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# Schottky-Drain Technology for AlGaIn/GaN High-Electron Mobility Transistors

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**Abstract**—In this letter, we demonstrate 27% improvement in the buffer breakdown voltage of AlGaIn/GaN high-electron mobility transistors (HEMTs) grown on Si substrate by using a new Schottky-drain contact technology. Schottky-drain AlGaIn/GaN HEMTs with a total 2- $\mu\text{m}$ -thick GaN buffer showed a three-terminal breakdown voltage of more than 700 V, while conventional AlGaIn/GaN HEMTs of the same geometry showed a maximum breakdown voltage below 600 V. The improvement of the breakdown voltage has been associated with the planar contact morphology and lack of metal spikes in the Schottky-drain metallization.

**Index Terms**—Buffer breakdown, GaN-on-silicon, high-electron mobility transistor (HEMT), power electronics, Schottky drain.

## I. INTRODUCTION

**D**UE TO their combination of high electron mobility ( $\mu_e$ ) and high critical electric field ( $E_c$ ), AlGaIn/GaN high-electron mobility transistors (HEMTs) are excellent candidates for the next generation of power electronic devices [1]. These excellent properties allow the fabrication of power circuits with unprecedented performance. For example, a 175–350-V boost converter based on the AlGaIn/GaN HEMT technology has recently achieved 97.8% conversion efficiency at 1-MHz switching speed with 300-W output power [3].

Most of the reported high-breakdown AlGaIn/GaN HEMTs are grown on SiC substrates, whose limited diameter (up to 4 in) and high cost severely hinder the commercialization of GaN-based power electronics. Due to the large available size and lower cost of silicon substrates, AlGaIn/GaN HEMTs grown on Si (111) are becoming attractive for GaN-based power switches. Recently, crack-free GaN grown on 150-mm Si substrates has been reported by several groups [4], [5] with a sheet resistance of 260  $\Omega/\square$  and mobility up to 1650  $\text{cm}^2/\text{V} \cdot \text{s}$  [5]. In addition, the GaN-on-Si wafers also enable the seamless integration of Si CMOS electronics with GaN power transistors [6], bringing a new degree of freedom for designing more compact systems, such as on-chip power distribution networks for microprocessors [7], [8].

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In spite of the great potential of GaN-on-Si power electronics, the breakdown voltages of standard AlGaIn/GaN HEMTs grown on Si are much lower than those grown on SiC. For example, the breakdown voltages of AlGaIn/GaN HEMTs with a total 2- $\mu\text{m}$  epitaxial layer on Si substrates are typically less than 600 V [9], [10], while for the same epitaxial layer thickness on SiC, a 1.9-kV breakdown voltage has been demonstrated [2]. Several approaches have been used to improve the device breakdown voltage, including increasing the epitaxial layer thickness [9]–[11], doping the buffer with Fe or C [12], [13], and using AlGaIn in the buffer [14]. Recently, a 1.8-kV breakdown voltage has been demonstrated in AlGaIn/GaN HEMTs on Si by increasing the buffer thickness to 6  $\mu\text{m}$  [10]. However, the growth of thick buffer layers increases the cost of GaN-on-Si wafers. In this letter, we demonstrate a new technology based on the use of a Schottky metallization in the drain contact to increase the buffer breakdown voltage by 27%.

## II. DEVICE FABRICATION

Both Schottky-drain and conventional ohmic-drain HEMTs were fabricated on  $\text{Al}_{0.26}\text{Ga}_{0.74}\text{N}/\text{AlN}/\text{GaN}$  heterostructures grown on 4-inch Si (111) substrates by Nitronex Corporation. These structures have a total 2- $\mu\text{m}$  undoped GaN/AlGaIn buffer, a 1-nm AlN interlayer, and a 17.5-nm AlGaIn barrier with a 2-nm GaN cap layer [16]. For the conventional HEMTs, Ti/Al/Ni/Au alloyed ohmic source and drain contacts were formed after 870  $^\circ\text{C}$  annealing for 30 s in  $\text{N}_2$  atmosphere. In the Schottky-drain HEMTs, unannealed Ti/Au metallization was used for the drain contact. Prior to this metallization, a 10-nm recess was performed on the  $\text{Al}_{0.26}\text{Ga}_{0.74}\text{N}$  barrier by a low-energy  $\text{BCl}_3/\text{Cl}_2$  plasma in an electron cyclotron resonance system to reduce the series resistance and turn-on voltage of the Schottky-drain contacts. Then, 150-nm mesa isolation was achieved by  $\text{BCl}_3/\text{Cl}_2$  plasma etching. Finally, Ni/Au/Ni Schottky gates were formed by e-beam evaporation. Both the ohmic-drain and Schottky-drain devices were simultaneously fabricated on the same wafer and in very close proximity from each other. These devices have the gate length ( $L_g$ ) of 2  $\mu\text{m}$ , gate-to-source spacing ( $L_{gs}$ ) of 1.5  $\mu\text{m}$ , and gate-to-drain spacing ( $L_{gd}$ ) varying from 5 to 20  $\mu\text{m}$ . For the buffer breakdown characterization, no gate was formed between the source and drain contacts. The breakdown voltage was measured with a Tektronix Curve Tracer as a voltage source and two Agilent 34401A multimeters to measure the current and voltage. The breakdown voltage is defined as the voltage when the leakage current reaches 1 mA/mm. Fluorinert was used to prevent surface flashover during measurements.

