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# Comparative simulation of DC and AC performances of $Al_{0.26}Ga_{0.74}N/GaN$ HEMT with BGaN Back-barriers

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**ABSTRACT**

*This paper discusses the influence of BGaN layer on the structure $Al_{0.26}Ga_{0.74}N/ B_{0.02}Ga_{0.98}N$ /GaN HEMT with T- Gate . The use of BGaN back barrier on this device enhances confinement of the electron in the device . We simulate DC and AC characteristics by using TCAD Silvaco. The result obtained shows a maximum drain current of 1 A/mm, a threshold voltage of -1.25 V, a maximum transconductance of 0.850 S mm-1, a Ion/Ioff ration of $1.5*10^9$, a Drain Induced Barrier Lowering (DIBL) of 166 mV/V, a Sub-threshold Swing (SS) of 300 mV/dec and a Gate-leakage of $5.10^{-22}$ A. In terms of AC performances, the device offers Ft of 600 GHz and Fmax of 1 THz. These results reveal that the use of BGaN back barrier has added benefits in performance which can be outstanding solution for high frequency switching and high-power applications*

**Keywords:** BGaN Back-Barrier ,HEMT, DC performances , AC Performances

## 1. INTRODUCTION

AlGaN /GaN High Electron Mobility Transistor (HEMT) have showed outstanding performance for a variety of high frequency and high-power application. Due to their exceptional material properties such as wide bandgap, high breakdown field, and high electron saturation velocity [1]. The GaN-based microwave power devices and the relative devices have wide potential application in the domain of communication Satellite and radar [2].

Semiconductors compound based on III-N materials such as GaN, AlN, BN and their alloys are direct gap semiconductors. These materials have emerged as materials of great interest in electronics and optoelectronics applications. In electronics, these materials make it possible to manufacture devices having a high power, a high frequency and operating at high temperature, such as field effect transistors, bipolar transistors, including transistors with high electron mobility [3].

Gallium-boron nitride (BGaN) is an alloy between boron nitride (BN) and gallium nitride (GaN). Boron nitride broadband prohibited films have drawn attention thanks to their remarkable properties such as thermal conductivity, hardness and excellent chemical stability. In addition, the network constants of the BGaN alloy can be adapted to those of SiC or AlN if enough incorporation of boron into the network is obtained [4]. Recently, the ternary BGaN was integrated in the conventional structure of the HEMT by Ougazzaden and al [5] to ameliorate the performance by enhancing the confinement of carriers in the two dimensional electron gas region [3].In fact, Beghdadli et al [6] have shown that electrical resistivity is strongly related to the incorporation of boron in BGaN alloys, while mobility increases up to 290 cm / Vs with increasing boron content up to at 1.75%. It can be said that a layer of BGaN can be very resistive

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with only a few percent boron, which could be very interesting for devices such as HEMTs. In addition, there is an improvement of the resistivity followed by an increase of the mobility of the carriers, thanks to the quality of good crystalline in the ternary BGaN [7].

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The resistivity of the BGaN as a function of the boron fraction where a very substantial increase in the resistivity of 2.7 × 10-2 Ω.cm is observed up to 7.4 × 104 Ω.cm[6].

Recently, our first work [8] based on AlGaN /GaN HEMT without BGaN layer show a good DC and RF characteristics. In order to benefit of the properties of BN, we will induce the ternary BGaN to improve the performance of AlGaN /GaN HEMT. In fact, this ternary can rise the GaN buffer resistivity and the electrons confinement when it is used.

In this work, we study the effect of BGaN back-barriers in AlGaN/GaN HEMT compared by the conventional HEMT present in the work [8]. The proposed Structure consist of $Si_3N_4$ passivation layer which exhibits remarkable increase in drain current densities with a compromise of increased gate leakage[9],and minimizing the trap effects which influence the performance of HEMT[10].Then, to improve the cutoff frequency of HEMT, there is a need to minimize the gate length (*Lg*) respecting the aspect ratio Lg/dgate-2DEG which be must sustained above 15 according to G.H.Jensen study[11] .Afterward ,to bring under control the problem of the disagreement mesh, these layers were grown on 4H-SiC substrate. 4H-SiC has the merit of small lattice mismatch to GaN epilayers, very high thermal conductivity and high resistivity [12]. A prominent literature has been demonstrated that the temperature in a GaN device growth on an 4H-SiC substrate is minimal compared to those fabricated on a sapphire substrate [13][14].

In this paper, we discuss the influence of the induction of BGaN ultrathin back-barrier in AlGaN/GaN HEMT with T-gate based 4H-SiC subtract. It also shows the significant improves the DC and AC performances by ameliorating the efficiency of modulation of the electrons in the channel using TCAD Silvaco software. The layer of BGaN is very resistive with a few percent of boron, it's very interesting for devices as HEMTs. Moreover, there will be improvement of the resistivity which increase the mobility of the carriers, because of the quality of good crystalline in the BGaN semiconductor. These results demonstrate the important of AlGaN/GaN/BGaN HEMT and indicate that are a splendid candidate for microwave and switching application.

## 2. PROPOSED STRUCTURE AND SIMULATION MODEL

The structure AlGaN/GaN/BGaN HEMT on 4H-SiC substrate was designed by using TCAD Silvaco software tool as presented in figure 1. The parameters of proposed device structure are: $Al_{0.26}Ga_{0.74}N$ Schottky layer and thickness of 24 nm, 35 nm n-type GaN channel layer, 8 nm $B_{0.02}Ga_{0.98}N$ back-barrier and a 300 nm thick n-type GaN as buffer layer. Finally, the structure was passivated with 10 nm $Si_3N_4$ layer with 4H-SiC substrate.

This structure had T-shaped gold gate (work function 5.1 eV) of length ($L_G$) 30 nm. The source-gate ($L_{SG}$) and drain-gate ($L_{DG}$) distance are 0.681 µm and 0.1084 µm respectively. Length of Source ($L_S$) and Drain ($L_D$) are 0.5 µm. Table 1 shows the doping parameters of the structure.

