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Structural Reliability of AlGaN/GaN High Electron Mobility Transistors

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Abstract

The GaN devices have significant advantages in terms of power density, characteristics and voltage range based on conventional compound semiconductors or Silicon. The aim of this work is to observe and analyze the results of 3D Structural Reliability of AlGaN/GaN HEMT structure. The work is mostly focused on the coupled behavior of Aluminum Gallium-nitride (AlGaN)/ Gallium-nitride (GaN) high-electron- mobility transistors (HEMTs). The modeling have to be performed considering to the various coupled properties like piezo- electric effect, inverse piezoelectric effect, mechanical stress, Joule heating effect etc. The Structural Reliability with modeling of AlGaN/GaN HEMTs is performed using ANSYS and MATLAB simulation software.

Keywords: *GaN, HEMT, AlGaN, AlN, SiC*

INTRODUCTION

Gallium-Nitride (GaN) is a very hard and mechanically stable material with large heat capacity. It is a direct wide- band gap, compound semiconductor and due to its physical properties and is considered as one of the most promising element for building high-power and high-frequency active devices. The technology can deliver considerably superior performance as compared to broadly employed silicon or III-VI solutions. The key advantages of GaN technology can be outlined as follows:

High Power density capability that is due to higher charges (i.e. than GaAs) which result in higher current (1 to 1.4 A/mm). Accordingly reported power densities are with an order higher than that of GaAs based devices. It has been discussed; GaN is ideal for high current and high power applications because it has a high breakdown field, electron mobility and saturation velocities. In addition, AlGaN/GaN junctions facilitate the formation of a two Dimensional electron gas due to polarization fields, conduction band discontinuity and GaN has a relatively high thermal conductivity of around 250 W/m/K. The large sheet charge density combined with the high mobility of GaN (2000 cm2/Vs) allows for high speed and high frequency operation. Combined with the large breakdown fields, large voltages and large powers can be obtained in AlGaN/GaN hetero structures. These properties make AlGaN/GaN device systems ideal for high power RF amplifiers, with applications such as RADAR and communications. A typical HEMT device structure is shown in Figure 1. There are many variations of this configuration, including different substrate materials (such as Si, Sapphire and Diamond) different stacking orders of GaN and AlGaN layers including various device capping structures, addition of other layers for further control of the 2DEG density and different Ohmic and Schottky contact materials [1].

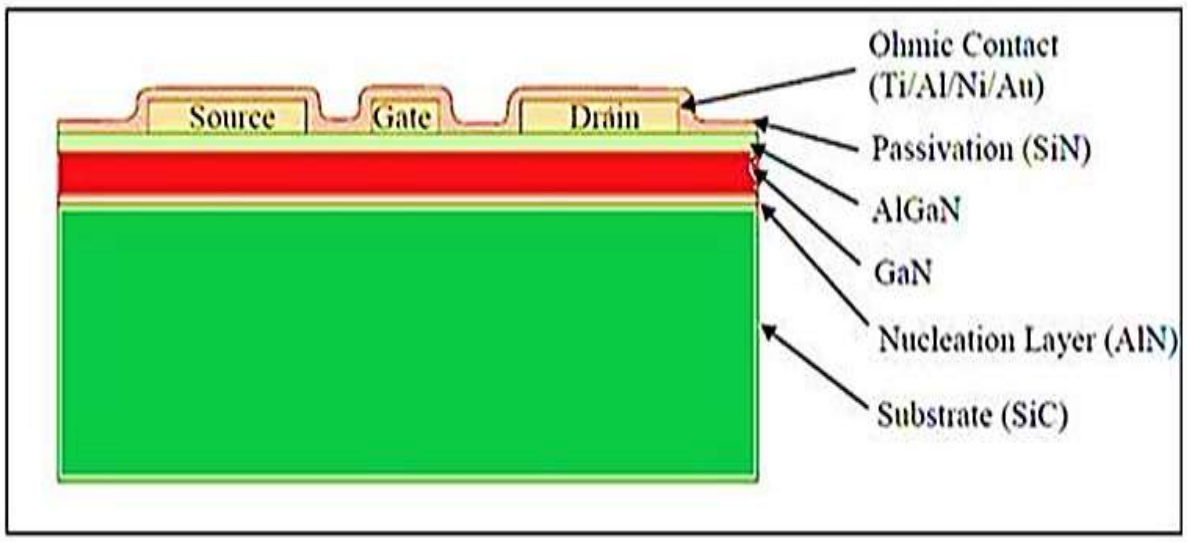

Figure 1: *A Typical HEMT Device (Not to scale) [1].*

Table 1: *Semiconductors Material Properties Figure of Merit [2].*

Material Property	**GaN**	**4H-SiC**	**GaAs**	**Si**
Band gap energy Eg (eV)	3.49	3.25	1.43	1.11
Breakdown electric field Ebr(106 V/cm)	4.0	3.5	0.4	0.25
Saturated electric field Esat (103 V/cm)	15	25	3	8
Electron mobility μ- (cm2/Vs)	2000	700	8500	1350
Hole mobility μ+ (cm2/Vs)	300	120	330	450
Saturation electron velocity *Vsat* (107 cm/s)	2.5	2.1	1.3	1.0
Maximum drift velocity υd (107 cm/s)	3.0	2.0	2.0	1.0
Thermal Conductivity κ (W/cmK)	1.5	4.9	0.56	1.5
Maximum temperature T(°C)	700	600	300	300
Relative dielectric constant εr	9.0	10	12.5	11.9
Baliga figure of merit (BFOM = $\varepsilon*\mu*Ebr3$)	24.6	3.1	9.6	1.0
Johnson figure of merit (JEM = $Ebr*vsat/2*\pi$)	80	60	3.5	1.0

Sapphire (Al_2O_3): Of the commonly employed substrates, sapphire has the largest lattice mismatch with GaN. Depending on their relative orientation to each other, the mismatch is between 14% and 23%. It is widely used; however, the main

disadvantage of this material, however, is has poor thermal conductivity [3].

