Breakdown Voltage Enhancement of Al_{0.1}Ga_{0.9}N channel HEMT With Recessed Floating Field Plate

Ramkumar Natarajan

SRM Institute of Science and Technology College of Engineering

Eswaran Parthasarathy (✉ eswaranp@srmist.edu.in)

SRM Institute of Science and Technology College of Engineering <https://orcid.org/0000-0003-0006-8649>

Research Article

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

Posted Date: July 19th, 2021

DOI: <https://doi.org/10.21203/rs.3.rs-706013/v1>

License: © ⓘ This work is licensed under a Creative Commons Attribution 4.0 International License.

[Read Full License](#)

Breakdown voltage enhancement of Al_{0.1}Ga_{0.9}N channel HEMT with recessed floating field plate

Ramkumar Natarajan¹ Eswaran Parthasarathy¹

¹ Department of Electronics and Communication Engineering, SRM Institute of Technology and Sciences, Chennai, India.

Email: eswaranp@srmist.edu.in

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 (HfO₂) passivation. The recessed floating field plate HEMT with gate length $L_G = 0.8 \mu\text{m}$, gate to drain distance $L_{GD} = 1 \mu\text{m}$, and HfO₂(SiN) passivation HEMT reports peak drain current density (I_{DS}) of 0.282(0.288) A/mm at $V_{GS} = 0\text{V}$, three terminal off-state breakdown voltage (V_{BR}) of 677 (617) V, 6.38 $\Omega\cdot\text{mm}$ 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 HfO₂ (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 AlGa_N HEMTs for future power switching and high-power microwave applications. The proposed device DC characteristics are validated with reported experimental work, which shows similar I_{DS} and 54% and 31% improvement in breakdown voltage on comparisons with conventional 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 power switches, RF amplifiers, and power diodes are commercially available in the market from multiple vendor [5]. On other hand, AlGa_N ternary channel-based HEMTs are also an interesting devices alternate to GaN-channel HEMTs in terms of high breakdown voltage due to ultrawide bandgap features of AlGa_N material. AlGa_N channel based HEMTs had proven its potential for fast-switching and low switching loss applications, particularly in high temperature and high radiation environments [6-26]. Existence of large critical electrical field ($> 3.3 \text{ MV/cm}$) and on par with GaN saturation velocity [27], the AlGa_N channel based HEMTs are recognized as the most optimistic candidates future high-power switching as well as microwave applications in harsh environments [28].

After the first successful demonstration of AlGa_N channel based HEMT for high power and microwave application [7], several research groups reported the high performance of AlGa_N 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 [8]. Takuma Nanjo et.al. reported the ternary channel (AlGa_N) HEMT on sapphire, the breakdown voltage of 1700 V for L_{GD} of $10 \mu\text{m}$ [9]. Sanyam Bajaj et al. reported Al_{0.75}Ga_{0.25}N channel HEMT with reduced source/drain contact resistances by n++ AlGa_N region [10]. The 20 nm Al₂O₃ 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 $2.0 \mu\text{m}$ gate length and $314 \mu\text{m}$ circumference [11]. Sakib Muhtadi et. al. revealed high Al-content AlGa_N 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 [12]. A high breakdown voltage of

2200 V was attained for 22 μm gate to drain distance device by adopting ohmic/Schottky-hybrid drain contacts [13]. Ming Xiao et. al. reported GaN/Al_{0.35}Ga_{0.65}N/AlN/graded channel HEMT and the device shown enhanced I_{DS} and high $I_{\text{on}}/I_{\text{off}}$ ratio with improved breakdown voltage [14]. The first RF performance on AlGa_N 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 $g_{\text{m,max}}$, and having $F_{\text{T}}/F_{\text{MAX}}$ of 28.4/18.5 GHz [15]. An RF simulation study on AlGa_N HEMT channel based HEMTs reported its potential for large signal RF application as well as power switching applications [21]. Zhang et al. proposed AlGa_N double channel HEMTs for improving carrier transport and 2DEG density [24], however the large negative threshold voltage of the device may result in off-state power loss.

