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Analytical Study of Temperature Effect on P-MODFET Using Quantum Band Distribution in Gan Channel on Sapphire Device

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ABSTRACT
This paper based on the simulation result carried out to observe on temperature effects on AlGaN/GaN heterostructure. The MODFET device is considered taking into account the channel, and delta doped quantum barrier, and ionized scattering, which reduces the mobility from ideal case. Results shows that the operating temperature in normal situation should be such that it avoid self heating effects, taking into account quantum nature of MODFET. Thermal mobility increases due to ionized donors. Mid range we observe fall in mobility psudomorphic character and in Low range decrease in mobility phonon scattering.
Index Terms— AlGaN / GaN Psudomorphic, Modfet, delta doping, ionized donor, temperature, mobility, quantum confinement. gate implant.

1. INTRODUCTION

The present state of technology focus on utilizing heterostructures for electo-optic devices as well as communication systems, radar systems and novel bio-sensors. Current semiconductor technology uses silicon or gallium arsenide (GaAs) for low frequency switching applications. Silicon devices are easily processed, cost effective, however this technology does not allow for high frequency without the introduction of noise.

Wide bandgap semiconductors material, particularly AlGaN / GaN and other material systems having wide bandgap can provide a feasible solution for high power and high frequency applications [1]. GaN is a direct bandgap material which has led its application in lasers and LEDs. But it has its own set of unique challenges in fabrication of high performance Modulation Doped Field Effect Transistors (MODFET). A quick glance at the following table (1) shows that inspite of these challenges AlGaN / GaN has many favorable qualities specially thermal conductivity which is even better then Si. It can be effectively utilized specially for MODFET devices.

Larger power handling capabilities of the devices are determined from the higher breakdown voltage. The higher thermal conductivity allows generated heat to be

removed and thus allowing for higher power operation for longer durations. The higher saturated electron velocity results in a higher operating frequency.

The current issues with AlGaN/GaN are related with manufacturing and thermal management. This paper will look at improving thermal management by studying the effects of different substrates on the operation of AlGaN/GaN MODFETs. The improved thermal management will support better operation and improved reliability.

The AlGaN/GaN hetero-structure is used to take advantage of the two-dimensional electron gas (2DEG). The interface of the AlGaN/GaN materials creates piezoelectric and spontaneous polarization effects using an undoped hetero-interface. The result is a high density electron gas with a high mobility. This modulation doping for a channel of high mobility electrons contributes to naming the device as the modulation doped field effect transistor (MODFET), selectively doped hetero-field-effect transistor (SDHT), and the

two dimensional electron gas field-effect transistor (TEGFET) device.

2. DEVICE STRUCTURE

The typical GaN structure forms a crystalline Wurtzite lattice, but under certain growth conditions can form a zinc-blend structure.

The material issues for growing GaN have to look at lattice matching and use of a transition material to the substrate. Typical methods for growing GaN are using MBE or MOCVD.

The material properties are important in determining the strain in GaN films. The factors affecting the temperature and strain are examined by Freeman [2] and Kisielowski et al. [3] [4].

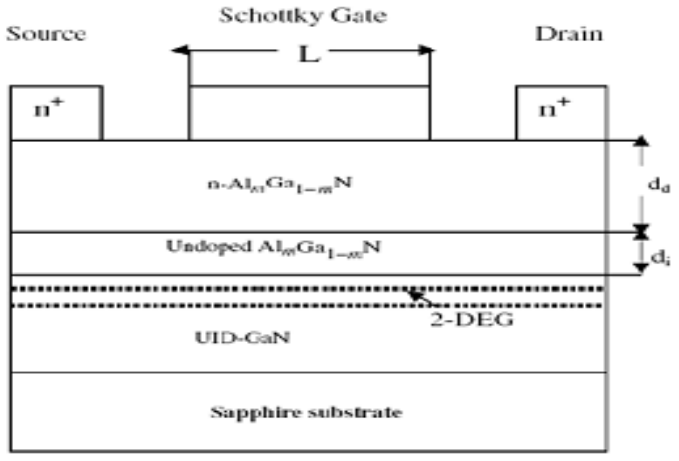


Fig. 1. Modfet Structure

Table 1: Comparison of properties of Material System [5].

