Pre-passivation Plasma Surface Treatment Effects on Critical Device Electrical Parameters of AlGaN/GaN HEMTs

David J. Meyer[1*], Joseph R. Flemish[1], and Joan M. Redwing[1]

[1] Department of Materials Science and Engineering, The Pennsylvania State University, University Park, PA 16802
[*] Email: djm308@psu.edu , Tel: 814-865-0889

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Abstract

This work reports on our investigation of fundamental aspects of surface modification and passivation relating to manufacturability of reliable AlGaN/GaN HEMT devices. We have found that successful mitigation of the RF dispersion in these HEMTs is highly dependent on the type of pre-passivation surface treatment. Surface plasma treatments consisting of C_2F_6, O_2, Cl_2, or NH_3 used in conjunction with PECVD SiN_x allow for the best pulsed I-V characteristics. Less dependent on pre-passivation surface treatment are dc I-V parameters such as interdevice isolation current and gate leakage current, whose magnitude can be altered greatly by varying SiN_x film deposition conditions.

INTRODUCTION

Over the past decade, GaN based transistors have emerged as contenders for replacing existing Si and GaAs devices in various high power RF applications. In order to compete with these mature technologies, GaN technology must offer clear advantages in device performance and robustness to justify added costs. AlGaN/GaN HEMTs with breakdown voltages greater than 120 V and RF output power density in the 9 – 30 W/mm range,[1-5] represent an order of magnitude improvement over state-of-the-art silicon LDMOS and GaAs based transistors. While these results are encouraging, several problems such as RF dispersion, high gate leakage and interdevice isolation currents, and premature device breakdown still hinder full scale commercialization of GaN based technology.

In previous work[6,7] we have demonstrated that by applying certain plasma treatments to the HEMT surface immediately prior to SiN_x passivation, RF dispersion shown by pulsed I-V measurements can be reduced dramatically. To increase our understanding of how these pre-passivation surface treatments affect other critical device parameters, we have expanded our electrical characterization procedure to include several additional dc I-V tests. The experimental results that will be presented in this paper suggest that, in general, interdevice isolation current, gate leakage current, and off-state breakdown voltage have relatively little dependence on pre-passivation surface treatments. Instead we find that these dc parameters may have a much stronger dependence on the SiN_x film deposition conditions.

EXPERIMENTAL

The HEMT heterostructures used for this study were grown on 3" semi-insulating 6H SiC substrates (from II-VI Incorporated) by MOCVD, and were purchased from IQE-RF. The device epilayers consisted of a 1.7 μm thick undoped GaN layer followed by an 18 nm $Al_{0.27}GaN$ layer and a 2 nm GaN capping layer. Device processing was carried out on quarter-sized pieces of the wafer, which were then diced into 6 mm × 6 mm die for experimentation. Ohmic metallization was attained by e-beam evaporation of Ti/Al/Ni/Au (15/100/50/50 nm) followed by 60 seconds of rapid thermal annealing at 875 ºC. The resulting ohmic contact resistance was 0.4 ± 0.1 Ω mm. HEMT mesa isolation was achieved through Cl_2 plasma in an ICP reactor and was followed by gate metallization of Ni/Au (50/100 nm) by e-beam evaporation and liftoff in an N-methyl-2-pyrrolidone based photoresist stripper. Gate contacts were defined by contact lithography and had dimensions of 1 × 100 μm^2, with gate-source and gate-drain spacing of 1.5 μm and 2 μm, respectively. Unpassivated devices had average threshold voltages of V_{th} = -2.4 ± 0.1 V, saturated drain current of I_{DSS} = 332 ± 34 mA/mm, and average maximum transconductance of $g_{m,max}$ = 122 ± 8 mS/mm. Hall effect measurements of unpassivated van der Pauw structures showed ungated HEMT channel sheet resistance R_s = 477 ± 26 Ω/□, 2DEG sheet carrier concentration $n_s = 8 \pm 1 \times 10^{12}$ cm^{-2}, and Hall mobility μ_H = 1610 ± 55 $cm^2/V{\cdot}s$.

