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Design and performance analysis of front and back Pi 6 nm gate with high K dielectric passivated high electron mobility transistor

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ABSTRACT

Advanced high electron mobility transistor (HEMT) with dual front gate, back gate with silicon nitride/aluminum oxide (Si3N4/Al2O3) as passivation layer, has been designed. The dependency on DC characteristics and radio frequency characteristics due to GaN cap layers, multi gate (FG and BG), and high K dielectric material is established. Further compared single gate (SG) passivated HEMT, double gate (DG) passivated HEMT, double gate triple (DGT) tooth passivated HEMT, high K dielectric front Pi gate (FG) and back Pi gate (BG) HEMT. It is observed that there is an increased drain current (Ion) of 5.92 (A/mm), low leakage current (Ioff) 5.54E-13 (A) of transconductance (Gm) of 3.71 (S/mm), drain conductance (Gd) of 1.769 (S/mm), Cutoff frequency (fT) of 743 GHz maximum oscillation frequency (Fmax) 765 GHz, minimum threshold voltage (V_{th}) of -4.5 V, on resistance (Ron) of 0.40 (Ohms) at $V_{gs} = 0$ V. These outstanding characteristics and transistor structure of proposed HEMT and materials involved to apply for upcoming generation high-speed GHz frequency applications.

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1. INTRODUCTION

In power electronics for the past decades, silicon (Si) is the predominant material and long-established material. Silicon material possesses low saturation velocity and low operating temperature capability for handling power. There is the prerequisite of large current, faster-switching speed, high transconductance, high power density, and high-efficiency requirements for radio frequency (RF) applications [1]. Silicon is limited to reporting these requirements. Gallium arsenide (GaAs), gallium nitride (GaN), indium phosphide (InP), and silicon carbide (SiC) are conventional available wide band gap materials [2]. Comparatively among these materials, GaN has the properties to meet the prerequisite. GaN can be operated at high temperatures, it has a wide band gap, high saturation velocity, and high critical field. For high-power applications, GaN is a suggestable and suitable material [3], [4]. GaN has balancing properties and more advantages compared to Si, SiC, GaN, and GaAs where it can withstand the performance of the transistor [5]. GaN has achieved demand among the other semiconductor materials which is widely used in designing modern electronics and solid-state switches [6]. A narrow channel enables it to work at very high frequencies, providing low noise performance. GaN-based high electron mobility transistor (HEMT) provides a narrow channel [7]. In HEMT two different semiconductor materials with the same lattice constant, and different band gaps are layered on one other. The two-dimensional electron gas (2DEG) is developed at the interface of 2 different materials. Electron mobility

takes place from source to drain. A wide variety of HEMTs are present such as T, gama gate, camel shape gate (CG), multiple grating field plate (MGFP), gate field plate (GFP), discrete field plate (DFP) gate based MOS-HEMT. Early breakdown effects, Leakage current, and short channel effect are the limitation of the existing transistor. In the Pi gate, GaN HEMT also small leakage current, and dynamic power losses are present across the Schottky gate.

For the existing HEMT to improve the characteristics of the device GaN layers, front Pi gate, and back Pi gate are incorporated [8]. These cap layers passivation layers provide sealing the first layer of HEMT structure from external atmospheric fluctuations [9]. The proposed high K dielectric FG and BG HEMT overcomes the limitation of dual gate HEMT and exhibits optimized HEMT Structure which gives optimistic DC and RF characteristics [10]. The results show that high K dielectric FG and BG HEMT results improved on current, trans conductance, drain conductance, maximum oscillation frequency, improved Cutoff frequency, with reduced leakage current [11]. In this structure GaAs, GaN, InP, and SiC can meet the improved performance parameters compared to conventional HEMT. Among these materials, GaN has high saturation velocity, high wideband gap, and high critical field properties. Therefore, Gallium Nitride HEMT structure is suitable for low power applications.

To overcome these effects existing convention transistors are modified. For the existing HEMT to improve the characteristics of the device GaN layers, front Pi gate, and back Pi gate are incorporated HEMT is constructed by deploying two semiconductor substances with identical lattice constant, and distant band gap materials are stacked on one another. At the interjunction of these 2DEG is formed. A broad class of HEMTs is existent namely Gama gate, T gate, GFP, CG, DFP, MGFP Gate HEMT. These are limited by early high Leakage current, breakdown effects, and more short channel effects. Conventional transistors are optimized to overcome these effects.

