Breakdown Voltage Enhancement of Al$_{0.1}$Ga$_{0.9}$ N Channel HEMT with Recessed Floating Field Plate

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Abstract
In this paper, electrical and microwave characteristics of Al$_{0.1}$Ga$_{0.9}$ N channel HEMTs was reported. The device performance were evaluated for conventional gate, field plate gate, and recessed floating field plate with Silicon nitride (SiN)/Hafnium oxide (HfO$_2$) passivation. The recessed floating field plate HEMT with gate length $L_G = 0.8 \mu m$, gate to drain distance $L_{GD} = 1 \mu m$, and HfO$_2$ (SiN) passivation HEMT reports peak drain current density ($I_{DS}$) of 0.282 (0.288) A/mm at $V_{GS} = 0 V$, three terminal off-state breakdown voltage ($V_{BR}$) of 677 (617) V, $6.38 \Omega \cdot mm$ of ON-resistance ($R_{ON}$), transconductance ($g_{m,max}$) of 93 (95) mS/mm, and $F_T/F_{MAX}$ of 11.4/49 (12/22) GHz. The HfO$_2$ (SiN) passivation device demonstrated the Johnson figure of merit (JFoM) of 7.71 (7.404) THz.V and $F_{MAX} \times V_{BR}$ product of 33.173 (13.574) THz.V. The high JFoM along with high $F_{MAX} \times V_{BR}$ indicates the potential of the ultrawide bandgap AlGaN HEMTs for future power switching and high-power microwave applications. The breakdown voltage ($V_{BR}$) of the floating field plate HEMT is improved 54 % from conventional HEMT and 31 % improvement from gate field plate HEMT.

Keywords Floating Field plate · breakdown voltage · electric field · high power applications · HEMTs

1 Introduction
Group III-nitride based wide-bandgap semiconductors are used in high power microwave and switching applications. Owing the unique combination of high electron density, higher mobility, and high critical electric field of conventional GaN channel-based high electron mobility transistors enables high power and high frequency operation for the past two decades [1–4] and GaN based based power switches, RF amplifiers, and power diodes are commercially available in the market from multiple vendor [5]. Moreover, GaN-HEMTs are widely used in low-noise microwave applications due to its excellent noise performance [6–8]. On other hand, AlGaN ternary channel-based HEMTs are also an interesting devices alternate to GaN-channel HEMTs interms of high breakdown voltage due to ultrawide bandgap features of AlGaN material. AlGaN channel based HEMTs had proven its potential for fast-switching and low switching loss applications, particularly in high temperature and high radiation environments [9–29]. Existence of large critical electrical field (> 3.3 MV/cm) and on par with GaN saturation velocity [30], the AlGaN channel based HEMTs are recognized as the most optimistics candidates future high-power switching as well as microwave applications in harsh environments [31].

After the first successful demonstration of AlGaN channel based HEMT for high power and microwave application [10], several research groups reported the high performance of AlGaN channel HEMTs. T. Nanjo et.al. investigated the HEMT on AlN buffer and the device shown enrich $V_{BR}$ by suppressing the drain leakage current [11]. Takuma Nanjo et al. reported the ternary channel (AlGaN) HEMT on sapphire, the breakdown voltage of 1700 V for $L_{GD}$ of 10 $\mu$m [12]. Sanyam Bajaj et al. reported Al$_{0.75}$Ga$_{0.25}$ N channel HEMT with reduce source/drain contact resistances by n++ AlGaN region [13]. The 20 nm Al$_2$O$_3$ gate dielectric MISFETs demonstrated 14 mS/mm of $g_{m,max}$ and 224 V of breakdown voltage ($V_{BR}$). Albert G. Baca et al. demonstrated a circular HEMT with a $V_{BR}$ of 810 V for 2.0 $\mu$m gate length and 314 $\mu$m circumference [14]. SakibMuhtadi et al. revealed high Al-content AlGaN channel HEMTs on AlN buffer and the device shown better thermal conduction. Operated up to 40 V at 0.25 A/mm without current collapse [15]. A high breakdown voltage of 2200 V was attained for 22 $\mu$m gate to drain...
distance device by adopting ohmic/Schottky-hybrid drain contacts [16]. Ming Xiao et al. reported GaN/Al0.35Ga0.65N/NAIN/graded channel HEMT and the device shown enhanced \( I_{DS} \) and high \( I_{on}/I_{off} \) ratio with improved density [27], however the large negative threshold voltage channel HEMTs for improving carrier transport and 2DEG of the device may result in off-state power loss.

