the comparison and comparative analysis whereas Section IV provides the discussions. Finally, Section V draws the conclusions.

II. Device Structure And Polarization Data

A. Device Structure

The cross-section of the device structure considered in this work is shown in Fig. 1.

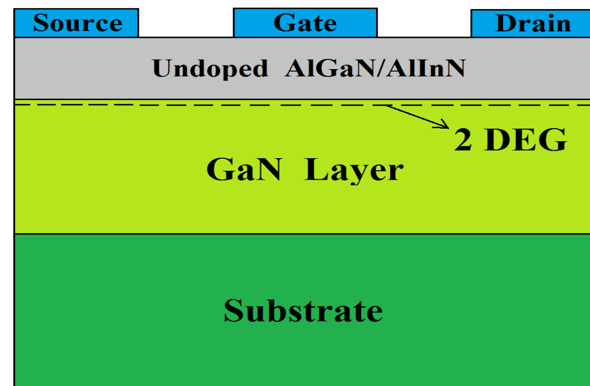


Fig. 1.Cross-sectional view of the HEMT

The top layer is either AlGaN or AlInN followed by 3µm GaN and substrate. The 2DEG is formed between the AlGaN/AlInN barrier and GaN heterojunction.

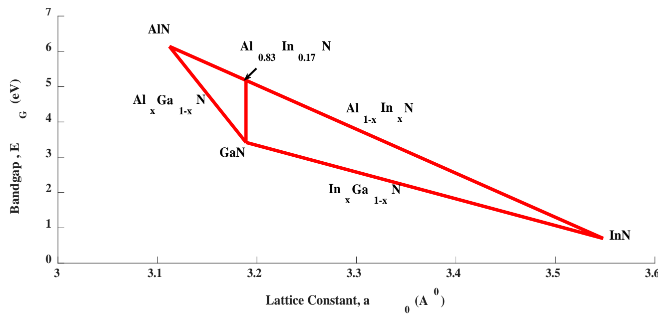


Fig. 2. Bandgap (eV) vs. Lattice Constant (Å)

In case of $Al_xGa_{1-x}N$, the piezoelectric polarization, P_{PE} contributes significantly to the total polarization. As it is evident from Fig.2 that there is some considerable difference in lattice constant present between $Al_xGa_{1-x}N$ and GaN which induces strain in the structure. From the equation of P_{PE}, it is clear that it is directly proportional to lattice mismatch i.e., $(a_0 - a)$. The lattice mismatch is dependent on the Aluminium mole fraction in $Al_xGa_{1-x}N$. The Al mole fraction is generally taken between 0.2~0.3 in the existing literatures

TABLE 1.Material Parameters of AlN,GaN and InN binary alloys

Parameters	AlN	GaN	InN
$e_{31} - e_{33}\left(\frac{C_{31}}{C_{33}}\right)$	-0.86	-0.68	-0.9
$a_0(A^0)$	3.112	3.189	3.548
$P_{SP}(Cm^{-2})$	-0.081	-0.029	-0.032
$E_G(eV)$	6.14	3.42	0.7
ε_r	8.5	9.5	15.3

TABLE 2. Material Parameters of $Al_xGa_{1-x}N$ and $Al_{1-x}In_xN$ ternary alloys

Parameters	Description	$Al_xGa_{1-x}N$	$Al_{1-x}In_xN$
$\phi_b(x)/q$	Schottky Barrier with Nickel used at the gate	$0.84 + 1.3x$	$2.96 - 3.7x$
$E_G(x)/q$	Band Gap	$6.14x + 3.42(1-x) - x(1-x)$	$0.7x + 6.14(1-x)$
$\Delta E_c(x)/q$	Band Offset with GaN	$0.7(E_{g(AlGaN)} - E_{g(GaN)})$	$0.7(E_{g(AlInN)} - E_{g(GaN)})$
$P_{SP}(x)$	Spontaneous Polarization	$-0.029 - 0.052x$	$-0.081 + 0.049x$
$P_{PE}(x)$	Piezoelectric Polarization	$2\left(\frac{a_0 - a}{a}\right)\left[e_{31} - e_{33}\left(\frac{C_{31}}{C_{33}}\right)\right]$	$2\left(\frac{a_0 - a}{a}\right)\left[e_{31} - e_{33}\left(\frac{C_{31}}{C_{33}}\right)\right]$
$\varepsilon_r(x)$	Dielectric Constant	$9.5 - 0.5x$	$15.3x + 8.5(1-x)$

