Investigation of AlGaN/GaN HEMTs Passivated by AlN Films Grown by Atomic Layer Epitaxy

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AlGaN/GaN high electron mobility transistors (HEMTs) are attractive for high power, high frequency and high power switching applications, however limitations in performance can arise from charge trapping effects. Surface passivation is necessary to mitigate surface state charge trapping, which results in current collapse. Typically, plasma-enhanced chemical vapor deposition (PECVD) SiN_x is used to passivate AlGaN/GaN HEMT surface states. Recently, thin (4 nm) AlN films grown by atomic layer deposition (ALD) have been demonstrated to provide effective passivation [1]. In this work, we investigate AlN passivation layers grown by atomic layer epitaxy (ALE) with thickness up to 40 nm and growth temperatures (T_g) up to 500 °C for improved passivation. The passivation schemes are characterized using a DiVA™ pulsed I-V measurement system and a novel on-wafer probe card boost converter test setup. AlN films grown at 300 °C are deposited after gate processing. The 500 °C AlN films are deposited following mesa and ohmic processing, then following ALE AlN deposition, gate fabrication using a KOH based recess etched followed by gate metal lift-off completes the process. ALE surface preparation includes UV ozone for carbon contamination removal, followed by HCl and HF treatments and a low damage *in situ* nitrogen plasma pretreatment for removal of native surface oxide. Then, AlN layers are grown by ALE using high purity trimethylaluminum (99.999%) and nitrogen (99.999%). Current collapse for each passivation scheme is compared by the ratio of DC drain current ($I_{DS,STATIC}$) to the maximum pulsed drain current ($I_{DS,MAX,PULSE}$) at pulse width of 500 ns and pulse separation of 1 ms, as shown in Figure 1. SiN_x resulted in the largest observed current collapse, where $I_{DS,STATIC}$ reached 84% of $I_{DS,MAX,PULSE}$. The 300 °C grown AlN films provided improved passivation, where $I_{DS,STATIC}$ reached 92% and 97% of $I_{DS,MAX,PULSE}$ for 4 nm and 40 nm thick films respectively. Also, 300 °C grown AlN outperforms SiN_x passivation during “off-state” stressing. “Off-state” stress is applied at a gate quiescent point ($V_{GS,Q}$) of -4 V and drain quiescent biases ($V_{DS,Q}$) up to 50 V, while the device is pulsed to obtain the transfer characteristics at V_{GS} = 1 V. Change in dynamic on-resistance ($R_{ON,DYN}$) (Figure 2) and maximum drain current ($I_{DS,MAX}$) (Figure 3) are shown for each passivation scheme during “off-state” stressing. A boost converter test setup (Figure 4) constructed on a probe card is used to characterize the switching performance of each of the passivation scheme. During the “on-state” operation of the boost converter, lower V_{ds} indicates lower $R_{ON,DYN}$ for the devices passivated by AlN. The maximum value of V_{ds} is pinned at the DC boost converter output voltage, therefore, higher maximum V_{ds} indicates higher efficiency. ALE AlN films grown at 300 °C offer improved passivation over PECVD SiN_x, and thicker (40 nm) AlN films are more effective than the thinner (4 nm) AlN films. Additional results will be presented on current collapse of higher quality AlN films grown at 500 °C by ALE. Atomic force microscopy (AFM) measurements show slightly reduced root mean squared (RMS) deviation of the surface from 6.2 to 5.8 nm for films grown at 300 °C and 500 °C respectively (Figure 6). Additionally, AlN passivated AlGaN/GaN HEMTs will be integrated into the “diamond before gate” process [2] for reducing self-heating. Higher thermal conductivity of AlN compared to SiN_x provides opportunity for improved thermal management while providing effective passivation.

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[2] M.J. Tadjer, et. Al. IEEE Electr. Dev. Lett. **33**, 23-25 (2012)

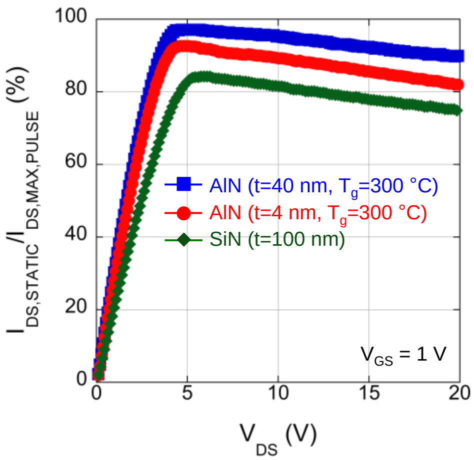

Figure 1. Current collapse for AlGaN/GaN HEMTs passivated by AlN and SiN, shown by the ratio of collapsed DC drain current ($I_{DS,STATIC}$) to the maximum drain current from pulsed I-V measurements ($I_{DS,MAX,PULSE}$).

