Leakage Current and Two-Tone-Linearity Investigations on 0.5µm AlGaN/GaN HEMTs

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Abstract

This paper presents the results of leakage current and two-tone-linearity measurements on 0.5µm AlGaN/GaN HEMTs. For these investigations three different process and epitaxial variations have been characterized. The first was a variation of the epitaxy, the second was variation of the gate metallization and the third variation involved modification of plasma pre-treatments before gate metallization. By using an epitaxial structure with an AlN interlayer an improvement of 5dB in linearity was obtained. Moreover, it was observed that the leakage current can vary up to a factor of 10 by changing the pre-treatment before gate metal deposition or by changing the barrier metal layer between Schottky and top gate metal.

I. INTRODUCTION

GaN wide-bandgap semiconductors are an attractive material for high power and high efficiency microwave applications due to high breakdown voltages, high sheet carrier density and good thermal conductivity. UMS has developed and qualified an industrial AlGaN/GaN 0.5µm gate length HEMT process for power applications up to 7GHz. Key figures of merit for many applications are the leakage current and the two-tone-linearity of the devices. These aspects were carefully investigated. In recent years, several reports have been published on improvements of AlGaN/GaN HEMTs by modifying the epitaxial structure, mostly by aggressive reduction of the barrier thickness [1]. These epitaxial modifications often require an adaption of the utilized process modules to the new epitaxy. In parallel, it would be beneficial to find process improvements to improve leakage current and linearity of the resulting devices. These process modifications should be compatible with volume production and also be easy to implement. In this paper we report on such methods that influence the leakage current and the two-tone-linearity by changing the epitaxy, the gate metal or use of additional treatments during device processing.

II. TECHNOLOGY AND FABRICATION

The epitaxial structures consist of a GaN cap layer and an undoped AlGaN barrier layer grown on an insulating GaN buffer. The layers were grown on a 4” semi-insulating 4H SiC substrate by MOVPE. Three different epitaxies have been used - see Figure 1. For the fabrication of Ohmic contacts a Ti/Al based metalisation was utilized. Device isolation was achieved by ion implantation. A dielectric-assisted gate module was used to achieve high yield on large periphery devices for power applications. According to this processing scheme, 0.5µm gate-foot openings are defined in the dielectric by optical lithography and subsequent dry-etching. In a second step the gate head is realized. During this step, a number of process variations were implemented. At first, the pre-treatment before the gate metal was varied (two different nitrogen plasmas were used) and in a second step, the gate metal itself was varied, see Figure 2.

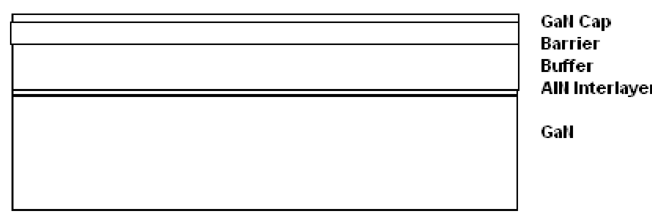

Figure 1: schema of the used epitaxies

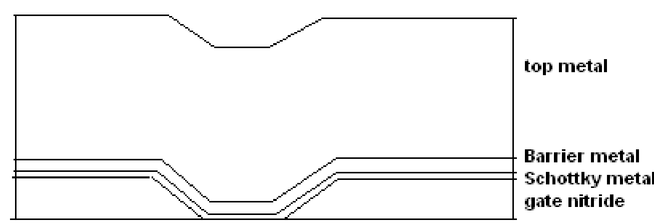

Figure 2: schema of used gate metal stack

III. IMPACT ON LEAKAGE CURRENT AND OUTPUT POWER

Nitride treatment investigation:

The impact of the nitrogen plasma process utilised before gate metal deposition is clearly visible in Figure 3. By using a downstream-plasma, the leakage current, measured at $V_{DS} = 50V$, is reduced by a factor of 10 compared to an ICP-plasma. This is observed on all investigated epitaxial variants. The process fluctuation with ICP-plasma is also visible as one wafer with 21% Aluminum content shows the same leakage current level (yellow box) as the wafer which received the downstream-plasma.

