Received: *26 October 2023* | *Revised:* *5 January 2024* | *Accepted:* *23 February 2024*
DOI: 10.37917/ijeee.21.2.13 *Early View* | *December 2025*

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Iraqi Journal for Electrical and Electronic Engineering
Original Article

Investigation of InAlGaN/GaN HEMT Device with SiC Substrate and Cap Layer in Self Heating Resistance for Microwave Applications

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Abstract
The electrical and radio frequency (RF) characteristics of InAlGaN/GaN high electron mobility transistors (HEMTs) device with cap layer are presented in this work. In this work, Silicon carbide was used as a substrate for its excellent thermal conductivity. Here, the thermal model was used to investigate the simulation of temperature distribution at 300k. Moreover, the DC and AC performance characteristics of the device were investigated using Silvaco Atlas Technology Computer Aided Design TCAD simulator. The results showed that, the maximum obtained drain current that was 1.35 A. In addition to, the RF parameters were extracted. The cut-off frequency f_t is (73 GHz), the maximum oscillation frequency f_{max} is (353 GHz), maximum stable gain (Gms) and maximum available gain (Gma) with a value of about (116 dB). The obtained results showed that the InAlGaN/GaN HEMT device based on SiC performance is suitable for microwave applications.

Keywords
GaN HEMTs, 2DEG, Radio Frequency RF, TCAD, Silicon Carbide.

I. INTRODUCTION

The basic component utilized in modern electronics are high electron mobility transistors (HEMTs) devices, which are based on two-dimensional electron gas. Gallium nitride (GaN) High Electron Mobility Transistors (HEMTs), characterized by high density of tow dimensional electron gas (2DEG), high electron saturation velocity, and high break down voltage [1], which is an excellent material for these devices. These devices can be utilized in a variety of applications, including RF, high speed, high temperature, high power applications and amplifier in wireless communication systems. Authors in [2–4] the results of comparison of HEMTs without a 2 cap layer shows that HEMTs with cap layers can increase maximum drain current Ids, current gain, cutoff frequency ft, maximum oscillation frequency fmax, transconductance gm. Four and Kameche in [5], shown how III-V materials, GaN, can utilized for high frequency and high power applications. Using 4H-SiC as the substrate, which has a high thermal conductivity, can maintain a good heat transfer and prevent self-heating, as was mentioned by Pandit and his team in [6]. The use of Si3N4 as a passivation layer exhibits a significant rise in drain current densities with a compromise of higher gate leakage, as well as decreasing the trapping effects that affect HEMT performance, as was demonstrated by Jabli and his team in the work [5]. According to the TCAD simulation in [7, 8], adding the GaN cap layer lowers the peak electric field at the gate's drain side edge and raises the breakdown voltage. This layer enhanced the DC and RF performance of the simulated GaN HEMT device for power and RF applications. In this paper, InAlGaN/GaN with Sic substrate HEMT heterojunction

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device with cap layer and Si3N4 passivation layer have been simulated using Silvaco Atlas simulator. The AC and DC response with RF characteristics were investigated at 300k.

II. DEVICE STRUCTURE AND DESIGN IMPLEMENTATION

TCAD tools can be used to design, implement, and analyze the behavior of electronic devices. In order to achieve convergence throughout the large bias range, the mesh was accurately adjusted. In [9], the AlGaN/GaN was compared with InAlGaN/GaN, the InAlGaN/GaN heterostructure exhibits a significantly higher concentration of 2DEG as a result of the use of a thin InAlGaN barrier. Therefore, the simulated device of this work is InAlGaN/GaN HEMT which designed on 1.5 micron SiC substrates as shown in Fig. 1. The thickness of the passivation layer (Si3N4) is 500 nm which improves the electrical characteristic of the device. As mentioned early, the simulation results of the HEMTs can be improved by adding a cap layer. So, the second layer of the simulated device is the cap layer with n-doped with thickness is 1nm. Also, Undoped barrier layer of InAlGaN with 25nm thick have been used with Undoped GaN layer with 10nm thick to form 2DEG channel layer. A 1nm nucleation layer i.e. Aluminum Nitride AlN layer was inserted between GaN layer and substrate. 3 This layer is required to enable the growth of GaN on Silicon carbide [9]. SiC have been used as a substrate to improve thermal performance of the device. Fig. 1 shows the structure of the device and the parameters value of the structure are shown in Table I [10]. The small signal equivalent circuit of GaN HEMT on SiC simulated device is chosen for this work is presented in Fig. 2. The circuit inside shaded rectangular in Fig. 2 represent the intrinsic parameters, where the elements outside the rectangular are the extrinsic elements.

