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# Strain relaxation and thermal effects on the drain conductance in AlGa<sub>m</sub>N/GaN HEMT

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**Abstract**— In this work the effects of technological and electrical parameters of Al<sub>m</sub>Ga<sub>1-m</sub>N/GaN High Electron Mobility Transistors (HEMT) on the output conductance "g<sub>d</sub>" was studied in the first part. In the second part, the effect on g<sub>d</sub> of thermal and self heating in the device was analyzed. This study was made by taking into account the effects of spontaneous and piezoelectric polarizations in the heterojunction AlGa<sub>m</sub>N/GaN and the relaxation of the crystal lattice induced by the aluminum mole fraction.

An analytical model for the electrons concentration "n<sub>s</sub>" in the 2DEG and the current I<sub>ds</sub> in the channel for strong inversion regime was presented. By solving the Poisson equation and Schrödinger self-consistent calculations, including the spontaneous and piezoelectric polarizations, lattice relaxation, self heating and thermal effects the current I<sub>ds</sub> was calculated. The output conductance g<sub>d</sub> according to the voltage V<sub>ds</sub> are deduced thanks to the analytical description of the calculated current I<sub>ds</sub>.

**Keywords**—GaN, HEMT, AlGa<sub>m</sub>N/GaN, drain conductance, self heating.

## I. INTRODUCTION

High-electron-mobility transistors (HEMTs) based on Al<sub>m</sub>Ga<sub>(1-m)</sub>N/GaN heterostructures are very promising for applications in high power and high temperature electronics operating at high frequencies owing to their outstanding electrical properties such as high breakdown voltage, high peak electron velocity and high sheet electron concentration in two-dimensional electron gas (2DEG) structures [1–2]. Performance of HEMTs can be estimated from some important electrical quantities that characterize them and which are good indicators for the performance of high frequency component. They must therefore have a high transconductance, low output conductance and a high cutoff frequency.

The output conductance characterizes a transistor in the saturated operation. It measures changes in the drain current relative to changes in drain voltage V<sub>ds</sub>, with constant gate voltage V<sub>gs</sub>. Calculating the power gain of the component requires knowledge of the output conductance, which allows, among other to account for the saturation drain current. From a physical standpoint, the drain conductance g<sub>d</sub>

characterizes the confinement of electrons in the channel.

In this paper, we presented an analytical model for the electrons concentration "n<sub>s</sub>" in the 2DEG and the current I<sub>ds</sub> in the channel of HEMT for strong inversion regime by solving the Poisson equation and Schrödinger self-consistent calculations. Thanks to the analytical description of the current I<sub>ds</sub> we are able to demonstrate changes in the output conductance g<sub>d</sub> according to the voltage V<sub>ds</sub>, including the spontaneous and piezoelectric polarization, lattice relaxation, self-heating and thermal effects on the Al<sub>m</sub>Ga<sub>(1-m)</sub>N/GaN HEMT drain conductance g<sub>d</sub>.

## II. THEORETICAL ANALYSIS

Fig. 1 shows the cross-sectional schematic of the AlGa<sub>m</sub>N/GaN HEMT structure. The device structure consists of a thick undoped Gallium Nitride (GaN) layer grown on a substrate (SiC, Sapphire or Al<sub>2</sub>O<sub>3</sub>) where an undoped layer Al<sub>m</sub>Ga<sub>1-m</sub>N of thickness (d<sub>i</sub>) called spacer was grown in order to reduce impurity scattering. Then, a doped layer Al<sub>m</sub>Ga<sub>1-m</sub>N of thickness (d<sub>d</sub>) and concentration (N<sub>d</sub>) was grown. On the last layer, the gate was realized. When a gate voltage V<sub>gs</sub> is applied through a Schottky contact of this structure, the sheet carrier concentration "n<sub>s</sub>" of the 2DEG formed at the AlGa<sub>m</sub>N/GaN heterojunction at a given temperature is given by [3].