2. DEVICE STRUCTURE AND SIMULATION PARAMETERS

Dual Pi gate HEMT with hetero passivation layer is shown in Figure 1 structure. Since Si_3N_4/Al_2O_3 exhibits the least C_{GS} and $C_{GD,}$ reducing surface traps, it is chosen as passivation layers [12]. 3 unique features of the structure, one is it consists of 2 Pi gates, secondly, it consists of a hetero passivation layer [13]. The unique properties of AlN make its usage in lighting, renewable energy, electronics, and optics. It is a solid nitride of aluminum material [14]. At room temperature, it has approx. 6eV of the band gap [14]. AlN layer used for carrier confinement reduction in alloy scattering improved scattering [15]. GaN Cap layer of 2 nm is deployed on the top of the structure [16]. By using GaN cap layer carrier mobility improved, improve transport mechanism [17]. The probability of penetrating the mobility electron into AlGaN is reduced due these layers [18]. High conduction is possible due to the presence of cap layer [19]. Scattering of alloy reduced, and better confinement of carrier, improved conductivity and mobility is observed by employing the cap layer on the top of heterostructure which proposed makes easy to fabric ohmic contact. A dual gate increases I_D drain current and reduces leakage current, in turn, reflects on transconductance [20]. Silicon dioxide (SiO_2), silicon carbide (6H-SiC), Si, and GaN of material with wide band gap semiconductors ultra-power microwave and radiofrequency application required material with high band gap [21]. These requirements can be met by the above for the past decades' work on transistors is processed to reduce the size of the transistor [22]. But too much reduction in the size of the transistor results increase in leakage current, increase in power dissipation losses [23], so hetero materials with high electron mobility are loosening to overcome the limitation of existing conventional transistors. Marino *et al.* [24] proposed HEMTs increase conductivity drain current (I_D), trans conductance (gm), on resistance (R_{on}), and threshold voltage (V_{th}). Off current (I_{off}), f_T, f_{max} get reflected in a positive direction. The performance of 6 nm gate HEMT is compared with different passivation layers ie $SiO_{2,}$ Si_3N_4, $Al_2O_{3,}$ and $Si_3N_4/Al_2O_{3,}$ the proposed device is verified with passivation and without passivation layer using the TCAD tool. In multiple directions, the structure is simulated and verified using the Silvaco TCAD tool [25]. Less lattice mismatch materials are used and designed the structure keeps cost in view. The proposed structure operates at high power and high-frequency operation. The electrons may scatter during the active state to avoid this problem SiO_2 is used to confine the electron in the channel and let the electron flow from source to drain [26] aluminum nitride (AlN) material is used to reduce the material mismatch. If there is more mismatch electron scatter and leads to scattering losses. SiO_2 and Si materials are used to lower scattering due to alloy disorder aluminum with different mole fractions is used to improve the performance [27]. ATLAS method and models were used for the proposed device.

It is observed by Johnson's figure of merit that GaN ideal candidate for high temperature and high power due to its high electron mobility, saturation velocity, and high breakdown voltage. These cap layers passivation layers provide sealing the first layer of HEMT structure from external atmospheric fluctuations the narrow channel plays a key role that triggers the device to work at microwave frequencies, this is provided by GaN. HEMT is constructed by deploying two semiconductor substances with identical lattice constant, and distant band gap materials are stacked on one another A broad class of HEMTs is existent namely Gama gate,

T gate, GFP, CG, DFP, MGFP gate HEMT. Back barrier layer (BBL) thickness results in reduction in leakage current and dynamic R_{on} BBL can be varied from 0 to 200 nm GaN channel is wurtzite crystal structure.it possess high Bandgap of 3.49 (EV) with electron mobility of 900 (cm_2/vs), electron peak velocity is 2.7×10^7 (cm/s), 2DEG sheet electron density is 20×10^{12} (cm^{-2}), Critical breakdown field 3.3 (MV/cm), thermal conductivity >1.7 (W/cm-K), relative dielectric constant (ε_r) -9.0 GaN material possess high thermal conductivity, high saturation drift velocity. These properties are required for the device to work in high frequency for having high power switching and to work at high temperatures Heterojunction is formed when two material of different band gaps with almost the same lattice constant. The field effect transistor that incorporates heterojunction is called the HEMT.

