Mechanism of improving forward and reverse blocking voltages in AlGaN/GaN HEMTs by using Schottky drain*

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In this paper, we demonstrate that a Schottky drain can improve the forward and reverse blocking voltages (BVs) simultaneously in AlGaN/GaN high-electron mobility transistors (HEMTs). The mechanism of improving the two BVs is investigated by analysing the leakage current components and by software simulation. The forward BV increases from 72 V to 149 V due to the good Schottky contact morphology. During the reverse bias, the buffer leakage in the Ohmic-drain HEMT increases significantly with the increase of the negative drain bias. For the Schottky-drain HEMT, the buffer leakage is suppressed effectively by the formation of the depletion region at the drain terminal. As a result, the reverse BV is enhanced from −5 V to −49 V by using a Schottky drain. Experiments and the simulation indicate that a Schottky drain is desirable for power electronic applications.

Keywords: AlGaN/GaN high-electron mobility transistors (HEMTs), forward blocking voltage, reverse blocking voltage, Schottky drain

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1. Introduction

AlGaN/GaN high-electron mobility transistors (HEMTs) have been widely investigated as promising candidates for power electronics applications.[1–5] Besides the high forward off-state blocking performance and low on-resistance (R_{on}), excellent reverse blocking capability is also desired in a number of applications, such as electric vehicles, class-S amplifiers, and bidirectional switches.[6,7] The drain terminal may be biased at a negative voltage in these applications and this would result in a significant increase of the drain current. In previous studies, an AlGaN/GaN HEMT with an integrated recessed Schottky protection diode was fabricated and the reverse blocking capability of this device was better than −110 V.[8] In addition, the forward blocking voltage of the AlGaN/GaN HEMT with Schottky drain has been proven to be higher than that of the device with Ohmic drain due to better contact morphology.[9] However, the improvement mechanism of forward and reverse blocking voltages (BVs) by using Schottky drain has rarely been investigated explicitly.

In this paper, we present that a Schottky drain can enhance the forward and reverse blocking voltages simultaneously and we then investigate the improvement mechanism of the two blocking voltages by using a Schottky drain. The Schottky drain is not etched to reduce the on-resistance R_{on} and the onset voltage is a little higher than that in recessed Schottky-drain HEMT. There are two reasons for the non-recessed Schottky drain. Firstly, one extra photomask and one etching process are needed for the recessed Schottky drain, which would increase the process complexity. Secondly, the etching process would introduce new trap states, which may influence the analysis of device breakdown.

2. Device fabrication and dc characteristics

Figure 1 shows the schematic cross section of the fabricated AlGaN/GaN HEMT with a Schottky drain. The heterostructure was grown on 2-in (1 in = 2.54 cm) sapphire substrate by the metal-organic chemical vapor deposition (MOCVD). The epitaxial layers consisted of a 140-nm AlN nucleation layer, a 1.4-μm GaN buffer layer, and a 20-nm $Al_{0.30}Ga_{0.70}N$ barrier layer. Hall measurements showed a sheet carrier density of 0.7×10^{13} cm^{-2} and an electron mobility of 1508 cm^2/V·s. Two types of devices were fabricated on this wafer, which were: a conventional Ohmic-drain HEMT and a Schottky-drain HEMT. The first step of the device fabrication was to anneal the e-beam evaporated Ti/Al/Ni/Au (20 nm/140 nm/55 nm/45 nm) at 830 °C for 30 s to realize the Ohmic contact. Then, mesa isolation was performed by reactive ion etching (RIE) with Cl_2. The metal stack of Ni/Au (45 nm/200 nm) was deposited to form the Schottky gate and the Schottky drain. The devices were passivated with SiN

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layer to suppress current collapse. All of the devices had a gate length (L_G) of 0.8 μm, the gate–source spacing (L_{GS}) of 0.7 μm, and a gate–drain spacing (L_{GD}) of 2 μm.