As shown, an epitaxial structure without a GaN cap layer results in a high gate-leakage current. With the downstream-plasma treatment we were able to reduce the level of gate-leakage current, but it is still much higher than what has been observed on material with a GaN cap.

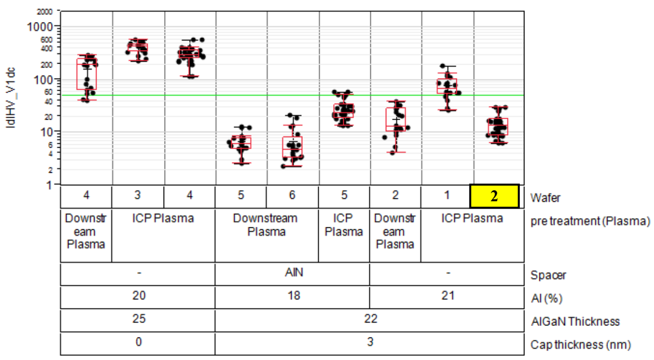

Figure 3: leakage current vs. gate metal pre treatment

Continuos-wave RF output power was measured by on-wafer load-pull measurements at 2GHz up to 6dB compression at $V_{DS} = 50V$ and a quiescent drain current of $I_{dq} = 7mA/mm$. For a gate periphery of 1.0mm no influence of process parameters could be observed, as can be seen in Figure 4.The wafer which received the ICP plasma treatment and which exhibits significantly lower leakage current (yellow box in Figure 3), shows an increase in output power density of 0.4W/mm compared to a complimentary wafer. The effect of the utilised ICP-plasma on the output power density is within the measurement accuracy of ±0.2W/mm.

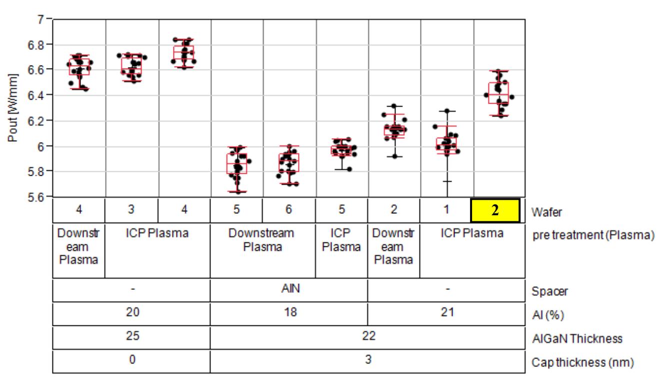

Figure 4: output power vs. gate metal pre treatment

Gate metal investigation:

The gate metallization utilised for the Schottky contacts on HEMTs should have a low resistivity, a high Schottky barrier and stable thermal behavior. Due to the low resistivity, Au is a good contact material, but Au at the semiconductor interface can be responsible for high leakage current levels [2]. Ni or Pt metalisations as the interface between semiconductor and Au do not necessarily hinder Au diffusion and poor adhesion to to the semiconductor surface can also result [2]. Au diffusion could be suppressed by a combination of Ni or Pt and Au with a third metal in between acting as a diffusion barrier. For the gate metal stacks we investigated, we observed that the leakage current is dependent on the utilised metal stack. Wafers with a WTi diffusion barrier layer between the Schottky metal (Pt) and the top metal (Au) show a significantly higher leakage current level. However, if we deposit these layers in nitrogen atmosphere, a thin Tungsten Titanium nitride layer is formed which results in a 10-fold reduction in leakage current compared to the non-nitrogen treated metal system, as shown in Figure 5. The wafer with Ni as Schottky material shows the lowest leakage current among all samples. With the modification of the metal stack, an adaption of the anneal temperatures for the different metal stacks was also necessary.