The bandgap of the Al_xGa_{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 [29];

$$LFOM = \frac{V_B^2}{R_{\text{on}}} = q \mu_{\text{ch}} n_s E_c^2 \quad (1)$$

The LFOM of a material depends on the sheet charge density (n_s), critical electric field (E_c), and mobility of the channel (μ_{ch}). Since the critical electric field of AlGa_N channel is higher ($E_c \sim E_g^n, 2 < n < 2.5$) than the GaN channel, Al_xGa_{1-x}N 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;

$$JFOM = V_B \cdot F_T = \frac{E_c v_{\text{sat}}}{2\pi} \quad (2)$$

The JFOM of material systems is the product of F_T and V_{BR} . The critical electric field (E_c), and electron saturation velocity (v_{sat}) influences the JFOM of the HEMT. Since the low Al composition Al_xGa_{1-x}N channel saturation velocity is on par with GaN channel, along with enhanced critical field improves the JFOM of AlGa_N channel HEMTs than GaN-based HEMTs. The high V_{BR} is achieved for long channel L_G , long L_{GD} HEMTs, along with Al-rich AlGa_N channel [6-26]. Whereas, the smaller L_G , L_{GD} , and low Al composition of AlGa_N 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, Al_{0.1}Ga_{0.9}N channel HEMT for improve the V_{BR} of the device with satisfactory RF performance. $L_G = 0.8 \mu\text{m}$, and $L_{\text{GD}} = 1 \mu\text{m}$ Al_{0.31}Ga_{0.69}N/Al_{0.1}Ga_{0.9}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 section 2. The physics-based simulation models are described in section 3. The DC and microwave characteristic of proposed HEMT with experimental validation is discussed in section 4 with concluding remarks.

2. Device Structure Description

The Al_{0.1}Ga_{0.9}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 Al_{0.31}Ga_{0.69}N barrier, 100 nm Al_{0.1}Ga_{0.9}N channel, and

2.2 μm buffer. The device DC and RF performance are evaluated for 100 nm SiN and HfO₂ passivation. The model device used in simulation has a 0.8 μm gate length, 1 μm gate to drain distance, and 0.8 μm 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 $1.01 \times 10^{13} \text{ cm}^{-2}$ of electron density and $810 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$ of carrier mobility in the 2DEG.

Figure 1. Structure of Al_{0.1}Ga_{0.9}N channels (a) conventional HEMT (Device A), (b) Gate field plate (Device B), (c) Recessed floating field plate. (Device C).

Figure 2. Conduction band and interface charge diagram of $\text{Al}_{0.31}\text{Ga}_{0.69}\text{N}/\text{Al}_{0.1}\text{Ga}_{0.9}\text{N}$ heterostructure.

3. Simulation models

The proposed HEMT is analysed using 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 [30];

$$P_{total} = [P_{PE}(bottom) + P_{SP}(bottom)] - [P_{PE}(top) + P_{SP}(top)] , \quad (3)$$

The P_{total} at the top/bottom hetero interface depends on the spontaneous (P_{SP}) and piezoelectric polarization (P_{PE}) of the materials. The temperature dependent mobility model $\mu_0(T, N)$ describes as following form [27];

$$\mu_0(T, N) = \mu_{\min}^{\beta_1} \left(\frac{T}{300} \right) + \frac{(\mu_{\max} - \mu_{\min}) \left(\frac{T}{300} \right)^{\beta_2}}{1 + \left[\frac{N}{N_{ref} \left(\frac{T}{300} \right)^{\beta_3}} \right]^{\alpha \left(\frac{T}{300} \right)^{\beta_4}}} \quad (4)$$

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 τ_n and holes lifetime τ_p , temperature, trap energy level E_{trap} [31];

$$R_{net}^{SRH} = \frac{n - n_{ie}^2}{\tau_p \left[p + n_{ie} \exp\left(\frac{-E_{trap}}{KT}\right) \right] + \tau_n \left[p + n_{ie} \exp\left(\frac{-E_{trap}}{KT}\right) \right]^r} , \quad (5)$$

The Selberherr's impact ionization model considered for device breakdown simulation [32] and the impact ionization carrier generation rate described as follows:

$$G = (\alpha_n |J_p| + \alpha_p |J_n|) / q \quad (6)$$

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 [31] for the simulation.

