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Analysis and Impact of Al mole concentration ‘x’ in Double Heterojunction AlGaN with Source and Gate Field plated HEMT for High breakdown and High Frequency applications

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Abstract

This paper investigates the variation of Al mole content/concentration in AlGaN buffer on the DC, Subthreshold Slope (*SS*), ON-state resistance (R_{ON}), RF performance and the impact of source and gate filed plate in OFF-state breakdown (BV_{OFF}) of AlGaN double heterostructure (DH) High Electron Mobility Transistor (DH-HEMT). The layer with AlGaN back-barrier/ buffer layer shows improved bottom potential barrier height at the backside of GaN channel creates confinement of charge carriers leads to high two-dimensional electron gas (*2DEG*). The proposed source and gate field plate in DH-HEMTs structure helps to increase the BV_{OFF} by modulating the distribution of electric field profile results in an increase of breakdown voltage with varying device geometry and a significantly reduced the OFF-state leakage current.

Keywords- AlGaN/GaN HEMT, Source field plate (SFP), Piezoelectric and Spontaneous Polarization, Heterostructure, power transistors, 2DEG.

1. INTRODUCTION

The GaN-based HEMT is a potential candidate for future high power switching transistor technology, because of the presence of high saturation velocity, and the high *2DEG* density at the hetero-interface. The device with AlGaN/GaN HEMT offers an excellent power handling capability by means of high breakdown critical field (3 MV/cm) and the potential to support a large channel current in the channel [1]-[3]. This proves the superiority of the devices for high frequency and power switching applications [1]-[4]. The device with lower BV_{OFF} restricts output power, device reliability, and consequently the implementation of GaN-based HEMT in high power switching, driver and control circuits [4]. Although there are several methods to increase the device BV_{OFF}, thus improving the performance of the device have been proposed [8], [14], the detailed device optimizations steps to improve breakdown mechanisms in these devices are not exactly known. The several mechanisms induce a breakdown in HEMTs, including excessive device leakage current, punch-through of electrons in the buffer underneath the gate, and finally the presence of an impact ionization effect in the channel. Breakdown voltage in GaN based HEMTs and other field-effect devices (*FETs*) is, in many cases, initiated by electron current underneath the gate depletion region of the transistor through the insulating buffer layer and known as space-charge injection of electrons into the GaN buffer layer [8], carrier spill-over [9], or buffer-layer punchthrough effect [10], [11]. The punchthrough of the electrons into the buffer causes rapid increase of the subthreshold drain leakage current.

In this paper, we present an improved bottom confinement by introducing an $Al_xGa_{1-x}N$ layer with increasing Al content 'x' in the buffer. A binary GaN interlayer between the AlGaN buffer and the barrier serves as a channel for the *2DEG*, i.e., we considered the combination as an AlGaN/GaN/$Al_xGa_{1-x}N$ DH-HEMT. To the best of author's knowledge, no theoretical study on the impact of source/gate field plate and influence of the 'x' in the $Al_xGa_{1-x}N$ buffer layer on device performance. In order to enhance the BV_{OFF} further, we propose a novel source and gate field plated AlGaN/GaN Single hetero (SH) and Double heterojunction (DH)-HEMT structures and the impact of Al mole concentration 'x' of $Al_xGa_{1-x}N$ buffer is analyzed for the first time.

2. DEVICE STRUCTURE AND PARAMETERS

The proposed structure includes a 1 µm $Al_xGa_{1-x}N$ back-barrier/buffer layer with different mole concentrations from x = 0%, 4% and 8%, a 10 nm GaN channel layer, 16 nm/2 nm $Al_{0.2}Ga_{0.8}N$ barrier/ spacer layers. Below the gate, there is a 3 nm GaN cap layer with n-type doped concentration of 5×10^{18} cm^{-3} and 50 nm silicon nitride (SiN) passivation. The separation of source to gate (L_{gs}) and gate to drain (L_{gd}) is 1 µm and 6 µm respectively, and the gate length L_g is 0.8 µm, gate field extension L_{GFP} of 0.5 µm and a source field extension $L_{SFP} = L_{gs}+L_g+L_{GFP}$. The regions with high doping are created under the source/drain electrodes down to the GaN channel to control contact resistance with source and drain contact length L_s/L_d = 0.5 µm. A double heterostructure (DH) is formed by inserting a thin GaN layer grown in between two AlGaN layers, which we call the channel layer. The top AlGaN layer is called barrier layer and the bottom one is called a buffer layer [5]. Due to the presence of polarizations in wurtzite crystal structure of GaN, it induces a positive and a negative charge created at the heterointerface between the AlGaN barrier/ GaN channel and GaN channel/ AlGaN buffer layer [6]. In SHFET only a positive charge emerges at the AlGaN barrier layer and the GaN layer heterointerface [5]–[7]. The most important feature of the DH-HEMT is the enhancement of the 2DEG mobility and of the 2DEG electron distribution.

3. RESULTS AND DISCUSSION

For the AlGaN DH-HEMT and SH-HEMT buffer structure, a 1-μm-thick Unintentionally-doped (UID) doped $Al_xGa_{1-x}N$ buffer with x % of 0%, 4%, and 8% at the buffer interface to the GaN channel layer was discussed. All devices had a 10-nm UID GaN channel layer and 2 nm $Al_{0.2}Ga_{0.8}N$ spacer layer, followed by 16 nm $Al_{0.2}Ga_{0.8}N$ barrier layer is shown in Fig 1. To assess the impact of the AlGaN buffer x-mole concentration in source and gate field plated AlGaN DH-HEMT, the simulations are performed using the hydrodynamic (HD) model and analysis is performed using a Sentaurus TCAD simulator.

