Optimization of AlGaN/GaN HEMT SiN Passivation by Mixed Frequency PECVD

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Keywords: AlGaN/GaN, high electron mobility transistors, passivation, Silicon Nitride, PECVD

Abstract

We demonstrate a high frequency (13.56 MHz) / low frequency (100-360 kHz) plasma enhanced CVD (PECVD) process, commonly employed for the passivation of AlGaN/GaN high electron mobility transistors (HEMTs), tuned to minimize surface degradation caused by low-frequency ion surface bombardment. Under optimized conditions, bilayer PECVD SiN maintained mobility, reduced on-resistance, improved drain-source current density, minimized dynamic on resistance degradation upon off-state drain voltage stress, and minimized additional tensile stress in the device.

INTRODUCTION

Gallium Nitride high electron mobility transistors (HEMTs) with a thin ternary or a quaternary barrier have found promising applications as high frequency, high electric field, high power devices. Despite the proximity of the 2D electron channel to the surface, carrier scattering due to external factors such as surface traps have been traditionally mitigated by means of a passivation layer such as SiN [1-4]. The effective and ubiquitous SiN passivation of AlGaN/GaN HEMTs in the literature has enabled researchers to focus on upstream issues, often under-reporting the details of SiN deposition in the experimental process description. While in most cases III-N surface passivation was not the focus of their work, it is well-known that low-frequency plasma in mixed-frequency plasma enhanced CVD (PECVD) SiN deposition could introduce undesirable damage to the surface of the III-Nitride heterostructure and consequently degrade device performance. Specifically for PECVD, a low-frequency (LF, 100-360 kHz) RF generator is required as only electrons can follow the high frequency (HF, 13.56 MHz) power. As a result, additional surface traps on the AlGaN surface could be created by ions energized from the LF plasma. In this letter, we present a systematic study of HEMT degradation due to mixed-frequency PECVD SiN deposition, as well as a bilayer SiN process for optimized AlGaN/GaN HEMT passivation.

EXPERIMENTAL

Standard mixed-frequency PECVD processes are typically optimized for low stress and high uniformity in deposition rate and index of refraction across the wafer. In our PECVD tool (Oxford Instruments PlasmaLab 100), this is achieved by a high/low frequency plasma process supplied by the manufacturer and optimized on-site for general cleanroom use (300 °C, 20 W, 650 mT, 20 sccm SiH_4, 23.5 sccm NH_3, 980 sccm N_2, 13/7 sec. high/low frequency pulsed power, ~12 nm/min deposition rate). The ratio of the HF and LF cycles' duration in this process was optimized to minimize stress in the film. Such a deposition process is expected to result in a SiN film with a refractive index close to that of stoichiometric Si_3N_4 (1.98-2.01) [4-6]. In practice, the film stress, etch rate, and refractive index will vary depending on the specific tool employed. In our experience, a slightly N-rich SiN film (n ~ 1.95) results in improved AlGaN/GaN HEMT electrical performance, most likely due to reduced dangling bond concentration at the III-Nitride surface.

All HEMT samples were fabricated from a 2 nm/17.5 nm/1.8 µm thick GaN/$Al_{0.27}Ga_{0.73}N$/GaN wafer on a (111) Si substrate (R_{SH} ~689 Ω/sq.), grown by metal-organic CVD at Nitronex, Inc. Device isolation regions were defined by a Cl_2/Ar inductively coupled plasma (ICP) process (10/5 sccm Cl_2/Ar, 5 mTorr, 150 W ICP, 40 W RF, ~60 nm/min for ~100 nm deep mesas). Ohmic contacts with specific contact resistivity ρ_c of 3.25x10-5 Ω-cm^2 (1.5 Ω-mm) were deposited by e-beam evaporation of 20/120/40/50 nm Ti/Al/Ni/Au and rapid-annealed at 850 °C for 30 s in N_2. Probing pads lifted off over the Ohmic contacts consisted of 20/200 nm thick Ti/Au stacks. The Schottky gate contacts consisted of 20/200 nm thick Ni/Au. The SiN passivation process split was then performed (see Table I), followed by a 60 sec. (~100 nm/min) contact opening etch in SF_6 ICP plasma. All metallization and dielectric deposition steps were preceded by a cleaning procedure consisting of a 5 min. UV-O_3 clean, a 30 sec. 1:10 HCl:H_2O dip, and a 30 sec. buffered HF dip immediately prior to deposition [7]. Measured devices had a gate length of 3 µm, gate-source spacing of 2.5 µm, and a gate-drain spacing of 10 µm in order to maximize the effects of the SiN passivation in the access region.