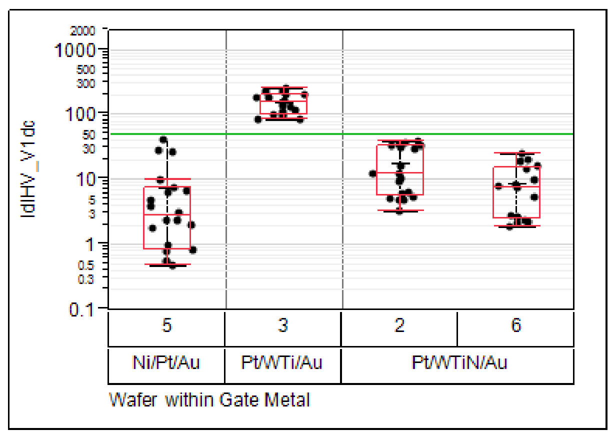

Figure 5: leakage current vs. gate metal composition

Other electrical parameters were also seen to vary based upon variation of gate metal stack. For example, the sheet resistance is 5% higher on wafers with WTi or WTiN, which we attribute to a reduction of the utilised gate metal anneal temperature. A slightly higher drain saturation current was also measured, but the most pronounced shift has been observed for the threshold voltage Vg100 (measured at 1/100 of drain saturation current). The use of Platinum as Schottky metal resulted in a shift of approximately -200mV in negative threshold voltage shift, which can be attributed to the higher work function of Pt ($\varphi_{m,Pt} = 5.65eV$, $\varphi_{m,Ni} = 5.15eV$, [3]) compared to Ni, see Figure 6. The impact of the utilised barrier metal with or without nitrogen is negligible.

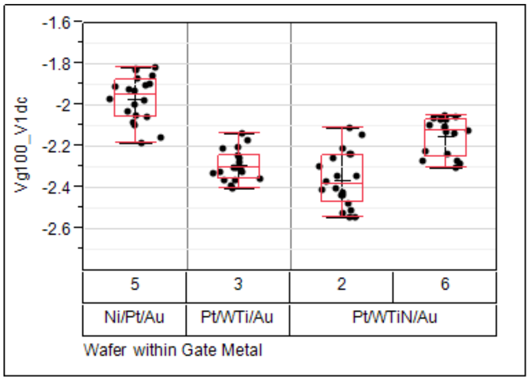

Figure 6: Vg100 vs. gate metal composition

The load-pull measurements at 2GHz show a small impact of the used gate metal stack on the RF output power density. With Ni as Schottky material the mean value of the output power is 0.4W/mm higher compared to wafers with a Tungsten Titanium nitride barrier. The difference in RF output power between WTi and WTiN barrier is only 0.2W/mm which is in the range of the measurement accuracy, see Table 1.

Wafer	Gate Metal	Pout (W/mm)
06	Pt WTiN Au	5.4
05	Ni Pt Au	5.8
03	Pt WTi Au	5.2
02	Pt WTiN Au	5.4

Table 1: Output power at 2GHz (Mean value)

IV. TWO-TONE-LINEARITY INVESTIGATIONS

Measurement conditions and test structure dependency:

The previously detailed epitaxy and process variations have also been characterized by two-tone load-pull measurements at a center frequency of f_C = 2.7GHz and a tone-spacing of Δf = 10MHz to determine the two-tone linearity represented by IMD3. All measurements presented in the following section have been performed at a drain voltage of V_{DS} = 50V and a quiescent drain current density of I_{dq} = 7mA/mm. Two different test structures have been characterized on-wafer. Both structures are coplanar devices, with gate peripheries of 2.4mm (6x400µm) and 1.0mm (2x500µm), respectively.

In fig. 7, a comparison of the IMD3 performance between a 6x400µm device and a 2x500µm device is given. A strong dependency of the two-tone linearity on the test structure layout is also observed.

