High Uniformity Normally-OFF GaN MIS-HEMTs Fabricated on Ultra-Thin-Barrier AlGaN/GaN Heterostructure

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***Abstract*—Ultra-Thin-Barrier (UTB) AlGaN/GaN heterostructure is utilized for fabrication of normally-OFF GaN metal-insulator-semiconductor high-electron-mobility transistors (MIS-HEMTs). The sheet resistance of 2-D electron gas (2DEG) in the UTB $Al_{0.22}Ga_{0.78}N$(5-nm)/GaN heterostructure is effectively reduced by SiN_x passivation grown by low-pressure chemical-vapor-deposition (LPCVD), from 2570 to 334 Ω/□. The fabricated Al_2O_3/AlGaN/GaN MIS-HEMTs exhibit normally OFF behavior with good V_{TH} uniformity and low V_{TH}-hysteresis. 20 mm-gate-width power devices featuring a low R_{ON} of 0.75 Ω ($I_{D,MAX}$ = 6.5 A) are also demonstrated on the platform.**

***Index Terms*—Normally-OFF, GaN MIS-HEMTs, ultra-thin-barrier AlGaN/GaN heterostructure, LPCVD-SIN_x passivation.**

I. Introduction

AlGaN/GaN metal-insulator(oxide)-semiconductor high-electron-mobility transistors (MIS/MOS-HEMTs) with partially or fully recessed gate, have emerged as promising candidates for next-generation normally-OFF power switching devices [1-6]. With polarization-induced high density and mobility 2-D electron gas (2DEG) at AlGaN/GaN hetero-interface, lower on-resistance (R_{ON}) can be achieved compared with Si-based MOSFETs [7]. However, precise thickness control of the recessed AlGaN barrier, typically being etched down to less than 6 nm [8], is one of the most challenging steps toward high performance gate-recessed normally-OFF AlGaN/GaN MIS-HEMTs. Self-terminated recess process and structures, such as inserting an etch-stopping layer [3] and selectively oxidation of the AlGaN barrier layer [9, 10], are highly desirable. A double-channel MOS-HEMT structure with good barrier-over-recess tolerance has also been developed recently [11].

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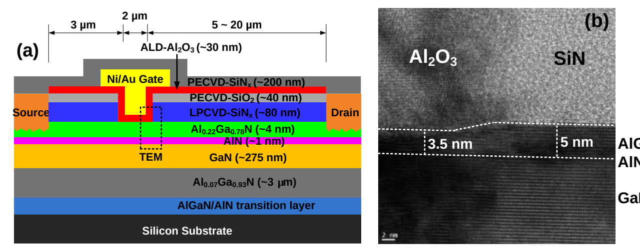

Fig. 1. (a) Schematic device structure of normally-OFF Al_2O_3/AlGaN/GaN MIS-HEMTs fabricated on UTB AlGaN/GaN heterostructures. (b) TEM cross-sectional view of the device's gate corner.

To overcome the controllability issue of gate recess, ultra-thin-barrier (UTB) AlGaN/GaN heterostructures have also been proposed [12-13]. Natural normally-OFF operation can be realized, but the HEMTs/MIS-HEMTs suffer from high R_{ON} owing to the low 2DEG density in gate-source and gate-drain access region. Passivation dielectrics like SiO_2 and SiN_x are able to restore the 2DEG to a comparable density as that in conventional AlGaN/GaN heterostructures, while their physical origin remains to be investigated. With UTB-AlGaN/GaN heterostructures, the gate-recess etching of the AlGaN barrier is transferred to etching of the passivation layer using fluorine-based plasmas (if passivation is done first), and the AlGaN barrier can be a good etch-stopping layer.

In this work, high V_{TH}-uniformity, low R_{ON} normally-OFF GaN MIS-HEMTs are fabricated on an UTB-AlGaN/GaN heterostructure, with R_{ON} being effectively reduced by SiN_x passivation grown by low-pressure chemical-vapor-deposition (LPCVD).