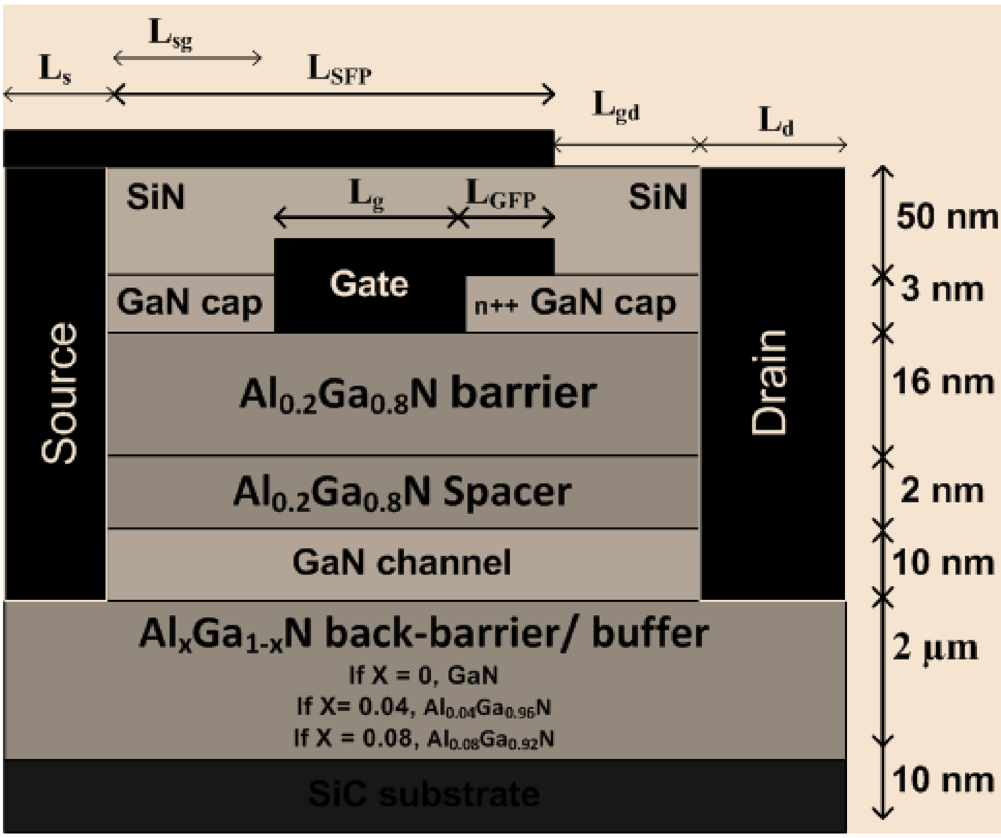

Fig 1: Schematic cross-sectional view of the proposed source and gate field plated DH-HEMTs with different Al mole concentration in $Al_xGa_{1-x}N$ back-barrier/ buffer.

The calibration and validation of simulation deck is performed by comparing our transfer characteristics of drain current (I_{ds}) versus gate-voltage (V_{gs}) in linear scale are well-matched to the reported measured data of [1] as shown in Fig. 1a. After achieving the matching, the model is applied for simulating our proposed source and gate Field-plated SH and DH-HEMT with different mole concentrations in $Al_xGa_{1-x}N$ buffer, which also has a similar material combination.

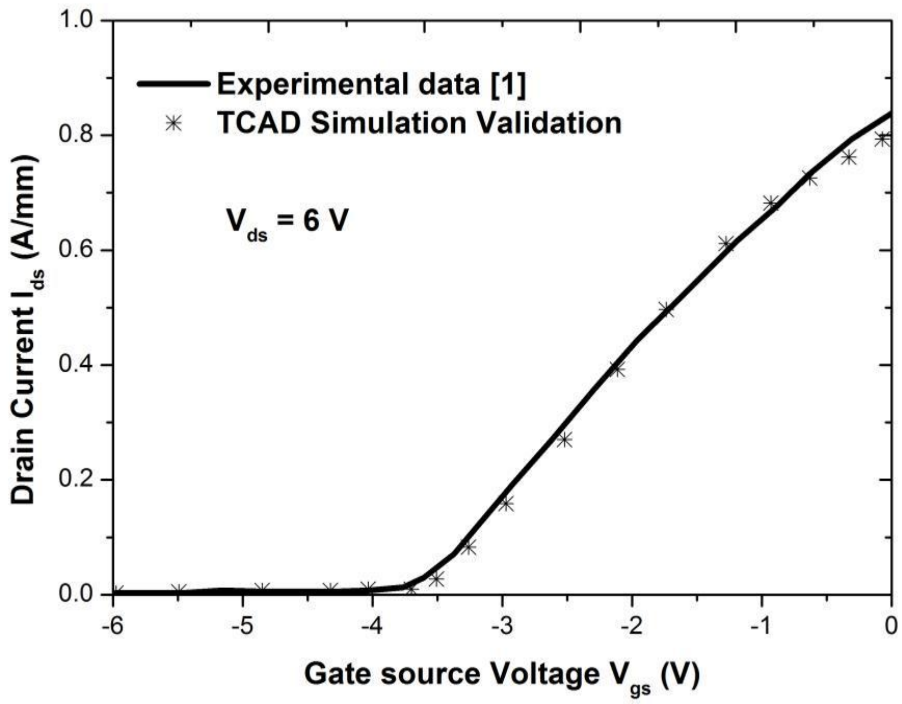

Fig 1a: Experimental [1] (solid line) and simulated (symbols) transfer characteristics of HEMT after tuning the simulation model to match the experimental curve.

