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Analysis and Characterization of Normally-Off Gallium Nitride High Electron Mobility Transistors

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Abstract: High electron mobility transistor (HEMT) based on gallium nitride (GaN) is one of the most promising candidates for the future generation of high frequencies and high-power electronic applications. This research work aims at designing and characterization of enhancement-mode or normally-off GaN HEMT. The impact of variations in gate length, mole concentration, barrier variations and other important design parameters on the performance of normally-off GaN HEMT is thoroughly investigated. An increase in the gate length causes a decrease in the drain current and transconductance, while an increase in drain current and transconductance can be achieved by increasing the concentration of aluminium (Al). For Al mole fractions of 23%, 25%, and 27%, within Al gallium nitride (AlGaN) barrier, the GaN HEMT devices provide a maximum drain current of 347, 408 and 474 mA/μm and a transconductance of 19, 20.2, 21.5 mS/μm, respectively. Whereas, for Al mole fraction of 10% and 15%, within AlGaN buffer, these devices are observed to provide a drain current of 329 and 283 mA/μm, respectively. Furthermore, for a gate length of 2.4, 3.4, and 4.4 μm, the device is observed to exhibit a maximum drain current of 272, 235, and 221 mA/μm and the transconductance of 16.2, 14, and 12.3 mS/μm, respectively. It is established that a maximum drain current of 997 mA/μm can be achieved with an Al concentration of 23%, and the device exhibits a steady drain current with enhanced transconductance. These observations demonstrate tremendous potential for two-dimensional electron gas (2DEG) for securing of the normally-off mode operation. A suitable setting of gate length and other design parameters is critical in preserving the normally-off mode operation while also enhancing the critical performance parameters at the same time. Due to the normally-on depletion-mode nature of GaN HEMT, it is usually not considered as suitable for high power levels, frequencies, and temperature. In such settings, a negative bias is required to enter the blocking condition; however, in the

before-mentioned normally-off devices, the negative bias can be avoided and the channel can be depleted without applying a negative bias.

Keywords: High electron mobility; GaN; HEMT; bipolar transistors gallium nitride; heterojunctions; MOS devices

1 Introduction

Today 40% of the energy consumed in the world is shared by electric energy. This share is anticipated to increase further about by 60% in 2040 [1]. Modern societies will strongly depend upon the production and management of electric energy. The electricity not only will have to be produced with environmentally friendly approaches (e.g., favouring the renewable energies) but also will have to be distributed and used more efficiently. Power Electronics is a key technology between energy generation and end-user. Power electronic devices do energy conversion from direct current (DC) to alternating current (AC), AC to DC and DC to AC according to requirements [2]. A large portion (up to 54%) of the energy is dissipated in Silicon (Si) devices during electricity conversion processes [3]. Swapping Silicon with wide bandgap semiconductors such as silicon carbide (SiC) and gallium nitride (GaN) in power electronics can minimize 20%–25% of the overall electricity consumption worldwide (with a potential saving of more than $30 billion/year) [4]. We can save energy with power electronic devices by reducing the power loss and retaining the higher conversion efficiency. The demand for highly efficient power electronic application goes on increasing in consumer electronics with an increase in power consumption. The silicon-based devices can't be able to meet all requirements of higher voltage, higher current, large switching frequency and higher efficiency.

As compared to silicon, the energy bandgap of GaN is 3.4 eV which lies in wide bandgap semiconductors and due to this reason gallium nitride high electron mobility transistor (GaN HEMT) can be operated at high temperature, higher breakdown field, low on-resistance and high Baliga figure of merit (BFOM) [5]. Material characteristics have a very significant influence on the fundamental features of the device. Fig. 1 represents the comparison of four materials Si, SiC, GaN and gallium arsenide (GaAs) in terms of the electric field, saturation velocity, melting point and thermal conductivity. GaN has higher electric field and electron peak velocity which results in higher electron mobility and low leakage current [6]. Moreover, GaN functions at high voltages with low leakage current due to its higher breakdown electric field and it also operates in higher frequencies because of its high electron mobility [7]. GaN represents excellent electrical and physical characteristics than silicon. GaN is an exceptional material for large power and high-frequency devices [8].

GaN HEMTs are very similar to traditional field-effect transistors (FET). Like FET it has also three terminals drain, source and gate which represent the subcategory of voltage-controlled Power switches. The difference is, in HEMT we are using the heterojunction in between GaN and aluminium gallium nitride (AlGaN) instead of a doped region in FET. Because of two operating modes of GaN HEMTs, these are divided into two types of categories such as depletion-mode or normally-on and enhancement-mode or normally-off. In the case of depletion-mode of GaN HEMTs, the source and drain electrodes are placed in the barrier layer of AlGaN which is on the uppermost side of GaN transistor to build the ohmic contact with two-dimensional electron gas (2DEG) which is below the AlGaN layer [9]. In radio frequency (RF) applications, the depletion-mode of GaN HEMTs is frequently used as power amplifies but has restricted applications in power converters or power electronics [10].
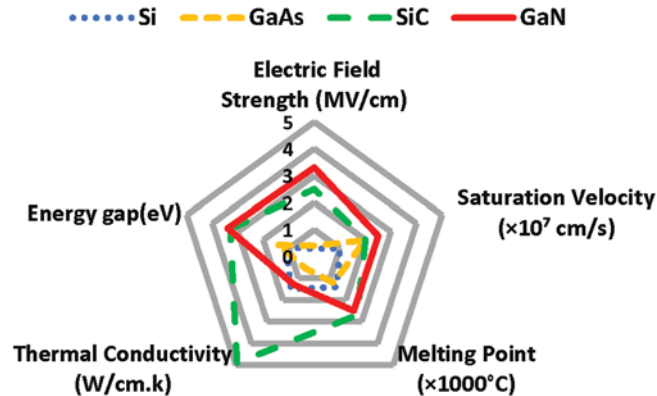
Figure 1: Material characteristics of GaN and Si [7]