20n Al_2O_3 thickness was deployed. $Al_{0.75}$ $Ga_{0.25}N$, $Al_{0.52}Ga_{0.45}N$, AlN (Spacer layer), GaN, AlN, $Al_{0.52}Ga_{0.45}N$, $Al_{0.75}Ga_{0.25}N$ these materials are deployed in this sequence respective with 36 nm, 38 nm, 34 nm, 43 nm, 34 nm, 38 nm, 36 nm. Spacer layer is to improve the density of 2DEG aluminum nitride is stable at temperatures over 2,000º in inert atmosphere. It possesses high thermal conductivity. Dual pi gate HEMT with hetero passivation layer is proposed. SiO2, 6H-SiC, Si, and GaN of material with wide band gap semiconductors ultra-power microwave and RF application required material with high Band Gap. The proposed high K dielectric FG and BG HEMT overcomes the limitation of dual gate HEMT and exhibits optimized HEMT structure which gives optimistic DC and RF characteristics.

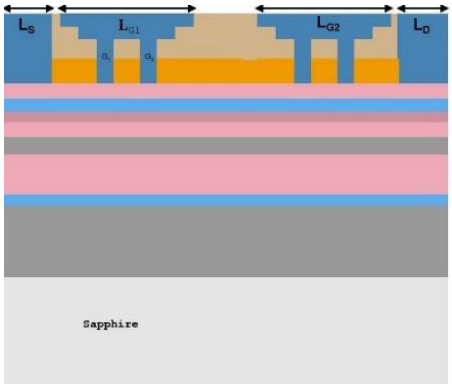

Figure 1. Double gate HEMT with Si_3N_4/Al_2O_3 passivation layers

3. SIMULATION RESULTS AND DISCUSSION

Device simulations are performed using the Silvaco TCAD tool. In this paper various existing transistors having T shaped gates, camel shaped gates, MGFP gates, GFP gates, and DFP gate-based MOS-HEMT. The first layer of the HEMT will form a tight bond with the metal to create the seal. This sealing eliminates elements from corroding. Figure 1, shows HEMT with a dual Pi gate [28]. Dual gate eliminates short channel effects, helps to use the device in high-frequency applications, and increases the efficiency of the channel Figure 2, shows the proposed structure consists high K dielectric FG-BG HEMT structure with Si_3N_4/Al_2O_3 passivation layers. The two gates play a key role in improving drain current and conductance. The performance of the device is optimized. To optimize results, the position of metal is also an important constraint. The depletion region in the channel gets modified which adds to the performance improvement of the device. The capacitance is related as in the (1), where A is the area of the capacitance, $\varepsilon_o$is free space permittivity, K is dielectric constant of the material, t is capacitor oxide insulator thickness. As the capacitance is related to *k* by altering *k* we can improve the capacitance, where the derive current can be improved.

$$C = \frac{kA\varepsilon_O}{t} \quad (1)$$

$$I_{D,Sat} = \frac{WC\mu(V_G - V_{th})^2}{2L} \quad (2)$$

The drain current of a proposed device is calculated using (2), where drain current is directly proportional to gate capacitance, width of the channel, mobility of the carrier and inversely proportional to length of the gate. The threshold voltage and gate voltages are measured in volts and its range up to 1v. The saturated drain current of this device is more than the hetero junction and conventional HEMT.

Figure 3 shows drain current changes concerning various drain voltage characteristics of HEMTs with various physical structures of 6 nanometers at $V_{gs} = 0$ V i.e., Single Pi gate passivated (SGP) HEMT, double gate passivated (DGP) HEMT, double gate triple tooth passivated (DGT) HEMT, high K dielectric FG and BG HEMT at gate voltage $V_{gs} = 0\ V$ is shown. It results in an increased drain current (I_d) of 5.92 A/mm appearing for the proposed high K dielectric FG and BG HEMT.