**TABLE 1** Doping parameter

| Doping concentration | Value |
| --- | --- |

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| | |
|---|---|
| GaN Cap doping n-concentration | $1*10^{22}$per $cm^3$ |
| AlGaN layer doping n-concentration | $1*10^{19}$ per $cm^3$ |
| GaN channel doping n-concentration | $1*10^{17}$per $cm^3$ |
| BGaN layer doping n-concentration | $1*10^{16}$ per $cm^3$ |

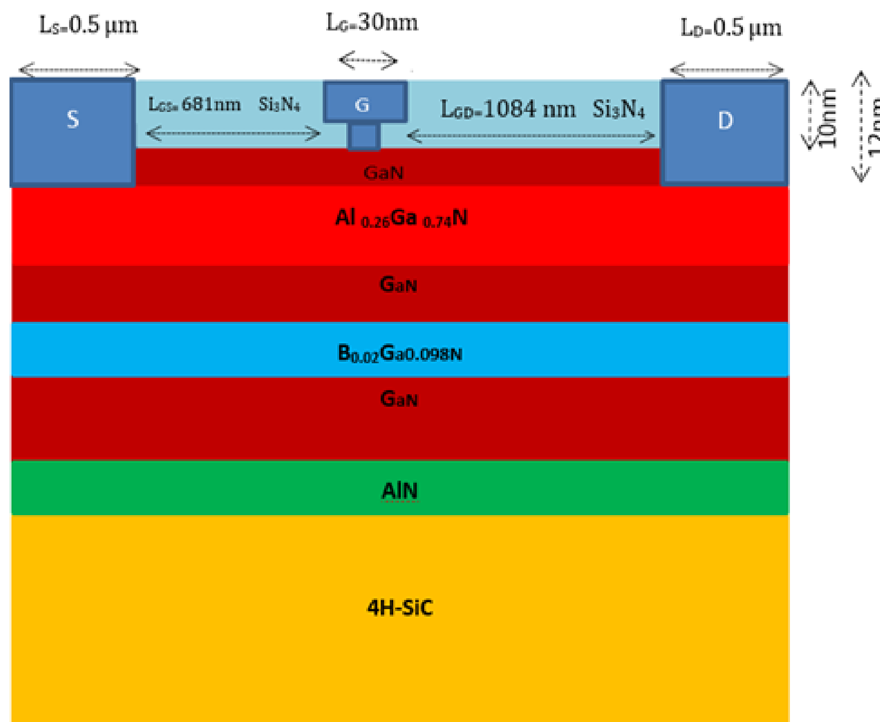


**Figure1.** the structure of HEMT proposed.

In the ATLAS part of the input file; the contacts, materials and models are defined. For the GaN region, we declare the dependence of the mobility of the charge carriers on the doping; the recombination parameters (lifetime) are also applied. For AlN regions, the low field mobility and the lifetime of the charge carriers are explicitly specified in the material instruction. The new material $B_{0.02}Ga_{0.98}N$ and $Al_{0.26}Ga_{0.74}N$ are defined by a specific command. [15] The structures designed from the DEVEDIT program are given in 2D figure 1. The basic parameters of the will be calculated and introduced, like electron affinity ,lattice constant, , density of states masses and permittivity by the following equations:

The lattice constant "a" of AlGaN can be calculated by linear interpolation[16]:

$$a\,(Al_xGa_{1-x}\,N) = xa(AlN) + (1-x)a(GaN) \quad (1)$$

$$a\,(B_xGa_{1-x}\,N) = xa(BN) + (1-x)a(GaN) \quad (2)$$

with a(BN) = 0.253 nm, a(AlN) = 0.3112 nm, and a(GaN) = 0.3189 nm.

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The bandgap of AlGaN and BGaN are calculated from [16][17]:

$$E_G\,(Al_xGa_{1-x}\,N) \;=\; xE_G\,(\,AlN\,) + (1-x)\,E_G(GaN)\; - 1.3x\,(1-x) \tag{3}$$
$$E_G\,(B_xGa_{1-x}\,N) \;=\; xE_G\,(BN\,) + (1-x)\,E_G(GaN)\; - 7.28x\,(1-x) \tag{4}$$

With $E_G(GaN) = 3.415$ eV, $E_G(BN) = 5.8$ eV, and $E_G(AlN) = 6.15$ eV. [1]

The affinity of electron is given by [17]:

$$\frac{\Delta EC}{\Delta EV} = \frac{0.7}{0.3} \tag{5}$$

The permittivity as a function of composition fraction x is given by [18]:

$$\varepsilon\,(Al_XGa_{1-x}N) = 8.5x + 0.89(1-x) \tag{6}$$
$$\varepsilon\,(B_XGa_{1-x}N) = 8.5x + 0.89(1-x) \tag{7}$$

The density of nitride of states masses [19]:

$$m_e\,(Al_xGa_{1-x}\,N) \;= 0.314x + 0.2(1-x)\,,\, m_h\,(Al_xGa_{1-x}\,N) \;= 0.417x + 1.0(1-x) \tag{8}$$
$$m_e\,(B_xGa_{1-x}\,N) \;= 0.35x + 0.2(1-x)\,,\, m_h\,(Al_xGa_{1-x}\,N) \;= 0.37x + 1.0(1-x) \tag{9}$$

**TABLE 2** Simulation parameter

| **Parameter** | GaN | AlN | $B_{0.02}Ga_{0.96}N$ | $Al_{0.26}Ga_{0.74}N$ | 4H-SiC |
|---|---|---|---|---|---|
| **Eg(ev)** | 3.43 | 6.13 | 3.33 | 3.88 | 3.36 |
| **χ(cm²/vs)** | 4.1 | 2.2 | 4.16 | 3.78 | 3.24 |
| **Nc(cm⁻³)** | 2.24 $10^{18}$ | 4.41 $10^{18}$ | 2.29 $10^{18}$ | 2.75 $10^{18}$ | 1.23$10^{19}$ |
| **Nv(cm⁻³)** | 2.5 $10^{19}$ | 6.75 $10^{18}$ | 2.46 $10^{19}$ | 1.95 $10^{19}$ | 4.58$10^{18}$ |
| **ε** | 8.9 | 8.5 | 8.86 | 8.79 | 6.63 |

## 3. RESULTS AND DISCUSSION

### 3.1 DC PERFORMANCES

The principle function of HEMT can be explained by the band diagram of energy. It presents the conduction and valence band energies as a function of depth from surface along the vertical direction of the device AlGaN/B0.02Ga0.98N/GaN and AlGaN/GaN are shown in the figure 2.

