Effect of gate length on breakdown voltage in AlGaN/GaN high-electron-mobility transistor*

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The effects of gate length L_G on breakdown voltage V_{BR} are investigated in AlGaN/GaN high-electron-mobility transistors (HEMTs) with $L_G = 1$ μm∼ 20 μm. With the increase of L_G, V_{BR} is first increased, and then saturated at $L_G = 3$ μm. For the HEMT with $L_G = 1$ μm, breakdown voltage V_{BR} is 117 V, and it can be enhanced to 148 V for the HEMT with $L_G = 3$ μm. The gate length of 3 μm can alleviate the buffer-leakage-induced impact ionization compared with the gate length of 1 μm, and the suppression of the impact ionization is the reason for improving the breakdown voltage. A similar suppression of the impact ionization exists in the HEMTs with $L_G > 3$ μm. As a result, there is no obvious difference in breakdown voltage among the HEMTs with $L_G = 3$ μm∼ 20 μm, and their breakdown voltages are in a range of 140 V–156 V.

Keywords: AlGaN/GaN high-electron-mobility transistors (HEMTs), breakdown voltage, gate length

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1. Introduction

Owing to their high two-dimensional electron gas (2DEG) density, electron mobility, and high breakdown electric field, AlGaN/GaN high-electron-mobility transistors (HEMTs) have become excellent candidates in power electronics and high frequency applications.[1–6] The value of gate length has influences on transconductance, cutoff frequency, and maximum frequency of oscillation.[7,8] Numerous studies focused on reducing the gate length to improve high-frequency characteristics.[9,10] Breakdown voltage is also a very important parameter for these applications. However, the effect of gate length L_G on breakdown voltage V_{BR} has rarely been investigated.

In this paper, the effect of gate length on breakdown voltage is investigated through experiments and simulations. With the increase of L_G, V_{BR} is first increased, and then saturated at $L_G = 3$ μm. In order to explain the relation between V_{BR} and L_G, leakage currents and software simulation are utilized to discuss the buffer leakage current and buffer-leakage-induced impact ionization.

2. Device structure and fabrication

Figure 1 shows the schematic cross section of AlGaN/GaN HEMT fabricated in this paper. The AlGaN/GaN heterostructure was grown on sapphire substrate in a metal–organic chemical vapor deposition (MOCVD) system. The epitaxial layers included a 100-nm AlN nucleation layer, 1.4-μm GaN buffer layer, 1-nm AlN interlayer, 21-nm AlGaN barrier layer, and 1.5-nm GaN cap layer. The sheet carrier density and 2DEG mobility were tested to be 1.01×10^{13} cm^{-2} and 1915 cm^2/V·s respectively by Hall effect measurements.

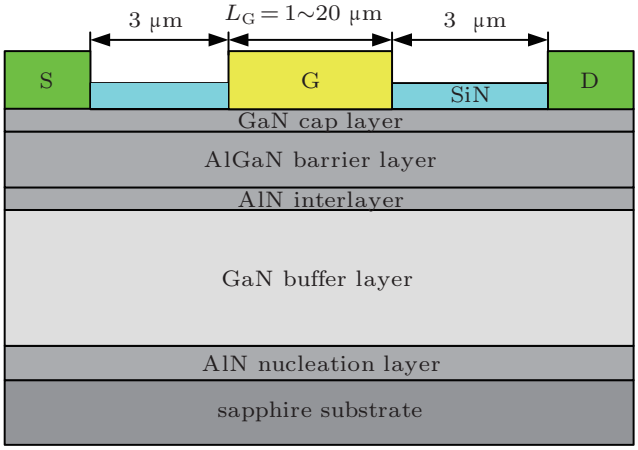


Fig. 1. (color online) Schematic cross section of AlGaN/GaN HEMT.

Source and drain electrodes were formed by evaporating Ti/Al/Ni/Au followed by annealing in N_2 ambient at 830 °C for 30 s. Then, mesa isolation was carried out by Cl-based reactive ion etching (RIE). Next, a Schottky gate was formed by evaporating Ni/Au/Ni. The devices were passivated with SiN layers to reduce surface states. The gate-source spacing and gate-drain spacing are all 3 μm. Six kinds of devices were fabricated with different gate length L_G values, and the gate length values are 1, 3, 5, 8, 13, and 20 μm.

