Using the CnCV Technique to Explore AlN as an Alternative Passivation Layer in GaN HEMT Technology

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Abstract

AlN has shown potential promise as an alternative passivation dielectric to the standard Al_2O_3 in GaN HEMT structures. In this work we investigate thermal ALD AlN as an alternative for Al_2O_3 passivation of the AlGaN surface in a HEMT structure. However the replacement of a passivation dielectric in a device requires careful investigation and can be a costly and time consuming process. Therefore, the low cost, quick feedback corona non-contact CV (CnCV) technique has been employed in this investigation in order to efficiently study thermal ALD AlN passivation in a non-contact, preparation-free manner. The CnCV technique was used to assess key HEMT structure parameters such as pinch-off voltage (Vp) and 2DEG sheet charge (Q_{2DEG}) on a thickness skew of thermal ALD AlN and reference process Al_2O_3 passivated HEMT structures. This allowed efficient determination of the AlN thickness necessary for matching of the Q_{2DEG} to the Al_2O_3 reference process. Dielectric thickness non-uniformity of the AlN was also assessed directly on the AlGaN HEMT structure using CnCV measured SASS voltage (not possible using standard ellipsometry). Reduction of D_{it} at the AlGaN interface for the thermal ALD AlN compared to Al_2O_3 was also demonstrated by photo-assisted CnCV results with confirmation from dynamic Rds(on) measurements on final device structures. This work demonstrates the distinct advantages the CnCV technique and the results show the promise of thermal ALD AlN as an alternative passivation dielectric for AlGaN.

INTRODUCTION

In this work the corona non-contact CV (CnCV) technique has been utilized to assess thermal aluminum nitride (AlN) as a potentially advantageous alternative to the mainstream Al_2O_3 passivation layer commonly used in GaN HEMT technology. Plasma-enhanced ALD AlN has been previously reported to reduce D_{it} at the interface between ALD passivation and AlGaN in HEMT structures, with positive impact on GaN device stability [1]. Less is known about thermal ALD AlN in GaN devices. Compared with PE-ALD, thermal ALD has several advantages such as batch processing, a simpler and more mature toolset and no potential plasma damage to passivated surface [2].

Replacing a material, such as a passivation dielectric, in a device requires significant process flow modifications and re-development of individual process steps. This can be a very costly and time-consuming process. Therefore a low cost, quick feedback metrology technique to carefully investigate new materials can be very advantageous. In this respect the CnCV technique can be of great benefit. CnCV offers non-destructive, preparation-free wafer level measurement. Since 2018 it is available in tools designed specifically for wide-bandgap semiconductor technology. CnCV tools have been already extensively applied for characterization of SiC, GaN and AlGaN/GaN HEMT [3,4].

The non-contact electrical measurements in CnCV are based on precise dosing of charge, ΔQ_C, on the surface, performed with a corona discharge in air. The charging serves as a bias and the response is monitored as a change of the surface voltage, ΔV, measured with a non-contact Kelvin probe.

EXPERIMENTAL RESULTS AND DISCUSSION

The key parameters extracted from CnCV measurements is this study include pinch-off voltage (V_P), 2DEG sheet charge (Q_{2DEG}) and positive SASS voltage (the dielectric tunneling voltage under positive corona bias). For ALD dielectrics the SASS voltage typically scales with ALD cycles, providing a measure of the deposition process and film thickness.

A skew of thermal ALD AlN samples with varying ALD cycles was deposited on standard normally-on AlGaN/GaN HEMT structures on Si substrates. Reference process samples included thermal ALD Al_2O_3 coated and bare AlGaN/GaN HEMT structures.

Figs 1 and 2 show the capacitance-voltage, CV, and capacitance-charge, CQ, characteristics measured on thermal ALD AlN samples along with with the reference Al_2O_3 and bare HEMT samples. CV is used for the determination of V_P and 2DEG sheet charge. The latter is obtained by integration of the capacitance similar to the conventional contact CV technique. The unique CnCV C-Q characteristics allow the novel direct determination of the 2DEG sheet charge as the amount of deposited charge from the initial state condition (0 charge in Fig. 2) to the pinch off condition, Vp. The measured sheet charge values, Q_{2DEG}, are presented in Fig 3. They are normalized to the Al_2O_3 value, treated as the reference. Good agreement between the two independent determinations of Q_{2DEG} is evident. With the information in Fig. 3, one can quickly target what number of AlN ALD cycles that will give the closest 2DEG sheet charge to the reference Al_2O_3 process. In the present skew, the 50 cycle AlN sample has a 1.2x higher

Q_{2DEG} than the reference Al_2O_3 sample. This type of process targeting for a new material is made cost and time effective with the CnCV technique.