4. Results and Discussions

The proposed recessed floating gate HEMT (Device C) transfer characteristic is depicted in Fig. 3 for $V_{DS} = 10$ V and V_{GS} swept from -6 V to 0 V. The conventional and gate field plate HEMTs also exhibited similar response. $\text{Al}_{0.1}\text{Ga}_{0.9}\text{N}$ HEMT with $L_G = 0.8$ μm has reached the maximum output current (I_{DS}) of 0.28 A/mm and $g_{m, \max}$ of 95 mS/mm. The threshold voltage of the HEMT is extracted as -3 V. The V-I characteristics of the proposed Device C is shown in Fig. 4 for $V_{GS} = -3$ to 0 V and V_{DS} swept from 0 V to 10 V. Device A and Device B also exhibited similar output characteristics. The extracted ON-resistance (R_{ON}) of the device from the V-I characteristics ($V_{GS} = 0$ V) is 6.38 $\Omega\cdot\text{mm}$. The device is perfectly pinched-off at $V_{GS} = -3$ V. The proposed device R_{ON} resistance is comparatively lower than the reported works [7-25]. The transfer and output characteristics of simulation result of conventional $\text{Al}_{0.1}\text{Ga}_{0.9}\text{N}$ channel HEMT is validated with experiment result of [24] and it is shown in Fig. 5 and Fig. 6 respectively. The simulated results were well correlated with the reported experimental work.

Figure 3. Transfer characteristics of recessed floating gate HEMT (Device C).

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

Figure 5. Transfer characteristics for $L_G = 0.8 \mu\text{m}$ of $\text{Al}_{0.1}\text{Ga}_{0.9}\text{N}$ channel HEMT (Device C) and experimental work [24].

Figure 6. Output characteristics for $L_G = 0.8 \mu\text{m}$ of $\text{Al}_{0.1}\text{Ga}_{0.9}\text{N}$ channel HEMT (Device C) and experimental work [24].

The HEMT breakdown simulation was carried out at off-state condition ($V_{GS} = -8 \text{ V}$). The electric field (E-field) distributions for SiN and HfO_2 passivation of (a) Device A, (b) Device B and (c) Device C are depicted in Fig. 7 and Fig. 8 respectively. The permittivity (ϵ_r) and thickness (t) of the insulator (passivation) modulates the E-field. High permittivity HfO_2 ($\epsilon_r=25$) passivation smoothening the E-field at gate and drain edge [32-34].

From Fig. 7(a) (SiN passivation) and Fig. 8(a) (HfO_2 passivation), it is observed that a peak E-field exist at the gate edge, which lower the V_{BR} of the device. Therefore, sinking the field distribution becomes the alternate solution to enhance the V_{BR} . In general, the gate field plate (FPs), source field plate (SFPs), and drain connected field plate techniques are used to suppress the electric field [35]. 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) (HfO_2 passivation) and it reshaping the field distribution.

Figure 7. E-field distribution for SiN passivation of (a) Device A (b) Device B (c) Device C.

Figure 8. E-field distribution for HfO₂ passivation of (a) Device A, (b) Device B and (c) Device C.

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 solely depends on field plate length, passivation permittivity, thickness of the passivation, and recess depth.

Figure 9. Off-state breakdown characteristics of $L_G = 0.8 \mu\text{m}$ $\text{Al}_{0.1}\text{Ga}_{0.9}\text{N}$ channel HEMTs.