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3. Results and discussion

The source–drain spacing increases with the increase of gate length from 1 μm to 20 μm, leading to the increase of on-state resistance. As a result, the maximum drain current I_{Dmax} decreases with the increase of gate length. As shown in Fig. 2(a), I_{Dmax} of the HEMT with $L_G = 1$ μm is 743 mA/mm. In contrast, I_{Dmax} is reduced to 342 mA/mm for the HEMT with L_G = 20 μm. In addition, the maximum transconductance $G_{m,max}$ decreases with the increase of gate length as shown in Fig. 2(b). $G_{m,max}$ decreases from 161 mS/mm for the HEMT with $L_G = 1$ μm to 82 mS/mm for the HEMT with $L_G = 20$ μm.

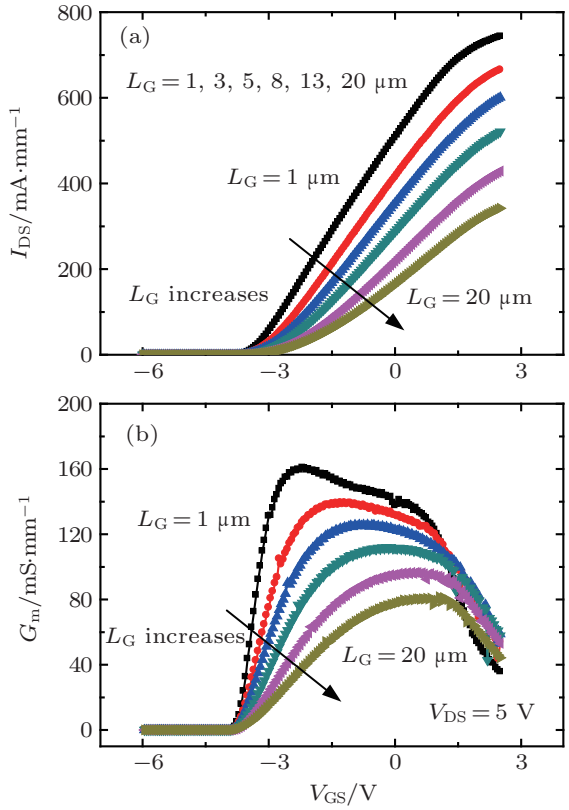


Fig. 2. (color online) *I–V* transfer characteristics of the AlGaN/GaN HEMTs with different gate length values: (a) I_{DS} versus V_{GS} and (b) G_m versus V_{GS}.

Figure 3 shows the breakdown characteristics of the AlGaN/GaN HEMTs with different gate length values. For the HEMT with $L_G = 1$ μm, breakdown voltage V_{BR} is 117 V. In contrast, the values of V_{BR} are in a range of 140 V–156 V for the HEMTs with $L_G = 3$ μm–20 μm. V_{BR} is first increased, and then saturated at $L_G = 3$ μm. In order to explain the relation between V_{BR} and L_G, breakdown characteristics of the HEMTs with $L_G = 1$ μm and $L_G = 3$ μm are first analyzed.

Figure 4 shows three leakage currents, I_D, I_G, and I_S, in the HEMTs with $L_G = 1$ μm and $L_G = 3$ μm during the breakdown measurements. Source current I_S first decreases, and then increases, resulting in an inflection point.[11] As shown in Fig. 5, I_S consists of source–gate leakage current I_{sg} and buffer leakage current I_{ds}, which flow in different directions. Before the inflection point, the source current is mainly composed of source–gate leakage current, which is part of gate leakage current. The buffer leakage current increases with the increase of the drain voltage. When the buffer leakage current exceeds the source–gate leakage current, the inflection point occurs. After the inflection point, the increase of I_S results from the increase of the buffer leakage current.[11]