The CnCV SASS voltage measurements were used to gain quick, direct insight into thermal ALD AlN growth on AlGaN. The ΔSASS voltage values in Fig. 4 are after subtraction of SASS voltages measured on a bare AlGaN HEMT structure without an ALD layer. Therefore the ΔSASS values reflect the growth of thermal ALD AlN films on AlGaN as a function of ALD cycles. At 50 cycles and above the dependence becomes linear. However values deviating from the linear dependence below 50 cycles may be an indication of an incubation effect analogous to that in thermal ALD AlN growth on Si that occurs for the first 50 cycles [5]. The SASS voltage was also used to assess the within wafer thickness variation of passivation films on HEMT structures. This application is especially important considering that ellipsometry measurements of AlN thickness on complex AlGaN/GaN structures are difficult and require extensive modelling. The across wafer diameter line scans of the SASS voltage are shown in Fig. 5 for the AlN skew and the reference Al_2O_3 sample. Larger within wafer non-uniformity is evident for some of the AlN samples when compared to the ref. Al_2O_3.

Pulsed Ids(Vds) curves measured shortly after off-state quiescent biases on final device transistors in Fig. 6 show a reduction in dynamic Rds(on) for the 50 cycles thermal AlN compared to the reference Al_2O_3. This is ascribed to lower D_{it} levels at the AlGaN interface which is corroborated by photo-assisted CnCV measurements showing a lower deep interface state concentration for the thermal ALD AlN passivated samples compared to the reference Al_2O_3.

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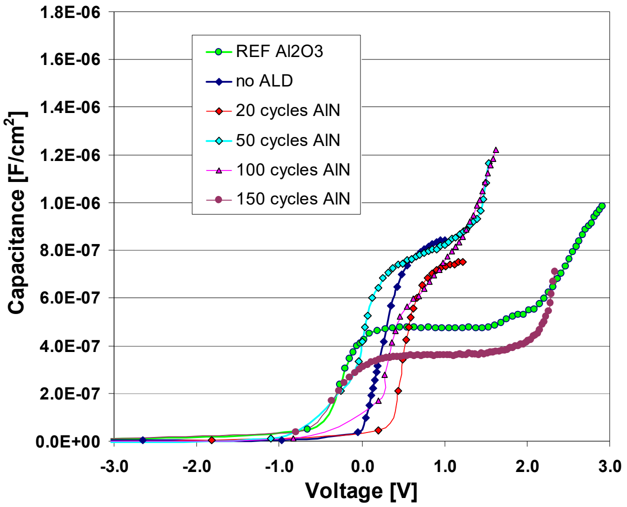

Figure 1. CV characteristics for the skew of thermal ALD AlN samples along with the reference ALD Al_2O_3 and bare HEMT samples.

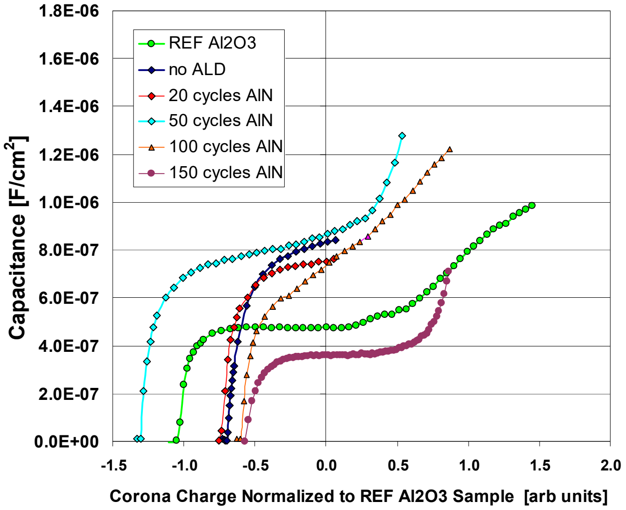

Figure 2. CQ characteristics for the skew of thermal ALD AlN samples along with the reference ALD Al_2O_3 and bare HEMT samples. Corona charge on x-axis has been normalized to the reference Al_2O_3 sample.

