PROJECT REPORT ON

"STUDY OF GaN HEMT DEVICES FOR RF APPLICATION"

Submitted by: **Tamanpreet Singh**

UNDER THE GUIDANCE OF

Dr Sonalee Kapoor

A BREIF HISTORY

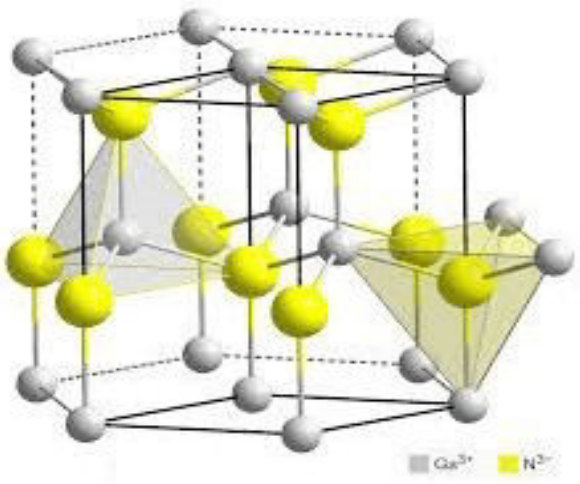
The first Gallium Nitride (GaN) material was produced by passing ammonia over hot Gallium by Jusa and Hahn in 1938. Since then numerous research breakthroughs and progress have been made in GaN based electronics . Originally, nitride semiconductors were considered as suitable candidates for optoelectronics due to their unique properties such as direct tunable bandgap from 6.2eV (AlN) to 0.7eV (InN), piezoelectricity and polarization and so on. Large area GaN was grown by hydride vapor phase epitaxy (HVPE) directly on sapphire by Maruska and Tietjen in 1969 and in 1993 high brightness blue light emitting diodes (LEDs) was developed by Nichia. Since then this material system has become primary choice for blue LEDs, blue LASER diodes and other optoelectronic devices

Today, GaN-based transistors are starting to become key components of power amplifiers (PAs) impacting high-power transmitter design at microwave frequencies. This has opened up a new arena for nitride semiconductors in the area of electronics. Gallium-Nitride-based high electron mobility transistors (GaN HEMTs) are proving to be attractive candidates for high voltage (HV) and high frequency (HF) applications. As the market for cellular, personal communications services, and broadband access are expanding and fifth-generation (5G) mobile systems are coming closer to reality, GaN-based RF and microwave power amplifiers are beginning to be the focus of attention.

WHAT IS GALLIUM NITRIDE(GaN)

It is a very hard, mechanically stable wide bandgap semiconductor. With higher breakdown strength, faster switching speed, higher thermal conductivity and lower on-resistance, power devices based on GaN significantly outperform silicon-based devices. Gallium nitride crystals can be grown on a variety of substrates, including sapphire, silicon carbide (SiC) and silicon (Si). By growing a GaN epi layer on top of silicon, the existing silicon manufacturing infrastructure can be used eliminating the need for costly specialized production sites and leveraging readily available large diameter silicon wafers at low cost.

GaN is used in the production of semiconductor power devices as well as RF components and light-emitting diodes (LEDs). GaN has demonstrated the capability to be the displacement technology for silicon semiconductors in power conversion, RF, and analog applications.



GaN: MATERIAL PROPERTIES AND APPLICATION

For mm-wave applications, a variety of power amplifier technologies are vying for market share including Si-LDMOS (Lateral-diffused MOS) and Bipolar transistors, GaAs MESFETs, GaAs (or GaAs-InGaP) heterojunction bipolar transistors (HBTs), SiC (Silicon Carbide) MESFETs and GaN HEMTs. The competitive advantage of GaN in this area is due to its superior and unique properties such as high electron density , high electron mobility in two dimensional electron gas, good thermal conductivity and high breakdown field.According to a recent survey by Strategies Unlimited, the total GaN Electronic Device market is expected to reach USD 500 M by the end of this decade [2]. RF and microwave applications are likely to be the largest share of the GaN device market. The targets for GaN HEMT are both military and commercial applications. The former include RADARs (ship-board, airborne and ground) and high performance space electronics. The latter include: Base station transmitters, C-band Satcom, Ku-K band VSAT and broadband satellites, LMDS and digital radio.

In addition to the RF market, properties unique to GaN material systems such as high breakdown field and low on-resistance are opening up new avenues in power conversion market. Already several applications between 20 V to 1200 V in the power electronic marketplace are being designed using GaN on Si platform. These applications include switch mode power supplies (SMPS), DC-DC converters, Power ICs (PIC) etc. As the silicon-based power FET is approaching a performance plateau, further enhancements are incremental and costs of advancements are becoming prohibitively high. Thus, to meet new requirements and challenges, novel materials and transistor structures are needed. Even though silicon carbide (SiC) FETs have emerged and

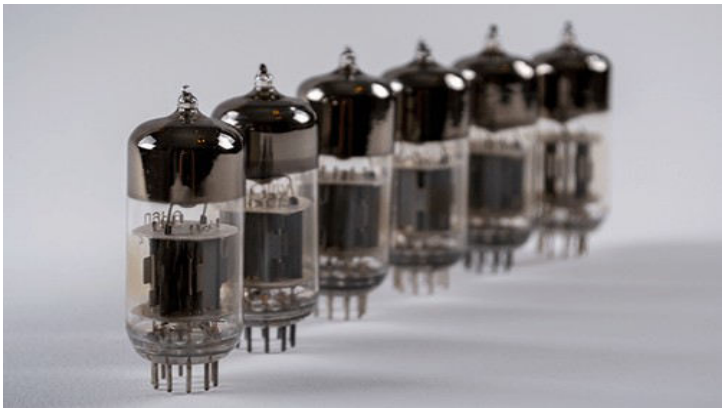
have been undergoing refinements for the past 10 years to address these issues, they suffer from significant cost premiums due to limited-quality material supply, as well as the intrinsic cost structure of the material. At this critical juncture, GaN HEMTs find a unique opportunity to meet these demands .It is clear that at present, GaN is about to make significant strides in power electronic industry. As mentioned earlier there are two main reasons for this: namely, significantly lower specific on-resistance (Ron) and high breakdown voltage (BV). For the same BV, GaN has 10 times lower Ron than SiC. This improves the figure of merit of GaN devices. For the same BV voltage, GaN power devices will have lower footprint or the footprint could be traded for higher BV and lower Ron.

Since GaN HEMTs are poised to take the lead in the above mentioned applications, it becomes necessary to understand the operating principle of the device. Once the underlying physics of device operation is well understood, simple physics-based compact models can be developed for circuit design. The central objective of this thesis is to develop such a compact model for highly scaled GaN HEMTs for RF circuit design

WHAT IS GnA HEMT ?

High electron mobility transistors(HEMTs) are transistors that use a 2-dimensional electron gas (2DEG) that is created by a junction between two materials with different band gaps. Gallium nitride (GaN) based HEMTs feature faster switching speed, higher thermal conductivity and lower on-resistance than comparable silicon-based solutions. These features allow GaN transistors and integrated circuits to be used in circuits to increase efficiency, shrink the size, and reduce the cost of a wide variety of power conversion systems.

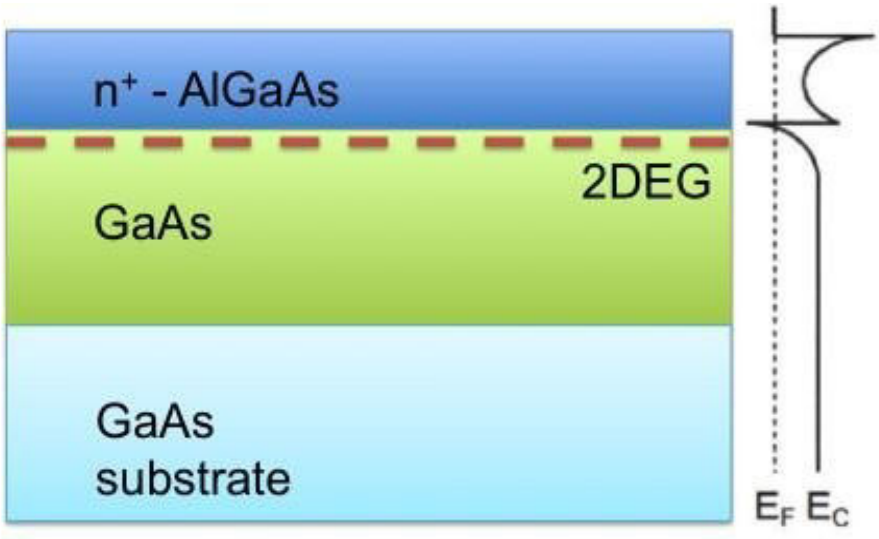
Since the dawn of the electronics age over a hundred years ago, power design engineers have been on a quest for the ideal switch, one that will rapidly and efficiently convert raw electrical energy into a controlled, useful flow of electrons. First came the vacuum tube but inefficiency, as evidenced in the heat that they generate, and their large size and high cost created limits to their ultimate use. Next, in the late ‘50s, the transistor gained widespread use; with its small size and better efficiency they appeared to be the “holy grail” and rapidly displaced tubes while creating enormous new markets unreachable by vacuum tube technology.