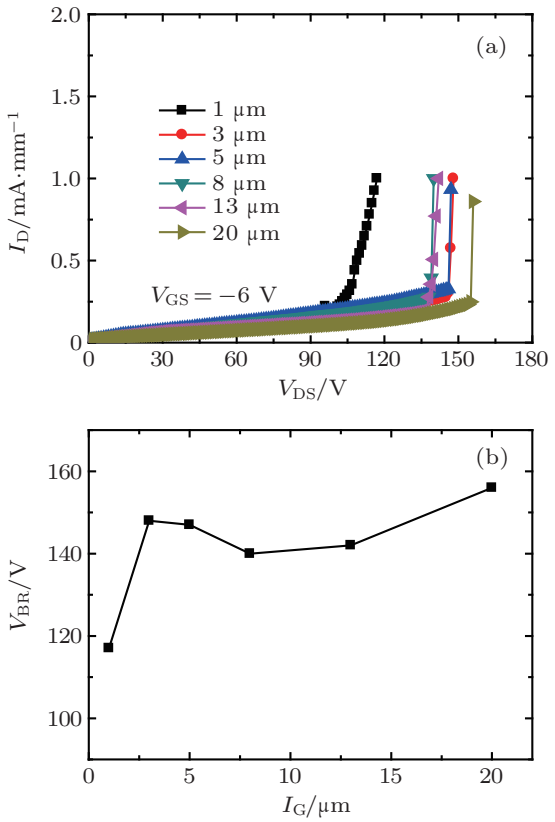


Fig. 3. (color online) (a) Breakdown characteristics and (b) V_{BR}–L_G dependence of the AlGaN/GaN HEMTs with different gate length values.

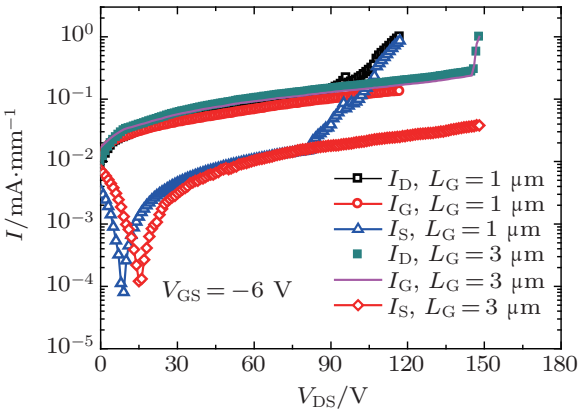


Fig. 4. (color online) Variations of I_D, I_G, and I_S with V_{DS} (drain–source voltage) during the breakdown measurements in HEMTs with $L_G = 1$ μm and $L_G = 3$ μm.

As shown in Fig. 4, V_{BR} for the HEMT with $L_G = 3$ μm is 148 V, which is 31 V higher than that for the HEMT with

$L_G = 1$ μm. For the HEMT with $L_G = 1$ μm, I_S increases quickly at $V_{DS} = 82$ V, and achieves 1 mA/mm at $V_{DS} = 117$ V, indicating that the device breakdown is induced by the buffer leakage current. In contrast, I_S increases slowly for the HEMT with $L_G = 3$ μm during the whole breakdown measurement. The breakdown for the HEMT with $L_G = 3$ μm is induced by the gate leakage current. The increase of V_{BR} for the HEMT with $L_G = 3$ μm compared with the HEMT with $L_G = 1$ μm is due to the suppression of the buffer leakage current. In order to explain the reason for suppressing the buffer leakage current, Silvaco-ATLAS software is utilized to investigate the depletion region and electric field distributions in the AlGaN/GaN HEMTs.

Figures 6(a) and 6(d) show the electron concentration distributions of the AlGaN/GaN HEMTs with $V_{GS} = -6$ V and $V_{DS} = 0$ V. With the increase of the drain terminal, the depletion region under the gate is shrinking, which results from the effect of drain induced barrier lowering (DIBL). For $V_{DS} = 100$ V, the depletion region in the HEMT with $L_G = 1$ μm is smaller than that in the HEMT with $L_G = 3$ μm as shown in Figs. 6(b) and 6(e). The comparison of these two depletion regions indicates that a larger gate length can suppress DIBL more effectively.

