0.2-μm AlGaN/GaN High Electron-Mobility Transistors With Atomic Layer Deposition Al_2O_3 Passivation

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***Abstract*—We report a successful application of atomic layer deposition (ALD) aluminum oxide as a passivation layer to gallium nitride high electron-mobility transistors (HEMTs). This new passivation process results in 8%–10% higher dc maximum drain current and maximum extrinsic transconductance, about one order of magnitude lower drain current in the subthreshold region, 10%–20% higher pulsed-IV drain current, and 27%–30% higher RF power with simultaneously 5–8 percentage point higher power-added efficiency. The achieved improvement in device performance is attributed to the outstanding quality of the interface between III-N and the ALD aluminum oxide resulting from the uniqueness of the adopted ALD process, featuring a wet-chemical-based wafer preparation as well as a pregrowth self-cleaning procedure in the growth chamber. This technology can be readily integrated into the HEMT-based integrated circuit fabrication process, making the ALD aluminum oxide-passivated GaN HEMTs excellent candidates for multiple microwave and millimeter-wave power applications.**

***Index Terms*—Aluminum oxide (Al_2O_3), atomic layer deposition (ALD), gallium nitride (GaN), high electron mobility transistor (HEMT), passivation, pulsed-IV, RF power.**

I. INTRODUCTION

PASSIVATION is becoming increasingly important for GaN high electron-mobility transistors (HEMTs) as the demand for high power devices and circuits for applications at higher frequencies is getting ever stronger. This is because the field plate, which has been widely adopted in GaN HEMTs for improving power and reliability [1], would degrade the device gain due to the additional parasitic capacitance that it would introduce. Furthermore, the vertical scaling for thinner gate barrier, needed for keeping up the aspect ratio of devices with reduced gate lengths to be operational at higher frequencies, would make the channel of the GaN HEMT more sensitive to the traps originating from surface states. The resulting trapping effects could lead to severe deterioration in power performance (observable in pulsed-IV), poor uniformity and reproducibility, and potential reliability concerns as well. It has been well known that the surface states are created by dangling bonds, threading dislocation, and ions absorbed from the ambient environment [2]. Screening the surface states from the channel of the HEMT devices by a doped cap layer is an effective way to address the adverse effects from traps, but this approach usually requires gate recess to ensure decent aspect ratio and Schottky characteristics, which can be a challenge for maintaining the uniformity and reproducibility of devices. That is why new passivation technologies like those reported in [3]–[4] keep on emerging as it may be a more cost-effective solution to trapping effects in GaN HEMTs.

In this letter, we report an *ex situ* passivation with atomic layer deposition (ALD) aluminum oxide (Al_2O_3) layer to significantly improve the power performance of the no-field plate GaN HEMT. The unique physical properties of Al_2O_3, in particular wide band gap, high breakdown field, and high thermal stability, make it extremely attractive as a passivation material for GaN HEMTs. In addition, the fact that ALD growth is composed of self-limiting chemical reaction cycles to form ultrathin, uniform, conformal, and pin-hole free films makes it highly desirable as a manufacturing technology. It is the inclusion of a wet-chemical-based wafer preparation and a pregrowth self-cleaning as part of the passivation process that leads to the outstanding quality of Al_2O_3/epi interface and the resulting markedly enhanced device performance, highlighting the two key features that distinguish our work from those reported previously [5]–[7].

II. DEVICE FABRICATION

The epitaxial structures for the GaN HEMT were grown by metal-organic chemical vapor deposition. The epitaxial layers on the 3-in semi-insulating SiC substrate include a thin AlN nucleation layer, an Fe-doped GaN buffer, an undoped GaN buffer, an undoped AlGaN gate layer, and a 2-nm undoped GaN cap layer. The fabrication process for 0.2-μm GaN HEMTs, as described in [8], includes inductively coupled plasma mesa isolation etching, annealed Ti/Al/Au-based ohmic contact, and the definition of 0.2 μm T-gates. The only difference in this letter is the use of ALD Al_2O_3 to replace plasma-enhanced chemical vapor deposition (PECVD) SiN as the passivation layer.

Before being loaded into the ASM F-120 ALD system for the deposition of ALD Al_2O_3 passivation layer, the wafer

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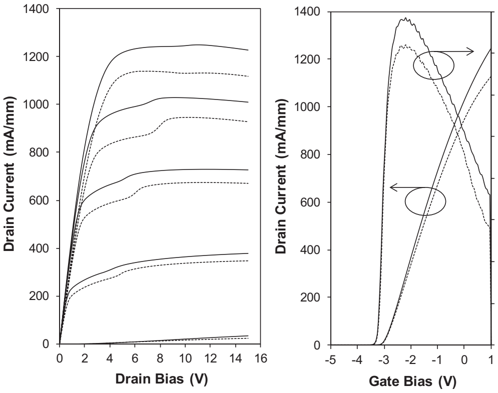


(a) (b)

Fig. 1. (a) Output IV characteristics and (b) transfer curves and transconductance for 0.2-μm GaN HEMTs with PECVD SiN (dashed lines) and ALD Al_2O_3 passivation (solid lines). The gate bias for the top curve of the IV characteristics is 1 V, and the step of the gate bias is -1 V. The transfer curves and transconductance of both devices were measured at a V_{ds} of 10 V.