For the proposed Device C dimensions, the off-state breakdown voltage characteristics of HEMTs are plotted in Fig. 9. The recessed floating field plate HEMT shown remarkable V_{BR} of 677 (617) V for HfO_2 (SiN) passivation. However, the conventional HEMT shown V_{BR} of 307 (297) V and gate filed plate shown V_{BR} of 462 (428) V. From this analysis of off state breakdown voltage simulation, the floating field plate demonstrated 54% improvement in V_{BR} than conventional HEMT, and 31 % higher than the gate field plate HEMT.

Figure 10. Electron concentration distribution of SiN passivation (a) Device A, (b) Device B and (c) Device C at breakdown voltage condition.

Figure 11. Electron concentration distribution of HfO₂ passivation (a) Device A, (b) Device B and (c) Device C at breakdown voltage condition.

The Fig. 10 and Fig. 11 shows the simulation results of electron concentration distribution of HEMTs at breakdown condition. The larger depletion region of floating field plate shown in Fig.10 (c) and Fig.11 (c), suppressed E-field near the drain side of gate edge, and high critical field of Al_{0.1}Ga_{0.9}N channel are the major reason for improving the breakdown voltage of the proposed HEMTs.

Figure 12. Microwave performance of SiN passivation HEMTs.

Figure 13. Microwave performance of HfO₂ passivation HEMTs.

The microwave performance of the SiN and HfO₂ passivated Device C are depicted in Fig. 12 and Fig. 13 respectively. The conventional HEMTs are showing better F_T 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 Equation (9) and (10).

$$P_{RF} = \frac{I_{max}[V_{br} - V_{knee}]}{8} \quad (7)$$

$$F_T = \frac{G_m}{2\pi(c_{GS} + c_{GD})} \quad (8)$$

$$F_{MAX} = \frac{F_T}{\sqrt{(R_i + R_s + R_g)g_0 + (2\pi F_T)R_g C_{GD}}} \quad (9)$$

The I_{DS} and V_{BR} of a transistor expected to be very high for delivering high RF output power density as shown in Equation (8). The proposed recessed floating field plate HEMT shown 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.

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_G (0.8 μm).

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

Author, Year	Reference No	Gate length (L_G)	Gate to drain distance (L_{GD})	Drain current (I_{DS})	Breakdown voltage (V_{BR})	Cut-off frequency (F_T/F_{MAX})
V. Adivarahan et al., 2008	[7]	1 μm	3 μm	0.11 A/mm	463 V	-
T. Nanjo et al.,	[8]	1 μm	2 μm	0.14	350 V	-

2009				A/mm		
Takuma Nanjo et al., 2013	[9]	1 μm	3 μm	0.18 A/mm	500 V	-
Sanyam Bajaj et al., 2016	[10]	0.7 μm	1.1 μm	0.05 A/mm	224 V	-
Albert G. Baca et al., 2016	[11]	2 μm	10 μm	-	810 V	-
W. Zhang et al., 2018	[13]	3 μm	6 μm	-	500 V	
Ming Xiao et al., 2018	[14]	1 μm	5 μm	0.3 A/mm	408 V	
Albert G. Baca et al., 2018	[15]	80 nm	0.5 μm	0.1 A/mm	92 V	28.4/18.5 GHz
Andrew M. Armstrong et al., 2019	[16]	3 μm	2.7 μm	0.1 A/mm	620 V	-
Hao Xue et al., 2019	[17]	160 nm	0.6 μm	0.42 A/mm	170 V	20/40 GHz
Yachao Zhang et al., 2020	[24]	0.8 μm	1 μm	0.24 A/mm	143 V	-
Shahadat H. Sohel et al., 2020	[25]	0.7 μm	3.5 μm	0.3 A/mm	125 V	14/22 GHz
This work (SiN Passivation)		0.8 μm	1 μm	0.288 A/mm	617 V	12/22 GHz
This work (HfO2 Passivation)		0.8 μm	1 μm	0.282 A/mm	677 V	11.4/49 GHz