RESULTS AND DISCUSSION

Reference HEMTs fabricated using the standard SiN deposition process described earlier (row 1 in Table I) exhibited significantly degraded performance, as measured by Hall on a van der Pauw (VdP) structure with active area exposed to the plasma process: $R_{SH} > 1500$ Ω/□, $\mu_H = 516$ cm^2/V·s, $N_{SH} = 4.6\times10^{12}$ cm^{-2}, compared to $R_{SH} = 602$ Ω/□, $\mu_H = 1455$ cm^2/V·s, $N_{SH} = 7.14\times10^{12}$ cm^{-2} measured on a gated, plasma-protected VdP. We emphasize that identically-processed HEMTs on commercial quality AlGaN/GaN exhibited only about 10-15% degradation in Hall mobility; however, degradation in on resistance was still substantial as indicated by step-stress pulsed I-V measurements [8].

TABLE I

CHARACTERISTICS OF SIN PASSIVATED HEMTS USED IN THIS WORK.

ID	Total SiN thickness (nm)	Barrier HF-SiN growth time (sec.)	HF/LF SiN growth time (sec.)	Refractive index, n	E_G (eV)
Ref	100.1	0	510	1.903	4.14
A	96.1	15	495	1.956	4.18
B	98.6	30	480	1.931	4.16
C	102	60	450	1.903	4.05
D	107.2	180	330	1.890	3.99
E	119.1	510	0	1.889	3.63

The sample split presented in Table I aimed to minimize the LF-plasma ion damage to the III-Nitride surface by inserting a thin SiN film grown by HF-plasma before the HF/LF plasma process. Bilayer SiN in samples B-E consisted of 15-180 sec. HF-SiN (3-35 % of the 510 sec. total growth time) followed by the standard HF/LF SiN deposition used in the passivation of the reference HEMT. Sample E was passivated using only HF-SiN. The variation in bilayer SiN thickness resulted from the ~15% faster growth rate for HF-SiN, compared to the standard HF/LF SiN process. As shown in Table I, samples A-E (grown consecutively) exhibited decreasing refractive index and energy gap, measured by ellipsometry, as the HF-SiN content increased. Gated VdP structures on samples A-E, on average, exhibited $R_{SH} = 596$ Ω/ , $\mu_H = 1466$ cm^2/V·s, $N_{SH} = 7.26\times10^{12}$ cm^{-2}, whereas the average Hall parameters on the plasma exposed VDP's were $R_{SH} = 514$ Ω/ , $\mu_H = 1333$ cm^2/V·s, $N_{SH} = 9.22\times10^{12}$ cm^{-2} (shown in Fig. 1a for the individual samples). The stress in the HF-SiN films was tensile, as confirmed by the wafer bow of reference Si wafers with 100 nm thick HF-SiN, resulting in increased N_{SH}, reduced R_{SH}, and a negative shift in threshold voltage V_{TH} (Fig. 1). The lowest mobility values were measured for the samples with thinnest (sample A) and thickest (sample E) HF-SiN films, most likely due to LF-plasma induced surface states in the former sample and increased hot electron scattering in the channel for the latter. Thus, a 7-14 nm thick (30-60 sec. deposition) HF-SiN was determined as the optimal thickness for a bilayer mixed-frequency PECVD process AlGaN/GaN HEMT passivation.

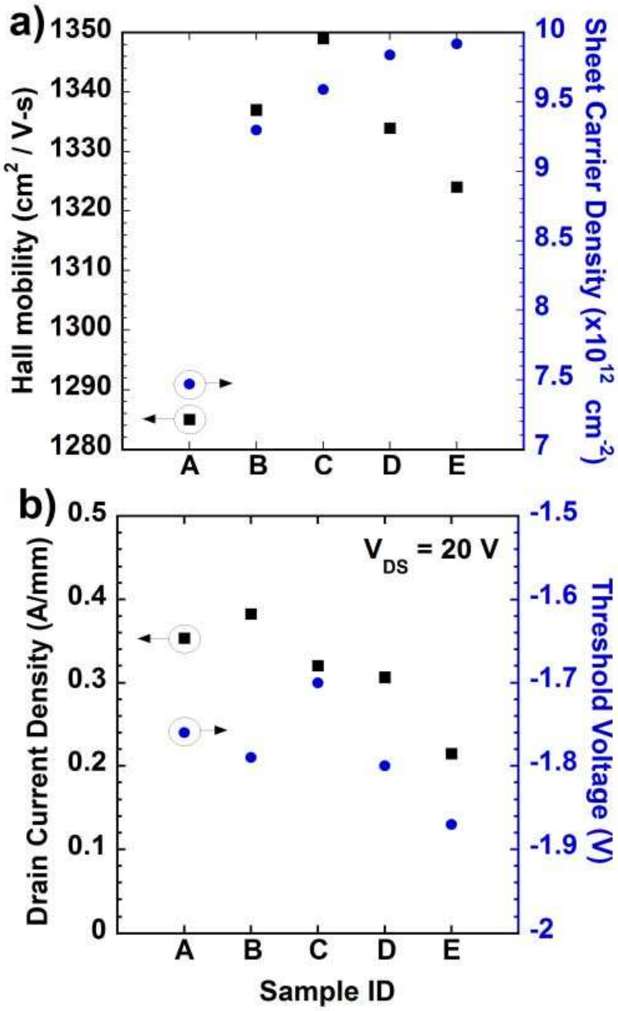

Fig. 1. a) Hall mobility (μ_H), sheet carrier density (N_{SH}), b) saturation drain current density ($J_{DS,SAT}$), and threshold voltage (V_{TH}) for samples A-E.