From (3) Cutoff frequency (f_T) depends on the length of the gate (Lg) and the saturation velocity of the material and trans conductance. As drain current increases, trans conductance increases. As the trans conductance is directly proportional to the cutoff frequency, the cutoff frequency increased to 743 GHz. So, by proper placement of the transistor gate, the required cutoff frequency can be attained.

$$Cutoff\ Frequency = \frac{Vsat}{2 \prod Lg} \tag{3}$$

Figure 4 shows the Cutoff frequency (f_T) concerning gate length, of HEMTs with various physical structures of 6 nanometers at $V_{gs} = 0\ V$ i.e., single Pi Gate passivated HEMT, double gate passivated HEMT, double gate triple tooth passivated HEMT, high K dielectric FG and BG HEMT at gate voltage $V_{gs} = 0\ V$ is shown. It resulted in an increased Cutoff frequency (f_T) of 743 GHz. appeared for proposed high K dielectric FG and BG HEMT.

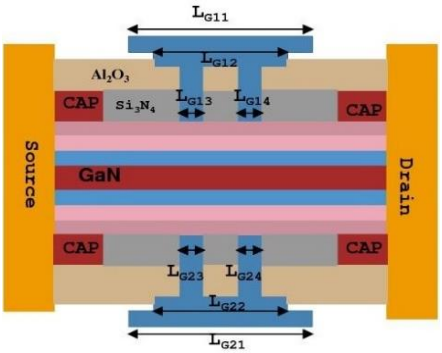

Figure 2. High K dielectric FG-BG HEMT structure with Si_3N_4/Al_2O_3 passivation layers

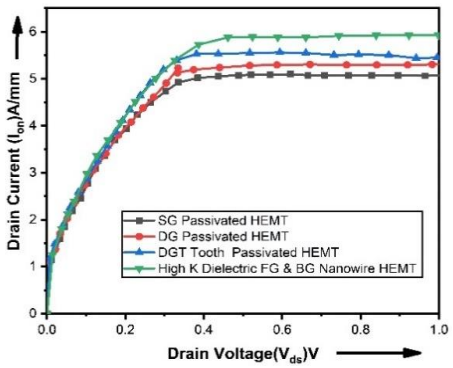

Figure 3. Drain current changes concerning various drain voltage characteristics for HEMTs with various physical structures of 6-nanometer technology at $V_{gs} = 0\ V$

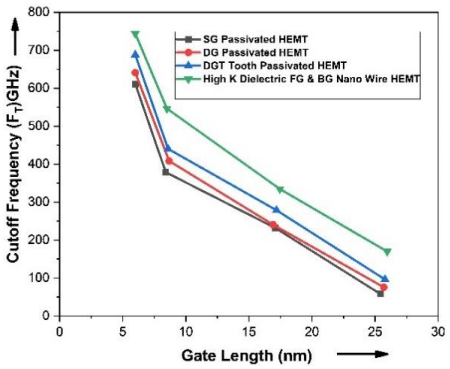

Figure 4. Cut-off frequency variations at different gate lengths for various physical structures at $V_{ds} = 0.2\ V$

Trans conductance (gm) is defined as the ratio of change in drain current (I_d) to the change in the change in the gate to source voltage (V_{GS}) represented in (4).

$$Transconductance\ = \frac{dI_D}{dV_{GS}} \tag{4}$$

Figure 5 shows Trans conductance (G_m) concerning gate voltage V_{gs} for HEMTs with various physical structures of 6 nanometers at $V_{ds} = 0.2\,V$ i.e., Single Pi Gate passivated HEMT, double gate passivated. HEMT, double gate triple tooth passivated HEMT, high K dielectric FG and BG HEMT at various gate voltage is shown. It is shown that increased trans conductance of 3.71 S/mm. appeared for proposed high K dielectric FG and BG HEMT. Figure 6 shows the variations of drain current density with various gate voltage for single gate, single gate passivation layer and double gate passivation layer structures. In this figure, it is observed that the current density characteristics are varies according to the various gate voltage by considering single gate, single gate passivation and double gate with passivation model using different work functions.

Table 1 shows the DC characteristics exhibited by HEMT with various passivation on layers. Such as SiO_2, Si_3N_4, Al_2O_3, and Si_3N_4/Al_2O_3, single gate with a passivation layer (SGP) [29], DGP, passivated double gate with triple tooth (DGP-TT), the characteristics such as drain current (I_D), Trans conductance (g_m), I_{off}, cut off frequency (f_T), obtained from Si_3N_4/Al_2O_3 passivated dual gate GaN HEMT with triple tooth are illustrated. it is observed that DGP-TT N=3 HEMT exhibited optimized results of $I_D = 4.9$ A/mm, the leakage current of 9.5E-11(A), transconductance of 2.7 S/mm, cutoff frequency 560 GHz, drain conductance 0.657 (S/mm), on resistance 0.6 (ohm mm) [30]. The gate to source capacitance is product of trans conductance and cut off frequency represented in (5) where gm is trans conductance [31].