$$n_s(x, T, m) = \frac{\epsilon(m)}{q(d_d + d_i + \Delta d)} (V_{gs} - V_{th}(T, m) - V_c(x)) \quad (1)$$

Where  $q$  is the electron charge,  $m$  is the Al mole fraction in Al<sub>m</sub>Ga<sub>1-m</sub>N,  $\epsilon(m)$  is the AlGa<sub>m</sub>N dielectric constant,  $d_d$  is the AlGa<sub>m</sub>N barrier

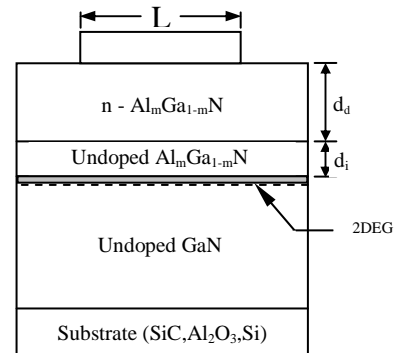


Figure 1. Schematic AlGa<sub>m</sub>/Ga<sub>1-m</sub>N HEMT structure used thickness,  $d_i$  is the spacer layer thickness,  $\Delta d$  is the effective thickness of 2-DEG,  $V_{gs}$  is the applied gate-source voltage and  $V_c(x)$  is the channel potential at a position  $x$ . The threshold voltage  $V_{th}(T, m)$  dependant of the temperature  $T$  and the mole fraction of the AlGa<sub>m</sub>/Ga<sub>1-m</sub>N HEMT is given by the following expression:

$$V_{th}(T, m) = \phi_m(m) - \Delta E_c(T, m) - \frac{qN_d d_d^2}{2\epsilon(m)} - \frac{\sigma(m)}{\epsilon(m)} (d_i + d_s) \quad (2)$$

With  $N_d$  is the doping density of AlGa<sub>m</sub> layer and  $\phi_m(m)$  the Schottky barrier height given by [4].

$$\phi_m(m) = 0.84 + 1.3m \text{ [eV]} \quad (3)$$

and  $\Delta E_c(T, m)$  is the conduction band discontinuity at the Al<sub>m</sub>Ga<sub>1-m</sub>N/ GaN interface given by [5]:

$$\Delta E_c(T, m) = 0.70 \left[ E_{c}^{AlGa_m} (T, m) - E_{c}^{GaN} (T) \right] \text{ [eV]} \quad (4)$$

The major factor which controls 2-DEG is the aluminium composition of AlGa<sub>m</sub>. The variation of Al mole fraction affects directly the polarization

$$P_{pz} (Al_m Ga_{1-m} N) = \begin{cases} \left( \left( \frac{2(a(0) - a(m))}{a(m)} \right) \times \left( e_{31} - \frac{e_{33}(m)C_{13}(m)}{C_{33}(m)} \right) \right) \rightarrow \text{for } 0 \leq m \leq 0.38 \\ \left( \left( \frac{2(2.33 - 3.5m)}{a(m)} \right) \times \left( e_{31} - \frac{e_{33}(m)C_{13}(m)}{C_{33}(m)} \right) \right) \rightarrow \text{for } 0.38 \leq m \leq 0.67 \\ 0 \rightarrow \text{for } 0.67 \leq m \leq 1 \end{cases} \quad (6)$$

Where  $a(0)$  and  $a(m)$  are the lattice constants,  $C_{13}(m)$  and  $C_{33}(m)$  are elastic constants and  $e_{31}(m)$  and  $e_{33}(m)$  are piezoelectric constants of Al<sub>m</sub>Ga<sub>1-m</sub>N layer. In the above expression, it has been assumed that GaN layer is fully relaxed. This is a reasonable assumption since the thickness of GaN is much larger than that of strained AlGa<sub>m</sub> layer and thus  $P_{pz}(\text{GaN}) \sim 0$ . The drain current  $I_{ds}$  in the 2-DEG channel can be obtained from the current density equation by [7]:

$$I_{ds}(T, m, x) = wq\mu(T, x) \left( n_s(T, m, x) \frac{dV_c(x)}{dx} + \frac{K_B T}{q} \frac{dn_s(T, m, x)}{dx} \right) \quad (7)$$

