# Plasma Surface Pretreatment Effects on Silicon Nitride Passivation of AlGaN/GaN HEMTs

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**Abstract**

**Several plasma and wet-chemical surface treatments have been tested to determine their effectiveness in improving SiN passivation of the AlGaN surface in HEMT devices. Mitigation of RF dispersion was evidenced by dramatic improvements in pulsed IV data after various plasma surface treatments and SiN passivation were applied to gate-level processed HEMTs. To examine surface chemistry as a result of these treatments, XPS was used to obtain atomic concentrations and bonding information.**

## INTRODUCTION

Although the development of high-power HEMT devices based on AlGaN/GaN heterostructures has progressed rapidly over the last decade, commercialization of circuits based on these devices has been delayed in part by concerns of reliability. In particular, these devices are prone to rapid and long-term degradation due to the presence of defect-related charge traps. The relatively slow charging and discharging of these defect states, with time constants in the microseconds range, cause HEMTs to experience RF dispersion and current collapse.[1-4] Mitigation of RF dispersion has been demonstrated in the literature by passivating the AlGaN surface using a variety of dielectric films with the most commonly reported one being SiN deposited by PECVD.

This work reports on our investigation of fundamental aspects of surface modification and passivation relating to manufacturability of reliable HEMT devices. We have found that the pretreatment of the AlGaN surface immediately prior to plasma deposition of SiN is a critically important step in achieving passivation efficacy. The effects of plasma and wet chemical treatments prior to passivation have been evaluated with regard to the resulting electrical characteristics of the HEMTs and the chemical properties of the AlGaN surface.

## EXPERIMENTAL

The HEMT heterostructures used for this study were grown on sapphire substrates by MOCVD, and were provided by Emcore Corporation. The device epilayers consisted of a 1.7 µm thick undoped GaN layer followed by a 23 nm $Al_{0.32}GaN$ layer. 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. Gate contacts were defined by contact lithography and had dimensions of 1 µm × 100 µm. Unpassivated devices had average threshold voltages of $V_{th}$ = -4.2±0.1 V and average maximum transconductance of $g_{m,max}$ = 132±60 mS/mm.

After gate contact definition, several different prepassivation surface treatments were utilized followed by encapsulation in SiN. These treatments included various $SF_6$, $O_2$, $NH_3$, $N_2$ plasmas as well as wet treatments using either an SC1 clean (hot aqueous $NH_4OH/H_2O_2$) or 10:1 BOE (aqueous $NH_4F/HF$). Two different plasma systems were used to administer the prepassivation surface treatments. Plasmas involving $SF_6$ and $O_2$ were carried out in a magnetically enhanced ICP reactor that had backside cooling of the substrate. Chamber pressure during the treatment was held at 8 mTorr, while RF power was 400 W and 40 W to the inductive coil and substrate electrode, respectively. With these conditions, induced DC bias levels reached -100 V to -130 V. Plasmas that included $NH_3$ and $N_2$ gaseous precursors were applied to the sample directly before passivation, in the same PECVD chamber, utilizing a parallel plate, shower head geometry. The pressure was held at 2.7 Torr for these plasma treatments, as well as for the SiN deposition. In the case of the wet-chemically treated samples and the $SF_6/O_2$ plasma-treated samples, SiN encapsulation was performed within a few hours of pretreatment.

## RESULTS AND DISCUSSION

Among the various surface pretreatments and SiN deposition parameters evaluated, we have found that the measured DC and pulsed IV electrical characteristics can vary greatly. Figure 1 shows the change in HEMT channel sheet resistance that resulted from 30 seconds (unless otherwise denoted) of plasma pretreatment followed by approximately 800 Å of SiN encapsulation. The refractive index of the SiN film used in these experiments was