B. Polarization Data and Equations

The III-Nitride based HEMT exhibit high spontaneous polarization and strain induced piezoelectric polarization due to lattice mismatch between two layers. TABLE 1 and TABLE 2 include different spontaneous and piezoelectric polarization constants of binary materials (AlN, GaN and InN) and ternary alloy (AlGaN and AlInN) [7]. These properties of the binary materials are utilized to calculate the molar fraction dependent $Al_xGa_{1-x}N$ and $Al_xIn_{1-x}N$ ternary alloy properties using Vegard's law. Therefore, any property of the ternary material $A_xB_{1-x}C$ is determined as:

$$P(A_xB_{1-x}C) = xP(AC) + (1-x)P(BC) \qquad (1)$$

Table 2 includes all the parameters of the ternary alloys used to further calculate different characteristics of AlGaN and AlInN HEMTs in MATLAB [6,8].

on HEMT.

On the other hand, $Al_{1-x}In_xN$ has an upper hand on $Al_xGa_{1-x}N$. From Fig. 2, it is seen that when the Indium mole fraction is around 0.17~0.18, $Al_{1-x}In_xN$ is completely lattice matched with GaN. This causes the $Al_{0.83}In_{0.17}N/GaN$ structure to be completely strain free. So, almost no piezoelectric polarization component is present in the total polarization. However, only the spontaneous polarization of $Al_{1-x}In_xN$ is alone very larger than the total polarization of $Al_xGa_{1-x}N$. Therefore, $Al_{1-x}In_xN$ is an attractive material over $Al_xGa_{1-x}N$ because of its strain free nature and large polarization value.

The difference in polarization between two layers in the structure gives rise to polarization induced positive charge density σ at the heterointerface. The polarization induced charge density (cm^{-2}) between the top and bottom layers of the heterointerface can be calculated as,

$$\sigma_{top/bottom} = P_{SP}(bottom) - \{P_{SP}(top) + P_{PE}(top)\} \qquad (2)$$

Here, the bottom layer i.e., GaN for both AlGaN and AlInN HEMTs is considered completely relaxed. Therefore, no piezoelectric polarization for GaN layer is included in the calculation.
The calculated charge density σ is used to calculate the threshold voltage of the HEMT and is given by [6,7],

$$V_{th}(x) = \frac{\phi_b(x)}{q} - \frac{\Delta E_c(x)}{q} - \frac{\sigma(x)d}{\varepsilon_r(x)\varepsilon_0} \qquad (3)$$

Here, ϕ_b is the Schottky barrier height of the ternary materials with Nickel gate, ΔE_c is the conduction band offset of the ternary material with GaN which is calculated by taking 70% of the bandgap difference between two layers, d is the barrier that is ternary material thickness above GaN, ε_r is the dielectric constant of the ternary material, ε_0 is the permittivity of free space and q is the electronic charge.
To compensate the effect of polarization induced positive charge, electrons having a density of $n_s(m^{-2})$ accumulate at the quantum well of the heterointerface. The 2D sheet carrier density, considering the total depletion assumption, is given by [6,7],

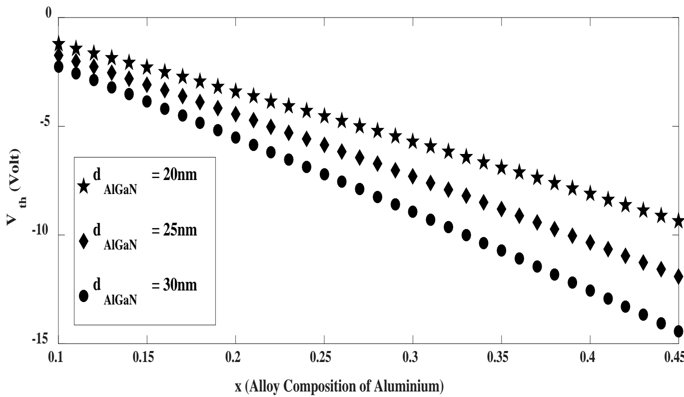
$$n_s(x) = \frac{\varepsilon_r(x)\varepsilon_0}{qd}\left[V_G - V_{th}(x) - \frac{E_F}{q}\right] \qquad (4)$$

Where, V_G is the gate voltage, V_{th} is the threshold voltage and E_F is the Fermi energy.

