

# Static and Dynamic Characteristics of an Appropriated and Recessed n-GaN/AlGaIn/GaN HEMT

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**Abstract**—The objective of this paper is to simulate static I-V and dynamic characteristics of an appropriated and recessed n-GaN/Al<sub>x</sub>Ga<sub>1-x</sub>N/GaN high electron mobility (HEMT). Using SILVACO TCAD device simulation, and optimized technological parameters; we calculate the drain-source current ( $I_{DS}$ ) as a function of the drain-source voltage ( $V_{DS}$ ) for different values of the gate-source voltage ( $V_{GS}$ ), and the drain-source current ( $I_{DS}$ ) depending on the gate-source voltage ( $V_{GS}$ ) for a drain-source voltage ( $V_{DS}$ ) of 20 V, for various temperatures. Then, we calculate the cut-off frequency and the maximum oscillation frequency for different temperatures.

We obtain a high drain-current equal to 60 mA, a low knee voltage ( $V_{knee}$ ) of 2 V, a high pinch-off voltage ( $V_{GS0}$ ) of 53.5 V, a transconductance greater than 600 mS/mm, a cut-off frequency ( $f_T$ ) of about 330 GHz, and a maximum oscillation frequency ( $f_{max}$ ) of about 1 THz.

**Keywords**—n-GaN/AlGaIn/GaN HEMT, drain-source current ( $I_{DS}$ ), transconductance ( $g_m$ ), cut-off frequency ( $f_T$ ), maximum oscillation frequency ( $f_{max}$ ).

## I. INTRODUCTION

Al<sub>x</sub>Ga<sub>1-x</sub>N/GaN based High Electron Mobility Transistors (HEMTs) have attracted considerable attentions due to their potentialities for high-voltage and high power operations in power electronics as well as in microwave applications [1]. The GaN material is appealed with properties of high peak electron velocity, high saturation velocity, high breakdown fields and thermal stability due to its wide bandgap for such applications, and also the potential to form lattice matched heterojunctions with other group III-nitride materials.

The main usage areas of HEMTs are; analog, numerical and wireless communication systems [2]. The most straightforward approach to enhance the performance of FET devices is the use of ultra-short gate lengths on a channel material with improved transport characteristics. The difficulty in growing high quality Al<sub>x</sub>Ga<sub>1-x</sub>N with high Al composition has hindered experimental approaches for developing an optimized device structure with a channel layer composed of these materials. It is therefore of great importance to

investigate the possibility of THz frequency operation using these heterojunctions [3].

In this paper; we consider an appropriated and recessed n-GaN/Al<sub>x</sub>Ga<sub>1-x</sub>N/GaN HEMT, and we study its static and dynamic characteristics. Using SILVACO TCAD device simulation; we calculate the drain-source current ( $I_{DS}$ ) depending on the drain-source voltage ( $V_{DS}$ ) for different values of the gate-source voltage ( $V_{GS}$ ), and  $I_{DS}$  depending on  $V_{GS}$  for  $V_{DS} = 20$  V. Then we calculate the cut-off frequency, and the maximum oscillation frequency; at various temperatures.

## II. RESULTS AND DISCUSSION

Based on the literature and especially [4], we use an unconventional recessed n-GaN/Al<sub>x</sub>Ga<sub>1-x</sub>N/GaN HEMT structure. We give in Fig. 1, a schematic cross section of transistor we will simulate in SILVACO.

We set the aluminum content equal to 10% in Al<sub>x</sub>Ga<sub>1-x</sub>N donor layer, the gate-source spacing equal to 0.35μm, and the gate length equal to 50nm. The cap-layer is n-doped with a concentration equal to  $5 \times 10^{21} \text{ cm}^{-3}$ , and the donor layer is n-doped with a concentration equal to  $2 \times 10^{20} \text{ cm}^{-3}$ . All other layers are nonintentionally doped.

