AlGaN/GaN High Electron Mobility Transistor (HEMT) Reliability

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Abstract — **The reliability characteristics of AlGaN/GaN HEMTs are reviewed. Basic effects such as the discrepancy between DC predicted and RF measured power are addressed together with effects such as drain current and power degradation observed following RF stress. Technologies based on sapphire, SiC and Si substrates are considered. The impact of process such as passivation, as well as design i.e. barrier layer are considered. DC and microwave properties are considered in the study. Low frequency noise is also discussed in conjunction with degradation following stress.**

I. INTRODUCTION

AlGaN/GaN High Electron Mobility Transistors (HEMTs) utilize wide bandgap semiconductors and thus offer the possibility of operation with higher output power than other III-V semiconductor devices. Recent advances in GaN technology open also the possibility for microwave but also mm-wave operation. The use of widebandgap semiconductors extends the temperature tolerance and the radiation hardness of the devices and circuits. Different substrates have been used for growth of III-V Nitrides and include sapphire, SiC and Si. As III-Nitride technology progresses from research to development and production, reliability becomes an important aspect to address in order to understand the limitations imposed by fundamental material, design and processing and find solutions to overcome them.

Although little has been reported on the reliability of AlGaN/GaN HEMTs, various related concerns such as the discrepancy between DC predicted and RF measured power have been discussed. Current and power degradation have also been observed following RF stress [1]-[2]. Various solutions to suppress these problems have been proposed and include passivation, device design i.e. barrier thickness control, as well as field plate technology. In addition to the traditionally employed techniques such as DC and microwave characterization, a very promising technique for monitoring the reliability characteristics is the evaluation of device low frequency noise (LFN). This paper reviews various reliability issues of GaN-based HEMTs and discusses recent achievements in this area together with possible mechanisms responsible for device degradation.

II. PERFORMANCE LIMITATIONS IN GAN-BASED HEMTS

GaN-based HEMTs manifest a number of deficiencies in their operation. A major problem that was noticed at the early development stage of GaN technology was the difference in DC and RF characteristics. This led in discrepancy between the DC predicted and RF measured performance and is schematically represented in Fig. 1. Current slump or current dispersion lead in changes of the maximum drain current and knee voltage. These result in a change of load line and reduced power and gain.

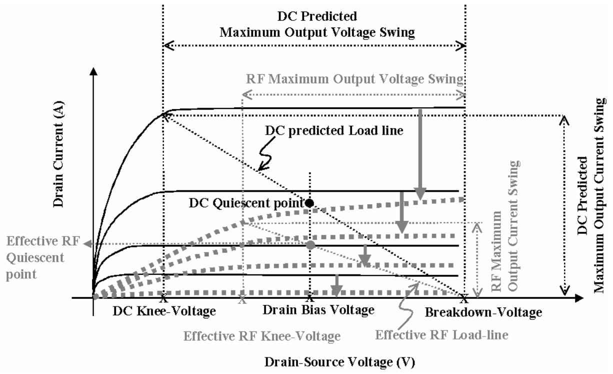

Fig. 1. Schematic representation of current slump in AlGaN/GaN HFETs (solid line I-V: DC characteristics; dotted/grey line: I-V following current slump)

Surface trapping-detrapping of electrons at surface states has been suggested as a possible mechanism responsible for the above effects. Trapping can compensate part of the surface component of spontaneous polarization and reduce the 2DEG electron concentration. The effects taking place resemble those produced by a “virtual gate” [3] between the actual gate and the drain. Another explanation of RF current slump [4] is the reduction of compressive strain of GaN under the gate and tensile strain of ungated AlGaN upon negative bias application. The nonumiformity of strain may lead in a 2DEG concentration decrease and thus resistance increase of the access (ungated) region. The time constants involved in the above effects appear at first to be compatible with the “virtual gate” mechanism but further work is necessary to confirm the origin of the trapped electrons, which may come not only from gate but also from the channel.

Transconductance g_m and output resistance R_{ds} dispersion are also providing means of evaluating the performance limitations of devices. AlGaN/GaN HFETs were evaluated for this purpose and the observed small transconductance dispersion characteristics suggest that the source resistance dispersion is small [1]. On the other hand, R_{ds} presents in general more obvious dispersive characteristics, which become more pronounced when the gate voltage becomes more negative.

