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Effects of gate shaping and consequent process changes on AlGaN/GaN HEMT reliability

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The effect of gate shape and its necessary fabrication process on the reliability of AlGaN/GaN high electron mobility transistors (HEMT) was studied on devices fabricated on the same wafer, using DC and pulsed HEMT analysis. Simulations were used to determine the difference in electric field on the surface and in the barrier for the three gate shapes studied, I-shaped, slanted and recessed slanted. Prior to each electrical characterization during stress, devices were exposed to ultraviolet illumination to probe only newly generated traps rather than the filling of pre-existing electronic traps. Degradation was seen to increase with electric field strength; in each device type traps were generated by device stress at the location of the peak electric field. It was found that HEMTs with I-shaped gates showed larger degradation under the same stress conditions than devices with slanted gates. This was due to a higher electric field at the interface between the SiNx passivation and the AlGaN barrier layer resulting in higher surface trap generation. HEMTs with slanted recessed gates showed indications of barrier trapping while surface trapping effects played a smaller role.

1 Introduction
AlGaN/GaN high electron mobility transistors (HEMTs) have attracted great attention in the semiconductor community due to their excellent RF power performance and robustness [1, 2]. They are the subject of reliability research in order to determine the mechanisms that drive their degradation, as at present reliability issues are still a concern. Electronic trap generation has been found to be an important limiting factor for device reliability [3]. However, detailed mechanisms behind many degradation issues of AlGaN/GaN HEMTs are not yet fully established, with reliability improvement methodologies currently being largely empirical. The occurrence of traps (both pre-existing and stress induced) has been studied with different techniques including optical as well as electrical techniques; traps with activation energies of 0.12 eV and 0.45 eV as well as 0.5 eV have been found, predominantly located in the drain access region next to the gate contact [4, 5]. Usual degradation effects include, in varying combinations, a change in maximum drain current, gate leakage current increase, changes of the transconductance characteristic, a shift in the threshold voltage as well as an increase in drain current dispersion [6]. A number of device structure modifications have been proposed to suppress these effects and consequently improve the devices’ reliability including surface passivation which succeeded in minimizing gate leakage currents and electron trapping effects [7,8] while others employed different cap layers between the gate contact and the passivation layer [9]. Field plates have been used to spread and smooth electric field distributions (which are typically in the MV/cm range) at junctions to increase the breakdown voltage [1]. In particular, different gate shapes were used to reduce peak electric fields and to mitigate device degradation [10]. It has been observed that defect generation at either the semiconductor top surface or in the AlGaN layer of a device can be responsible for device degradation [11], including potential contributions from oxygen related defects [12, 13] and dis-
locations [14]. In a more pronounced degradation stage surface pitting has also been observed [15]. Stressing at pinch off conditions showed an increase in gate leakage currents and the creation of defects through mechanisms that are not fully understood [16]. In this work AlGaN/GaN HEMTs fabricated on the same wafer, but with different gate shapes were investigated to gain insight into the effect of the gate shape on trap generation in the device. This approach eliminates any effect on the study of material and process variations other than those needed to generate the different gate shapes. Devices with a slanted gate, with or without gate recess, are compared with a simple I-shaped gate as a reference.

2 Experimental Details
AlGaN/GaN HEMTs studied here were grown by metal organic chemical vapor deposition (MOCVD) on a SiC substrate with a 2 μm semi-insulating GaN buffer, 0.7 nm AlN interlayer and 25 nm thick AlGaN barrier layer (26% Al content). The HEMTs had standard Ohmic source and drain contacts with a gate-source spacing of 0.5 μm and a gate-drain spacing varying between 2 and 6 μm for all gate shapes. Three gate shapes were considered, all fabricated on the same wafer: I-shaped, slanted and slanted recessed as illustrated in Figure 1 with a gate width of 150 μm. The 0.9 μm long I-shaped gate was deposited first followed by the deposition of the 160 nm SiN, passivation layer. In the case of the other two gate shapes, the passivation layer was deposited first and 55° slanted sidewall openings etched into it using a CF₄/O₂ reactive ion etch. For the recessed device 15 nm of the AlGaN barrier was removed using a Cl₂ plasma etch followed by a 15 s CF₄ etch to reduce gate leakage.

This was followed by the deposition of the slant gate metal, which also formed an integrated gate connected field plate of 0.25 μm length. The results discussed here correspond to a 1 μm long slant gate and a 0.7 μm long slant recessed gate. Standard Ni/Au gate contact metallizations were used in all cases. Further details of the tested device structures can be found in reference [10].