The effect of the bilayer SiN deposition process is evident in Fig. 2a, where we present a comparison in DC output characteristics for samples B (14 nm thick HF-SiN) and E (119 nm thick HF-SiN), showing about a factor of 2 higher drain current density (J_{DS}) for sample B. We further present a comparison of dynamic on resistance ($R_{ON,DYN}$) measured under pulsed IV conditions using an Accent DiVA D265EP analyzer (200 ns on-state pulse width, 1 ms pulse separation, 99.98% duty cycle). The reduction in $R_{ON,DYN}$ for 0 V quiescent drain bias correlated well with the increase in N_{SH} as thicker, more tensile HF-SiN was grown. However, pulsed measurements after a 50 V quiescent drain bias revealed lowest degradation for sample B, where $R_{ON,DYN}$ increased from 13 Ω-mm to 28.6 Ω-mm.

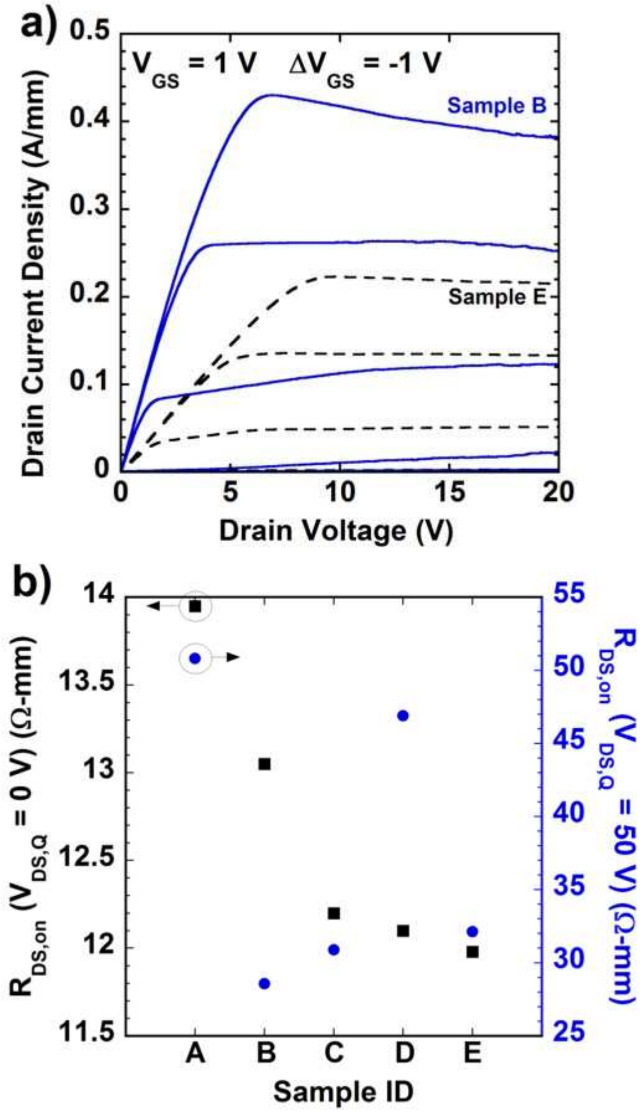

Fig. 2. a) Comparison in DC I_{DS}-V_{DS} characteristics for samples B and E. b) $R_{DS,ON}$ as a function of 0 V and 50 V quiescent drain-source bias for samples A-E.

CONCLUSIONS

We demonstrated a high frequency (13.56 MHz) / low frequency (100-360 kHz) plasma PECVD process tuned to minimize mobility degradation caused by low-frequency ion surface bombardment. An optimized process for SiN deposition that achieves high mobility, low change in on-resistance, and low additional tensile stress in the device was developed. While excellent HEMT performance has been shown with SiN grown in situ with the AlGaN/GaN heterostructure by molecular beam epitaxy or metal organic CVD [9, 10], a thick PECVD SiN cap is still commonly employed for HEMT passivation. Our data suggested that initiating PECVD with a thin HF-SiN layer mitigated plasma damage to the AlGaN surface. While one would expect this effect to be minor on commercial quality HEMT material, damage from any possible source must be removed in order to maximize device reliability, which is a crucial requirement for the commercial success of GaN.

ACKNOWLEDGEMENTS

The authors thank Dr. Marc Christophersen, Dr. Doe Park, and the NRL Nanoscience Institute staff (Mr. Walter Spratt and Mr. Dean St. Amand) for PECVD tool maintenance. Research at NRL was supported by the ONR.

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