After gate contact definition and electrical characterization of each individual die, various surface treatments were applied immediately prior to passivation with SiN_x. The plasma gaseous precursors that were utilized in this study included C_2F_6, NH_3, O_2, BCl_3, and Cl_2. Prior to plasma exposure, each sample was submerged for 60 seconds in BOE 10:1 (aqueous NH_4F/HF) followed by DI H_2O rinse and N_2 dry. Subsequent surface treatments were carried out in one of three different plasma chambers. C_2F_6 and NH_3 plasma treatments were applied in the same PECVD chamber used for SiN_x deposition, employing a set of parallel plate electrodes with showerhead delivery of the precursors. O_2-containing plasma treatments were

performed in an identical chamber on the same cluster tool as the SiN_x PECVD chamber, allowing for samples to be transferred under low vacuum via robotic arm to receive passivation after plasma exposure. Lastly, Cl_2 and BCl_3 plasma treatments were performed in an ICP reactor that had backside cooling of the substrate. In order to minimize any appreciable surface etching with the Cl-based chemistries, plasma power was only delivered to the ICP electrode, which resulted in negligible induced biases. The temperature, pressure, and plasma power that were used for each treatment are summarized below in Table I. After surface treatment, each sample was passivated with approximately 80 nm SiN_x (n = 1.95) that was deposited at a temperature of 300 ºC and pressure of 2.7 Torr.

TABLE I
PLASMA SURFACE TREATMENT PARAMETERS

Treatment	Temp.	Pressure	Plasma Power
C_2F_6	300 ºC	1 T	200 W
NH_3	300 ºC	2.7 T	35 W
O_2	50 ºC	1 T	200 W
Cl_2	25 ºC	6 mT	ICP: 500 W/RF: 0 W
BCl_3	25 ºC	6 mT	ICP: 300 W/RF: 0 W

Plasma exposure duration was 30 seconds in each case.

To examine RF dispersion in HEMT devices, pulsed I-V characteristics were measured over a large range of high electric field state QBPs (-5 V ≤ V_{GS} ≤ 0 V, 0 V ≤ V_{DS} ≤ 25 V) with an Accent DiVA 225EP system and Cascade RF probes. By performing pulsed I-V measurements with short (200 ns) pulses, the presence and effect of surface or barrier layer charge trapping centers with time constants on the order of microseconds or longer was detected. The effect that this trapped charge exhibits is often referred to as virtual gating, current collapse, or RF dispersion and has been previously documented in the literature. [8,9]

By comparing pulsed I-V curves generated from a high electric field QBP (i.e. V_{GS} = -5 V, V_{DS} = 10 V) to ones generated from a zero electric field QBP (V_{GS} = 0 V, V_{DS} = 0 V) the presence of occupied charge trapping centers can be observed. In order to make relative comparisons from sample to sample, we have defined a metric for pulsed I-V performance that we call "current recovery." Current recovery is the fractional comparison of the pulsed I_{DSS} measured from an arbitrary QBP to the pulsed I_{DSS} measured from the zero electric field QBP. Expressed as a percentage, current recovery is given by,

$$\text{Current Recovery(Q BP')} = \frac{\text{Pulsed } I_{DSS} \text{ from QBP'}}{\text{Pulsed } I_{DSS} \text{ from Zero E-Field State}}$$

where I_{DSS} is defined as the value of drain to source current, I_{DS}, when V_{DS} = 10 V and V_{GS} = 0 V.

