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GATE LEAKAGE CURRENT REDUCTION WITH ADVANCEMENT OF GRADED BARRIER AlGaN/GaN HEMT

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The gate leakage current reduction solution of AlGaN/GaN HEMT *device issue has been addressed in this paper with compositional grading of* AlGaN *barrier layer. This work is also conjugated with the critical thickness limitation of heterostructure material growth. Hence, critical thickness calculation of* AlGaN *over* GaN *has been kept in special view.* 1D *Schrodinger and Poisson solver was used to calculate the* 2DEG *concentration and effective location to use it in the ATLAS device simulator for the predictions. The proposed* $Al_{0.50}Ga_{0.50}N/Al_{0.35}Ga_{0.65}N/Al_{0.20}Ga_{0.80}N/GaN$ HEMT *structure exhibits the leakage current of the order of around* 15 *nA/mm at gate voltage of* 1 *V.*

Keywords: GaN, AlGaN, *HEMT, 2DEG, CRITICAL THICKNESS, GRADED BARRIER, GATE LEAKAGE CURRENT.*

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1. INTRODUCTION

An intense outlook of Gallium Nitride (GaN) and its alloys always create attention towards their application in very high power, high temperature, high frequency devices as well as these devices are also better for high linearity demands. In AlGaN/GaN heterostructure, discontinuity of the spontaneous polarization vector at the AlGaN/GaN heterointerface and the piezoelectric charge due to lattice-mismatch of AlGaN on GaN induces high channel charge to the AlGaN/GaN HEMT. Higher channel charge increases the device's current handling capability. The increasing aluminum percentage in the barrier increases the polarization driven charges thus increases the effective 2DEG concentration in the channel [1]. However there is a limiting factor to the increment of Al molar fraction in AlGaN barrier. This is the critical thickness of AlGaN over GaN. This issue has been addressed in this paper with a solution of graded AlGaN barrier, thus improving the gate leakage current.

2. RESULT AND DISCUSSION

2.1 Critical thickness of AlGaN over GaN

The well known polarization model of AlGaN/GaN HEMT gives the idea that the total polarization charge i.e. the sum of spontaneous and piezoelectric charges (P_n) is proportional to the Al mole fraction (x) [2].

$$P_n = -0.0492x^2 - 0.0593x - 0.034 \quad (1)$$

Hence the HEMTs provide the approximately Al molar fraction proportional 2DEG in the GaN channel layer. When the AlGaN barrier thickness exceeds the critical limit, the interface between the GaN channel and AlGaN barrier suffers from crystal defects. These defects act as the recombination centers and affect the saturation drain current of the device. The interface roughness scattering [3] decreases the mobility of the carriers because of high interface electric field generated from high 2DEG charge density. Another scattering mechanism works in case of high Al composition in barrier, which is known as alloy disorder scattering. This scattering mechanism is also significant for AlGaN/GaN heterostructure because of the high electron effective mass, high sheet charge density and large alloy scattering potential [4].

The critical thickness of AlGaN over GaN has already been computed theoretically and it has also been found out experimentally by various groups. Theoretically, the critical thickness of any lattice mismatched crystal lattice is calculated as in the Matthews Blakeslee model [5] is given by the following two equations:

$$h_1 = \frac{b}{8\pi(1+\nu)f}\left\{\ln\frac{h_1}{b}+1\right\} \tag{2}$$

$$h_2 = \frac{a(1-\nu)^2}{5f^2\pi} \tag{3}$$

where a is the lattice constant, b is the strength of dislocation, ν is the Poisson's ratio and f is the lattice misfit.The values of a, b, ν and f [6] provide a logarithmic curve as shown in Fig. 1, by putting trial and error method to find the thickness h_1 for all the Al mole fraction in AlGaN. The thickness h_1 is important in the sense that the AlGaN layer only feels strain without generating any defect within this limit. The crystal defects due to mismatch are generated within the region inside h_1 and h_2. If the layer thickness exceeds h_2 value the defects propagate to the film surface [6].