Vaccum tube

GENERIC HEMT STRUCTURE

(HEMT) is a heterojunction field-effect device. The heterostructure formed between two materials with different crystal structures and bandgaps aids in the formation of a quantum well at the interface.Although similar band confinement is achieved through inversion in MOSFETs, the key difference of a HEMT structure is that the two dimensional electron gas at this interface is highly mobile. Selective doping of heterostructure can be done to achieve an undoped channel. A rough schematic of a typical HEMT structure is shown below which shows the band structure along the heterostructure. The spatial separation of doped layer (n + -AlGaAs in this case) from the mobile electrons in the channel (GaAs in this case) enables high carrier mobility due to reduced ion impurity scattering.The first report on HEMT was published by Takashi Mimura in 1979. Many of the first generation HEMT devices belonged to the AlGaAs/GaAs or InAlAs/InGaAs family .



A rough schematic of a typical GaAs based HEMT heterostructure

Types of GaN:

GaN transistors inherited the very same terminology as their counterparts in silicon: gate, drain and source. Furthermore, a GaN device's on-state resistance and breakdown voltage has a similar significance to their equivalents in silicon. On-state resistance curves (RDS(ON)) versus voltage across gate-source curves are similar to MOSFETs in silicon. The on-state resistance temperature coefficient of GaN FETs is comparable to the MOSFET silicon as it is positive, but the value is comparatively low. GaN power devices' basic structure is divided primarily into two groups. One is the planar system manufactured on substrates of Si or Silicon Carbide (SiC). The other is the unit of vertical conduction produced by homoepitaxial. GaN can be classified based on structure as Lateral and Vertical; and based on mode of operation as depletion-mode and enhancement-mode.

Classification based on structure:

GaN device is classified based on structure as Lateral and Vertical structure and are summarized as below:

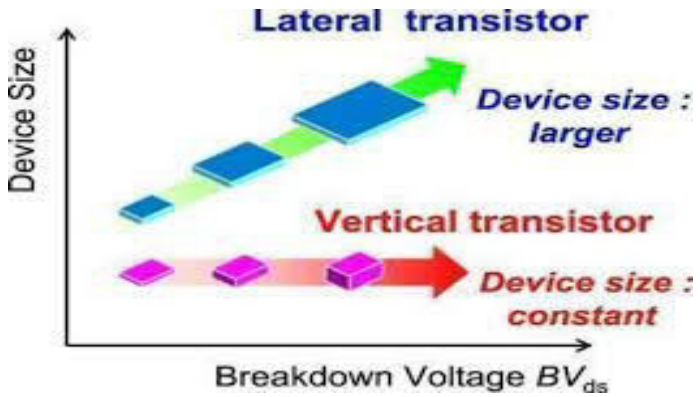
1)The Lateral Structure of GaN devices

2) The Vertical Structure of GaN devices

The Lateral Structure of GaN devices

Over the past decade, Lateral power devices that rely on heterostructures from AlGaN / GaN achieved outstanding efficiency. Lateral GaN transistors shown in Fig.1(a) are now commercially available on Silicon substrates with maximum operating voltage up to 650 V. In order to reach breakdown voltages above 1 kV, vertical GaN on-GaN diodes and transistors are being tested . Although the lateral structures achieve good operating performance it has certain limitations as follows:

- The size of the lateral device increases dramatically as power increases.
- Requires large lateral dimension in proportion to voltage and current ratings .
- In high voltage applications, cautious management of electrical field profiles in the lateral dimension between contacts is needed. Significant lateral spacing of the gate / drain must be maintained to allow high voltage of breakdown, which decreases the effective current density.
- Thermal handling is made worse by the fact that all current flow is limited near the top surface to a relatively thin portion of the system .
- Such factors combined impede the cost-effective scaling to high voltage / current ratings of lateral devices.



The Vertical Structure of GaN devices

In contrast to lateral design, a vertical GaN device architecture shown in Fig.1 (b) overcomes the limitations of lateral counterpart because high electric fields occur between contacts on the bottom and top of the structure in the vertical dimension only . Vertical transistors will restrict the area of the device, as the increase in the voltage breakdown is only allowed by increasing the drift layer thickness as displayed . Development of vertical GaN transistors is a technological challenge for potential widespread use of GaN, because the Vertical system easily achieves high-current and high-voltage operations. A new vertical GaN transistor structure is suggested in which the p-type gate is built over the GaN drift layers' V-groove. The vertical system indicates low on-state average resistance of 1.0m Ω / cm2 and high breakdown voltage of 1.7 kV .The following are the merits of Vertical GaN architecture :-

- The ability to achieve high Safe operating Range with the same size of the chip.
- Easier thermal management
- Vertical GaN devices are most likely to combine currents above 100 A with voltages exceeding 600 V.
- Specific junction designing methods are used to control and form the electrical field at the edges of the devices in order to achieve high breakdown voltage. These include field plate, guard rings, termination of the bevel edge and extension of the end of the junction.

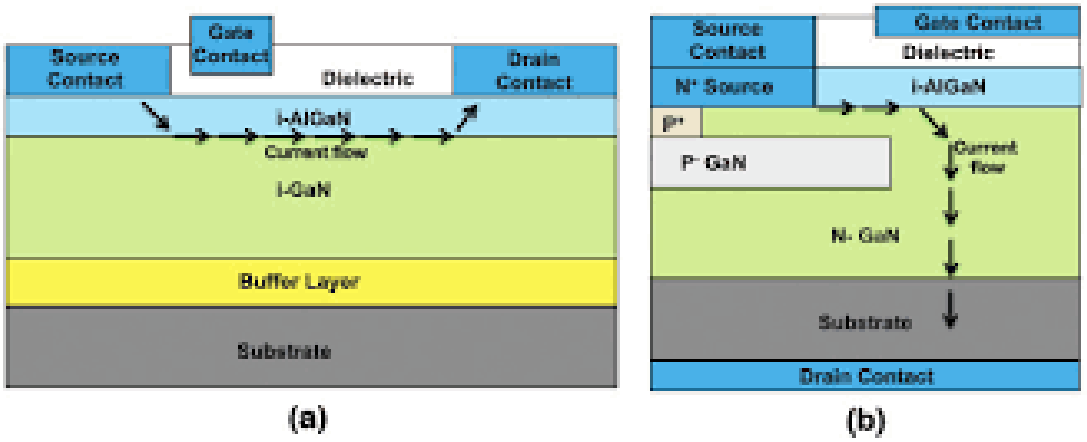


Fig.1. Conventional configuration of a GaN transistor: (a) Lateral architecture (b)Vertical architecture.

Classification based on Mode of Operation:

(a) Depletion mode of GaN devices

The basic structure of a GaN transistor is depicted in Fig. 4. It has gate, source, and drain electrodes similar to power FET. The source and drain electrodes perforate via the upper layer of AlGaN to create an ohmic contact with the 2DEG that lies behind it. When the electrons 2DEG is vanished it makes an electrical circuit between source and drain, and the semi-insulating will obstruct the current flow. A gate electrode replenishes the 2DEG. This gate electrode is developed on many of the early GaN transistors as a Schottky contact to the upper surface. When applying a reverse potential to this gate the Schottky barrier becomes reverse biased and the electrons below are depleted. So turning this device OFF requires a reverse potential comparative to both drain and source electrodes. This kind of transistor is named Heterostructure Field Effect Transistors (HFET) depletion mode, or d- mode.

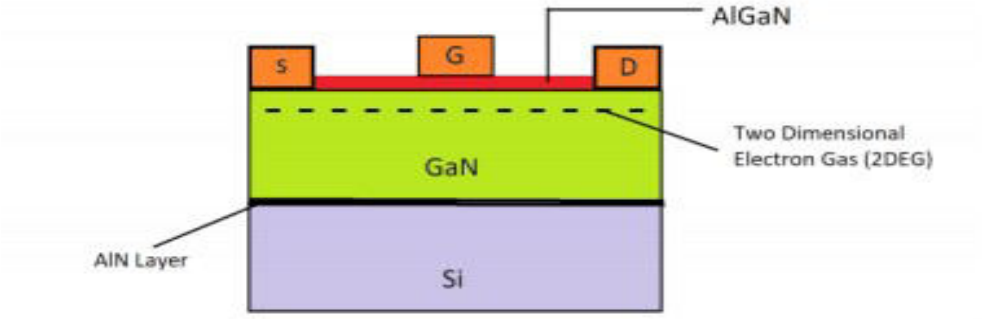


Fig 4. A typical AlGaN/GaN HFET

(b) Enhancement-mode of GaN devices

A thin coating of Aluminium Nitride (AlN) is grown on the silicon to include a base surface for the eventual development of a heterostructure of GaN. On the AlN a heterostructure of Aluminium gallium nitride (AlGaN) is formed and then GaN. This surface offers a base which creates the GaN FET. On the surface of the highly resistive GaN, a very small layer of AlGaN is grown. This thin layer produces a strained interface between surfaces of crystals GaN and AlGaN. A forward voltage is applied to the gate in the same way as switching on an n-channel, enhancement mode power MOSFET, to improve the FET. A cross-section of the structure is shown in Fig. 5. Extra metal layers are introduced to the electrons route into the gate, drain and source terminals.

