Carrier's transport mechanisms investigations in AlGaN/GaN HEMT thanks to physical modelling and low frequency noise measurements

G. Soubercaze-Pun [1], J.G. Tartarin [1], L. Bary [1], S. Delage [2], R. Plana [1] , and J. Graffeuil[1]

[1]LAAS-CNRS and Paul Sabatier University, 7 av. du Colonel Roche, 31077 Toulouse cedex 4, France
Email: gsouberc@laas.fr ; Phone: 00-33-(0)5-61-33-69-09
[2] THALES TIGER, Orsay, domaine de Corbeville, France

Abstract — **This paper deals with the carrier's transport mode involved in AlGaN/GaN HEMT grown on sapphire substrate according to biasing conditions. Low frequency noise measurements on the drain current source are found to be closely related to the path of the carriers occurring in the two dimensions electron gas (2DEG) and in the AlGaN layer: thus a correlation is found between the $1/f^{\gamma}$ frequency index γ and the biasing condition of the device. Physical modelling is used in order to corroborate the γ dependence with the transport mechanism of the carriers, thanks to DC simulations and energetic band diagrams analysis**.

I. Introduction

AlGaN/GaN high electron mobility transistor offers excellent potential for microwave power applications due to its material properties featuring high thermal conductivity, high breakdown critical field, high electron mobility, high saturation velocity.

Thus, these characteristics of this wide bandgap material perfectly match the requirements for commercial and military systems, particularly in the X and Ku band. For instance, CW output power of 6.6W/mm at 10GHz has already been published [1]. Performances of HEMT devices such as a transconductance close to 215mS/mm [1], transition frequency F_t and maximum oscillation frequency F_{max} of respectively 46GHz and 92GHz [1], sheet carrier density about 10^{13} cm^{-2}[2] [3] illustrate the advantages of such a technology versus the GaAs or Si based technologies. GaN wide band gap technology can make use of three different substrates for GaN epitaxy (sapphire, silicon and silicon carbide). Sapphire and silicon carbide substrates are widely used, but their relatively large lattice mismatches with the GaN require an AlN nucleation buffer growing layer.

We have already investigated on HEMT grown on silicon and sapphire substrates [4] [5] thanks to low-frequency noise (LFN) measurements in order to locate and model the LFN sources, and improve the process definition. The purpose of this paper is to give an insight of the γ noise slope from $1/f^{\gamma}$ LFN measurements for transistors grown on sapphire. We have noticed γ fluctuations ranging from 0.7 to 1.25 on tested devices, depending on the biasing conditions [4]. We firstly present DC and low frequency noise characterisations. Physical simulation software is used as a tool to correlate the low frequency noise spectra with the static output characteristics. Once the physical simulator is calibrated, it is supposed to traduce faithfully the operating mode of the device. Simulations of energetic band diagrams are used in the second part to assess the γ dependence on carriers transport mechanisms in the device. Afterwards we show the impact of carriers tunnelling from the two dimensions electron gas through the AlGaN spike layer, on the relative density noise measurements.

II. Device technology and static simulations

A. Physical DC simulations

HEMT devices used for this study are developed at IEMN institute with a MOCVD technique grown on a sapphire substrate.

Their features are:

F_t=50Ghz; F_{max}=75Ghz; g_m=160ms/mm.

The physical simulation is performed with Atlas software from Silvaco. This software is not dedicated to wide band gap material simulation, but some adjustments on the parametric equations enabled us to make it run for the HEMT structures under study. However, some effects such as piezo-electric field simulation cannot be taken into account with that software. This point will be discussed later on, but seems not to affect the frequency index γ of the LFN of the devices.

The HEMT modelled transistor has a 300Å AlGaN thickness with Al rate close to 30%, and an AlGaN N type doping of $5*10^{18}cm^{-3}$. The gate length is 0.5µm, and source-drain spacing is 2µm.

During the Atlas material calibration, we have used the following relations for AlGaN:

-band gap equation is given with 3.52+2.32x+0.0796(1-x) where x is the Al rate [6] [7]

-Shottky barrier equation is 0.91+ 2.44x [8]

-static dielectric constant is defined as 9.7-1.2x [9]

-the mobility in GaN has been introduced according to the expression from [9] and the saturation velocity given by $Vsat = \frac{Vsat_{300}}{(1+An)+An(T/300)}$ has been coded with the C-interpreter into Atlas simulator. For the temperature dependence of the mobility, we used the equation given by [10] for the thermo-chemical properties of GaN material.