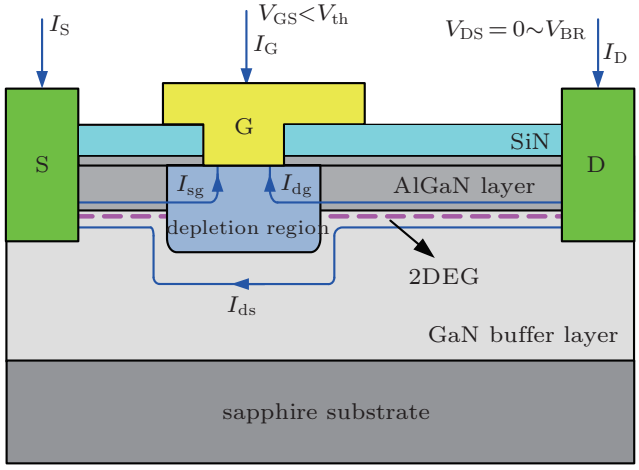


Fig. 5. (color online) Off-state leakage currents in AlGaN/GaN HEMTs during the breakdown measurements. Gate leakage current I_G consists of source–gate leakage current I_{sg} and drain–gate leakage current I_{dg}.

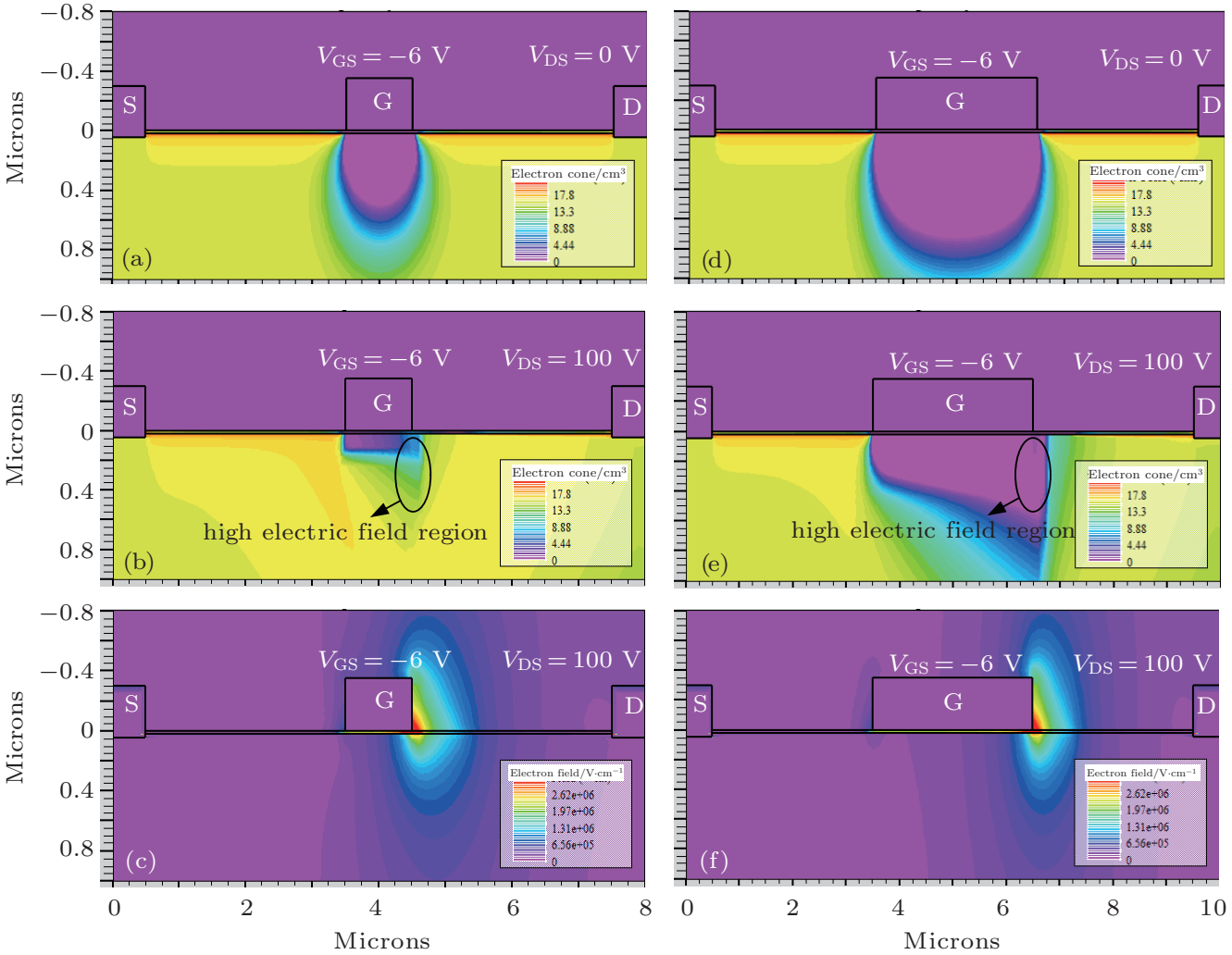


Fig. 6. (color online) Off-state logarithmic electron concentration distributions of the AlGaN/GaN HEMTs respectively with (a) $L_G = 1$μm, $V_{DS} = 0$ V; (b) $L_G = 1$ μm, $V_{DS} = 100$ V; (d) $L_G = 3$ μm, $V_{DS} = 0$ V; (e) $L_G = 3$ μm, $V_{DS} = 100$ V. Electric field distributions of the AlGaN/GaN HEMTs respectively with (c) $L_G = 1$ μm, $V_{DS} = 100$ V; (f) $L_G = 3$ μm, $V_{DS} = 100$ V. All the devices are biased at $V_{GS} = -6$ V and simulated by Silvaco-ATLAS software.

With the drain biased at a high value, there exists an electric field peak at the drain-side edge of the gate terminal as shown in Figs. 6(c) and 6(f). Correspondingly, the GaN-based materials around the gate are in the high electric field region. As shown in Fig. 6(b), part of the high electric field region in the HEMT with $L_G = 1$ μm is not depleted, and electrons can be injected from the source to this part of the high electric field region, which may initiate impact ionization and the following avalanche breakdown. Hence, the buffer leakage current increases quickly due to the impact ionization at $V_{DS} = 82$ V, and achieves 1 mA/mm at $V_{DS} = 117$ V. For the HEMT with $L_G = 3$ μm, the high electric field region is almost completely depleted, and the electrons from the source are difficult to be injected into the high electric field region. The buffer leakage current of the HEMT with $L_G = 3$ μm does not show the abrupt increase during the whole breakdown measurement. Therefore, the gate length of 3 μm can alleviate the buffer-leakage-induced impact ionization compared with the gate length of 1 μm, and the suppression of the impact ionization is the reason for improving the breakdown voltage.