Zhang et al. proposed AlGaN double for large signal RF application as well as power switching AlGaN HEMT channel based HEMTs reported its potential applications [24]. The first RF performance on AlGaN channel based HEMT was reported by Albert G. Baca et al. An 80 nm gate length HEMT yields \( I_{DS} \) of 0.16 A/mm, and 24 mS/mm of \( g_m_{max} \), and having \( F_T/F_{MAX} \) of 28.4/18.5 GHz [18]. An RF simulation study on AlGaN HEMT channel based HEMTs reported its potential for large signal RF application as well as power switching applications [24]. Zhang et al. proposed AlGaN double channel HEMTs for improving carrier transport and 2DEG density [27], however the large negative threshold voltage of the device may result in off-state power loss.

The bandgap of the \( Al_{x}Ga_{1-x}N \) tailoring by varying the Al composition (0 < x < 1). The high critical breakdown field and low on resistance (\( R_{on} \)) are key parameters for power switching applications. Lateral Figure of Merit (LFOM) is used to estimate the potential of a material for power switching [32];

\[
LFOM = \frac{V_B^2}{R_{on}} = q\mu_{ch}n \varepsilon_n^2 C
\]

The LFOM of a material depends on the sheet charge density \( n_s \), critical electric field \( E_n \), and mobility of the channel \( \mu_{ch} \). Since the critical electric field of AlGaN channel is higher \( \left( E_n \sim 2 \right) \) than the GaN channel, Al0.1Ga0.9N channel offers significant improvement in \( V_{BR} \) even at high temperature over GaN. The JFOM measures the ability of the materials for high power microwave applications;

\[
JFOM = V_B F_T = \frac{E_n \nu_{sat}}{2\pi}
\]

The JFOM of material systems is the product of \( F_T \) and \( V_{BR} \). The critical electric field \( E_n \), and electron saturation velocity \( \nu_{sat} \) influences the JFOM of the HEMT. Since the low Al composition Al0.1Ga0.9N channel saturation velocity is on par with GaN channel, along with enhanced critical field improves the JFOM of AlGaN channel HEMTs than GaN-based HEMTs. The high \( V_{BR} \) is achieved for long channel \( L_G \), long \( L_{GD} \) HEMTs, along with Al-richAlGaN channel [9–29]. Whereas, the smaller \( L_G, L_{GD} \), and low Al composition of AlGaN channel results in improved cut-off frequency with the suppressed \( V_{BR} \) and hence, there is a trade-off between \( V_{BR} \) and device speed (cut-off frequency) of HEMTs.

In this work, we proposed the recessed floating field plate, Al0.1Ga0.9N channel HEMT for improve the \( V_{BR} \) of the device with satisfactory RF performance. \( L_G = 0.8 \ \mu m, \) and \( L_{GD} = 1 \ \mu m \) Al0.31Ga0.69 N/Al0.1Ga0.9 N HEMT on sapphire substrate is investigated using Silvaco ATLAS TCAD numerical simulation for SiN and HfO2 passivation.

The HfO2 passivation device shown remarkable improvement in breakdown voltage than SiN passivation. The organization of this work as follows; Device structure description for conventional gate HEMT (Device A), Gate field plate HEMT (Device B), and recessed floating field plate HEMTs (Device C) is discussed in Sec. 2. The physics-based simulation models are described in Sec. 3. The DC and microwave characteristic of proposed HEMT with experimental validation is discussed in Sec. 4 with concluding remarks.