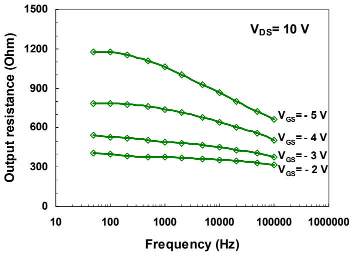

Fig. 2. Measured output resistance as a function of frequency and bias conditions for a 0.25×200 μm^2 AlGaN/GaN HEMT

The strong dependence of the output resistance dispersion on the bias conditions suggests that when the gate bias changes toward the pinch-off condition, the channel is beyond thermal equilibrium and free carrier injection into trapping states is enhanced. The injected charge results in an electric field, which modulates the shape of the channel leading to a more pronounced frequency dependence.

Low-frequency noise can finally be used to evaluate and optimize the characteristics of HFETs. Small gate noise levels were observed in submicrometer GaN HEMTs even under high gate-drain reverse bias conditions [5]. A Hooge parameter as low as ~ 2.7×10^{-5} was extracted, and was found to be comparable to traditional III-V FETs. The results suggest that the dominant noise sources may stem from the gated channel area and screening effects may impact the observed 1/f noise characteristics. Lorentz components were observed under high drain voltages. Low-frequency noise may be used to study material quality and was shown to be correlated to device reliability. Presence of bulges revealing the existence of generation-recombination (G-R) mechanisms could for example, be indicative of unreliable device features. These will be discussed further in the paper.

III. Reliability in AlGaN/GaN HFETs

A. DC and RF Stress and Reliability Related Effects

Unpassivated and passivated devices were subjected to DC and RF stress and their DC, microwave characteristics, as well as, their low-frequency noise were measured before and after stress [6], [7], [8]. Emphasis was placed on analyzing the effects taking place upon stress rather than obtaining a measure of lifetime characteristics of the devices. The DC stress consisted of applying bias (V_{GS}=-2 V, V_{DS}=10 V) for 22 hours, while RF-stressed devices were biased with the same DC bias condition and briefly exposed to RF power at 5 GHz for one hour. The RF tests were conducted under maximum gain conditions with the help of a FOCUS electromechanical tuner. The "DC-stressed" devices showed no current reduction at the set bias point after an initial stress test of a couple of hours. On the other hand, RF-stressed devices showed significant drain current reduction after exposure for an hour to a low input power level of 3 dBm. Additional DC and RF stress by a couple of hours did not lead to any further degradation. This observation may suggest that deep traps responsible for such effects are fully occupied leaving no room for further carrier trapping. Deep traps due to shallow impurities within GaN and AlGaN have in fact been reported in this material system. In addition, O or Si has been accounted in different reports to be responsible for DX transitions within the III-V nitrides.

Fig. 3 shows typical DC characteristics of unpassivated devices before and after DC stress. Unstressed unpassivated devices demonstrate very flat saturation characteristics and good quality of ohmic and Schottky contacts. The DC I-V characteristics before and after DC stress are also shown in the forward and reverse biasing configurations, respectively. Source and drain terminals were interchanged in the reverse configuration compared with the "stress bias configuration". Similar measurements were conducted after RF stress.

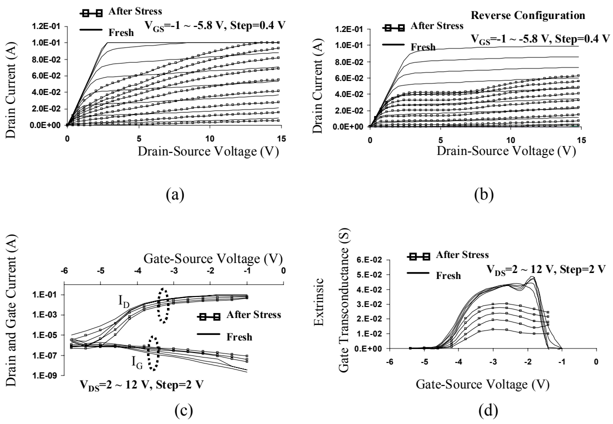

Fig. 3. (a) Drain I-Vs (forward); (b) Drain I-Vs (reverse); (c) Transfer Curves and $I_{g, leak}$; (d) Transconductance (V_{gs}, V_{ds})

The difference in the time within which degradation was observed following the two stressing procedures (several hours for DC stressing vs. <1 hour for RF stressing), suggests that the effects observed are activated easier by RF excitation. For both types of stresses, the drain current recovered by no more than 3% with a very long time constant in the order of 10 hours.

The I-V characteristics of both DC- and "RF-stressed" devices showed better saturation characteristics in the "reverse" testing configuration suggesting that only the drain (and not source) access region and its associated resistance were impacted. This could be associated with electron trapping within the barrier or surface leading in depletion of the 2DEG and increase of channel resistance between gate and drain. Under linear operation conditions, this would lead in current level reduction and knee voltage increase, followed by an effective output power reduction. Under "reverse" testing, the region previously acting as drain-gate channel becomes now the source-drain region leading therefore to a g_m decrease. As a result, the device current is reduced below the values used before stress. A positive shift in the pinch-off voltage was observed only after RF stress and was found to take place both for passivated and unpassivated devices.

