

GaN-on-Silicon transistors with extremely low off-state leakage current above 3 kilovolts

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For future efficient and low-cost power electronics, GaN high-electron-mobility transistors (HEMTs) on silicon (Si) substrate are highly promising owing to their superior intrinsic properties such as large band-gap, high breakdown field strength and high electron saturation velocity. However, GaN-on-Si transistors suffer from poor critical electrical field strength of the Si substrate, which creates a parasitic conduction at the buffer/substrate interface leading to device breakdown [1, 2]. That is why, the highest reported breakdown V_{BR} values for GaN-on-Si HEMTs with off-state leakage current lower than $1 \mu\text{A}/\text{mm}$ are still below 1.5 kV, which is basically limited by the Si substrate as well as the associated GaN-based epi-layers material quality.

In this paper, we report for the first time floating substrate GaN-on-Si HEMTs with extremely low off-state leakage current ($< 1 \mu\text{A}/\text{mm}$) beyond 3 kV resulting from the Si substrate removal followed by a backside deposition of a thick AlN film.

The AlGaIn/GaN/AlGaIn double heterostructures, grown by MOCVD deposition on a Si(111) substrate, consisted of $5.5 \mu\text{m}$ buffer layers (transition layers and an $\text{Al}_{0.08}\text{Ga}_{0.92}\text{N}$ back barrier), followed by a 150 nm GaN channel, 20 nm $\text{Al}_{0.25}\text{Ga}_{0.75}\text{N}$ barrier layer and a 50 nm in situ Si_3N_4 cap layer. Ohmic contacts were formed directly on top of the AlGaIn barrier by alloying Ti/Al/Ni/Au stack using an 875°C rapid thermal annealing. Device isolation was achieved by N_2 implantation. Metal-insulator-semiconductor (MIS) gate structure was employed by depositing Ni/Au metal stack directly on the in situ Si_3N_4 cap layer. Once the front-side processing was completed, the backside Si substrate was locally etched up to the AlN nucleation layer around the entire device as shown in Figure 1 and 2. Then, $15 \mu\text{m}$ thick AlN delivering a high breakdown field ($> 4\text{MV}/\text{cm}$) was deposited on the backside by Pulsed Vapor Deposition (PVD).

Figure 3 shows the DC characteristics of AlGaIn/GaN HEMTs using a gate-drain spacing (L_{GD}) of $40\mu\text{m}$ before and after local Si substrate removal (LSR) and AlN deposition. The shift of threshold voltage is attributed to the desorption of fluorine during the 300°C AlN backside deposition. The three-terminal breakdown measurements performed with floating substrate on GaN-on-Si HEMTs with and without LSR are shown in Figure 4. The use of LSR and thick AlN dielectric layer enabled a remarkable increase of the breakdown voltage from 1.2kV to more than 3 kV by maintaining extremely low off-state leakage current ($< 1 \mu\text{A}/\text{mm}$) beyond 3kV. Figure 5 represents a benchmark for GaN-on-Si HEMTs demonstrating breakdown voltages at $I_{OFF} \leq 1\mu\text{A}/\text{mm}$ beyond 1kV. The AlGaIn/GaN HEMT using $L_{GD}=40\mu\text{m}$ achieved state-of-the-art off-state leakage current of about $0.5 \mu\text{A}/\text{mm}$ at 3kV after LSR and deposition of thick AlN dielectric layer, which confirms the suppression of the substrate conduction phenomena and the benefit of the implementation of the AlN ultra-wide bandgap. In order to investigate the dynamic IV characteristics current collapse measurements will be performed. This result paves the way for high voltage and low leakage operation of GaN-on-Si power devices for high-efficiency power conversion systems.

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[1] N. Herbecq, I. Roch-Jeune, N. Rolland, D.Visalli, J. Derluyn, S. Degroote, M. Germain, and F. Medjdoub, '1900 V, 1.6 mΩ cm² AlN/GaN-on-Si power devices realized by local substrate removal', Appl. Phys. Express, 2014, 7, (3), p. 034103.

[2] N. Herbecq, I. Roch-Jeune, A. Linge A, B. Grimbert, M. Zegaoui and Medjdoub GaN-on-silicon high electron mobility transistors with blocking voltage of 3 kV, Electronic Letters, 2015, 51 (19), p.1532-1534.