5. Conclusion

Breakdown voltage performance analysis of $\text{Al}_{0.1}\text{Ga}_{0.9}\text{N}$ channel HEMT is reported with floating field plate and AlGaIn 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 filed plate technique, which further elevated the breakdown performance of the AlGaIn channel HEMTs. The insertion of floating filed plate 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 $F_{\text{T}}/F_{\text{max}}$ 11.4/49 GHz for a high- k HfO₂ passivation. HfO₂ and SiN passivated Device C shows 54% and 31% improvement in breakdown voltage on comparisons with conventional HEMT. The excellent breakdown power performances along with RF characteristics of the ultrawide bandgap AlGaIn channel based HEMTs are attractive alternate devices for next geneartion power electronics and RF applications.

Declarations: Manuscripts is prepared strictly adhering to the norm of the journal, contains 5 Sections and no sub sections.

Funding: NOT APPLICABLE

Conflicts of interest/Competing interests- The authors declare that there is no conflict of interest reported in this paper.

Availability of data and materials: NOT APPLICABLE

Code availability: NOT APPLICABLE

Authors' contributions: All the works reported in this paper is original and have done together by Ramkumar Natarajan and Eswaran Parthasarathy.

Ethics approval: NOT APPLICABLE

Consent to participate: NOT APPLICABLE

Consent for publication: Not applicable as the manuscript does not contain any data from individual.

Acknowledgements: The authors acknowledge the Department of Electronics and Communication Engineering, SRM Institute of Science and Technology, Chennai, India for research facility and support to carry out this research work.

Disclosure of potential conflicts of interest: NOT APPLICABLE

Research involving Human Participants and/or Animals: NOT APPLICABLE

Informed consent: NOT APPLICABLE

References

1. Zeng, Fanming; An, Judy X.; Zhou, Guangnan; Li, Wenmao; Wang, Hui; Duan, Tianli; Jiang, Lingli; Yu, Hongyu. (2018) A Comprehensive Review of Recent Progress on GaN High Electron Mobility Transistors: Devices, Fabrication and Reliability, Electronics 7, 12: 377. <https://doi.org/10.3390/electronics7120377>
2. Fabrizio Roccaforte, Patrick Fiorenza, Giuseppe Greco, Raffaella Lo Nigro, Filippo Giannazzo, Ferdinando Iucolano, Mario Saggio (2018) Emerging trends in wide band gap semiconductors (SiC and GaN) technology for power devices, Microelectronic Engineering, 187–188:66-77, <https://doi.org/10.1016/j.mee.2017.11.021>
3. K. Husna Hamza, D. Nirmal (2020) A review of GaN HEMT broadband power amplifiers, AEU - International Journal of Electronics and Communications,116: 153040 <https://doi.org/10.1016/j.aeue.2019.153040>
4. Ma, Chao-Tsung; Gu, Zhen-Huang. (2019)Review of GaN HEMT Applications in Power Converters over 500 W" Electronics 8,12:1401. <https://doi.org/10.3390/electronics8121401>
5. Flack, T.J., Pushpakaran, B.N. & Bayne, S.B. (2016) GaN Technology for Power Electronic Applications: A Review. Journal of Elec Materi ,45:2673–2682 <https://doi.org/10.1007/s11664-016-4435-3>
6. Takuma Nanjo, Misaichi Takeuchi, Muneyoshi Suita, Yuji Abe, Toshiyuki Oishi, Yasunori Tokuda and Yoshinobu Aoyagi (2007) First Operation of AlGaIn Channel High Electron Mobility Transistors, , Applied Physics Express,1: 011101, <https://doi.org/10.1143/APEX.1.011101>