Device I_{ds} versus V_{ds} characteristics were carried out on devices with L_{gs} of 1 µm, a L_g of 0.8 µm, and L_{gd} of 6 µm shown in Fig 2. For these simulations, the V_{gs} is kept at 5 V and V_{ds} in the range between 1 to 10 V. The total I_{ds} is lowered by an increase in the x–mole fraction of the buffer layer. Moreover, the 2DEG concentration is also found to decrease with the increase of ‘x’ in the $Al_xGa_{1-x}N$ buffer. The decrease in the 2DEG concentration can be attributed to the increase in the negative polarization that develops at the bottom GaN/AlGaN interface. Hence, overall, increase in the “Al” mole fraction of the AlGaN buffer improves the confinement of the 2DEG but simultaneously decreases its carrier concentration [5].

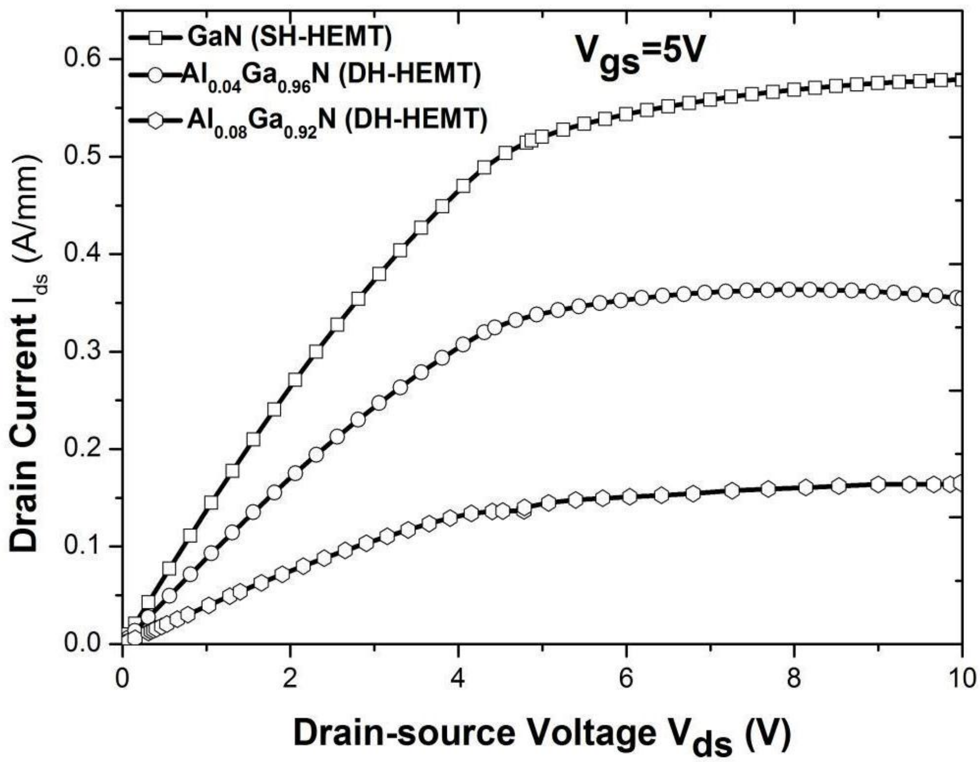

Fig 2: I_{ds}-V_{ds} characteristics for devices with different Al mole concentration 'x' in $Al_xGa_{1-x}N$ back-barrier/ buffer layer with x = 0%, 4%, and 8%, measured at a gate voltage of V_{gs} = 5 V.

DC transfer characteristics (I_{ds}-V_{gs}) for the source and gate Field-plated SH and DH-HEMTs with L_{gd} = 6 µm are shown for devices in Fig. 3. For the GaN buffer layer (SH-HEMT), the maximum drain current $I_{ds,max}$, measured at V_{ds} = + 10 V, was 0.712 A/mm, and the threshold voltage (V_t) = −2.47 V. By increasing the Al concentration 'x' in the back-barrier/ buffer layer to x = 0 %, 4 %, and 8 %, the $I_{ds,max}$ was reduced to 0.712, 0.46, and 0.182 A/mm, respectively, and the V_t was shifted toward the positive gate bias to V_t = −2.47, −1.463, and −0.7599 V, respectively, the drain voltage is kept at 10 V. The decrease of the $I_{ds,max}$ and the increase of the V_t in field plated HEMTs indicate a reduction in the sheet carrier concentration in the 2-DEG channel [6], [7]. In addition, from the extracted results it is clear that, one of the advantages of the DH-HEMT over SH-HEMT is the lower device leakage current in the order of 1×10^{-5} A/mm below threshold. The significant reduction of OFF-state drain leakage current in the DH-HEMTs clearly indicates that the increase of improved bottom confinement and potential barrier provided by the AlGaN back-barrier/buffer layer below the 2DEG GaN channel. It prevents the spilling of electrons over from the channel to the buffer at high V_{ds} [7].

