Influence of a drain field plate on the forward blocking characteristics of an AlGaN/GaN high electron mobility transistor*

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In this paper, the influence of a drain field plate (FP) on the forward blocking characteristics of an AlGaN/GaN high electron mobility transistor (HEMT) is investigated. The HEMT with only a gate FP is optimized, and breakdown voltage V_{BR} is saturated at 1085 V for gate–drain spacing $L_{GD} \geq 8$ μm. On the basis of the HEMT with a gate FP, a drain FP is added with $L_{GD} = 10$ μm. For the length of the drain FP $L_{DF} \leq 2$ μm, V_{BR} is almost kept at 1085 V, showing no degradation. When L_{DF} exceeds 2 μm, V_{BR} decreases obviously as L_{DF} increases. Moreover, the larger the L_{DF}, the larger the decrease of V_{BR}. It is concluded that the distance between the gate edge and the drain FP edge should be larger than a certain value to prevent the drain FP from affecting the forward blocking voltage and the value should be equal to the L_{GD} at which V_{BR} begins to saturate in the first structure. The electric field and potential distribution are simulated and analyzed to account for the decrease of V_{BR}.

Keywords: AlGaN/GaN high electron mobility transistor, forward blocking voltage, drain field plate

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1. Introduction

The AlGaN/GaN high electron mobility transistor (HEMT) is a promising candidate for power switching applications[1–3] due to its superior properties, such as high breakdown voltage V_{BR} and low specific on-resistance R_{ON}. Various field plate structures have been proposed to improve the forward off-state blocking characteristics, including the gate field plate (FP),[4–6] source FP,[7] slant FP,[8] and multiple FPs.[9] These FPs can increase the forward blocking voltage significantly by modulating the electric field. In a conventional GaN-based HEMT, there is no depletion region formed in the vicinity of the drain contact during forward drain bias. Hence, the drain FP in a conventional AlGaN/GaN HEMT has rarely been reported and the influence of the drain FP on the forward blocking capability has seldom been investigated.

The reverse blocking capability is very important for power switching applications besides the forward blocking performance. When the drain electrode experiences a negative voltage, a high reverse breakdown voltage becomes very necessary because it can protect the power switching HEMT from having excessive gate current. Treidel *et al.*[10] demonstrated an AlGaN/GaN HEMT with Schottky drain technology to enhance the reverse blocking capability. The combination of a drain FP and a Schottky drain is an effective way to further enhance the reverse blocking capability.[11] However, an unsuitable drain FP may reduce the forward blocking voltage. Thus, the drain FP needs to be optimized to ensure that it does not degrade the forward blocking performance.

In this paper, we present an AlGaN/GaN HEMT with a gate FP and a drain FP and investigate the influence of the length of the drain FP on the forward blocking voltage. The significance of this paper lies in two aspects. First, the negative influence of the drain FP on the forward blocking voltage is investigated in a conventional AlGaN/GaN HEMT. Second, the drain FP is optimized to prevent it from degrading the forward blocking performance in the Schottky-drain AlGaN/GaN HEMT. With a forward drain bias applied, there is a little depletion layer formed at the drain terminal in the Schottky-drain AlGaN/GaN HEMT, leading to no electric field peak at the drain terminal. Therefore, the details discussed and the results shown in this paper can be applied to the investigation of HEMTs with Schottky-drain electrodes directly.

2. Device structure and simulation

Two kinds of HEMT structures are simulated as shown in Fig. 1, each including a 2-μm unintentionally doped (UID) GaN buffer layer and a 20-nm UID $Al_{0.3}Ga_{0.7}N$ barrier layer. The devices of the first structure are the AlGaN/GaN HEMTs each with a gate FP. The gate length $L_G = 1$ μm, gate–source spacing $L_{GS} = 1$ μm, and gate–FP length $L_{GF} = 3$ μm are kept constant, whereas the gate–drain spacing L_{GD} varies from

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4 μm to 20 μm. The devices of the second structure are the AlGaN/GaN HEMTs each with a gate FP and a drain FP. The L_G, $L_{GS,}$, and L_{GF} of this structure are the same as those of the first one. Additionally, L_{GD} is set to be 10 μm and the drain–FP length L_{DF} is changed from 1 μm to 6 μm in steps of 1 μm. The drain electrode discussed in this paper is made of Ohmic metal. The background doping concentrations in the AlGaN layer and the GaN layer 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 1×10^{13} cm^{-2} along the interface of the heterojunction.