The juxtaposition of a large gap material (AlGaN) with a small gap material (GaN) implies the creation a discontinuity on the conduction band at the interface of the two materials AlGaN and GaN and this is called heterojunction.

This heterojunction induces the creation of a potential well which is indicated by the circle No.1, in both structures without and with BGaN Back-Barrier are where the two-dimensional gas (2DEG) is created. Electrons are transmitted and cumulated in this well. Besides, there is an increase in the conduction band as well as the formation of an energy peak which is indicated by circle No. 2 in HEMT with BGaN back-barrier. The peak is an electrostatic barrier that opposes the electrons migration from the potential well and which makes the escape of electrons from this well more difficult.

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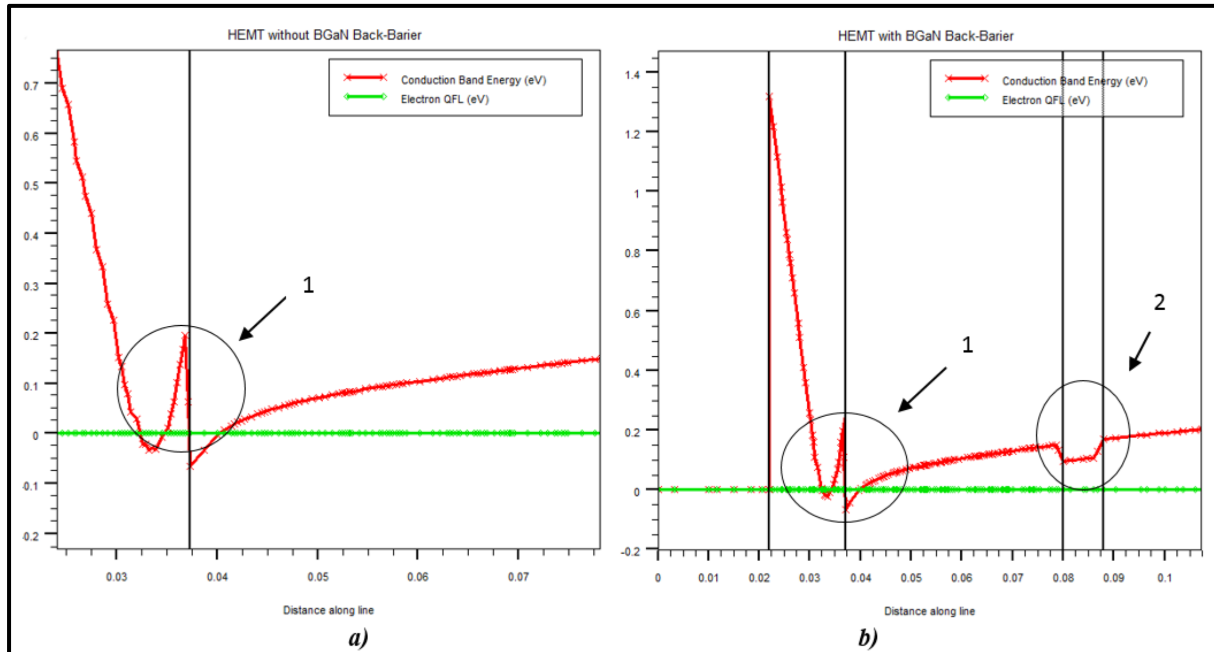


**Figure2.** Band diagram of energy *a)* $Al_{0.26}Ga_{0.74}N$ /GaN HEMT , *b)* $Al_{0.26}Ga_{0.74}N$ /$B_{0.02}Ga_{0.98}N$/GaN HEMT

Figure 3 presents the output characteristics ($I_{DS}$ - $V_{DS}$) calculate the $I_{DS}$ current flowing between the drain and the source by varying the $V_{DS}$ voltage from 0 V to 10 V, for different values of gate-source control voltage ($V_{GS}$) from 0 V to - 2 V. The result exhibits the maximum drain current obtained is 1A/mm for the device with back barrier which is better than the 0.6 A /mm acquired from the structure without back barrier [8].

The ( $I_{DS}$ - $V_{DS}$) characteristics display a good pinch voltage. This demonstrates that the electrons are well confined with the BGaN back-barrier layer.