Silicon: Si possesses an acceptable thermal conductivity and is reasonably priced. The lattice mis-match with GaN is 17% and its lattice constant is larger than that of GaN. Hence, GaN grows with a tensile stress, which leads to creation of crystal defects, which reduce the performance of the device [3].

PROPERTIES OF GAN HEMT

Electrical Properties

Substrates: The most widely used substrates in the GaN technology are Si, sapphire (Al_2O_3) and SiC. The advantage of the diamond is its high thermal conductivity, while the use of GaN reduces the density of impurities. One of the main task of a substrate is to conduct and dissipate heat generated considered to be equal to Joule heat H = j .E [3].

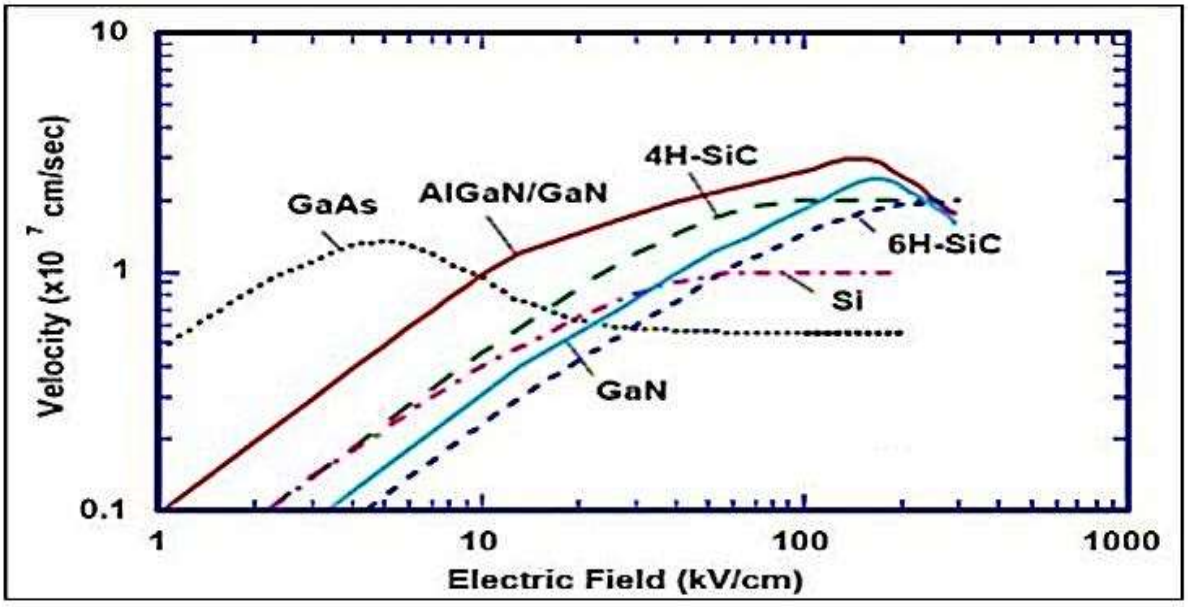

Figure 2: *Electric Field vs. Velocity [4].*

A semiconductor material for high frequency and high output power applications should have a wide energy gap, a low value of dielectric constant, high thermal conductivity and high breakdown field. Wide band-gap provides an ability to support high internal electric fields before breakdown occurs and also results in improved radiation resistance [4]. The dielectric constant indicates the capacitive loading capability of a transistor and affects the device terminal impedance. The dielectric constant of wide band-gap semiconductors is about 20% lower than the conventional semiconductors which permit them to be about 20% larger in area for given impedance. Increased area allows for higher RF currents and therefore higher RF power. The thermal conductance of the material defines the ease with which power can be dissipated from the device which, otherwise would result in higher chip.

Piezoelectric Polarization: The HEMT polarization electric field is mainly dependent on AlGaN/GaN crystalline growth face (Ga-face or N-face), AlGaN thickness and increased aluminium content in AlxGa1-xN layer. It is the sum of the piezoelectric polarization field of AlGaN layer and the resulting spontaneous polarization field of AlGaN/GaN layers, respectively. Figure 2 illustrate a schematic of the crystal structure grown of GaN layer, Ga-face (0001) and N-face (000$\bar{1}$) respectively. Most AlGaN/GaN HEMTs are grown on Ga-face (001) [1].

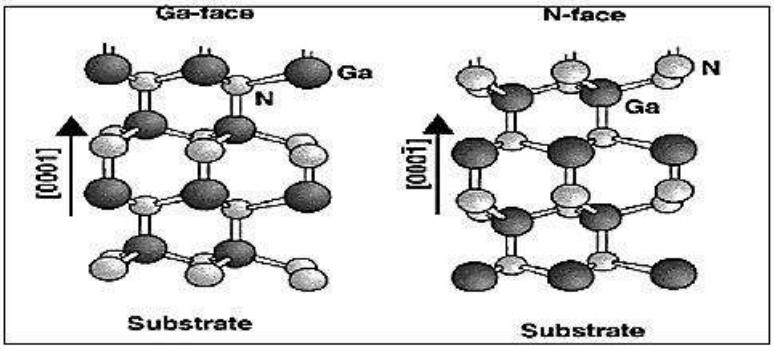

Figure 3: *Schematic of the Crystal Structure of the Growth Orientation, Ga-face N-face GaN [4].*

The piezoelectric polarization effect (*PPE*) is induced by the distortion of the crystal lattice due to the lattice constant difference between AlGaN and GaN. It results from the tensile stress caused by the growth of the strained AlxGa1-xN on GaN (Ga-face). Due to the large value of the present piezoelectric effect a large sheet of charges results at both faces of AlGaN layer as;