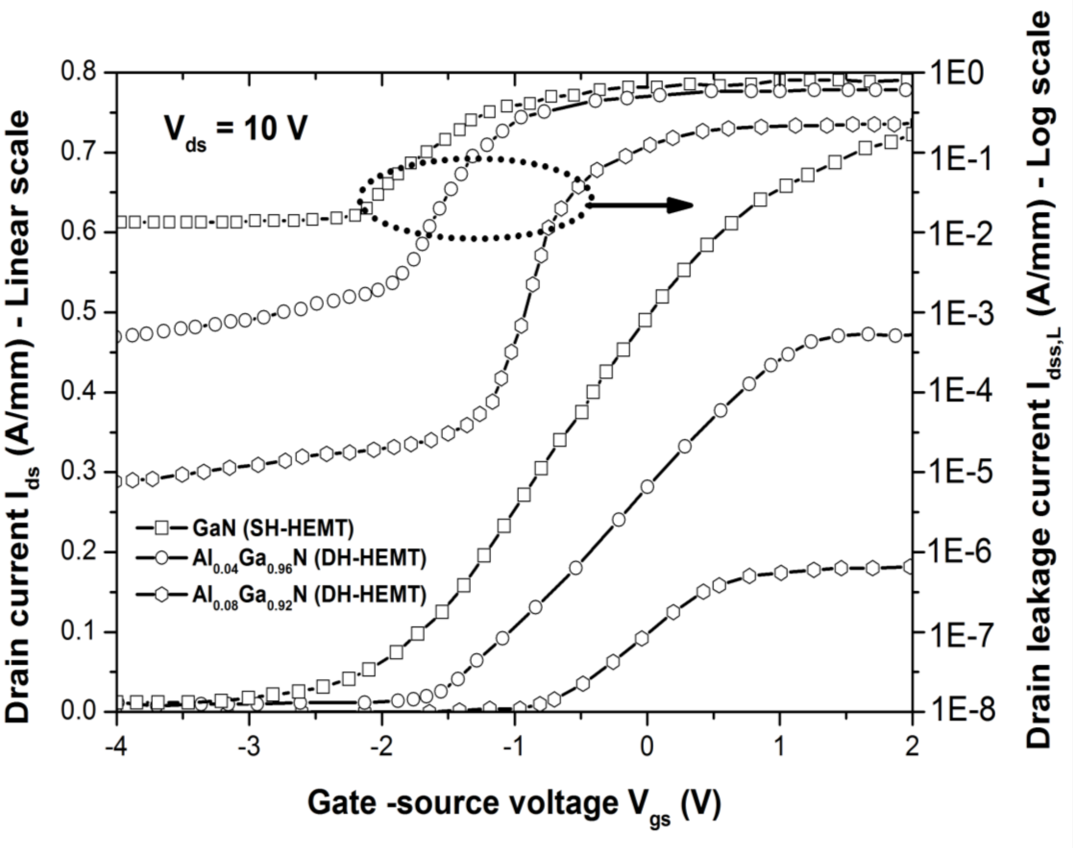

Fig 3: I_{ds}-V_{gs} (linear and log scale) characteristics of the proposed source and gate field plated AlGaN DH-HEMT with different Al mole concentration on buffer x = 0%, 4%, and 8%.

The transconductance (g_m) specifies the gain and current carrying ability of the device [9], [12]. The peak g_m of the device, as shown in Fig. 4, is about 0.1328 S/mm and 0.194 S/mm for x = 4% and 8% in the $Al_xGa_{1-x}N$ back-barrier/ buffer layer, which is a little lower than the value of SH-HEMT with x= 0% is about 0.2086 S/mm for GaN buffer. The decreased $I_{ds,max}$ and peak g_m of the DH-HEMT result from the lower density of 2DEG in the GaN channel [10].