It is commonly accepted that the discrepancy between DC and RF characteristics is due to the frequency dependent trapping/de-trapping processes. However, the similarity of the degradations in DC characteristics of the devices exposed to RF and DC stress, suggests that the DC-RF power discrepancy could also be partly due to frequency independent degrading mechanisms, the presence of which degrade the devices permanently.

B. Device Design and Reliability

AlGaN/GaN HEMTs with different Al mole-fractions and geometries can be investigated to understand the impact of the 2DEG polarization dependence. DC, RF and LFN measurements were performed for this purpose. The Al mole fraction was varied from 0.2 to 0.3 and 0.4 and the gate length as well as the gate-drain spacing were varied. The observations made in this study reconfirm the role of hot carriers in the shift in the pinch-off voltage of AlGaN/GaN MODFETs, and suggest that keeping the Al mole-fraction to lower values or using a thicker barrier layer in exchange for the loss in drain current density and gate transconductance might be the remedy for this degradation [7]-[8].

C. Low-Frequency Noise-based Reliability

LFN measurements were used to identify whether RF degradation stems from the same physical mechanisms as DC degradation (i.e., hot carriers being trapped in the surface). Despite the similarity of the impact of RF and DC stress on DC characteristics, LFN being a more sensitive material and device qualification tool allows one to see better the differences resulting from the two types of stresses. Through the LFN measurement of drain noise current of passivated and unpassivated devices, before and after DC and RF stress, it is revealed that a change in the characteristics of drain noise current is only observable whenever there is a change in the saturation characteristics (output resistance). Such a change is related to a modification of the drain access resistance. Although the positive shift in the pinch-off voltage takes place both for passivated and unpassivated devices, the variation of gate and drain noise current characteristics of these two device families upon RF stress do not resemble indicating that the noise and pinch-off variations are not correlated.

While with surface passivation, the variation in LFN and output resistance upon stresses are suppressed, the positive shift observed in the pinch-off voltage taking place upon RF stress, is endured. This could originate from the trapping of hot electrons in the surface states located under the gate electrode or at the states on the gate electrode/semiconductor interface, under the gate electrode.

Although this region is far from the velocity saturation region (VSR), the same randomizing effect of high frequency signal facilitates the hot electrons of VSR region to end up within the gated surface. Fig. 4 shows schematically possible surface trapping mechanisms.

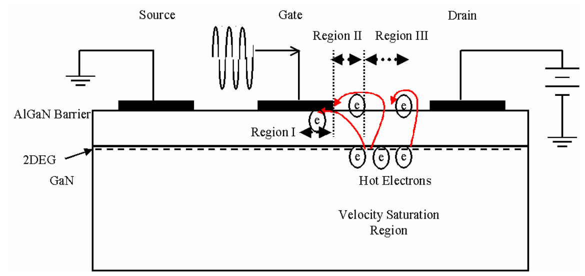

Fig. 4. Hot electron trapping effects at the AlGaN/GaN HEMT surface

Under DC stress it is only trapping of hot electrons at states in Region III which impact the device characteristics, while upon RF stress in addition to this, a randomizing effect of the high frequency variable electric field will make trapping of electron in surface states in Region I and II more likely to be present. These two regions are accountable for the changes observed in gate noise current and pinch-off voltage upon RF stress. The same randomizing effect of high frequency signal, may also explain the smaller time constant of the device degradation upon RF stress.

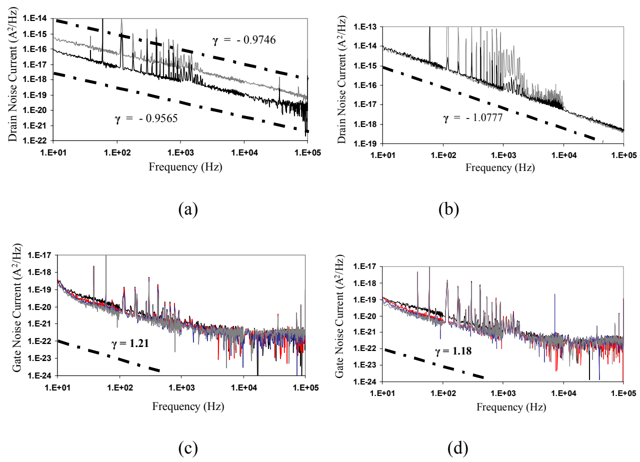

Fig. 5. Low frequency Noise of GaN-based HEMTs. (a) S_{ID}: passivated typical (black) and unreliable (grey)-V_{ds}=0.25V, V_{gs}=0V; (b) same as for (a) but for V_{ds}=3V, V_{gs}=-1V; (c) S_{IG} of typical HEMT at V_{gs}=-3V, V_{ds}=0.25-3V; (c) S_{IG} of unreliable HEMT at same bias as (c).

