

Theoretical investigation of kink effect with deep defects and temperature in AlGaIn/GaN HEMTs

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A compact and accurate analytical model for the I-V characteristics of kink effect on AlGaIn/GaN high electron mobility transistors is presented. At first, we have developed the conventional charge-control model for the current-voltage characteristics of AlGaIn/GaN HEMTs with considering defect concentration. In a second step, we incorporated the temperature effect with defect concentration. The relation between the kink effect, existing deep centers and temperatures has also been confirmed by using an electrical approach, which allows to adjust some of electron transport parameters in order to optimize the output current. As has been found, to incorporate the kink effect in current-voltage characteristics calculations versus temperatures and to affirm that this anomaly is due to the presence of defects, our results agree well with published experimental data.

(Received September 24, 2012; accepted April 11, 2013)

Keywords: AlGaIn/GaN, GaN, High electron mobility transistor (HEMT), Current-voltage characteristics, Kink effect, Deep defects and temperature

1. Introduction

In recent years, high electron mobility transistors (HEMT's) based on AlGaIn/GaN designed to operate at high temperature [1], high breakdown fields [2], high carrier velocities, high power applications at microwave frequencies [3] and low power consumption [4], have become the basis of an advanced microwave-power-device technology [5]. These features result from superior electronic transport properties of the active channel. Also, the large sheet carrier concentration and the high confinement of 2DEG at the heterointerface make HEMTs suitable for high speed applications [5]. A considerable progress and intense research has been achieved. However, the improvement of these performances is still subject to the influence of defects and traps, which are responsible for anomalies in I_{ds} - V_{ds} output characteristics. Similarly to other III-V transistors, the AlGaIn/GaN HEMT's are limited by some anomalies like kink effect found in I_{ds} - V_{ds} output characteristics [6,7]. Many research experiments are directed towards understanding and eliminating these parasitic effects and minimizing the trapping effects [4, 8]. However, there are only few analytical studies which explained the origin of this effect. The kink effect may occur at different drain voltage values V_{kink} and may have a different bias dependence [9], light sensitivity [10], relationship with impact ionization [9,11], dynamic behavior [11], and dependence of surface treatments [12]. Different explanations for the kink effect have been suggested in the literature, namely, channel impact ionization [10], field-dependent trapping/detrapping in deep defects [13], and combined

impact ionization and field-assisted emission from deep levels [11].

In this paper, we will be interested to develop a compact analytical study using an accurate charge control model to characterize the DC and microwave performance of AlGaIn/GaN HEMT's. The model is extended to evaluate the 2DEG sheet density, based on the electron transport in order to study the DC output current-voltage characteristics. The aim of the present work is also focused to investigate the impact of parasitic effect on transport properties of AlGaIn/GaN HEMT's. The relation between the kink effect, existing deep centers and temperature has also been confirmed by using an electrical approach. The theoretical results carried out on HEMTs AlGaIn/GaN, make it possible to model this anomaly found in the device.

2. Theoretical formulation and results

2.1 Transport characteristics of ideal in AlGaIn/GaN HEMTs

A HEMT is mainly used as a voltage-controlled power source. Indeed, a variable bias- voltage applied to the gate allows to vary the drain-source current. This effect is related to the variation of the 2DEG sheet carrier density under gate-source voltage applied. In fact, any change in the gate bias-voltage V_{gs} induces a modification of the electronic population as well as the conductivity in the channel. Under total depletion approximation, the total charge depleted in the AlGaIn barrier is obtained by solving Poisson's equation [1, 14]:

$$n_s(m) = \frac{\varepsilon(m)}{e(d_d + d_i)} \left(V_{gs} - V_{th} - \frac{E_F}{e} \right) \quad (1)$$

where E_F is the Fermi energy, m is assumed to be the Al mole fraction in AlGaIn, $\varepsilon(m)$ is dielectric constant of $Al_mGa_{1-m}N$, d_d is the doped AlGaIn layer thickness, d_i is the thickness of undoped AlGaIn spacer layers, V_{gs} denotes the applied gate bias, V_{th} is the threshold voltage and e is the electron charge. For strong inversion regime, the relation between the density n_s of 2DEG in the GaN channel versus the gate voltage is of the form:

$$n_s = \beta \left(V_{gs} - V_{th} - V(x) \right)$$

$$\text{With} \quad \beta = \frac{2em_e^* \varepsilon(m)}{2de^2 m_e^* + \varepsilon \pi \hbar^2} \quad (2)$$