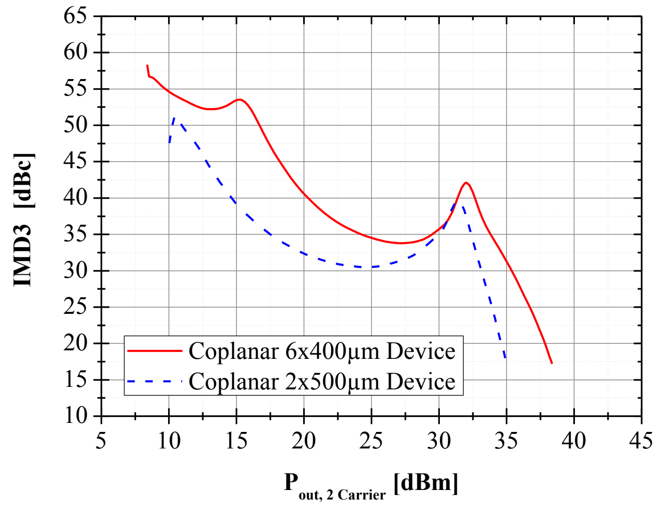

Fig. 7: Two-tone linearity performance at 2.7GHz and a tone spacing of 10MHz measured on a 6x400µm and a 2x500µm device at V_{DS} = 50V.

To compare the two-tone linearity, the linearity represented by IMD3 is plotted versus the respective output power. The major difference in IMD3 performance between the two structures is attributed to the difference in gate periphery. The absolute output power is lower for the 1.0mm device than for the 2.4mm device. Due to this, the overall curve for the 2x500µm device is shifted with respect to the output power towards lower values for P_{out}. The slope of the IMD3 vs. Pout curve is also different in the back-off region which confirms the systematic difference between the two test structures. This confirms that comparisons in two-tone linearity performance due to process variation must be carried out on the same type of test structure. For comparison purposes, all linearity results in the following sections in this paper are plotted in variability charts for better illustration of the on-wafer homogeneity and the wafer-to-wafer variability. For each characterized position on the wafer, the value of IMD3 is taken from the IMD3 versus Pout characteristic at 20dB PBO.

The impact of epitaxy configuration on two-tone linearity:

Different epitaxy configurations have been characterized by on-wafer two-tone load-pull measurements. The thickness of the AlGaN barrier layer has been varied, as well as the respective Aluminum content. Furthermore, on some varients, an AlN interlayer between GaN buffer and AlGaN barrier layer has been introduced to enhance the charge carrier low field mobility and the sheet charge density for a given Aluminum content in the barrier.

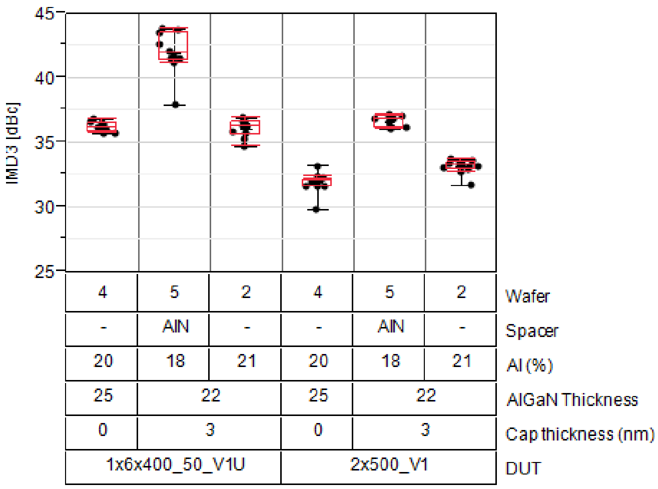

Fig. 8: Two-tone linearity performance at 2.7GHz and a tone spacing of 10MHz measured on a 6x400µm and a 2x500µm device at V_{DS} = 50V.