In the field of power electronics, during start-up of power converters, a negative bias should be induced in gate otherwise a short circuit will happen. But enhancement-mode can be used in power electronics application or power converters because this normally-off device would not experience this constraint. Enhancement-mode of GaN HEMTs performs in an analogous way to metal-oxide field-effect transistors (MOSFET) in which channel is not built-in like normally-on GaN transistors, therefore, the positive voltage is applied at the gate terminal connecting the source. This positive voltage attracts the electrons to form a bidirectional channel between the source and drain. The entire resistance of the conducting channel becomes minimum because of these electrons which are pooled in the 2DEG [11]. The device remains on till the positive voltage connected to the gate terminal. Whenever voltage is detached from the gate, the device turns into off condition because electrons beneath it disperse, removing the conductive channel. In other words, if the gate bias entails the negative voltage, then the design is described as a Depletion-mode design of HEMT. The electron carrier's density inside the channel relies on the voltage which has employed at the gate terminal [12]. The recent developed GaN HEMTs models cannot work as a comprehensive design for GaN RF devices and GaN power devices due to the complexity in the design construction. Various ML algorithms predict the output of a GaN HEMT device by mapping the data into decision models [13].

This paper is focused on designing and analysing the appropriate model of normally-off GaN HEMTs with considering the suitable structural parameters such as gate length, aluminium mole concentrations, buffer and barrier variations. The impact of these variations will be inspected on electrical parameters such as drain current, transconductance and gate voltages. This paper is arranged as follows. Section 2 reviews the detailed study of the evaluation of GaN HEMT technology and a brief history of how normally-off structures were implemented with different techniques. Section 3 introduces the device simulation mechanisms and deals with the implementation of a GaN HEMT structure using p-GaN gate technique to make device normally-off. Two normally-off structures are studied and discussed in this section and their characteristics curves are also analyzed. In Section 4, structural parameters are varied to analyse the impact on electrical parameters. The effects of drain current on variations of aluminium concentrations in buffer and barrier are investigated. Section 5 represents the effects of gate length on the drain current. Section 6 discusses the effect of gate length and aluminium concentrations on transconductance. Section 7 concludes the overall contribution of the paper.

2 Background, State-of-the-Art and Future Outlook

In the power electronics industry, silicon power devices have dominated the 20th century. In the 1950s, bipolar power transistors (BJT) and Silicon controlled rectifier (SCR) were introduced. Power electronics industry migrates to metal oxide silicon transistor (MOS) gated devices in the 1980s. Those applications which operate at a power supply voltage below 220 V, silicon power MOSFET turn into a well-known device of choice. To remove most of the defects in silicon power devices such as high on-state resistance insulated gate bipolar transistor (IGBT) was introduced in the 1980s [14]. IGBTs minimizes the cost and reduces the extent of power electronic circuitry by developing it more efficient technology for consumer and industrial users along with minimum on-state voltage drop and excellent performance. To displace the broadly acknowledged technology, new technology must propose significant perfections to the reduction in the on-state voltage and switching losses, while preserving all the additional features [15]. Countless innovative concepts were anticipated and established for silicon power devices that were accessible as products in the 1990s. For any novel anticipated expertise, it is necessary to exceed the fulfilment of not only the old silicon power devices but be capable to contend with these more eminent productions of silicon devices as well [14]. Based on elementary material properties of semiconductors, the first examination related to the performance of power devices was established in 1980 and published in 1982. To estimate the possible developments in the on-state resistance of FET based power devices by adding silicon with different semiconductor substances formed a simple equation, now usually referred to as BFOM. By swapping silicon with GaAs, this examination showed 13.7-times improvement. GaAs based power devices beginning to emerge as a direct result of estimation in the 1980s [16].

Afterwards, GaAs power rectifiers having a breakdown voltage of 200 V have been developed and accessible from numerous companies. Swapping silicon with extensive bandgap semiconductor corporeality, these strategies represent the first-power semiconductor products [17]. In the 1990s, improvement of unipolar devices of the existing hexagonal silicon carbide (6H-SiC) polytype substance, BFOM for SiC provided the solid incentive for this cause. The initial device based on SiC for operating in high-voltage up to 400 V as a Schottky rectifier of SiC along with minimum on-state voltage drops up to 1 V is demonstrated by north Carolina state university (NCSU) in 1992 [18,19]. Attention in GaN raised in the 1990s because of its better capabilities for utilisation in the illumination and cellular amplifier industries [20]. Marketable products created with this substance have developed remarkable demands in these markets. Newly, important attention has arisen in exploiting the new substance for constructing power devices that might potentially reach the achievement of silicon-based power devices and be more extra cost effectual as compared to silicon carbide power devices [17]. The GaN HEMT has been under examination because of their outstanding performance in high power electronic devices. There is an essential need to understand the operation of the device by designing a model which could be used to enhance electrical features of GaN HEMT design for high power and high-frequency operation [21]. AlGaN/GaN heterostructures based HEMT have demonstrated greater performance than that of Silicon counterparts at larger voltage, greater current and higher frequency and temperature [22]. This material has a stronger electric field with the advantage of the more mobility and electron density of 2DEG developing at the AlGaN/GaN interface [23]. Normally-on mode AlGaN/GaN HEMT is utilized for those applications which require minimum voltage and limited frequency range. To use in power switching applications, enhancement-mode features are needed to assure secure handling because of higher voltage [24].