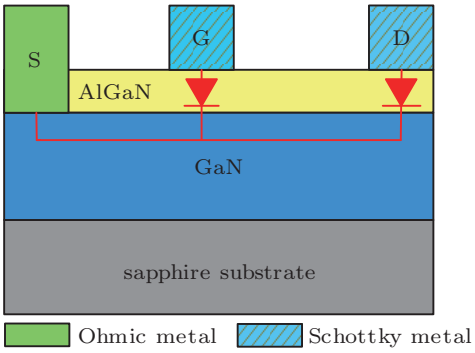


Fig. 1. (color online) Schematic cross section of the fabricated Schottky-drain AlGaN/GaN HEMT.

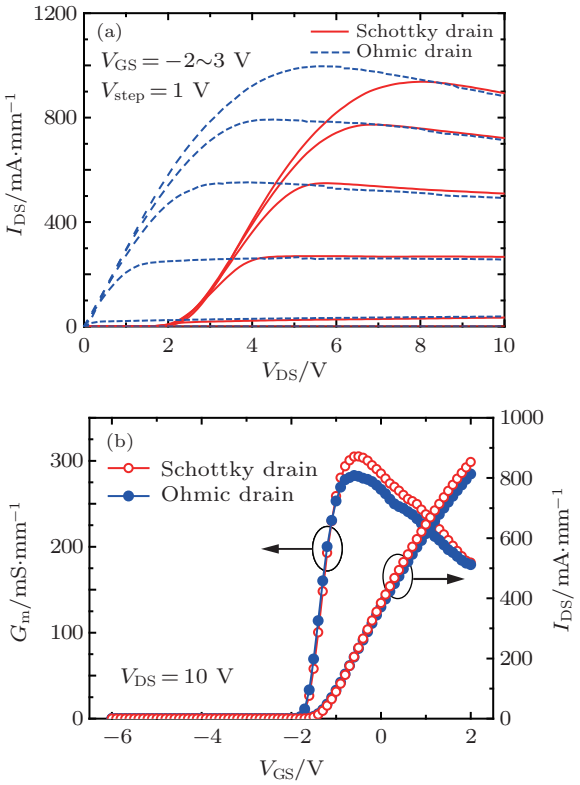


Fig. 2. (color online) DC characteristics of the Ohmic-drain HEMT and the Schottky-drain HEMT. (a) Output curves and (b) transfer curves at $V_{DS} = 10$ V.

The dc-output characteristics of the two fabricated HEMTs are shown in Fig. 2(a). For the Ohmic-drain HEMT, the maximum drain current (I_{DSmax}) is 996 mA/mm. The I_{DSmax} of the Schottky-drain HEMT is 937 mA/mm, which is a little lower than that of the Ohmic-drain HEMT. An onset voltage of 1.7 V (at the drain current of 1 mA/mm) was observed from the dc-output characteristics of the Schottky-drain HEMT. The AlGaN barrier layer at the drain terminal was not removed, and the Schottky-drain metal cannot be connected to the two-dimensional electron gas (2DEG) directly. Thus, the onset voltage is larger than the reported value of 1 V.[8] The onset voltage of 1.7 V increases the on-resistance R_{on} from 3.45 Ω·mm to 7.55 Ω·mm. As shown in Fig. 2(b), the peak transconductance ($G_{m,max}$) is 305 mS/mm for the Schottky-drain HEMT and 282 mS/mm for the Ohmic-drain HEMT, respectively. The threshold voltages for the two HEMTs are both −1.6 V, which are determined at $I_{DS} = 1$ mA/mm.

3. Discussion of the device breakdown mechanism

The three-terminal OFF-state breakdown characteristics of the two devices during forward and reverse drain bias are shown in Fig. 3. The forward blocking voltage increases from 72 V of the Ohmic-drain HEMT to 149 V of the Schottky-drain HEMT. Meanwhile, the reverse blocking voltage increases from −5 V to −49 V by using a Schottky drain. Therefore, the forward and reverse blocking voltages increase simultaneously by using a Schottky drain. In order to investigate the improvement mechanism of the forward and reverse BVs in Schottky-drain HEMT, we carry out the analyses of forward and reverse biases, respectively.