Fig. 5 shows the drain and gate noise spectral density of typical and unreliable devices under various bias conditions. Devices referred to as unreliable show excessive gate leakage. The γ factor represents the frequency exponent of the spectral density and is close to one. No bulge signatures were observed in any of the biasing regimes. While highly sensitive gate noise current is incapable to predict the gate failure under RF stress, drain noise current values of the fresh devices in the linear operation regime for both passivated and unpassivated device categories demonstrate signatures for degradation prediction. These valuable signatures make the degradation prediction of these devices possible without the requirement for exploiting expensive, destructive, and time consuming life-time tests, which are most of the time exposing the devices to unreasonably extreme stress conditions.

IV. Review of Reliability Observations

Gate and drain lag of GaN HEMTs were found to have time constants of 10^{-5} to 10^{-4} s and are responsible for dispersion between DC and pulsed I_{ds}-V_{ds} characteristics [9]. Surface related donor-like traps (E_v + 0.3 eV) are related to these effects and interact with holes attracted to the surface by negative polarization charges and the associated upward band bending. Undoped GaN HEMTs on SiC with thinner AlGaN barrier (138 Å vs. higher values up to 260 Å) appeared in one study to be more reliable and showed a change of only 0.5 dB in their initial power of 8.8 W/mm at 40 V after a 180 hr RF stress at this bias [10]. The availability of low dislocation free standing GaN substrates could reduce the reliability problems arising by the use of GaN-based layers grown on SiC or sapphire, which have threading dislocation densities of 10^{-9} cm^{-2} and therefore considerable leakage. 9.4 W/mm devices made on such substrates driven at 25 V and 3dB gain compression support this expectation by showing stable properties over 200 hrs with only 0.18 dB power degradation [11].

RF technology for base transceiver stations has been evaluated using 0.6 µm × 800 µm AlGaN/GaN HEMTs on SiC. The devices were tested at a baseplate temperature of 25 °C under class AB (-3 dB) and showed 22 % RF power degradation after the first 10 hrs and 24% after 24 hrs, indicating the major challenges faced for insertion of this technology in wireless infrastructures [12]. Power amplifiers with more than 100 W CW output power at 2.1 GHz were realized on SiC substrates using 36 mm gate width. Their devices were tested under P_{-3dB} conditions at a V_{ds} of 60 V and showed no degradation of power and gain over 1000 hrs [13]. Eudyna has also presented a 10W GaN HEMT module with 10W saturation power and 30 dB gain that showed no degradation in RF power under RF overdrive at -3dB over 1000 hrs [14].

Very promising characteristics were finally demonstrated by GaN on Si technology. Fig. 6 shows the reliability results of devices of this type developed at Nitronex and presents 20 year lifetime characteristics [private communication].

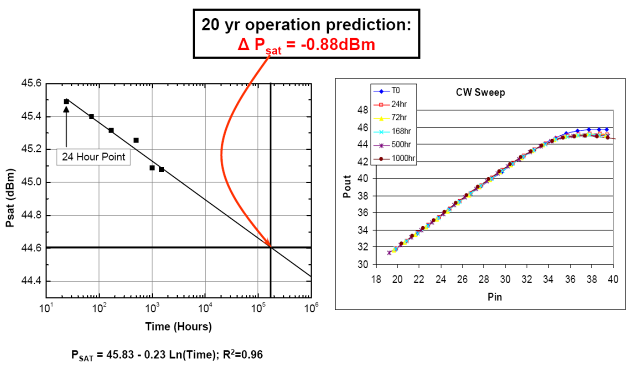

Fig. 6. GaN HEMTs on Si: output power evolution with time (left) and P_{out} vs. P_{in} characteristics over time (right).

V. Conclusion

The reliability characteristics of AlGaN/GaN HEMTs have been reviewed. DC and RF stress were considered and the basic limitations of the devices were addressed. These include among other DC predicted and RF measured power differences, dispersion in g_m and R_{ds} and gate lag. The mechanisms underlying such effects have been discussed. Low frequency noise has finally been investigated in conjunction with RF stress and reliability diagnosis. Reliability results obtained by various groups are also reported for GaN-based devices of various designs manufactured on different types of substrates.

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