	Si	GaAs (AlGaAs/InGaAs)	InP (InAlAs/ InGaAs)	4H SiC	GaN (AlGaN/ GaN)
Bandgap (eV)	1.1	1.42	1.35	3.26	3.49
Electron Mobility (cm^2/Vs)	1500	8500	5400	700	900
Saturated (peak) electron Velocity ($x10^7$ cm/s)	1.0 (1.0)	1.0 (2.1)	1.0 (2.3)	2.0 (2.0)	1.5 (2.7)
2DEG sheet electron density (cm^{-2})	NA	$<4x10^{12}$	$<4x10^{12}$	NA	$1\text{-}2x10^{13}$
Critical breakdown field (MV/cm)	0.3	0.4	0.5	2	3.3
Thermal conductivity (W/cm-k)	1.5	0.5	0.7	4.5	>1.7
Relative dielectric constant ($\square_r$)	11.8	12.8	12.5	10	9

For the typical AlGaN/GaN MODFET the device will have a Gallium face to the thin-film AlGaN. The face is dependent on growth conditions and material it is grown on. With the sapphire substrate it can be directly grown on and results in a Gallium face with the Nitride face bonding to the sapphire. The material issues for growing GaN have to look at lattice matching and use of a transition material to the substrate. In our study we have consider modeled Ga face with N face to α-Al_2O_3 substrate as standard design parameter.

Vargaftman et. al. [6] worked on the temperature dependence of the GaN energy gap varying 72 meV over a range of 0 to 300^o Kelvin. This work uses values and parameters based on averages and best value numbers which is also used earlier by Freeman et. al. and other published papers. So these values are standard.

The other main material in the heterojunction is AlGaN which is a ternary alloy. The energy gap for the material will be based on the composition of the alloy. The alloy composition is controlled by $Al_xGa_{1-x}N$ in which x is the percentage of Aluminum concentration. This becomes an important factor in the operation of the MODFET device. The concentration affects the amount of band bending that occurs in the conduction band and therefore affects the operation of the device. Also the material thickness will have the effect on the operation by changing the stress in the thin film as well as causes stress induced polarization (P_{sp} & P_{pz}).

The Schottky Gate is the common metal gate contact for III-V MODFETs. The material chosen for the Schottky gate varies with transistors designs. The gate metal is Ti, Al, Ni, or Au or an alloy composed of two or more of these materials. The alloy

composition and the choice of deposition method of the alloy will have an effect on the Fermi level in the material. The basic Schottky gate is used for the modeling in present work.

The last material component is the substrate on which the device sits and provides mechanical support. The substrate is the material in which the devices are fabricated. For GaN technology the typical substrates are sapphire or silicon carbide (SiC). We choose sapphire for our model. Instead of using very large number of layers (20-40), we have selected Pseudomorphic MODFET structure, because it is developed by changing material layers, with each subsequent layers is of different composition to bring lattice mismatch below critical lattice mismatch (Lc).

3. EQUATIONS AND SIMULATION PARAMETERS

The goal of the modeling was to analyze the thermal effect on mobility w.r.t. to ionized donors and to produce a model that can validate the characteristics seen by the actual device. The structure was designed in TCAD, and is as shown in fig. 1. To define mobility equations two possible options are either to work with Freeman's equation or with Albrecht equation [7]. We have taken Albrecht equation which uses modified monte-carlo method for electron transport characteristics on GaN. Also this equation is suitable for high temperature simulation without much computational requirement. It can be written as

$$\frac{1}{\mu} = a\left[\frac{N_I}{10^{17}\ cm^{-3}}\right]\ln\left(1+\beta_{CW}^2\right)\left[\frac{T}{300\ K}\right]^{-3/2} + b\left[\frac{T}{300\ K}\right]^{3/2} + \frac{c}{e^{(\phi/T)}-1}$$