II. Device Fabrication

The schematic cross section of the fabricated normally-OFF Al_2O_3/AlGaN/GaN MIS-HEMTs is depicted in Fig. 1(a). The UTB-AlGaN/GaN heterostructure wafer used in this work was grown by metal organic chemical vapor deposition (MOCVD) on 4-inch Si substrate. The AlGaN barrier consists of a ~4-nm $Al_{0.22}Ga_{0.78}N$ layer and ~1-nm AlN interface enhancement layer (IEL), as shown in Fig. 1(b). The as-grown wafer yields a 2DEG density of 2.7×10^{12} cm^{-2} and a sheet resistance of

TABLE I Electrical properties of the 2DEG in UTB $Al_{0.22}Ga_{0.78}N$(5-nm)/GaN heterostructure with 80-nm LPCVD-SiN_x passivation

80-nm LPCVD-SiN passivation	2DEG Sheet resistance (Ω/□)	2DEG sheet density (e/cm^2)	2DEG mobility (cm^2/V·s)
Before passivation (Hall)	2570	2.7×10^{12}	869
After passivation (Hall)	334	9.5×10^{12}	1980
After passivation (TLM)	325	---	---

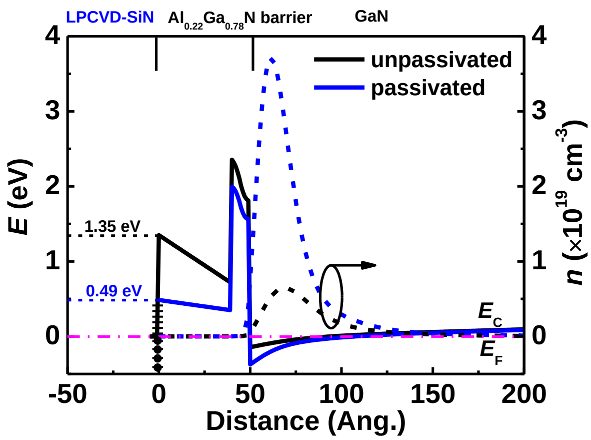

Fig. 2. Simulated conduction-band of the UTB $Al_{0.22}Ga_{0.78}N$/AlN(5-nm)/GaN heterostructure with and without LPCVD-SiN passivation.

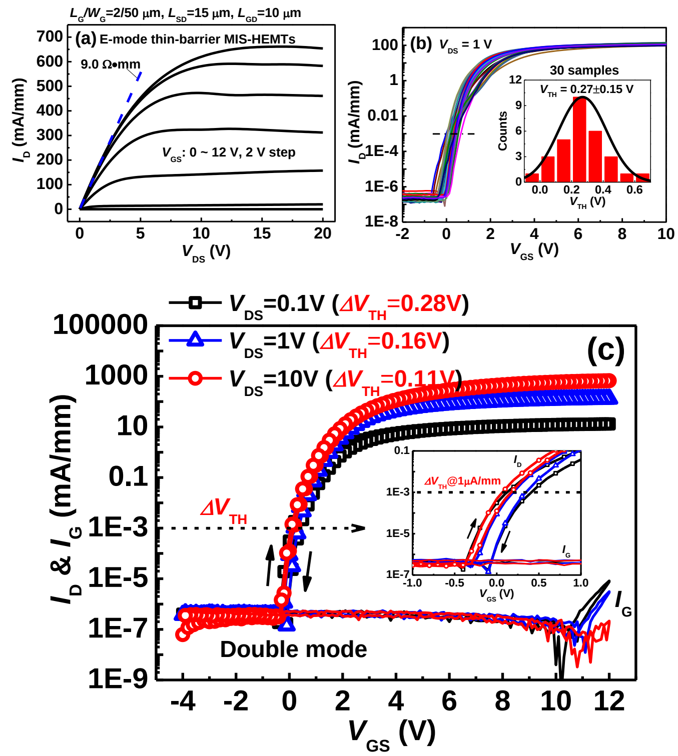

Fig. 3. (a) dc *I-V* characteristics of the fabricated normally-OFF Al_2O_3/AlGaN/GaN MIS-HEMTs. (a) dc output characteristics. (b) dc transfer characteristics and threshold voltage uniformity measured at V_{DS} = 1 V. (c) V_{TH}-hysteresis characteristics in transfer measurements at various V_{DS}.

