Improved GaN-based Current Aperture Vertical Electron Transistor (CAVET)

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ABSTRACT—The objectives of this research are to improve and optimize a vertically structure HEMT device based on AlGaN/GaN heterojunctions. This novel proposed structure with double gate command would allow for a better dispersion of the electric field, with peaks lower and farther from the surface than a lateral structure. The research focuses on estimating the performance of a GaN-based vertical structure called a "Current Aperture Vertical Electron Transistor (CAVET)" that combines a two-dimensional electron gas (2DEG) and a vertical structure with technology, operation, settings, and performance that can be seen in power applications. Performance operating at high frequencies and low power loss consumer, a device that will, therefore, lead function to best in electrical power and higher system efficiency with $I_{DS}$ equal 0.95 A, -6 V for pinch-off, $f_t/f_{MAX}$ are 110/250 GHz and 14 % for Drain-lag.

KEYWORDS—CAVET, GaN, Power, Silvaco Tcad.

I. INTRODUCTION

Direct gap semiconductors are compounds based on III-N materials such as GaN, AlN, and their alloys [1]. These materials have emerged as very desirable materials for use in electronics and optoelectronics [2]. These materials are favored in electronics devices, such as field effect transistors and bipolar transistors, which have high power, high frequency, and the capacity to function at high temperatures [3].

GaN is the most representative wide band semiconductor material, and the GaN material system has the best theoretical electro-optical and photoelectric conversion efficiency to date, making it a viable alternative for high-temperature, high-frequency, high-power microwave devices [4]. GaN has a wide bandgap of 3.4 eV, a critical breakdown electric field of 3.5 MV/cm, a high saturated electron drift velocity of $2.5 \times 10^7$ cm/s, and a small dielectric constant of 9.8, when compared to SiC [5-6].

With the development of large-size and high-quality with material based GaN technology, GaN materials have great application potential in the field of power electronics [7]. AlGaN-GaN HEMT devices can achieve lower on-resistance than other materials, which reduces the open-state losses and improves the conversion efficiency of the system [8-9]. All these effective properties make heterojunction AlGaN/GaN an effective choice for this application in the field of work that can withstand high temperatures and large irradiation effect [10].

The uses of CAVET device with GaN have been shown in previous papers to improve breakdown voltage and suppress current collapse. Due to the current collapse phenomenon in high-voltage GaN devices, the on-resistance increases with increasing applied voltage that entire are reported in the literature [11-21].

In this paper, an AlGaN/GaN HEMT device with different parameter in geometry and doping has been simulated by Silvaco Tcad software. The results demonstrate that that device can improve the peak electric field and increase the leakage current. At the same time, the geometry and doping of the device is optimized by simulation, and the characteristics and performance of the device are further improved.

II. MODELING

Figure (1.a) represents the simulated structure which has a dimension of 100 µm on the z axis (depth), The structure includes the different constituent layers and the electrodes, it is given by Silvaco Tcad. The doping of the structure is represented by figure (1.b). Doping was used in this work under the drain and source electrode with a concentration of $9.10^{21}$ cm$^{-3}$. The importance of this high doping is to simulate the diffusion of electrons in the semiconductor and to achieve very good Ohmic contacts.

Figure (1.c) and figure (1.d) illustrate the evolution of the speed of electrons and the speed of hole respectively in room temperature and $V_{DS}=V_G=0$ V, the conductivity of electron mobility is accumulating according to the activation in the channel and under the passivation layer, in contrast to the hole’s mobility, which accumulate at the bottom of the device in a buffer layer.

Table 1. Device geometrics and doping parameters

<table>
<thead>
<tr>
<th>Thickness/Distance</th>
<th>Doping [Atom/cm$^2$]</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>GaN Layer</strong></td>
<td>0.9 x 3.5</td>
</tr>
<tr>
<td><strong>AlGaN Layer</strong></td>
<td>0.025 x 3.2</td>
</tr>
<tr>
<td><strong>AlN Layer</strong></td>
<td>0.11 x 0.1</td>
</tr>
<tr>
<td><strong>SiO2 Layer</strong></td>
<td>0.11 x 3.0</td>
</tr>
<tr>
<td>$L_{GS}$</td>
<td>0.65</td>
</tr>
<tr>
<td>$L_{GD}$</td>
<td>0.925</td>
</tr>
<tr>
<td>Width</td>
<td>50</td>
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</table>

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III. RESULTS AND DISCUSSIONS

A. DC Analysis

The physical model used in simulation in Silvaco Tcad is thermodynamics with room temperature at 300 K, the self-heating is included for all structure in source electrode part by thermal contact by ATLAS in BLAZE and GICA model.

Figure (2.a) represents the energy band diagram of the studied structure. It shows the conduction and valence band energies as a function of depth, from the surface. The behavior of HEMT can be described by an energy band diagram. It’s based on the matching of a large-gap material to a small-gap material, which involves the creation of a discontinuity in the conduction band at the interface between the two materials. The AlGaN/GaN heterojunction creates a potential well (two-dimensional gas) in the narrow gap materials (GaN), which electrons are transferred from the donor layer and accumulated [22]. The conduction band discontinuity is greater; which improves the confinement of the electrons.

Figure (2.b) shows the transfer characteristic. It’s the drain-source current as a function of the gate-source voltage. The gate-source voltage varies from 2 V to –10 V while the drain voltage is fixed at 10 V. The channel of the device consists of a uniform depletion zone due to the presence of two gates, which enables an increase in efficiency as a result high pinch off voltage more than 6 V [23].