B. DC Measurements

DC measurements have been carried out with the D225 dynamic I(V) analyser from Accent. Pulsed measurements have already been performed to appreciate the thermal evaluation of the device. We can notice from DC measurements on *figure 1* the presence of a bend at low drain voltage. At high drain-source voltage, we can observe a decrease of the DC characteristics induced by the component self heating which affects the saturation velocity.

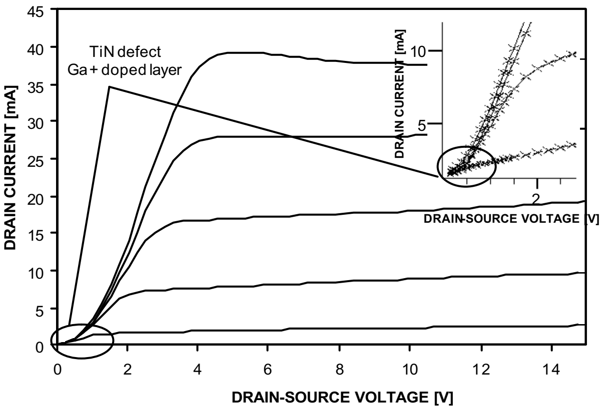

Fig. 1. DC output characteristics of HEMT device $0.5*2*50\ \mu m^2$ on sapphire substrate: measurements with Accent D225 and physical simulation with Atlas from Silvaco International (insert)

III. LOW FREQUENCY NOISE MEASUREMENTS

A. γ frequency index variations within HEMT grown on Sapphire substrate

The LFN $1/f^{\gamma}$ noise measurement is the most sensitive method to evaluate the ideal ohmic contact and device quality [11]. We investigate *(figure 2)* on the dependence of the relative low frequency noise density S_{ID}/I_D^2 versus the dynamic drain source resistance in the ohmic and saturated region. For a same resistance value, the carrier noise contribution on the drain access is more important at low V_{DS} voltage: this is due to the presence of a non-linear resistor behavior at low V_{DS} voltage *(figure 1)* responsible of the bend on the output characteristics. This DC defect is simulated as a thin insulated interfacial layer between the drain (and source) metal and the 2DEG layer. This thin layer can be attributed to the diffusion of Ti from drain (source) contact near the GaN layer : Ti substitutes to Ga forming thin layer TiN defect and Ga^+ doping. This highly resistive layer prevent the carriers to reach from the drain or source contact to the 2DEG. However, the device still runs as a HEMT structure due to an atypical behaviour of the transport mechanism of carriers: the electrons flow from AlGaN to the 2DEG near the source contact thanks to the presence of a piezoelectric field at the AlGaN/GaN vicinity. But these electrons have to overcome the opposite piezoelectric field near the drain access to be collected. When the drain voltage increases at low V_{DS}, the spike action near the AlGaN/GaN interface is less important because the Fermi level between gate and drain is higher in GaN than in AlGaN. So the carriers crossing becomes easier and therefore the relative low frequency noise density decreases. The knee in relative density low noise at lowest resistor values underlines the beginning of the saturated operating mode of the device but however the relative low frequency noise density remains well below the level obtained when the defect acts.

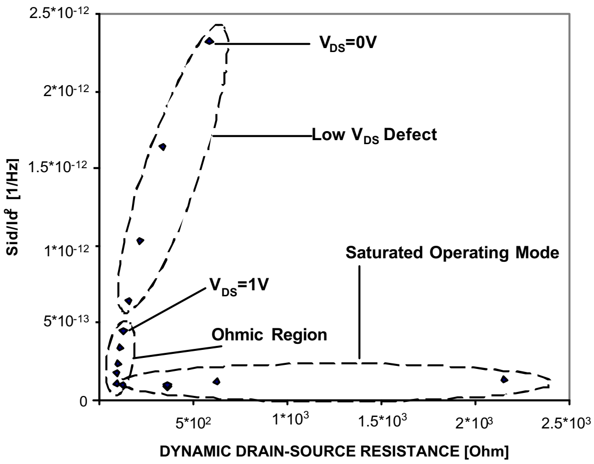

Fig. 2. Relative low noise density S_{ID}/I_D^2 versus the dynamic drain source resistance in the ohmic and saturated region, for a HEMT featuring $0.5*2*50\mu m$ on sapphire wafer