Many techniques have been developed to obtain the normally-off GaN HEMT. By applying the very small thin barrier layer of AlGaN with very depressed aluminium fractions, 2DEG depletion can be achieved. The first genuine solution anticipated for enhancement-mode of GaN HEMT was the depressed thin barrier layer below the critical thickness which is necessary for the generation of such channel in the region under the gate terminal [25]. Normally-off behaviour of GaN HEMTs can also be achieved by introducing the fluorine gas below the gate electrode [26,27]. Another approach of achieving the normally-off GaN HEMTs is to introduce the local surface oxidation methods or interjecting the nitric oxide (NiOx) based interlayer under the gate to obtain the positive Vth shift [28]. To overcome these various restrictions, the hybrid metal insulator semiconductor high electron mobility transistor (MISHEMT) structures were developed [29]. The AlGaN barrier layer is removed under the gate in this device establishing the channel employing a metal-insulator semiconductor (MIS) system. Therefore, this method associates the benefits of an enhancement-mode MIS channel having the least immunity of the 2DEG. Though, the selection of the dielectric sheet is very crucial in GaN power designs and also necessary for MIS HEMTs. It explicitly influences both the carrier movement and threshold voltage durability [30]. Possibly, the most capable technique is the usage of a p-GaN (or p-AlGaN) layer below the gate contact region on the interface of AlGaN/GaN heterostructure. Without the presence of an externally injected bias at gate terminal which means gate to the source, voltage is zero. The channel becomes depleted of carriers at (VG = 0) due to the advancement of band diagram. As a result, the exhaustion of the 2DEG channel occurs in this case. This method is getting a great consideration within the scientific society because of this fact that barely "real" enhancement-mode of GaN HEMT which is accessible to date on a commercial level is based on a p-GaN gate. Although, enhancement-mode of HEMT technology with p-doped GaN is slightly complicated and HEMT performance can be significantly affected by numerous design and processing circumstances. Many other significant safety features connected to the enhancement-mode of p-GaN gate GaN HEMT technology with AlGaN buffer that includes threshold voltage and balance charge trapping tools [31].

The essential benefit of the GaN HEMT is that it has a considerably lesser figure of merit (FOM) than that of silicon super-junction (SJ) and SiC-MOSFETs [23]. The switching FOM is the multiplication of the gate charge and the resistance between the drain and source terminals in the on-state [32]. 2DEG is produced by polarization effects of heterojunction within GaN HEMT which shows the depletion-mode naturally normally-on behaviour of these devices that exclude them from most power electronics applications [33]. For normally-off enhancement-mode operation, the p-type layer of GaN or AlGaN is introduced under the gate metal in many reported researches. GaN-based power semiconductors are largely adjacent structures [34]. GaN HEMT models are usually analysed using Computer-aided design (CAD) based approaches.

3 Device, Design, Simulations and Characteristics

In this section, we present the design analysis of enhancement-mode of GaN HEMT using Technology computer-aided design (technology CAD or TCAD) which signifies a multipurpose plus flexible program intended for two- and three-dimensional design modelling. The electric characteristics of these enhancement-mode structures with different buffers, aluminium concentrations and gate lengths are scrutinized with the help of ATLAS simulator which is more compact and reliable. In this research, we consider the normally-off GaN HEMT model design in two-dimensional matrix-mesh format [35]. Every mesh point denotes a physical location inside the modelled design and program simulates transport characteristics through differential equations

resulting from Maxwell's equations at these mesh points [36]. Different numerical analyses are used to solve for electrostatic potential and carrier densities within the design. Most commonly used is the Newton Raphson method. Different parameters of normally-off GaN HEMT are studied such as gate length, transconductance, drain current, gate voltage, aluminium mole fraction and various other effects are also analysed while designing the enhancement-mode model.

Two normally-off structures have been analysed due to normally-on behaviour of GaN HEMT, using p-GAN gate where the gate is p-doped. One structure is designed using AlGAN buffer with AlGAN barrier and GaN channel. The second GaN HEMT structure is based on GaN buffer with AlGaN back barrier. The characteristic curves with AlGaN buffer are shown in Fig. 3. The curves are plotted on different gate voltages. The drain current rises with growing gate voltage at static drain voltage or fixed gate voltage with increasing drain voltage. With higher gate voltages, more electrons are attracted into the bidirectional channel. This increased electron density drives to accretion in drain current. The dimensions of the GaN HEMT device structure With AlGaN Buffer are as follows [37]:
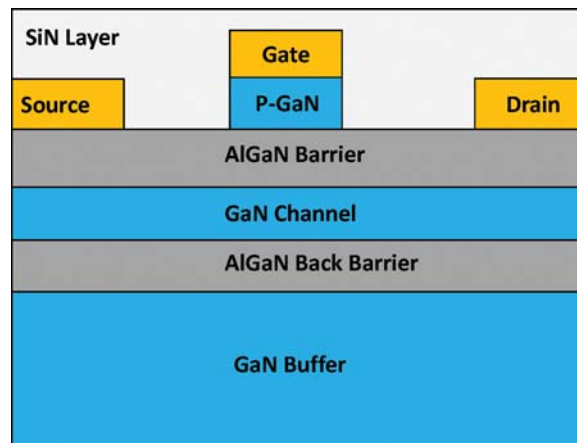