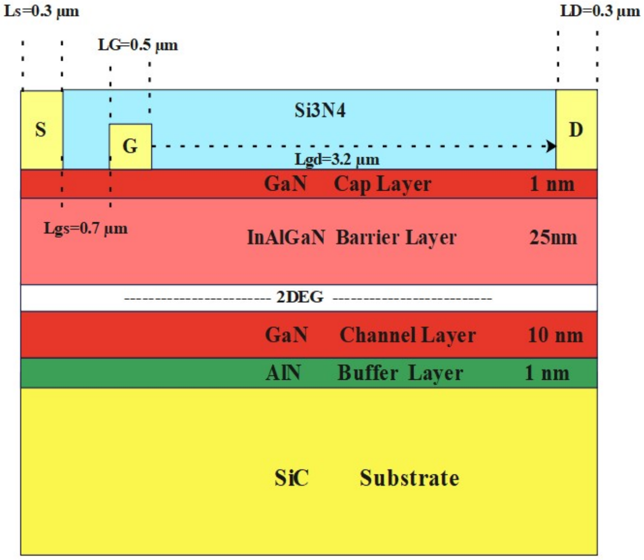

Fig. 1. Proposed Structure of InAlGaN/GaN with Passivation Layer (Si3N4)

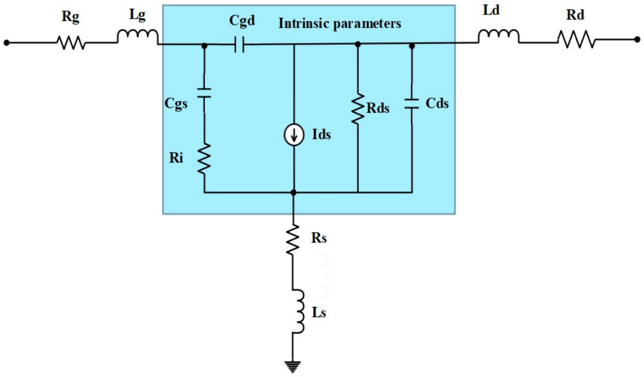

Fig. 2. Equivalent Circuit of GaN HEMT [1]

Large number of physical models offered by Silvaco tool to describe the physical behavior of semiconductor devices. Also, the heat flow problem is self-consistently eliminated in the structure after the statement sets the thermal boundary condition on the electrode to 300K [10]. The Silvaco physical models that have been used in the simulation are listed in the Table II. Silvaco ATLAS user's manuals recommended that SRH model Should be used in most simulations which uses fixed minority carrier lifetimes [10]. NEWTON, GUMMEL, and BLOCK have been used for 2D simulation to solve equations. The Block method have been used for thermal model which included in the simulation.

The physical properties of the material, InAlGaN/GaN, is obtained through linear function according to the Vegard law [11]. Also, a Two-Dimension mesh have been utilized to build the structure in Tony plot. Fig. 3 shows the structure of the simulated device.

III. THE RESULTS AND DISCUSSION

In this paper, the effect of GaN HEMT with cap layer on drain current (I_{DS}), transconductance (g_m), current and power gain, have been investigated by using Silvaco Atlas TCAD tool. Since the maximum operating frequency (f_{max}) and cut-off frequency (f_t) of a transistor determine its RF performance, therefore, the maximum oscillation frequency and cut-off frequency were also examined.

A. The Transfer Curve and Transconductance (g_m)

To analyze the behavior of the designed transistor, transfer characteristic and output characteristic have to draw. Threshold voltage can know from the DC transfer characteristics.