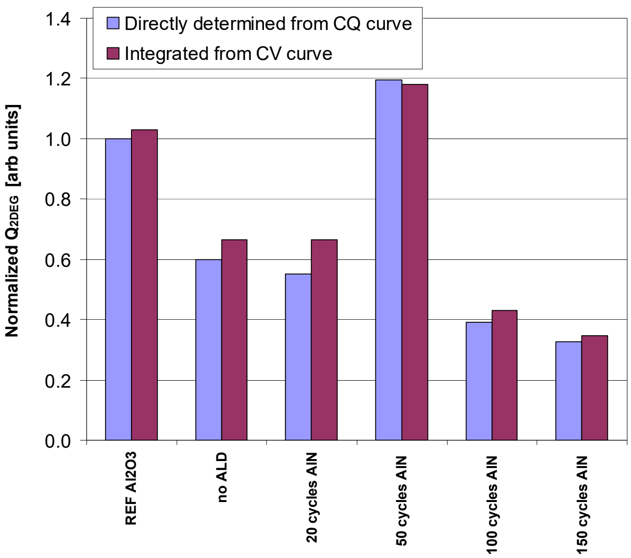

Figure 3. 2DEG sheet charge (Q_{2DEG}) comparison of thermal ALD AlN skew to the reference thermal ALD Al_2O_3 layer. The Q_{2DEG} values are normalized to the ref. Al_2O_3 sample. The 50 cycle AlN sample has 1.2x larger Q_{2DEG} than the ref. Al_2O_3.

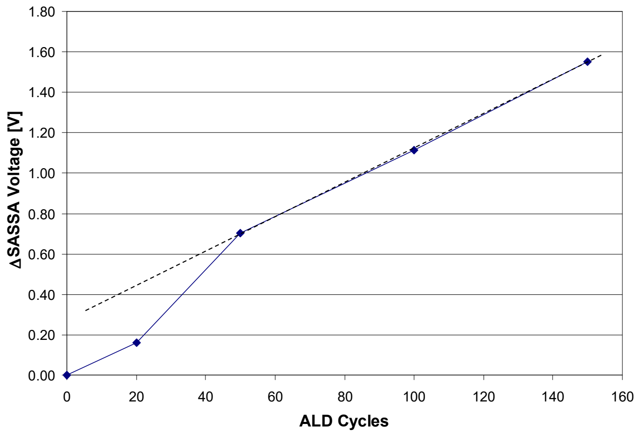

Figure 4. ΔSASS voltage (measure of physical thickness) versus thermal ALD growth cycles for AlN on AlGaN indicates incubation effect for cycles below 50.

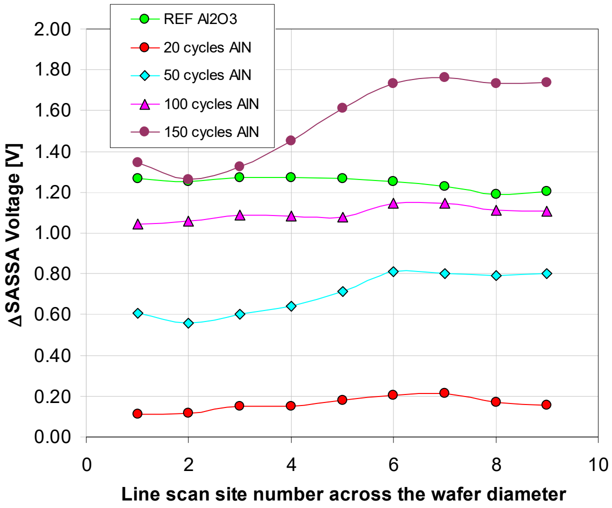

Figure 5. A line scan across the wafer diameter of the ΔSASS voltage (indicator of physical thickness) for the thermal ALD AlN skew and ref. Al_2O_3 passivated HEMT structures. Larger within wafer non-uniformity was observed for the some of the AlN samples than the ref Al_2O_3.

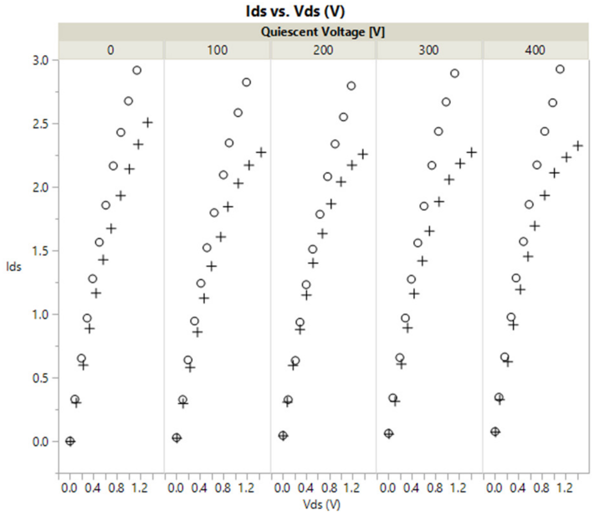

Figure 6. Current-Voltage (Ids vs Vds) results from pulsed IV on final device transistors show improvement in passivation evidenced by the reduction in dynamic Rds(on) for the 50cycle thermal ALD AlN sample (open circles) compared to the ref Al_2O_3 sample (crosses).