Figure 2: The cross-sectional view of proposed GaN HEMT structure

- Source and drain lengths are 1 μm and widths are 110 nm.
- Gate length is 1.4 μm and Width is 100 nm.
- P-GaN layer length underneath the Gate is equal to gate length but width is 110 nm.
- The lengths of Al0.05GaN0.95 Buffer, GaN Channel, Al0.23GaN0.95 Barrier, and SiN Layer are 10.4 μm which is equal to device length.
- The width of Al0.05 GaN0.95 Buffer is 2 μm.
- The width of the GaN Channel is 35 nm.
- Width of Al0.23 GaN0.95 Barrier is 15 nm.
- The width of the SiN Layer is 35 nm.
- The total device width is 2.36 μm. Spacing between the source to the gate is 2 μm but the gate to drain is 5 μm.

Another structure of enhancement-mode GaN HEMT transistor for power electronic application with the modified GaN buffer and AlGaN back-barrier is manifested. It is also converted into normally-off mode by introducing a p-GaN layer underneath the gate which depletes the channel when the device is off [38]. By introducing the GaN buffer with AlGaN back-barrier, the device

becomes more compatible with power electronic applications due to despicable on-state resistance, the higher threshold voltage and securing the normally-off operation. The cross-sectional view of the proposed structure is shown in Fig. 2 and its characteristic curves are shown in Fig. 3.
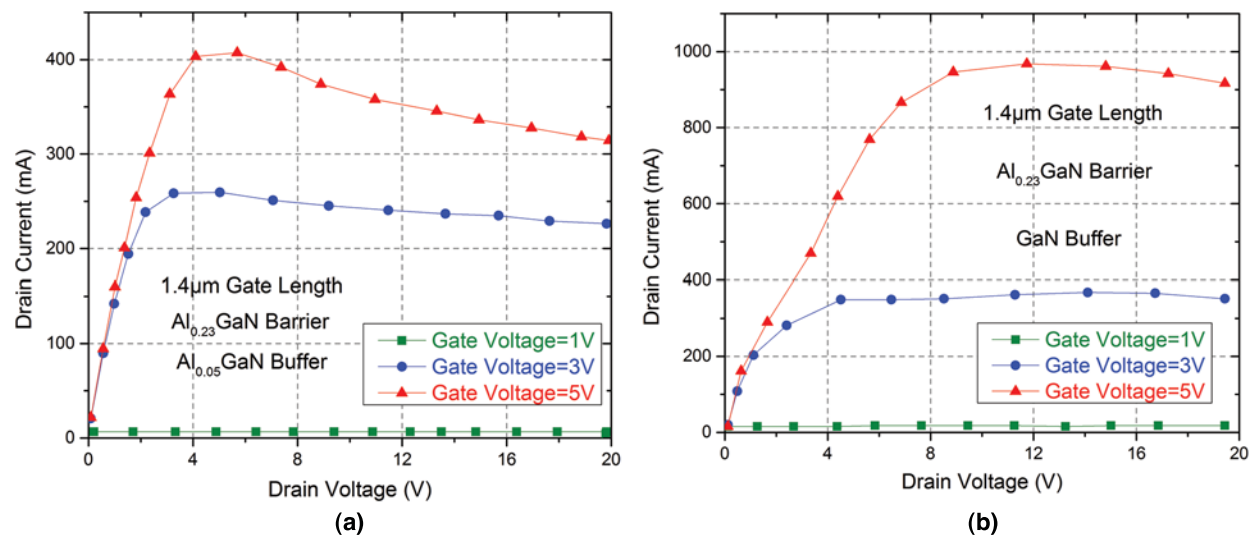
Figure 3: Simulation results for the impact of Drain Voltage and Gate Voltage on Drain Current for the proposed GaN HEMT. (a) AlGaN buffer, (b) GaN buffer

Theses curves are also taken from three different gate voltages 1 v, 3 v and 5 v. In the enhancement-mode structure, we have to apply the positive source to the gate voltage. The positive voltage at the gate terminal produces the quantum well at the interface of AlGaN and GaN structure. The electrons are attracted to that quantum well which leads to the formation of 2DEG. Higher the positive voltage, higher will be the depth of quantum well and more will be the drain current. This structure gives a higher drain current as compared to the previous model with the same conditions. The high electron density is achieved in GaN HEMT because electrons flow within the bidirectional channel separate from their donor atoms which minimize the collisions and scattering of electrons [39]. As a result, the mobility of electrons has been increased. This high mobility electrons start penetrating GaN buffer under the GaN channel and their mobility is reduced inside the buffer. The concentration of electrons within the channel is also reduced. Therefore, AlGaN back-barrier is introduced underneath the channel to concentrate the electrons within the channel [40]. AlGaN back-barrier has higher energy level as compared to the channel and electrons from the channel cannot jump to this barrier. The dimensions of the proposed device structure for GaN HEMT With GaN Buffer are as follows:

- Source and drain lengths are 1 μm and widths are 110 nm.
- Gate length is 1.4 μm and Width is 100 nm
- P-GaN layer length underneath the Gate is equal to gate length but width is 110 nm.
- The lengths of Al0.05GaN0.95 Buffer, GaN Channel, Al0.23GaN0.95 Barrier, SiN Layer are 10.4 μm which is equal to device length.
- The width of the GaN buffer is 2 μm.
- The width of the Al0.05GaN back-barrier is 35 nm.
- The width of the GaN Channel is 15 nm.