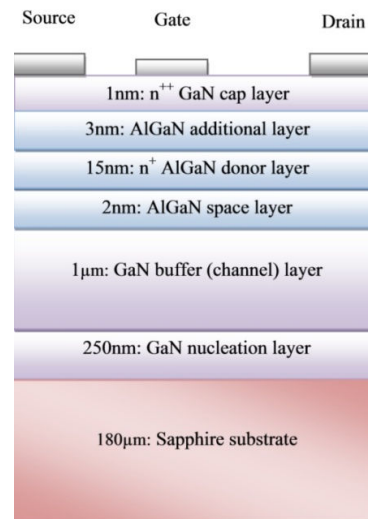


Fig. 1 Schematic cross section of simulated n-GaN/AlGaIn/GaN HEMT

In our n-GaN/AlGaIn/GaN HEMT structure, we use a spacer layer which increases the density and mobility of

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carriers in the channel, and a "recess gate" which helps to improve two aspects:

- The cap layer because it is heavily doped, improves the characteristic of ohmic contacts. However, in the case of a planar structure, the Schottky contact is found placed on a highly doped layer, which consequently leads to degradation of the gate contact. With the recess, we manage to burn the cap layer overlying the undoped AlGaIn barrier layer. The gate is deposited on an undoped material, which allows having low leakage current gate. The recess allows therefore having good ohmic contacts on a doped layer and a good Schottky contact on an undoped layer. The major difficulty in etching the gate recess is that it is not known precisely stop etching at the interface layer between the cap layer and the AlGaIn layer.

Note also that the "recess" of the gate moves off the foot of gate drain side, which will not be located at the most sensitive interface insulator/semiconductor but in the volume of the semiconductor which is less sensitive area. This is an added benefit that can also help improving the performance of the component.

- The second aspect concerns the reduction of gate length  $L_g$  to improve the performance of microwave HEMT. This reduction must be done by maintaining the aspect ratio  $(L_g / a) > 5$  where  $L_g$  is the gate length and "a" is the thickness of the barrier layer. If we decrease the gate length, it is necessary to reduce the thickness of the active layer under the gate, to maintain an aspect ratio greater than 5. This issue of aspect ratio is one of the major locks of performance optimization of the component.

Fig. 2 shows the 2D structure and meshing we use in our n-GaN/AlGaIn/GaN HEMT simulation; it is very thin in the regions of ohmic metal contacts, in the Schottky region, in the region of the donor layer, and at the AlGaIn/GaN heterointerface where the two-dimensional electron gas is formed.

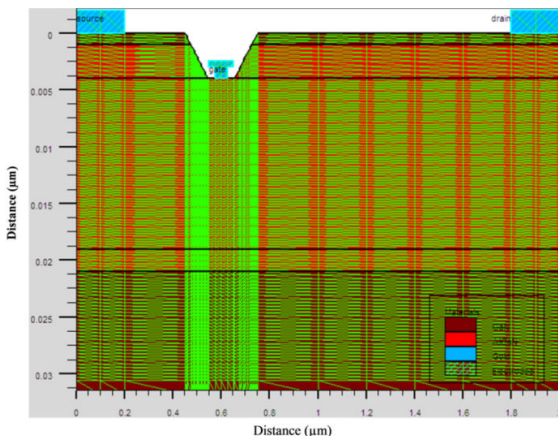


Fig. 2 2D structure and meshing of simulated n-GaN/AlGaIn/GaN HEMT

We first calculate the drain-source current ( $I_{DS}$ ) as a function of the drain-source voltage ( $V_{DS}$ ), for different values of gate-source voltage ( $V_{GS}$ ) at room temperature (ambient temperature of 300 K). Then, we set the gate-source voltage ( $V_{GS}$ ) equal to zero and we calculate  $I_{DS}$ - $V_{DS}$  characteristic for various temperatures. The results are illustrated respectively by Figs. 3 and 4.

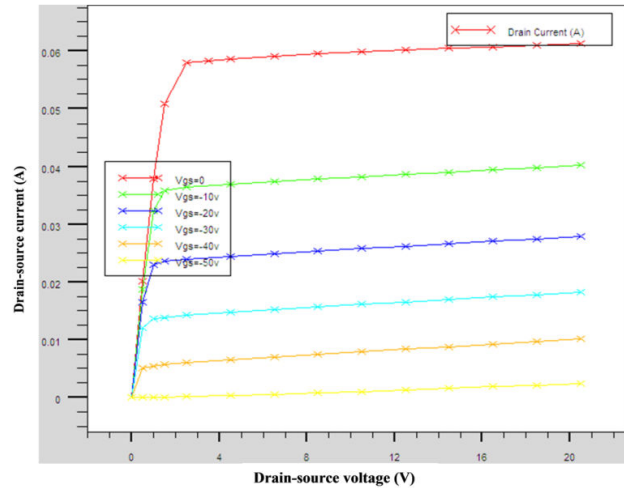


Fig. 3 Evolution of the drain-source current ( $I_{DS}$ ) as a function of the drain-source voltage ( $V_{DS}$ ), for different values of gate-source voltage ( $V_{GS}$ )

