Link Between Silicon Nitride Stoichiometry, Vertical Epitaxial Conductivity and Current Collapse in AlGaN/GaN Power Devices

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Abstract

Vertical conductivity between the channel and the carbon doped GaN buffer in AlGaN/GaN HEMTs is critical for the suppression of buffer-related current collapse. Here we show for the first time that this leakage path can be controlled by changing the LPCVD SiN_x passivation stoichiometry. We demonstrate a direct correlation between SiN_x stoichiometry, buffer leakage, and suppression of dynamic R_{ON} dispersion.

INTRODUCTION

AlGaN/GaN HEMTs and MISHEMTs have shown much promise for use in high power, high switching-speed applications. There still exist performance challenges before these devices become a dominant force in the power switching market. Current collapse and device leakage are both important performance parameters which can be controlled by various methods such as gate shaping [1] and optimization of the buffer [2]. Modifying the passivation has been shown to change device leakage and surface related current collapse [3]. We show that LPCVD SiN_x stoichiometry is a parameter which affects not only surface related leakage and charge storage [4] but can also control buffer-related current collapse, otherwise known as dynamic R_{ON} dispersion. Current collapse and device leakage are both important performance challenges that must be controlled in AlGaN/GaN HEMTs before these devices are fit for the power switching market.

APPROACH

Devices were fabricated on a set of nominally identical wafers using a 650V GaN-on-Si depletion mode process [5]. The only step which varied in the process was the stoichiometry of the first LPCVD SiN_x passivation layer. The Si-content of the SiN_x layer increased from wafers A to D, with details displayed in Table I. Si-content is controlled by changing the DCS/NH_3 ratio during deposition while keeping pressure constant. The GaN wafers were grown on p-type Si. The epitaxy consisted of a strain relief layer (SRL), a carbon doped GaN buffer, a GaN channel and a 20 nm $Al_{0.2}Ga_{0.8}N$ barrier; the total epitaxial thickness was ~ 5 µm. This work extends our investigation of the impact of SiN_x stoichiometry on surface charges and field plate effectiveness [6] to include changes to charge trapping in the carbon doped GaN buffer. Changes to leakage and dynamic R_{ON} were measured. Substrate bias sweep measurements were made. These are surface insensitive and can identify the presence of charge storage and the location and magnitude of leakage paths within the buffer stack [7]. Wafers with low vertical conductivity between the 2DEG and the C:GaN buffer will allow negative charge to accumulate at the top of the C:GaN layer when substrate biased [7], leading to channel pinch-off at a smaller substrate bias. This negative charge will reduce the on-state 2DEG current resulting in current-collapse. Conversely a high vertical conductivity between the channel and the C:GaN layer will suppress channel pinch-off during substrate bias as positive charge accumulates at the bottom of the C:GaN layer. This positive charge is easily neutralized on bias removal due to the diode-like behavior between the 2DEG and C:GaN.

TABLE I
LPCVD SiN_x PROPERTIES BY WAFER

Wafer	DCS/NH_3	Stress (MPa)	Refractive index
A	0.33	1132	2.01
B	2.49	428	2.10
C	3.30	275	2.14
D	4.38	117	2.21

RESULTS AND DISCUSSION

Increasing the Si-content in the LPCVD SiN_x layer increases its conductivity. Fig. 1 shows six orders of magnitude difference in leakage through the 70nm LPCVD SiN_x layer between the stoichiometric Si_3N_4 on wafer A and the Si rich SiN_x layer on wafer D. This leads to wafers with highest Si-content SiN_x passivation, C and D, having the highest drain leakage (Fig. 2). However, these Si rich wafers show suppression of current collapse after off-state

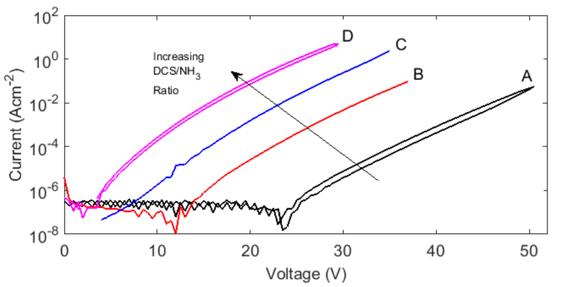

Fig. 1. Leakage through LPCVD SiN_x layer measured on 100 µm by 100 µm test structure.