Where  $w$  is the channel width,  $K_B$  is the Boltzmann constant,  $V_c(x)$  is a channel potential and  $\mu(T, x)$  is the temperature dependent mobility given by [3]:

$$\mu(T, x) = \frac{\mu_0(T)}{1 + \frac{1}{E_1} \frac{dV_c(x)}{dx}} \quad (8)$$

$$E_1 = \frac{E_c v_{sat}}{\mu_0(T) E_c - v_{sat}}$$

Where  $\mu_0(T)$  is the low field mobility,  $E_c$  is the critical electric field and  $v_{sat}$  is the saturation

induced sheet charge density. The polarization induced charge density  $\sigma_{pz}(m)$  is given by [6].

$$\left| \sigma_{pz} \right| = \left| P_{SP_{Al_m Ga_{1-m} N}}(m) + P_{PZ_{Al_m Ga_{1-m} N}}(m) - P_{SP_{GaN}} \right|$$

$\sigma(m)$  is the total polarization induced charge density. The strain relaxation of Al<sub>m</sub>Ga<sub>1-m</sub>N barrier is one of the most crucial parameter for design and optimization of high aluminium content in Al<sub>m</sub>Ga<sub>1-m</sub>N/GaN HEMTs. However, at high Al mole fractions, a partial relaxation of the Al<sub>m</sub>Ga<sub>1-m</sub>N barrier layer is due to lattice strain relaxation that affects the device characteristics significantly. Thus, the total polarization is the sum of piezoelectric and spontaneous polarization fields, which induce a sheet charge density  $\sigma_{pz}$  at the heterointerface. At given aluminium mole concentration in Al<sub>m</sub>Ga<sub>1-m</sub>N layer, there is a critical barrier layer thickness which the strain in the layer decreases. For thickness range of 200-400 Å, the barrier layer is expected to be fully strained for  $0 \leq m \leq 0.38$ , partially relaxed for  $0.38 \leq m \leq 0.67$  and fully relaxed for  $0.67 \leq m \leq 1$ . Thus, the piezoelectric polarization induced charge density dependent of Al content is given by [4]:

velocity. Using equations (1) and (8) in equation (7), and integrating along the channel we can obtain:

$$I_{ds}(T, m) = \frac{-A_2(T, m) + \sqrt{A_2(T, m)^2 - 4A_1(T, m)A_3(T, m)}}{2A_1(T, m)} \quad (9)$$

With

$$A_1(T, m) = \left( \frac{\mu_0(T) E_c - v_{sat}}{E_c v_{sat}} \right) (2R_s + R_d) - \left( \frac{w\mu_0(T)q^2 D \epsilon(m)}{(\epsilon(m) + 2q^2 D(d_d + d_i))} \right) (R_d^2 + 2R_s R_d) \quad (10)$$

$$A_2(T, m) = \left( \frac{2w\mu_0(T)q^2 D \epsilon(m)}{(\epsilon(m) + 2q^2 D(d_d + d_i))} \right) (V_{ds}(R_s + R_d) - V_{gs}(T, m)(2R_s + R_d)) - L \left( \frac{\mu_0(T) E_c - v_{sat}}{E_c v_{sat}} \right) V_{ds} \quad (11)$$

$$A_3(T, m) = \left( \frac{2w\mu_0(T)q^2 D \epsilon(m)}{(\epsilon(m) + 2q^2 D(d_d + d_i))} \right) \left( V_{gs}(T, m) V_{ds} - \frac{V_{ds}^2}{2} \right) \quad (12)$$

$$V'_{gs}(T, m) = V_{gs} - V_{th}(T, m) - \frac{K_B T}{q} \quad (13)$$

Where  $R_s$  and  $R_d$  are the source and drain resistances respectively and  $V_{ds}$  is drain to source voltage.