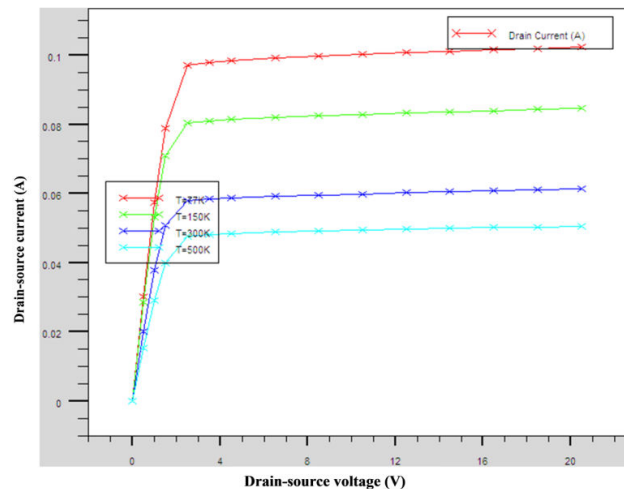


Fig. 4 Evolution of the drain-source current ( $I_{DS}$ ) as a function of the drain-source voltage ( $V_{DS}$ ) for different temperatures,  $V_{GS}$  is set equal to zero

When applying a gate voltage more negative, the Fermi level decreases compared to the energies involved in the 2DEG channel, resulting in decreased electron density and hence a decrease in drain-current  $I_{DS}$ .

To obtain a current/voltage excursion as large as possible, one must have a knee voltage ( $V_{knee}$ ) as low as possible. The series resistance  $R_{on}$  is even lower than the knee voltage is small. It is inversely proportional to the carrier mobility. When

you have a low value of  $V_{knee}$ , this means that the electron mobility is high.

- We find a knee voltage equal to 2 V, a very good value compared to those in the literature.
- We do not observe any negative differential resistance in the output characteristic, and then there is no self-heating effect.
- Kink effect is a phenomenon that is not explained in HEMTs and appears to be related to the phenomenon of impact ionization and trapping effects. It results in an increase in the output current in the saturation zone, even for very low values of gate-source voltage. This increase in current does not exceed 4 mA in our case.
- When the temperature increases, the free electrons undergo more interactions and their mobility deteriorates. This causes a decrease in the drain-source current  $I_{DS}$ .
- The best current (100mA) is obtained at a temperature of 77 K which corresponds to the best electron mobility in GaN. At 300 K, the maximum current ( $I_{DS}$ ) is equal to 60mA.
- At 500 K which is a high temperature, we obtain a current of about 50 mA which is quite important; the component can operate at high temperatures.

Now we set the drain-source voltage ( $V_{DS}$ ) equal to 20 V; and we calculate the drain-source current ( $I_{DS}$ ) depending on the gate-source voltage ( $V_{GS}$ ) at room temperature, then for different temperatures. The results are illustrated respectively by Figs. 5 and 6.

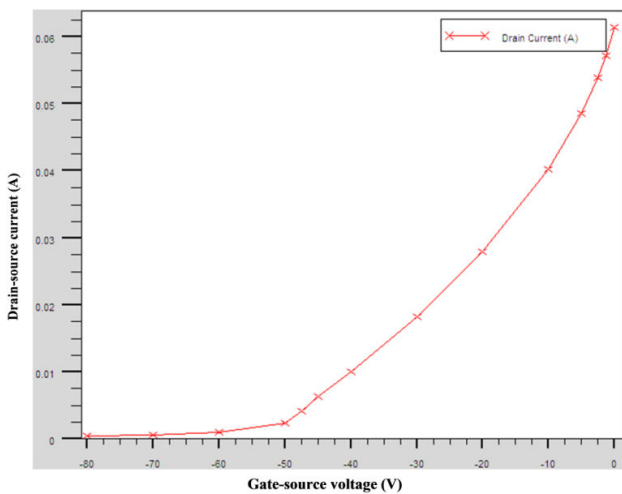


Fig. 5 Evolution of the drain current as a function of the gate voltage, at room temperature, and  $V_{DS} = 20$  V