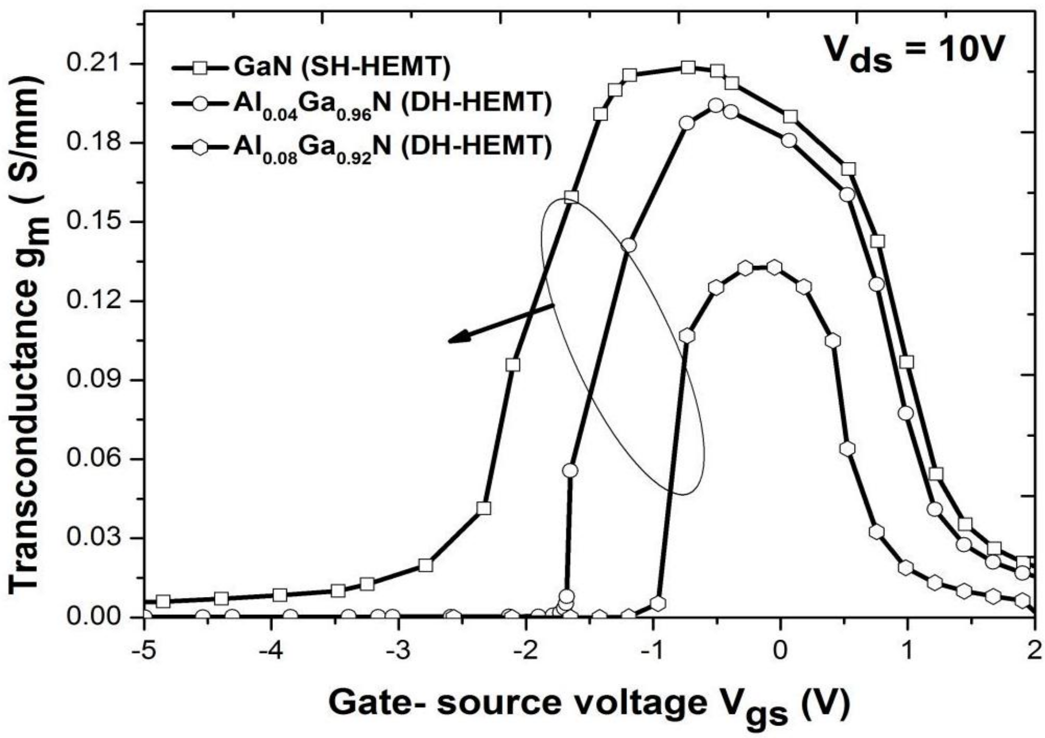

Fig 4: Transconductance (g_m) characteristics of the source and gate field plated AlGaN DH-HEMTs with different 'x' in the back-barrier/ buffer to x = 0%, 4%, and 8%.

For a GaN power device, V_t is when the 2DEG in the channel situated below the gate is fully depleted by the potential created by the gate electrode. From the Fig 5, it was clear that for Al concentration x in the buffer layer to x = 4%, and 8%, the threshold voltage V_t was found to be −1.463 V, and −0.7599 V, respectively, which is a more positive than the value of SH-HEMT device with x= 0% is about −2.47 V. The difference in V_t is caused by the difference in concentration of 2DEG in the GaN channel between the DH-HEMT and SH-HEMT. The SH-HEMT device has a higher 2DEG density in the well and needs a more negative V_{gs} to deplete the GaN channel [7]. As in the Fig 5, the result shows the variation of 'x' in $Al_xGa_{1-x}N$ buffer and the reduction of subthreshold slope (*SS*) in the DH-HEMTs. This reduction of *SS* in DH-HEMT is due to the improved conduction band offset at the bottom side in the AlGaN back barrier/ buffer [8]. This enables deeper potential well in the GaN channel, which enables better confinement of 2-DEG. From the Fig 5, it was clear that the *SS* decreases with increasing the value of 'x' in the buffer layer to x = 0%, 4%, and 8%, the maximum *SS* was increased to 160mV/decade for SH-HEMT (x = 0%), 160 mV/decade (x = 4%), and 80 mV/decade (x = 8%) for DH-HEMT respectively.

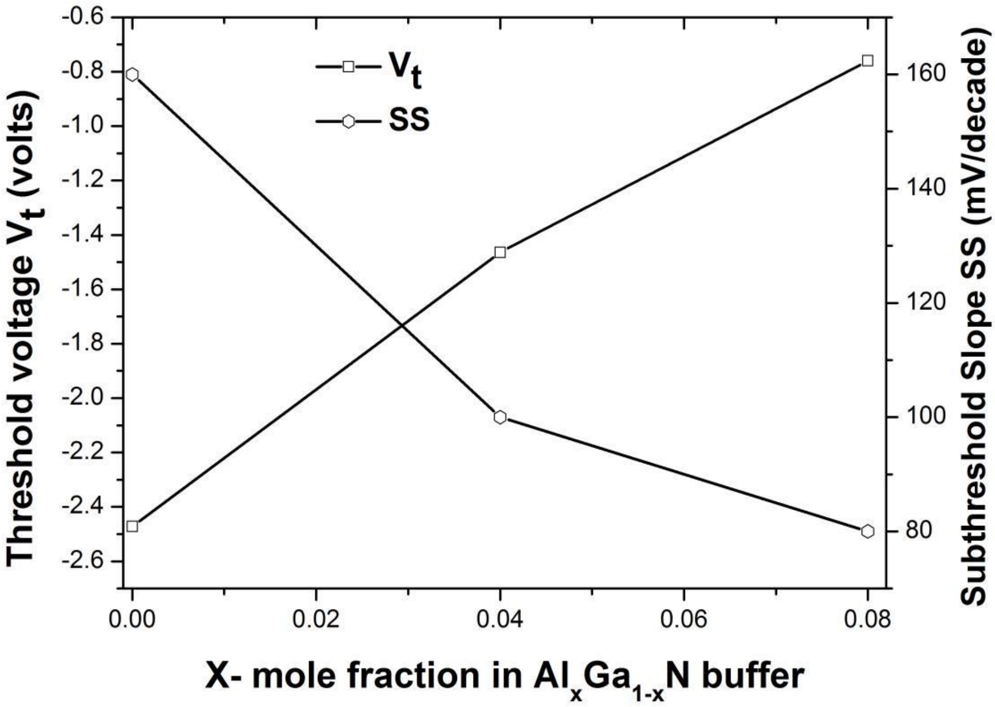

Fig 5: Variation of V_t and *SS* with different 'x' in buffer x = 0%, 4%, and 8%. *SS* extracted at V_{ds} = 0.1 V.