2570 Ω/□ (Table I). While after 80-nm LPCVD-SiN passivation, the 2DEG density is remarkably increased to 9.5×10^{12} cm^{-2}, and the sheet resistance is reduced to 334 Ω/□. The corresponding 2DEG mobility is increased from 869 to 1980 cm^2/V s, which suggests a good AlGaN(AlN)/GaN interface with insignificant roughness scattering [14].

A net positive charges of 4.56×10^{12} cm^{-2} is confirmed to be present at the LPCVD-SiN_x/III-nitride interface, as determined by capacitance-voltage (*C-V*) characterizations of Metal/LPCVD-SiN_x/III-nitride MIS diodes with various SiN_x thickness. If considering the negative polarization charges on AlGaN surface, the positive charges introduced by the LPCVD-SiN_x passivation is about 3.26×10^{13} cm^{-2} [15-16]. Doping effect of Si source used in LPCVD may be responsible for such high induced positive charges, which brings down the surface potential of the ultra-thin AlGaN barrier from 1.35 to 0.49 eV, as confirmed by the simulated energy band diagram shown in Fig. 2 [17]. The reduction of surface potential of AlGaN barrier by LPCVD-SiN_x, contributes to an effectively enhanced 2DEG density in UTB AlGaN/GaN heterostructures (Fig. 2).

Prior to the 80-nm LPCVD-SiN_x passivation, the UTB-AlGaN/GaN heterostructure wafer was first cleaned with standard RCA treatment. Then source-drain passivation was etched away by low power CHF_3/SF_6 plasmas in an inductively-coupled-plasma (ICP) system, followed by wet treatment of the exposed AlGaN barrier surface in a diluted HCl. Then a Ti/Al/Ni/Au ohmic metal stack was evaporated and annealed at 830 °C in N_2 ambient after liftoff. After plenary isolation, the contact resistance is extracted to be 1.34 Ω·mm, which could be reduced by additional pre-ohmic recess etching of the AlGaN barrier before metal evaporation [18]. The passivation layer in the gate region was also etched with the same F-based plasmas. After HCl/NH_4OH wet cleaning of the etched surface, 30-nm Al_2O_3 gate dielectric was deposited by ALD with *in-situ* remote-plasma pretreatments (RPP), followed by post-dielectric annealing [5]. Ni/Au bilayer was finally evaporated as the gate electrodes. Fig. 1(b) shows the cross-sectional TEM of the fabricated gate. Slight etching of the AlGaN barrier (~1.5 nm) is observed.

III. Results and Discussion

Fig. 3(a) shows the output characteristics of the fabricated MIS-HEMTs with L_G/L_{GD} of 2/10 μm. A maximum I_D of 661 mA/mm and R_{ON} of 9.0 Ω·mm are achieved at gate bias of +12 V. V_{TH} of the fabricated devices is extracted to be 0.27 V at V_{DS} = 1 V, under a current criterion of I_D = 1 μA/mm (Fig. 3(b)). Owing to the as-grown ultra-thin AlGaN barrier, intentional recess etching of the AlGaN barrier is eliminated, contributing to improved V_{TH} controllability and uniformity. A small standard deviation of 0.15 V is achieved by sampling of 30 devices across the whole wafer, as shown in the inset of Fig. 3(b).

Thanks to the RPP before ALD-Al_2O_3, the deep states at Al_2O_3/AlGaN interface are remarkably suppressed [5]. The clockwise V_{TH}-hysteresis of the MIS-HEMTs decreases from 0.28 to 0.11 V as the drain bias increases from 0.1 to 10 V, as shown in Fig. 3(c) and its inset. Such reduction may be caused by field-assisted detrapping at high V_{DS}. Residual interface states and, plasma-induced lattice damage to the AlGaN barrier