Then we plot $1/f^{\gamma}$ LFN slope variation from the drain spectral density with the drain bias voltage in *figure 3*. At low drain bias, we can notice a decrease of the slope. This decrease stops when the drain bias voltage is high enough to make the device run in its ohmic operating mode. Then the slope remains constant at γ=0.72 till the electric field in the 2DEG between gate and drain reaches a critical value corresponding to V_{DG}=2.5V. This change in γ is attributed to a modification of the carrier's conduction mode: the electrons migrating from the two dimensional electron gas to the AlGaN parasitic channel is performed along the total gate-drain length at V_{DG} of 2.5V and gradually occurs only in the 2DEG with a collection in the AlGaN near the drain contact. The transport at higher V_{DS} values is thus attributed to a transport mainly in the two dimensional electron gas and is associated to a nearly γ=1 value. This interpretation is consistent with the physical simulations of the device, thanks to the simulation of energetic band diagrams of *figure 4*. The decrease of the slope at low V_{DS} values is due to the weak impact of the spike when the drain bias voltage increases. So there is a conduction path through AlGaN layer, GaN layer and ohmic contacts. This curious operating mode exists because the ohmic contact process introduces resistive inclusions in the GaN layer near the source and drain side (defect at low V_{DS} in *figure 1*). This transport mechanism is illustrated on *figure 4b* when the drain voltage V_{DG} increases. The conduction becomes dominant in the 2DEG. Nevertheless this conduction occurs only because a low resistive path does exit very close to the drain contact. This one is involved by a Fermi level located over the conduction level.

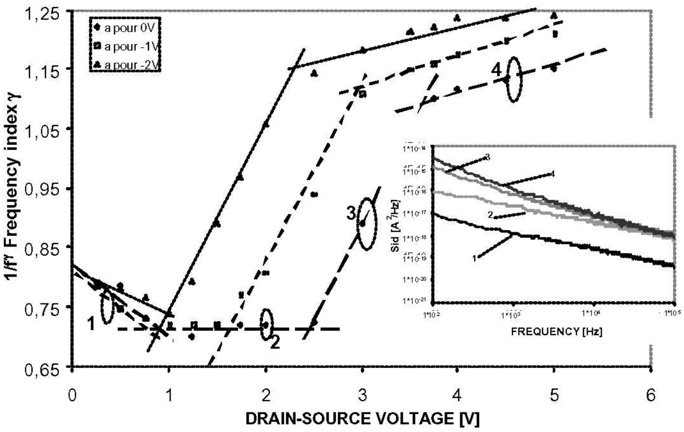

Fig. 3. Variation of $1/f^{\gamma}$ slope (from S_{ID}) versus the drain voltage for HEMT on sapphire.

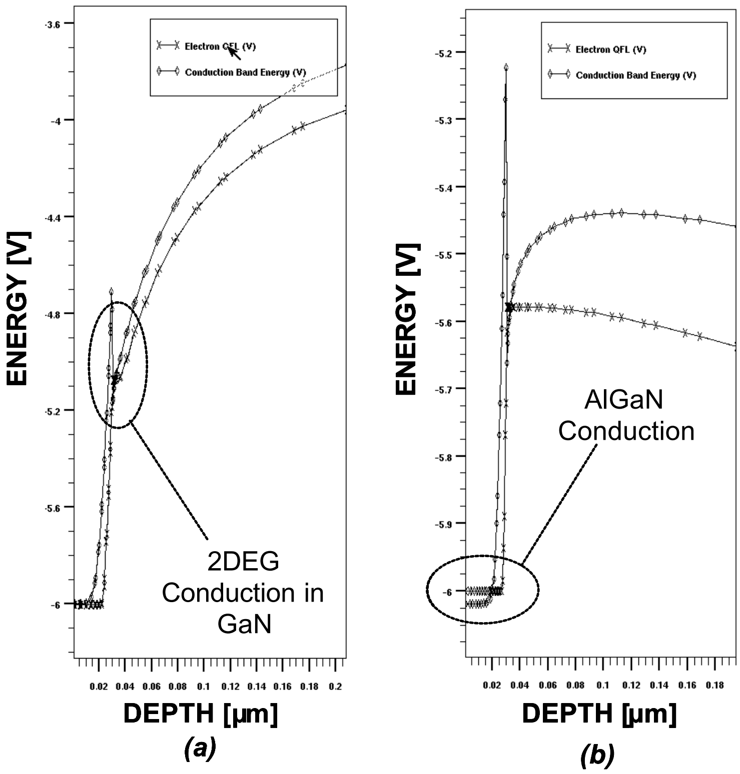

Fig. 4. Band diagrams for VDG in saturated regime
(a) Saturated regime close to the gate contact (see fig 5)
(b) Saturated regime close to the drain contact (see fig 5)

For an easier understanding, the *figure 5* represents the carrier's transport path within the device.