Fig 6 shows the variation of ON-state resistance (R_{ON}) versus buffer Al mole concentration of x = 0%, 4%, and 8%. For this, we changed the acceleration of the drain voltage between 0 V to 3 V, when the simulation was first conducted to obtain the I-V characteristic in the DC mode for three different Al mole concentrations to change the state of the gate voltage by different bias values, V_{gs} = 0.8 V to – 0.8 V with a step of -0.2 V. The device R_{ON} extracted at V_{gs} = 0.8 V and V_{ds} in the range between 0 and 1.0 V extracted from I_{ds}-V_{ds} DC characteristics shown in Fig.2. A clear benefit in terms of a large V_t has been predicted by the utilization of an AlGaN back-barrier/ buffer with high Al content will deplete the 2-DEG, which will in turn lead to an increased parasitic resistance [10]. This will eventually cause a higher device R_{ON} of 7.285 ohm•mm for GaN buffer SH-HEMT with x= 0%, 11.41 ohm•mm and 13 ohm•mm for AlGaN back-barrier/ buffer DH-HEMT with x= 4% and 8%. The R_{ON} of the device should be very low to reduce the power consumption in the switching process.

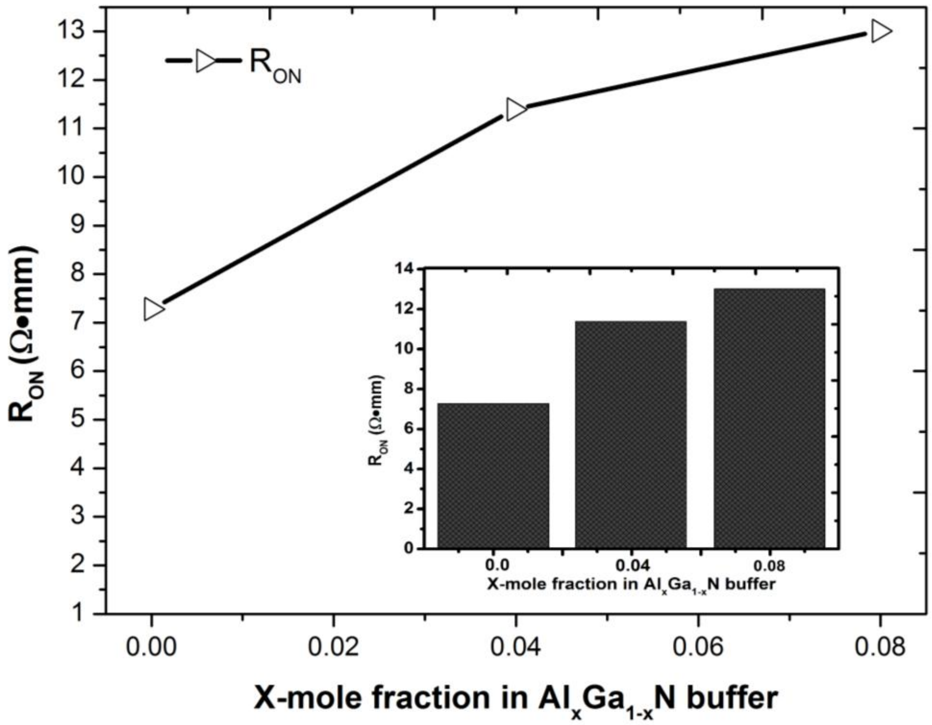

Fig 6: Variation of R_{ON} for the source and gate field plated AlGaN DH-HEMTs with different Al mole concentration 'x' in buffer x = 0%, 4%, and 8%.

The capacitance-voltage (*C-V*) characteristics with varying 'x' in AlGaN back-barrier/buffer. The higher bandgap AlGaN barrier behaves as a dielectric and such 2DEG is formed in GaN at $Al_{0.2}Ga_{0.8}N$/GaN interface [13]. Thus a high electron concentration at the AlGaN layer is responsible for the constant capacitance for a wide range of gate bias. The effective total gate capacitance C_{gg} between the gate and 2DEG can be considered as the series capacitance of the reference AlGaN barrier layer ($C_{Barrier}$) and of the highly doped GaN Cap layer (C_{cap}) expressed as:

$$\frac{1}{C_g} = \frac{1}{C_{cap}} + \frac{1}{C_{Barrier}} \quad (1)$$

where C_{cap} is the capacitance due to GaN Cap layer and $C_{Barrier}$ is the capacitance of the depleted AlGaN barrier layer. C_{AlGaN} can be expressed as [9], [12]

$$C_{Barrier} = \frac{\varepsilon_0 \varepsilon_b L_g W}{(T_B + \Delta d)} \quad (2)$$

where, ε_b and T_B are the permittivity and thickness of the $Al_{0.2}Ga_{0.8}N$ barrier layer, respectively, and Δd is the position of the maximum of the wave function of 2DEG in the quantum well (QW). The gate capacitance C_{gg} of the DH-HEMT device, as shown in Fig 7, is about 0.3587 nF/mm and 0.35866 nF/mm for Al concentration 'x' in the buffer layer to x = 4%, and 8%, which is a little lower than the value of SH-HEMT x= 0% device is about 0.3589 nF/mm.