Here GaN–AlGaN material family specific co-efficients used in simulation are:

a=2.61x10^{-4} v-s-cm^2

b= 2.9x10^{-4} v-s-cm^2

c= 1.7x10^{-2} v-s-cm^2

$$\phi = \frac{h\,\varpi}{2\pi\,k\beta}\ ,$$

$$\beta_{CW}^2 = 3\left[\frac{T}{300\ K}\right]^2\left[\frac{N_I}{10^{17}\ cm^{-3}}\right]^{2/3}$$

N_I = ionized donor concentration,

The significance of β is that it controls the curvature of the mobility Vs Temperature curve. Inside the channel the quantum band distribution and shifting of Fermi level i.e. its deviation due to temperature give the alteration in mobility. So for the selection of proper operating condition and better performance of the device such study is very advantageous [8].

4. RESULTS AND DISCUSSION

As the expression of mobility consist of three terms. We will first obtain the effect of temperature on each and every term present in expression and then find variation of total or net mobility value with temperature. So let part A is the first set of term of the equation, which is affected by temperature, material parameters and also by the ionized donor concentration. For this investigation of mobility versus temperature, ionized donor concentration is kept constant at a value $1e^{16}$ /cm^3.

$$PartA \;\Rightarrow\; a\left[\frac{N_I}{10^{17}\,cm^{-3}}\right]\ln\left(1+\beta_{cw}^{2}\right)\left[\frac{T}{300\;K}\right]^{-3/2}$$

Essentially with part A we find that mobility increases with temperature leading to uncontrolled thermal runaway as shown in figure 2.

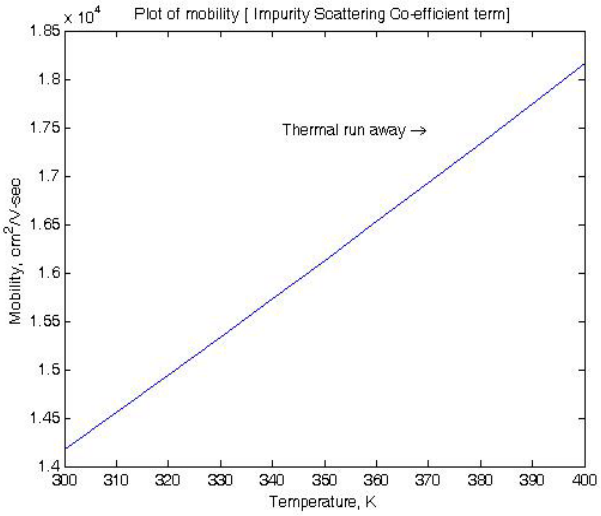


Fig 2. Plot of Part C Mobility comp. [impurity Scattering comp.] Vs T

Next, the simulation output of Part B of the equation, acoustic phonon limited mobility is plotted as mobility versus temperature. It represents elastic scattering of

carriers in the device. This implies that electrons dissipate energy only at acceleration above acoustic phonon excitation. Fig. 3 shows the result of part B [9].