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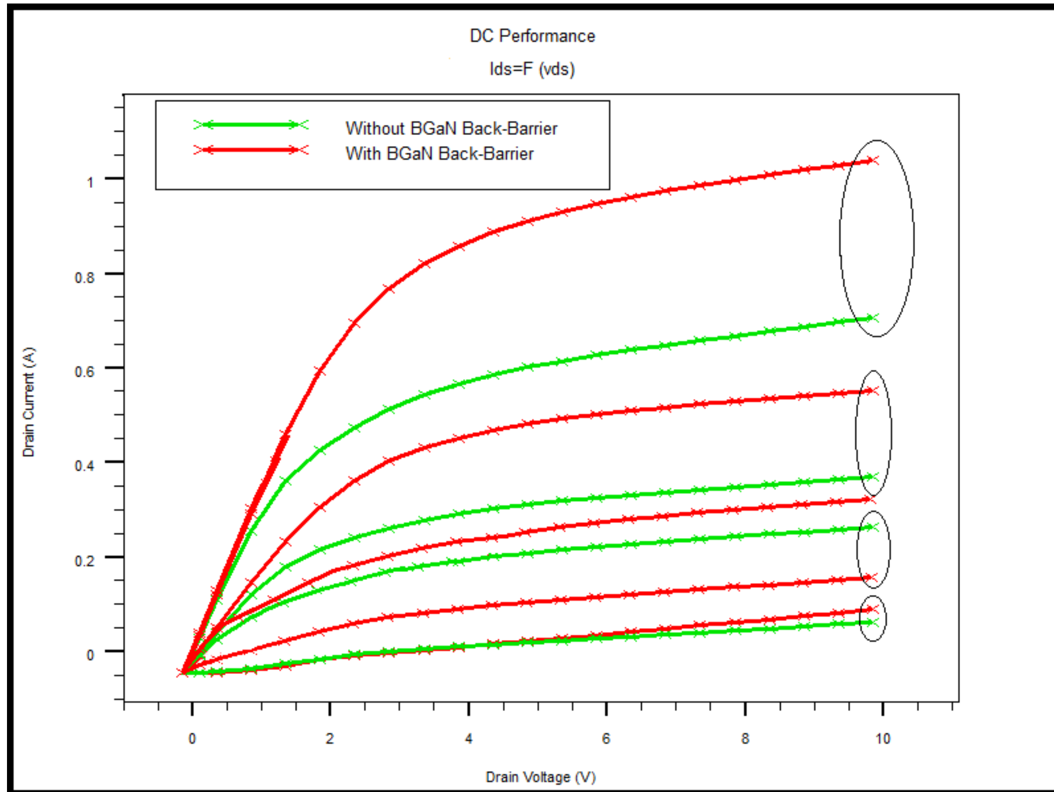


**Figure 3.** Ids -Vds characteristics while $V_{GS}$ is swept from 0.0 V to -2 V.

Figure 4 shows the transfer characteristic which represents the evolution of the drain-source current (Ids) as a function of the gate-source voltage for a constant drain-source voltage set here at 1.0 V. The threshold voltage $V_{th}$ is about -1.5 V for the structure with BGaN back-barrier, which is lower than the value achieved of -3.5 V for HEMT without BGaN back-barrier.

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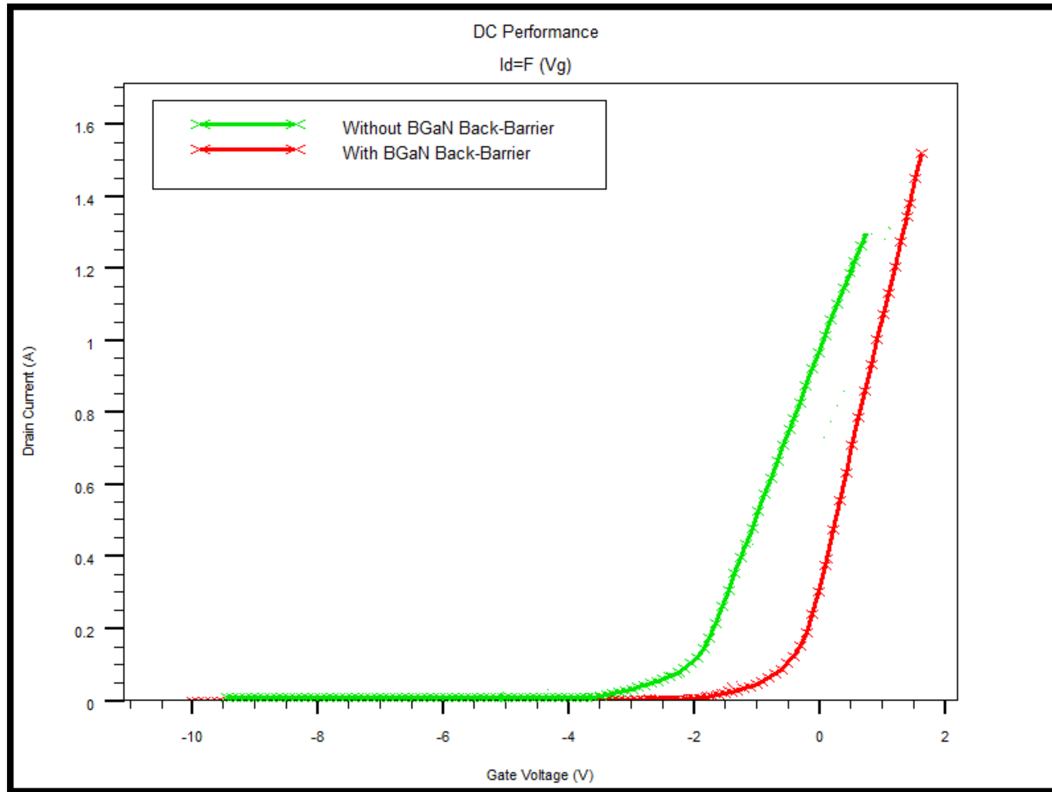


**Figure 4.** ($I_{DS}$-$V_{GS}$) characteristic while the $V_{ds}$ =1.0 V.

The variation of the transconductance (Gm) was presented in figure 5. The simulation displays a maximum transconductance of 850 mS/mm at $V_G$= -1.0 V for the structure with BGaN back-barrier, which is better than 200 ms/mm obtained for the HEMT without BGaN back-barrier.

The curve of the simulated structure is explained by a strong concentration of electrons available for conduction As we all know that boron is resistive[5] .Consequently, when we make 2% of the concentration of boron, the resistivity of the electrostatic barrier increases in same time the mobility of the electrons increases which improves the electron confinement and directly increases the $I_{DS}$ output current and since the transconductance is proportional to the $I_{DS}$ current, Gm also increases.

