# ALD-grown Ultrathin AlN Film for Passivation of AlGaN/GaN HEMTs

Sen Huang, Qimeng Jiang, Shu Yang, Chunhua Zhou, Kevin J. Chen

Dept. of Electronic and Computer Engineering, Hong Kong University of Science and Technology, Hong Kong
Tel: (852) 2358-8969, Fax: (852) 2358-1485, Email: eekjchen@ust.hk

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## Abstract

**An effective passivation technique for AlGaN/GaN HEMTs is presented. This technique features ultrathin AlN film grown by atomic layer deposition (ALD). With *in-situ* remote plasma pretreatment prior to the AlN deposition, atomic sharp interface between ALD-AlN and III-nitride can be obtained. Significant current collapse suppression and dynamic ON-resistance reduction are demonstrated in the ALD-AlN passivated AlGaN/GaN HEMTs under high drain bias switching conditions.**

## INTRODUCTION

GaN-based high-electron mobility transistors (HEMTs) are capable of delivering low loss, high breakdown voltage, fast-switching, high-power handling for power switch applications. However, the polarized surface of AlGaN/GaN HEMTs easily suffers from surface-state-induced adverse effects such as current collapse [1], especially at high-voltage switching conditions [2]. PECVD-grown $SiN_x$ has been demonstrated as an effective passivation material to suppress the current collapse [3] in RF/microwave power amplifiers that typically require moderate drain bias voltage, e.g. 28 V or 42 V. For power switching at high drain bias larger than 100 V, Chu et al. demonstrated that $SiN_x$-passivation needs to be combined with sophisticated multiple field-plate to achieve low current collapse and high breakdown voltage simultaneously [2].

The recently developed oxide-based high-*k* dielectrics such as $Al_2O_3$ [4, 5] and $HfO_2$ [6], have also been deployed as the materials for surface passivation. However, the high density deep interface-states exist at the oxide/(Al)GaN interface [7, 8], and they could result in current collapse at high drain bias. Thus, the nitride-based oxygen-free high-*k* dielectrics such as AlN featuring much smaller lattice mismatch to GaN, larger bandgap and better thermal conductivity than $SiN_x$, is a compelling candidate for passivation with low interface states for GaN-based devices [9-11].

In this work, we demonstrate an effective passivation technique featuring ultrathin AlN film grown by plasma enhanced ALD on AlGaN/GaN HEMTs. Assisted by *in-situ* remote plasma pretreatment (RPP), atomic sharp interface is obtained between the ALD-grown AlN and III-nitride surface, resulting in significant reduction of the current collapse and the dynamic ON-resistance (dynamic_$R_{on}$) in AlGaN/GaN HEMTs, especially when the devices are switched from high drain bias.

## DEVICE FABRICATION

The sample used in this work is a commercial $Al_{0.26}Ga_{0.74}N$/GaN HEMT wafer grown by MOCVD on (111) silicon substrate. The fabrication processes started with mesa etching. Ohmic contacts were formed by an alloyed Ti/Al/Ni/Au metal stack. Ni/Au was used for the gate electrode. Four samples with various surface conditions were then prepared: sample 1 (S1) without the RPP and passivation, sample 2 (S2) with wet solution based cleaning and PECVD-grown 100 nm $SiN_x$ passivation, sample 3 (S3) with the RPP and ALD-grown 4 nm AlN passivation, and sample 4 (S4) with the RPP only. Agilent B1505A power device analyzer/curve-tracer was used for dc and current collapse characterization of HEMT S1-S4.

The *in-situ* RPP used for S3 and S4, features $NH_3$, Ar, $N_2$ plasma applied in sequence at a substrate temperature of 300 $^oC$. Atomic force microscopy confirmed that such pretreatment is able to create a good sample surface with visible atomic steps. After the RPP, the 4-nm AlN layer was deposited at 300 $^oC$ using plasma $N_2/H_2$ and trimethylaluminum (TMA) precursors as the N and Al sources. An atomic sharp interface between the ALD-AlN and AlGaN/GaN HEMT is obtained, as confirmed with high resolution transmission electron microscopy (HRTEM) shown in Fig. 1.

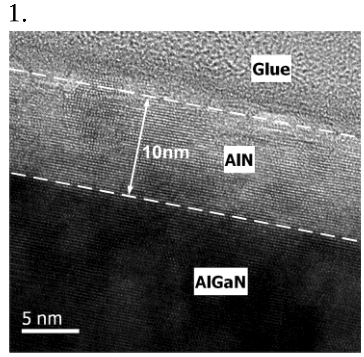


Fig. 1 HRTEM cross-section view of the interface between a 10 nm ALD-AlN and the AlGaN/GaN HEMT sample. Thicker AlN was used for observation purpose.