7. Takuma Nanjo, Misaichi Takeuchi, Muneyoshi Suita, Toshiyuki Oishi, Yuji Abe, Yasunori Tokuda, and Yoshinobu Aoyagi (2008) Remarkable breakdown voltage enhancement in AlGa_N channel high electron mobility transistors, *Applied Physics Letters*, 92:263502. <https://doi.org/10.1063/1.2949087>
8. T. Nanjo, M. Takeuchi, A. Imai, M. Suita, T. Oishi, Y. Abe, E. Yagyu, T. Kurata, Y. Tokuda, Y. Aoyagi (2009) AlGa_N channel HEMTs on AlN buffer layer with sufficiently low off-state drain leakage current, 45:1346 – 1348, <https://doi.org/10.1049/el.2009.2711>
9. Takuma Nanjo; Akifumi Imai; Yosuke Suzuki; Yuji Abe; Toshiyuki Oishi; Muneyoshi Suita; Eiji Yagyu; Yasunori Tokuda (2013) AlGa_N Channel HEMT With Extremely High Breakdown Voltage, in *IEEE Transactions on Electron Devices*, 60:1046-1053. <https://doi.org/10.1109/TED.2012.2233742>
10. Sanyam Bajaj, Fatih Akyol, Sriram Krishnamoorthy, Yuewei Zhang, and Siddharth Rajan (2016) AlGa_N channel field effect transistors with graded heterostructure ohmic contacts, *Appl. Phys. Lett.* 109:133508. <https://doi.org/10.1063/1.4963860>
11. Albert G. Baca, Andrew M. Armstrong, Andrew A. Allerman, Erica A. Douglas, Carlos A. Sanchez, Michael P. King, Michael E. Coltrin, Torben R. Fortune, and Robert J. Kaplar (2016) An AlN/Al_{0.85}Ga_{0.15}N high electron mobility transistor, *Appl. Phys. Lett.* 109:033509. <https://doi.org/10.1063/1.4959179>
12. Sakib Muhtadi; Seong Mo Hwang; Antwon Coleman; Fatima Asif; Grigory Simin; MVS Chandrashekhar; Asif Khan (2017) High Electron Mobility Transistors With Al_{0.65}Ga_{0.35}N Channel Layers on Thick AlN/Sapphire Templates, in *IEEE Electron Device Letters*, vol. 38: 914-917. <https://doi.org/10.1109/LED.2017.2701651>
13. W. Zhang, J. Zhang, M. Xiao, L. Zhang and Y. Hao (2018) High Breakdown-Voltage (>2200 V) AlGa_N-Channel HEMTs With Ohmic/Schottky Hybrid Drains, in *IEEE Journal of the Electron Devices Society*, 6:931-935. <https://doi.org/10.1109/JEDS.2018.2864720>
14. Ming Xiao; Jincheng Zhang; Xiaoling Duan; Weihang Zhang; Hengsheng Shan; Jing Ning; Yue Hao (2018) High Performance Al_{0.10}Ga_{0.90}N Channel HEMTs," in *IEEE Electron Device Letters*, 39:1149-1151. <https://doi.org/10.1109/LED.2018.2848661>
15. Albert G. Baca; Brianna A. Klein; Joel R. Wendt; Stefan M. Lepkowski; Christopher D. Nordquist; Andrew M. Armstrong; Andrew A. Allerman; Erica A. Douglas; Robert J. Kaplar (2019) RF Performance of Al_{0.85}Ga_{0.15}N/Al_{0.70}Ga_{0.30}N High Electron Mobility Transistors With 80-nm Gates," in *IEEE Electron Device Letters*, 40:17-20, <https://doi.org/10.1109/LED.2018.2880429>