- Width of Al0.23GaN0.95 Barrier is 15 nm.
- The width of the SiN layer is 295 nm.
- The total device width is 2.36 μm. Spacing between the source to the gate is 2 μm but the gate to drain is 5 μm.

4 Effects of Aluminium Mole Fractions

The HEMT construction is based on phenomena of high electron mobility which described as 2DEG because of development of heterostructure in between the AlGaN and GaN [41]. 2DEG flows in between this region of AlGaN and GaN. Due to placing the p-GaN under the gate, when 2DEG is unbiased, p-GaN layer accumulates the positive charge due to the impurity of a p-type semiconductor, these positive charges deplete the electrons within the channel [42]. When two different materials having large bandgap are combined while keeping equivalent crystal structure, a heterostructure is formed and energy discontinuity is created in a band diagram. In conduction band, the notch is produced and in the valence band, the valley is produced due to bandgap discontinuity [31]. The difference of lattice constant determines the quality of junction produced between such materials. Two materials having a larger difference between lattice constants, there is a larger prospect of the interface defect [43]. The similarity in lattice constant is an essential condition to develop suitable heterojunction and excellent heterostructure based design. If we are combining the corporealities such as AlGaN and GaN, the only constraint which is to be measured is the composition of aluminium since it expresses the bandgap energy and lattices constant of AlGaN [44]. Variations of aluminium mole fraction exhibit different effects on AlGaN barrier and buffer.
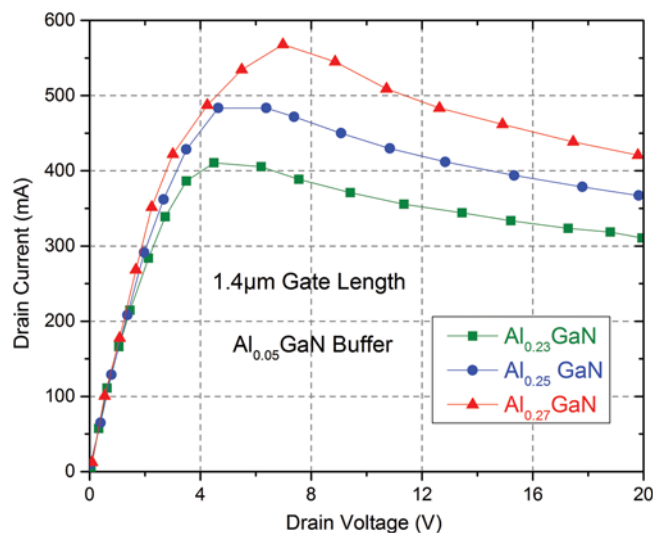
4.1 Barrier Effects

Initially, we examine the effects of aluminium mole fraction (typically in the range from 15%–20%) on AlGaN GaN-based GaN HEMT. In the heterojunction transistor, two materials with different bandgaps, ensures that the work functions and electron affinities are combined. Electrons are transferred from material to another. The material that donates electrons has to be a higher bandgap and work function material as compared to that material which accepts the electrons. The larger the bandgap difference between the materials, more electrons will be transferred to the other material to balance the energy level and hence more will be the current. The bandgap of AlGaN can vary from 3.4 eV to 6.2 eV depending upon the aluminium concentrations. The resulting band structure of any heterojunction transistor estimates the electrical behaviour of any device. The higher bandgap is produced with an increase in aluminium mole concentration in AlGaN barrier layer which leads to more increase in conduction band discontinuity that appears in greater confinement of carriers in the channel in between AlGaN and GaN, providing large mobility to accompany with a high electron density [44].

Effect of aluminium concentration in the barrier layer of GaN HEMT with (20% or higher) was recorded in the last few years. It is necessary to examine systematically the dependency of aluminium mole fraction in the barrier layer of GaN HEMT. The structure parameters such as aluminium mole concentrations are to be varied to study the effects on electrical parameters such as drain voltage and current as well as gate voltage and current. We can control the drain current by varying the aluminium fractions. Drain voltage and drain current are directly proportional to each other. If we kept the gate voltage constant, drain current tends to increase with an increase in drain voltage. The gate voltage is also proportional to the drain current. If we increase the gate voltage by keeping the drain voltage constant, drain current increases. Simulation results

show the drain current also increases with an increase in aluminium concentration in the AlGaN barrier [45].

The maximum drain current is 347 mA with the aluminium mole fraction of 0.23. The drain current increases up to 408 mA with the aluminium mole fraction of 0.25 which further increases up to 474 mA with the aluminium mole fraction of 0.27 as shown in Figs. 4 and 5. Electron density in the 2DEG of the transistor channel is reduced giving high threshold voltage due to low aluminium concentrations in AlGAN barrier. The drain current goes on in-creasing with increasing aluminium fraction in the barrier [46]. These results are taken by applying the three different aluminium concentrations with fixed drain voltages. These show that, with an increase in aluminium concentrations, more electrons accumulate in the bidirectional channel and drain current increases with it. Hence, relatively high aluminium mole fraction is introduced within the AlGaN barrier to achieve high electron density in 2DEG within GaN channel [42].