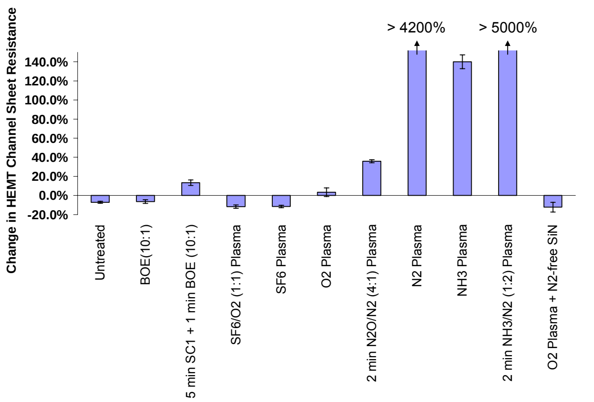


Figure 1 – Change in HEMT channel sheet resistance measured by CTLM after various plasma and wet chemical pretreatments and SiN (n = 1.99) encapsulation.

approximately n = 1.99. We note that two interesting trends emerge in this data. The first trend is that plasma pretreatments involving $SF_6$ result in lower HEMT channel sheet resistance than in untreated or 10:1 BOE treated samples. X-ray photoelectron spectroscopy (XPS) analysis of similarly processed non-metallized samples revealed that a large incorporation of fluorine (around 25 at. %) was found at the AlGaN surface in the form of Al-F and Ga-F bonds. In contrast, only a small concentration (around 3 at. %) with no significant sign of Al-F or Ga-F bonding was found on the 10:1 BOE sample. The second trend observed in Figure 1 is that ion bombardment by excited $N_2$ species is very detrimental to HEMT DC characteristics. Since $N_2$ is a common carrier gas used for plasma deposition of SiN, this raises some concern that the HEMT heterostructure could be exposed to some $N_2$ damage, even if for only a short time during growth.

To examine RF dispersion characteristics of HEMT devices, we have used an Accent Optical 225 EP DiVA system to measure pulsed IV characteristics taken from two QBPs; in the first case from a high electric field state between the drain and gate with $V_{DS}$ = 6 V, $V_{GS}$ = -5 V and in the second from a zero electric field state with $V_{DS}$ = 0 V, $V_{GS}$ = 0 V. By using a short pulse length of 200 ns, surface states with time constants on the order of 1 μs or longer that become occupied under high electric field conditions do not have the opportunity to fully discharge by the time HEMT channel current is measured. This trapped charge induces a field effect that can be observed as virtual gating. The differences of pulsed IV curves generated from a high-field QBP to ones generated from a zero-field QBP reveal the presence of trapping centers that would degrade RF performance and result in RF dispersion. As a metric for pulsed IV performance, the percentage ratio of $I_{DSS}$ measured from the high-field QBP to $I_{DSS}$ measured from the zero-field QBP is used, which we have termed "current recovery." $I_{DSS}$ in this experiment was defined as the value of drain to source current, $I_{DS}$, when $V_{DS}$ = 10 V and $V_{GS}$ = 0 V.

We find that in unpassivated HEMT devices with initial current recovery percentages that are approximately 15%, various $SF_6$ and $O_2$-containing plasma pretreatments followed by silicon nitride encapsulation can improve current recovery to 85 – 95%. Figure 2 illustrates the pulsed IV data for a device that received a 30 second $SF_6$ plasma pretreatment followed by SiN (n = 1.99) encapsulation. In contrast, when these devices are untreated or pretreated with aqueous 10:1 BOE, silicon nitride passivation only results in 30 – 40% current recovery. When comparing this pulsed IV data to XPS data, the improved current recovery correlates with a reduction of carbon on the surface. In the $SF_6$ and $O_2$ plasma pretreated samples, surface concentrations of carbon ranged from 5 – 7 at. %, while in untreated and 10:1 BOE treated samples carbon concentration was between 14 – 20 at. %. Table 1 summarizes the changes in HEMT channel sheet resistance, pulsed IV data, and carbon surface concentration as measured by XPS for several of the treatment schemes we examined.