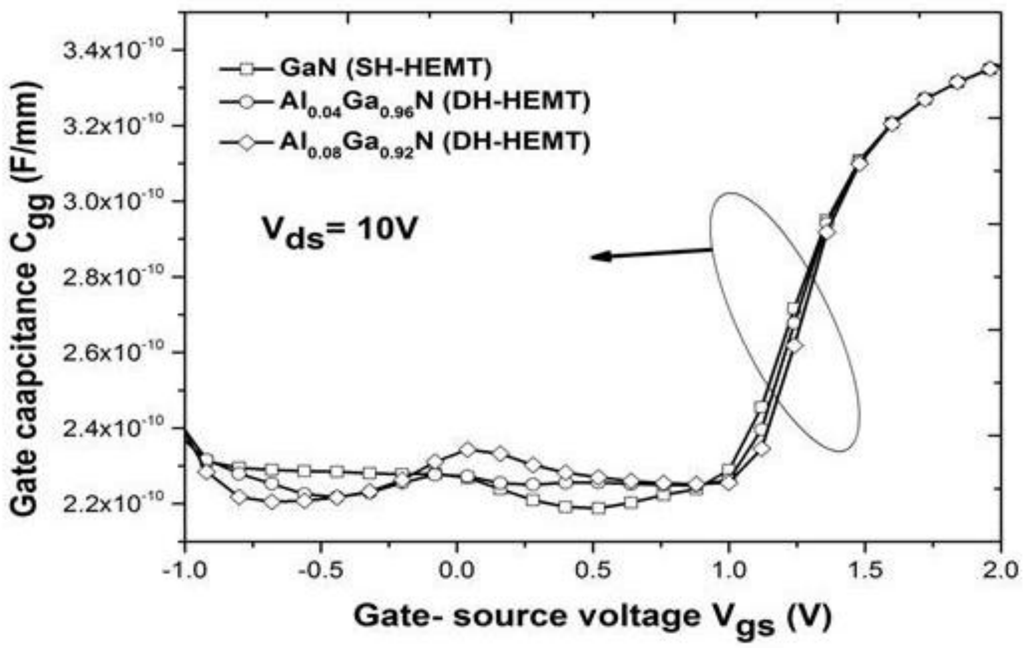

Fig 7: Gate capacitance C_{gg} versus V_{gs} characteristics of source and gate field plated AlGaN DH-HEMTs with different Al mole concentration in buffer x = 0%, 4%, and 8%.

The cut-off frequency (f_t) is a figure of merit for transistors which describes the performance of device in high frequency applications [9]. The calculated values of f_t for the proposed source and gate field plated DH-HEMTs with AlGaN double heterostructure (DH-HEMT) are much higher than the values of SH-HEMTs with GaN buffer. The f_t is the frequency when the current gain is unity and it was calculated by

$$f_t = \frac{g_m}{2\Pi C_{gg}} \tag{3}$$

From the graph, it was clear that DH-HEMTs shows higher operating cutoff frequency compared to that of the SH-HEMTs due to reduced C_{gg} compared to that of SH-HEMT. From Fig 8, it was clear that for Al concentration 'x' in the buffer layer to x = 0%, 4%, and 8%, the maximum cutoff frequency f_t was decreased to 31 GHz for SH-HEMT (x= 0%), 31.9 GHz, and 33 GHz for DH-HEMT (x = 4% and 8%) respectively.

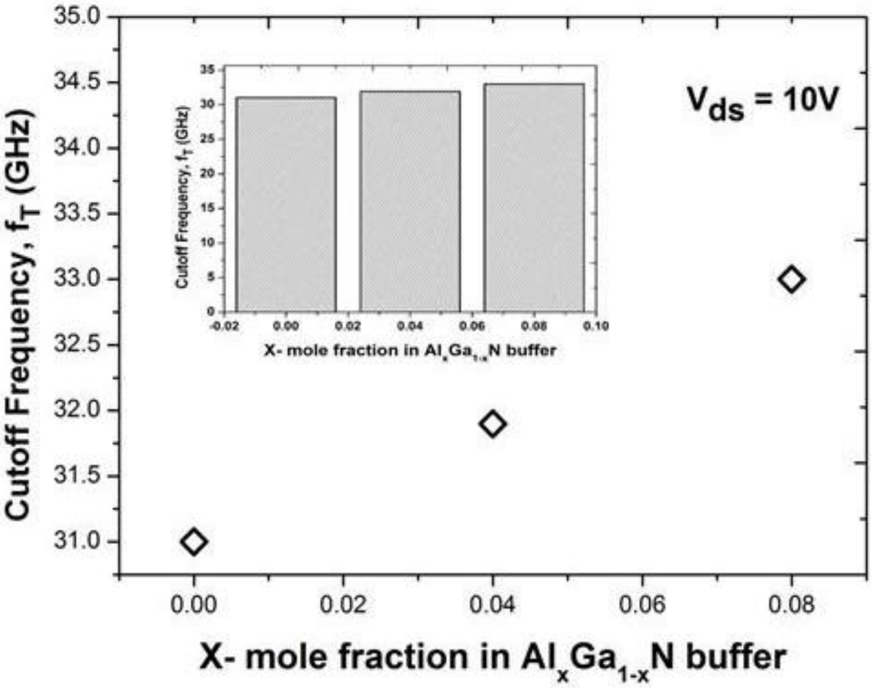

Fig 8: Variation of cutoff frequency f_t of the source and gate field plated AlGaN DH-HEMTs with different Al mole concentration 'x' in buffer x = 0%, 4%, and 8%.