was cleaned in acetone, methanol, and isopropanol to remove organic residues as well as in ammonia solution to eliminate the surface oxide layer. More details on pretreatment can be found in [9]. Then the chamber was slowly ramped up to the growth temperature of 300 °C, followed by a self-cleaning of oxide with tri-methyl-aluminum (TMA). Afterward, the Al_2O_3 layer was grown with alternating pulses of TMA and water precursors in nitrogen carrier gas at a rate of 0.86 Å/cycle. Note that the cleaning steps adopted prior to the Al_2O_3 layer growth effectively "unpin" the Fermi level by removing the oxide on the epitaxial layer, enabling a low as-grown interface trap density, D_{it}, of about 10^{11} to 10^{12} $cm^{-2}eV^{-1}$ for the interface between the ALD Al_2O_3 film and the GaN cap layer, which can even be slightly lower than 10^{11} $cm^{-2}eV^{-1}$ after the postdeposition annealing is performed [10]. Note the photo-assisted CV gives only a rough estimation of the average D_{it} across a portion of the band gap of GaN. To facilitate comparing performance, a reference wafer has also been fabricated with the PECVD SiN deposited at 250 °C after ammonia plasma pretreatment.

III. RESULTS AND DISCUSSION

Fig 1(a) and (b) compares the *IV* and transfer characteristics of the devices with PECVD SiN and ALD Al_2O_3 passivation layers. Because of the nominally identical epitaxial structures on which both devices were fabricated, they show almost identical pinch-off voltages of about -3 V. However, the device with Al_2O_3 passivation has a maximum drain current (measured at a gate bias V_{gs} of 1 V and a drain bias V_{ds} of 10 V) and maximum extrinsic transconductance (measured at a V_{ds} of 10 V) that are about 10% and 8% higher than those of the SiN device, respectively. This is due primarily to the markedly lower parasitic resistance indicated in Fig. 1(a) as a result of the reduced sheet resistance with the improved interface between the Al_2O_3 and the GaN cap layer, similar to that reported in [6].

Fig. 2 shows both the subthreshold transfer and Schottky characteristics of the two devices in logarithm scale. A distinct feature of the Al_2O_3-passivated device is that its subthreshold drain current is about one order of magnitude lower than that of the SiN device. Meanwhile, it can also be noted that the subthreshold drain currents of these two devices (both measured at a V_{ds} of 10 V) coincide with their corresponding two-terminal reverse gate currents at a V_{gs} of -15 V. It becomes apparent that the subthreshold drain currents of the two HEMTs are solely contributed by their own reverse gate currents. It is the outstanding quality of the interface between Al_2O_3 and GaN cap layer to which the improvements in both reverse Schottky characteristics and subthreshold drain current should be unambiguously attributed.

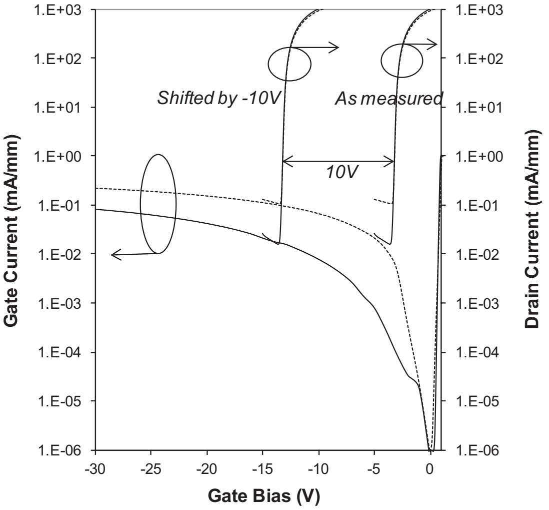
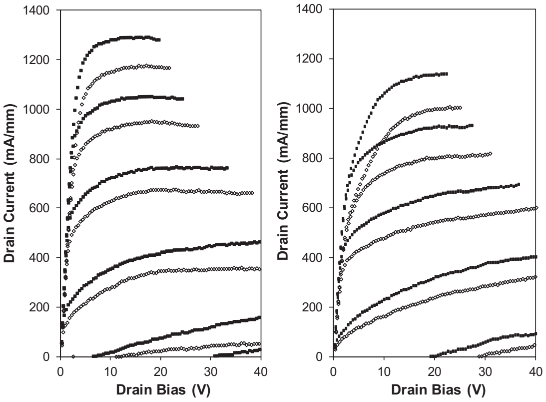


Fig. 2. Schottky diode characteristics and the transfer curves in logarithm scale for 0.2-μm GaN HEMTs with PECVD SiN (dashed lines) and ALD Al_2O_3 passivation (solid lines). The pair of transfer curves on the left side of the figure was obtained with shifting the "as measured" pair on the right side by 10 V. This is to illustrate that the subthreshold drain current originates solely from their corresponding two-terminal reverse Schottky diode leakage current in these devices.