DC characterization of HEMT samples was performed using a Keithley 4200 Semiconductor Characterization System with pre-amplifiers on two of the SMUs to ensure accurate measurement of low level currents. Mesa-to-mesa interdevice isolation current, I_{ISO}, was measured using 6 × 100 μm^2 isolation test structures. While grounding one electrode, the voltage on the other electrode, V_{ISO}, was swept from 0 to 60 V while simultaneously measuring current. Gate leakage current, $I_{G,leak}$, was measured by grounding the source contact, fixing the gate voltage at -5 V, and ramping the drain voltage from 0 V to 45 V. Lastly, off-state breakdown voltage, V_{BR}, was defined as the measured gate to drain voltage when grounding the source, setting the gate voltage to -5 V, and forcing 1 mA/mm of current into the drain contact.

RESULTS AND DISCUSSION

The research presented in this paper is organized into two separate studies. In the pre-passivation surface treatment study, each HEMT sample received an experimental surface treatment shown in Table I, followed by passivation with a standard SiN_x film. Conversely, in the SiN_x film deposition study, each sample received the same C_2F_6 plasma treatment from Table I prior to passivation, but was subsequently encapsulated with SiN_x films deposited under various conditions.

Pre-passivation Surface Treatment Study

A general observation that emerged from the results of this study was that a variety of plasma surface treatments could be used in conjunction with SiN_x passivation to improve the HEMT pulsed I-V performance. Compared with no surface treatment or treatment with BOE 10:1 only, C_2F_6, NH_3, O_2, and Cl_2 plasmas significantly enhanced the passivation efficacy. Figure 1 shows HEMT pulsed I-V current recovery data before passivation, after SiN_x passivation with no pretreatment, and after O_2 plasma treatment and SiN_x.

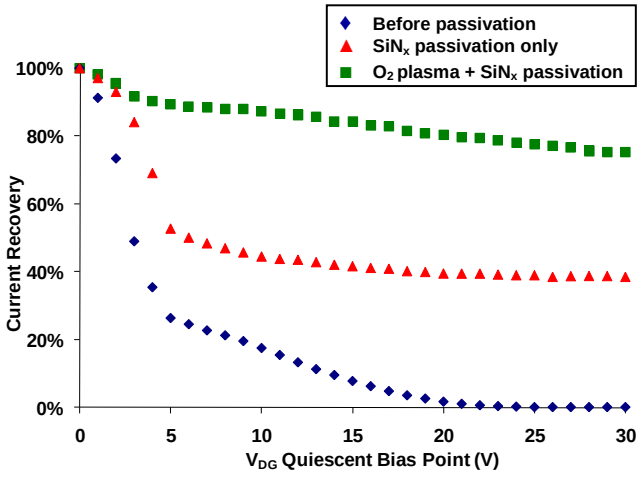

Figure 1 – Current recovery vs. V_{DG} QBP for 1 × 100 μm^2 HEMTs before passivation, after SiN_x passivation with no treatment, and after SiN_x passivation with O_2 plasma treatment.

To clarify how V_{DG} was defined, the first 6 data points of the curves in Figure 1 had V_{DS} QBP = 0 V, while the gate voltage QBP was ramped down from 0 V to -5 V. At V_{DG} QBP > 5V, V_{GS} QBP = -5 V and V_{DS} QBP is increased from 0 V to 25 V. Selected data points for current recovery in other surface treatment cases are given in Table II. The values shown are averaged from four devices and typically had standard deviations of approximately 1 – 4 %, except for the BCl_3 case where it was 18%.

TABLE II
SURFACE TREATMENT EFFECTS - PULSED I-V CURRENT RECOVERY

Pre-passivation Treatment	Before Passivation Current Recovery		After Passivation Current Recovery	
	V_{DG} QBP = 11 V	V_{DG} QBP = 30 V	V_{DG} QBP = 11 V	V_{DG} QBP = 30 V
BOE 10:1 only	13%	0%	41%	29%
C_2F_6	13%	0%	88%	78%
NH_3	2%	0%	86%	47%
O_2	14%	0%	86%	75%
Cl_2	13%	0%	83%	69%
BCl_3	15%	0%	46%	22%

The current recovery vs. V_{DG} QBP curves for the C_2F_6 and Cl_2 treatments were very similar to the O_2 plasma curve shown in Figure 1. NH_3 plasma treatment produced similar current recovery data in the mid-range V_{DG} QBPs, but degraded at the higher values. The BCl_3 treatment case resulted in fairly low current recovery values and also caused a significant amount of SiN_x film delamination.