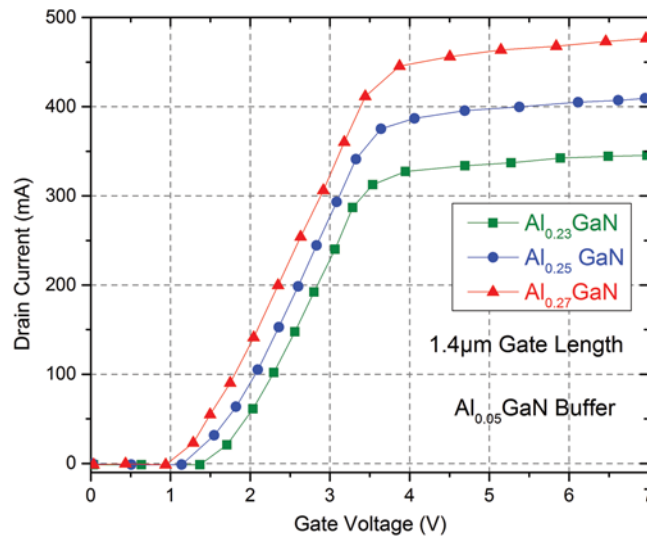**Figure 4:** Effects of aluminium concentration in AlGaN barrier (drain voltage *vs.* drain current)

4.2 Buffer Effects

The Effect of aluminium fractions in the buffer is quite different as compared to the barrier.

The drain current decreases with more addition in aluminium mole fractions [47]. With an increase in aluminium concentration in AlGaN buffer, the buffer energy level is enhanced due to the increase in the bandgap. Since electrons tend to transfer from higher bandgap material to the lower one.

Therefore, now electrons are transferred from AlGaN buffer to the GaN Chanel in which 2DEG is already built-in due to electrons. The scattering of electrons has been increased due to repulsions and collision effects. If the buffer layer energy level equals to channel, some electrons enter into the buffer from the channel due to high mobility of 2DEG. Hence AlGaN buffer must have the slighter higher energy level than the GaN channel to avoid these penetrations. Back-barrier of higher bandgap with GaN buffer can also be used. Neither electrons from the GaN channel nor GaN buffer can cross back-barrier. Mobility of electrons and drain current are increased in these configurations. The maximum drain current is 342 mA with the aluminium

mole fraction of 0.07 and maximum drain current decreases to 329 mA with the aluminium mole fraction of 0.10 which further decreases to 283 mA when aluminium mole fraction further increases to 0.15 as shown in Figs. 6 and 7. Drain current reduces due to the reduction in electron density within the channel between the AlGaN and GaN. The electron density within the channel is slightly reduced due to the increase in aluminium concentration in the buffer of GaN HEMT. Hence a minimum aluminium concentration in AlGaN buffer underneath the GaN channel is subject to obtain the high electron density in 2DEG [48].

Figure 5: Effects of aluminium concentration in AlGaN barrier (gate voltage *vs.* drain current)
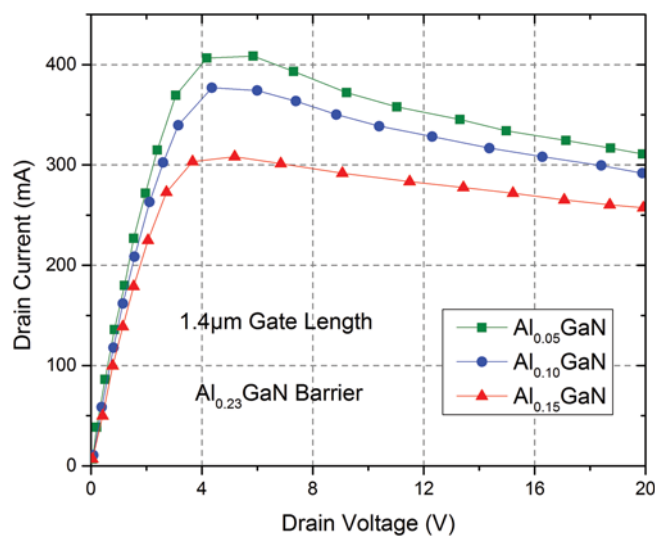
Figure 6: Effects of aluminium concentration in AlGaN buffer (drain voltage *vs.* drain current)
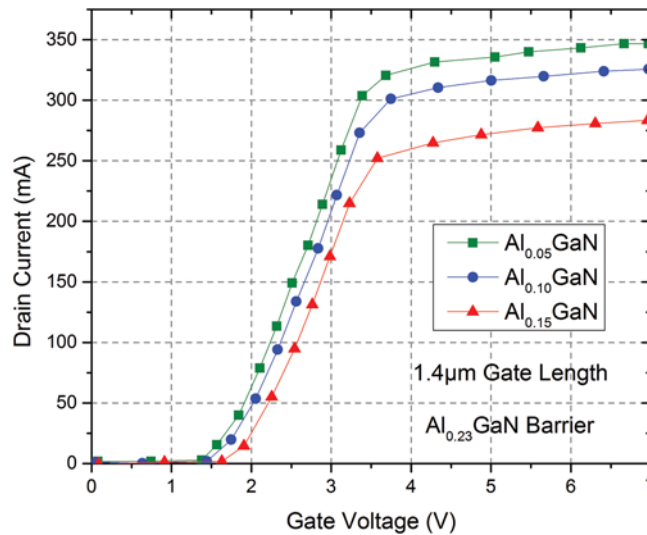
Figure 7: Effects of aluminium concentration in AlGaN buffer (gate voltage *vs.* drain current)

5 Effects of Gate Length on Drain Current

Influence of variation in p-GaN gate dimension has studied to understand the reliability of this device. By increasing the gate length, drain current decreases because of lowering the density of 2DEG within the channel under the gate that diminishes the drain current. The reduced gate length is larger acceptable for power electronic applications [49].