IMD3 performance for various eptitaxial structures are depicted in Fig. 8. As can be seen, the GaN cap layer or the Aluminum content in the AlGaN has no influence on the linearity performance, however, the introduction of an AlN interlayer, results in an 4-5dB improvement in IMD3 compared the epitaxy configurations without AlN interlayer.

The impact of gate metal and plasma pre-treatment on two-tone linearity:

The effect of different gate metal stacks and the associated plasma pre-treatment prior to gate metal deposition on linearity performance have been characterized by on-wafer two-tone load-pull measurements. The results are shown in fig. 9. These results, together with the variation of the plasma-pretreatment, given in fig. 8, show that neither the actual gate metal stack configuration nor the applied downstream-nitrogen-plasma or ICP-nitrogen plasma have any impact on the two-tone linearity performance of the devices. The measurement accuracy is in the range of 2dB.

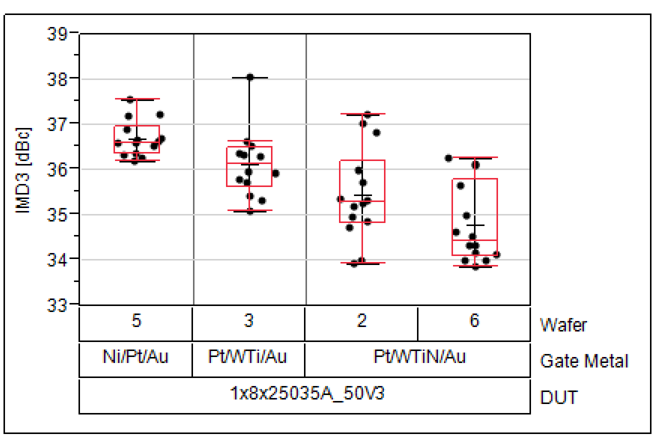

Fig. 9: Two-tone linearity performance at 2.7GHz and a tone spacing of 10MHz measured on a 8x250µm device at V_{DS} = 50V with different gate metal stacks

V. Conclusions

In this work we have demonstrated better control of the gate-leakage current in AlGaN/GaN HEMTS by an optimized plasma treatment process. This improvement is independent of the utilised epitaxy configuration. The most pronounced effects have been observed on epitaxial material without a GaN cap, where the leakage current decreased from 500µA/mm down to below 200µA/mm. In addition to this improvement, a gate metal stack with a thin Titanium Nitride layer in combination with Tungsten between the Schottky interface metalisation and bulk gate metal layer shows a further reduction in gate leakage current. With this adaption we observed a 10-fold reduction in leakage current. One explanation for this improvement is that the WTiN layer suppresses Au diffusion to the semiconductor surface.

In contrast to the leakage current measurements, changes in the gate metal stack and also the plasma pre-treatment show no impact on the linearity performance of the tested devices. As expected, we observed improved linearity performance on devices with wider gate periphery but the main performance improvement was gained by varying the epitaxy itself. By using an epitaxy with an AlN interlayer a higher linearity was observed compared to a standard epitaxy configuration.

References

[1] H. Xing, T. Zimmermann, D. Deen, K. Wang, C. Yu, T. Kosel, P. Fay, and D. Jena, Ultrathin all-binary AlN/GaN based high-performance RF HEMT Technology, 2008 GaAs MANTECH Technical Digest, pp. 125-128, April 2008.

[2] H. Jung, et al, Reliability behavior of GaN HEMTs related to Au diffusion at the Schottky interface, Phys. Status Solidi C 6/7 976-979, 2009

[3] Monroy et al, Thermal stability of Pt and Ni-based Schottky contacts on GaN and $Al_{0,31}Ga_{0,69}N$, Semiconductor Sci. Technology 17, L47-54, 2002

Acronyms

HEMT: High electron mobility transistor
IMD3: Third-Order Intermodulation Distance
PBO: Power Back-Off