16. Andrew M. Armstrong, Brianna A. Klein, Albert G. Baca, Andrew A. Allerman, Erica A. Douglas, Albert Colon, Vincent M. Abate, and Torben R. Fortune (2019) AlGa_N polarization-doped field effect transistor with compositionally graded channel from Al_{0.6}Ga_{0.4}N to AlN, *Appl. Phys. Lett.* 114:052103. <https://doi.org/10.1063/1.5058263>
17. Hao Xue, Seongmo Hwang, Towhidur Razzak, Choonghee Lee, Gabriel Calderon Ortiz, Zhanbo Xia, Shahadat Hasan Sohel, Jinwoo Hwang, Siddharth Rajan, Asif Khan, Wu Lu, (2020) All MOCVD grown Al_{0.7}Ga_{0.3}N/Al_{0.5}Ga_{0.5}N HFET: An approach to make ohmic contacts to Al-rich AlGa_N channel transistors, *Solid-State Electronics*, Volume 164: 107696. <https://doi.org/10.1016/j.sse.2019.107696>
18. Zhong-Xu Wang, Lin Du, Jun-Wei Liu, Ying Wang, Yun Jiang, Si-Wei Ji, Shi-Wei Dong, Wei-Wei Chen, Xiao-Hong Tan, Jin-Long Li, Xiao-Jun Li, Sheng-Lei Zhao, Jin-Cheng Zhang and Yue Hao (2019) Breakdown Voltage Enhancement in Ga_N Channel and AlGa_N Channel HEMTs Using Large Gate Metal Height, *Chinese Phys. B*, **29**: 027301. <https://doi.org/10.1088/1674-1056/ab5fb9>
19. Shahab Mollah, Mikhail Gaevski, Kamal Hussain, Abdullah Mamun, Richard Floyd, Xuhong Hu, M V S Chandrashekhar, Grigory Simin and Asif Khan (2019) Current collapse in high-Al channel AlGa_N HFETs, *Appl. Phys. Express*, **12**:074001 <https://doi.org/10.7567/1882-0786/ab24b1>
20. Erica A. Douglas, Brianna Klein, Andrew A. Allerman, Albert G. Baca, Torben Fortune, and Andrew M. Armstrong (2019) Enhancement-mode AlGa_N channel high electron mobility transistor enabled by p-AlGa_N gate, *Journal of Vacuum Science & Technology B*, **37**:021208, <https://doi.org/10.1116/1.5066327>
21. Shahed Reza, Brianna A. Klein, Albert G. Baca, Andrew M. Armstrong, Andrew A. Allerman, Erica A. Douglas and Robert J. Kaplar (2019) High-frequency, high-power performance of AlGa_N-channel high-electron-mobility transistors: an RF simulation study, *Japanese Journal of Applied Physics*, **58**:SCCD04. <https://doi.org/10.7567/1347-4065/ab07a5>
22. Yinhe Wu; Jincheng Zhang; Shenglei Zhao; Weihang Zhang; Yachao Zhang; Xiaoling Duan; Jiabo Chen; Yue Hao (2019) More Than 3000 V Reverse Blocking Schottky-Drain AlGa_N-Channel HEMTs