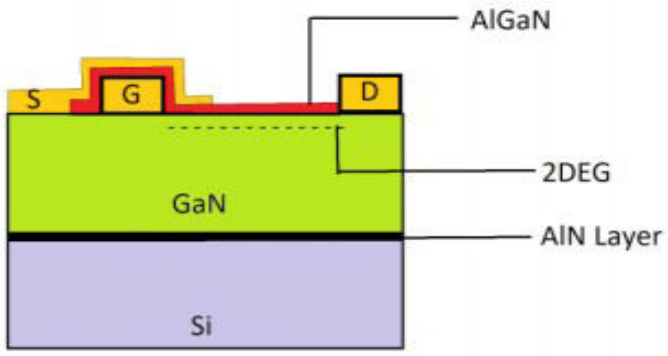


Fig 5. A typical Enhancement-mode GaN FET structure

Fabrication Techniques in AlN/GaN – based systems

Features of this material system are high concentrations of 2DEG sheet carrier at the heterojunction interface, high carrier electron speed and large variations of electrical breakdowns, thus attaining superior performance in comparison to AlGaN / GaN products. With advances in material growth and processing methods, good output in this device includes 2DEG sheet carrier concentration above 3 * 1013 cm-2 with relatively minimal sheet resistance, Rsh < 150 /mm, input drain current density above 2 A / mm and cut-off frequency above 100 Ghz.

Ohmic Contact Optimisation

Using less-resistance, thermally stabilized Ohmic contacts(OC) with good surface morphology gives optimal performance of AlN / GaN based HEMT systems. This has been needed for the following facts:

1) Obtaining the high drain current
2) Reducing on state-resistance
3) Minimizing power leakage in OC due to large current densities.
4) Obtaining the high external transconductance resulting in an increase in the current gain cut-off frequency, as well as the maximum operating frequency of the devices.

For these facts, the processing of OC optimization in the AlN / GaN substance networks for HEMT and MOS-HEMT is essential for achieving better device efficiency. Descriptions of the optimization of the Ohmic touch method have been mentioned here.

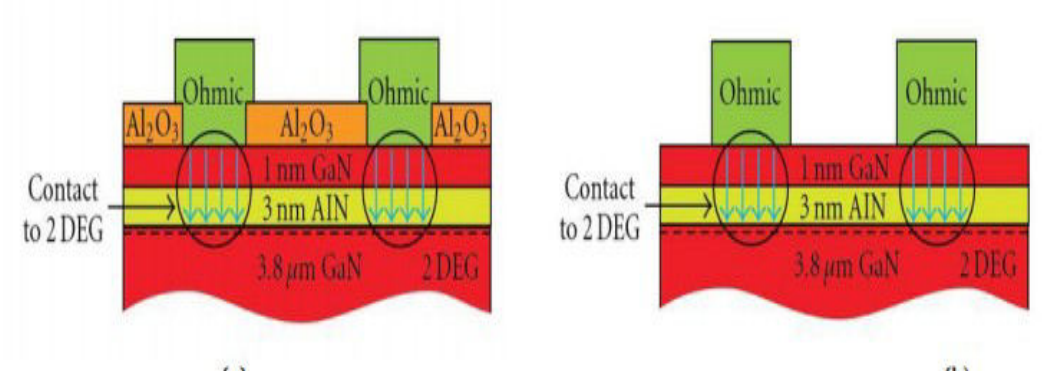


Fig 6: Optimized overview of TLM processing for AlN / GaN HEMT samples: (a)Vulnerable and unpassivate.(b) safe and passive.

OCs are fabricated and differentiated by GaN samples which are both shielded (primarily with an evaporated Al 2 nm later oxidized to form Al2O3) and non-protected / unsecured (as grown). Illustration 6a explains the configured transmission line design methodology (TLM) for unprotected and non-passive AlN / GaN HEMT samples and Fig. 6b. shows a description of the configured AlN / GaN MOS-HEMT data sets for secure and passive TLM processing. A summary of the optimized RC and RSh standards on HEMT and MOS-HEMT is given in data. The protected surface resistance of the sample is 159 range / mm, which is 1/3 of the unprotected sample (450 range / mm). On the side, the TLM tests of unprotected and unpassivated samples showed very low contact resistance

with an average value of 0.31· mm. The below details gives an example to handle OC safely.

Table 1: Optimized tests and values in the AlN / GaN material structure for HEMT and MOS-HEMT applications.

Samples	Description	RC(Contact Resistance in Ω/·mm)	RSh(Sheet Resistance in Ω/mm)
A	Unsecured and unpassivated (HEMT)	0.310	480
B	Secured and passivated (MOS-HEMT)	0.490	159

Transmission Line Design Methodology

TLM Processing for the system seen in Figure 6b involves optimizing wet etching using 16H3PO4: HNO3: 2H2O Al etch solution which offers very less contact resistance and very little sheet resistance as described . Figure 7 shows the measured I-V characteristics on 5 µm TLM gap distance of annealed OC during different Al etch times before deposition of Ohmic metal. The sample B2's treatment systems, in which Al is etched to 20 secs, given the best I-V graph relative to other etching times. This sample 's average RC and RSh values are 0.49Ω / mm, and correspondingly 159 Ω/ mm. Nevertheless, it causes impact in the contact resistance if the sample is maintained longer in the etchant.

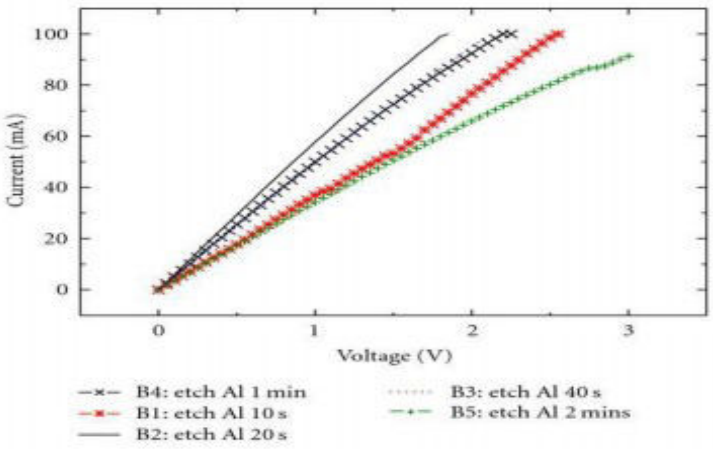


Fig.7 Current versus Voltage characteristics (5 m TLM gap spacing of annealed OC under various Al etch times prior deposition of Ohmic metal)

Gate Wrap-Around MOS-HEMT Optimisation

A method to gate wrap-around configuration, where the gate contact covers the drain as depicted in Figure 8, is utilized for process growth and optimisation on AlN/GaN HEMT structures. This method involves metallisation of the Ohmic and the gate, excluding the mesa-isolation process. During process growth, 10 mm x 10 mm of data sets cleaved from a 2 inch wafer are used. Production of the device starts with routine sample cleaning with deionized water, acetone and isopropanol. In Figure 6a, automated Ohmic contact processing is used for the production of unprotected and unpassivated AlN / GaN HEMT units. Hcl: 4H2O solution is used for deoxidation before ohmic metal deposition in the OC areas. Ohmic metal contacts are created by evaporation of Ti / Al / Ni / Au, accompanied by a lifting-off step and then annealing at 800 ° C for 30 seconds. Gate metal links are then done by evaporation with Ni / Au followed by lifting-off AlN / GaN structures are well understood to be very responsive to liquid treatment, so unsecured and unpassivated AlGaN / GaN HEMTs (from identical growth circumstances) are also handled and manufactured to provide reliable statistics.

DC tests are carried out by placing the probe's needles just above source (S), drain (D), and gate (G) structures. Figure 9(a) illustrates the IDS -VDS characteristics of exposed and nonpassive 3 µm devices on the AlGaN / GaN HEMT structure. Devices built on this material system had strong gate regulation of drain currents up to 1 V gate bias and achieved a peak drain current of ~800 mA/mm. The devices also exhibited good pinch-off properties and good saturation. On the other hand, devices built on the AlN / GaN HEMT structure shown in Figure 9(b) showed very high leakage currents and did not pinchoff, and the drain current is very low

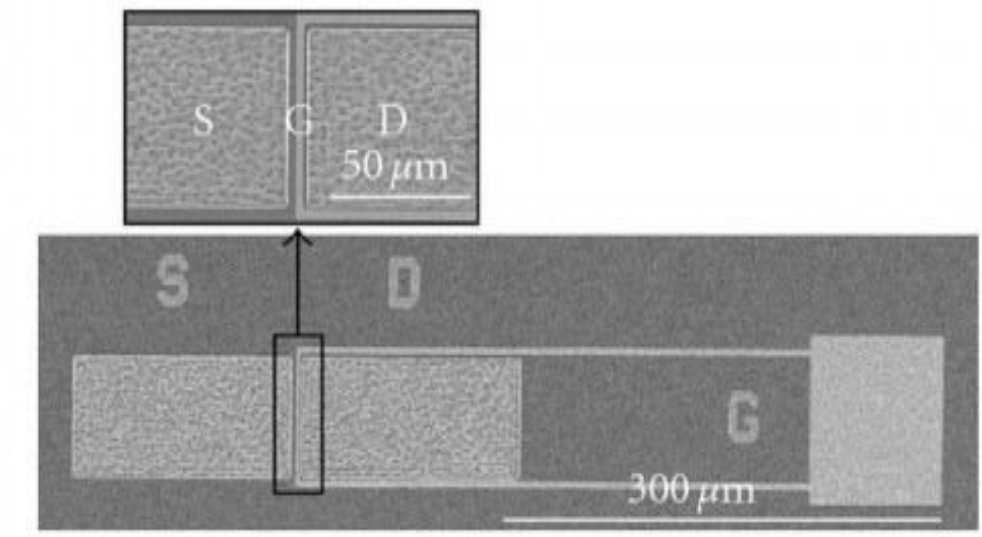


Fig 8: SEM gate wrap-around MOS-HEMT micrograph. Inset: µm device and µm device.