Fig. 9 shows the results of the breakdown voltage simulations for devices with different x–mole fraction in their AlGaN back-barrier/ buffer layer. Fig. 9 plots I_{ds} as a function of V_{ds} to calculate BV_{OFF}. The V_{gs} is kept in –6 V with substrate connected to ground. The DH-HEMT improves the BV_{OFF} of the device compared to the device with SH-HEMT with increasing source (L_{SFP}) and gate field plate (L_{GFP}) length. The purpose of the DH-HEMTs was to improve the device BV_{OFF} by reducing the OFF-state leakage current with increased bottom confinement in the buffer layer. This reduces the effect of carrier punchthrough of the device. The enhancement of the BV_{OFF} in DH-HEMT is achieved by two effects. The improved confinement in the channel efficiently prevents the punchthrough effect, and the severe peak electrical field under the drain side of the gate with the introduction of source and drain field plate which reduces the Schottky-gate tunneling leakage [1], [7], [8]. We see that by introducing a source and gate field plate (L_{SFP} and L_{GFP}), the BV_{OFF} becomes higher. This is because the high electric field at the gate and drain edge of the device is reduced by introducing field-plate, thereby increasing BV_{OFF} with increasing L_{SFP} and L_{GFP} for different Al content 'x' in the AlGaN back-barrier/ buffer.

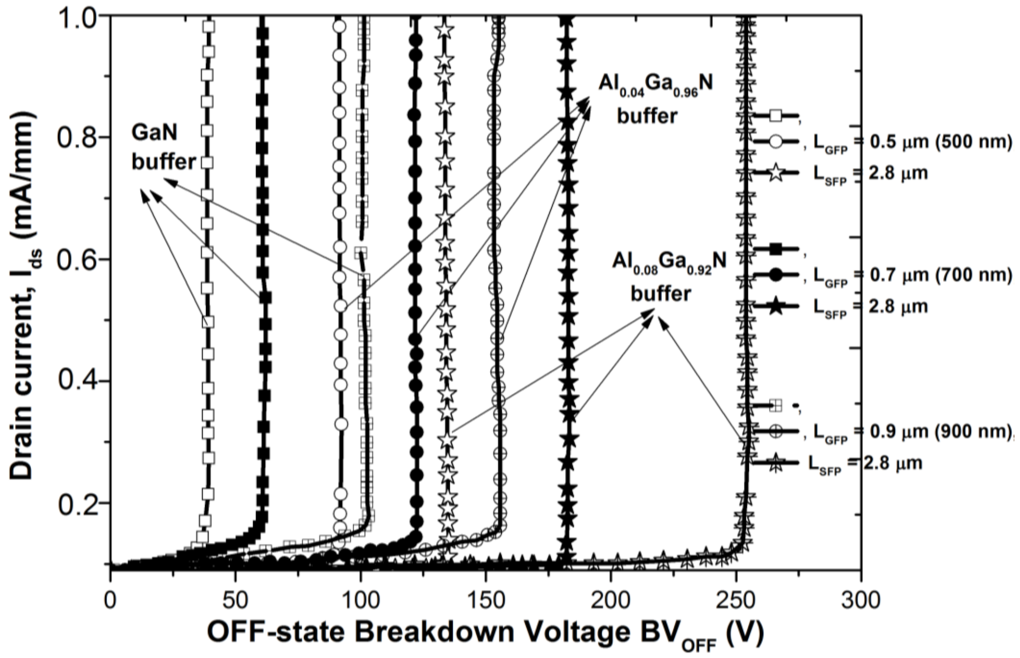

Fig 9: OFF-state breakdown characteristics of the source and gate field plated with AlGaN double heterostructure (DH-HEMTs) with different Al mole concentration in buffer x = 0%, 4%, and 8% with substrate grounded for constant L_{SGF} = 2.8 µm and different L_{GFP} = 0.5, 0.7, 0.9 µm.

4. CONCLUSION

In summary, we comprehensively discussed GaN channel with source and gate field plated double heterostructures from a theoretical and simulation point of view. The detailed investigation of DH-HEMTs with a wide band-gap buffer layer replacing the GaN buffer layer with SH-HEMTs along with source and gate field plate on BV_{OFF} is analyzed. The introduction of an AlGaN back-barrier/ buffer layer leads to a superior confinement of the carriers in the GaN channel, provided by a reduction in I_{dsmax} and an increase of threshold voltage (V_t), reduced subthreshold slope (SS) and breakdown voltage (BV_{OFF}) is achieved. For Al mole concentrations (x = 4% and 8%) in the AlGaN buffer layer, DH-HEMTs prevent the effect of punchthrough in the buffer layer and reduce the subthreshold drain leakage current, thus significantly increase the device OFF-state breakdown voltage BV_{OFF}. Overall, it was demonstrated that the $Al_{0.2}Ga_{0.8}N/GaN/Al_xGa_{1-x}N$ DH-HEMT with source and gate field plated approach showed improved performance and it is a most promising device technology for high-power switching and electronic applications.

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