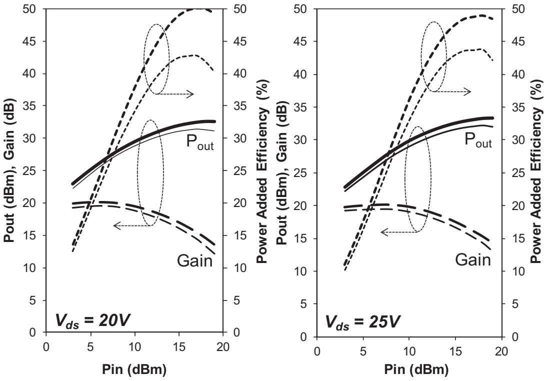
Pulsed-*IV* performance of the SiN- and Al_2O_3-passivated devices is characterized with a pulse width of 200 ns and a separation of 2 ms at two different quiescent points. Fig. 3(a) shows that, at quiescent point of $V_{gs} = 0$ V and $V_{ds} = 0$ V, the Al_2O_3-passivated device (solid symbols) has approximately 10% higher maximum drain current and markedly improved knee at low V_{ds} in comparison with its SiN counterpart. The performance advantage brought by the Al_2O_3 passivation becomes even more obvious when pulsed-*IV* characteristics are recorded at the deep pinch-off quiescent point of $V_{gs} = -5$ V and $V_{ds} = 30$ V. Fig. 3(b) indicates the Al_2O_3 device has a more than 20% higher pulsed maximum drain current than that of the SiN device. Furthermore, we have hardly observed any change in pulsed-*IV* characteristics with variation in ALD Al_2O_3 layer thickness, which is in contrast to that reported in [7], even though the ALD Al_2O_3 layer we used for passivation is much thinner. This is probably another indicator of the high interface quality of ALD Al_2O_3 film on the epitaxial layer in this letter.

Also worthy of mentioning is that the uniformity of pulsed-*IV* characteristics would be markedly improved if the ALD Al_2O_3 layer were used as the passivation layer. This is particularly apparent at low drain bias regions where the current collapse is most severe. We have examined the



(a) (b)

Fig. 3. Pulsed-IV characteristics for 0.2-μm GaN HEMTs with PECVD SiN (open symbols) and ALD Al_2O_3 passivation (solid symbols). The devices were measured at quiescent points of (a) $V_{gs} = 0$ V and $V_{ds} = 0$ V and (b) $V_{gs} = -5$V and $V_{ds} = 30$ V. The V_{gs} for the top curves is 1 V, and the V_{gs} step is -1 V. The pulse has a width of 200 ns and a separation of 2 ms.



(a) (b)

Fig. 4. Output power, associated power gain, and power-added efficiency as a function of drive for 0.2-μm 4 × 100 μm HEMTs passivated with PECVD SiN (thin lines) and ALD Al_2O_3 (thick lines) at a frequency of 10 GHz. The devices were biased at an identical drain current of 200 mA/mm and at a V_{ds} of (a) 20 V and (b) 25 V.

pulsed drain current at V_{gs} of 0 V and V_{ds} of 5 V of both types of devices. Across a 3-inch wafer, the standard deviations of the pulsed drain current of Al_2O_3-passivated devices are 11 and 20 mA/mm at zero and deep pinch-off quiescence points, respectively, comparing favorably with the corresponding 49 and 54 mA/mm measured on the SiN devices. The improved uniformity and consistency of pulsed-*IV* performance with the use of the ALD Al_2O_3 passivation layer would certainly contribute to higher yield of monolithic microwave integrated circuits based on these devices, making it a more manufacturing friendly technology.

Although the two devices show very similar current gain cut-off frequency f_T of 54–55 GHz and maximum oscillation frequency f_{max} of 117–120 GHz at a V_{ds} of 20 V, the on-wafer microwave power measurement performed using a load-pull system, as expected, discloses distinct difference. Both 4 × 100 μm devices were operated at a drain current of 200 mA/mm with the input and output matches tuned for maximum output power. Fig. 4(a) shows the 10-GHz continuous-wave output power, associated power gain, and power-added efficiencies (PAE) at a V_{ds} of 20 V. The Al_2O_3-passivated device (thick lines) shows about 1.2 dBm or 30% higher maximum output power (4.55 versus 3.5 W/mm) and approximately 8 percentage point higher PAE than those of the SiN device (thin lines). When the V_{ds} is increased to 25 V, the Al_2O_3-passivated device is still 1 dBm or 27% higher in output power (5.28 versus 4.15 W/mm) and 5 percentage points higher in PAE as shown in Fig. 4(b).

CONCLUSION

ALD Al_2O_3-passivated GaN HEMTs have demonstrated significant improvement in dc, pulsed-*IV* and RF power performance over those passivated with PECVD SiN. These results have been attributed to the effective alleviation of trapping effects by the outstanding Al_2O_3-GaN interface quality made possible by the Al_2O_3 passivation layer grown by ALD, a versatile process fully compatible with the HEMT fabrication flow. ALD Al_2O_3-passivated GaN HEMT is a highly manufacturable and high-performance candidate for many microwave and millimeter-wave high-power applications.

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