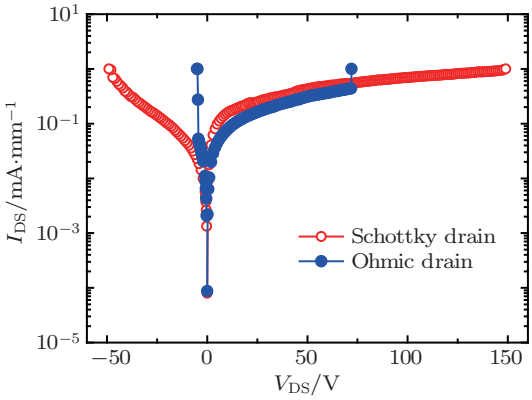


Fig. 3. (color online) Measured three-terminal OFF-state breakdown characteristics of the Ohmic-drain HEMT and the Schottky-drain HEMT at $V_{GS} = -6$ V.

The leakage currents through the drain/source/gate terminals in the two HEMTs during the forward BV measurement are shown in Fig. 4. For the two HEMTs, the drain leakage current is dominated by the buffer leakage current. The buffer leakage current in Ohmic-drain HEMT increases abruptly at $V_{DS} = 72$ V and induces the device breakdown. A similar buffer leakage exists in the Schottky-drain HEMT when V_{DS} is less than 72 V. For the Schottky-drain HEMT, the buffer leakage does not increase abruptly at $V_{DS} = 72$ V. On the contrary, I_S increases slowly to the criterion of 1 mA/mm at $V_{DS} = 149$ V. The forward BV of the Schottky-drain HEMT would be higher for a lager leakage current criterion.

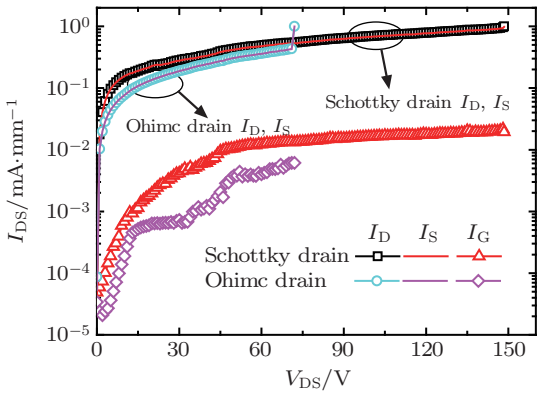


Fig. 4. (color online) I_D, I_S, and I_G during the forward OFF-state I–V measurement in Ohmic-drain and Schottky-drain HEMTs with $V_{GS} = -6$ V.

Figure 5 shows a comparison between the Schottky contact and the Ohmic contact. In previous work, the cross sections of the two contacts have been studied by using scanning electron microscope (SEM).[9] It was observed that deep metallic spikes around the Ohmic contact could be formed after high temperature annealing. These deep spikes would cause the electric-field lines to concentrate at the spikes, leading to the premature breakdown at the drain terminal. After the evaporation and lift-off of the Ti/Al/Ni/Au metal, the contact between the metal and the AlGaN material actually becomes a Schottky contact. In order to form an Ohmic contact, the metal should penetrate into the GaN-based materials and be connected to 2DEG directly by the annealing process. The penetration is uneven for the evaporated metal and it will inevitably form metal spikes. However, the Schottky drain can be formed without the annealing process, thus the contact between the Schottky metal and the AlGaN material is very smooth. As a result, a higher forward BV is achieved in the Schottky-drain HEMT compared with the Ohmic-drain HEMT.