2 Device Structure Description

The Al0.1Ga0.9 N channel geometry of conventional gate HEMT (Device A), Gate field plate HEMT (Device B), and recessed floating field plate HEMTs (Device C) are displayed in Fig. 1(a), (b), and (c) respectively. The device grown on sapphire substrate and consists of 23 nm Al0.31Ga0.69 N barrier (\( E_g \sim 3.989 \) eV), 100 nm Al0.1Ga0.9 N channel (\( E_g \sim 3.563 \) eV), and 2.2 \( \mu m \) buffer. The device DC and RF performance are evaluated for 100 nm SiN and HfO2 passivation. High Al composition in the Al0.1Ga0.9N channel attenuates the mobility of the device [30] and also a very low Al composition in the Al0.1Ga0.9N channel degrades the breakdown voltage of the device. Therefore, we have used the optimum value of Al composition to balance the mobility as well as breakdown voltage of the HEMT. The model device used in simulation has a 0.8 \( \mu m \) gate length, 1 \( \mu m \) gate to drain distance, and 0.8 \( \mu m \) gate to source distance. The source and drain ohmic contacts are realized by setting the work function of the source/drain electrode to 3.4 eV and Schottky contact was made by setting the gate electrode work function as 5.2 eV for the TCAD simulation. The conduction band offset along with interface charge details of the heterostructure shown in Fig. 2. At room temperature TCAD simulation exhibited 1.01 \( \times 10^{13} \) cm\(^{-2}\) of electron density and 810 cm\(^2\)V\(^{-1}\)s\(^{-1}\) of carrier mobility in the 2DEG.

3 Simulation Models

The proposed HEMTis analyse during several device physics models in TCAD simulation including mobility model, recombination models, carrier transport, and polarization models.

Polarization charge at the heterostructure interface is as follows [33]:
The $P_{\text{total}}$ at the top/bottom heterointerface depends on the spontaneous ($P_{\text{SP}}$) and piezoelectric polarization ($P_{\text{PE}}$) of the materials. The temperature dependent mobility model $\mu_0(T,N)$ describes as following form [30];

$$
\mu_0(T,N) = \mu_{\text{min}} \left( \frac{T}{300} \right)^{\beta_1} + \frac{(\mu_{\text{max}} - \mu_{\text{min}}) \left( \frac{T}{300} \right)^{\beta_2}}{1 + \left[ \frac{N}{N_{\text{ref}} \left( \frac{T}{300} \right)^{\gamma}} \right]^\alpha} \tag{4}
$$

$P_{\text{total}} = [P_{\text{PE}\,\text{bottom}} + P_{\text{SP}\,\text{bottom}}]$

$- [P_{\text{PE}\,\text{top}} + P_{\text{SP}\,\text{top}}]. \tag{3}$

Fig. 2 Conduction band and interface charge diagram of Al$_{0.31}$Ga$_{0.69}$N/Al$_{0.1}$Ga$_{0.9}$N heterostructure
The capture of phonon transition within the forbidden bandgap due to trap states, Shockley-Read-Hall (SRH) recombination model is used. The SRH model expresses as a function of electron life time $\tau_n$ and holes life time $\tau_p$, temperature, trap energy level $E_{\text{trap}}$ [34];

$$P_{\text{net}}^{\text{SRH}} = \frac{n - n_{i\text{e}}}{\tau_p \left[ p + n_{i\text{e}} \exp \left( \frac{-E_{\text{trap}}}{kT} \right) \right] + \tau_n \left[ p + n_{i\text{e}} \exp \left( \frac{-E_{\text{trap}}}{kT} \right) \right]}.$$  

(5)

The Selberherr’s impact ionization model considered for device breakdown simulation [35] and the impact ionization carrier generation rate described as follows:

$$G = \left( \alpha_n |J_p| + a_p |J_p| \right)/q$$  

(6)

Where, $E$ is the electric field, electrons ionization rate $\alpha_n = A_n \exp(-B_n/|E|)$ and holes ionization rate $\alpha_p = A_p \exp(-B_p/|E|)$. The fitting parameters $A_n$, $A_p$, $B_n$, and $B_p$ values are taken from [34] for the simulation.