The drain current (Id) is represented in the equations given below according to the article of Charfeddine et al. [50].

$$I_d = \frac{zuB_e}{Lg}\left(v_g - v_{th} - \frac{v_d}{2}\right)v_d \tag{1}$$

In above relations, Lg represents the gate length, Vg, V_{th} and V_d represent the gate voltage, threshold voltage and drain voltage respectively. Z is channel width and μ is the mobility of carriers.

$$I_{ds} = BuF\left(\sqrt{(v_g - v_{th})^2 + F^2 L_g^2} - FL_g\right) \tag{2}$$

The maximum saturation drain current is represented in the above equation. Where F is the critical electric field. According to previous analytical modelling of Charfeddine, drain current and gate length are inversely proportional to each other. Drain current minimizes with increase in gate length. Simulation results have shown in Fig. 8 which matches with this analytical modelling that shows drain current reduces by increasing the gate dimensions. With the variation of 1 μm in gate length, the drain current reduces from 347 mA/μm to 272 mA/μm due to decrease in the deepness of quantum well. This is essentially due to the reduction of confinement of carriers because the gate length of the p-GaN gate is increased. This phenomenon leads to a reduction in the intensity of 2DEG within the GaN channel which indeed lessens the drain current inside the channel. From the simulation results shown below, it can be concluded that whenever the gate length is expanded to a certain limit, the chances of the controllability of the electric field has enhanced below the

channel generated by the gate contact. Therefore, Peak value of the electric field has reduced and it leads to increase the regularity of the electric field beneath the gate contact. The passage of electrons accompanying the 2DEG inside the channel becomes more complicated which leads to a decline in maximum current density. After a certain point, also known as an optimum point, there is less significant variation in the maximum current density when the gate length is increased beyond the optimum point. Because after achieving the minimum possible gate length, the electric field beneath the channel generated by gate contact takes no much variations.
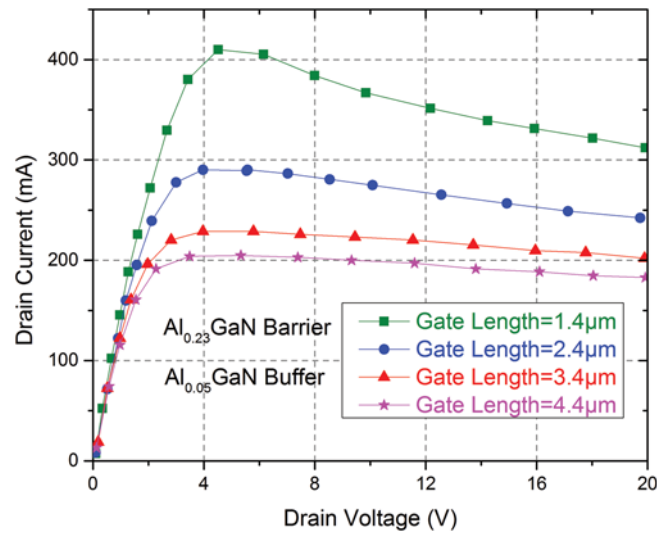
Figure 8: Effect of gate lengths on drain current (drain voltage *vs.* drain current)
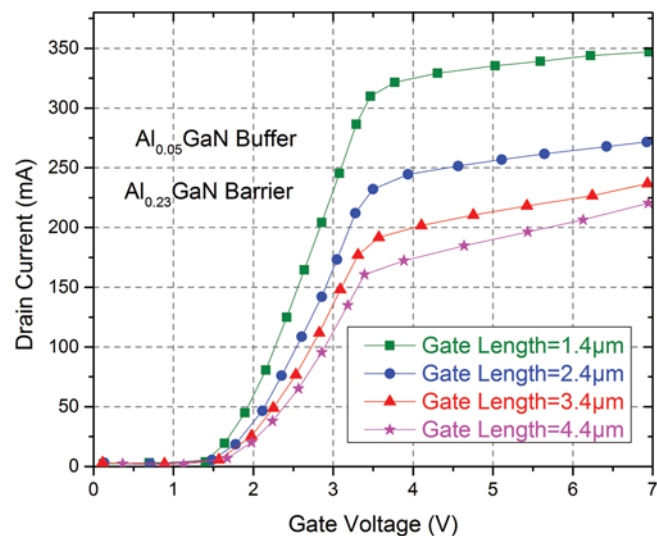
Figure 9: Effect of gate lengths on drain current (gate voltage *vs.* drain current)

Further, the drain current becomes 235 mA/μm when gate length increases to 3.4 μm. This is less decrease as compared to the previous one because more increase in gate length, the closer will be the optimum point. The drain current reduces to 221 mA/μm when the gate length is further extended to 4.4/μm as shown in Fig. 9.