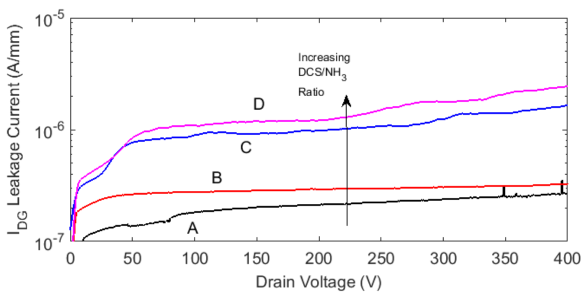

Fig. 2. Off-state drain leakage (V_{GS} = -5V) measured on fully processed AlGaN/GaN HEMTs.

drain bias stress (Fig. 3). Wafer B is close to optimal with low drain leakage and low current collapse. The stoichiometric Si_3N_4 of wafer A showed low drain leakage but unacceptably high current collapse.

In Fig. 4(a), wafer A shows a reduced channel current after a bidirectional substrate sweep, which since substrate measurements are surface insensitive indicates negative charge storage in the buffer. This demonstrates that the location of the negative charge responsible for the high current-collapse seen in Fig. 3 is at least partially in the buffer. The 'clockwise' change in current seen in Fig. 4(a) for wafers B-D indicates positive buffer charge storage and good electrical coupling (i.e. vertical leakage) between the C:GaN and the 2DEG [7]. To explain the data, wafer B requires a small vertical leakage in the GaN channel layer and C&D have a higher vertical leakage. This leakage path suppresses negative charge build-up and hence reduces buffer-related current collapse. Fig. 4(b) is an equivalent circuit model of the epitaxial stack. The data is consistent with changes in the SiN_x stoichiometry changing the vertical conductivity between the 2DEG and the C:GaN buffer, highlighted in red. Increasing the Si-content in the LPCVD SiN_x increases this conductivity.

Counter-intuitively, it is clear that changing the surface passivation can change the bulk leakage properties in the upper part of the epitaxial stack. The cause for this change in vertical conductivity may be linked to reported changes in diffusivity of ions through this blocking layer [8], and this mechanism will be investigated in future work.

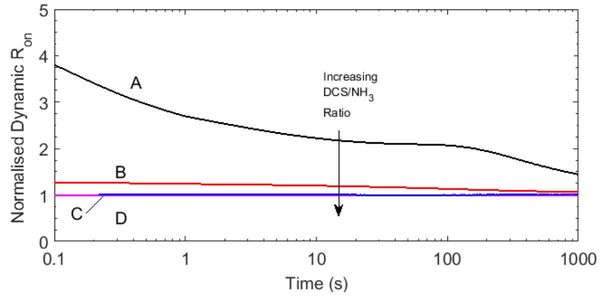

Fig. 3. Normalised dynamic on-resistance measured on fully processed AlGaN/GaN HEMTs after 1000s off-state stress (V_{GS}=-5V, V_{DS}=100V).

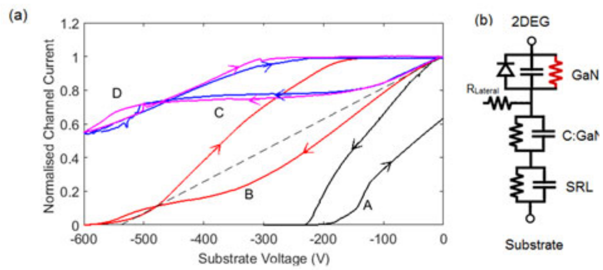

Fig. 4. (a) Substrate bias sweeps performed on HEMTs held in on-state (V_{GS}=0V, V_{DS}=1V). Source to drain distance is 15 µm. Source and gate were shorted. Capacitive behavior is indicated with the dashed line. A faster than capacitive change in current indicates negative charge storage in the buffer, leading to current collapse as with wafer A. Slower than capacitive change indicates positive charge storage as with wafers B, C and D; (b) Equivalent circuit model of epitaxial stack, the resistance of highlighted resistor changes between the wafers leading to different charge storage in the buffer.

Conclusions

LPCVD SiN_x passivation stoichiometry not only affects leakage, charge trapping and reliability at the surface but can also be used to change the conductivity within the bulk of the GaN epitaxy between the 2DEG and the C:GaN layer. This conductivity is crucial for controlling buffer-related charge storage for improved current collapse performance of AlGaN/GaN HEMTs. We demonstrate an optimum combination of low drain leakage and low current-collapse.

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ACRONYMS

C:GaN : Carbon doped GaN epitaxial layer
DCS : Dichlorosilane
HEMT : High electron-mobility transistor
LPCVD : Low pressure chemical vapor deposition
PECVD : Plasma enhanced chemical vapor deposition
2DEG : Two-dimensional electron gas