These findings, along with the TLM findings detailed in the above, indicate that there are certain issues with the processing of AlN / GaN HEMT structures not seen in AlGaN / GaN HEMTs. Exposure to multiple processing chemicals such as resist developer and solvent solutions may help to reduce OC resistance, and at the same time it may have led to the durability of AlN / GaN epilayer structures deteriorating. Study cited by Fan et al. concerning the production of low OC on n-GaN materials, where reduced OC resistance is caused by damage to the RIE process used prior to depositing the OC metallisation. The devices however suffered from surface vulnerability and heavy leakage currents. Thus the epitaxial layers of AlN / GaN need to be covered during device processing. A new production process for AlN / GaN based devices is therefore developed which involves the use of Al2O3 thermally grown to protect the very sensitive AlN epilayer from exposure to liquid chemicals throughout the process as stated earlier for TLM experiments (Figure 7). This Al2O3 produced by thermal oxidation Al evaporated, acts as a passive surface and a dielectric gate for the transistors.

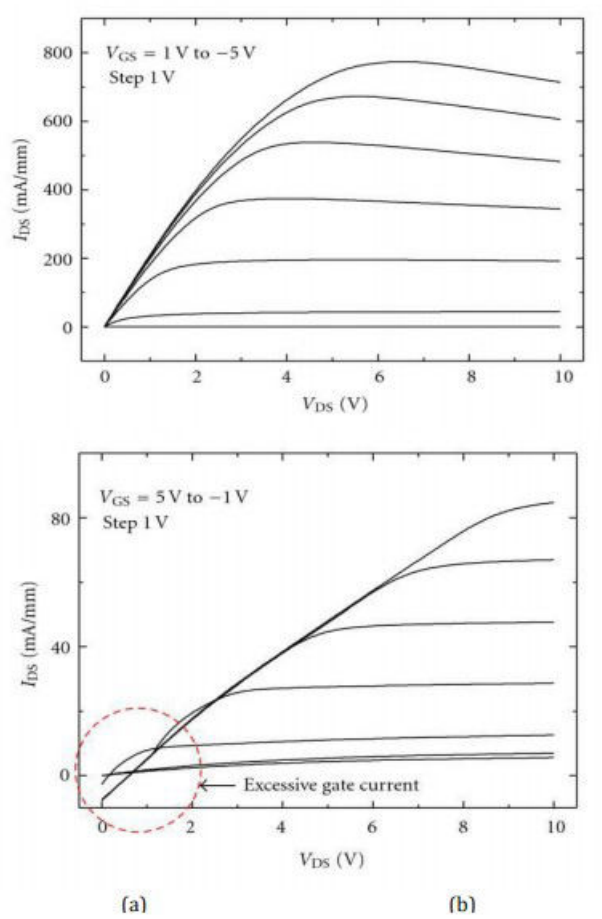


Fig 9:-Characteristics of non-protected and non-passivated devices with 3 µm (a) AlGaN / GaN HEMT and (b) AlN / GaN HEMT.

The processing includes:-

(a) material cleaning and deoxidation
(b) 2 nm Al deposition
(c) Ohmic region etching and thermal oxidation
(d) ohmic metallisation and annealing
(e) gate metallisation and unit calculation.

To further investigate the impacts of OC optimization on device performance, devices are produced in the OC area using varying Al etching time. Fig.11 shows a typical characteristics of AlN / GaN MOS-HEMT devices produced from 3 µm to 100 µm doors, with different etching times, 10 secs and 20 seconds. The devices are biased from VGS =+3V to -4V with a phase size of 1 V. It is obvious that a 20 sec Al etch has a substantial effect on the output of the system with the drain current (IDS) at zero gate voltage greater than twice that of a system with 10 secs of etching time. Compared to similar findings on the very same epilayer structure for the AlN / GaN HEMT (unprotected and unpassivated system), these findings demonstrate that AlN / GaN MOS-HEMT with far greater and excellent transistor properties protects and passivates the AlN / GaN layers during production.

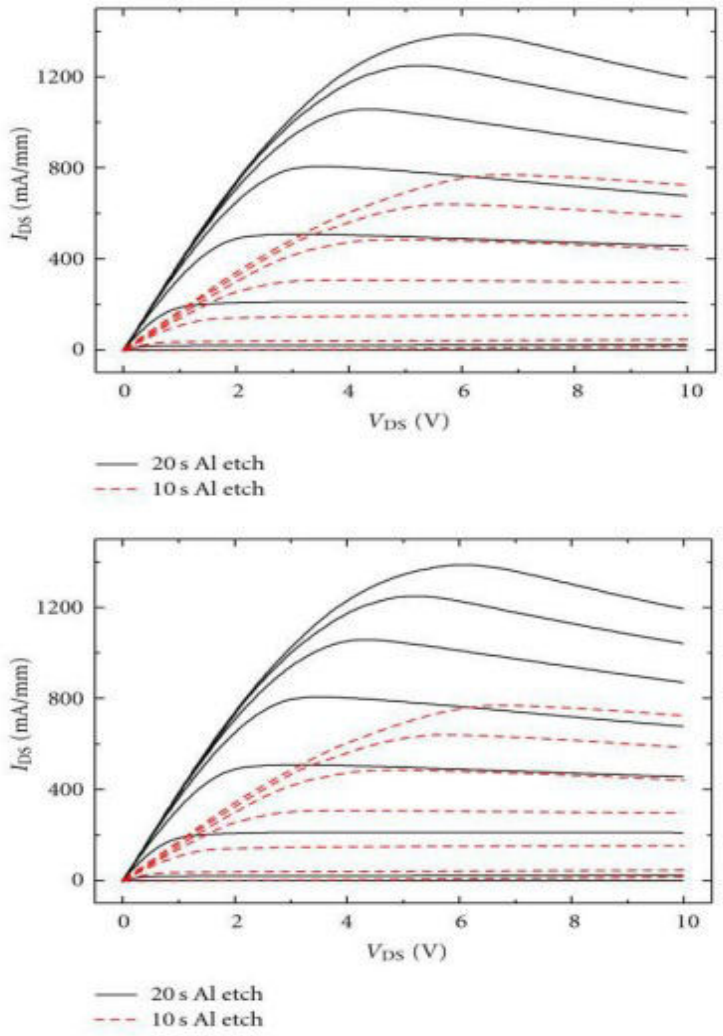


Fig 11: IDS against VDS characteristics of AlN/GaN MOS-HEMT devices with different etching times.

QUADRUPLE GATE (QG) GaN-MOSHEMT

Despite the development of epitaxial growth and production methods, gallium nitride (GaN)-based products are being commonly used in numerous electronic devices, optoelectronic devices, and sensors. To maximize the effectiveness of GaN-based HEMTs, the modified gate size, the reduced gate-to-channel gap and the lowered parasite resistance and parasitic capacitance have been widely used. By raising the parasitic capacitance of the top metal

gate in the T-gate structure, the cut-off frequency of the unit gain will be decreased. Figure 12(a) and (b) demonstrate the QG-embedded T structured GaN-based MOSHEMT and standard GaN-based single gate MOSHEMT schematics. In this analysis, a molecular beam epitaxial ammonia system was used to sequentially grow a 20-nm-thick AlN nucleation surface, a 2.0-µm-thick carbondoped I layer, an undoped 0.5-µm-thick layer I and an undoped 35nm-thick layer Al0.15Ga0.85N on c-plane sapphire substrates. The BCl3 etchant has been used to etch and render mesa regions in a reactive ion etching system with a mesa insulation area of 310 µm/310 µm to generate mesa regions of standard single-gate GaN-based MOSHEMTs and QG-embedded T engineered GaN-based MOSHEMTs. Following the surface treatment process, the source and drain regions of GaN-based MOSHEMTs are modeled using a standard method of photolithography.