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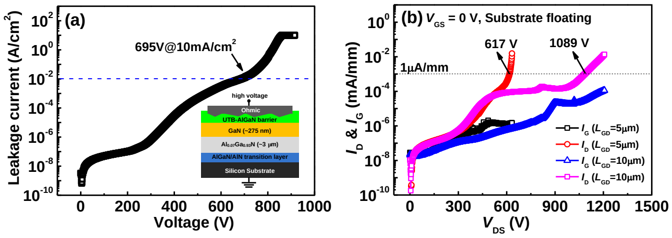

Fig. 4. (a) Two-terminal vertical breakdown characteristics of the GaN-on-Si wafer. (b) Three-terminal breakdown characteristics of the fabricated normally-OFF Al_2O_3/AlGaN/GaN MIS-HEMTs.

during dry etching of LPCVD-SiN_x, are the possible origins for the hysteresis that needs to be optimized.

Assisted by the thick $Al_{0.07}Ga_{0.93}N$ buffer, a high vertical breakdown voltage (V_{BD}) of 695 V is also realized on the GaN-on-Si wafer (Fig. 4(a)). Using a leakage criterion of 1 μA/mm, three-terminal V_{BD} of the fabricated MIS-HEMTs (L_{GD} = 10 μm), is measured to be 1089 V with substrate floating. It is source-to-drain leakage that triggers the breakdown (Fig. 4(b)). The corresponding V_{BD} for devices with L_{GD} = 5 μm is 617 V.

Pulsed *I-V* measurements were used to characterize the current collapse in the fabricated normally-OFF MIS-HEMTs, as shown in Fig. 5(a). The pulse period and width used are 10 μs and 200 ns, respectively. The dynamic R_{ON} is increased by about 10% at quiescent bias of (0, 60V), compared with the (0, 0) reference. It is probably due to interface traps caused by re-oxidation of the RCA-treated AlGaN barrier surface during transferring into the LPCVD chamber [19], or border/bulk traps in the LPCVD-SiN_x passivation layer. With the improved V_{TH} controllability, 20 mm-gate-width normally-OFF AlGaN/GaN MIS-HEMTs, featuring a low R_{ON} of 0.75 Ω ($I_{D,MAX}$ = 6.5 A), are also demonstrated on the LPCVD-SiN_x-passivated UTB-AlGaN/GaN heterostructure (Fig. 5(b)).

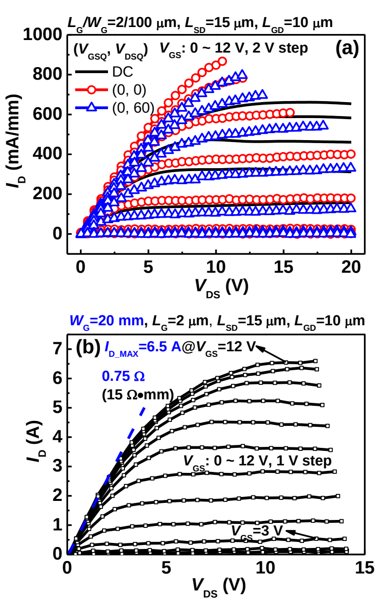

Fig. 5. (a) Pulsed I_D-V_{DS} characteristics of the fabricated normally-OFF Al_2O_3/AlGaN/GaN MIS-HEMTs from various quiescent bias point (V_{GSQ}, V_{DSQ}). The pulse period and width are 10 μs and 200 ns respectively. (b) *I-V* characteristics of a fabricated 20-mm-gate-width devices.

IV. Conclusion

High performance normally-OFF Al_2O_3/AlGaN/GaN MIS-HEMTs featuring good V_{TH}-uniformity were fabricated on UTB-AlGaN/GaN heterostructure, adopting LPCVD-SiN passivation for efficient R_{ON} reduction. An 80-nm LPCVD-SiN_x passivation layer remarkably reduces 2DEG sheet resistance of an $Al_{0.22}Ga_{0.78}N$(5-nm)/GaN heterostructure from 2570 to 334 Ω/□. 650V/0.75Ω normally-OFF power devices are successfully demonstrated on the UTB-AlGaN/GaN heterostructure, which is promising for fabrication of high-yield normally-OFF GaN-based MIS-HEMTs.

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