where m_e^* is the effective mass of electrons, d represents the channel thickness, and \hbar is the Planck's constant. The heterostructures to be investigated consist of AlGaIn/GaN HEMTs with a 1- μ m thick GaN as a buffer layer, followed by a 30-nm thin AlGaIn barrier. The device gate length and width were 3 and 150 μ m, respectively. Calculation were carried out for $m=0.25$ and $N_D=10^{18} \text{cm}^{-3}$. The local lattice temperature is assumed to be constant, i.e. 300K, and the HEMT structures do not contain any defect. As a main feature, AlGaIn/GaN HEMTs have a high electron mobility and a high saturated velocity. Thus, under a drain-source bias voltage, an enhanced electron transport can occur through the channel. Let J_{ds} be the current density, it is expressed as follow [7,14]:

$$J_{ds} = -Z \mu e n_s \frac{dV(x)}{dx} \quad (3)$$

where Z is the channel width and μ is the carriers mobility. In Eq. (3), we have neglected the diffusion current and the dependence of μ with the built-in electric field. The drain-source current I_{ds} is obtained by integrating J_{ds} along the channel. The boundary conditions are [7]: $V(x=0) = R_s I_{ds}$ and $V(x=L) = V_{ds} - (R_s + R_d) I_{ds}$, where R_s and R_d are the parasitic source and drain contact resistances respectively, and V_{ds} is the drain-source voltage. In the linear regime, since I_{ds} is small, the voltage drops across source and drain resistance accesses can be neglected. Therefore, the drain-source current is expressed according to:

$$I_{ds} = \frac{Z \mu \beta e}{L} \left(V_{gs} - V_{th} - \frac{V_{ds}}{2} \right) V_{ds} \quad (4)$$

In saturation regime, the channel current tends to saturate and ceases to increase with the drain-source voltage. It is straight forward to establish at the drain gate ($x=L$):

$$I_{dsat} = Z \mu \beta e \left(V_{gs} - V_{th} - \frac{V_{ds}}{2} \right) F_s \quad (5)$$

Here, F_s represents the critical electric field for velocity saturation. According to Equation (4) and (5), V_{dsat} as well as I_{dsat} are given by:

$$V_{dsat} = \left(V_{gs} - V_{th} + F_s L \right) - \sqrt{\left(V_{gs} - V_{th} \right)^2 + F_s^2 L^2}$$

and

$$I_{dsat} = \beta e \mu F_s \left(\sqrt{\left(V_{gs} - V_{th} \right)^2 + F_s^2 L^2} - F_s L \right) \quad (6)$$

2.2 Electrical analysis of kink effect in AlGaIn/GaN HEMTs

Applications of AlGaIn/GaN HEMTs are limited by the presence of defects such as the electron trapping states at the active surface zone which can induce a kink effect in the drain-source current. The kink effect has been explained as due mainly to hot-electron impact ionization or/and field-assisted trapping/detrapping [13] of deep lying centers. Indeed, under substantially lower energies, the impact ionization induces detrapping of negatively charged deep levels, which leads to an increase in the electron sheet concentration of 2DEG. For excitation energies higher than the band gap, a band-to-band ionization can also occur and gives rise to the creation of electron-hole pairs. It is worth to mention that the latter mechanism is a very rare event because of the large band gap of GaN channel and the low drain bias voltages. The second detrapping process is associated with electron emissions induced by the built-in electric field. The emitting traps are expected to be located in the active zone, namely in AlGaIn barrier or in GaN channel. In addition, this mechanism is electrically activated at $V_{ds}=V_{kink}$. Beyond the pre-kink bias, the two processes are competitive and both govern the electron transport in an operating HEMT. Assuming that only a single deep trap is present in the host lattice with a concentration N_T and based on the balance equilibrium, the proportion of ionized traps is expressed as:

$$N_T^+ = -\frac{1}{2} \left(N_D + \frac{N_c}{2} e^{\left(\frac{E_T - E_c}{kT} \right)} \right) + \frac{1}{2} \sqrt{\left(\frac{N_c}{2} e^{\left(\frac{E_T - E_c}{kT} \right)} + N_D \right)^2 + 2N_c N_T e^{\left(\frac{E_T - E_c}{kT} \right)}} \quad (7)$$

where N_D represents the density of residual donor impurities, $(E_c - E_T)$ is the binding energy of the trap, N_c is the density of states in the conduction-band and T is the local lattice temperature. By taking into account the ionized electron traps, the electron sheet concentration in the channel will be given by the modified relationship:

$$n_s'(m) = N_T^+ L + \beta \left(V_{gs} - V_{th} - V(x) \right) \quad (8)$$

As a direct consequence, activated electrons from deep traps can participate noticeably to the conductive channel current. For V_{ds} larger than the pre-kink bias, the drain-source voltage and the drain current should have both the following forms:

$$V'_{dsat} = \left(V_{gs} + \frac{N_T^+ L}{\beta} - V_{th} + F_s L \right) - \sqrt{\left(V_{gs} + \frac{N_T^+ L}{\beta} - V_{th} \right)^2 + F_s^2 L^2} \quad (9)$$

And

$$I'_{dsat} = \beta e \mu F_s \left(\sqrt{\left(V_{gs} + \frac{N_T^+ L}{\beta} - V_{th} \right)^2 + F_s^2 L^2} - F_s L \right) \quad (10)$$

Using the above modified model (Eqs. 7, 9 and 10), we obtain the new characteristics I_{ds} - V_{ds} which reveals the kink effect for various values of the gate voltage and for the same transistor. The results as depicted in Fig.1. Compared to the inset characteristics, we notice an increase in the drain current in stationary regime of the kink effect. It consists of a sharp increase in the drain-source current at a certain drain-to-source voltage ($V_{ds}=V_{kink}$). This effect is related to a sudden liberation of electrons, and it appears for high drain-to-source voltage V_{ds} increasingly in order to pinch off the channel. This variation of the drain current induces an increase of the drain/source output conductance (g_{ds}), a low voltage gain and a decrease of the amplification factor, resulting in a degradation of the field effect transistors performance.

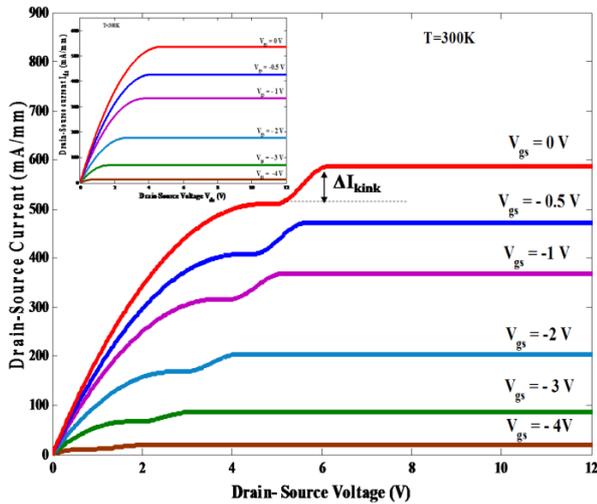


Fig.1. Theoretical spectra I_{ds} - V_{ds} at $T=300K$ showing the kink effect. In the inset, calculated I_{ds} - V_{ds} ideal characteristics for an AlGaIn/GaN HEMTs at different gate voltage.

From the difference between the ideal characteristics and those taking into account the kink effect (Fig. 1 and in the inset), we can determine the evolution of the kink current intensity (ΔI_{Kink}) for several values of gate voltage (Fig.2).

The evolution of the kink current calculated theoretically by using our electric model are compared with the existing experimental data from the literature [15] and curves present the same allure. From Fig.2, we show that (i): The variation of the kink current decreases when the gate voltage decreases. (ii): ΔI_{kink} is more important for the gate voltage (V_{gs}) from 0 to -3V and tends to disappear when V_{gs} approaches the channel pinch-off. The difference between the experimental and theoretical plots can be attributed to the measure condition and Schottky contact optimization [16].

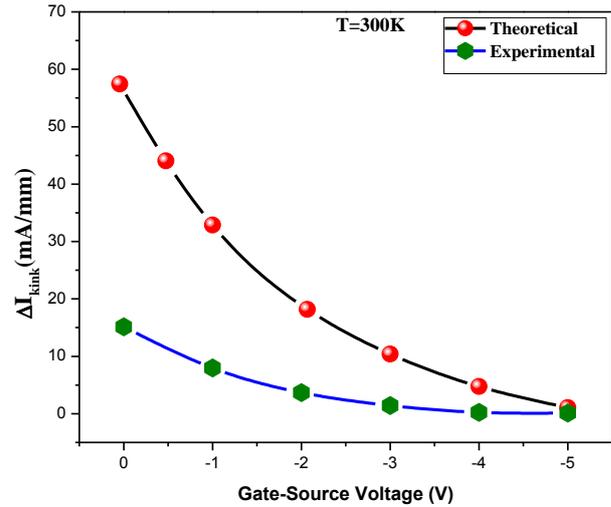


Fig. 2. Evolution of the kink current ΔI_{kink} at $T=300K$ as a function of gate-source voltage. Theoretical and experimental results are compared.