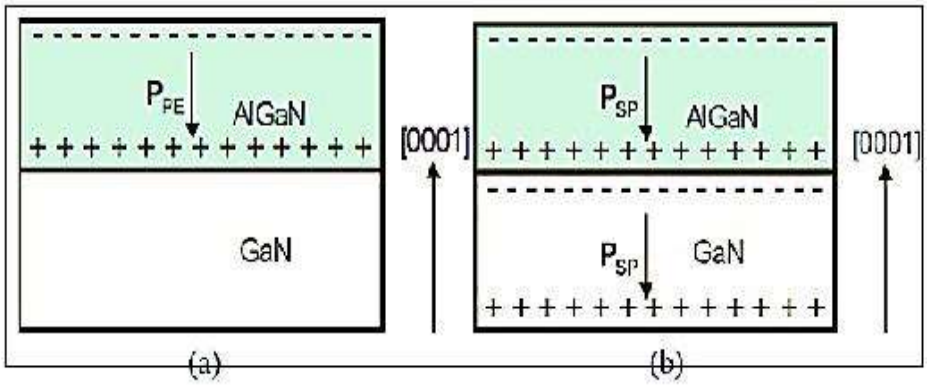

Figure 4: *Polarization Electric Field for a Strained AlGaN Crystal Grown on Relaxed GaN Crystal (Ga- face crystal growth) (a) Large Piezoelectric Electric Field Induced Charge Sheet in Strained AlGaN (b) Spontaneous Electric Field Induced Charge sheet in both GaN and AlGaN crystals [6].*

Spontaneous Polarization: The spontaneous polarization (*PSP*) for GaN and AlN are pointing towards the substrate for Ga-face hetero structures. It results from the built-in static electric field in an unstrained crystal. It appears when the crystal lacks inversion symmetry and the bond between two atoms is not purely covalent. The electron charge cloud shifts towards one atom along the direction in which the crystal lacks inversion symmetry. The net positive charge is shifted to one face of the crystal, and a net negative charge is created in opposite face. In Figure 5 (b), an illustration of the spontaneous polarized electric fields and equivalent induced sheet charges are present for GaN and AlGaN crystals (Ga-face crystal growth).

The piezoelectric in the strained AlGaN layer and spontaneous polarization in AlGaN/GaN have the same orientation (i.e. Ga-face crystal growth orientation). Since polarization field in the AlGaN layer is higher than the GaN buffer layer the presence of a polarization field. Discontinuity at the AlGaN/GaN interface will induce a very high positive sheet charge.

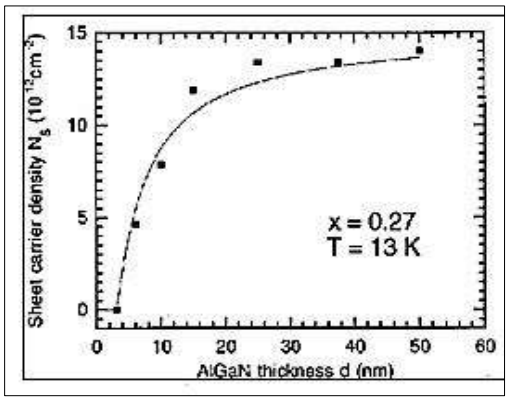

Figure 5: *Dependence of the 2DEG Sheet.*

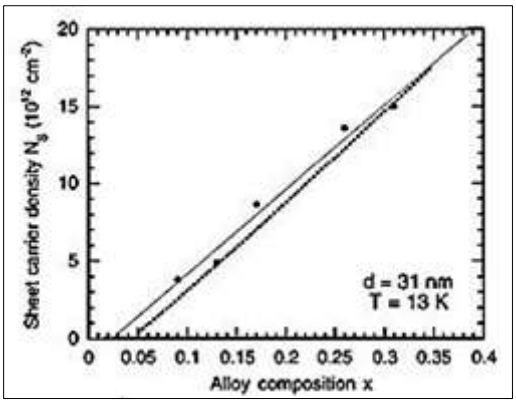

Figure 6: *Dependence of 2DEG sheet density on density on AlGaN layer thickness [4]. Al mole fraction (x) in AlxGa1-xN material.*

It causes voltage delay in the device operation and restricts fast drain-current and voltage excursions in HEMTs RF output power. In the following, the dominant trapping mechanisms in HEMTs are presented, as illustrated in Figure 7.

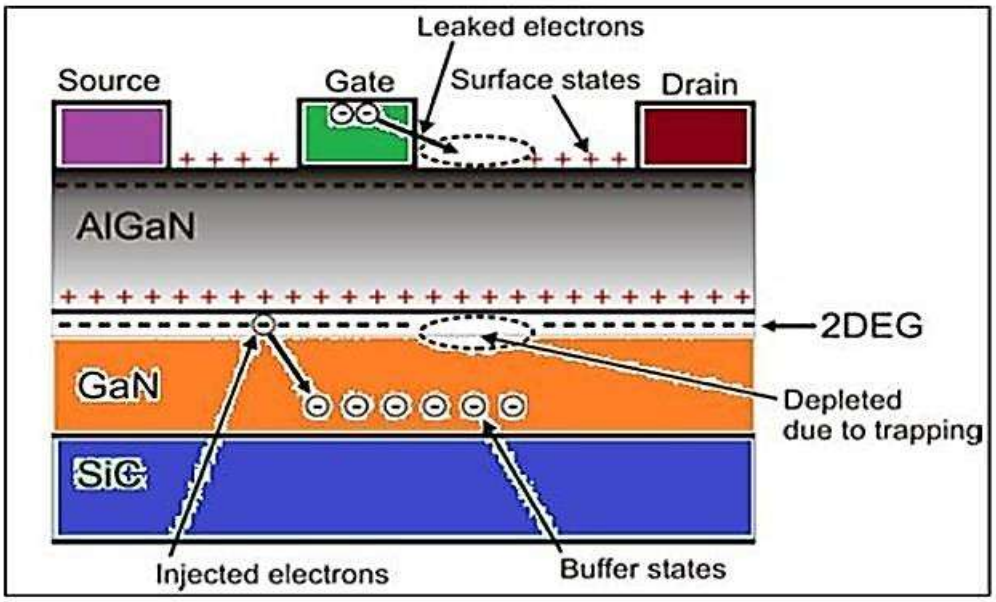

Figure 7: *AlGaN/GaN HEMT Structure Illustrating Polarization, Trapping Mechanisms (surface, buffer), and Buffer Current Conduction with Their Impact on 2DEG Electrons [5].*