When the device does not run in its HEMT mode (at low drain bias), carriers cannot cross the spike between AlGaN/GaN near the drain because they do not have enough kinetic energy for tunnelling, so the only way for the electron to reach the drain access is to cross the TiN layer. Then the resistance on the carrier's path is very important and a knee appears on DC characteristics at low drain bias (and a high normalized drain spectral density is measured). Between source and gate the piezo-electric field ensure the carriers drifting from AlGaN to GaN. In ohmic regime for V_{DG}>2.5V the carriers have enough kinetic energy to jump the spike and the opposite piezo-electric field. The conduction takes place in AlGaN as well as in the 2DEG, and their collection is performed from the AlGaN to the drain contact (TiN layer impeding the collection from 2DEG). Then, in saturated regime according to the physical simulation, the conduction mainly occurs in the GaN layer because it offers a weak resistance *(figure 4 (a))*. Close to the drain, contact carriers pass into AlGaN to avoid the high resistive TiN layer. The physical simulation on *figure 4 (b)* shows an AlGaN conduction due to the Fermi level upper than the conduction band. So carriers can be collected by the drain contact. Finally, we have noticed with the physical simulation that for different operating modes of the device, no drift is possible in the AlGaN space charge region under the gate as expected.

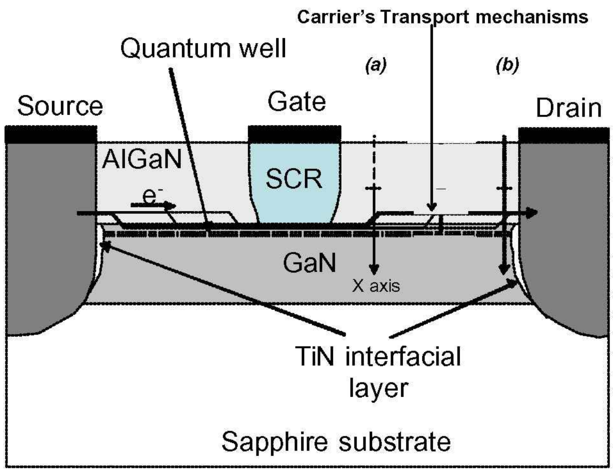

Fig. 5. AlGaN/GaN simplified HEMT structure, with TiN interfacial thin layer defects and different carrier's transport mechanisms according to the device biasing
(a) Cross section near the gate to be correlated with figure 4 (a)
(b) Cross section near the drain to be correlated with figure 4 (b)

B. γ frequency index variations within HEMT grown on Silicium substrate

AlGaN/GaN HEMT grown on silicon substrate have already been investigated. The devices do not feature any knee on the low drain bias DC characteristics. We can assess that the process of the ohmics contacts does not create any TiN thin resistive layer. The conduction path of the carriers is then located in the GaN layer thanks to its weak resistivity compared to AlGaN layer. Then the device does not have any parasitic conduction mode.
The γ frequency index behaviour in *figure 6* for many biasing conditions (V_{GS}, V_{DS}) exhibit a γ=1 constant value consistent with a single conduction path in the 2DEG whatever the operating mode of the device. This result corroborates the previous interpretations on the device grown on sapphire substrate.

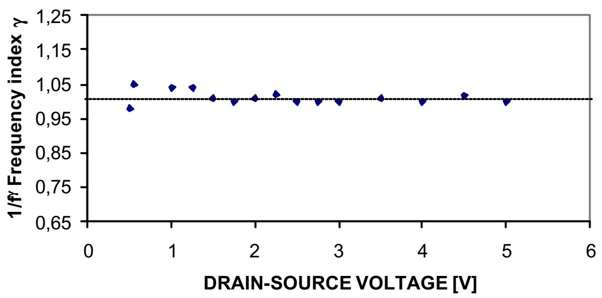

Fig. 6. γ frequency index ($1/f^{\gamma}$ from S_D) versus V_{DS} in ohmic and saturated regime for AlGaN/GaN HEMT grown on silicon substrate 0.5*2*50 μm^2

IV. CONCLUSION

In this paper, a physical modeling of HEMT devices grown on sapphire and silicon substrates has been realized. In the first part we have analyzed the DC characteristics using a physical simulator. Then a correlation between band diagrams and low frequency noise measurements has shown that the carriers conduction mode has got an impact on the variation of the low frequency noise frequency index γ according to biasing conditions.
We have linked the conduction path of the carriers with the frequency index. Then we have noticed that γ is varying from 0.7 to 1.25 for HEMTs grown on sapphire, and that γ is getting constant (γ=1) for HEMTs grown on silicon substrate. The variation of $1/f^{\gamma}$ noise slope is assumed to be related with different conduction modes associated to various device's layers.
The ohmics contacts in AlGaN/GaN field effect transistors constitute a strategic challenge to get good quality materials, possessing low $1/f^{\gamma}$ noise levels and 'conventional' DC characteristics.

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