These HEMTs are simulated using Silvaco-ATLAS software. The breakdown voltages mentioned in this paper refer to the forward blocking voltages. The breakdown voltage is defined as the voltage at the intersection of the saturation segment and the rapidly rising segment resulting from the impact ionization of the simulated I_{DS}–V_{DS} curve. The impact ionization is modeled as $\alpha_0 \exp(-E_C/E)$, where $\alpha_0 = 2.9\times10^8$ cm^{-2} and $E_C = 3.4\times10^7$ V/cm.[12] The exact values of the material parameters are identical to those in Ref. [13]. All the simulations concerning the breakdown voltage are carried out with the gate biased at −6 V, where the devices are fully pinched-off.

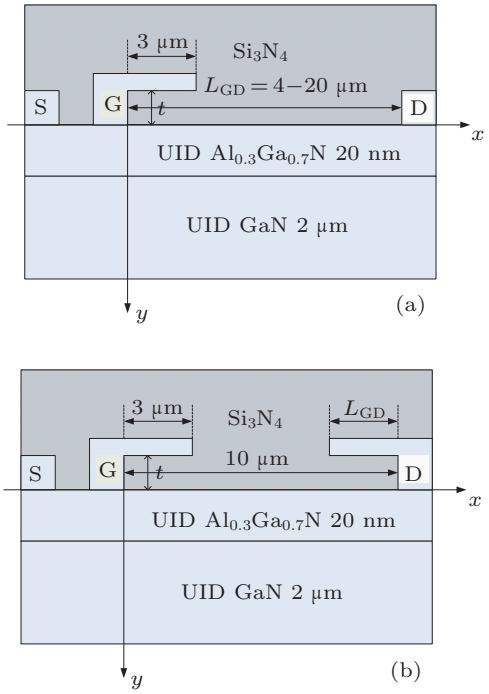


Fig. 1. Schematic cross sections of (a) HEMT with a gate FP and (b) HEMT with a gate FP and a drain FP.

3. Results and discussion

The HEMTs of the first structure are simulated at first. An optimum $t = 0.55$ μm is obtained by using the method utilized in Ref. [13]. As shown in Fig. 2, V_{BR} increases linearly with increasing L_{GD} for $L_{GD} \leq 8$ μm, and it is saturated at $V_{BR} =$ 1085 V. In addition, R_{ON} increases linearly with increasing L_{GD} for the whole process. For $L_{GD} = 7$ μm, the breakdown voltage is 1060 V and the specific on-resistance is as low as 0.76 mΩ·cm^2. This translates to a rather high figure-of-merit of power device $V_{BR}^2/R_{ON} = 1.48\times10^9$ V^2·mΩ^{-1}·cm^{-2}, which is among the best values reported for AlGaN/GaN HEMTs to date.

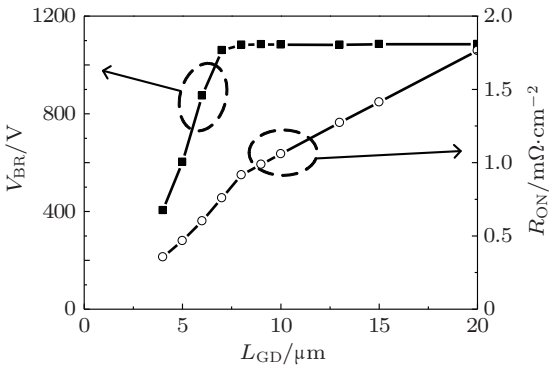


Fig. 2. The V_{BR} and R_{ON} each as a function of L_{GD} for HEMT with a gate FP.

Although V_{BR} is saturated at $L_{GD} = 8$ μm, L_{GD} of the second structure must exceed 8 μm in order to investigate the influence of the L_{DF} on the breakdown voltage comprehensively. Hence we set $L_{GD} = 10$ μm. The breakdown electric field distribution for the HEMT of the first structure with $L_{GD} = 10$ μm is shown in Fig. 3. It can be observed from Fig. 3 that $L_{GD} = 8$ μm is sufficient to provide the maximum $V_{BR} = 1085$ V.

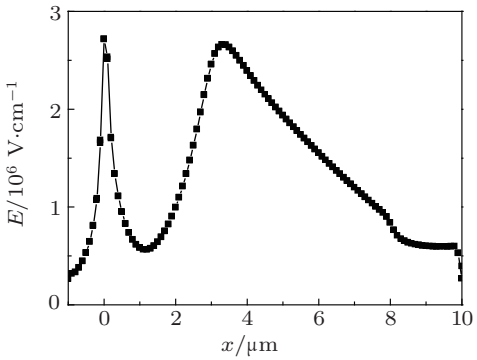


Fig. 3. Breakdown electric field distribution along the two-dimensional electron gas (2DEG) for the first structure with L_{GD} = 10 μm.