$D = \frac{4\pi m^*}{h^2}$  is conduction band density of state of 2DEG system,  $m^*$  is effective mass of electron and  $h$

is Planck constant. The drain conductance is an important microwave parameter that determines the maximum voltage gain attainable from the device. The drain conductance of the  $\text{Al}_m\text{Ga}_{1-m}\text{N}/\text{GaN}$  HEMT is evaluated as [3]:

$$g_d(T, m) = \frac{1}{2A_1(T, m)} \left( \frac{\partial A_2(T, m) / \partial V_{ds}}{\sqrt{A_2(T, m)^2 - 4A_1(T, m)A_3(T, m)}} - 1 \right) - \frac{2A_1(T, m) \partial A_3(T, m) / \partial V_{ds}}{\sqrt{A_2(T, m)^2 - 4A_1(T, m)A_3(T, m)}} \quad (14)$$

With:

$$\begin{aligned} \frac{\partial A_1(T, m)}{\partial V_{ds}} &= 0 \\ \frac{\partial A_2(T, m)}{\partial V_{ds}} &= A(R_s + R_d) - \left( \frac{\mu_0(T)E_C - v_{sat}}{E_C v_{sat}} \right) \\ \frac{\partial A_3(T, m)}{\partial V_{ds}} &= A(V'_{gs}(m) - V_{ds}) \\ A &= \frac{2w\mu_0(T)q^2 D \varepsilon(m)}{(\varepsilon(m) + 2q^2 D(d_d + d_i))} \end{aligned}$$

The electrons mobility depends strongly on temperature and electric field present which it decreases with increasing temperature.

### III. RESULTS AND DISCUSSION

Fig. 2 shows the dependence of drain-source current ( $I_{ds}$ ) versus drain-source voltage ( $V_{ds}$ ) for Al mole fraction of AlGaN varying from 0.20 to 0.75 at room temperature (300 K). We note that the current  $I_{ds}$  increase when the value of the mole fraction "m" increase. The current  $I_{ds}$  depend strongly on the Al content of the top layer. This is essentially due to the increasing of the channel electron density induced by the enhanced polarization charge when an Al contents vary from 0.20 to 0.75 [8]. The increase in aluminum mole fraction induces a strong discontinuity in the conduction band and a strong piezoelectric polarization, this is due to an increase in the concentration of 2DEG in the channel, and therefore it induces a large current value.

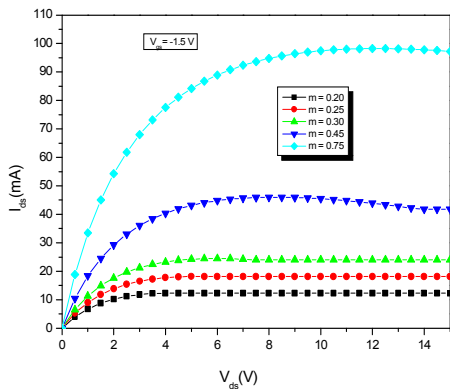


Figure 2. Variation of drain current  $I_{ds}$  with voltage  $V_{ds}$  at different Al mole fractions  $m$  for  $V_{gs} = -1.5\text{V}$ .