$$PartB \quad => \quad b\left[\frac{T}{300\ \ K}\right]^{3/2}$$

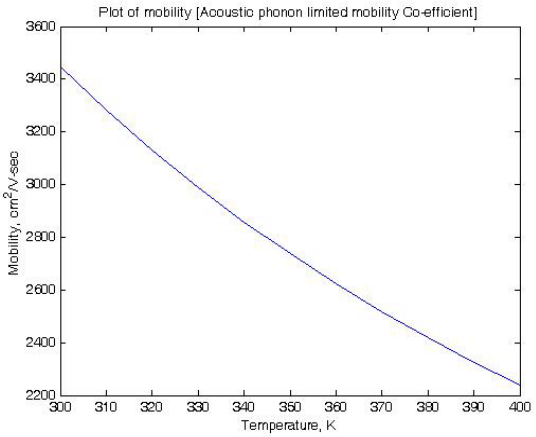
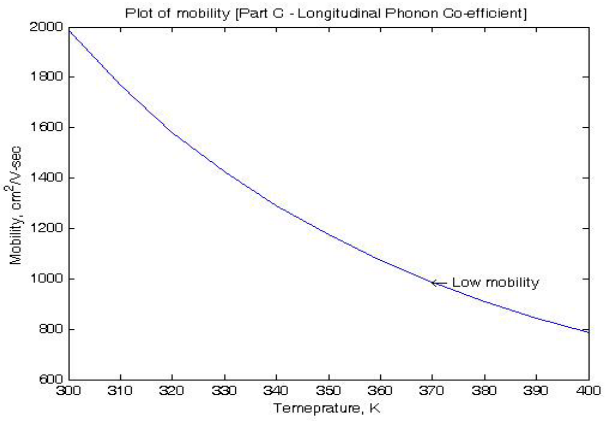


Fig. 3 Plot of Part B Mobility comp. [acoustic Phonon Scattering] Vs T

In Simulation output Part C (fig. 4) of the equation, longitudinal optical phonon limited mobility, plotted as mobility versus temperature causes further mobility droop, now the net effect of B and C part of equation is to bring the mobility down to realistic device values. Hence the final cumulative result which accounts for thermal runaway, acoustic phonon, and optical phonon is given in fig. 5.

$$PartC \quad => \quad \frac{c}{e^{(\phi / T)} - 1}$$



· Fig. 4 Plot of Part C Mobility comp. [Longitudinal Phonon Scattering] Vs T

In equation, Part B and Part C are dominated by temperature parameter. The large net decrease in mobility is due to Part C, LO Phonon, and self heating effect as seen in fig. 5, which give the net total effect of all the parts on the mobility of AlGaN / GaN structure.

The doping at moderate levels was simulated for different range of 0.1×1e17 to 2.0×1e17 and it was found that mobility decreased substantially, with increasing ionized donor concentration .

5. CONCLUSION

In device engineering this analysis is crucial in proper dose selection as well as selecting compositional value for ternary alloys to be fabricated on sapphire substrate. Higher doping leads to degenerate band bending overlapping of sub-bands, with temperature rise. The working temperature should be such as to avoid self heating effects, taking into account quantum nature of MODFET. Thermal mobility increases due to ionized donors. In Mid range the fall in mobility observed due to psudomorphic character. In low temperature range the decrease in mobility is due to phonon scattering. Thus the results of this work enable a device engineer to properly tailor the fabrication steps so as to develop a functional, efficient and reliable working device. In embedded application such as bio-sensors the device engineering aspect of this work will lead to highly efficient P-MODFET design with better thermal characteristics.

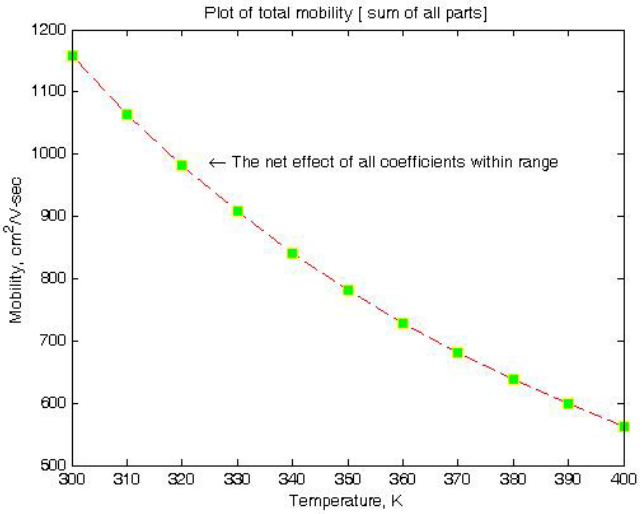


Figure 5.

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