The drain electrode may experience a negative voltage in some power electronic applications, such as class-S amplifiers and bidirectional switches. Hence, excellent reverse blocking capability is necessary in these applications. Treidel *et al.*[10] demonstrated an AlGaN/GaN HEMT with Schottky-drain technology to enhance the reverse blocking capability. The combination of drain FP and Schottky drain is an effective way to further enhance the reverse blocking capability.[11] Figure 4 shows the enhancement of reverse blocking capability in a Schottky-drain AlGaN/GaN HEMT using a drain FP. When the drain electrode experiences a negative voltage, the drain

FP can mitigate the electric field peak located at the drain terminal edge by introducing another electric field peak located at the drain-FP edge. However, an unsuitable drain FP may reduce the forward blocking voltage. Thus, the drain FP needs to be optimized to ensure that it does not degrade the forward blocking performance.

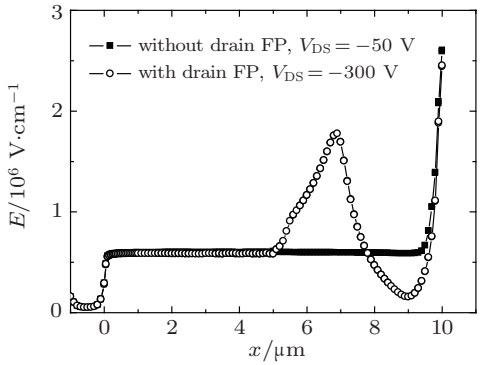


Fig. 4. Electric field distribution along the 2DEG in Schottky-drain AlGaN/GaN HEMTs with and without a drain FP ($t = 0.55$ μm, $L_{DF} = 3$ μm).

Figure 5 shows the breakdown characteristics of the HEMTs of the second structure and a HEMT without drain FP ($L_{DF} = 0$ μm). For $L_{DF} = 0$ μm, 1 μm, and 2 μm, the breakdown voltages are 1085 V, 1081 V, and 1070 V, respectively, suggesting that V_{BR} varies very little for $L_{DF} \leq 2$ μm. For $L_{DF} > 2$ μm, V_{BR} decreases obviously with the increase of L_{DF}. Furthermore, the larger the L_{DF}, the larger the decrease of V_{BR}, i.e., ΔV_{BR}. When L_{DF} rises to 6 μm, V_{BR} reduces to 700 V. Therefore, L_{DF} should be smaller than 2 μm to prevent the drain FP from affecting the breakdown voltages of the HEMTs. In other words, the distance between the gate edge and the drain-FP edge needs to be larger than 8 μm, which is equal to L_{GD} at which V_{BR} begins to saturate in the first structure. In addition, the length of the drain FP hardly affects the specific on-resistance.

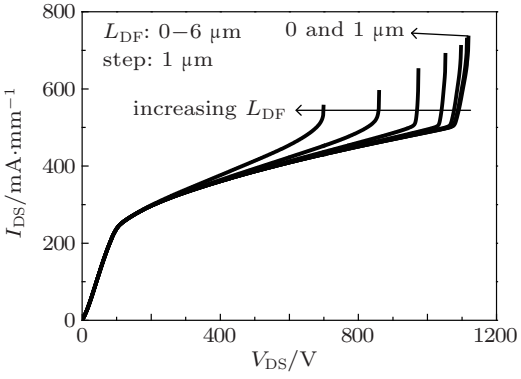


Fig. 5. The I_{DS}–V_{DS} curves for the HEMTs with a gate FP and a drain FP.