6 Effects of Gate Length and Aluminium Concentration on Transconductance

Transconductance is the characteristic of several power electronic components. As Conductance is complementary of resistance, therefore, transconductance is the proportion of the variation in current at the output terminal to the variation in voltage at the input terminal. It is formulated as gm. Transconductance is the function of the gate length.

$$g_m = \frac{\Delta I}{\Delta v} \tag{3}$$

The transconductance modifications for varying gate lengths have conferred in Fig. 10. It has been observed that by increasing the gate length from 1.4 μm to 3.4 μm, the transconductance reduces due to decrease in the drain current with an increase in gate length. We can infer from these simulations result that minimum gate expansion is more suitable and compatible for immense power and switching applications.
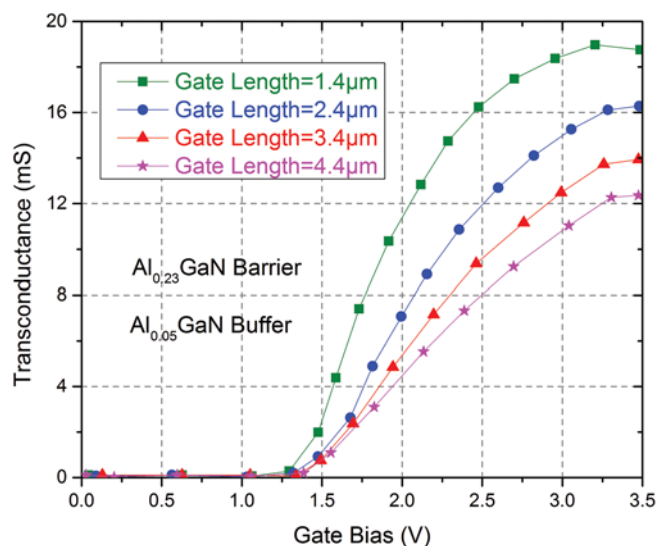

Figure 10: Effect of gate lengths on transconductance

From simulation results shown in Fig. 7 and also from previous obtained results it can be observed that after increasing the gate length with certain limit, the passage of electron in 2DEG is more complicated and due to this transconductance decreases similar to drain current. Transconductance decreases up to the optimum point after which there is no much variation of transconductance when the gate length is beyond the optimum point. At 1.4 μm gate length, the value of transconductance is 19 ms/μm which decreases to 16 ms/μm when the gate length is 2.4 μm but this decrease is much less as we further increase the gate length up to 4.4 μm. The transconductance modifications for varying aluminium concentrations in the AlGaN barrier have presented in Fig. 11. Since the drain current increases with an increase in aluminium

concentrations, therefore transconductance gradually tends to increase with an increase in drain current.
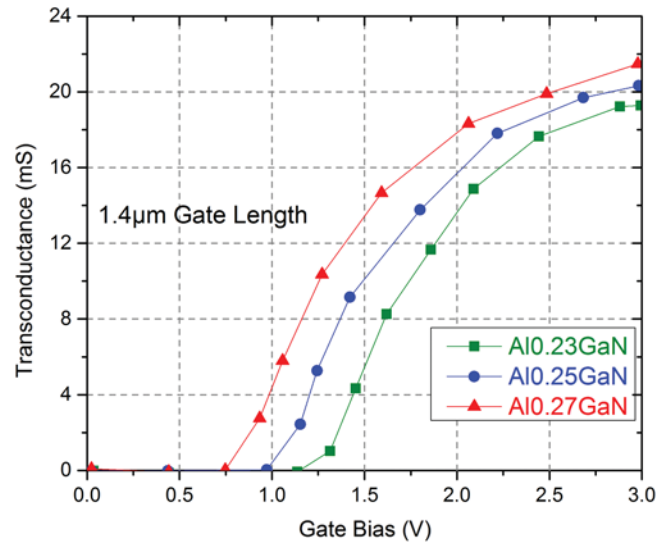
Figure 11: Effect of aluminium concentrations on transconductance

The conducted study is of high significance in designing the appropriate model of GaN HEMT for next-generation power electronics. This permits power electronic projects at higher frequencies that enable a reduction in the size and cost of devices. The smaller size of devices with high power rating revolutionizes the field of electronics. These devices can operate on high switching speed and having low leakage current due to reduction in intrinsic carrier concentrations. The conducted analysis can help in meeting the increasing stringent performance and design requirements of electronic materials in terms of higher conversion efficiency with lower energy loss, cost and size of power devices.

7 Conclusion

In this research work, the analysis of the proposed design of normally-off GaN HEMT has been presented for power electronic applications. The electrical parameters such as drain current, gate voltage and transconductance have been analysed by varying the structural parameters which include gate length, aluminium mole concentration in buffer and barrier and by applying the different types of buffers. With more addition of aluminium concentration in the buffer, the drain current can be reduced due to the decrease in the electron density within the channel. The drain current always tends to increase with an increase in aluminium mole concentrations within the barrier. The variation of gate length has also impacted on the behaviour of drain current. Drain current reduced with an expanding gate length up to an optimal length of the gate. After optimal length, a further increase in gate length could not cause a significant decrease in drain current. The same behaviour was observed with transconductance factor that reduced just like drain current with an expansion in gate length up to an optimal point. Transconductance can be increased gradually with increase in aluminium concentrations in the barrier. GaN buffer produced much better results and performance as compared to AlGaN buffer in terms of higher drain current

and higher breakdown voltage. So, the proposed design device can be operated at higher voltage, higher temperature and higher switching frequency. The suitable gate length, higher aluminium mole fraction in barrier but a lower aluminium fraction in the buffer and utilizing the GaN buffer instead of AlGaN buffer is more compatible to secure the normally-off operation for power electronic applications. This work will help fabricate the normally-off GaN HEMT for power applications experimentally.

Conflicts of Interest: The authors declare that they have no conflicts of interest to report regarding the present study.

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