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

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Abstract

An effective passivation technique for AlGaN/GaN HEMTs is presented. This technique features AlN ultra-thin film grown by plasma enhanced atomic layer deposition (ALD). With in-situ remote plasma pretreatments prior to the AlN deposition, atomically sharp interface between ALD-AlN and III-nitride has been obtained. Effective 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 ON-resistance, high breakdown voltage, fast-switching speed, high-power handling capability for power switch applications [1-5]. However, AlGaN/GaN HEMTs typically feature a channel that is at a short distance (e.g. ~20 nm) from the polarized surface, and could easily suffer from surface-state-induced adverse effects such as current collapse [6, 7], especially at high-drain-voltage switching conditions [8]. PECVD-grown SiNx has been widely adopted as an effective passivation material to suppress the current collapse [7, 9] in RF/microwave power amplifiers that typically require moderate drain bias voltage. For power switching at high drain bias (>100 V), Chu et al. have shown that SiNx-passivation alone is not adequate, and needs to be combined with sophisticated multiple field-plates to achieve low current collapse at high drain bias switching [8].

On the other hand, oxide-based high-k dielectrics such as Al2O3 [10, 11] and HfO2 [12], have been deployed as the passivation layer while also being used as the gate dielectric layer in AlGaN/GaN MIS-HEMTs (metal-insulator-semiconductor HEMTs). All the reported transient characteristics of these devices were measured at low drain bias. Recently, it has been revealed that high-density deep (and slow) interface-states exist at the Al2O3/(Al)GaN interface [13, 14], partially due to the easy formation of Ga-O bonds [15]. The charging/discharging of these slow interface states under high electric field could lead to current collapse in AlGaN/GaN HEMTs under large drain bias.

Thus, the nitride-based high-k dielectrics such as AlN emerges as a compelling candidate for passivation with low interface states for GaN-based devices [16-21], because of its smaller lattice mismatch to GaN and larger bandgap (compared to SiNx).

In-situ MOCVD grown ultra-thin AlN films have been implemented as the gate dielectric in MIS-HEMTs [16, 19]. Thick AlN layer had also been deposited on AlGaN/GaN HEMTs by dc sputtering and used as the heat spreading layer, for devices on low-thermal-conductivity sapphire substrate [20, 21]. However, the possible surface damage induced by the high-energy sputtering ions makes the control of AlN/III-nitride interface and the consequent passivation a challenging task. Up to now, there is no report on the transient behavior of AlN-passivated AlGaN/GaN power HEMTs switching from OFF-state at high drain bias larger than 100 V. Whereas, atomic layer deposition (ALD) with its self-limiting digital growth mechanism, offers the opportunity to create precisely controlled thickness but is rarely used to grow AlN [22]. Moreover, the remote plasma used in ALD also facilitates in-situ low-damage remote plasma pretreatment (RPP) that could remove the surface native oxide with minimum surface damages. The in-situ pre-passivation surface treatments by plasma such as NH3 [23] has been shown to result in improved reliability in SiNx-passivated AlGaN/GaN HEMTs.

In this work, we demonstrate an effective passivation technique featuring AlN ultra-thin film grown by plasma enhanced ALD on AlGaN/GaN HEMTs. Assisted by in-situ RPP, atomically 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 switch from high drain bias.

DEVICE FABRICATION

The sample used in this work is a commercial Al0.26Ga0.74N/GaN HEMT wafer grown by MOCVD on 4-inch (111) silicon substrate. It includes a 1.8 μm GaN buffer, a thin AlN (~1 nm) interface enhancement layer, an 18 nm undoped AlGaN barrier and a 2 nm undoped GaN cap. The fabrication processes started with mesa etching.
Ohmic contacts were formed by an alloyed Ti/Al/Ni/Au metal stack. The specific contact resistance is 0.7 Ω•mm. Ni/Au was used for the gate electrode. Four samples with various surface conditions were prepared: sample 1 (S1) without the RPP and passivation, sample 2 (S2) with HCl/NH4OH cleaning (but without RPP) and PECVD-grown 100 nm SiNx passivation, sample 3 (S3) with the RPP and ALD-AlN passivation, and sample 4 (S4) with the RPP only.

The in-situ RPP features NH3, Ar, N2 plasmas applied to the sample in sequence at a substrate temperature of 300 °C. For the ALD-AlN passivation of S3, a 4-nm AlN layer was deposited immediately after the RPP at 300 °C, using N2-H2 and trimethylaluminum (TMA) plasma precursors as the N and Al sources. The growth rate is ~0.6 Å/cycle. For all the devices characterized in this work, the gate length $L_G$ and gate-source separation $L_{GS}$ are 1.5 and 1 μm, respectively. The gate-drain separation $L_{GD}$ is designed to be 2, 5 and 10 μm. All the measurements were performed with the substrate grounded unless specified otherwise. Anatomically sharp interface between the ALD-AlN and AlGaN/GaN HEMT is observed, as shown in the high resolution transmission electron microscopy (HRTEM) (Fig. 1 (a)). Regional polycrystalline domains appear at the top portion of the AlN layer.