All three device types were stressed under the same bias conditions: 20 hours of voltage bias stress in the off-state at a drain source voltage of 20 V at a gate voltage 0.5 V below the threshold voltage $V_{th}$ ($V_{th}$=-5V for both I-shaped and slant gate devices, $V_{th}$=-2.5V for the slant recessed gate device). Measurements were performed on 3 devices each showing similar results; and in the following representative results are shown. During stress, drain and gate current were monitored with time while every 2 hours stress was interrupted for more extensive electrical testing, namely DC output characteristics, transconductance and threshold voltage, gate lag (the gate had 0.1 μs long pulses at open channel separated by 0.1 ms at pinch-off, while the drain was DC biased) as well as drain current ($I_d$ transient measurements). The latter was performed to measure the trap density by applying an off-state voltage pulse (-10V) at the gate contact for 1 s filling or emptying traps depending on their location in the device. The gate was then pulsed to 1V with a drain voltage of 0.5 V and the effect of de-trapping monitored via recording $I_d$ and representing results in terms of $dI/d(log(time))$ against $log(time)$, which allows discrimination of different trap levels. More details on the technique can be found in [4]. Prior to all of the electrical testing, i.e. before and after stress, at every 2 hour interval as well as after a control measurement after 8hrs of device inactivity, the devices were exposed to UV illumination at 344 nm for 30 s. This de-populated all pre-existing traps, so that only newly generated traps are measured in the electrical analysis. The technique can therefore distinguish between recoverable and permanent device degradation.

Figure 2 shows representative results of $I_d$ transient measurements as part of an analysis that established 344 nm as the optimal wavelength to de-trap pre-existing electronic traps in the device. It also demonstrated the effectiveness of the UV illumination approach. Different peaks can be distinguished in Figure 2 showing the diversity in trap emission time, predominantly showing two trap types, denoted here Tp1 and Tp3, similar as in Ref[4]. Measurements were taken before and after stress as well as after 8 hours of device inactivity. In this experiment voltage stress was applied for 1 hour only so that pre-existing traps are filled, but no significant new trap generation occurred in the device. The two recovery methods under investigation here were UV illumination for 30 seconds (Figure 2a) as well as device inactivity for 8 hours (Figure 2b).
Figure 2 $I_d$ transient trapping characteristics $dI_d/d(\log(time))$ as a function of time of AlGaN/GaN HEMTs with I-shaped gate after 1 hour of off-state stress at $V_g=20V$, $V_d-V_g=0.5V$ and after 30 sec of UV illumination (a) and 8 hours of device inactivity (b).

The height of the trap peaks increases with stress and then decreases close to the initial levels following both recovery methods (UV illumination and 8 hour long device inactivity), i.e. insignificant numbers of traps are generated. This supports the use of UV illumination during the subsequent 20 hours stress analysis to eliminate signals of pre-existing traps from the measurements and to allow analysis of device degradation only. It removes the need for an 8 hour rest period which is not practical to perform in long-time reliability testing. Visible light illumination has been used in the past to measure electrical characteristics independent of trapping effects for different devices [17], while only broadband UV illumination in particular has been used during electrical stressing [18].

3 Results and Discussion

Figure 3 illustrates DC output characteristics of the AlGaN/GaN HEMTs prior to and after electrical stress. Different features in the stress-induced changes are apparent for devices with different gate shapes. For HEMTs with an I-shaped gate, a change in slope in the linear region together with a reduction in the maximum drain current ($I_{d_{\text{max}}}$) can be observed. For HEMTs with a slant gate, a smaller decrease in slope in the linear region is apparent, and an increase in the maximum drain current $I_{d_{\text{max}}}$, while the slant recessed gated device shows no change in slope, but an increase in $I_{d_{\text{max}}}$ is found. The percentage change of the slope of the DC characteristics shown in Figure 3 is further emphasized in Figure 4. A decrease of the drain current $I_d$ after stress can only be observed for I-shaped gated devices. In contrast the DC characteristics of slant gated devices, with and without recess, are dominated by a threshold voltage shift. This is represented by an increased $I_{d_{\text{max}}}$ and is further confirmed by extrapolated $V_{th}$ values from transconductance measurements as seen in Figure 5b.

Figure 4 Percentage change of the on-resistance due to 20 hours of electrical stress for I-shaped, slant and slant recessed gated devices. Values extrapolated from data corresponding to Figure 3.
A different form of degradation following stress is observed for either the slant gated or slant recessed gated devices. The slanted non-recessed device shows a much smaller decrease in the linear slope, i.e. a change in linear resistance and much smaller knee-walkout, indicating a smaller contribution from surface traps. However, for slant non-recessed devices there is in addition a consistent increase of \( I_{\text{max}} \) for all \( V_{gs} \) values indicating a threshold voltage shift due to stress-induced barrier traps underneath the gate. For the slanted recessed gated devices (Figure 3c) no sign of newly generated traps on the AlGaN surface can be seen. The absence of a decrease in slope and consequent shift in knee voltage as well as the increase in \( I_{\text{max}} \) (more pronounced than for slanted gated devices) indicates that stress has induced barrier traps underneath the gate which dominate the degradation (Figure 5b). Figure 3 therefore shows different locations for stress-induced trap generation: predominant signs for surface trapping in I-shaped gated devices and predominant signs of barrier trapping underneath the gate for slanted recessed gated devices. Slant non-recessed devices showed no significant degradation, i.e. only small amounts of trap generation.