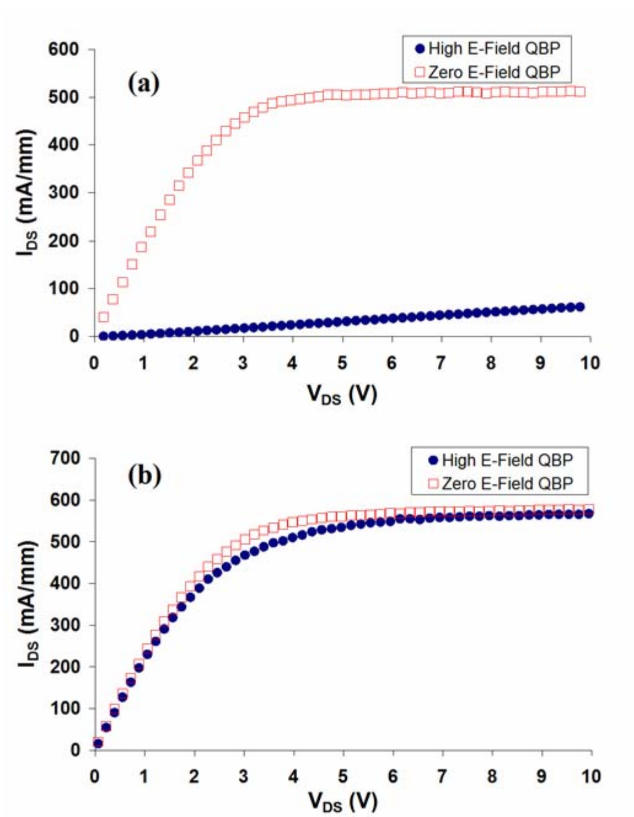


Figure 2 – Pulsed $I_{DS}$ vs. $V_{DS}$ curves of AlGaN/GaN HEMT with $V_{GS}$ = 0 V before (a) and after (b) $SF_6$ plasma pretreatment/SiN (n = 1.99) encapsulation. Drain and gate voltages were pulsed from ($V_{DS}$ = 6 V, $V_{GS}$ = -5 V) for the high E-field QBP (●) and from ($V_{DS}$ = 0 V, $V_{GS}$ = 0 V) for the zero field E-field QBP (□) with 200 ns pulses.

TABLE I

CHANGE IN UNGATED HEMT CHANNEL SHEET RESISTANCE ($\Delta R_S$) AND PULSED IV CHARACTERISTICS FOR VARIOUS ALGAN SURFACE TREATMENTS AND SILICON NITRIDE ENCAPSULATION LAYERS.

| | **$SiN_x$ Index = 1.88** | | | **$SiN_x$ Index = 1.99** | | | |
|---|---|---|---|---|---|---|---|
| | | **Current Recovery** | | | **Current Recovery** | | |
| **Surface Treatment** | **$\Delta R_S$ (%)** | **Pre-SiNx** | **Post-SiNx** | **$\Delta R_S$ (%)** | **Pre-SiNx** | **Post-SiNx** | **Carbon Conc.** |
| Untreated | + 10.7 | 6 % | 11 % | - 7.1 | 10 % | 33 % | 20.2 at. % |
| BOE ($NH_4$:HF) | + 6.0 | 10 % | 17 % | - 8.6 | 13 % | 40 % | 14.4 at. % |
| BOE→ $O_2$ Plasma | - 0.5 | 10 % | 91 % | - 5.0 | 7 % | 91 % | 5.4 at. % |
| BOE → $SF_6$ + $O_2$ Plasma | + 3.8 | 10 % | 87 % | - 11.7 | 13 % | 83 % | 5.8 at. % |
| BOE → $SF_6$ Plasma | + 4.4 | 13 % | 89 % | - 11.5 | 11 % | 96 % | 7.5 at. % |
| 120 sec $NH_3/N_2$ Plasma | - | - | - | >+5000 | - | - | - |

## CONCLUSIONS

Based on our observed results, we believe that the choice of surface prepassivation treatment method is equally, if not more important than the choice of passivation film for AlGaN/GaN HEMTs. Certain plasma surface treatments examined in our study outperformed wet chemical ones, allowing mitigation of almost all RF dispersion. Plasma treatments left the AlGaN surface with less adventitious carbon than wet chemical or no treatment, which may have been responsible for higher SiN passivation efficacy.


## ACKNOWLEDGEMENTS

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## ACRONYMS

SiN: Silicon Nitride
HEMT: High Electron Mobility Transistor
PECVD: Plasma-Enhanced Chemical Vapor Deposition
MOCVD: Metal-Organic Chemical Vapor Deposition
ICP: Inductively-Coupled Plasma
BOE: Buffered Oxide Etch
QBP: Quiescent Bias Point