# 2.5-Ampere AlGaN/GaN HFETs on Si Substrates with Breakdown Voltage > 1,250V

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## Abstract

**We report the performance of high-voltage AlGaN/GaN heterojunction field effect transistor (HFET) switches grown on Si substrates. Measured *I-V* characteristics of 10-mm-wide GaN HFETs showed an off-state blocking voltage > 1,250 V and a specific on-resistance ($R_{ds(ON)}A$) of 6.2 mΩ-cm$^2$.**

## INTRODUCTION

To go beyond the silicon limit for solid-state power switches, GaN-based HFETs that feature high-current-drive, high switching-frequencies, and high-temperature-operation capabilities have sparked great interests for high-power switching applications in recent years [1-2]. Using GaN-based power transistors, it is expected that high-performance power electronics can be realized to achieve low-energy-loss, compact, high-temperature, high-switching-speed, and hence high-efficiency systems. These features are actively sought in power electronic industries to overcome these challenges for next-generation solid state electronic switches that current Si-based power electronics are lacking [3-5].

The commonly used substrate platforms for the implementations of GaN HFETs are on either SiC, GaN, or sapphire substrates [6-8]. In recent years, silicon substrates also have been extensively studied to exploit potential low-cost commercialization opportunities for power electronics due to good thermal conductivity and the availability for large-wafer sizes. Tremendous efforts have led to quite a few successful demonstrations of high-performance GaN HFETs on Si substrates. For examples, Hikita *et al.* developed a high power-power AlGaN/GaN HFET with a breakdown voltage of 350 V and a specific on-resistance of 1.9 mΩ-cm$^2$ by using a source-via grounding (SVG) design through 4 inch conductive Si substrate [9]. Iwakami *et al.* reported GaN HFETs with a breakdown voltage of 750 V and a specific on-resistance of 2.6 mΩ-cm$^2$ on 5-inch Si substrates [10]. Ikeda *et al.* also reported GaN HFETs with high breakdown voltage of over 1.8 kV and specific on-resistance of 7 mΩ-cm$^2$ on 4 inch Si substrates [11].

In this paper, we report depletion-mode 2.5-A AlGaN/GaN HFETs that have the specific on-resistance of 6.2 mΩ-cm$^2$ and the blocking voltage of greater than 1.25 kV with the drain leakage current < 2.2 μA/mm. A study on the blocking voltage and the on-state resistance suggests that these switching figure of merits scales linearly with the gate-to-drain distance up to at least 2-kV for fabricated GaN-on-Si transistors.

## DEVICE STRUCTURES AND FABRICATION PROCESSING

The AlGaN/GaN HFET epi-wafers in this study were acquired from a commercial vendor. These wafers consist of a 4.8-μm un-doped GaN buffer layer and a 30 nm-thick un-doped $Al_{0.25}Ga_{0.75}N$ barrier layers that were grown on 3-inch *p*-type Si substrates. The piezoelectric field induced 2-Dimensional electron gas channel has a sheet resistance of 460 Ω/□.

The fabrication processing of AlGaN/GaN HFETs power transistors begins with a mesa isolation using an inductively coupled plasma (ICP) etching system. Typical Ti/Al-based ohmic contact resistance ($R_c$) is 1.5 Ω-mm. The gate electrode is a 200-nm thick nickel deposited in an electron-gun evaporator. For the post device-level processing steps, the transistors are passivated by a layer of BCB, followed by the via-accessing-hole opening. Finally, the Metal-1 layer is deposited for interconnection between unit cells. No field plates were fabricated in this study. Devices with the gate width ($W_G$) of 3 mm, 5 mm, 6 mm, and 10 mm, respectively, were fabricated and evaluated. For example, a microscope photograph of a 10-mm-wide GaN power HFET is shown in the inset of Fig. 1.

## RESULTS AND DISCUSSION

The quasi-static pulsed I-V was measured in an Agilent B1505A digital curve tracer. The pulse width is 50 μs with the duty cycle of 0.5%. Shown in Fig. 1 are the $I_{ds}$-$V_{ds}$ characteristics of a fabricated AlGaN/GaN HFETs. This device has a gate width ($W_G$) of 10 mm, a gate-to-drain distance ($L_{GD}$) of 18.5 μm, a gate-to-source distance ($L_{GS}$) of 2 μm, and the gate length ($L_G$) of 3.5 μm. From the $I_d$-$V_{gs}$ measurement (not shown), the threshold voltage is -4.6 V and $I_{dss}$ is 265 mA/mm, respectively. In Fig. 1, a maximum current of > 3 A is also achieved at $V_{GS}$ = 1 V. The on-state resistance of 1.8 Ω is measured at $V_{DS}$ = 1 V and $V_{GS}$ = 0 V.