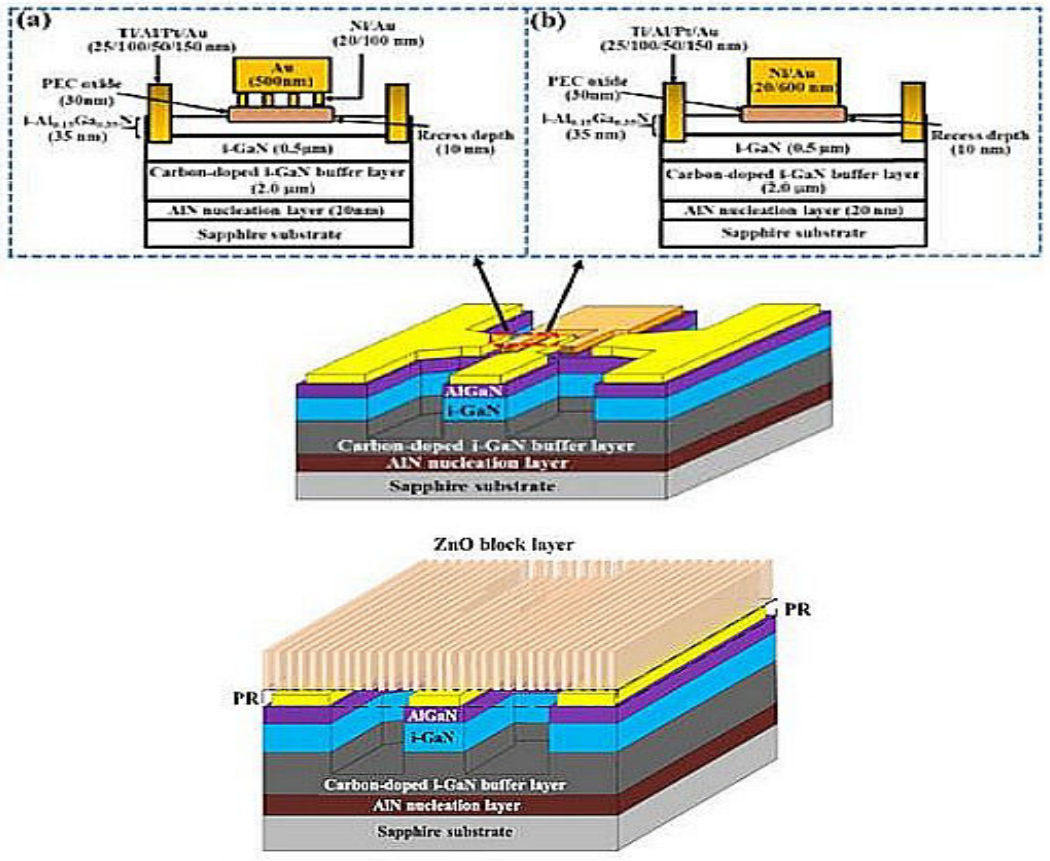
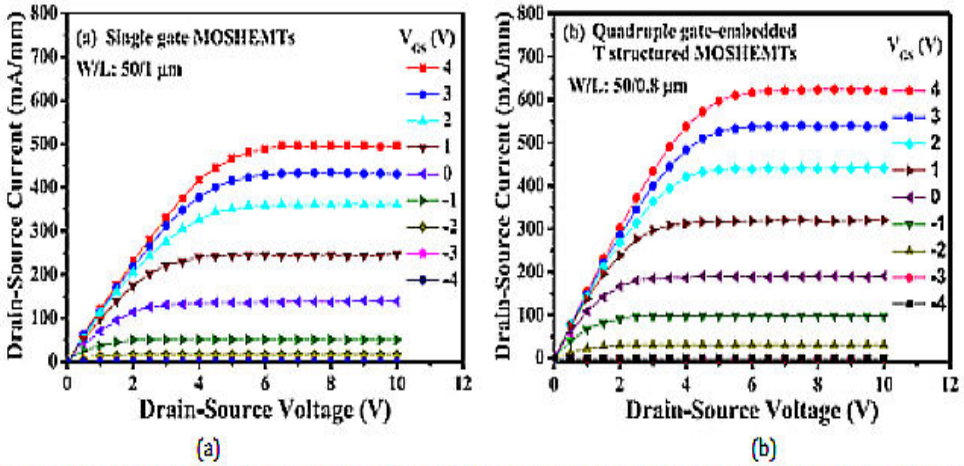


Fig. 12: Schematic configuration: (a) QG-embedded T-structured GaN based MOSHEMTs and (b) Traditional single gate GaN based MOSHEMTs. (c) Stripped ZnO block layer on the devices.

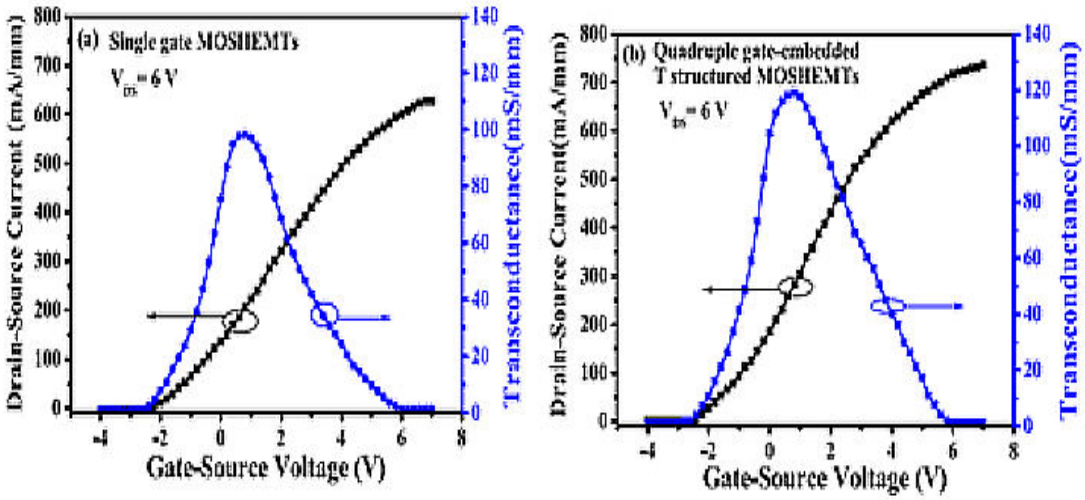
Figure 14(a) and (b) illustrates the drain-source current (IDS) dependence on the drain-source voltage (VDS) of traditional single-gate GaN-based MOHEMTs and four-gate-embedded T structured GaN-based MOSHEMTs operating at different gatesource voltages (VGS). The greater electron drift velocity and the screening effect in the QG-embedded T structured GaNbased MOSHEMTs may cause further enhancement of the drain-source saturation current. Figure 15 respectively (a) and (b), shows the reliance of the drain-source current and the extrinsic transconductance of traditional single-gate GaNbased MOSHEMTs on VGS and the QG-embedded T structured GaN-based MOSHEMTs

operating at VDS = 6 V. The QGembedded T structured GaN-based MOSHEMTs were produced using the photolithography process of laser interference, the process of photo-electrochemical oxidation and the sacrificial layer PMMA. The novel gate structure strengthened the DC efficiency of the consequent devices.



(a) (b)

Figure 14: I_{DS} Vs V_{DS} Characteristics (a) Single gate GaN based MOSHEMTs and (b) QG-embedded T structured MOSHEMTs.



(a) (b)

Figure 15: I_{DS} Vs V_{GS} Characteristics (a) single gate GaN based MOSHEMTs and (b) QG-embedded T structured MOSHEMTs.

High Electron Mobility Transistor

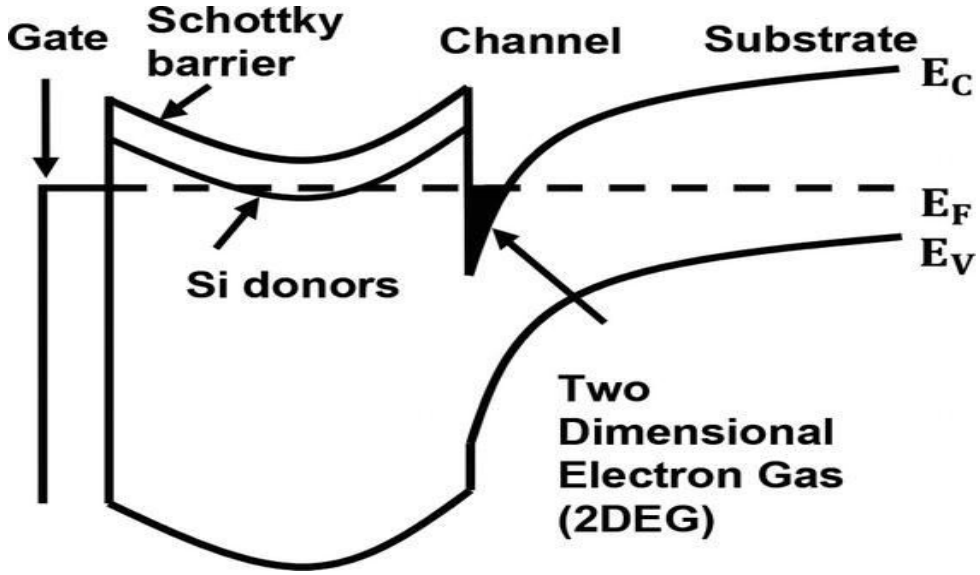
The metal-semiconductor field effect transistor (MESFET) has been the "workhorse" of the microwave industry for many years. The MESFET was and is still used as the active device for both low noise and power amplifiers as well as for transfer switches, attenuations, oscillators, and mixers. Its fabrication is also compatible with the manufacture of monolithic circuits. But the performance limits of the MESFET have been reached. The high electron mobility transistor (HEMT) is one of the devices that offers improved performance as compared with MESFETs for many applications. The HEMT or High Electron Mobility Transistor is a type of field effect transistor (FET), that is used to offer a combination of low noise figure and very high levels of performance at microwave frequencies. This is an important device for high speed, high frequency, digital circuits and microwave circuits with low noise applications. These applications include computing, telecommunications, and instrumentation. And the device is also used in RF design, where high performance is required at very high RF frequencies.