TABLE I. STRUCTURE PARAMETERS

structure parameters	Values (micrometer)
Gate length (LG)	0.5
Drain length (LD)	0.3
Source length (LS)	0.3
Gate source length (LGS)	0.7
Gate drain length (LGD)	3.2

TABLE II. SILVACO PHYSICAL MODELS

Models	Purpose
SRH	The Shockley-Reed-Hall recombination
calc.strain	Determines the strain in the area
lat.temp	Enables Self-heating effect
impact selb	Model for breakdown voltage
FLDMOB	Impact mobility with electric field

It was produced by connecting the linear portion of transfer curve with the abscissa axis [12]. For drain-source voltages V_{ds} of 5.0 V and 15.0 V, the threshold voltages are about -2.75V and -2.81V respectively as shown in Fig. 4.

The transconductance (g_m) of GaN HEMT devices, is the main nonlinear components. The relation between the DC transfer curve (I_{ds} vs. V_{gs}) and the transconductance gm is shown in Fig. 5, which is actually defined as the transfer characteristic's derivative. The peak transconductance of the simulated device is gm=280ms at drain source voltage V_{ds} equal to 1volt as shown in Fig. 5a and gm=522.7 ms at drain source voltage V_{ds} equal to 3 volt as shown in Fig. 5b. The transconductance expression is as shown in equation (1):

$$gm = \frac{\partial Ids}{\partial Vgs} \tag{1}$$

B. The output conductance (g_{ds})

The output conductance gds which represent the ratio of the changes of the drain current to the changes of the drain voltage is defined in equation (2).Fig. 6 represents the output transconductance g_{ds} at a single level of V_{gs} =0 and V_{ds} range from 0V to 10V.

$$gds = \frac{\partial Ids}{\partial Vds} \tag{2}$$

C. The DC Response of the Device (I_{DS} –V_{DS} Characteristics)

As mentioned early, to analyze the behavior of the designed transistor the transfer curve and output characteristic have

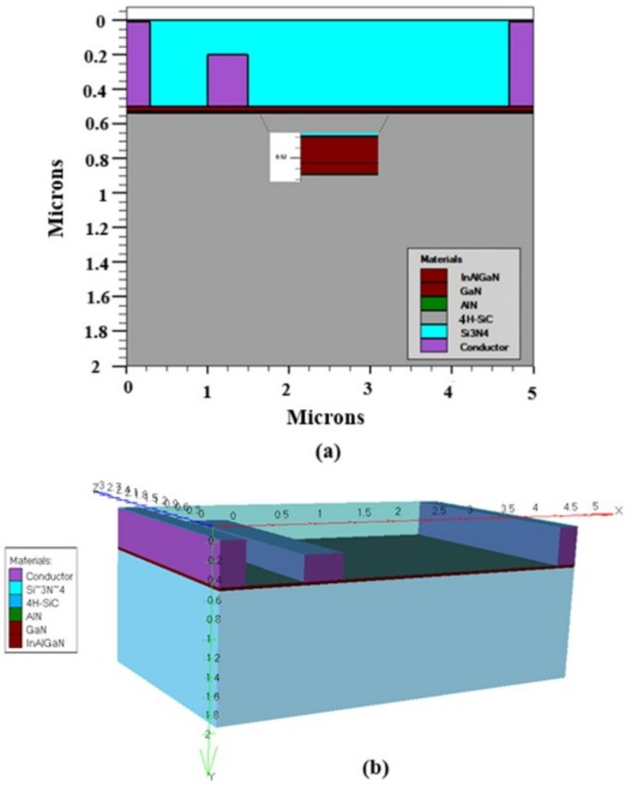

Fig. 3. Rectangular Gate GaN HEMT Device Structure in (a) 2- Dimension, (b) 3- Dimension.

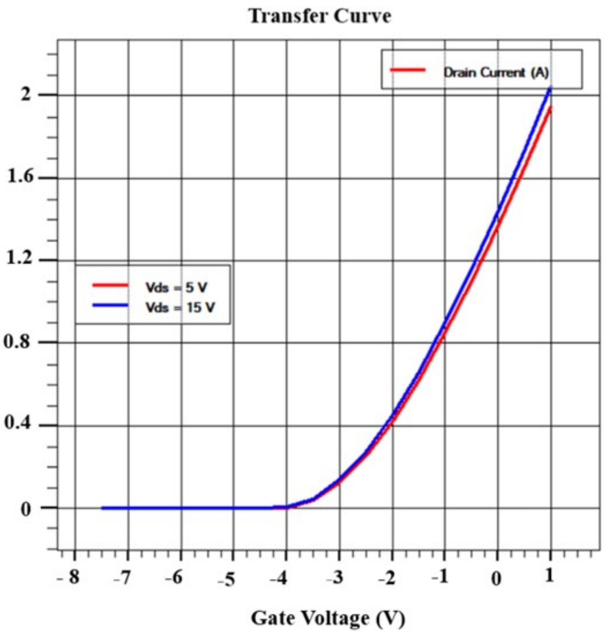

Fig. 4. Drain current vs Gate voltage (Transfer curve).