4 Results and Discussions

The proposed recessed floating gate HEMT (Device C) transfer characteristic is depicted in Fig. 3 for $V_{\text{DS}} = 10$ V and $V_{\text{GS}}$ swept from $-6$ to 0 V. The conventional and gate field plate HEMTs also exhibited similar response. Al$_{0.1}$Ga$_{0.9}$N HEMT with $L_G = 0.8$ $\mu$m has reached the maximum output current ($I_{\text{DS}}$) of 0.28 A/mm and $g_{\text{m,max}}$ of 95 mS/mm. The threshold voltage ($V_{\text{th}}$) of the HEMT is extracted as -3 V. The $V_{\text{th}}$ of the

![Fig. 3 Transfer characteristics of recessed floating gate HEMT (Device C)](image)

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![Fig. 4 I-V characteristics of recessed floating gate HEMT (Device C)](image)

Fig. 4 I-V characteristics of recessed floating gate HEMT (Device C)

![Fig. 5 Transfer characteristics for $L_G = 0.8$ $\mu$m of Al$_{0.1}$Ga$_{0.9}$ N channel HEMT (Device C) and experimental work [27]](image)

Fig. 5 Transfer characteristics for $L_G = 0.8$ $\mu$m of Al$_{0.1}$Ga$_{0.9}$ N channel HEMT (Device C) and experimental work [27]

![Fig. 6 Output characteristics for $L_G = 0.8$ $\mu$m of Al$_{0.1}$Ga$_{0.9}$ N channel HEMT (Device C) and experimental work [27]](image)

Fig. 6 Output characteristics for $L_G = 0.8$ $\mu$m of Al$_{0.1}$Ga$_{0.9}$ N channel HEMT (Device C) and experimental work [27]
Fig. 7  E-field distribution for SiN passivation of (a) Device A (b) Device B (c) Device C
Fig. 8 E-field distribution for HfO$_2$ passivation of (a) Device A, (b) Device B and (c) Device C.
HEMT obtained from VGS intercepted of the linear extrapolation in the active region. The V-I characteristics of the proposed Device C is shown in Fig. 4 for VGS = -3 to 0 V and VDS swept from 0 V to 10 V. Device A and Device B also exhibited similar output characteristics. The extracted ON-resistance (Ron) of the device from the V-I characteristics (VGS = 0 V) is 6.38 Ωmm. The Ron resistance of the device extracted from the output characteristics at VGS = 0 V by taking the slope (1/Ron = ID/VD) corresponding to ¼ th of maximum drain current (IDS, max). The device is perfectly pinched-off at VGS = -3 V. The proposed device Ron resistance is comparatively lower than the reported works [10–28].

The transfer and output characteristics of simulation result of conventional Al0.1Ga0.9N channel HEMT is validated with experiment result of [27] and it is shown in Figs. 5 and 6 respectively. The simulated results were well correlated with the reported experimental work.

The HEMT breakdown simulation was carried out at off-state condition (VGS = -8 V). The electric field (E-field) distributions for SiN and HfO2 passivation of (a) Device A, (b) Device B and (c) Device C are depicted in Figs. 7 and 8 respectively. The permittivity (ɛr) and thickness (t) of the insulator (passivation) modulates the E-field. High permittivity HfO2 (ɛr=25) passivation smoothening the E-filed at gate and drain edge [35–38].

From Fig. 7(a) (SiN passivation) and Fig. 8(a) (HfO2 passivation), it is observed that a peak E-field exist at the gate edge, which lower the VBR of the device. Therefore, sinking the field distribution becomes the alternate solution to enhance the VBR. In general, the gate field plate (FPs), source field plate (SFPs), and drain connected field plate techniques are used to suppress the electric field [39]. The gate field plate techniques demonstrated the improved breakdown voltage by alleviating high E-field as shown in Fig. 7(b) (SiN passivation) and Fig. 8(b) (HfO2 passivation) and it reshaping the field distribution.