## RESULTS AND DISCUSSION

A transient output characterization was conducted to evaluate the dynamic_R$_{on}$ of devices with different passivation conditions. The devices would first be set at OFF-state by applying a gate bias ($V_{GS}$ = -3 V in this work) bellow the pinch-off voltage, while $V_{DS}$ is swept from 0.75 V (the drain bias at the ON-state) to a preset value. Then the device is switched back to the ON-state by applying $V_{GS}$ = 0 V and $V_{DS}$ = 0.75 V at which a dc ON-state current no less than 100 mA/mm is obtained. The output resistance measured at $V_{GS}$ = 0 V and $V_{DS}$ = 0.75 V was used to evaluate the dynamic_R$_{on}$ and current collapse.

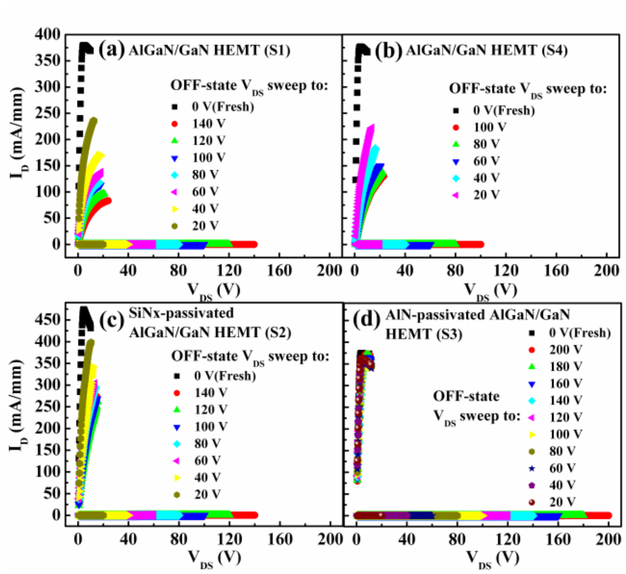

Fig. 2 Transient output characteristics of AlGaN/GaN HEMTs with $L_{GD}$=5 µm (a) without passivation and the RPP (S1), (b) without passivation but with the RPP (S4), (c) with $SiN_x$ passivation (S2), and (d) with the RPP and ALD-AlN passivation (S3). The switching from OFF-state to ON-state is just once for each curve, and the switching time is ~70 ms.

The output switching characteristics measured in S1, S2, S3 and S4 are plotted in Fig. 2. The unpassivated devices in S1 and S4 show significant current collapse that becomes worse as the OFF-state drain bias increases. $SiN_x$ passivation is shown to be most effective at smaller OFF-state drain bias stress, while starts to show its limitation at larger drain bias. On the other hand, the ALD-AlN passivated devices (Fig. 3(d)) exhibit much smaller current collapse, even with an OFF-state drain bias applied to 200 V, suggesting a more effective surface passivation.

For devices with various values of $L_{GD}$, the ratio of dynamic_R$_{on}$ to static_R$_{on}$, was drawn as a function of the OFF-state drain bias stress in Fig. 3. The much slower increase of the dynamic_R$_{on}$ in S3 implies that AlN thin film grown by ALD passivation could be a promising candidate for GaN-based power switches, especially at high drain bias switching conditions.

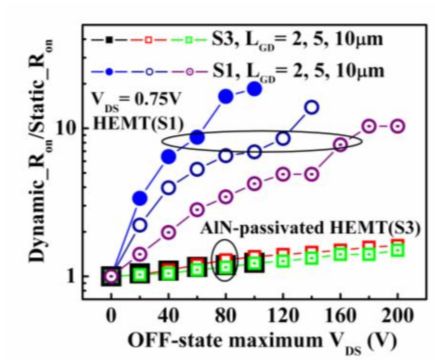

Fig. 3 Ratio of dynamic_R$_{on}$ and static_R$_{on}$ with varied OFF-state drain bias stress for S1 (without the RPP and passivation) and S3 (with the RPP and ALD-AlN passivation).

## CONCLUSIONS

A passivation technique using a 4-nm-thick AlN film deposited by ALD along with *in-situ* remote plasma pretreatment is demonstrated for AlGaN/GaN power HEMTs. Significant current collapse suppression and dynamic_R$_{on}$ reduction are achieved in ALD-AlN passivated AlGaN/GaN HEMTs without the use of field-plate.

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## ACRONYMS

ALD: Atomic Layer Deposition
AlGaN/GaN HEMTs: AlGaN/GaN High Electron Mobility Transistors
HRTEM: High Resolution Transmission Electron Microscopy
MOCVD: Metal Organic Chemical Vapor Deposition
PECVD: Plasma Enhanced Chemical Vapor Deposition