Working Principle Of HEMTs

HEMTs are essentially heterojunctions formed by semiconductors having dissimilar bandgaps. When a heterojunction is formed, the conduction band and valence band throughout the material must bend to form a continuous level. The wide band element has excess electrons in the conduction band as it is doped with donor atoms (or due to polarization charge in GaN-based HEMTs). The narrow band material has conduction band states with lower energy. Therefore, electrons will diffuse from wide bandgap material to the adjacent lower bandgap material as it has states with lower energy. Thus, a change in potential will occur due to movement of electrons and an electric field will be induced between the materials. The induced electric field will drift electrons back to the conduction band of the wide bandgap element. The drift and diffusion processes continue until they balance each other, creating a junction at equilibrium like a p-n junction. Note that the undoped narrow bandgap material now has excess majority charge carriers, which yield high switching speed. An interesting fact is that the low bandgap undoped semiconductor has no donor atoms to cause scattering and thus ensures high mobility.

Another interesting aspect of HEMTs is that the band discontinuities across the conduction and valence bands can be engineered to control the type of carriers in and out of the device. This diffusion of carriers leads to the accumulation of electrons along the boundary of the two regions inside the narrow bandgap material. The

accumulation of electrons can lead to a very high current in these devices. The accumulated electrons are also known as 2DEG.Figure4shows the generalized band diagram formed at the heterojunction for typical HEMTs. Both the conduction band (Ec) and valence band (Ev) bend with respect to the Fermi level (EF) resulting in a quantum well filled with 2DEG and eventually, a conducting channel is formed.

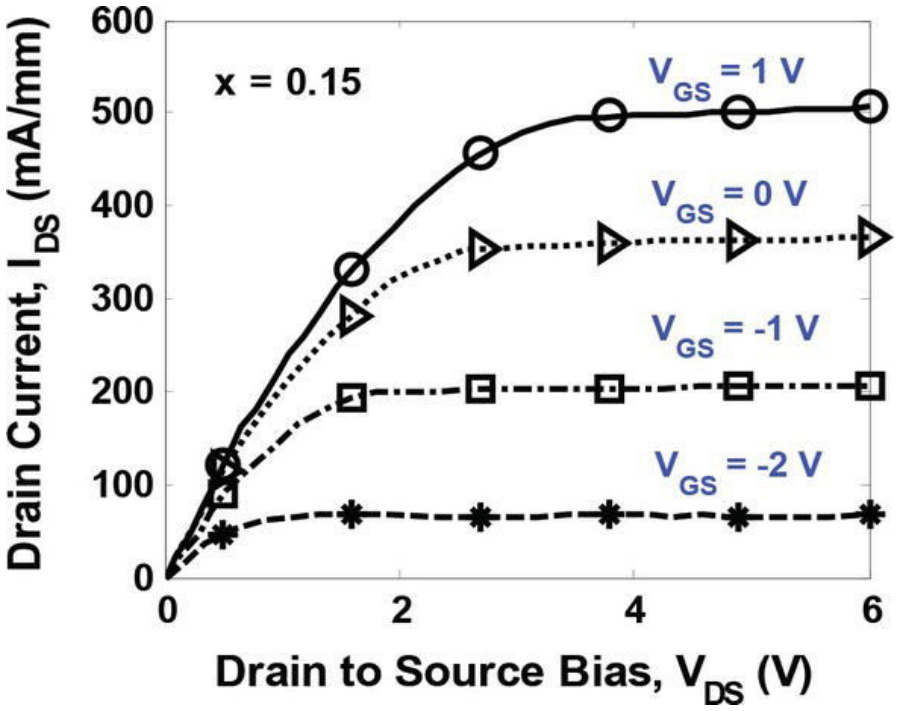


Generalized energy band diagram of HEMTs.

Current-voltage characteristics

An improved charge control model forI-Vcharacteristics of AlGaN/ GaN HEMTs was presented in 2008 . This model includes Robin boundary conditions in the solution of 1-D Schrödinger equation and customizable eigen values in the solution of 2-D Poisson's equation. Nonlinear polarization and parasitic resistance of source and drain have been incorporated in this model. The model estimates drain

current assuming second-order continuity with analytical representation of transconductance. The device structure used in this model is almost similar to that of Figure2. However, the only difference is that a doped AlGaN layer of 22 nm with doping concentration,ND= 2 × 1018cm−3 is present above the undoped AlGaN layer to enhance polarization. The I-Vresult plotted using this analytical model is shown below for different gate voltages.

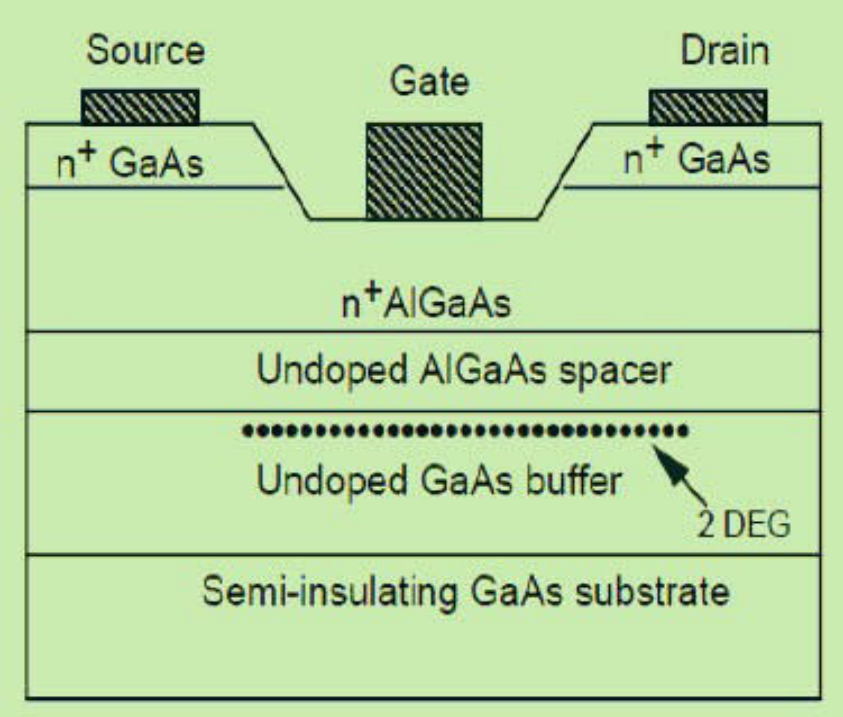


I–Vcharacteristics for an Al0.15Ga0.85N/GaN HEMTs. The gate-to-source bias is swept from 1 to −2 V at a step of −1 V.

High Electron Mobility Transistor (HEMT) Construction

The key element that is used to construct an HEMT is the specialised PN junction. It is known as a hetero-junction and consists of a junction that uses different materials either side of the junction. Instead of the p-n junction, a metal-semiconductor junction (reverse-biased Schottky barrier) is used, where the simplicity of Schottky barriers allows fabrication to close geometrical tolerances.

The most common materials used Aluminium Gallium Arsenide (AlGaAs) and Gallium Arsenide (GaAs). Gallium Arsenide is generally used because it provides a high level of basic electron mobility which has higher mobilities and carrier drift velocities than Si.