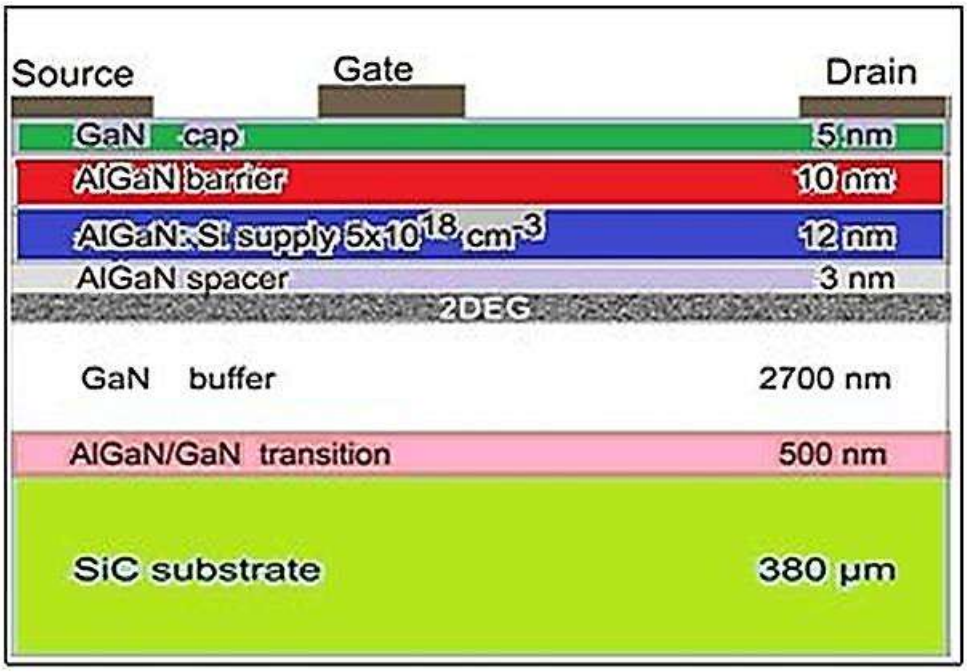

Figure 8: *AlGaN/GaN HEMT on SiC the AlGaN/GaN Structure Topology [2].*

HEMT topology is presented in Figure 8: The layer structure is generally composed of substrate layer, the nucleation layer, buffer, carrier supply, barrier, and cap layers.

RELIABILITY CONCERNS

Thermal*:* As AlGaN/GaN devices can operate at exceptionally high power densities for example over 30 W/mm. The overall power is large and as a result considerable heat generation in the active region becomes a crucial issue in terms of device performance and reliability. Considerable self-heating negatively impacts transport properties. The electron mobility and drift velocity reduce with increasing temperature mainly due to enhanced polar optical phonon scattering that in turn decreases the device output current and operational frequency (i.e. a decrease in DC and RF performance).

The Current saturation that occurs at an applied electric field that is relatively much lower than the electric field required (~200 kV/cm) for drift velocity of electron to saturate in bulk region of Gallium Nitride. The self-heating effect has also been observed in the current voltage characteristics, i.e., negative DC output conductance at large V_{ds} (voltage between drain and source) conditions.

Structural: In addition, mechanical stress inherent is in the AlGaN layer of AlGaN/GaN HEMTs due to the hetero-epitaxial growth and other processing methods that can negatively impact device performance. The 2-DEG in AlGaN/GaN HEMTs is responsible for the high current capability and is created in response to the large spontaneous/piezoelectric polarization in AlGaN which causes electrons to drift towards the hetero-interface and aggregate into the quantum well. The electronic performance of these devices is mainly limited by the sheet carrier density and electron mobility in the 2-DEG. These electrical attributes are a vital function of the mechanical strain built in the Aluminium Gallium Nitride layer. For example, imposing tensile in-plane strain in the Aluminium Gallium Nitride layer rises the piezoelectric field thus results in higher 2-DEG sheet carrier density in Ga (Al)-face hetero structures.

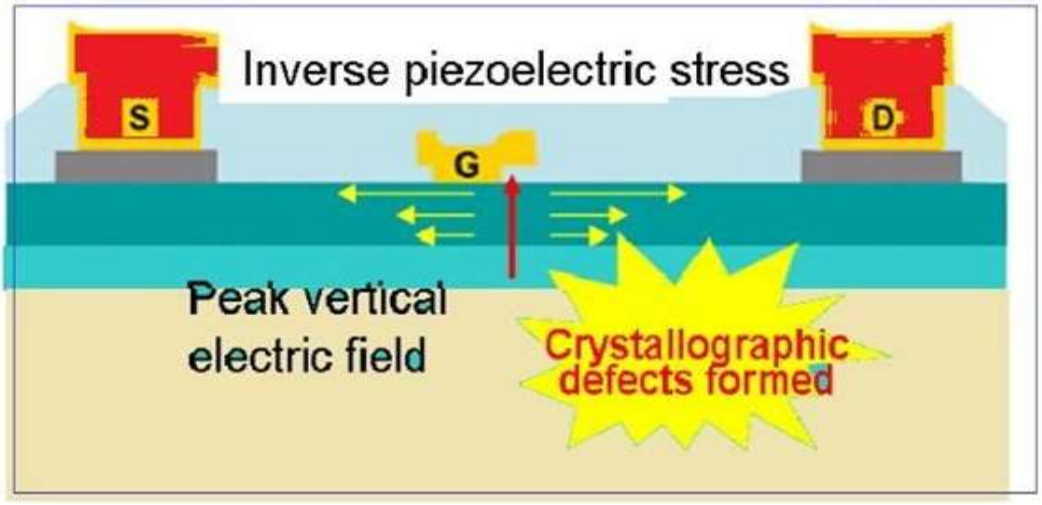

Figure 9: *AlGaN/GaN HEMT Degradation Driven by the Inverse Piezoelectric Effect [6].*