Fig. 3 shows, at room temperature, the variation of the  $\text{Al}_m\text{Ga}_{1-m}\text{N}/\text{GaN}$  HEMTs output conductance versus drain voltage at gate voltage fixed at  $-1.5\text{V}$  for different Al mole fractions, for partially relaxed (PR)  $m \geq 0.38$  and fully strained (FS) structures  $m \leq 0.38$ . We observe that the drain conductance increases with an increase in the Al mole fraction and decreases with an increase in drain voltage. Increasing the aluminum mole fraction in the heterojunction AlGaN/GaN induces a strong discontinuity in the conduction band and a strong piezoelectric polarization. The discontinuity of the conduction band  $\Delta E_C$  resulting from this phenomenon is more important leading to electron confinement. The electric field breakdown becomes higher in the GaN based devices. Therefore, the carrier densities and mobility are higher, so the output conductance increases. On the other hand, we notice that the output conductance decreases when  $V_{ds}$  increases and eventually becomes zero in the saturation region when the drain-source current saturates. We notice that for  $m \geq 0.38$ , the relaxation effect of the crystal lattice decreases the output conductance. The difference between the curves with and without relaxation is very large when the crystal lattice is fully relaxed ( $m = 0.75$ ) and less important when the AlGaN layer is partially relaxed ( $m = 0.45$ ). Indeed, for  $m \geq 0.38$ , the material is relaxed and the 2DEG density continues to increase, which affects the drain conductance  $g_d$ . The influence of relaxation is greater for higher values of molar fraction ( $m \geq 0.38$ ). This is a consequence of the lack of influence piezoelectric polarization due to the disappearance of the mechanical stress on the AlGaN layer.

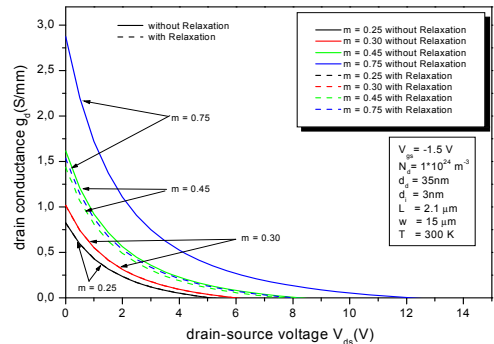


Figure 3. Variation of drain conductance as a function of drain-

source voltage at different Al mole fraction "m" of  $\text{Al}_m\text{Ga}_{1-m}\text{N}$  with and without relaxation

Fig 4-a and 4-b show the variations of the drain conductance  $g_d$  depending on the voltage  $V_{ds}$  for different values of the thickness " $d_d$ " of the doped layer  $\text{Al}_m\text{Ga}_{(1-m)}\text{N}$ , with and without relaxation for  $m=0.25$  and  $m=0.45$  respectively. We notice that for  $m=0.25$  ( $m < 0.38$ ) the lattice is fully extended and the output conductance takes larger values at increasing  $d_d$  (Fig 4-a),  $g_d$  increases when the doped  $\text{Al}_m\text{Ga}_{1-m}\text{N}$  layer thickness  $d_d$  increases. But beyond this value,  $m=0.45$  ( $m \geq 0.38$ ) the material is partially relaxed and degradation is observed in the value of the drain conductance  $g_d$  (Fig 4-b). We note that, when the thickness of the doped layer  $d_d$  increases, the drain conductance  $g_d$  increases. This increase is due to the increased carrier density in 2DEG, thus increasing the drain-source current for large values of  $d_d$ .

Fig 5-a and Fig 5-b show the variations of the drain conductance  $g_d$  versus the voltage  $V_{ds}$  for different values of the doping concentration  $N_d$  with and without relaxation for  $m=0.25$  and  $m=0.45$  respectively.

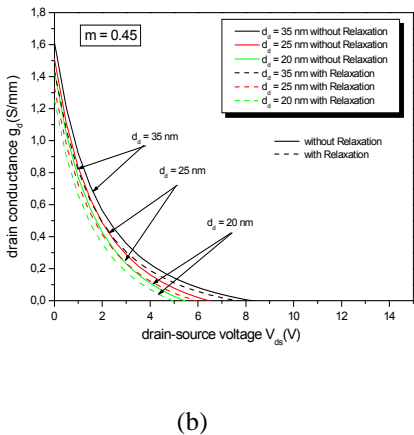
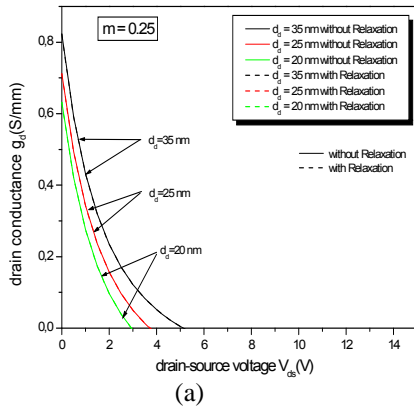