Schematic Cross Section of an HEMT

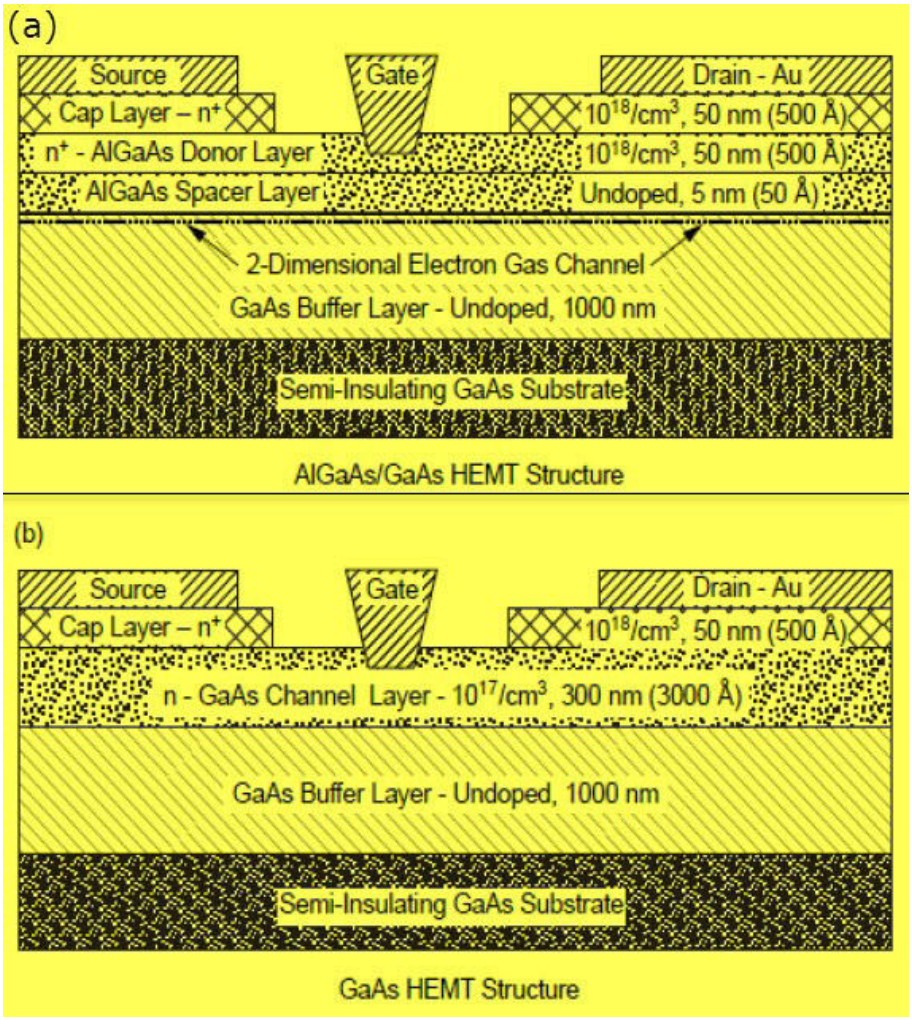
The manufacture of an HEMT as follows procedure, first an intrinsic layer of Gallium Arsenide is set down on the semi-insulating Gallium Arsenide layer. This is only about 1micron thick. After that, a very thin layer between 30 and 60 Angstroms of intrinsic Aluminium Gallium Arsenide is set down on top of this layer. The main purpose of this layer is to ensure the separation of the Hetero-junction interface from the doped Aluminium Gallium Arsenide region.

This is very critical if the high electron mobility is to be achieved. The doped layer of Aluminium Gallium Arsenide about 500 Angstroms thick is set down above this as shown in the diagrams below. The exact thickness of this layer is required and special techniques are required for the control of the thickness of this layer.

There are two main structures that are the self-aligned ion implanted structure and the recess gate structure. In self-aligned ion implanted structure the Gate, Drain and Source are set down and they are generally metallic contacts, although the source and drain contacts may sometimes be made from germanium. The gate is generally made of titanium, and it forms a minute reverse biased junction similar to that of the GaAs-FET.

For the recess gate structure, another layer of n-type Gallium Arsenide is set down to enable the drain and source contacts to be made. Areas are etched as shown in the diagram below.

The thickness under the gate is also very critical since the threshold voltage of the FET is determined by the thickness only. The size of the gate, and hence the channel is very small. To maintain a high-frequency performance the size of the gate should be typically 0.25 microns or less.



Cross-Sectional Diagrams Comparing Structures of an AlGaAs or GaAs HEMT and a GaAs

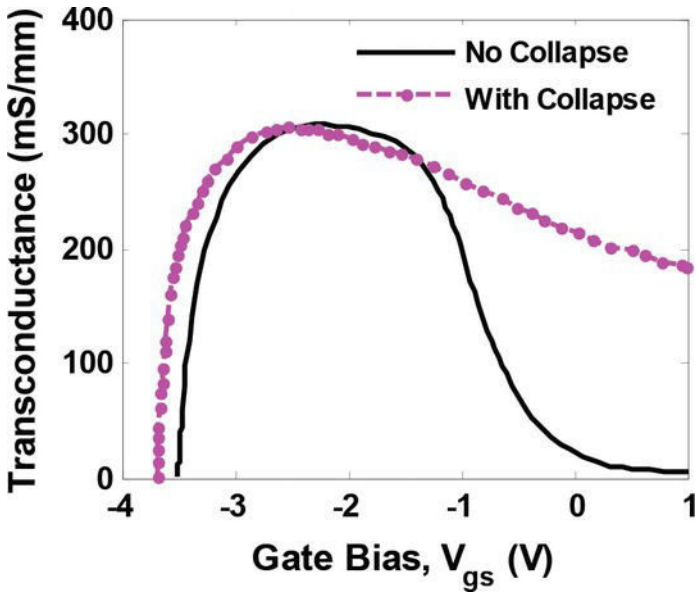
HEMT Operation

The operation of the HEMT is a bit different to other types of FET and as a result, it is able to give a very much enhanced performance over the standard junction or MOS FETs, and in particular in microwave RF applications. The electrons from the n-type region move through the crystal lattice and many remain close to the Hetero-junction. These electrons in a layer that is only one layer thick, forming as a two-dimensional electron gas.

Within this region, the electrons are able to move freely, because there are no other donor electrons or other items with which electrons will collide and the mobility of the electrons in the gas is very high. The bias voltage applied to the gate formed as a Schottky barrier diode is used to modulate the number of electrons in the channel formed from the 2 D electron gas and consecutively this controls the conductivity of the device. The width of the channel can be changed by the gate bias voltage.

Short channel I-Vcharacteristics with current collapse

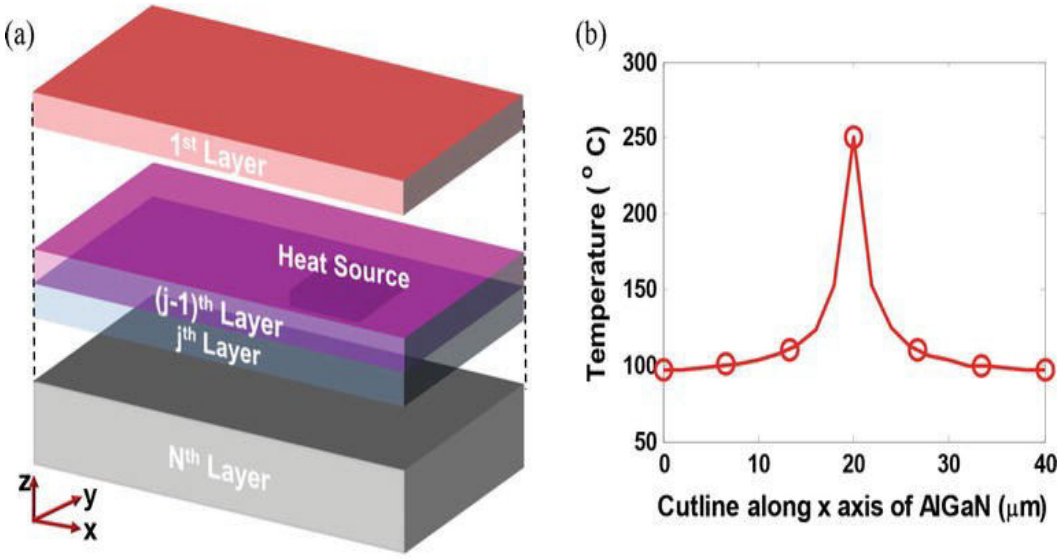
Current collapse is an undesirable but inevitable phenomenon in GaN-based HEMTs. It is a short channel nonideal effect where current depends on the previous memory of gate voltage. For I-Vcharacteristics of AlGaN/GaN HEMTS in presence of current collapse, another compact model was proposed. It incorporates trapping mechanism and gate edges and is based on experimental data. Capacitance-voltage (C-V) characteristics of AlGaN/ GaN HEMTs can also be calculated using this model. This model analyses device transconductance vs. gate bias when current collapse occurs. A comparative plot of transconductance with and without current collapse as determined by this compact short channel model is shown in below.



Comparison of transconductance with and without current collapse for AlGaN/GaN HEMTs.

Thermal effects with complex structures

Although AlGaN/GaN HEMT is a promising device for high frequency and high power applications, its performance can be degraded at high temperatures. Therefore, a thermal modeling is required to predict device performance at different temperatures. Bagnall et al. developed such a thermal model that incorporates thermal effects with closed form analytical solutions for complex multilayer structured HEMTs . This structure consists of N number of layers (j= 1, 2, 3, …, N) and a heat source placed within the layers as shown in below. The analytical modeling is carried out using Fourier series solution and validated using Raman thermography spectra. Distribution of temperature along AlGaN/GaN x-axis interface including heat source as presented by the model is shown in below.



(a) Complex multi-layer HEMT structure with a heat source, and (b) Temperature distribution alongxaxis for AlGaN/GaN HEMTs including the heat source.

Apart from these models, many other analytical models have been proposed for noise elimination, loss calculation, estimation of polarization, small signal analysis, etc.

Future Trends

The future HEMT devices based on two-dimensional carrier confinement seem very bright in electronics, communications, physics, and other disciplines. GaAs, InP, and GaN-based HEMTs will continue their journey toward higher integration, higher frequency, higher power, higher efficiency, lower noise, and lower cost. GaN, in particular, offers high-power, high-frequency territory of vacuum tubes and leads to lighter, more efficient, and more reliable communication systems.

HEMTs will continue to mold themselves into other kinds of FETs that will exploit the unique properties of 2DEG in various materials systems. In power electronics, GaN-based HEMTs can create a great impact on consumer, industrial, transportation, communication, and military systems. On the other hand, MOS-HEMT or MISFET structures are likely to be operated in enhancement mode with very low leakage current.