In this work, a recessed floating field plate structure is considered for further, to enhance the breakdown voltage of the HEMTs. The electric field distribution of proposed HEMTs are shown in Fig. 7(c) (SiN passivation) and Fig. 8(c) (HfO2 passivation).

The introduction of floating field plate, reshaped the electric field and suppressed the E-field near the gate edge effectively and a peak electric field found at the drain side edge of the floating field plate because of much closer with drain electrode and also the recessed field plate is very closer with 2DEG channel than gate field plate results in better surface field distribution, which enhances the breakdown voltage of the HEMTs. The E-field engineering soley depends on field plate length, passivation permittivity, thickness of the passivation, and recess depth.

For the proposed Device C dimensions, the off-state breakdown voltage characteristics of HEMTs are plotted in Fig. 9. The breakdown voltage of the HEMT extracted from ID-VD curves at the intersection of the extrapolated saturation segment (an VD saturated and a sudden increase in IP). The recessed floating field plate HEMT shown remarkable VBR of 677 (617) V for HfO2 (SiN) passivation. However, the conventional HEMT shown VBR of 307(297) V and gate field plate shown VBR of 462 (428) V. From this analysis of off state breakdown voltage simulation, the floating field plate demonstrated 54% improvement in VBR than conventional HEMT, and 31% higher than the gate field plate HEMT.

The Figs. 10 and 11 shows the simulation results of electron concentration distribution of HEMTs at breakdown condition. The larger depletion region of floating field plate shown in Figs. 10(c) and 11(c), suppressed E-field near the drain side of gate edge, and high critical field of Al0.1Ga0.9N channel are the major reason for improving the breakdown voltage of the proposed HEMTs.

The microwave performance of the SiN and HfO2 passivated Device C are depicted in Figs. 12 and 13 respectively. The FFT/FTMAX of the device extracted from current gain and power gain when it reaches 0 dB respectively. The conventional HEMTs are showing better FT than field plated HEMTs. Due to the introduction of additional field plate in the device structure, increases the parasitic capacitance (CGS and CGD) which limits the speed of the HEMTs as given in the Eqs. (9):

\[
P_{RF} = \frac{I_{max}[V_{br} - V_{knee}]}{8},
\]
Fig. 10  Electron concentration distribution of SiN passivation (a) Device A, (b) Device B and (c) Device C at breakdown voltage condition
Fig. 11  Electron concentration distribution of HfO$_2$ passivation (a) Device A, (b) Device B and (c) Device C at breakdown voltage condition
\[ F_T = \frac{G_m}{2\pi(\varepsilon_{Gm} + \varepsilon_{GD})}, \quad (8) \]

\[ F_{MAX} = \frac{F_T}{\sqrt{(R_i + R_s + R_g)g_0 + (2\pi F_T)R_gC_{GD}}}, \quad (9) \]

The \( I_{DS} \) and \( V_{BR} \) of a transistor expected to be very high for delivering high RF output power density as shown in Eq. (8). The proposed recessed floating field plate HEMT shows a \( F_T/F_{MAX} \) of 11.4/49 GHz for HfO2 passivation and 12/22 GHz for SiN passivation. The improved power performance along with the satisfactory cut-off frequency of the proposed HEMTs demonstrated its capability for future RF and power switching applications. Further the small signal RF characteristics can be enhanced by scale down the device dimensions.