Device Configuration **and** Dimensions: As shown in Figure 1, HEMT illustrations are typically shown in 2D format. 3D effects in a thermal HEMT model can be very significant and should not be ignored. Thus it is crucial to first interpret the High Electron Mobility Transistor dimension nomenclature used in literature as follows:

- "Length" signifies the left-to-right dimension (e.g. the space between source and gate varies in length).
- "Width" signifies the dimension pointing into the page; HEMT geometries do not change (i.e. uniform) with respect to this dimension.
- "Thickness" signifies the top-to-bottom dimension (e.g. as you travel Through the "thickness" direction, you pass through the AlGaN, GaN, and substrate layers) [7].
- The two GaN and substrate, 3-µm thickness of GaN, the substrate is made of sapphire (Al2O3) and the device active area width is50 µm. Using the GaN-to-substrate thickness of 3 µm gave a resultant substrate thickness of 390 µm.

FINITE ELEMENT RELIABILITY ANALYSIS

Components for Reliability

Basic Random Variables and Load Effects: It is describing the randomness in geometry, material parameters and loading. It supposes that one of the discretization schemes described. The state of the structure is determined by load effect quantities, such as displacements, strains, stresses, measures of damage, etc. to realization of χ. Let S denote a vector of any above effects whose values enter in the definition of the failure of the system. These two vectors are formulated by the mechanical transformation which is defined in simple situations in an algorithmic sense. A finite element computer code is an example of this method.

Research Methodology: The overall modeling approach for this thesis report is shown a flowchart in Fig-6. Fulfilling what was outlined in the thesis statement, the developed computer model will be able to perform not only a coupled thermal-structural-piezoelectric analysis, but will also be able to isolate the contribution of each physics subset and analyze how it ends up affecting the others when becoming coupled with them. This will be made possible by the many useful post-processing features of ANSYS which conveniently allows the visualization of both the location and value of maximum temperature and stress/strain. The user at any time can choose to momentarily deactivate a certain physics subset in order to see the contribution of another. In this

way it is probable to distinguish the contribution of stress/strain.

Scope of Work: The design of a Gallium Nitride - based power amplifier is remarkably different from the standard GaAs-based one in a perception that both the input and output impedance transformation ratios are substantially reduced for the same output power rating. With a gate length of 0.6 m, maximum drain current of 1 A/mm and a breakdown voltage of 80V, an Aluminium Gallium Nitride / Gallium Nitride High Electron Mobility Transistor naturally depicts an input capacitance of 2.7 pF/mm. Generally power amplifiers are typically the majority power-consuming building blocks of radio frequency transceivers.

Therefore, high-efficiency MMIC power amplifiers are desirable for reduced DC power consumption, simple thermal management, and longer operating lifetime for high-efficiency amplifier configurations. The class-E amplifier has a maximum theoretical efficiency of 100, MESFETs and GaN high-electron mobility transistors (HEMTs). The rate of advancement in the power density and total power available from AlGaN/GaN HEMTs has been astonishing. This has enlarged confidence in considering GaN HEMTs for commercial and Department of Defense applications, more willingly relatively than later.

AlGaN/GaN HEMT Models

Using the Sapphire (Al2O3) substrate to modeling of AlGaN/GaN HEMTs.
The various widths of the various layers are: Sapphire - 500 nm.
GaN - 300nm.
AlGaN - 40nm.

Also, the drain and source are made from gold while the gate is made from poly-silicon. The AlGaN/GaN HEMT is hetrostructure. Therefore the widths of the various layers are different sizes. The ratio of width GaN:AlaN is equal to 7.5:1. The other dimensions are 800 x 800 of the different material used. The all material properties of the sapphire, GaN, AlGaN, gold and poly-silicon are considered from literature. The GaN and AlGaN are piezo-resistive materials so they dependent on temperature.

Figure 10: *Specific Heat of the GaN at Different Temperature [8].*

Figure 11: *Thermal Conductivity of GaN [9].*

The expansion coefficient of the GaN α_a and α_c increases with temperature and is nearly constant at higher temperature, as shown in Figure 12 and Figure 13 respectively.