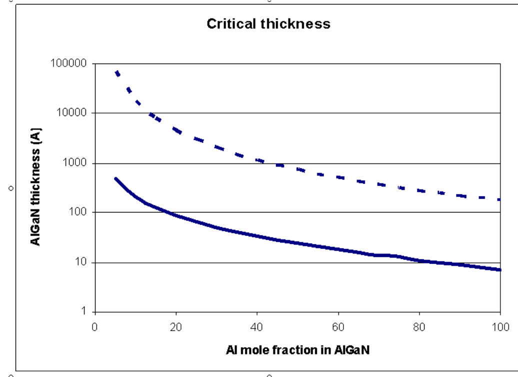

Fig. 1 – *Theoretical critical thickness limit of* AlGaN *over* GaN

The high Al content AlGaN barrier GaN HEMT [7] has already been tried but the main disadvantage is the interface defects due to the relaxed crystal growth of AlGaN over GaN causing the degradation of 2DEG mobility. One

of the solutions to this issue is the grading of AlGaN barrier layer for making up the lattice mismatch. The general approach for this kind of grading is maintained as decreasing Al molar fraction from channel to the surface [8].

2.2 The Device structure and 2DEG carrier concentration

We approached in a different way such that the requirement of high Al in the channel is maintained for the higher 2DEG achievement as well as the gate leakage current can be minimized as much as possible. We propose the device as shown in Fig. 2 which contains a graded barrier with highest Al content at the gate barrier interface.

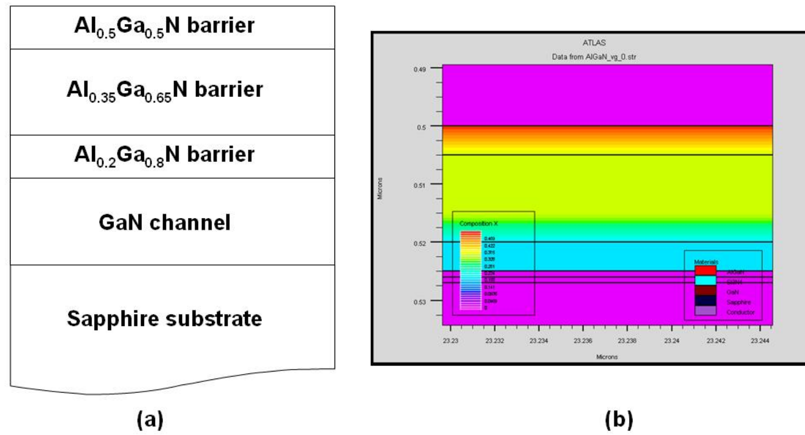

Fig. 2 – *Graded barrier* AlGaN/GaN HEMT *structure* (*a*) *Device structure* (*b*) *Simulated structure*

The topmost $Al_{0.5}Ga_{0.5}N$ barrier layer is having the maximum energy bandgap; hence it must have the better resistivity to the gate current flowing from gate to channel through barrier. We used the ATLAS device simulator to simulate the structures of (i) prevailing non graded AlGaN barrier HEMT, (ii) graded AlGaN barrier HEMT with lowest molar fraction at top and (iii) graded AlGaN barrier HEMT with highest molar fraction at top. The simulation required the most important thing that is the 2DEG charge density which we obtained from the "Bandeng" simulator for 1 dimensional Schrodinger-Poisson solver.

We used Fig. 1 to select the thickness of the AlGaN barrier of different molar fractions such that it stays nearest to the h1 line. So we selected 5 nm $Al_{0.5}Ga_{0.5}N$/15 nm $Al_{0.35}Ga_{0.65}N$/5 nm $Al_{0.2}Ga_{0.8}N$ barrier grading from top surface to the GaN channel.

The conduction energy band diagrams for the above mentioned three structures are given in Fig. 3. It is clearly understood that there are two positions of band bending in the conduction band in the vicinity of AlGaN/GaN interface. Hence, the 2DEG charge distribution must be different as that of conventional HEMT structures. The 2DEG charge distribution is an important factor to be put into ATLAS for device characteristics measurements.