When V_{ds} increases further to reach V_{dsat} , the electrons presents in two dimensional electron-gas (2DEG) have at this moment a sufficient kinetic energy to overcome the energy of AlGaIn barrier in the channel and can be capture by deep traps density N_T . Many studies have correlated kink effect with defects on AlGaIn/GaN transistors, but due to its complex behavior the origin of this effect is still a subject of controversy. For this reason, we developed an analytical current-voltage model for AlGaIn/GaN power HEMT that incorporates the expression of defect concentration N_T^+ . In order to understand the origin of the non-ideal current-voltage characteristics, we may assure that kink effect is related to the presence of deep level traps in the structure and prove the assumption that this kink effect is due to the major defects in the component. The results are shown in Fig.3. We can clearly notice the presence of defects. As can be seen from the characteristics, the kink current intensity (ΔI_{Kink}) increases with increases defects concentration.

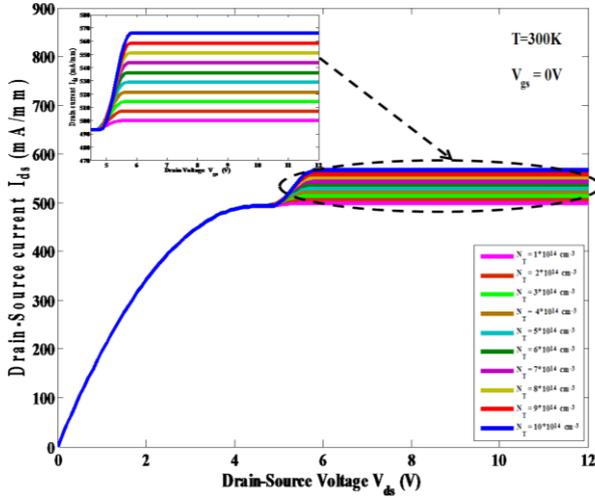


Fig. 3. Theoretical spectra I_{ds} - V_{ds} at $T=300K$. Defects are clearly shown for several values of N_T .

In order to illustrate the temperature effect on the kink effect, we have taken into account the temperature variation in Eq. (7) according to [17]:

$$\mu_T = \mu_{300} \left(\frac{T}{300} \right)^{-1.6}$$

with

$$\mu_{300} = \frac{P_1}{P_2 + (P_3 + V_{gs})^2} \quad (11)$$

Where P_1 , P_2 , P_3 are extracted parameters.

The results reveal a good agreement with this approach, which confirms the influence of temperatures in the I_{ds} - V_{ds} kink effect characteristics. This is expected since the increase of temperatures leads to decrease in kink current ΔI_{kink} . Fig.4 shows the drain-source current voltage (I_{ds} - V_{ds} - T) characteristics versus temperature and gate voltage V_{gs} have been performed. We observe a sudden rise in the drain current at a certain drain-to-source voltage at 150 K and 350 K especially for the high value of V_{gs} ($V_{gs}=0$ V), whereas it seems to be ideal at 450 K. As can be seen, higher kink current intensity (ΔI_{kink}) result when decrease temperature towards 150K. It has to be noticed that maximum values of ΔI_{kink} are expected to be attained for a lower temperatures.

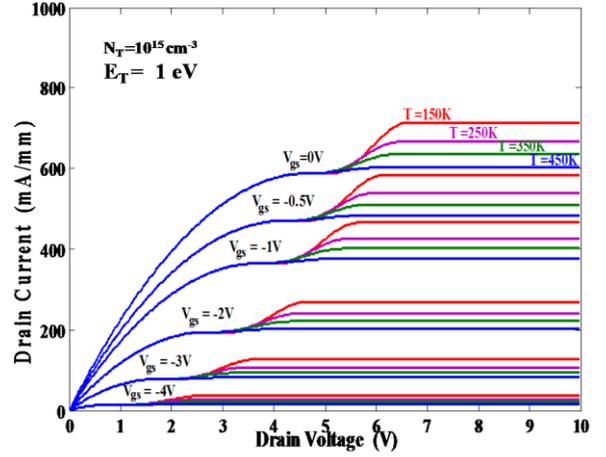


Fig.4. I_{ds} - V_{ds} characteristics as a function of temperature and at different gate voltage.