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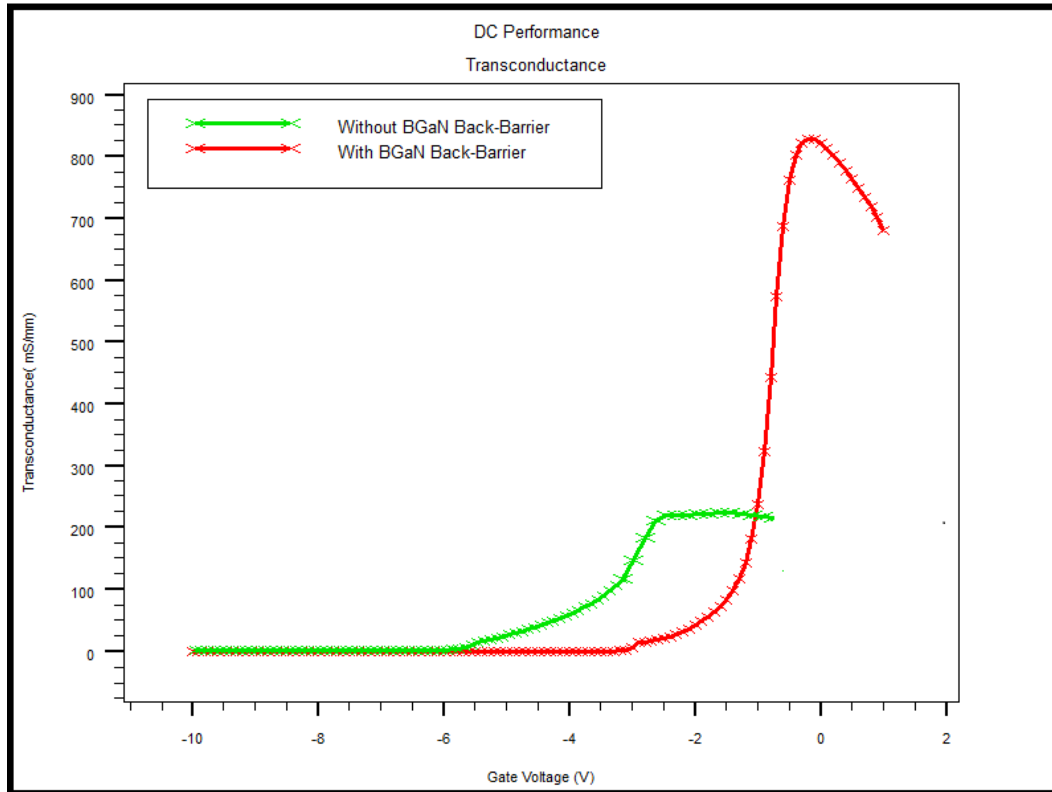


**Figure 5.** Transconductance (Gm) versus ($V_{GS}$)

Figure 6 shows the Sub-threshold Swing: SS is determined from the log characteristic ($I_{DS}$) versus $V_{GS}$. It corresponds to the gate-source voltage applied to reduce the drain current. the curve is on a logarithmic scale.

$$SS = Abs\,[V_{GS2} - V_{GS1}]\ [8] \quad (10)$$

The sub-threshold slope is therefore equal to 300 mV / dec . So, the HEMT with BGaN back barrier presents better sub-threshold Swing compared the structure without BGaN back-barrier which it was 200 mV/dec. [8]

We can also bring out the $I_{ON}$ and the $I_{OFF}$ to calculate the $I_{ON/IOFF}$ ratio.

The $I_{on} = 9.10^{0}$ and $I_{off} = 6.10^{-9}$ resulting in an $I_{on}/I_{off}$ ratio of $1.5*10^{9}$ . A large $I_{ON}$ / $I_{OFF}$ ratio indicates the quality of the device, in other words a low loss.

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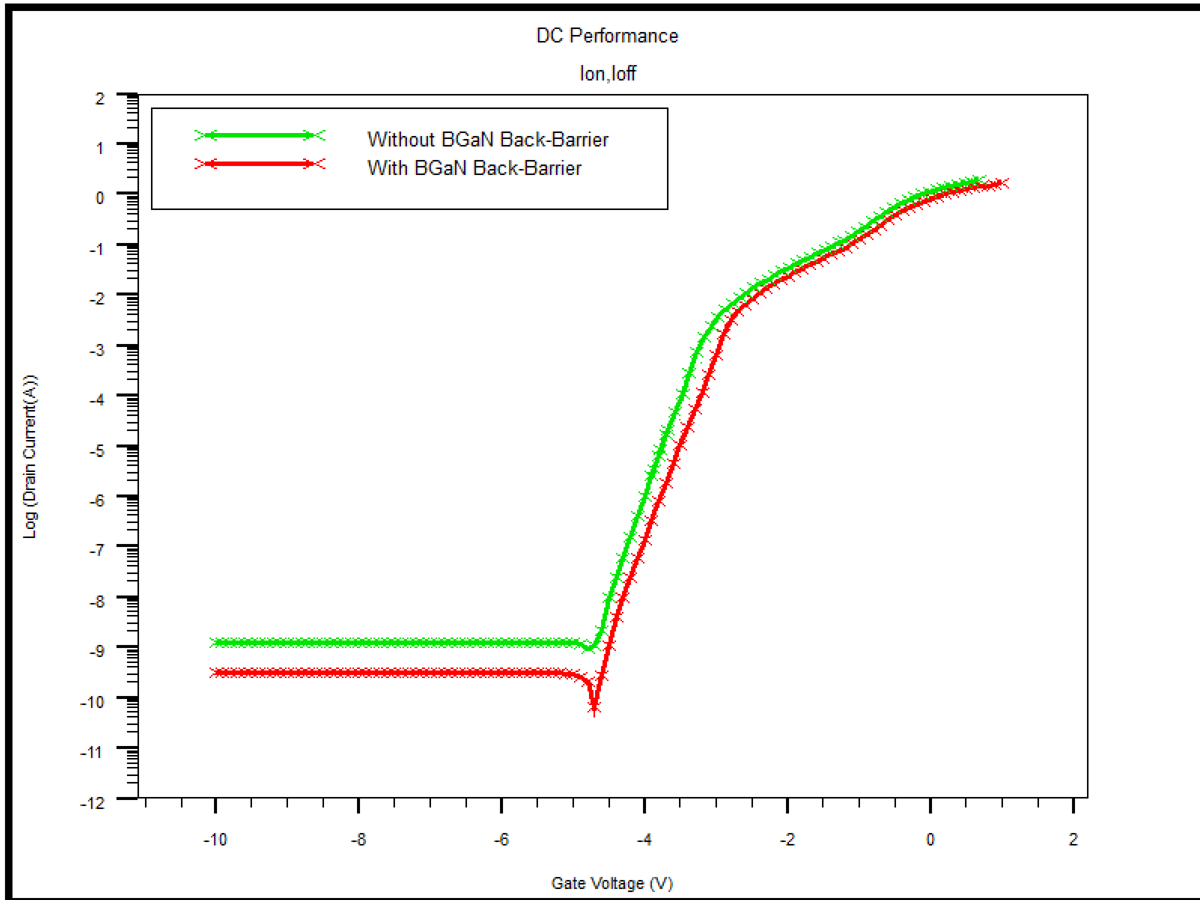