$$Gate\ to\ source\ capacitance:$$
$$Cgs = gm * 4 * 3.14 * fT \quad (5)$$

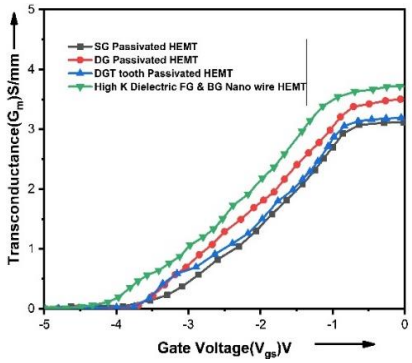

Figure 5. Trans conductance of various gate voltages

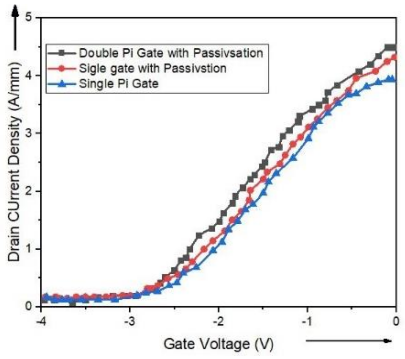

Figure 6. Variations of drain current density with various gate voltages for SG, SGP, DG-P

Table 1. Performance metrics for the reported structures

	Ion (A/mm)	I_{off} (A)E-11	Gm (S/mm)	FT (GHz)	GD (S/mm)	RON (Ωmm)
SiO2	3.75	9.40	1.33	470	0.356	1.36
Al2O3	3.98	8.99	1.37	493	0.389	1.2
Si3N4	4.2	4.50	1.41	521	0.409	1.3
Si3N4/ Al2O3	4.4	4.22	1.45	537	421	0.86
SG	-	-	1.33	537	0.356	0.8
SGP	4.4	-	1.45	537	0.421	0.79
DGP	4.6	-	1.72	540	0.534	0.77
DGP-TT, N=1	4	1.09	2	520	0.423	0.75
DGP-TT, N=2	4.2	7.46	2.4	530	0.45	0.72
DGP-TT, N=3	4.9	9.54	2.7	560	0.657	0.6

Figure 7 shows the maximum oscillation frequency (fmax) concerning gate voltage characteristics of HEMTs with various physical structures of 6 nanometers at $V_{ds} = 0.2\,V$ i.e., Single Pi gate passivated HEMT, double gate passivated HEMT, double gate triple tooth passivated HEMT, high K dielectric FG and BG HEMT at gate voltage $V_{gs} = 0\,V$ is shown. It resulted that, an increased Cutoff frequency (fT) of 743 GHz. Appeared for proposed high K dielectric FG and BG HEMT. Figure 8 shows on resistance (R_{on}) concerning drain voltage (V_{ds}) characteristics of HEMTs with various physical structure 6 nanometers at gate voltage = 0V i.e., single Pi gate passivated HEMT, double gate passivated HEMT, double gate triple tooth passivated HEMT, high K dielectric FG and BG HEMT at gate voltage $V_{gs} = 0\,V$ is shown. It resulted on resistance of (R_{on}) of 0.40 (Ohms) appeared for proposed the high K dielectric FG and BG HEMT.

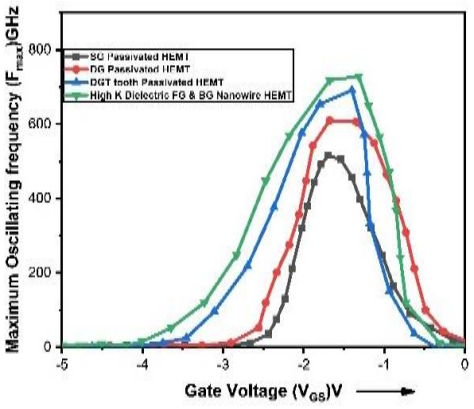

Figure 7. Maximum oscillation frequency with various gate voltages for SG passivated, DG passivated, DGT tooth passivated, high K dielectric HEMT