Gate leakage measurements on the different HEMT gates are shown in Figure 5a. Devices with I-shaped gates exhibit a higher gate leakage current, while devices with the slant gate show almost an order of magnitude lower gate leakage. Gate leakage currents for devices with slant recessed gates are in the range of \(-2\times10^{-6}\) to \(-4\times10^{-7}\) mA/mm, i.e. about 6 orders of magnitude lower than for HEMTs with an I-shaped gate. For the I-shaped gated device the gate leakage current increased notably with stress while this was not observed for the devices with slant and slant recessed gates.

Figure 6 shows the result of \( I_q \) transient measurements before stress, after stress and after a day of device inactivity. Trapping characteristics illustrate the trap time constants through peak position along the x-axis and density of traps present and active in the devices through peak height. The traps observed here are denoted in the following as \( T_{p1} \), \( T_{p3} \) and \( T_{p3}' \) using the same convention as in Ref [4, 20] where measurements showed a dominant \( T_{p1} \) peak that evolved into a more complex defect with different activation energies with stress while no further conclusions were drawn about trap levels \( T_{p2} \) and \( T_{p3} \) whose peak trap density (i.e. peak height) also increased with stress. We note that \( T_{p2} \) as observed in Ref [4, 20] is not clearly apparent in the measured data here. The interpretation of the \( I_q \) transient measurement technique used here, is based on the reasonable assumption that any occupied electron trap in the AlGaN layer or buffer underneath the gate will be emptied by the filling pulse in the measurement due to electrostatics, whereas surface electron traps in the access region
will be filled by electron capture assisted by leakage current from the gate [21, 22]. Hence the sign of the derivative of the transient gives a convincing indication of trap location with positive values indicating electron emission from surface traps and negative values indicating electron capture from the channel [22]. In the case studied here, Tp1 and Tp3 are therefore proposed to be surface traps, while Tp3’ is proposed to be a barrier or bulk trap. As all measurements are performed after UV illumination, including the control measurement after 8 hrs of device inactivity, any increase or decrease of the peak amplitude of Tp1, Tp3 and Tp3’ represents the generation of such surface or bulk/barrier traps. We also note the difference in the $I_d$ transient signal between the unstressed devices with different gate shapes. Both slanted gated devices, non-recessed and recessed, show a much lower peak amplitude and even the appearance of a barrier/bulk trap (Tp3’) while I-shaped gated devices have high positive peak amplitudes. As all devices were fabricated on the same wafer these differences in the trapping spectra are related to carriers being injected and collected via the gate into and from traps present and activated without stressing. Different strength and peak electric field position and location of the gate with respect to the different device layers will affect how effectively different traps can be observed.

For I-shaped and slant gate devices, Figure 6 shows an increase of the trapping characteristics which had originally positive amplitudes, i.e. only contributions from surface traps. This increase was much stronger for I-shaped gated HEMTs and therefore consistent with the previous conclusions of stronger degradation for this type of gate shape through generation of surface traps. Slant non-recessed gated devices show a similar development as I-shaped gated devices in the sense that peak amplitudes become slightly more positive. This could suggest the presence of a small surface trapping effect. In contrast, devices with a slant recessed gate, which exhibit a bulk trap Tp3’ (negative signal) and surface trap Tp1 (positive signal) prior to stress show a stress induced shift into negative peak amplitudes for slower traps indicating increased trapping in the barrier or buffer underneath the gate. The existence of barrier or buffer traps underneath the gate may not be surprising given the possibility of etch-induced damage in the AlGaN during the gate recessing.

These different trap generation locations for the different gate shapes are consistent with a series of $I_d$ transient measurements performed one after the other at different gate filling pulse voltages, as illustrated in Figure 7. No electrical stress was performed during this measurement. As the initial gate filling pulse fills surface traps next to the gate and empties barrier and buffer traps underneath the gate, the signal from both surface traps and buffer traps, i.e. electron emission and capture during data collection, is expected to decrease with decreasing filling pulse voltage magnitude.

![Figure 6](image6.png)

**Figure 6** Comparison of derivatives of transient measurements for (a) I-shaped, (b) slant and (c) slant recessed gate shapes: Before stress (solid black line), after 20 hrs off-state stress at $V_{ds}=20V$ (dash-dot green line), 8 hrs device inactivity (dashed orange line). All measurements taken after UV illumination.