**Figure 6.** Logarithmic plots of ($I_{DS}$-$V_{GS}$)

Figure 7 is used to determine the leakage current at the gate level. We have a very low minimum leakage current equal to $5 \times 10^{-22}$ A at $V_{GS} = 0$ V, and a maximum leakage current of $5 \times 10^{-20}$. The leakage of Current is consequent of the trapping effects ,the surface, and the short channel effects (SCE). Therefore ,the leakage of electron reduces the output current. These are excellent values to minimize the consumption.

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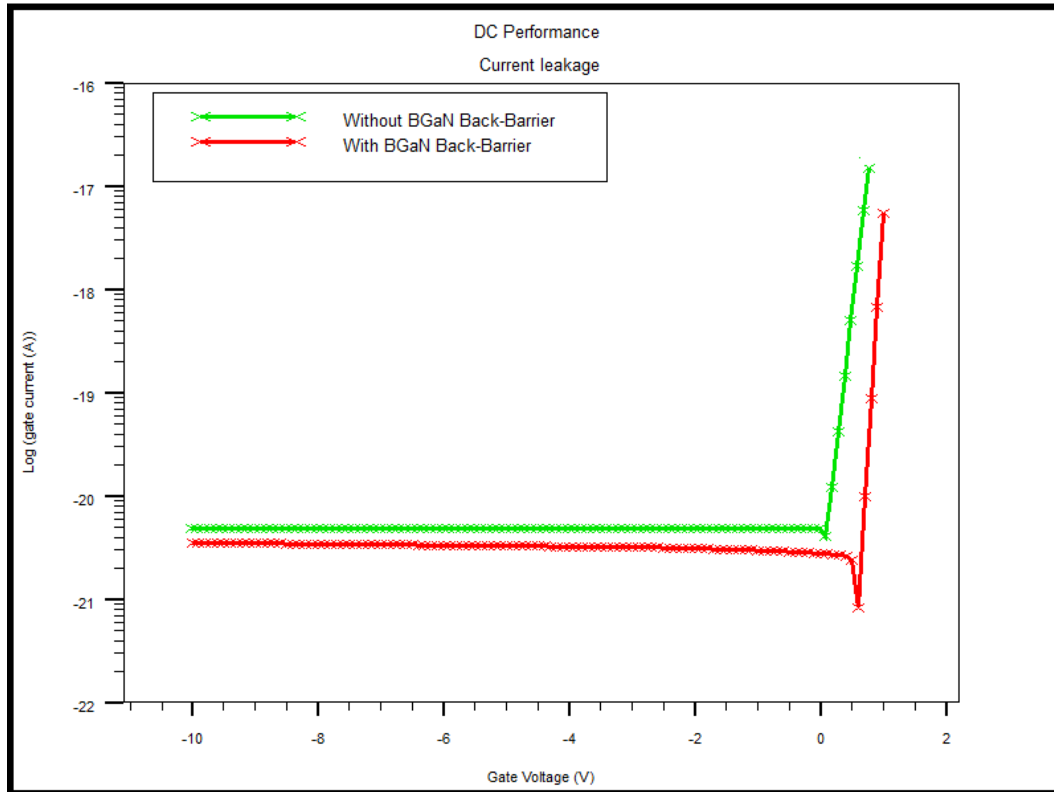


**Figure 7**. Leakage current of the gate

DIBL (Drain Induced Barrier Lowering ) is a more important phenomenon for high drain voltages in short channel transistors and is mainly used for digital applications.

We calculate the threshold voltage $V_{TH}$ for two different values of $V_{DS}$: 5 V and 8V. The curves are shown in Figure 8.

The values extracted from the program with BGaN back-barrier are: $V_{TH}$ = - 2.5 V for $V_{DS}$ = 8 V (green curve), and $V_{TH}$ = - 2.8 V for $V_{DS}$ = 16 V (red curve).

DIBL = Abs [$\Delta V_{TH}$ / $\Delta V_{DS}$][8]
(12)

The DIBL is 166 mV / V, it's a very good value and better than 22 mV / V as was showed in structure of HEMT without BGaN back-barrier.