Figure 4(a,b). Variation of drain conductance as a function of drain-source voltage at different doped  $\text{Al}_m\text{Ga}_{1-m}\text{N}$  layer thickness «  $d_d$  ». with and without relaxation for  $m=0.25$  and  $m=0.45$  respectively.

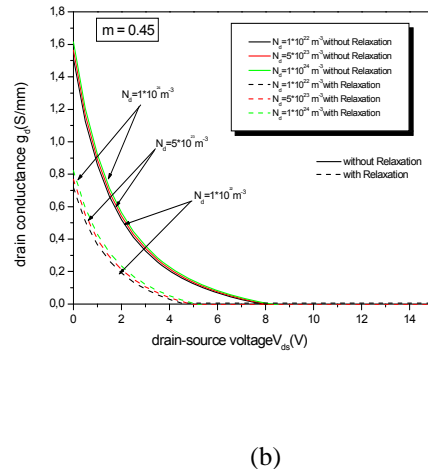
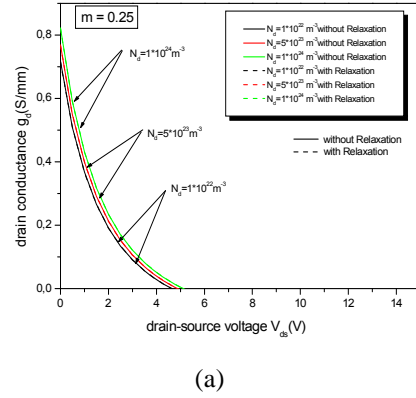


Figure 5(a,b). variation of drain conductance as a function of drain-source voltage at different doping density «  $N_D$  » with and without relaxation for  $m=0.25$  and  $m=0.45$  respectively.

We note that the curves of the drain conductance  $g_d$  for  $m=0.25$  (Fig 5-a) are superimposed in both cases with and without relaxation of the crystal lattice for each value of the concentration of the doping layer  $\text{Al}_m\text{Ga}_{1-m}\text{N}$ . While for  $m = 0.45$  (Fig 5-b), a significant difference is observed, this gap decreases the value of  $g_d$ . We note that if the concentration of doping  $N_d$  increase the drain conductance  $g_d$  increases. This is due to the increased density of 2DEG in the quantum well, so there is an increase of spontaneous polarizations and piezoelectric which exists at the interface of the  $\text{AlGaN}/\text{GaN}$  heterojunction and improved containment of electrons into the well potential.

Fig.6 shows the transfer characteristics of an  $\text{AlGaN}/\text{GaN}$  HEMT on the gate-source voltage when considering the thermal effect and the effect of self-heating. A degradation of drain-source current with increasing temperature of 300 K to 475 K was observed, this degradation becomes important when one considers the effect of self-heating.

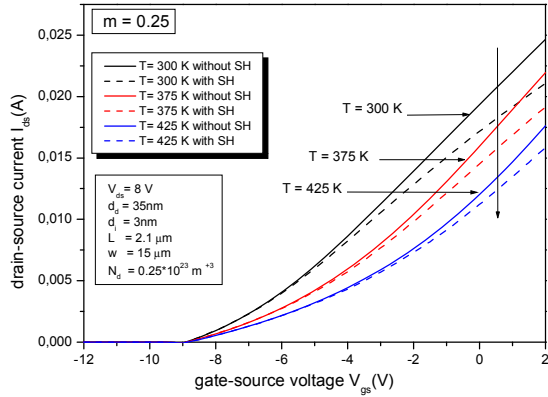


Figure 6. the transfer characteristics of HEMT with and without effect of self-heating and thermal effect for different temperature