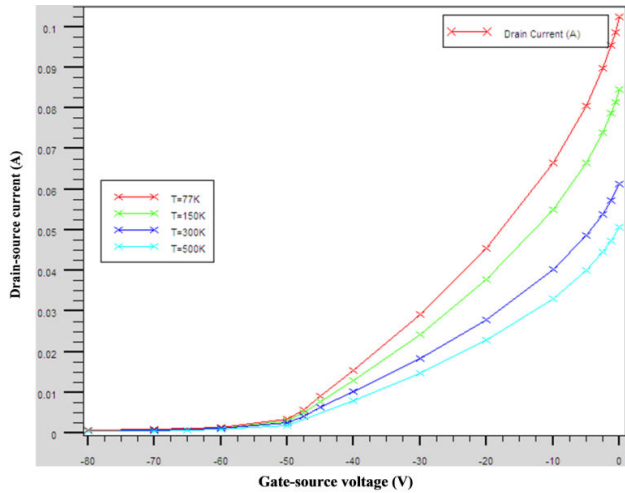


Fig. 6 Evolution of the drain current as a function of the gate voltage for different temperatures, at  $V_{DS} = 20$  V

- At room temperature, we find a pinch-off voltage  $V_{GS0}$  of the order of  $-53.5$  V, and a transconductance  $g_m$  of about 1.23 mA/V (or 616 mS/mm). This transconductance is among the best available values in the literature.

The HEMT is distinguished from other field effect transistors by its high transconductance. Knowing that the cut-off frequency is directly proportional to the transconductance, we can say already that our transistor could admit a high cut-off frequency.

When the temperature increases, both pinch-off voltage and transconductance decrease, but they are important to 500 K. The obtained values are reported in Table I.

At high frequencies, the HEMTs are characterized by two important parameters: the cut-off frequency  $f_T$  for which the modulus of the current gain is equal to 1 (0dB), and the maximum oscillation frequency  $f_{max}$  for which the unilateral power gain is equal to 1 (0dB). We calculate these two frequencies at room temperature; results are given respectively in Figs. 7 and 8.