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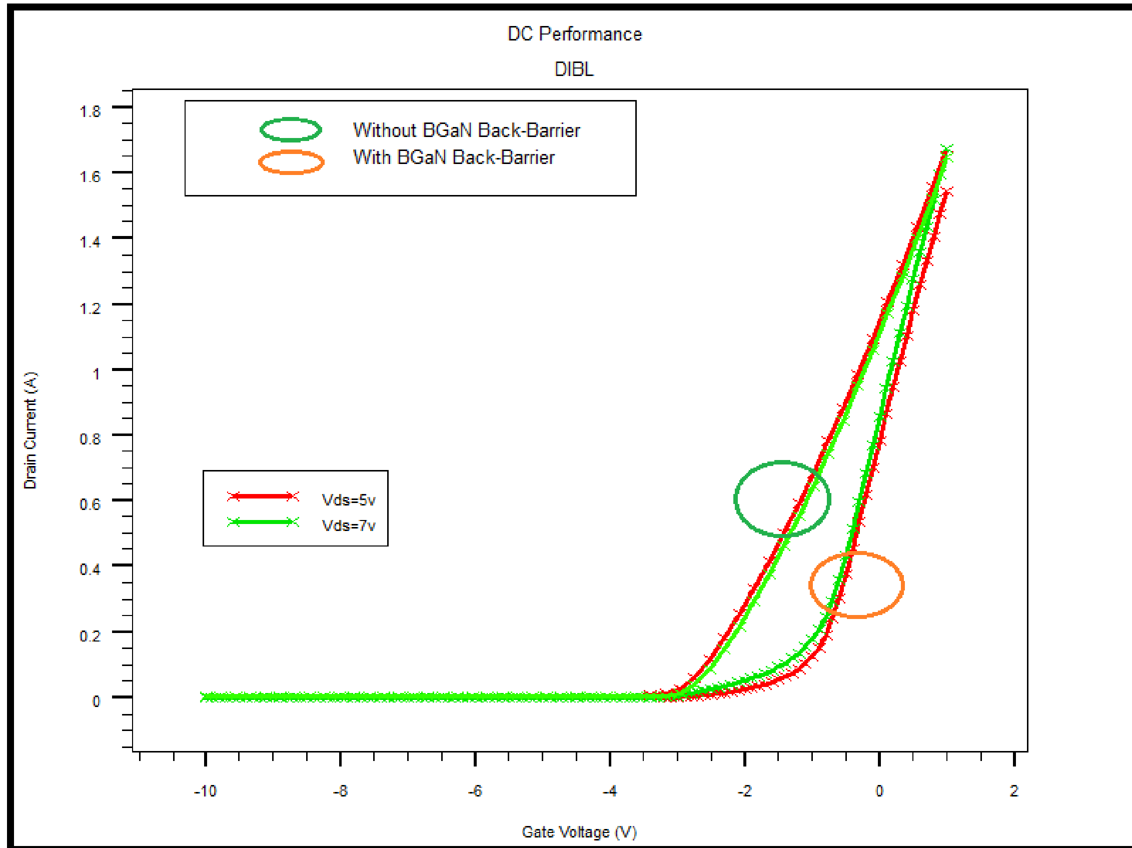


**Figure 8.** (Ids-Vgs) while $V_{DS}$ = 5.0 V and 7.0 V.

### 3.2 AC PERFORMANCES

Figure 9 illustrates two important characteristics in HEMT: the transition frequency (Ft) is the frequency for which the module of the current gain is equal to 1, and the maximum oscillation frequency (Fmax) for which the gain in power is equal to 1. The simulation was made at $V_{GS}$ = 0 V. The result shows a cutoff frequency equal to 600 GHz and a maximum oscillation frequency Fmax equal to 1THz for the structure with BGaN back-barrier. For the HEMT without BGaN back-barrier, the cut-off frequency is 50 GHz and the maximum oscillation frequency is approximately of 150 GHz.

We obtain improved frequencies by inducing $B_{0.02}Ga_{0.98}N$, which rises the resistivity of the buffer. It enhances the electron confinement and concentration at the AlGaN/GaN interface. The result obtained is outstanding comparing by the first work done without BGaN back barrier [8].

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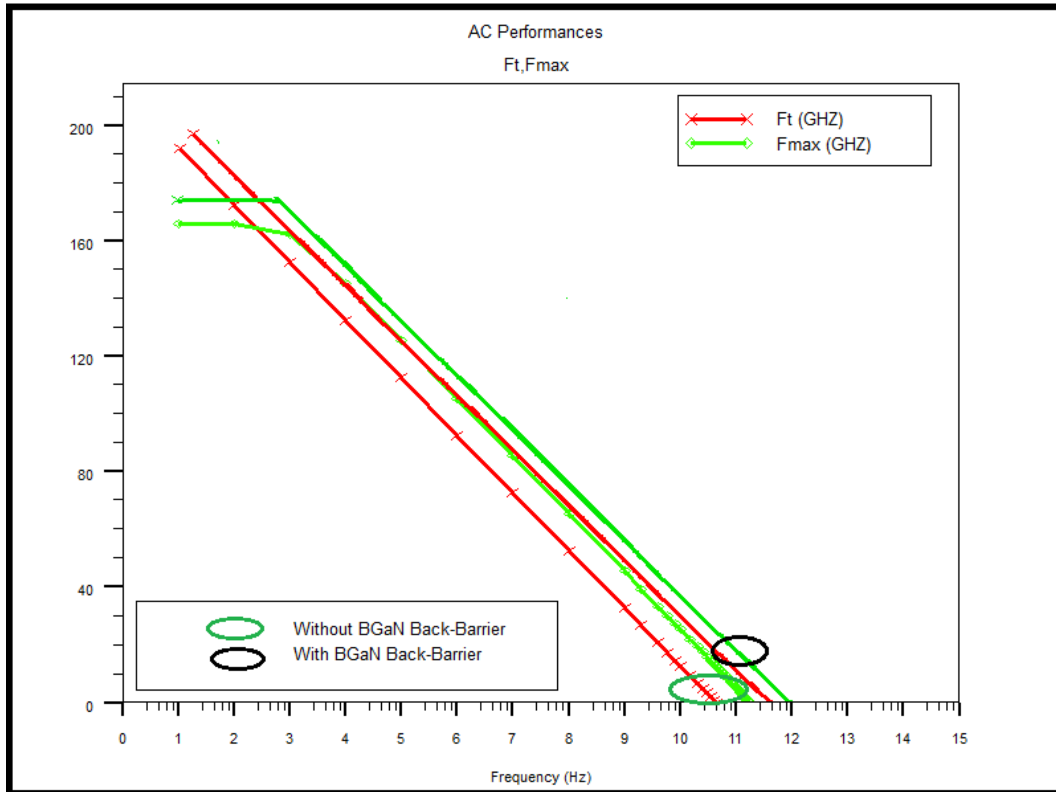


**Figure 9.** The transition frequency (Ft) and the frequency of maximum oscillation (Fmax) at VDS= 5.0 V /VGS=1.0 V.

Figure 10 shows stable maximum power gain (GMS) and available maximum power gain (GMA) for $V_{DS}$=5 V and $V_{GS}$= 1 V. The result acquired through a wide range of frequencies 1 kHz–1 THz. For the structure with BGaN back-barrier , the results present that the peak value of these tow parameters is about 115 dB. At 10 GHZ the GMA and GMS are 20 dB for the first structure and 25 dB for the second.It's improved compared to the HEMT without BGaN back-barrier which displayed 110dB. The result reveals a good stability performance showed by the device which make it appropriate for RF applications.