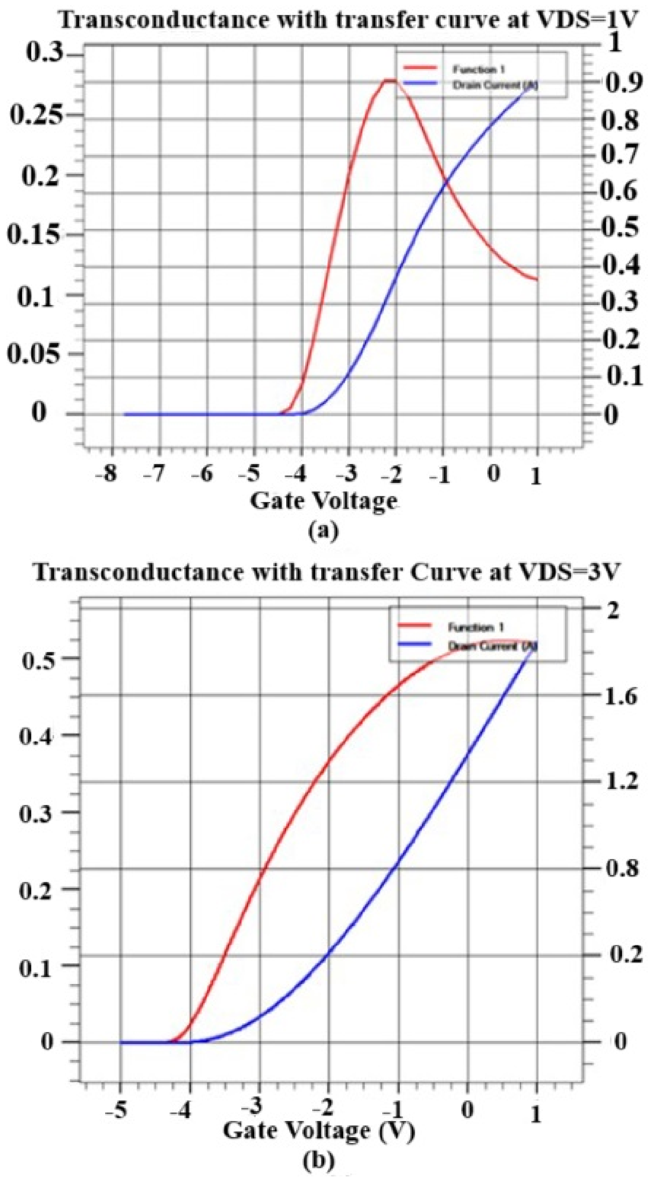

Fig. 5. The Transconductance (g_m) curve and the Transfer Curve versus the Vgs Voltage when (a) the V_{ds} =1V and (b) the V_{ds} = 3 V

been drawn. The most important one is the I-V i.e. output characteristics which represent the plot of the drain current I_{ds} versus drain voltage V_{ds} with different level of gate source voltage (V_{gs}).

1) The Normal Model

The Drain characteristics of the InAlGaN/GaN HEMT device without taking in the account the self-heating effect impact have been seen in Fig. 7. The curves were simulated at verity values of gate voltages, they are 0V, -1V, -2V, -3V and -4V respectively. The maximum drain current that have been obtained from the simulated device is Ids (max) = 1.353A. As shown in Fig. 7, the current of the device will be increased when the gate voltage increase.