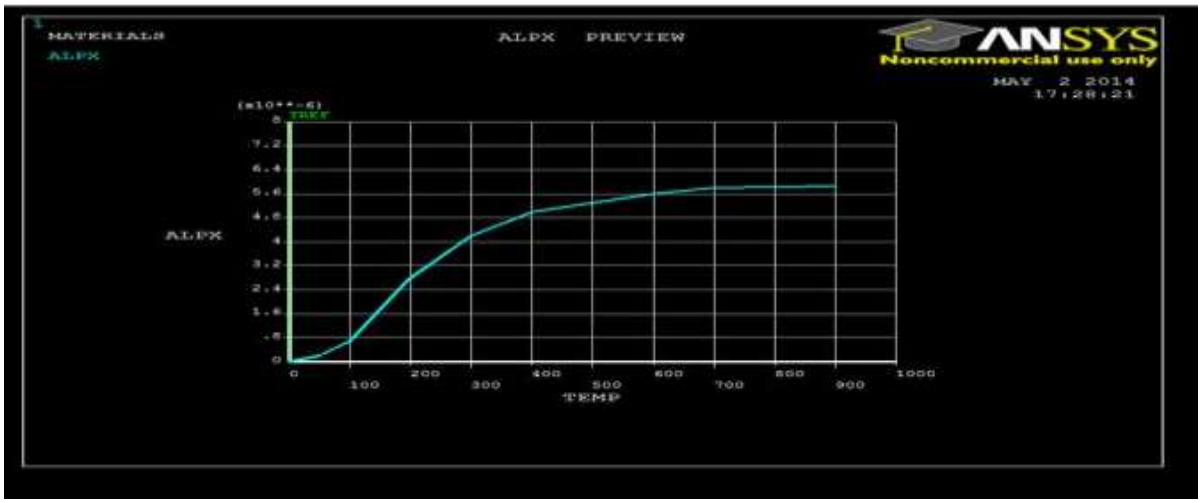

Figure 12: *Thermal Expansion Coefficient (α_a) of GaN [8].*

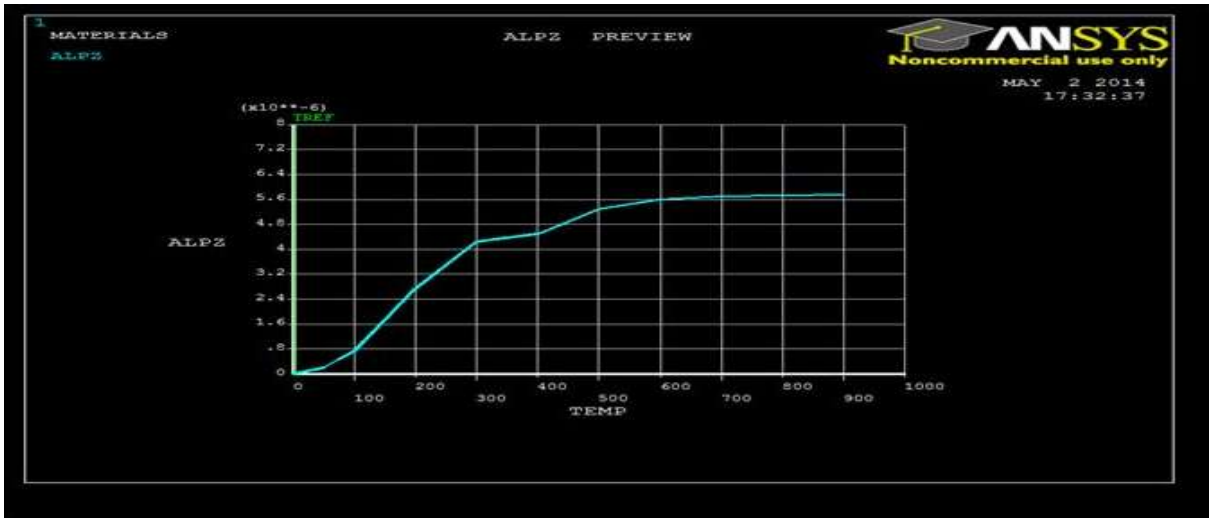

Figure 13: *Thermal Expansion Coefficient (α_c) of GaN [9].*

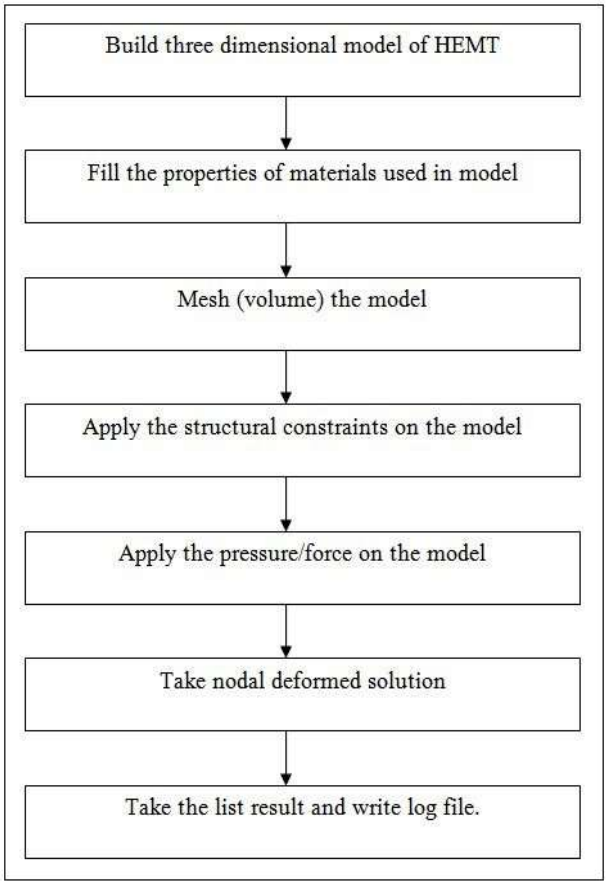

Figure 14: *Flowchart of Work, Outlining the Overall Approach to Achieve Objectives of the Work [10].*