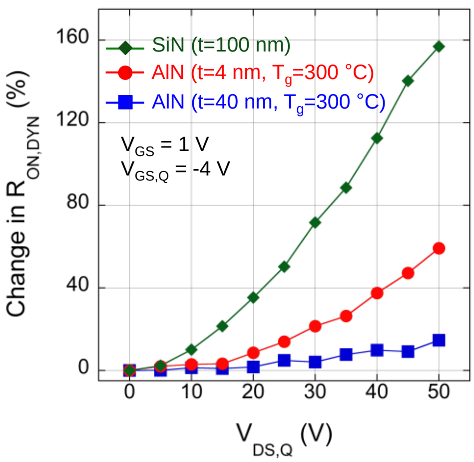

Figure 2. Increase of dynamic on-resistance of 300 °C AlN and SiN passivated AlGaN/GaN HEMTs during pulsed measurements with increasing drain quiescent point stress ($V_{DS,Q}$) in "off-state".

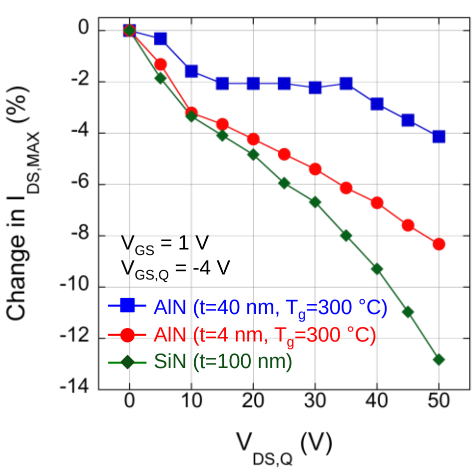

Figure 3. Reduction in $I_{DS,MAX}$ of AlN and SiN passivated AlGaN/GaN HEMTs during pulsed measurements with increasing "off-state" drain quiescent point stress ($V_{DS,Q}$).

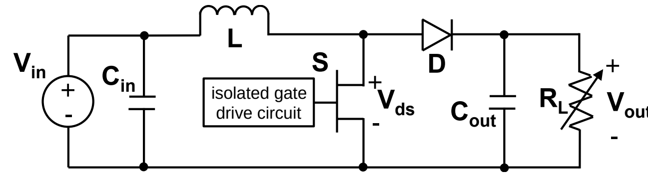

Figure 4. Block diagram of a boost converter test setup built on a probe card.

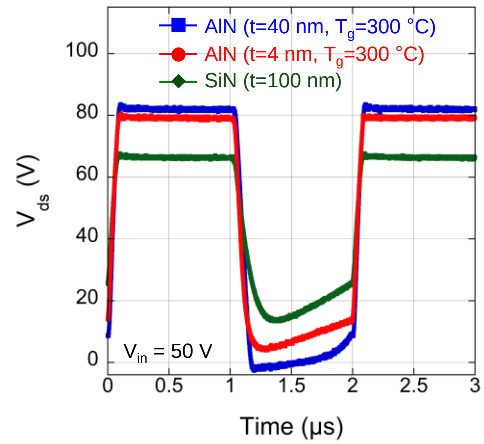

Figure 5. Drain voltage transient from boost converter test circuit on-wafer probe card for each passivation scheme. Input voltage (V_{in} = 50 V), frequency = 500 kHz, duty cycle = 50%, and with a load resistor (R_L = 5.6 kΩ).

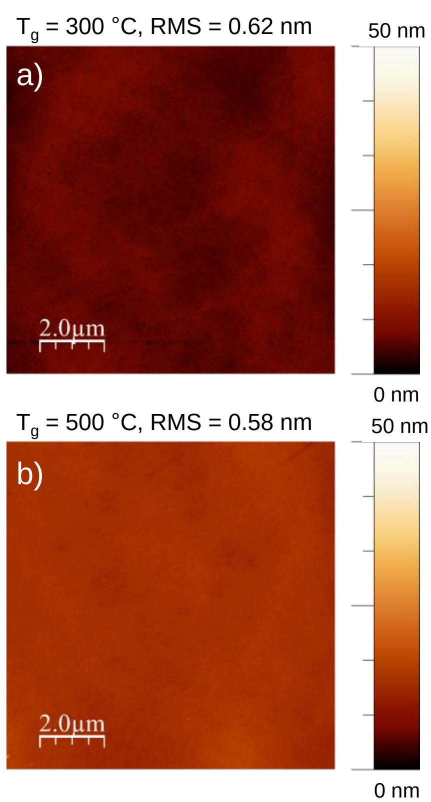

Figure 6. Surface roughness measured by AFM of ALE grown AlN films with growth temperature (T_g) of a) 300 °C and b) 500 °C.