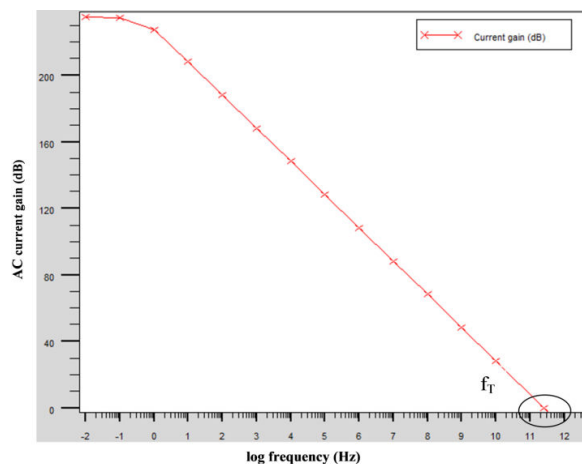


Fig. 7 Evolution of the current gain as a function of frequency

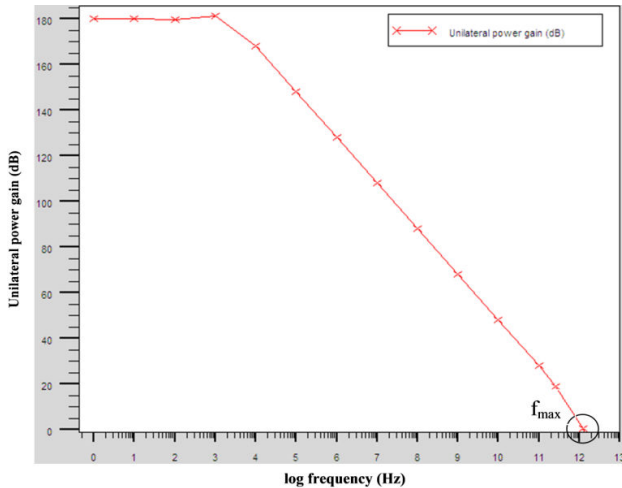


Fig. 8 Evolution of the power gain as a function of frequency

TABLE I  
PINCH-OFF VOLTAGE AND TRANSCONDUCTANCE FOR DIFFERENT TEMPERATURES

Temperature (K)	PINCH-OFF VOLTAGE (V)	Transconductance (mS/mm)
77	-54	1045.45
150	-53.75	858.9
300	-53.5	616.15
500	-52.5	512.95

At room temperature, we find a cut-off frequency  $f_T$  of about 331 GHz, and a maximum oscillation frequency  $f_{max}$  of about 1.1 THz.

In Figs. 9 and 10, we give the variation of these two frequencies as a function of temperature.

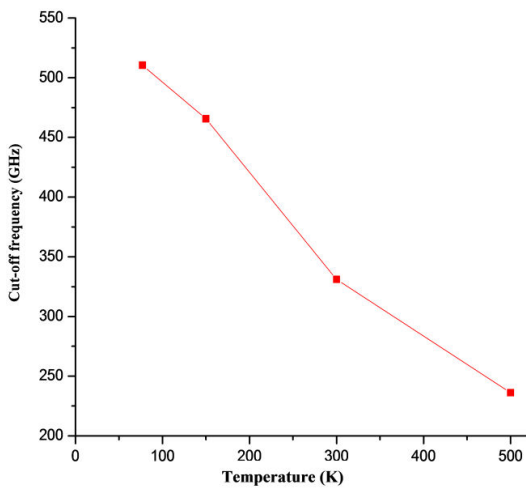


Fig. 9 Evolution of the cut-off frequency as a function of temperature

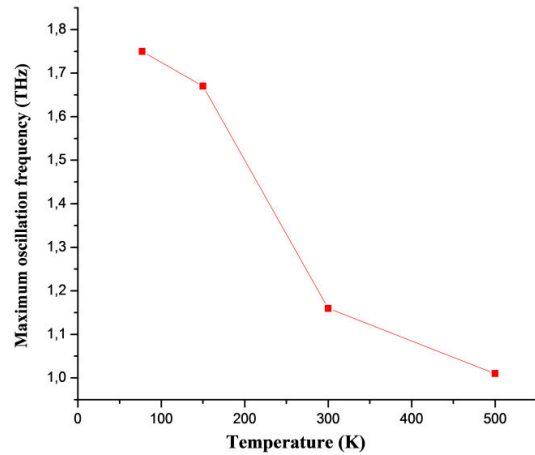


Fig. 10 Evolution of the maximum oscillation frequency as a function of temperature

- Both cut-off frequency and maximum oscillation frequency decrease significantly with increasing temperature; this is logical because the electron mobility decreases.
- The most important point to be drawn from these curves is the dynamic behavior of the transistor at high temperature. Indeed; at 500 K which is considered a high operating temperature, the transistor has a cut-off frequency of about 230 GHz and a maximum oscillation frequency of about 1 THz. This means that the device can operate in hostile environments at high temperatures.

### III. CONCLUSION

We performed a SILVACO TCAD simulation for an appropriated and recessed n-GaN/AlGaIn/GaN HEMT structure with ultra-short gate length. With a 50nm gate length, we found a drain current equal to 60mA, a low knee voltage equal to 2V, a pinch-off voltage of about  $-53.5$  V, a transconductance greater than 600 mS/mm, a cut-off frequency  $f_T$  of about 331 GHz, and a maximum oscillation frequency  $f_{max}$  of about 1.1 THz at room temperature.

According to these theoretical values, and compared to conventional AlGaIn/GaN HEMT structures and published works; our structure has the potential to be promising for making high-performance GaN-based HEMT, with THz frequency operation.

The  $n^{++}$  cap layer design in the n-GaN/AlGaIn/GaN HEMT provides lower ohmic contact, higher current density, higher transconductance, and higher microwave performance; and the recess GaN HEMT with ultra-short gate length provides a better performance in the high speed GaN HEMT application.

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