III. Comparison

In this section, the threshold voltage (V_{th}) and sheet carrier density (n_s) of AlGaN/GaN and AlInN/GaN are varied with respect to gate voltage and alloy composition and are compared to each other. Figures 3, 4 and 5 depict the results of two systems. The discussions on the results are provided in section IV.

A. Threshold Voltage Versus Alloy Composition at Different Barrier Thickness



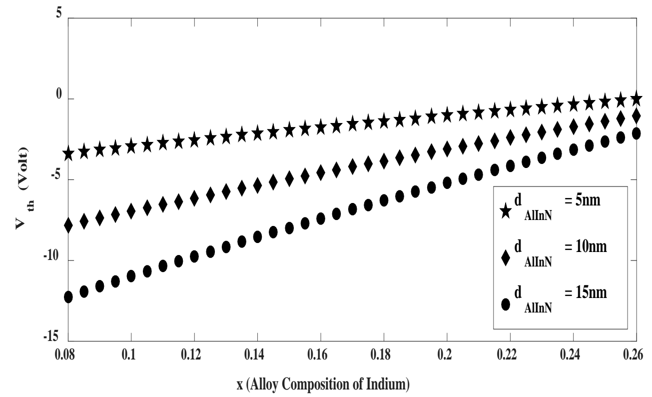
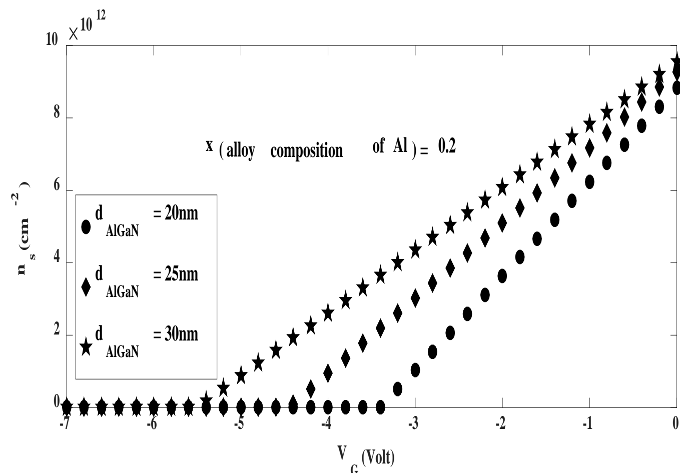


Fig. 3. Threshold voltage versus alloy composition of AlGaN/GaN and AlInN/GaN for different barrier thickness at zero gate voltage.

B. Sheet Carrier Density in 2DEG Versus Gate Voltage



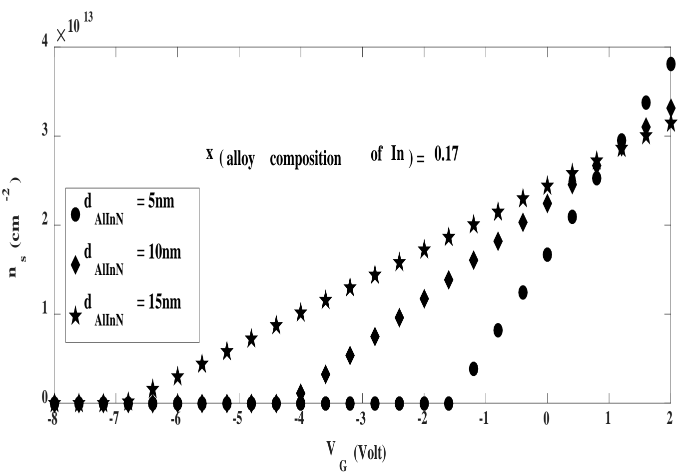


Fig. 4. Two dimensional electron gas density versus gate voltage of AlGaN/GaN and AlInN/GaN for different barrier thickness