- With >230 MW/cm² Power Figure-of-Merit," in IEEE Electron Device Letters, 40:1724-1727. <https://doi.org/10.1109/LED.2019.2941530>
23. Ming Xiao; Weihang Zhang; Yuhao Zhang; Hong Zhou; Kui Dang; Jincheng Zhang; Yue Hao (2019) Novel 2000 V Normally-off MOS-HEMTs using AlN/GaN Superlattice Channel, 31st International Symposium on Power Semiconductor Devices and ICs (ISPSD), pp. 471-474, <https://doi.org/10.1109/ISPSD.2019.8757585>
 24. Yachao Zhang, Yifan Li, Jia Wang, Yiming Shen, Lin Du, Yao Li, Zhizhe Wang, Shengrui u, Jincheng Zhang & Yue Hao (2020) High-Performance AlGa_N Double Channel HEMTs with Improved Drain Current Density and High Breakdown Voltage. Nanoscale Res Lett, 15:114 <https://doi.org/10.1186/s11671-020-03345-6>
 25. Shahadat H. Sohel, Andy Xie, Edward Beam, Hao Xue, Towhidur Razzak, Sanyam Bajaj, Sherry Campbell, Donald White, Kenneth Wills, Yu Cao, Wu Lu and Siddharth Rajan (2020), Improved DC-RF dispersion with epitaxial passivation for high linearity graded AlGa_N channel field effect transistors, Applied Physics Express 13:036502 <https://doi.org/10.35848/1882-0786/ab7480>
 26. Lei Li, Ryohei Yamaguchi, and Akio Wakejima (2020) Polarization engineering via InAlN/AlGa_N heterostructures for demonstration of normally-off AlGa_N channel field effect transistors, Appl. Phys. Lett. 117:152108 <https://doi.org/10.1063/5.0020359>
 27. M. Farahmand; C. Garetto; E. Bellotti; K.F. Brennan; M. Goano; E. Ghillino; G. Ghione; J.D. Albrecht; P.P. Ruden (2001) "Monte Carlo simulation of electron transport in the III-nitride wurtzite phase materials system: binaries and ternaries," in IEEE Transactions on Electron Devices, vol. 48:535-542. <https://doi.org/10.1109/16.906448>
 28. Patrick H. Carey; Fan Ren; Albert G. Baca; Brianna A. Klein; Andrew A. Allerman; Andrew M. Armstrong; Erica A. Douglas; Robert J. Kaplar; Paul G. Kotula, Stephen J. Pearton , (2019) Operation Up to 500 °C of Al_{0.85}Ga_{0.15}N/Al_{0.7}Ga_{0.3}N High Electron Mobility Transistors, in IEEE Journal of the Electron Devices Society 7: 444-452. <https://doi.org/10.1109/JEDS.2019.2907306>
 29. Michael E. Coltrin, Albert G. Baca, and Robert J. Kaplar (2017), Analysis of 2D Transport and Performance Characteristics for Lateral Power Devices Based on AlGa_N Alloys, ECS Journal of Solid State Science and Technology, 6: S3114-S3118 <https://doi.org/10.1149/2.0241711jss>
 30. O Ambacher, J Majewski, C Miskys, A Link, M Hermann, M Eickhoff, M Stutzmann, F Bernardini, V Fiorentini, V Tilak, B Schaff and L F Eastman(2002) Pyroelectric properties of Al(In)Ga_N/Ga_N hetero- and quantum well structures, J. Phys.: Condense. Matter, 14 :3399–3434. <https://doi.org/10.1088/0953-8984/14/13/302>
 31. SILVACO Int. ATLAS User's Manual; Device Simulation Software: Santa Clara, CA, USA, 2016; Available online: <https://www.silvaco.com>.
 32. P. Murugapandiyam, Md. Tanvir Hasan, V Rajya Lakshmi, Mohd Wasim, J Ajayan, N Ramkumar & D Nirmal (2020): Breakdown voltage enhancement of gate field plate Al_{0.295}Ga_{0.705}N/GaN HEMTs, International Journal of Electronics, <https://doi.org/10.1080/00207217.2020.1849819>
 33. Murugapandiyam, P., Nirmal, D., Ajayan, J., Aarthy Vargheese and N. Ramkumar (2021) Investigation of Influence of Si₃N₄ and SiO₂ Passivation in Gate Field Plate Double Heterojunction Al_{0.3}Ga_{0.7}N/GaN/Al_{0.04}Ga_{0.96}N High Electron Mobility Transistors, Silicon. <https://doi.org/10.1007/s12633-020-00899-z>.
 34. Kumar, J.S.R., Nirmal, D., Hooda, M.K., Surider Singh, J. Ajayan and L. Arivazhagan (2021) Intensive Study of Field-Plated AlGa_N/Ga_N HEMT on Silicon Substrate for High Power RF Applications. Silicon. <https://doi.org/10.1007/s12633-021-01199-w>.
 35. C Bulutay (2002) Electron initiated impact ionization in AlGa_N alloys, 2002 Semicond. Sci. Technol., 17:59-62. <https://doi.org/10.1088/0268-1242/17/10/102>