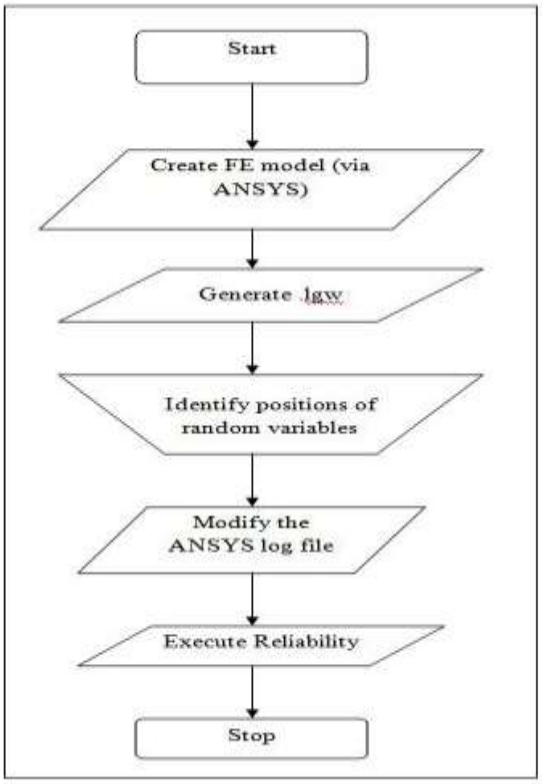

Figure 15: *Flowchart ANSYS MATLAB Combination*

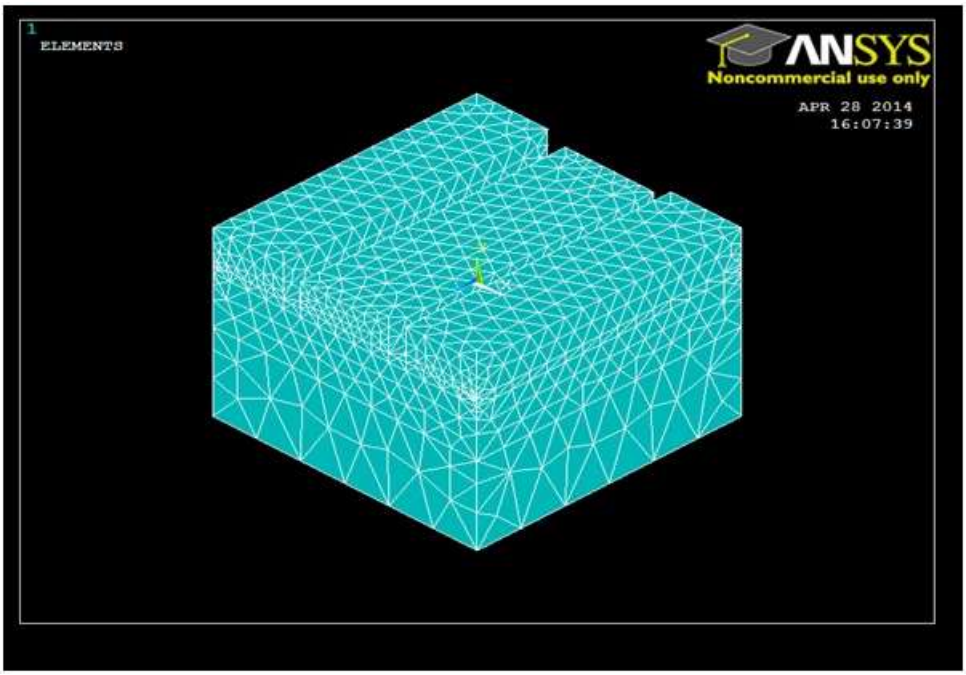

Figure 15: *FEM Model of AlGaN/GaN HEMT*

Results from Reliability Analysis:
Number of iterations: 14
Time to complete the analysis: 1.919
Reliability index beta1: -3.9118
Failure probability pf1: 9.99954e-01.

AlGaN/GaN HEMT Modeling:

The HEMT model is established with appropriate dimension on the ANSYS 12.1 Mechanical APDL. The materials layers are glue to adjacent layer. The FEM model is created on ANSYS by volume meshing. In the FEM model, the model is divided in large number of infinitesimal volumes. These volumes are called nodes in the ANSYS. The reaction solution is performed on the every node. The FEM model of the HEMT is shown in the following Figure 16.

RESULTS FROM SIMULATION ANALYSIS

Failure Probability: 5.01866e+01
Coefficient of variation of probability of failure: 9.34603e-01
Reliability index beta: NaN Number of simulations: 10000

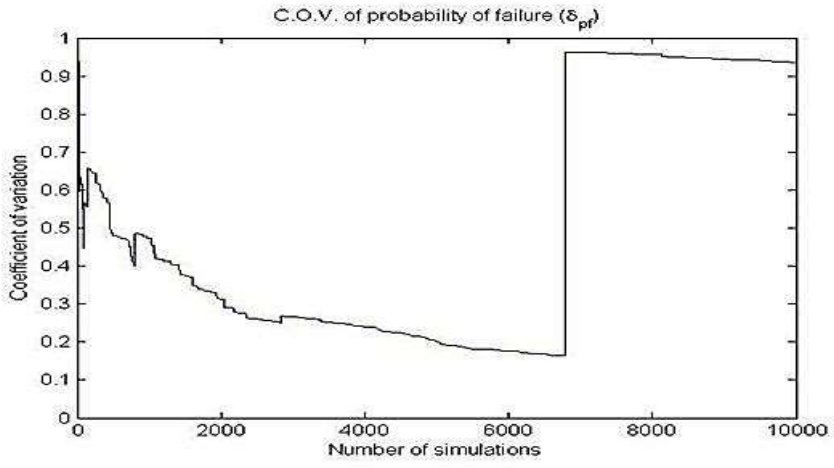

Figure 17: *Importance Sampling Simulation Analysis.*

RESULT SUMMARY AND DISCUSSION

The FEM model of the HEMT is constructed on the ANSYS. The various structural properties are calculated with the help of it. The list results of the deformations are used to FEM reliability analysis. It observed that the model is poorly deformed at ~12GPa, which is approximate to theoretical result. The structural reliability of the model 1 and model 2 are calculated on MATLAB. The summarized results of these two models are given in the following table. The model 1 is based on the nano- scale dimension; however the model 2 is based on the micro-scale dimension. The first order approximation (FORM), second order approximation (SORM) and coefficient of variance of failure probability are compared in the following table.

Table 2: *Comparison of Model 1 and Model 2.*

		Model 1	Model 2
FORM	β1	-4.4249	-3.9118
	Pf1	9.99995e-01	9.99954e-01
SORM	β2	-4.3848	-3.8657
	Pf2	9.99994e-01	9.99945e-01

From the above table it is clear that the failure probability of the nano-scaled model is greater than micro-scaled model. Hence, the fabrication of the nano-scaled GaN based HEMTs are more challenging work.

The electro-migration process are affected the reliability of the HEMTs. In nano-scaled HEMTs the gate leakage current is one important factor for the reliability of the devices.