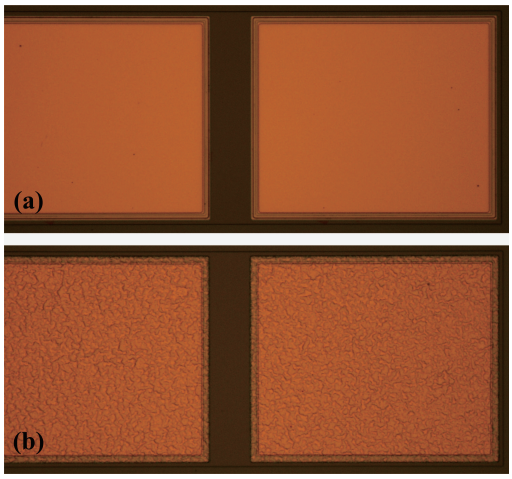


Fig. 5. (color online) Optical microscope images of (a) Ni/Au Schottky contact region and (b) Ti/Al/Ni/Au Ohmic contact region.

Figure 6 shows the leakage currents flowing through the drain/source/gate terminals in the two HEMTs during the reverse BV measurement. The breakdown of the Ohmic-drain HEMT is induced by the buffer leakage. For the Schottky-drain HEMT, the buffer leakage is suppressed effectively and the reverse BV is enhanced from -5 V to -49 V. The gate leakage currents decrease with the increase of the negative V_{DS}, and the I_G in the Schottky-drain HEMT decreases more slowly than that in the Ohmic-drain HEMT. The difference in leakage current between the two devices can be explained through software simulation.

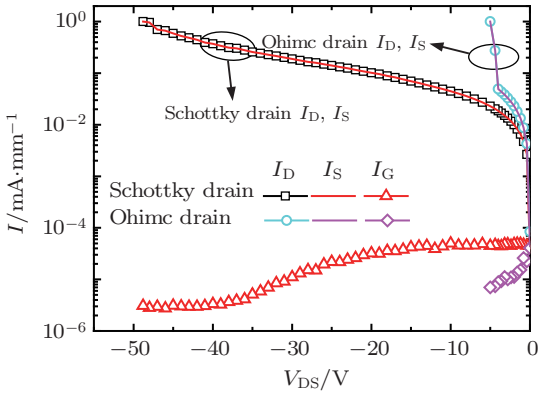


Fig. 6. (color online) I_D, I_S, and I_G during the reverse OFF-state I–V measurement in Ohmic-drain and Schottky-drain HEMTs with $V_{GS} = -6$ V.

The two devices are simulated by Silvaco ATLAS to investigate the breakdown mechanism. The simulated devices have similar structures to the fabricated HEMTs. The background doping concentrations in GaN and AlGaN layers are both assumed to be 1×10^{15} cm^{-3}. The positive polarization charge is modeled as a positive fixed sheet charge with a density of 0.7×10^{13} cm^{-2} along the interface of the heterojunction. The impact ionization is modeled as $\alpha_0 \exp(-E_C/E)$, where $\alpha_0 = 2.9 \times 10^8$/cm and $E_C = 3.4 \times 10^7$ V/cm.[10] Using the electron affinity values of 3.8 eV[11] and 1.9 eV[12] for GaN and AlN, respectively, the electron affinity value for $Al_{0.3}Ga_{0.7}N$ is calculated to be 3.23 eV.

Figure 7 shows the simulated logarithmic electron concentrations in two HEMTs for off-state condition during zero and reverse drain bias. Figure 7(a) shows the strong depletion under gate region in the Ohmic-drain HEMT with $V_{GS} = -6$ V and $V_{DS} = 0$ V. With the Ohmic drain biased at -5 V, the negative drain bias would be mainly applied to the gate depletion region. Thus, the voltage drop under the gate would decrease to a small value and the device would be turned on, as shown in Fig. 7(b). The voltage drop refers to the difference in potential between the gate and the 2DEG, and it determines the magnitude of the gate leakage. The density of 2DEG and electrons around the interface under the gate increase with the increase of the negative V_{DS}, leading to the rapid increase of the buffer leakage. The voltage drop under the gate decreases with the increase of the negative V_{DS}, resulting in a reduction of the gate leakage.