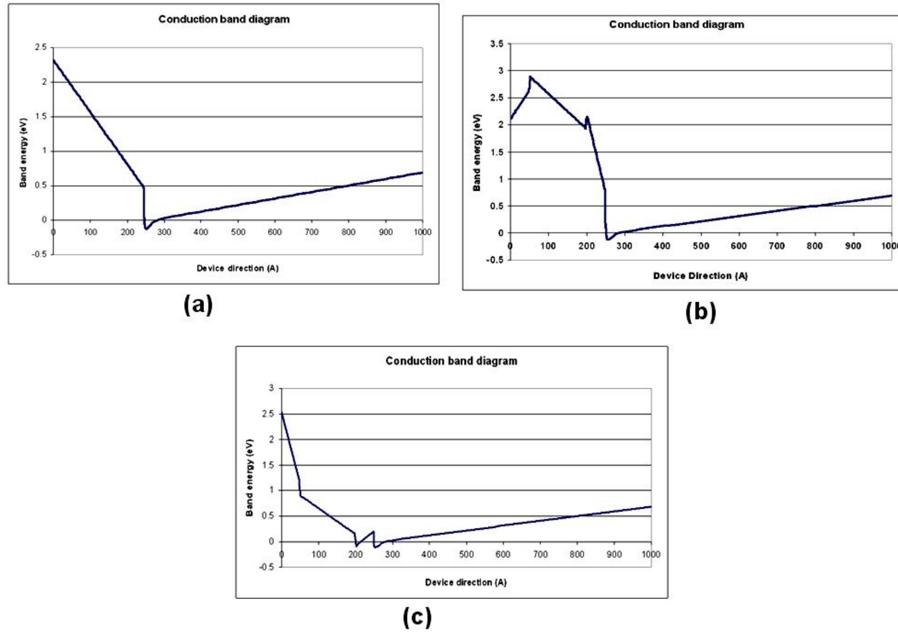

Fig. 3 *– The conduction energy band diagram for* (*a*) *conventional HEMT with* 35% AlGaN *barrier,* (*b*) *graded* AlGaN *barrier HEMT with lower molar fraction at top and* (*c*) *graded* AlGaN *barrier HEMT with higher molar fraction at top*

The 2DEG charge densities for the above mentioned first two structures are calculated by "Bandeng" simulator and it comes around 1.35E13 cm^{-2} and 1.31E13 cm^{-2} respectively. Our proposed structure is having two different 2DEG charge densities of 1.43E12 and 1.12E13 cm^{-2} at two adjacent locations. The total electron density has been plotted by exporting the "Bandeng" data to Microsoft excel format, and the locations of 2DEGs are identified.

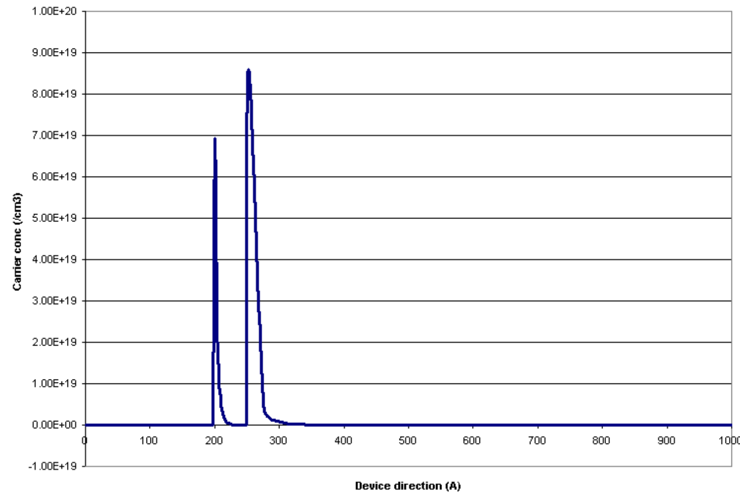

Fig. 4 *– Total electron charge densities in the proposed device*

The important material parameters that have been chosen in both "Bandeng" and "ATLAS" simulators for the best prediction are given below:

Table 1 *– Important material parameters of* GaN *and* AlN

Parameter description	GaN	AlN
Energy gap (eV)	3.400	6.200
Dielectric constant (rel. units)	10.400	8.800
Electron in plane effective mass (m0)	0.200	0.260
Heavy hole in plane effective mass (m0)	1.650	2.580
Light hole in plane effective mass (m0)	0.150	0.270
In-plane lattice constant (nm)	0.319	0.311
Stiffness constant C13 (Gpa)	105.000	115.000
Stiffness constant C33 (Gpa)	395.000	38.000
Piezoelectric constant e33 (C/m2)	0.650	1.550
Piezoelectric constant e31 (C/m2)	-0.330	-0.580
Spontaneous polarization (C/m2)	-0.029	-0.081
Nc300	2.07E+18	6.24E+18
Nv300	1.16E+19	4.88E+20
Affinity	3.500	1.935
Donor ionization energy (eV)	0.013	0.013
Acceptor ionization energy (eV)	0.170	0.750

2.3 Drain current and Gate current simulation

There are a lot of process techniques to minimize the gate leakage current in AlGaN/GaN HEMTs. Mainly the recessed gate technique [12], adjustment of the V-III ratio during AlGaN growth [9], oxygen plasma treatment of fabricated HEMT [10], and oxide filled MESA isolation [11] etc. have contributed towards achieving less gate current in AlGaN/GaN HEMT.