Figure (2.c) represents the output characteristic of the device. It is the evolution of the drain-source current as a function of the drain-source voltage for gate-source voltage from 0 V to -6 V. The maximum drain current is 0.95 A at V_{GS}=0 V. This shows that the electrons are well confined in CAVET. The model used integrates the source and drain parasitic resistances and enhances the polarization with an unbranched AlGaN layer present at under layer passivation in the device structure configuration.

The transconductance (g_m) is presented in Figure (2.d). The result displays a peak of the transconductance at 275 mS/mm with V_{DS} = 10 V. The heterostructure with an AlGaN-GaN interface comes closer to the 2DEG (two-dimensional electron gas) between the SiN passivation and AlN layer, leading to the formation of a triangular relationship as this interface is lifted [24]. The g_m characteristic is explained by the high concentration of electrons available to conduct.

Figure (2.e) show the characteristic of the gate leakage current as a function of the gate-source voltage, the drain voltage is fixed at 10 V. The gate leakage current of this structure is 2*10^{-6} A.
The impact of surface trapping and short channel effects is the leakage current at the gate and the output current is decreased as a result of electron leakage.

Figure (2.f) illustrate the $I_{ON}$ and the $I_{OFF}$ of the CAVET which we can extract the $I_{ON}/I_{OFF}$ ratio. the $I_{ON}/I_{OFF}$ ratio for $V_{DS}=1V$ is $10^5$ and for $V_{DS}=V_{DD}$ is equal $3.7*10^6$. A high $I_{ON}/I_{OFF}$ ratio shows that the device is of high quality, with a minimal loss. Latest advancement of HEMTs has a high $I_{ON}/I_{OFF}$ ratio value and attracts particular attention to power consumption in static and standby applications.

![Fig. 2. a) Diagram band versus Y- Thickness structure, b) Transfer characteristics of the CAVET, Output characteristic of the CAVET, e) Leakage current of the CAVET and f) DIBL effect in the CAVET.](image)

**B. AC Analysis**

Two crucial CAVET features are shown in (Figure 3.a) the transition frequency ($F_t$), which is equal to 110 GHz, and the maximum oscillation frequency ($F_{Max}$), which is equivalent to 250 GHz at $V_{GS} = 0$ V was used for the simulation. The result also displays the maximum power gain (GMS) that is stable and the greatest power gain (GMA) that is accessible at 90 dB.

The device is suitable for RF applications thanks to its performance and stability.

The figure (3.b) presents the stem stability factor over the frequency. The good stability is achieved over range from 100 GHz. The transconductance is above 260 (mS/mm) and it’s stable as is presented in figure (3.c).

![Fig. 3. a) Gains versus frequency, b) Streen factor versus frequency and c) Transconductance versus frequency.](image)

**C. Capacites Analysis**

The capacity of a substance to hold an electric charge is known as capacitance. All electronic equipment has standard capacitors, which store an electrical charge when a voltage is supplied to them.

Figure 4 represent the variation of the capacitance $C_{GD}$, $C_{GID}$, $C_{DS}$, $C_{GS}$ and $C_{GIS}$ over the range from 1 KHz to 1 THz the figure 3(a) and 3(b) as a function of the gate-source voltage ($V_{GS}$). $C_{GS}$ and $C_{GIS}$ is 4 pF, $C_{DS}$ is 1.5 pF, $C_{GD}$ is 40 pF and $C_{GID}$ is 30 pF.
D. Drain Lag

When the drain voltage is pulsed from the OFF state ($V_{DS} = 0\,\text{V}$) to the ON state ($V_{DS} > 0\,\text{V}$) with a constant gate voltage, the drain current experiences a transitory phenomenon known as "Drain-Lag" [25].

These electrons are accelerated by the electric field created by $V_{DS}$ when the drain voltage goes from OFF to ON, for a positive variation of $V_{DS}$ [26].

They are trapped by deep energy level traps positioned in the buffer and the substrate if the pulse duration is larger than the constant of capture time and less than the constant of emission time [27]. These electrons caught by the traps do not contribute to the current flowing through the channel [28]. When a result of $D_L$ is smaller in this structure CAVET, we extract from equation 1 is $14\%$ ($I_{DSS} = 0.45\,\text{A}$ & $I_{DSS0} = 0.51\,\text{A}$), as the traps full up, the drain current reduces until it achieves its permanent condition.

\[ D_L = \frac{I_{DSS} - I_{DSS0}}{I_{DSS}} \quad (1) \]

E. Compare Results

This approach offers key advances such as overcoming reduced Buffer Leakage (BL), enhanced Heat Dissipation (HD), reduced Access Resistance (AR), Increased Breakdown Voltage (BV), and improved RF performance, making it highly suitable for high-power and high-frequency applications in harsh environments.

The table presents the data from the literature study of an LNA-HEMT with different performances exhibited.

<table>
<thead>
<tr>
<th>This Work</th>
<th>[29]</th>
<th>[30]</th>
<th>[31]</th>
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<td>$I_{DSS}$ [A]</td>
<td>0.4</td>
<td>0.32</td>
<td>0.97</td>
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<tr>
<td>$V_F$ [V]</td>
<td>-6.0</td>
<td>-12</td>
<td>-6.0</td>
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<tr>
<td>$Gm$ [S/m]</td>
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<tr>
<td>$f_T$ [GHz]</td>
<td>34.5</td>
<td>32</td>
<td>24.3</td>
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<tr>
<td>$f_{Max}$ [GHz]</td>
<td>105</td>
<td>38</td>
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<tr>
<td>$C_{DS}$ [pF]</td>
<td>//</td>
<td>//</td>
<td>32</td>
</tr>
<tr>
<td>$C_{GS}$ [pF]</td>
<td>//</td>
<td>//</td>
<td>38</td>
</tr>
<tr>
<td>$D_L$ [%]</td>
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applications due to its minimal transit dispersion and low DC-RF dispersion.

REFERENCES