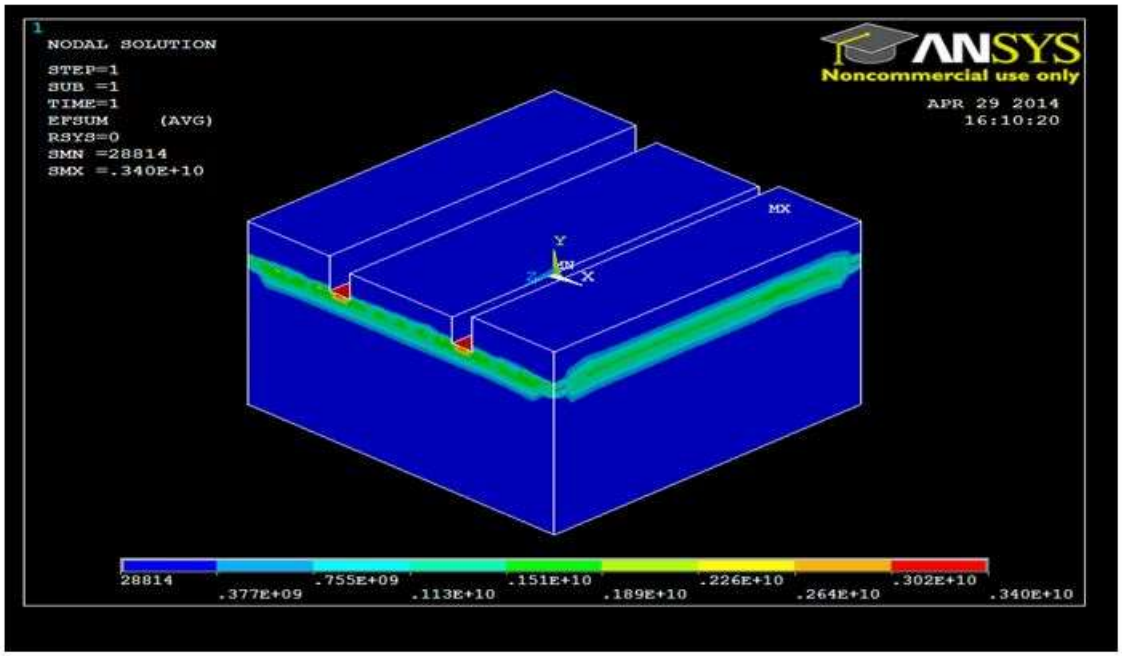

Figure 18: *Profile of the Electric Field when Voltage Applied on the Model.*

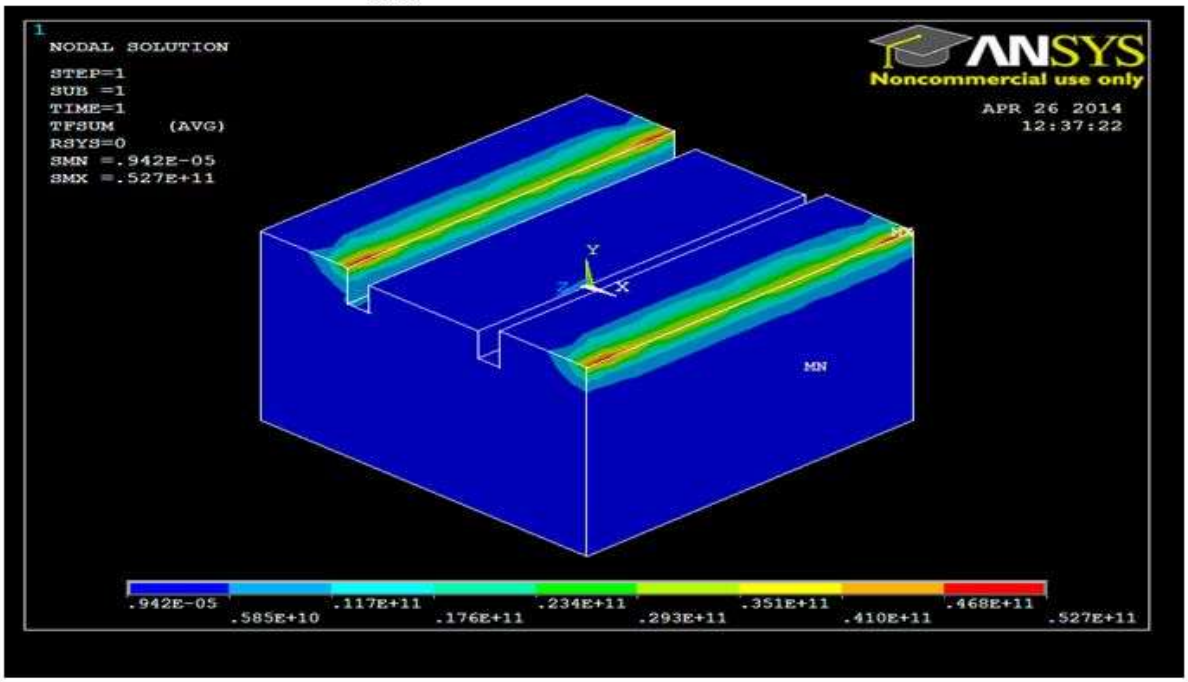

Figure 19: *Thermal Flux of the Model Due Temperature.*

CONCLUSION

This work investigates stress effects within AlGaN/GaN HEMT during operation. In order to better understand the lack of reliability currently seen in this material system. AlGaN/GaN HEMT is currently limited by their reliability. The causes of degradation are still under investigation. It is believed that peak temperatures, non-equilibrium effects, ballistic effects, thermal gradient stress, epitaxial residual stress and inverse-piezoelectric stresses all play a role in degradation. This complicated system is studied in structural behaviour in this work. The device is reliable bellow to ~12 GPa. The deformation of the device is under elasticity of the material. The electro-migration of HEMTs is caused of reliability of it. However, the HEMTs devices are worked up to 600 ^{0}C.

With the help of the finite element reliability using MATLAB (FERM), the first order, and second order approximation of the reliability is calculated. The reliability of the HEMTs is combination of structural and electrical effect. Hence it is required to combine the structural and electrical model to more generalised reliability of the HEMTs.

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