Device reliability study of GaN HEMTs using both low frequency noise and microwave noise temperature spectroscopy

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Abstract—Microwave noise temperature spectroscopy is performed on gated AlGaN/GaN high electron mobility transistors as a function of gate and drain bias. The results are combined with low frequency noise (LFN) spectroscopy to understand device degradation and specific mechanisms responsible for it. It was found that channel noise temperature shows a strong dependence to channel voltage. On the other hand self-heating related power dissipation is weakly correlated to the measured noise temperature. This indicates that microwave noise temperature can act as a useful reliability characterization tool.

Keywords—AlGaN/GaN HEMTs, low frequency noise, microwave noise, hot-electron

I. INTRODUCTION

In the last decade GaN based high electron mobility transistors have demonstrated excellent performances in terms of high power levels ($P_{\text{out}} \sim 40 \text{ W/mm}$) [1] and high operating frequencies ($f_{\text{max}} \sim 300 \text{ GHz}$) [2]. However reliability remains a key issue to address if the full potential of this material system is to be exploited for simultaneous high power and high frequency devices. In a previous work the authors demonstrated the use of LFN measurements to characterize microscopic degradation that takes place inside the device due to various stress conditions [3]. Channel and the gate stack were systematically probed by applying a combination of hot-carrier, self-heating and inverse-piezoelectric stress. It was found that in the channel region, the combined effect of self-heating and hot-carrier stress creates a permanent increase of defect density at the AlGaN/GaN interface. Also it has been recently pointed out that this regime of operation becomes important at higher RF power levels for a device biased in the power amplifier mode [4]. High frequency noise measurements are known to give physical insights into hot-carrier and self-heating effects [5], [6] but very few studies have been performed on gated devices under realistic bias conditions. This work shows the results of using both low frequency and high frequency noise as a spectroscopic tool to study device degradation and failure mechanisms at typical bias regimes in actual devices.

II. EXPERIMENTAL DETAILS

The devices under study are gated Al$_{0.26}$Ga$_{0.74}$N barrier based GaN transistors grown on silicon substrate. They have a source connected field-plate and a SiN passivation layer. The devices were packaged to avoid ambient light related instabilities to affect the measurements. More details can be found in a previous work [7].

Figure 1 shows the experimental setup to measure the high frequency device noise which is based on the circulator method developed by Gasquet [8]. The noise was measured at 2.20 GHz beyond the spectral range where the 1/f-like noise observed at low frequencies has a contribution. The device was biased at a typical class AB mode of operation with gate voltage greater than the threshold voltage to induce a channel at a constant drain bias. The measurements were not performed under pulsed condition thereby allowing the lattice temperature to reach steady state at each bias. The gate terminal was AC-open circuited with the help of a tuner to minimize the impact of both induced gate noise and thermal noise associated with gate resistance on the channel noise. It was found that at high drain biases the drain noise mainly stemmed from the channel electrons since the transconductance of the device was relatively constant while the measured device noise temperature increased with bias. The low frequency noise was measured by a setup developed by the authors in an earlier work [7].

III. RESULTS AND DISCUSSION

Figure 2 shows the effect of various bias points of the $I_D-V_{DS}$ load line on degradation in the channel and the gate stack. This work concentrates on the channel region and two important failure mechanisms based on self-heating and...
hot-carrier are explored in more detail. The methodology that is adopted here is to systematically probe each region of the load line by increasing gate and drain bias. Increasing the gate bias at a constant drain voltage will increase only the self-heating effect by allowing more carriers in the channel thereby changing the lattice temperature via increased phonon scattering. On the other hand, increasing the drain bias at a constant gate voltage will increase the channel electric field and result in an increased electron temperature. Figure 3 shows the measured noise temperature of the channel at 2.20 GHz for three different gate biases as a function of drain voltage ranging from the triode to the saturation regime. Although a precise quantitative relation between the channel electron temperature and the measured noise temperature is lacking at this time, qualitative trends can be readily seen in the measurements. Figure 4 shows the effects of self-heating and channel voltage on the measured noise temperature in the saturation regime of device operation. The effect of power dissipation was measured by keeping the drain voltage constant at 22 V and changing the gate bias from -1.2 V to -1.0 V which resulted in a drain current change from 50 mA to 100 mA. To observe the effect of drain voltage on device noise temperature the drain voltage was varied between 10 and 22 V at a constant gate bias of -1.1 V. The noise temperature shows a strong correlation to the channel electric field as opposed to the power dissipation. For an increase of 100% in the drain voltage at $V_{GS} = -1.1$ V, the noise temperature increases by ~ 70% indicating that it is correlated to the hot electron temperature of the channel. On the other hand, a similar increase in the power dissipation ($P_D = I_D \times V_D$) in the channel raises the noise temperature by only ~ 20%.

Now that a correlation between noise temperature and channel hot-electron temperature has been established one can understand the physical mechanisms at play which cause the dramatic degradation of LFN characteristics at high drain current and voltage as shown in figure 2. At high drain voltage and low channel current it was observed that no permanent degradation occurs in the channel region. Noise temperature measured in this regime pointed out that hot-carriers do indeed exist and show a correlating to the channel electric field. Thus, it can be concluded that hot-carriers alone don’t seem to be causing this degradation. On the other hand when high drain bias and currents exist in the channel, the LFN shows a permanent degradation. The Hooge parameter increased 15 times from its pre-stress value. In this regime, the Joule heating in the channel is significantly higher. Therefore, it can be inferred that the observed degradation in the LFN characteristics at high drain bias and current is linked more closely to the self-heating effect which enhances the rate of degradation at the interface than the hot-electron effect alone. This has also been pointed out by other groups[9]. Although more work is required to further delineate this effect, these early results do point to the role of thermally activated degradation processes in the high power regime.

CONCLUSIONS

In conclusion, LFN and microwave noise spectroscopy have been used to understand device degradation and physical failure mechanisms in the channel region of GaN HEMTs. The noise temperatures are systematically measured as function of gate and drain bias to generate self-heating and hot-carrier effects. Correlation between drain bias and noise temperature was discussed. Finally it was shown that microwave noise spectroscopy can act as a useful reliability characterization tool.

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REFERENCES

Device noise temperature measurement system. DC bias is applied via a parameter analyser and a high power PSU. The gate is kept AC open with the help of a tuner. The drain noise at 2.20 GHz is measured as a function of drain bias at three different gate biases.

The measured low frequency noise characteristics are shown for pre and post stressed GaN HEMTs at different stress bias points [3]. The channel is stressed with hot carrier and self-heating stress by varying drain or gate bias, respectively, keeping the other variable constant.

The channel noise temperature measured at 2.20 GHz as a function of drain voltage is shown for three different gate biases. Squares (■) are measured at \( V_{GS} = -1.2 \) V. Circles (●) are measured at \( V_{GS} = -1.1 \) V and triangles (▲) are measured at \( V_{GS} = -1.0 \) V.
Figure 4. The relative sensitivities of device noise temperature to a change in power dissipation (squares) and drain voltage (circles) are shown. The channel noise temperature is more strongly correlated to the drain voltage than to power dissipation.