![Figure 7](image7.png)

**Figure 7** Transient measurements (showing the total drain current rather than the derivative) without UV illumination for (a) I-shaped, (b) slant and (c) slant recessed gates performed at different initial gate voltage pulses measured immediately after one another starting with a -10V pulse and reducing it by 2V for each measurement. Note different y-axis scales.

However, the effect of filling pulse magnitude on bulk traps in the barrier underneath the gate is expected to be less pronounced as this region is completely depleted when applying a filling pulse $\leq V_{th}$ as discussed in Ref [19]. In Figure 7 it is apparent that for the I-shaped gated devices there is an increase in $I_d$ measured with decreasing filling pulse magnitude. This is consistent with the picture of surface traps being generated in this device by the device stress. For both slant gate variants $I_d$ decreases with time for all filling pulse amplitudes consistent with electron capture predominantly by bulk traps underneath the gate.
As the passivation layer is deposited first for the slant gated devices, so that an etching process is involved in the fabrication of these devices, while it is not for the fabrication of I-shaped gated devices, trapping effects due to process induced damage are likely to influence the device. This can be seen in the presence of a bulk trap Tp3’ prior to stress for slant gated devices while I-shaped gates show the presence of a surface trap Tp3.

A difference in peak electric field for different gate shapes has been reported previously through measurement and simulation [23, 24]. In order to gain a physical understanding of the basis of the different degradation mechanisms observed between different gate shapes, electric field distributions for the same gate geometries and dimensions as those used in the experiments were simulated using the Silvaco ATLAS software. The results are shown in Figure 8. It is confirmed that the electric field along the surface is indeed highest for the I-shaped gated devices while slant recessed gated devices produce the lowest electric field at the surface (Figure 8a). This supports experimental data which found high surface trap generation for I-shaped gates, reduced surface trapping for slant gates and no distinguishable surface trapping for slant recessed gates. These simulations are consistent with previously reported simulation results for gates with 90° and 45° sidewalls in GaN/AlGaN/GaN HEMTs [25].

Figure 8 Simulation results of electric field magnitude (a) from the gate along the SiN/AlGaN surface and (b) vertically down from the gate corner for I-shaped (black dashed line), slant (red short dashed line) and slant recessed (blue dotted line) gated devices at $V_{gs}=-20\text{V}$ and $V_{gs}=V_{ds}=-0.5\text{V}$.

The corner of the I-shaped gate naturally enhances the electric field at the gate edges. This has the potential to cause the higher gate leakage current shown in figure 5a. Slanting the gate will result in reducing this electric field at the gate edge corner at the SiN/AlGaN interface and is apparent in the reduction in gate leakage current, although this may also be associated with the CF$_4$ etch treatment used for the slanted and slant recessed, but not the I-shaped gates. Moving the gate corner into the AlGaN layer reduces the electric field at the SiN/AlGaN interface even further; with the peak electric field now lying in the AlGaN layer. Gate leakage mechanisms are suppressed for the recessed device as is shown experimentally in Figure 5a. Figure 8b shows electric field strength from the gate corner across the AlGaN barrier to the channel. Note that the gate corner for the recessed devices is positioned 15nm into the AlGaN barrier, so that the origin of the x-axis in Figure 8b corresponds to this position for the recessed devices, but corresponds to the SiN/AlGaN interface for non-recessed devices. The electric field vertically down into the barrier is similar for all gate shapes. Experimental data suggests trap generation in the barrier underneath the gate for the slant recessed gate, which is likely due to etch damage in the AlGaN layer.

4 Conclusions

AlGaN/GaN HEMTs fabricated on the same wafer, i.e. using identical epitaxial material, but with different gate shapes, were investigated to assess the impact of the gate shape on degradation susceptibility. I-shaped gated devices not only showed sizable surface trapping prior to stress but also experienced the generation of surface traps during off-state stress. In contrast slant gated devices, with or without recess, showed little or no surface trap generation indicating the effectiveness of this approach to control the electric field at the gate corners. However, the slant gated devices, which require etching through the gate passivation before the gate deposition, showed trapping behavior consistent with traps located in the AlGaN barrier before stressing most likely indicating some process induced damage within the bulk of AlGaN. It is proposed that the off-state stress results in an increase in surface related trapping for the slant non-recessed gated devices, while increased barrier related trapping was identified for the slant recessed gated devices. Electric field strength at the gate corner and the SiN/AlGaN interface is the driving force for trap generation in the degradation observed here. Simulation showed the peak electric field lay in the AlGaN barrier for recessed devices but at the surface, i.e. the SiN/AlGaN interface for non-recessed gates of both shapes.

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