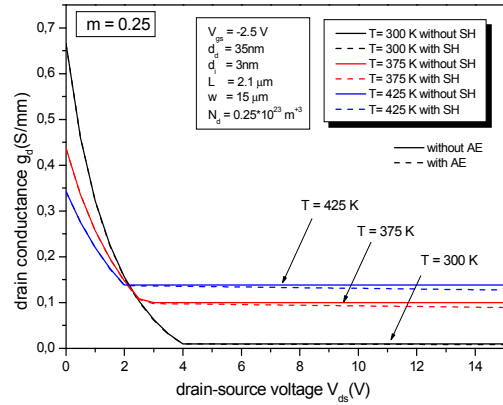


Figure 8. Dependence of drain conductance  $g_d$  on drain voltage  $V_{ds}$  for various values of temperature for  $V_{gs} = -2.5V$  and  $m = 0.25$ . When self-heating is not considered (solid lines) and when self-heating is considered (dashed lines).

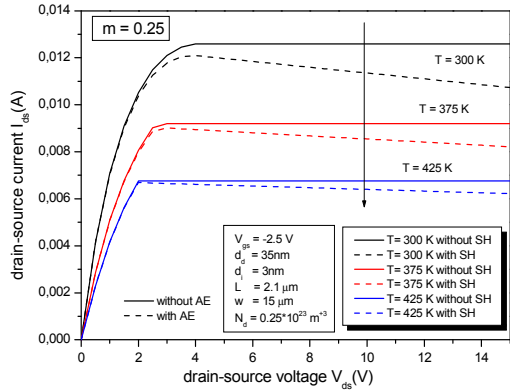


Figure 7. Dependence of drain current  $I_{ds}$  on drain voltage  $V_{ds}$  for various values of temperature for  $V_{gs} = -2.5V$  and  $m = 0.25$ . When self-heating is not considered (solid lines) and when self-heating is considered (dashed lines).

Fig.7 shows the current-voltage characteristics of a HEMT based heterostructure AlGaIn/GaN when considering the thermal effect and the self-heating (dashed lines). These characteristics show a negative resistance at higher drain voltage level. It is observed that, with increasing temperature from 300K to 425K, explicitly from an external source or by injecting more current in the transistor, a drain current decay. This is due to a decrease in the low field mobility of electrons where the electron transport in 2DEG channel is dominated by scattering with phonons. The self-heating is a local increase of crystal temperature due to dissipated Joule electric power. It is seen that the saturation drain current drops significantly when the temperature rises above room temperature from 300K to 425K. Also the saturation drain current does not vary much with the higher drain voltages. Our results can be compared with those obtained by Gangwani et al. [3]. The striking constant behaviour of drain current suggests the usefulness of these devices for high power applications [9,10]. Drain conductance  $g_d$  is deduced from the current  $I_{ds}$ .

#### IV. CONCLUSION

In this work, we have presented the simulation results obtained by studying the influence of different technological and electrical parameters, thermal and self-heating on the electrical characteristics determining the performance of the HEMT-based heterostructure AlGaIn/GaN as the output conductance with and without the effect of relaxation of the crystal lattice in the HEMT AlGaIn/GaN.

We note that, the increasing of the aluminum mole fraction "m" and concentration " $N_d$ " increase the carrier density " $n_s$ " in the 2DEG. Although, the increase of the doped layer thickness increases the output conductance. The influence of the crystal lattice relaxation on the electrical performance acts directly on the threshold voltage if the value of the mole fraction exceeds 0.38. We noted that when the temperature increases, the electron mobility decreases, this is due to a deterioration of transport properties which is dominated by the scattering with phonons. This decrease in mobility leads to a drop in drain current therefore a degradation of electrical characteristics that determine performance of the transistor.

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