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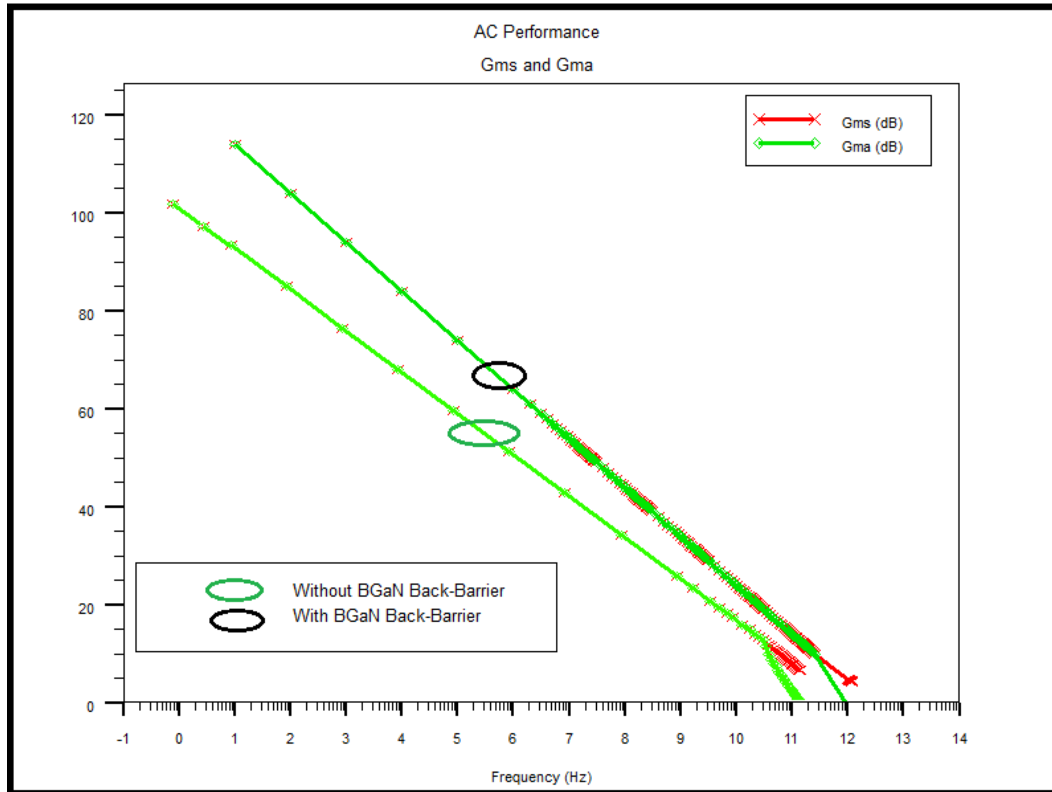


**Figure 10.** The simulated maximum gain power stability (GMS) and available maximum power gain (GMA) while $V_{DS}$=5 V and $V_{GS}$=1 V

The table 3 summarizes a comparison of the major performances (maximum drain current, threshold voltage, transconductance, cut- off frequency, Ion/Ioff, DIBL and SS) calculated in this work for the structure with BGaN back-barrier versus the result obtained by [22] [20] [21] [23] and [8].

From the results mentioned in table 3, comparing our first work [8] HEMT without BGaN back barrier and this work it figured out that the use of BGaN layer back-barriers utterly enhance the DC and RF performances of the high electron mobility transistor.

**Table 3** Comparison of the performances of the propose device versus references [22] [20] [21] [23] and [8].

| | [22] | [20] | [21] | [23] | [8] | **This work** |
|---|---|---|---|---|---|---|
| **ID (A/mm)** | 0.7 | 0.78 | 0.7 | 0.5 | 0.6 | **1** |
| **Vth (V)** | -3.5 | -3.6 | -4.29 | -3.9 | -3.5 | **-1.25** |
| **Gate-leakage (A)** | - | - | - | - | - | **$5 .10^{-22}$** |
| **Ft (Ghz)** | 226 | 119 | 53.8 | 30 | 50 | **600** |
| **Fmax (Ghz)** | 277 | 300 | 82.4 | 100 | 150 | **1000** |
| **Gm (S/mm)** | 300 | 350 | 600 | - | 200 | **850** |

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| Ion/Ioff | $10^{8.7}$ | $10^{9.4}$ | $10^{10}$ | - | $10^{9}$ | **1.5*10$^{9}$** |
|---|---|---|---|---|---|---|
| **DIBL (mV/V)** | - | - | 53 | - | 22 | **166** |
| **SS (mV /dec)** | - | - | 134 | - | 200 | **300** |

## *4* CONCLUSION

We have discussed $Al_{0.26}Ga_{0.74}N$ /GaN/$B_{0.02}Ga_{0.98}N$/ HEMT structures compared to the $Al_{0.26}Ga_{0.74}N$ /GaN HEMTs proposed in the first work [8] and other papers. The major purpose of this study was to ameliorate electron confinement and to prevent the leakage of electron for an AlGaN/GaN HEMT structure by inducing a back-barrier of BGaN beneath the channel. We obtained a maximum drain current of 1 A, a maximum transconductance of 850 mS/mm, and a high cut-off and maximum oscillation frequencies equal to 600 *GHz* and 1THz, respectively. The obtained results show that the layer of $B_{0.02}Ga_{0.98}N$ is barrier of electrostatic which preludes the leakage of electron from the channel to the lower layers, as consequence improvement of the DC and AC characteristics. The splendid results obtained made device highly attractive for future power electronics and switching applications.

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