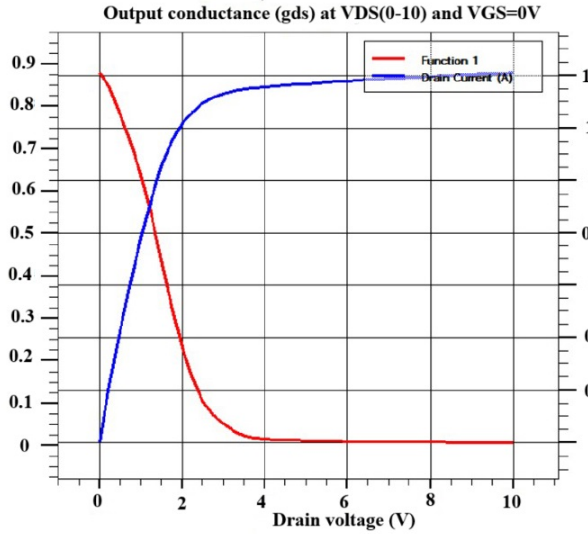

Fig. 6. Output conductance (g_{ds}) versus V_{ds} Voltage at V_{gs} = 0 V.

2) The Thermal Model

The primary challenges that have an undesirable effect on the device's performance and reliability are self-heating (SHE) and hot-electrons effects [13]. The effect of SHE of AlGaN/GaN HEMTs causes the increase of the channel temperature, which in turn leads to the drain current to drop when drain voltage V_{ds} increase, resulting in the degradation of device characteristics [14]. This negative slope in drain current characteristics can be reduced by using SiC substrate due to their excellent thermal conductivity. As seen in Fig. 8 below, the drain current characteristics have a very low negative slope which is caused by the self-heating effect. The maximum drain current that obtained from thermal model, Ids (max) = 1.352A, is approximately equal to the drain current obtained from natural model.

IV. THE AC RESPONSE

High electron mobility transistors (HEMTs), at high rate of frequency, are featured by two important variables: the cutoff frequency and the maximum frequency for which the current gain value and the unilateral power gain are equal to one (0 dB) respectively. The power gain has been assumed to be of greater importance than voltage gain for a circuit

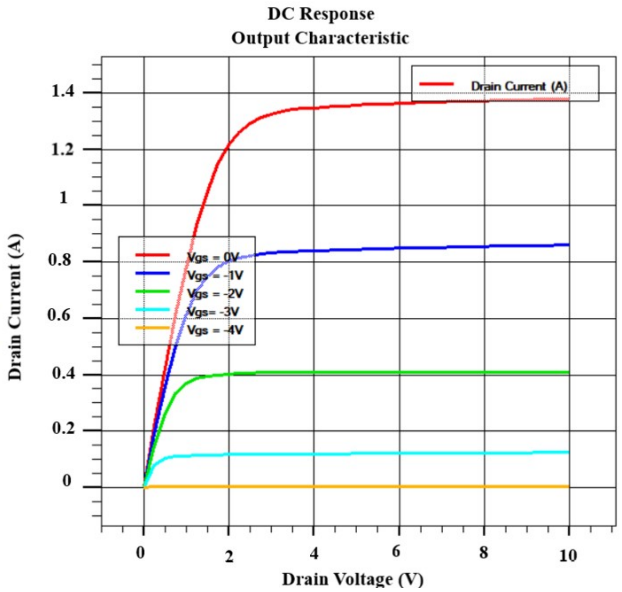

Fig. 7. I_{ds} - V_{ds} Characteristics with Different Level of V_{gs}.

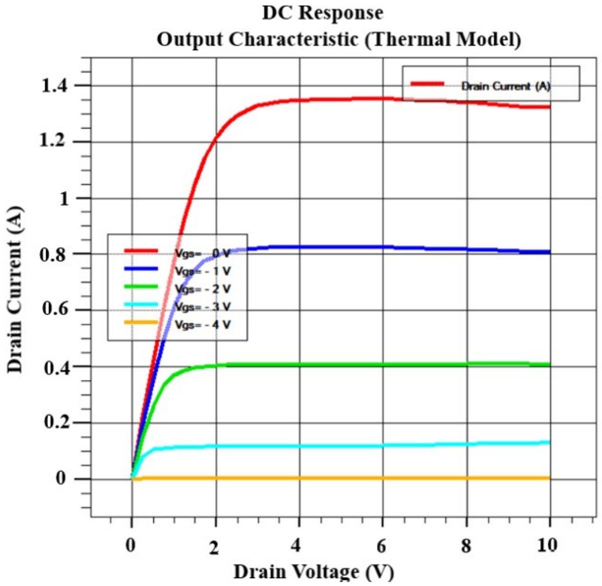

Fig. 8. Thermal Effect of I_{ds} - V_{ds} Characteristics.