To verify the validity of this model, we have taken as experimental support characteristics of a AlGaIn/GaN HEMT on sapphire substrate. Fig.5 shows a comparison of theoretically calculated characteristics with experimental results already published [15]. As clearly seen, the plots reveal a good agreement between the experimental data compared with the theoretical results. As evidenced from the latter study, the both results are in the same order of magnitude and evolution of kink current intensity.

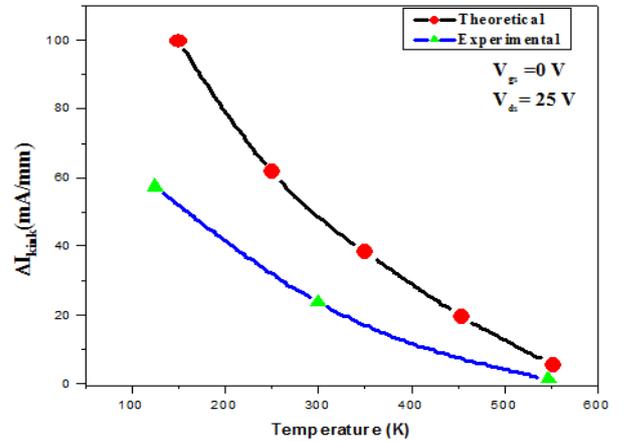


Fig. 5. Evolution of the kink current (ΔI_{kink}) as a function of temperature. Theoretical and experimental results are compared.

The threshold voltage shift (V_T) with temperature reveals the simulated characteristics I_{ds} - V_{gs} - T . As displayed in Fig.6, the threshold voltage is -4.25 V at 150 K, -3.75 V at 350 K and -3.5 V at 450 K. This shift $\Delta V = 0.25$ V is thought to be caused by deep levels associated with electrically active defects in the heterostructures [18]. Thus, the change in the carrier trap density is responsible for the increase of V_T with the increase of temperature.

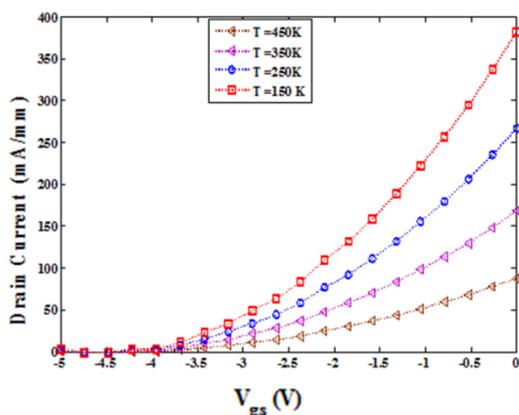


Fig.6. I_{ds} - V_{gs} characteristics at different temperature.

Several research teams have analyzed this effect in these kinds of transistors, but the origin of this last remainder still dubious and its explanation remains also classified like assumptions. Some studies have established a link between the kink effect and the impact ionization phenomena [19]. Typical of impact-ionization effects [20] is confirmed which supposes that the appearance of this effect coincides with the beginning of the impact ionization phenomenon due to a strong field on the side of the drain [21,22]. While other studies, have correlated this effect with the presence of traps in the structure [23]. Kruppa and Georgescu [23, 21] supposed that the possible origin of this effect is the presence of the major centers, related to the fact that the capture and the emission of the carriers are influenced by the electric field in the zone drain/grille. As Meneghesso et al [24], the kink effect is correlated to the evolution of the pinch-off voltage shifts, and suggested that the traps responsible for the appearance of this effect should be located under the gate, either in the AlGaIn barrier or in the GaN buffer. The present study proves that kink effect is intimately related to defects concentration and temperature has an influence on this parasitic effect.

3. Conclusion

In summary, the I_{ds} - V_{ds} drain source current-voltage characteristics of AlGaIn/GaN HEMTs have been developed based on the conventional charge-control model. The numerical simulation allowed the identification of an anomaly namely kink effect in AlGaIn/GaN HEMT's. The effect of defects concentration and temperatures has been taken into account in the model and was also performed on the HEMT transistors. As has been found, the kink effect depends on defects. For this purpose, we developed an electrical approach to evaluate the relation between the kink effect, deep level traps and temperature.

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