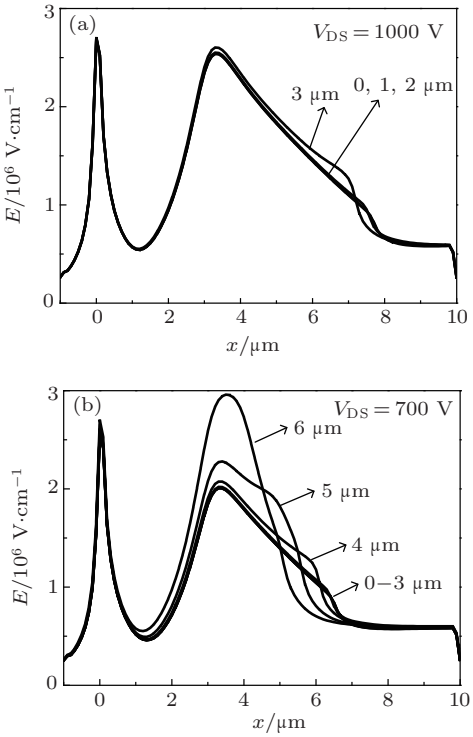


Fig. 6. Simulated distributions of the electric field along the 2DEG for (a) the HEMTs with $L_{DF} = 0$–3 μm and (b) the HEMTs with $L_{DF} = 0$–6 μm.

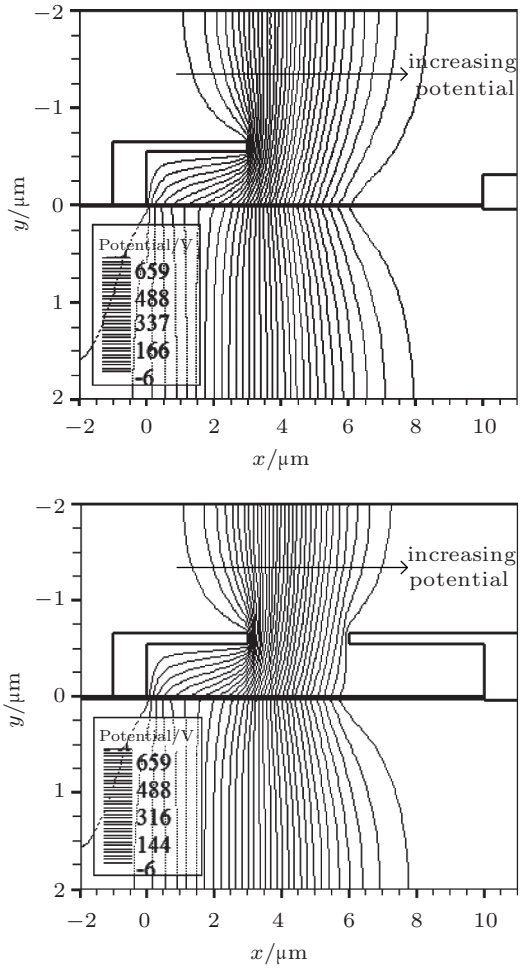


Fig. 7. Potential distributions for the HEMTs (a) without drain FP and (b) with $L_{DF} = 4$ μm; $V_{DS} = 700$ V.

To find out the reason why V_{BR} decreases with the increase of L_{DF}, the electric field distribution along the 2DEG is plotted in Fig. 6. With the drain terminal biased at 1000 V, the curves for L_{DF} = 0 μm, 1 μm, and 2 μm overlap completely, indicating that the three HEMTs have almost identical breakdown voltages. When L_{DF} increases to 3 μm, another electric field peak is introduced at the edge of the drain FP. With the increase of L_{DF}, the electric field peaks located at the gate FP edge and the drain FP edge become closer and their values increase simultaneously. Moreover, the larger the L_{DF}, the larger the increments of those two peaks. As a result, the breakdown voltage decreases faster for a larger L_{DF}. For $L_{DF} = 6$ μm, the two peaks overlap and turn into one peak. The behavior of the electric field can be explained by the potential distributions shown in Fig. 7. With the drain FP added, the potential distribution shifts toward the gate and the potential line density across the region between the gate FP and the drain FP increases. Thus, the electric field between the two FPs rises with the decrease of the distance between the two FPs.

4. Conclusion

In this paper, two kinds of HEMT structures are designed and simulated. The first structure with only one gate FP is optimized, and it is found that V_{BR} is saturated at 1085 V for $L_{GD} \geq 8$ μm. Although the breakdown voltage V_{BR} is saturated at $L_{GD} = 8$ μm, the L_{GD} in the second structure is set to 10 μm to investigate the influence of the drain-FP length L_{DF} on the forward blocking voltage comprehensively. When $L_{DF} \leq 2$ μm, V_{BR} decreases slightly compared with the device without drain FP. In contrast, V_{BR} decreases rapidly with the increase of L_{DF} for $L_{DF} > 2$ μm. Moreover, the longer the length of the drain FP, the larger the decrease of the breakdown voltage. Consequently, the distance between the gate edge and the drain FP edge should be larger than $L_{GD} = 8$ μm which is equal to L_{GD} at which V_{BR} begins to saturate in the first structure.

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