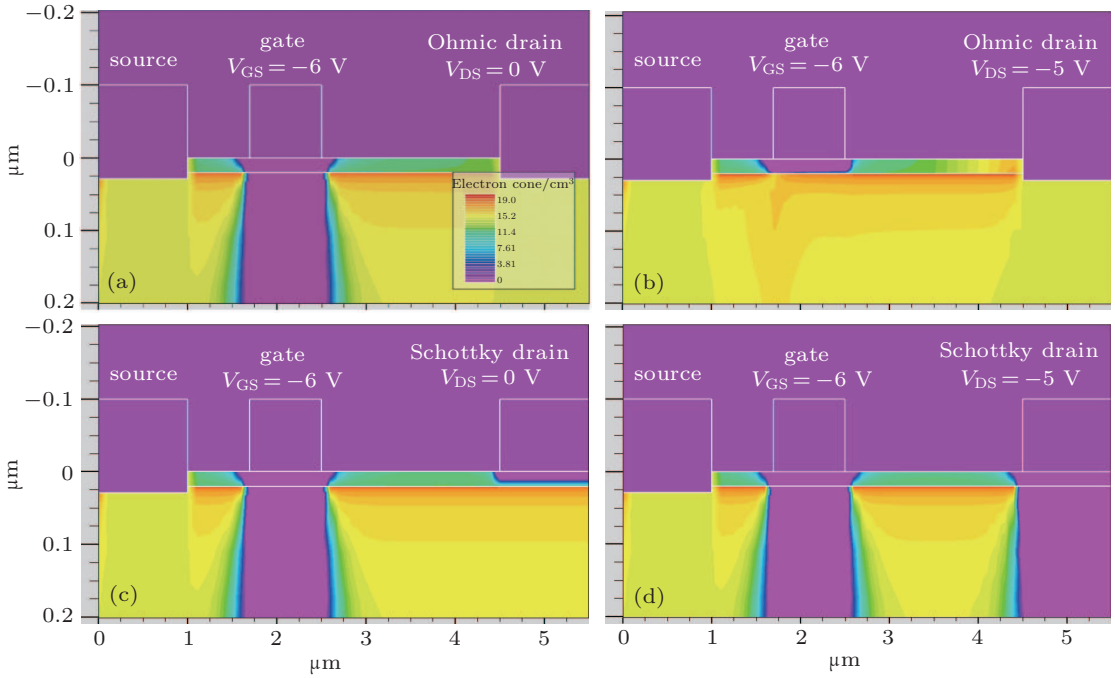


Fig. 7. (color online) Logarithmic electron concentration distributions of the Ohmic-drain HEMT with (a) $V_{GS} = -6$ V and $V_{DS} = 0$ V; (b) $V_{GS} = -6$ V and $V_{DS} = -5$ V. Logarithmic electron concentration distributions of the Schottky-drain HEMT with (c) $V_{GS} = -6$ V and $V_{DS} = 0$ V; (d) $V_{GS} = -6$ V and $V_{DS} = -5$ V.