The improved interface between the ALD-AlN and the GaN cap of AlGaN/GaN HEMT was confirmed with an X-ray photoelectron spectroscopy (XPS) study, as shown in Fig. 1 (b). The Ga 2p3/2 core-level spectra (which has a strong surface-sensitivity) was used to evaluate the relation between the Ga-related bonds and the surface conditions of HEMTs [24]. It should be noted that a thin (~2-nm) ALD-AlN film was used in the XPS measurement to facilitate the escape and the subsequent detection of the photoelectrons from the interface. With the RPP and subsequent ALD-AlN passivation, the Ga 2p3/2 peak exhibits clear core-level shifting (~0.8 eV) towards the low binding energy side, suggesting effective suppression of Ga-O bonds at ALD-AlN/GaN interface. The resulted core-level position of Ga 2p3/2 is ~1117.4 eV.

**RESULTS AND DISCUSSION**

The output characteristics of samples S1 and S3 were measured with the gate bias stepping up (or down) from (or grounded unless specified otherwise. Anatomically sharp interface between the ALD-AlN and AlGaN/GaN HEMT is observed, as shown in the high resolution transmission electron microscopy (HRTEM) (Fig. 1 (a)). Regional polycrystalline domains appear at the top portion of the AlN layer.

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toward) below the threshold voltage, and the results are plotted in Fig. 2. In S1, the output current is significantly lower at high gate bias when the gate bias is stepped up from below the threshold voltage, suggesting significant current collapse. In the AlN-passivated sample S3, very small discrepancies exist between the step-up and step-down measurements.

To characterize the current collapse under large drain-bias switching, we configured a measurement setup using Agilent B1505A power device analyzer/curve-tracer. The devices were first biased at OFF-state by applying a gate bias ($V_{GS} = -3 \text{ V}$ in this work) below the threshold voltage, while $V_{DS}$ is swept from 0.75 V (the chosen drain bias at the ON-state) to a preset value. The sweeping time during the OFF-state stress is 46 seconds. Then the devices were switched back to the ON-state by applying $V_{GS} = 0 \text{ V}$ and $V_{DS} = 0.75 \text{ V}$ at which a dc ON-state current no less than 100 mA/mm is obtained. The switching time is limited by the equipment at ~70 ms. The output resistance measured at the ON-state ($V_{GS} = 0 \text{ V}$ and $V_{DS} = 0.75 \text{ V}$) right after the switching was used to evaluate the dynamic $R_{on}$. White light was illuminated on the sample after each OFF-to-ON sweep to effectively refresh the devices.

The output characteristics measured by the method described above in S1, S2, S3 and S4 are plotted in Fig. 3. The ON-resistances measured from the “fresh” devices without any drain bias stress are regarded as the reference static $R_{on}$. The unpassivated devices S1 and S4 show significant current collapse that becomes more severe as the OFF-state drain bias increases. SiNx passivation is shown to provide current collapse suppression, but its effectiveness is limited under large drain bias. Meanwhile, the ALD-AlN passivated device S3 exhibits much smaller current collapse.

The benefits of AlN passivation are two-fold. First, low
oxygen concentration is achieved at the AlN/GaN interface, leading to reduced oxygen-induced slow-response interface states. The importance of reducing the oxygen concentration is illustrated by our recent experiment of implementing a passivation scheme featuring the in-situ RPP and a 15-nm ALD-grown Al₂O₃ as the passivation layer. In this experiment, serious current collapse still exists with drain bias switching from high voltage (> 40 V). Second, AlN’s larger bandgap of 6.2 eV, in comparison with 5.1 eV in Si₃N₄, could provide a more effective barrier that prevents electrons from being injected from the gate electrode to the surface of the GaN cap layer in the gate-to-drain access region under high drain bias.

For devices with various values of \( L_{GD} \), the dynamic \( R_{on} \) were summarized in Fig. 4. With the ALD-AlN passivation, significant current collapse suppression and much lower dynamic \( R_{on} \) are achieved. The much slower increase of the dynamic \( R_{on} \) under large drain bias switching provides a strong implication that ALD-AlN thin film passivation could be an effective and simple passivation technique for GaN-based power switches.

CONCLUSIONS

An effective passivation technique using a 4-nm AlN film deposited by plasma enhanced ALD along with in-situ remote plasma pretreatment is demonstrated for AlGaN/GaN power HEMTs. Significant current collapse suppression and dynamic ON-resistance reduction are achieved in ALD-AlN passivated AlGaN/GaN HEMTs without the use of field-plate.

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