Si CMOS technology is rapidly advancing toward 10 nm gate regime. To achieve this, power dissipation management in future generation ultra-dense chips will be a significant challenge. Operating voltage reduction may be a solution to meet this challenge. However, currently, it is difficult to accomplish this with Si CMOS while maintaining quality performance. Quantum well-based devices such as InGaAs or InAs HEMTs offer very high potential. Therefore,

HEMTs may extend the Moore's law for several more years which will be gigantic for the society.

From the past, it can be anticipated that, researching on new device models and structures of HEMTs will definitely result in new insights into the often bizarre physics of quantized electrons. ZnO, SiGe, and GaN have shown fractional quantum Hall effect (FQHE), the greatest exponent for impeccable purity and atomic order, which ensure the bright future of HEMT devices .

The concept of different kinds of physical and biosensors are still very new to these kind of devices. The ultra-high mobility that is possible in InAlSb/InAsSb-based system enables high-sensitivity micro-Hall sensors for many applications including scanning Hall probe microscopy and biorecognition . Three-axis Hall magnetic sensors have been reported in micromachined AlGaAs/GaAs-based HEMTs . These devices may be used in future electronic compasses and navigation. THz detection, mixing and frequency multiplication can also be used by 2DEG-based devices . GaN and related materials have strong piezoelectric polarization, and they are also chemically stable semiconductors. Combining functionalized GaN-based 2DEG structures with free-standing resonators, there is a possibility of designing sophisticated sensors . These can offer methods of measurements of several properties such as viscosity, pH, and temperature.

Without references, expansion of this technology in the

machine to machine (M2M) field is expected to be used in cloud networking-based various sensing functions. Diverse applications such as environmental research, biotechnology, and structural analysis can be greatly benefited with the help of newly emerged sensing technology which has high speed, high mobility, and high sensitivity characteristics. HEMT technology is expected to make a great change in the intelligent social infrastructure from the device level. A smart city system, transport system, food industry, logistics, agriculture, health welfare, environmental science, and education systems are examples where this technology can make exceptions .

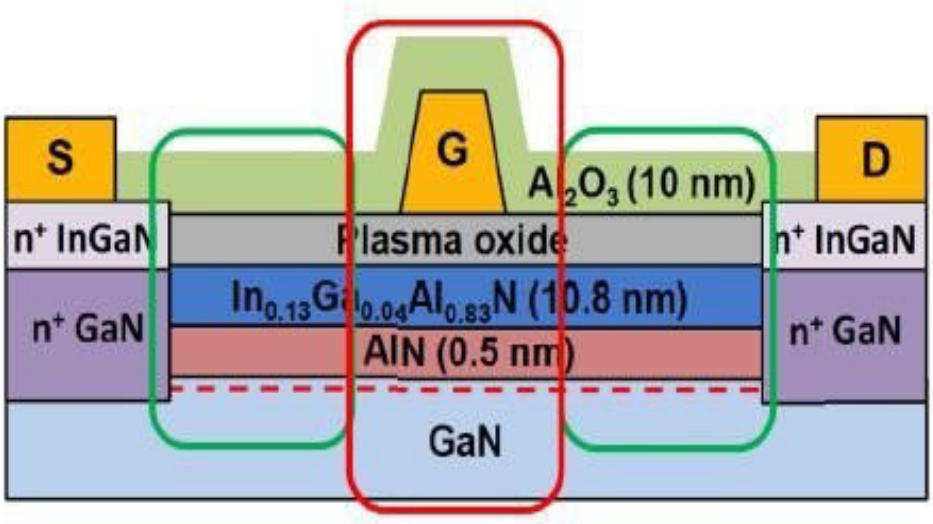
The rise of III-N-based solid-state lighting will lead to a continuous development of materials, substrates, and technologies pushed by a strong consumer market. In an analogy, III-N optoelectronics will challenge the light bulbs, while III-N electronics will challenge the electronic equivalent, the tubes .

PHYSICAL EFFECTS UNIQUE TO GAN

While charge and transport in GaN HEMTs are similar to HEMTs of other material systems, some properties are unique to GaN HEMTs. They are briefly described in this section.

Access regions

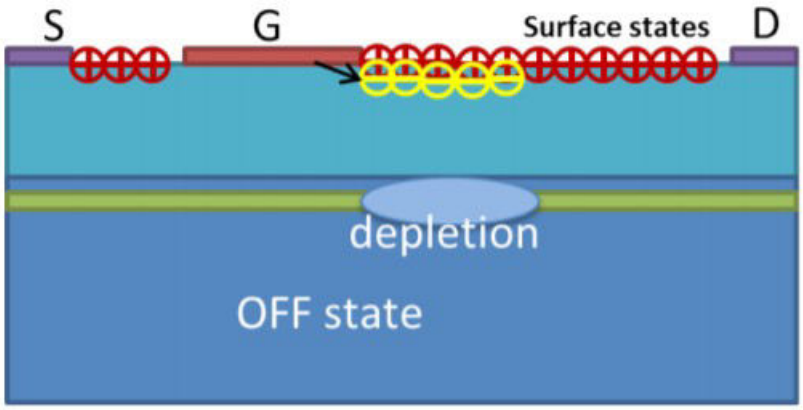
GaN HEMTs usually have Schottky gates and the source and drain are not selfaligned to avoid gate leakage. Even in cases where devices have gate dielectric, e.g. the devices fabricated at MIT currently do not have self-alignment. This results in 25 source and drain access regions which are essentially un-gated heterostructure regions .



Structure schematic showing different regions of interest (a) red-intrinsic transistor (b) green-access regions

Trapping effects

Charge trapping, current collapse or knee walk-out is a much discussed nonideality of GaN HEMTs . Simply put, current collapse is the increase in on-resistance and reduction in on-current during pulsed switching conditions. The effect is severe when the gate is biased to large negative voltages and the drain is biased to large positive voltages before switching. Several mechanisms have been proposed for this effect. Some of them include charging of virtual gate, gate-bias-induced nonuniform strain,and hot electron injection and trapping in the buffer. The theories are still controversial but the explanation of virtual gate charging appears most convincing. Figure below depicts a rough schematic of this scenario. Since the 2DEG in the channel of a GaN HEMT is created by donor type surface states, any impact on the surface states reflects in the 2DEG charge density. In the virtual gate charging scheme, the electrons from the gate compensate some of the surface states in the drain access region adjacent to the gate electrode. This results in the creation of a depletion layer in the channel next to the gate in the drain access region. This region is therefore like a virtual gated region which increases the drain access region resistance causing current collapse. This trapping effect is still to be incorporated in the model.



Schematic showing the reason for dynamic R_{on} effects.

RF APPLICATIONS OF GaN

Although gallium nitride is often associated with classic RF applications, such as power amplifiers (PA), there are numerous other significant applications of this innovative material. The ever-increasing levels of power and efficiency achieved by these devices are making them attractive, particularly in applications in the space and military sector (especially for military grade radars). Robustness, excellent thermal performances, reduced weight and dimensions, allow this material to be a better choice on other types of competing technologies even in low frequency RF applications. In military radars, when operating on frequency bands of different gigahertz, gallium nitride has proven to be the ideal solution for making solid state transmitters, replacing legacy technology based on klystron tubes. The latest generation military radars, operating with electronically scanned arrays (AESAs) and phased array modules, will greatly benefit from the availability of GaN-on-SiC based monolithic microwave integrated circuits (MMICs). The applications of GaN technology are not limited, however, to the space sector and military radar. In

the field of telecommunications, with mobile telephony in particular, this material is used to create various innovative solutions, such as those which underpin 5G technology. Gallium nitride-based components are progressively replacing traditional silicon-based ones in specific applications such as RF amplifiers and phased antenna arrays. The superior characteristics of GaN prove to ideal for an efficient management of both the sub-6-GHz band and the one above 20 GHz (millimeter waves, or mmWave). To meet the stringent requirements of the 5G network (fast data rate, large scale broadband and low latency), innovative technologies such as GaN, which are capable of operating at high frequencies (28 GHz and 39 GHz), are needed as they reduce the size of the receiving antennas as much as possible

REFERENCES

1) Wolfspeed, NC, 27709, USA. [Online]. Available: https://www.wolfspeed. com/rf/applications .

2) Golio and J. Golio, RF and Microwave Applications and Systems. CRC Press, 2008.

3) k J. Chen, O. H¨aberlen, A. Lidow, C. lin Tsai, T. Ueda, Y. Uemoto, and Y.-F. Wu, “GaN-on-Si Power Technology: Devices and Applications,” IEEE Trans. Electron Devices, vol. 64, no. 3, pp. 779–795, 2017.

4)J. M. Tirado, J. L. Sanchez-Rojas, and J. I. Izpura, “Trapping Effects in the Transient Response of GaN/GaN HEMT Devices,” IEEE Trans. Electron Devices, vol. 54, no. 3, pp. 410–417, Mar. 2007.

5)‘Modeling GaN: Powerful but challenging’-D. Lawerence et al., IEEE microwave magazine, Oct-2010.

6)L. D. Nguyen, A. S. Brown, M. A. Thompson, L. M. Jelloian, textit50-nm self-aligned-gate pseudomorphic AlInAs/GaInAs high electron mobility transistors,IEEE Trans. Electron. Dev. 39, 2007 (1992)