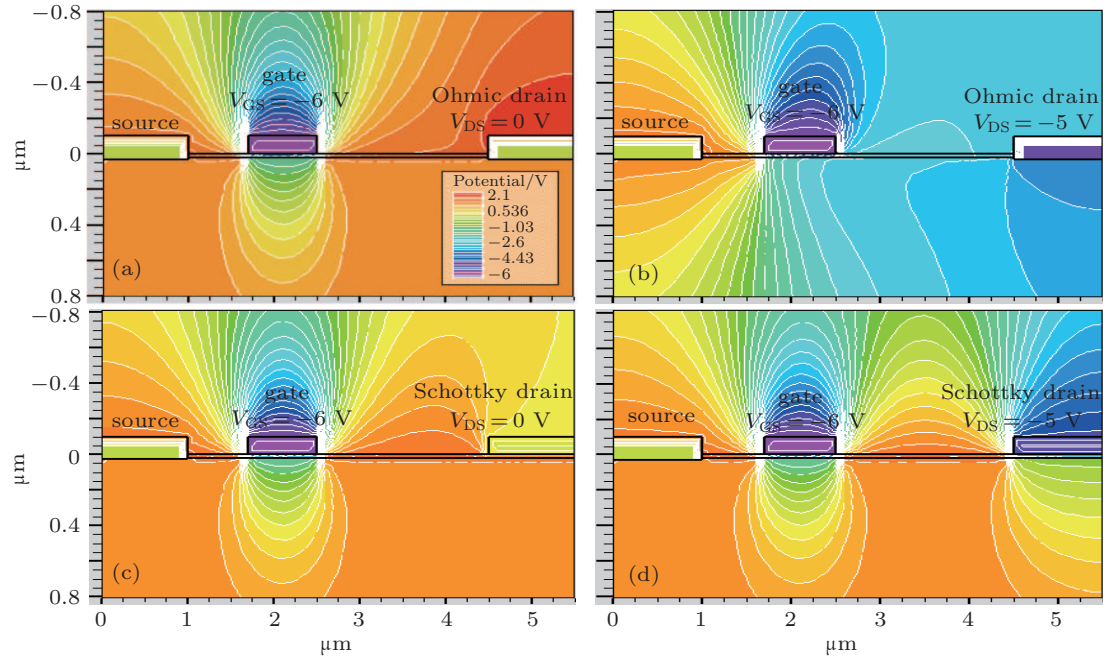


Fig. 8. (color online) Potential distributions of the Ohmic-drain HEMT with (a) $V_{GS} = -6$ V and $V_{DS} = 0$ V; (b) $V_{GS} = -6$ V and $V_{DS} = -5$ V. Potential distributions of the Schottky-drain HEMT with (c) $V_{GS} = -6$ V and $V_{DS} = 0$ V; (d) $V_{GS} = -6$ V and $V_{DS} = -5$ V.

The gate and drain terminals in the Schottky-drain HEMT are Schottky contacts, as shown in Fig. 1. There is a depletion region formed under the drain terminal with $V_{DS} = 0$ V, as shown in Fig. 7(c). As shown in Fig. 7(d), the depletion region near the drain terminal would be expanded with the increase of negative V_{DS}. The negative drain bias is mainly applied to the drain depletion region and the gate depletion region is hardly changed. Therefore, the buffer leakage is suppressed effectively by the two depletion regions and the reverse BV increases from −5 V of the Ohmic-drain HEMT to −49 V. In addition, the smooth Schottky contact may also have a positive effect on the suppression of the buffer leakage current. The voltage drop under the gate decreases slowly with the increase of the negative V_{DS}, thus the gate leakage current would

decreases slowly, as shown in Fig. 6.

In order to present the decrease of the voltage drop under the gate intuitively, the potential distributions of the two HEMTs under different bias conditions are shown in Fig. 8. For the Ohmic-drain HEMT, the potential under the gate is affected significantly by the addition of the negative V_{DS}. The voltage drop between the gate and the 2DEG is reduced by the increase of the magnitude of the negative V_{DS}, leading to the decrease of the gate leakage. In contrast, the potential under the gate is almost unchanged with the increase of the negative V_{DS} for the Schottky-drain HEMT.

4. Conclusion

The mechanism of improving the forward and reverse BVs in Schottky-drain AlGaN/GaN HEMT is investigated in this paper. By using the Schottky drain in the Schottky-drain AlGaN/GaN HEMT, the forward and reverse BVs are improved from 72 V and −5 V to 149 V and −49 V, respectively, suggesting that a Schottky drain can increase the two blocking voltages simultaneously. The analyses of leakage current components and software simulation are utilized to study the improvement mechanism. Experiment and simulation indicate that a Schottky drain is a desirable technique for power electronics applications.

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