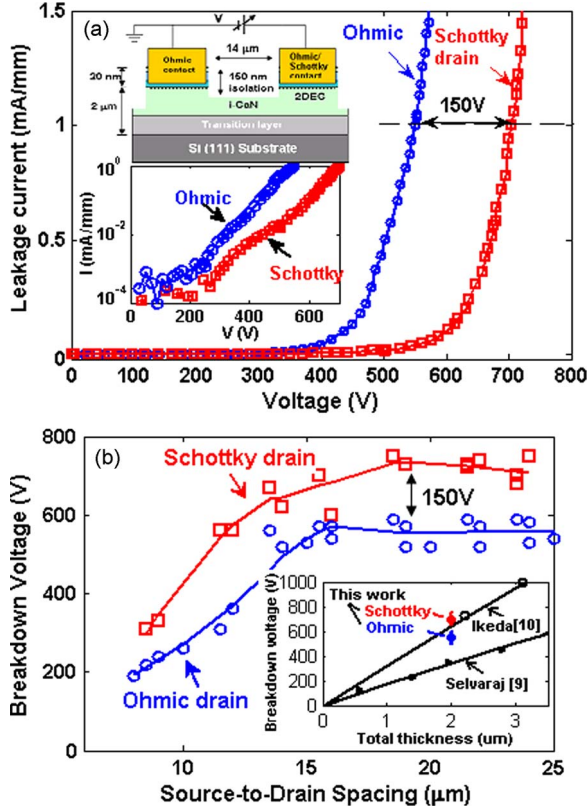


Fig. 1. (a) Buffer lateral leakage current of the ohmic-drain and Schottky-drain devices with 14- $\mu\text{m}$  contact spacing. The inset shows the leakage current in semilog scale and the measurement configuration. (b) Buffer lateral breakdown voltage as a function of source-to-drain spacing. The inset compares the maximum buffer breakdown voltages of the Schottky-drain and ohmic-drain devices with the reported maximum buffer breakdown voltages for different total epitaxial thicknesses.

### III. EXPERIMENTAL RESULTS

The buffer lateral breakdown voltage of the ohmic-drain and the Schottky-drain devices was measured in structures where a 150-nm-deep recess was performed between the source and drain contacts to eliminate the 2DEG [inset of Fig. 1(a)]. The Si substrate was floating during the measurement. Fig. 1(a) shows the typical lateral breakdown  $I$ - $V$  curves of a conventional ohmic-drain device and a Schottky-drain device with 14- $\mu\text{m}$  source-to-drain distance ( $L_{sd}$ ). The Schottky-drain device shows 150 V higher breakdown voltage than the ohmic-drain device, reaching 700 V, 27% improvement. To compare the leakage currents of the ohmic-drain and Schottky-drain devices, the same  $I$ - $V$  curves are shown in semilog scale in the inset of Fig. 1(a). The leakage current of the Schottky-drain device is five times lower than that of the ohmic-drain device. Fig. 1(b) shows the breakdown voltages for different source-to-drain distances. For source-to-drain spacing below 14  $\mu\text{m}$ , the breakdown voltage increases linearly with the distance. For source-to-drain spacing above 14  $\mu\text{m}$ , the breakdown voltage saturates, which is an indication of vertical current leakage from the GaN buffer to the Si substrate. Since the Si substrate is conductive (with sheet resistance of 2–4  $\text{k}\Omega/\square$ , measured from the Van der Pauw structure), the lateral voltage drop across the Si substrate is negligible, resulting in the breakdown saturation.

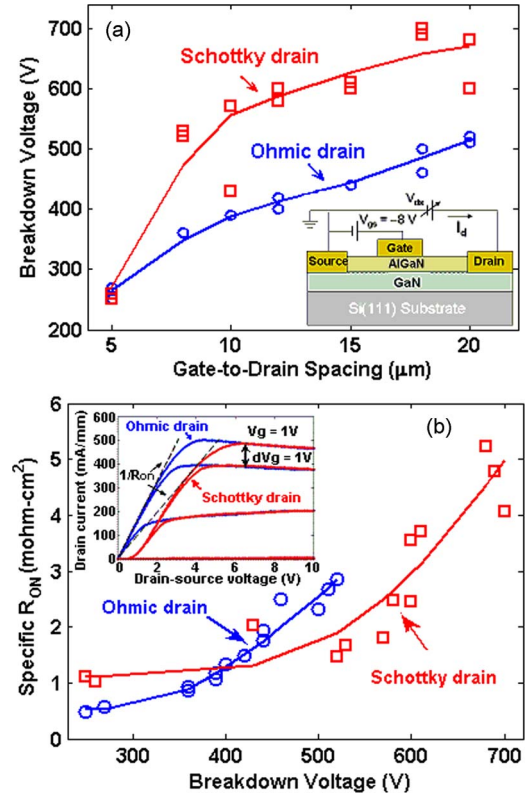


Fig. 2. (a) Three-terminal breakdown voltages as a function of gate-to-drain distances. (b) Specific  $R_{on}$  as a function of breakdown voltages. The inset shows the  $I$ - $V$  curves of the ohmic-drain and Schottky-drain devices with  $L_g = 2 \mu\text{m}$ ,  $L_{gs} = 1.5 \mu\text{m}$ , and  $L_{gd} = 10 \mu\text{m}$ .