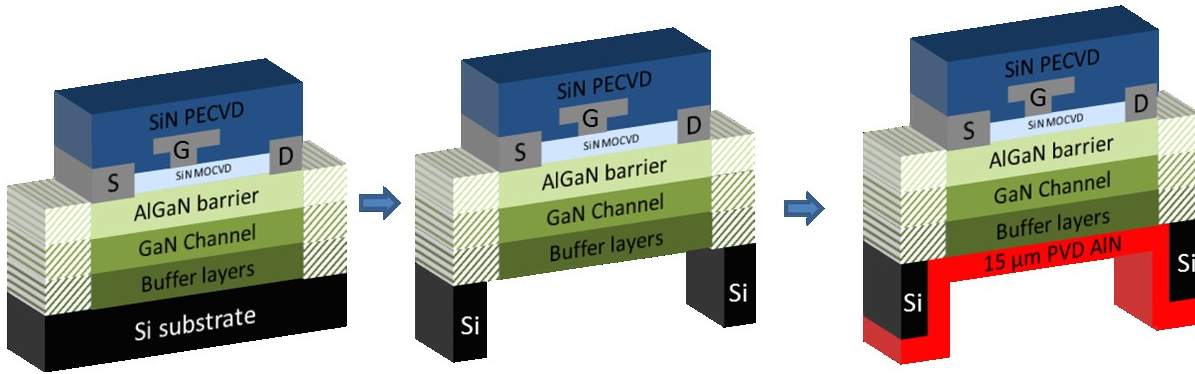


Figure 1 Schematic cross section of the AlGaN/GaN HEMTs after local substrate removal and PVD AlN deposition

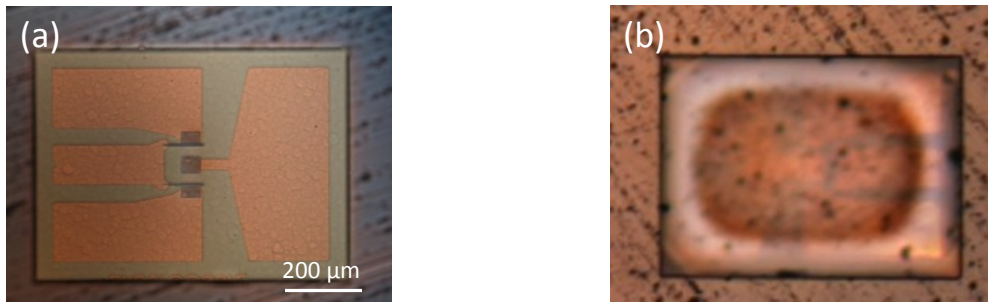


Figure 2 Optical microscopy images of AlGaN/GaN HEMTs (a) after local Si substrate removal and (b) after PVD AlN deposition

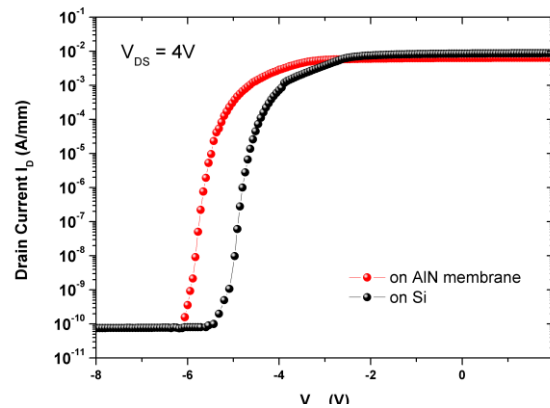


Figure 3 Transfer characteristics at $V_{DS} = 4V$ with $L_{GD} = 40\mu m$ of AlGaN/GaN HEMTs on Si and AlN membranes (LSR)

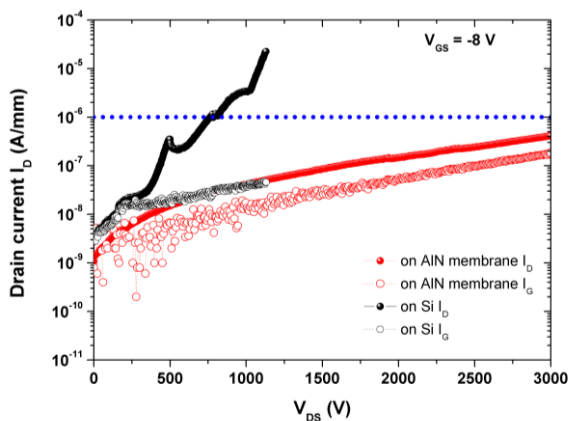


Figure 4 Off-state characteristics at $V_{GS} = -8V$ with $L_{GD} = 40\mu m$ of AlGaN/GaN HEMTs on Si and AlN membranes

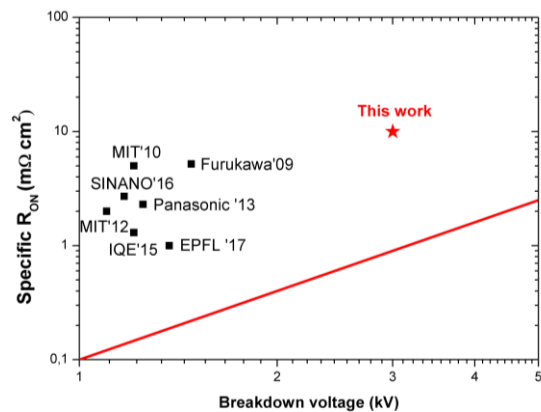


Figure 5 Benchmark of specific on-resistance $R_{ON,SP}$ vs. V_{BR} for GaN-on-Si HEMTs demonstrating breakdown at $I_{OFF} < 1\mu A/mm$