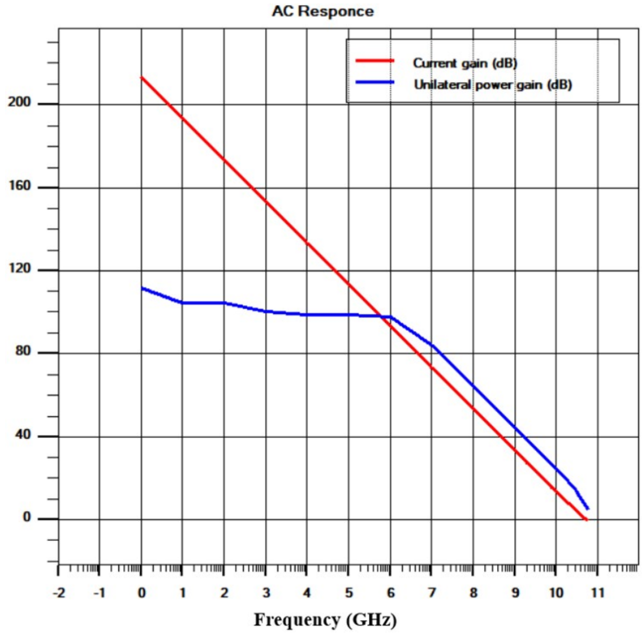

Fig. 9. Current and Power Gain as a Function of Frequency.

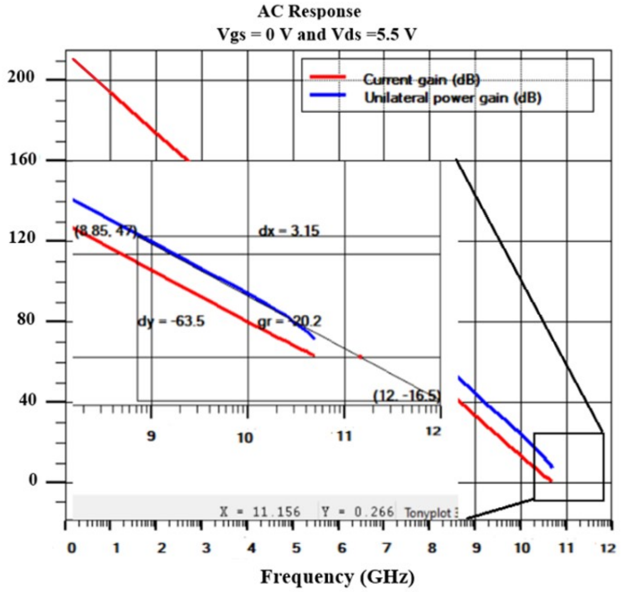

Fig. 10. Extraction of Maximum Frequency (f_{max}).

which operates in the microwave domain [15]. V_{ds} =5.5V, the maximum value of the current gain of 213.7 dB while the value of unilateral power gain is 111.7 dB. cut-off frequency of 73 GHz and a maximum frequency of 353 GHz as shown in Fig. 9.

Also, extraction of maximum frequency (f_{max}) is shown in Fig. 10.

The desired maximum theoretical power gain of the devices is represented by available maximum power gain (i.e. Gma or MAG) and maximum stable gain i.e. Gms [16, 17]. Higher Gma and Gms values are preferred for high-frequency applications. Because of GaN's electrical features, we have obtained an excellent result of Gma and Gms which are presented in Fig. 11. The peak value of Gma and Gms are obtained at 116 dB. This result illustrates the HEMT's excellent stability performance, which increases its attractiveness and suitability for RF and microwave applications.