This resistance value corresponds to an on-state resistance of 18 Ω-mm when normalized with the total gate width, or a specific on-resistance ($R_{ds(ON)}A$) of 6.2 mΩ-cm$^2$, where $A$ is defined by the active device area including the drift regions as well as the drain and the source ohmic contact electrodes.

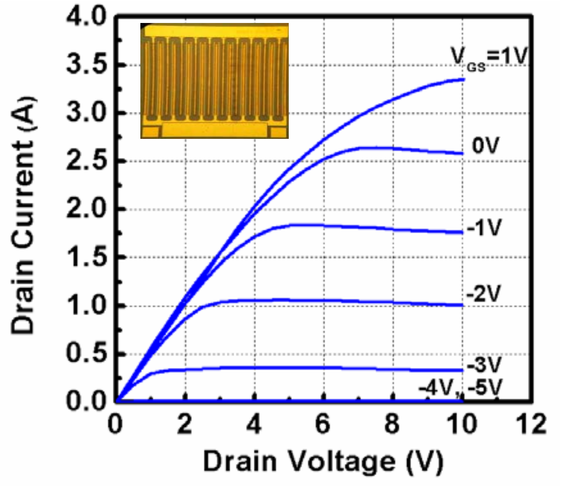

**Fig. 1 On-state characteristics of a fabricated AlGaN/GaN HFET on silicon with $W_G$ = 10 mm. (Inset) A microscope photograph of the fabricated AlGaN/GaN power HFETs.**

The off-state drain-to-source blocking voltage was also measured in a fluorinert environment. As shown in Fig. 2, a breakdown voltage ($BV_{ds}$) of greater than 1.25 kV was measured at $V_{GS}$ = -10 V. It is also noted that the leakage current is < 2.2 µA/mm for $V_{ds}$ up to 1.25 kV.

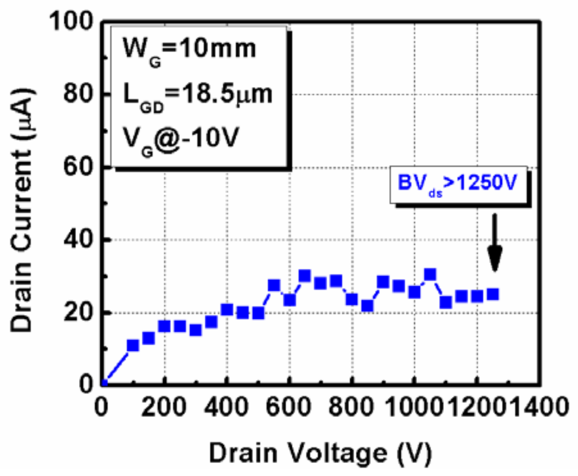

**Fig. 2 The off-state characteristics of an AlGaN/GaN HFET with $W_G$ = 10 mm and $L_{GD}$ = 18.5 µm.**

The lateral device scaling for the blocking voltage was studied on transistors with $W_G$ = 3 mm. As shown in Fig. 3, the off-state I-V characteristics for AlGaN/GaN HFETs with $L_{GD}$ = 7.5, 12.5, and 17.5 µm, respectively, are measured at $V_{gs}$ = -10 V. The drain leakage current of all devices under measurement is less than 1 µA before the catastrophic device breakdown. Fig. 4 shows that the blocking voltage and specific on-resistance of the fabricated AlGaN/GaN HFETs scale linearly with $L_{GD}$: as $L_{GD}$ increases from 7.5µm to 17.5µm, $BV_{ds}$ increases from 600 V to 1600 V. Similarly, $R_{ds(ON)}A$ increases linearly from 3.4 mΩ-cm$^2$ to 6.3 mΩ-cm$^2$ as with $L_{GD}$, increases from 7.5µm to 17.5µm. Based on this result, we may assume that the electric field drop uniformly at between the drain contact edge and the gate metal in the voltage blocking state. We can therefore estimate that the critical electric field at the drift region is 1.0 MV/cm.

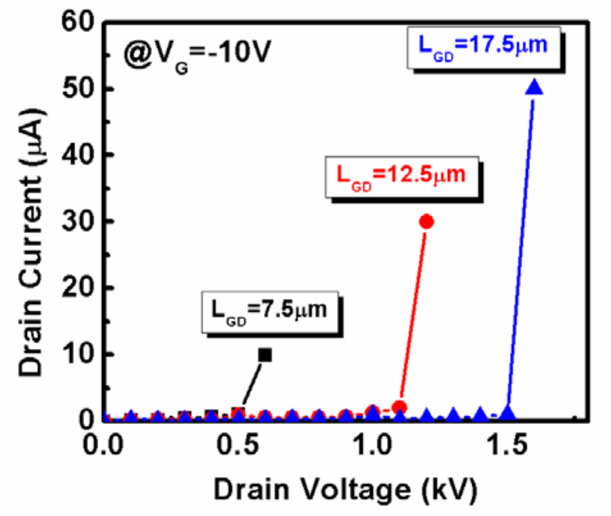

**Fig. 3 The off-state performance for AlGaN/GaN HFETs with $W_G$ = 3mm, $L_G$=4.5 µm, $L_{GD}$=7.5, 12.5, and 17.5 µm, respectively. The gate-to-source voltage is -10 V.**