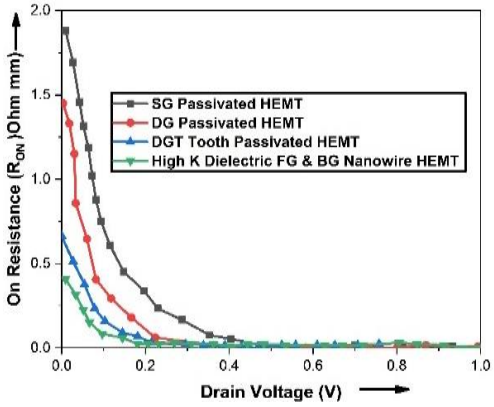

Figure 8. On resistance variation to various drain voltage for SG passivated, DG passivated, DGT tooth passivated, high K dielectric HEMT

In Table 2 comparison of existing HEMT structures characteristics are simulated and compared with the proposed structure characteristics. The proposed passivated dual Pi 6 nm gate length HEMT resulted in low leakage current (I_{off}), high drain current (on current), high trans conductance (g_m), high Cutoff frequency, low threshold voltage (V_{th}), high I_{on}/I_{off}. These improvised DC characteristics and RF characteristics help to implement the proposed HEMT in RF applications. Due to the high electron mobility of the material property, dual gate, passivation enhancement and optimized performance are obtained for the proposed structure.

T gate, Gama gate, CG, MGFP gate, GFP gate, and DFP Gate based MOS-HEMTs are the available transistors currently. The available transistor has its applications. Early breakdown effects are present in the existing MOS-HEMTs. Proposing the partitioned novel shape gate leads to resistance reduction which increases $f_{max.}$

The results show that high K dielectric front gate (FG) and back gate (BG) HEMT results improved on current, trans conductance, drain conductance, Maximum oscillation frequency, improved Cutoff frequency, with reduced leakage current. Proposed structure for high K dielectric FG and BG caped HEMT resulted in best results compared to other existing results. High drain current, high trans conductance, high drain conductance, low on-resistance, high cut off frequency, high maximum oscillation frequency (f_{max}), low leakage current, and high I_{on}/I_{off} are obtained.

Table 2. Comparison of existing HEMT structures characteristics is simulated and compared with the proposed structure characteristics

Gate Shape	MGFT	DFP	GFP	Camel	Gama	T	Pi	SG-P	DG P	DGTTP	Proposed Structure
(L_g) nm	20	20	20	20	20	20	6	6	6	6	6
I_{on} (A/mm)	2E-2	5E-2	5.5E-2	7E-2	1	2	4	4.4	4.6	4.9	5.92
I_{off} (A)(E-11)	360	250	60.2	47	43.2	18	8.65	1	2.63E-1	5.6E-2	1.2E-2
I_{on}/I_{off} (E+8)	5.56E-05	2.00E-04	9.14E-04	0.001	0.02	0.1	4.62E-01	4.40E+00	1.75E+01	8.75E+01	4.93E+02
f_{max} (GHz)	38	50	65	80	100	425	485	490	500	520	765
f_T (GHz)	14	18	40	60	90	310	400	537	540	560	743
g_m (S/mm)	0.098	0.217	0.297	0.327	0.501	0.9	1.51	1.45	1.72	2.7	3.71
V_{th} (V)	-1	-1	-1	-1.4	-1.5	-2.8	-3.7	-3.76	-3.8	-4	-4.5
g_d (S/mm)	0.084	0.091	0.095	0.098	0.116	0.148	0.353	0.456	0.534	0.657	1,769
R_{on} (Ωmm)	3.8	3.6	2.5	1.8	1.5	1	0.8	0.75	0.7	0.6	0.4

4. CONCLUSION

High K dielectric FG and BG 6 nano-wire HEMT with GaN Cap layer are proposed in the paper and its performance is analyzed for obtaining optimized results. The proposed structure is collated with a few existing HEMT structures. The DC characteristics and RF characteristics are sorted out and reported improved drain current of 5.92 (A/mm), trans conductance of 3.71 (S/mm), the reduced leakage current of 5.54E10-13 (A), Cutoff frequency of 743 GHz, maximum oscillation frequency of 765 GHz, drain conductance of 1.76 (S/mm), the threshold voltage of -4.5V, on resistance of 0.40 Ohms. The dominant characteristics of the proposed device aid to apply in high frequency application.

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