C. Sheet Carrier Density in 2DEG Versus Alloy Composition at Different Barrier Thickness

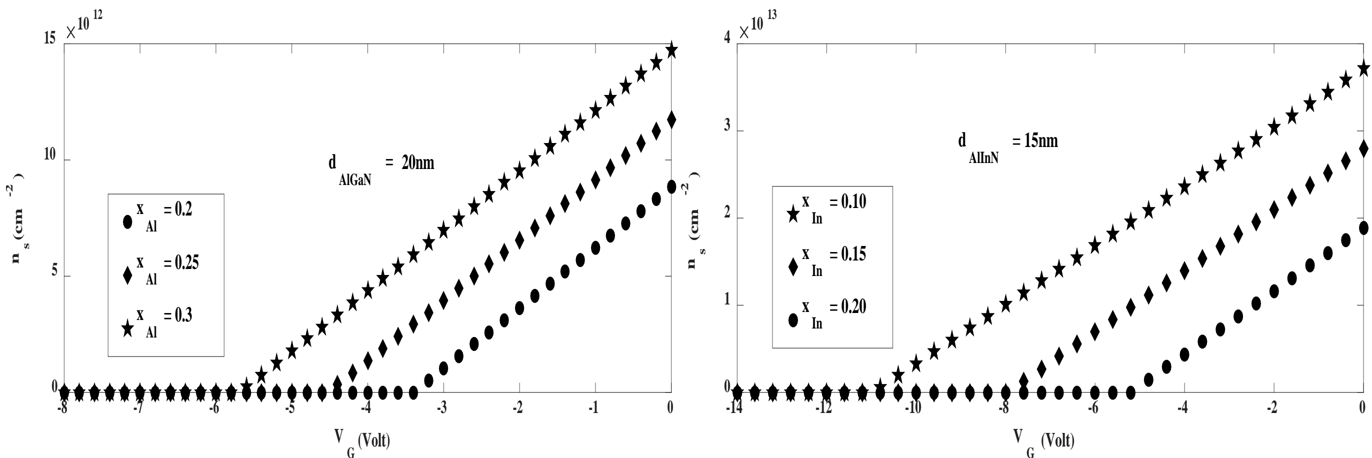


Fig. 5. Two dimensional electron gas versus alloy composition of AlGaN/GaNand AlInN/GaNfor different barrier thickness at zero gate voltage.

IV. Discussions

From Fig. 3 and Fig. 4, it is clear that threshold voltage decreases and the sheet carrier density in 2DEG increases with the increase in barrier thickness of both the devices as the polarization also increase. In Fig. 3 and Fig. 5, we see that for $Al_{1-x}In_xN$ HEMT the threshold voltage increases and the sheet carrier density in 2DEG decreases gradually with the increase of Indium mole fraction whereas the opposite happens for $Al_xGa_{1-x}N$ with the increase of Aluminum mole fraction. This is because the increase of Indium content in $Al_{1-x}In_xN$ alloy decreases the polarization but the Aluminium content in $Al_xGa_{1-x}N$ increases the total polarization. From the figures it is evident that at zero gate bias, $Al_{1-x}In_xN$ HEMT always exhibits larger sheet carrier density than the $Al_xGa_{1-x}N$ HEMT. So, generally $Al_{1-x}In_xN$ HEMTs always provide larger current density during its operation than $Al_xGa_{1-x}N$ HEMTs [6]. On the other hand, due to the lattice matched structure of $Al_{0.83}In_{0.17}N/GaN$, it contains almost no strain in the device. As a result, $Al_{1-x}In_xN$ based HEMTs are much more reliable than the $Al_xGa_{1-x}N$ based HEMTs and its attraction is increasing day by day. The effect of the surface states of varying ionization energy present in the band gap and the different scattering mechanisms due to charged impurities, dislocations in the device, phonon scattering have not been considered in this work. These effects in a GaN HEMT decrease the sheet carrier density which can be avoided by inserting an AlN spacer layer between the barrier layer and GaN.

V. Conclusions

The collection of different parameters and comparison of the 2DEG densities of the $Al_xGa_{1-x}N/GaN$ and $Al_{1-x}In_xN/GaN$ HEMTs have been presented in this paper. From the comparisons by different parametric variations it can be concluded that the usage of $Al_{1-x}In_xN/GaN$ HEMT is much more convenient. The lattice matched $Al_{1-x}In_xN/GaN$ HEMT provides larger sheet carrier density and less strain than the $Al_xGa_{1-x}N/GaN$ HEMT. The n_s of 2DEG calculated in this work can be used to find the capacitance-voltage characteristics, drain to source current density and leakage current of the devices. The present work can be extended by incorporating an AlN spacer layer which would improve the device characteristics significantly.

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