Our proposed structure that is the graded AlGaN barrier with the highest Al mole fraction at the top is simulated for verifying the gate leakage current. The device has been chosen with the field dependent mobility model, lattice heating model etc. [13] for the best predictions.

The simulation of output current results in a maximum drain current of 500 mA/mm in case of the conventional HEMT structure. The incorporation of graded barrier lowers the maximum drain current to around 60 mA/mm. This is because of the decreased 2DEG carrier concentration in the AlGaN/GaN interface. However, there is technique of inserting AlN interlayer at the interface of GaN and AlGaN, thus increasing the mobility as well as carrier concentration. The high bandgap AlN decreases the alloy disorder scattering along with it screens the carriers from the AlGaN barrier to decrease the alloy scattering. The proposed structure of graded barrier with highest Al molar fraction at the top, gives maximum drain current greater than that of prevailing graded barrier (with lowest Al molar fraction at the top) structure. This may be due to the double 2DEG carrier concentration at the interface.

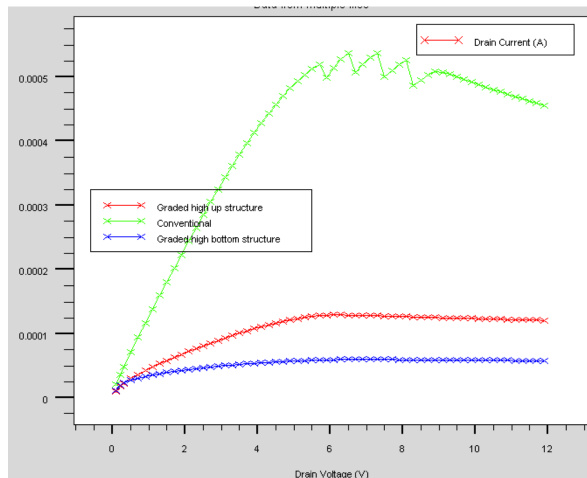

Fig. 5 *– Drain current vs drain voltage for three different structures*

The most important noticeable thing is that the gate current with a gate voltage of +1V for both the conventional and graded (with lowest Al mole fraction at the top) structure has comparable value in the range of 25 – 30 μA/mm. In case of our proposed structure, the gate current with the same gate voltage value is in the range of around 10 – 15 nA/mm.

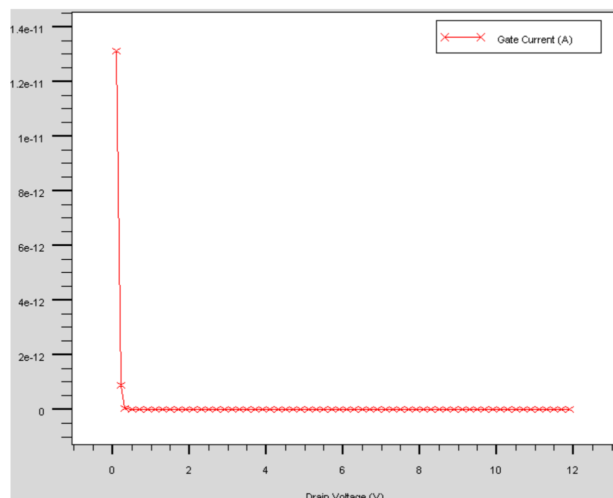

Fig. 6 *– Gate current vs drain voltage for proposed graded barrier (with highest* Al *at top)* AlGaN/GaN HEMT *structure*

The advancement of leakage current reduction comes from the fact of using highest bandgap AlGaN layer at the top. Although the maximum drain current is lower comparable to the conventional HEMT structure, the future strategy of the present work will be the incorporation of AlN interlayer in between GaN channel and AlGaN barrier. Due to the high bandgap of AlN, it can also be predicted that the gate leakage current may be lowered again.

3. CONCLUSION

We have successfully simulated the $Al_{0.50}Ga_{0.50}N/Al_{0.35}Ga_{0.65}N/Al_{0.20}Ga_{0.80}N/GaN$ HEMT structure by ATLAS device simulator for achieving gate leakage current. We used Mathew's model for critical thickness calculation of AlGaN thin film over GaN. We also used the 1D Schrцdinger and Poisson solver "Bandeng" for extracting 2DEG charge carrier density and its location. Finally we conceptualized the insertion of AlN interlayer in the same device for achieving more current density and carrier mobility.

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