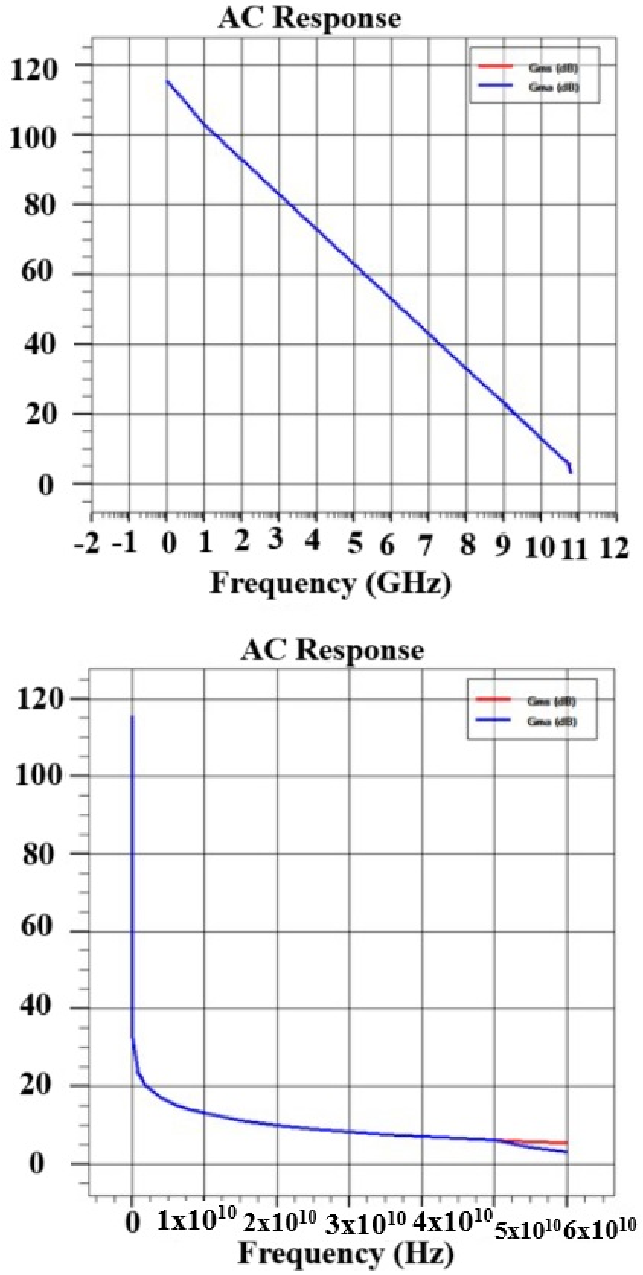

Fig. 11. Gms and Gma as a Function of Frequency.

Table III shows a comparison performance of our simulation results with different references. High transconductance, high frequencies, and high current are obtained from our simulated device. The increase in Gm values are suitable for RF and microwave applications.

V. CONCLUSIONS

In this work, the DC and AC characteristics of high electron mobility transistors HEMTs InAlGaN/GaN on SiC with cap layer were presented. Silvaco Atlas TCAD simulator was used to investigate the HEMTs InAlGaN/GaN device. The thermal model and self-heating effect of the device were recognized. The investigated GaN HEMT with cap layer on SiC substrate device showed high transconductance, high cut off and maximum oscillation frequencies, high drain current, high current gain, high power gain and excellent thermal conductivity. The extracted results proved that the device can employed for high power applications like power amplifiers and RF applications for its high break down voltage and high frequency.

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TABLE III. Performance Comparison Between References and Proposed Device

References	[2]	[5]	[6]	[7]	[8]	[9]	[10]	[11]	proposed work
2025	2015	2016	2017	2017	2018	2019	2020	2022	2024
Id(A)	1.1	0.65	0.4	0.782	0.8	0.5	0.6	0.5	1.35
Vth(V)	-2.3	-5.5	-3.7	-0.5	-5	-3.9	-3.5	-4	-2.75
ft(GHz)	126	2.6	19	24	63	30	50	79	73
fmax(GHz)	-	9.8	40	95	-	100	150	160	353
gm(mS)	-	120	-	-	100	-	200	-	522.7
Gm(dB)	374	123	53	527	170	-	110	160	116
Layers	Cap, Barrier, Exclusion, channel, Nucleation, substrate	Cap, Barrier, Spacer, channel, Nucleation, Substrate	Cap, Barrier, spacer, channel, Nucleation, substrate	Cap, Barrier, channel buffer, Nucleation, substrate	Cap, Barrier, spacer, channel, Nucleation, substrate	Cap, Barrier, channel, Buffer, Nucleation, substrate	Cap, Barrier channel, Nucleation, substrate	Cap, Barrier, channel, Nucleation, Substrate	Cap, Barrier, channel, Nucleation, substrate.

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