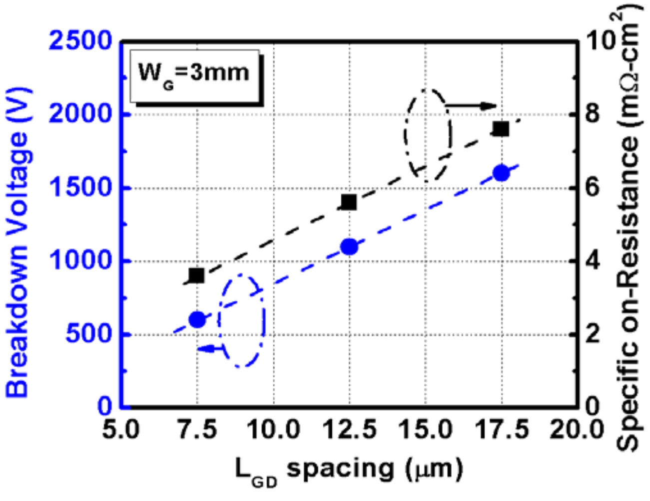

**Fig. 4 A plot showing the breakdown voltage (blue circle) and Specific on-resistance (black square) as a function of the $L_{GD}$ for fabricated AlGaN/GaN HFETs on silicon. The measured devices have $W_G$= 3 mm.**

To investigate the uniformity of $I$-$V$ characteristics, 40 devices with different $W_G$'s were measured. Fig. 5 shows the $R_{ds(on)}$-$L_{GD}$ dependency for devices with $W_G$ = 3 mm, 5 mm, 6 mm, and 10 mm, respectively. The devices under evaluation have $L_G$ of 3.5 µm and $L_{GS}$ of 2 µm. A linear extrapolation of $R_{ds(on)}$-$L_{GD}$ curve shows a slope of 0.1 Ω/μm with < 0.3 Ω standard deviation for given $W_G$'s. This suggests that the current distributes uniformly among all fingers in these multi-finger devices.

To evaluate the on-state resistance, one may normalize the averaged $R_{ds(on)}$ with the total gate width. The specific on-state resistance can be expressed as

$$R_{ds(on)}(\Omega - mm) = 2R_c + R_s + R_d + R_{ch}$$

,where $R_c$ is contact resistance, $R_s$ is the parasitic source resistance, $R_d$ is the parasitic drain resistance, and $R_{ch}$ is the channel resistance under the gate region. The schematic diagram is shown in Fig. 6.

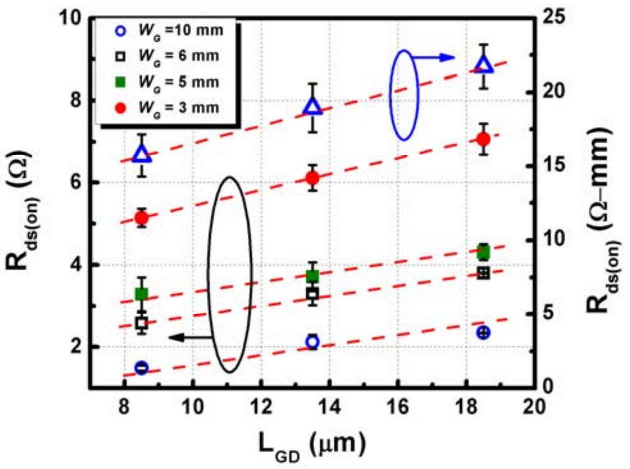

**Fig. 5 (Left y-axis) A plot showing the on-state resistances for the fabricated AlGaN/GaN HFETs grown on silicon with different $W_G$. (Right y-axis) The scaling effect of on-resistance normalized by the $W_G$. The measured devices have the same $L_G$ of 3.5 μm and $L_{GS}$ of 2 μm.**