DC I-V characterization results, given in Table III, showed that in every plasma treatment/passivation case, interdevice isolation current, gate leakage current, and breakdown voltage degraded from unpassivated values. The values for C_2F_6 and Cl_2 plasma treated samples were slightly better than the rest, but overall there was no particular surface treatment that could produce results comparable to the unpassivated sample.

TABLE III
SURFACE TREATMENT EFFECTS – DC I-V PARAMETERS

Treatment	$I_{ISO}(V_{ISO}=33V)$ (mA/mm)	$I_{G,Leak}$ (V_{DG}=33V) (mA/mm)	V_{BR} (V)
Unpassivated	2.1×10^{-7}	1.3×10^{-7}	79
BOE 10:1 only	1.1×10^{0}	1.0×10^{-1}	51
C_2F_6	3.6×10^{-2}	3.2×10^{-2}	68
NH_3	4.2×10^{0}	7.2×10^{-1}	10
O_2	2.0×10^{0}	2.3×10^{-1}	31
Cl_2	1.4×10^{-1}	3.3×10^{-2}	68

The results of this study suggest that appropriate HEMT surface treatment prior to passivation is critical to mitigating RF dispersion. A possible explanation as to why plasma treatments enhance passivation, may be due to their ability to reduce surface carbon, as we have seen in our previous XPS study,[6,7] allowing for unimpeded chemical reaction of impinging SiN_x precursors with the HEMT surface. In terms of dc I-V parameters, plasma surface treatment did not cause a large deviation from the BOE 10:1 control sample case. Instead, changes in dc I-V parameters started to emerge when we began varying SiN_x film deposition conditions.

SiN_x Film Deposition Study

PECVD depositon of SiN_x films can occur over a large range of parameters. Some of the variables that can be adjusted include plasma power, NH_3/SiH_4 ratio, temperature, and pressure. To study the effect of changing the passivation film deposition conditions on HEMT electrical performance, we chose to vary the NH_3/SiH_4 flow rate ratio from 2 to 10 and the plasma power from 50 W to 300 W. Each HEMT sample received the same pre-passivation C_2F_6 treatment, described in Table I. The most interesting result of this study can be observed in the interdevice isolation current data shown in Figure 2a.