tion. Therefore, the maximum achievable breakdown voltage in AlGaN/GaN HEMTs on Si substrate is limited by the GaN-to-Si vertical breakdown. Comparing with the maximum reported buffer breakdown voltages in the literature, the inset of Fig. 1(b) shows that the new Schottky-drain contact devices have the highest buffer breakdown voltage for a given epitaxial layer, 2  $\mu\text{m}$  in this case.

The three-terminal breakdown voltage ( $V_{bk}$ ) of the ohmic-drain and Schottky-drain HEMTs was measured under a gate-to-source bias of  $-8 \text{ V}$ , enough to pinch off the devices which have a threshold voltage of  $-2 \text{ V}$ . The maximum breakdown voltage of the ohmic-drain devices is between 500 and 600 V while the maximum breakdown voltage for the Schottky-drain devices is between 600 and 700 V, with some of them showing more than 700 V (up to 748 V). Although the results show some dispersion in different areas of the sample, the Schottky-drain devices always have higher breakdown voltages than the ohmic-drain devices when devices near to each other are compared [Fig. 2(a)]. On average, the Schottky-drain devices show more than 100 V higher breakdown voltage than the ohmic-drain devices.

The  $R_{on}$ -resistance ( $R_{on}$ ) of both the standard HEMTs and the Schottky-drain HEMTs was calculated from the  $I$ - $V$  curves, as shown in the inset of Fig. 2(b). The active area between source and drain is used for the specific  $R_{on}$  calculation, including a 2- $\mu\text{m}$  transfer length from contact pads. Because the Schottky-drain HEMTs can achieve the same breakdown

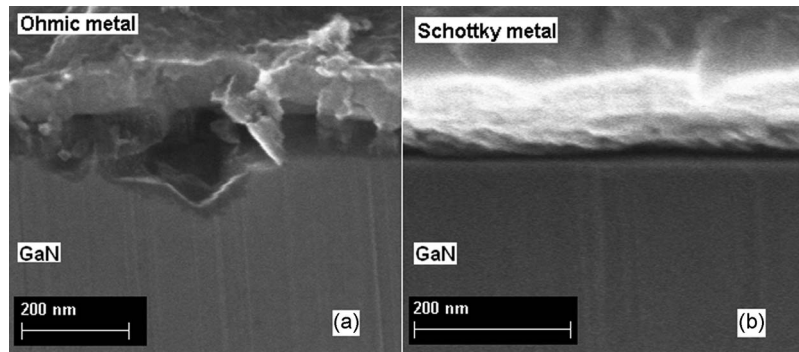


Fig. 3. SEM cross section of (a) ohmic contact on AlGaIn/GaN and (b) Schottky contact on AlGaIn/GaN HEMT structures grown on Si substrates.

voltage as the ohmic-drain HEMTs with shorter gate-to-drain spacing, they have lower specific  $R_{on}$  than the standard HEMTs for  $V_{bk} > 400$  V, as shown in Fig. 2(b). The use of Schottky-drain contacts has allowed the fabrication of transistors with  $4.5\text{-m}\Omega \cdot \text{cm}^2$  specific  $R_{on}$  at 700 V. In addition, the proposed Schottky-drain contact technology can also be used as an integrated protection diode for GaN power amplifiers, as reported in [15].

#### IV. DISCUSSION

To find out the origin of the increased breakdown voltage associated with the Schottky-drain contact, the samples were cleaved and the cross section of the ohmic and Schottky contacts was studied with a scanning electron microscope (SEM). In contrast to the flat AlGaIn/GaN surface underneath the Schottky contact [Fig. 3(b)], voids have been found in the GaN underneath the ohmic contact, as shown in Fig. 3(a). This finding is consistent with [17] where pits in the GaN were found after etching away the alloyed ohmic contacts. We believe that the voids in the GaN created by the alloyed ohmic contact are responsible for the higher leakage current and lower breakdown of the ohmic-drain devices. However, the detailed mechanism is not clear at this moment.

#### V. SUMMARY

In this letter, we have demonstrated that the use of Schottky-drain contacts can increase the buffer breakdown voltage of AlGaIn/GaN HEMTs grown on Si substrates. The use of this new technology allowed the fabrication of AlGaIn/GaN HEMTs with more than 700-V three-terminal breakdown voltage and a specific  $R_{on}$  of  $4.5\text{ m}\Omega \cdot \text{cm}^2$  on a GaN-on-Si sample with only  $2\text{-}\mu\text{m}$  total epitaxial layer. These results demonstrate the great potential of GaN-on-Si devices for power electronics.

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