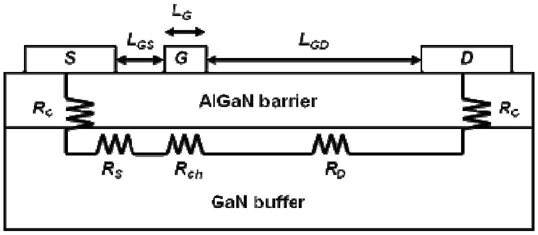

**Fig. 6 Resistance and scaling parameters for the calculation of the specific on-resistance in the AlGaN/GaN HFETs.**

Based on the TLM data, $R_s$ is 0.9 Ω-mm and $R_d$ is 8.5 Ω-mm, respectively, at the on-state for devices with $L_{GS}$ = 2 μm and $L_{GD}$ = 18.5 μm. By averaging the on-state resistance (in the units of W-mm), as shown in the Fig. 5 (right y-axis), $R_{ds(ON)}$ of 8.1 Ω-mm is obtained at $L_{GD}$ = 0. This value is a sum of $R_{ch}$, $R_s$ and 2×$R_C$. By subtracting $R_c$ and $R_s$ from the zero-drift-region resistance, $R_{ch}$ of 4.1 Ω-mm is obtained at $V_G$ = 0 V. Assume that $R_{ch}$ scales linearly with $L_G$, a relatively higher channel resistance is expected for these long gate-length devices [12].

Fig. 7 shows a competitive device performance comparison for GaN-based HFET switches. When the devices operate at $V_{ds}$ > 800 V, GaN HFETs show clear advantage of much reduced on-state resistance by at least a factor of 100 when compared to their silicon counterparts. State-of-the-art high-voltage GaN HFETs using different substrate platforms were also compared. Using sapphire substrate, a 5.5-A GaN MISFET with the on-resistance of 2.5 mΩ-cm$^2$ and blocking voltage up to 600V was achieved [7]. A 940-V GaN power transistor with the on-resistance of 3.6 mΩ-cm$^2$ was also reported for GaN HEFTs built on sapphire substrates [13]. When the GaN HFETs were built on SiC substrates, the high-voltage transistors achieved a blocking voltage of 1.9 kV and $R_{ds(ON)}$ of 2.2 mΩ-cm$^2$ with integrated slant field plate [14]. To date, the highest achievable blocking voltage for GaN HFETs is 9.4 kV with the on-resistance of 52 mΩ-cm$^2$ [15]. Comparing state-of-the-art GaN HFETs, it is fair to say that the device performance reported in this paper is among one of the best results for D-mode GaN-on-Si HFETs reported to date. Using the GaN-on-silicon platform, it is expected that the manufacturing cost of these power electronic devices will be drastically reduced and the fabrication processing steps can be transferable to the silicon CMOS fabrication facility.

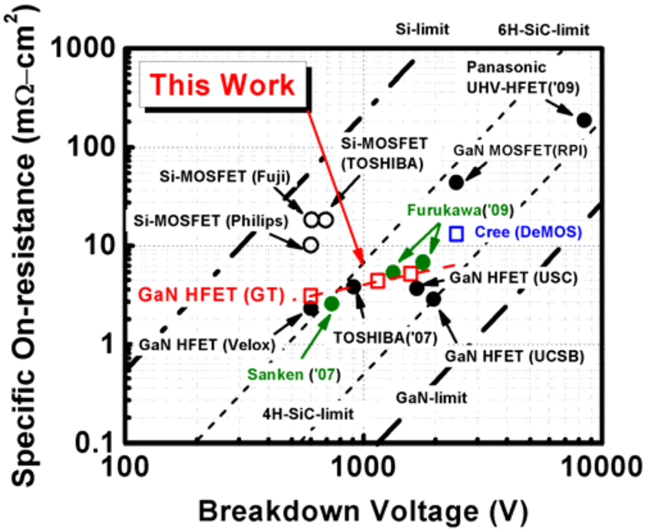

**Fig. 7 Breakdown voltage versus specific on-resistance for Si, and GaN devices on silicon (Furukawa, Sanken, GT), SiC (UCSB) and sapphire (TOSHIBA, Panasonic, Velox, USC, RPI) substrates.**

## CONCLUSIONS

D-mode AlGaN/GaN HFETs on Si with high breakdown voltage (> 1.6 kV) and low specific on-resistance (< 8 mΩ-cm$^2$) are demonstrated. The maximum drain current of 3 A is achieved at $V_{gs}$ = 1 V. The fabricated 10 mm-wide devices exhibit high breakdown voltage (> 1.25 kV) with a specific on-resistance of 6.2 mΩ-cm$^2$ and seem to be robust throughout high-voltage measurement cycles. The blocking voltage and on-resistance are also scaled linearly with the gate-to-drain distance up to 2 kV. These results suggest that GaN HFETs can be readily built on the Si substrates for high-voltage (>1 kV) applications.

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## ACRONYMS

HFET: Heterojunction Field Effect Transistor
$R_c$: Ohmic contact resistance
$W_G$: Gate width
$L_{GD}$: Gate-to-drain distance
$L_{GS}$: Gate-to-source distance
$L_G$: Gate length
$BV_{ds}$: Drain-to-source breakdown voltage
$R_{ds(on)}A$: Specific on-resistance
$R_{ch}$: Channel resistance