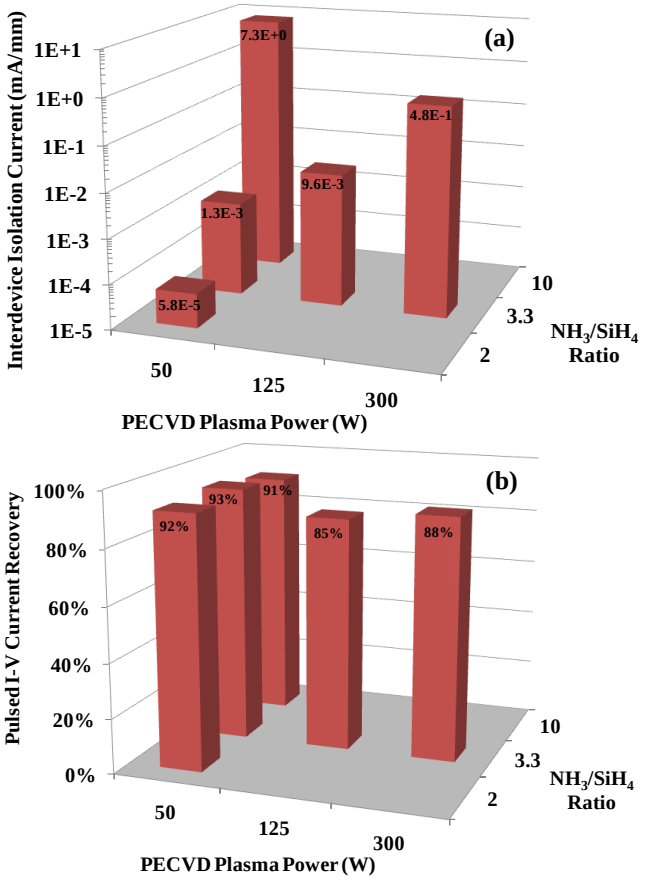

Figure 2 – (a) Interdevice isolation current density measured at V_{ISO} = 33V and (b) pulsed I-V current recovery data measured at V_{DG} QBP = 11 V for HEMTs pretreated with C_2F_6 plasma and passivated with various SiN_x plasma deposition conditions.

Two prominent trends appear in the data in Figure 2a. When fixing the plasma power at 50 W and increasing the NH_3/SiH_4 ratio, the SiN_x film composition changes as evidenced in part by a shift in refractive index from 2.1 to 1.8. This difference in composition may result in fixed charge differences in the SiN_x that modify the band structure at the SiN_x/HEMT interface, creating a slightly conductive pathway. To rule out the possibility of conduction through the SiN_x, 50 µm diameter MIS capacitors were fabricated and showed only 10 nA of leakage current at 7 MV/cm for the NH_3/SiH_4 ratio = 10, plasma power = 50 W SiN_x, a value several orders of magnitude less than what was observed for the smaller electric field strength used during the isolation test.

The I_{ISO} data also showed an increase with plasma power for a fixed NH_3/SiH_4 ratio = 3.3. A possible explanation for this trend may be that the semiconductor surface is damaged by ion bombardment or modified by nitrogen volatilization during the initial SiN_x deposition. Hashizume and co-workers have observed the formation of nitrogen vacancies on an AlGaN surface, as a result of exposure to H_2 plasmas.[10] They suggest that excited H^+ ions react with surface nitrogen atoms to create volatile NH_x species that leave the AlGaN. As two of the SiN_x gaseous precursors, SiH_4 and NH_3, are hydrides it is possible that a similar mechanism could occur here as there is likely a significant concentration of atomic hydrogen present during deposition.

Despite the large changes in interdevice isolation current, Figure 2b shows that the pulsed I-V current recovery was affected only slightly by the changes in SiN_x deposition. Gate leakage current and breakdown voltage data were purposefully omitted from this section because of their convolution with interdevice isolation current. Specifically, the probe pad to pad I_{ISO} was of the same or higher order of magnitude as the gate leakage current making it impossible to obtain an accurate gate leakage current or breakdown voltage measurement. Initial results illustrate this effect when the SiN_x in between mesas is removed and device characteristics are remeasured.

CONCLUSIONS

Two sets of experiments were conducted to investigate the effect of varying pre-passivation surface treatments and SiN_x film deposition conditions on HEMT electrical characteristics. By utilizing C_2F_6, O_2, Cl_2, or NH_3 plasmas prior to a standard SiN_x passivation, it was found that the pulsed I-V performance of HEMTs could be greatly enhanced. As a result of using a standard pre-passivation surface treatment followed by a variety of SiN_x film deposition conditions, it was found that interdevice isolation current could be changed drastically while leaving pulsed I-V performance relatively unchanged.

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ACRONYMS

2DEG:	Two-Dimensional Electron Gas
BOE:	Buffered Oxide Etch
DI:	Deionized
HEMT:	High Electron Mobility Transistor
ICP:	Inductively-Coupled Plasma
LDMOS:	Laterally-Diffused Metal-Oxide-Semiconductor
MIS:	Metal-Insulator-Semiconductor
MOCVD:	Metal-Organic Chemical Vapor Deposition
PECVD:	Plasma-Enhanced Chemical Vapor Deposition
QBP:	Quiescent Bias Point
SiN_x:	non-stoichiometric Silicon Nitride
SMU :	Source-Measure Unit