**Table 1** State of art AlGaN channel parameter and performance

| Author, Year | Reference No | Gate to drain distance (L GD) | Drain current (IDS) | Breakdown voltage (V BR) | Cut-off frequency (F T/FMAX) | J F o M (THz.V) |
|-------------|--------------|-----------------------------|-------------------|---------------------|-----------------------------|----------------|
| V. Adivarahan et al., 2008 | [10] | 0.11 A/mm | 0.14 A/mm | 463 V | - | - |
| T. Nanjo et al., 2009 | [11] | 0.18 A/mm | 0.05 A/mm | 500 V | - | - |
| Takuma Nanjo et al., 2013 | [12] | 0.18 A/mm | 0.05 A/mm | 224 V | - | - |
| Albert G. Baca et al., 2016 | [13] | 0.3 A/mm | 0.3 A/mm | 500 V | - | - |
| Sanyam Bajaj et al., 2016 | [14] | 0.1 A/mm | 0.24 A/mm | 408 V | - | - |
| Takuma Nanjo et al., 2013 | [12] | 0.1 A/mm | 0.28 A/mm | 92 V | - | - |
| Albert G. Baca et al., 2016 | [13] | 0.1 A/mm | 0.28 A/mm | 170 V | - | - |
| W. Zhang et al., 2018 | [16] | 0.1 A/mm | 0.28 A/mm | 2040 GHz | - | - |
| Ming Xiao et al., 2018 | [17] | 0.3 A/mm | 0.3 A/mm | 500 V | - | - |
| Albert G. Baca et al., 2018 | [18] | 0.3 A/mm | 0.28 A/mm | 28.4/16.5 GHz | 3.4 | 7.4 |
| Andrew M. Armstrong et al., 2019 | [19] | 3.5 A/mm | 3.5 A/mm | 620 V | - | - |
| HaoXue et al., 2019 | [20] | 620 V | 620 V | 14/22 GHz | 17.5 | 7.18 |
| Yachao Zhang et al., 2020 | [27] | 143 V | 143 V | 14/22 GHz | 17.5 | 7.18 |
| Shahadat H. Sohel et al., 2020 | [28] | 143 V | 143 V | 14/22 GHz | 17.5 | 7.18 |

**This work (SiN Passivation)**

- Gate length (L GD): 0.8 \( \mu \)m
- Drain current (IDS): 0.288 A/mm
- Breakdown voltage (V BR): 617 V
- Cut-off frequency (F T/FMAX): 11.4/49 GHz
- J F o M (THz.V): 7.718

**This work (HfO2 Passivation)**

- Gate length (L GD): 0.8 \( \mu \)m
- Drain current (IDS): 0.282 A/mm
- Breakdown voltage (V BR): 677 V
- Cut-off frequency (F T/FMAX): 11.4/49 GHz
- J F o M (THz.V): 7.718
The comparison of state of art AlGaN channel based HEMTs parameter and performance along with proposed Device C are tabulated in Table 1. The proposed Device C shows improved drain current, breakdown voltage, and RF performance among the reported work for $L_{GD}$ (1 μm) and $L_{CF}$(0.8 μm).

5 Conclusions

Breakdown voltage performance analysis of Al$_{0.1}$Ga$_{0.9}$N channel HEMT is reported with floating field plate and AlGaN buffer. A Physics-based Technology Computer Aided Design(TCAD) simulation results shows that the peak electric field near the drain-side of gate edge is majorly reduced by recessed floating field plate technique, which further elevated the breakdown performance of the AlGaN channel HEMTs. The insertion of floating field reshaped the E-field distribution in the access region effectively and reduced the E-field near the drain side of gate edge and thus enhanced the breakdown voltage. The proposed recessed floating field plate HEMT yields $V_{BR}$ of 677 V and $F_{max}$, 11.4 GHz for a high-k HfO$_2$ passivation. The breakdown voltage ($V_{BR}$) of the HfO$_2$ passivation floating field plate HEMT is improved 54% from conventional HEMT and 31% improvement from gate field plate HEMT. The excellent breakdown power performances along with RF characteristics of the ultrawide bandgap AlGaN channel based HEMTs are attractive alternate devices for next generation power electronics and RF applications.

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Authors’ Contributions All the works reported in this paper is original and have done with equal contribution in all the sections by Ramkumar Natarajan and Esvaran Parthasarathy.

Data Availability Not Applicable.

Code Availability Not Applicable.

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