The breakdown for the HEMT with $L_G = 1$ μm belongs to buffer-induced breakdown. The suppression of the buffer leakage changes the breakdown type into gate-induced breakdown for the HEMT with $L_G = 3$ μm. For the gate length larger than 3 μm, the high electric field region is almost completely depleted, which is similar to the case of $L_G = 3$ μm. A similar suppression of the impact ionization exists in each of the HEMTs with $L_G > 3$ μm. For the HEMTs with $L_G = 5$, 8, 13, and 20 μm, the device breakdown types are all gate-induced breakdown. As shown in Table 1, the gate leakage current values are almost equal to each other for the HEMTs with $L_G = 3$, 5, 8, 13, and 20 μm. As a result, there is no obvious difference in breakdown voltages among the HEMTs with $L_G = 3$ μm–20 μm, and they are in a range of 140 V–156 V.

In order to find out the accurate gate length in which the buffer-leakage-induced impact ionization can be alleviated, the simulation for the HEMT with $L_G = 2$ μm is carried out, and the results are shown in Fig. 7(a). For the HEMT with $L_G = 2$ μm, part of the high electric field region is not depleted, which may result in impact ionization and avalanche breakdown. Then, the simulation for the HEMT with $L_G = 2.5$ μm is carried out, and the results are shown in Fig. 7(b). For the HEMT with $L_G = 2.5$ μm, the high electric field region is almost completely depleted. Therefore, the gate length value in which buffer-leakage-induced impact ionization begins to be alleviated is in a range between 2 μm and 2.5 μm.

Table 1. Parameter values of AlGaN/GaN HEMTs. The threshold voltage V_{th} is defined as the gate voltage with drain leakage current reaching 1 mA/mm. The gate leakage current I_{gleak} values are obtained at $V_{GS} = -15$ V.

	I_{Dmax}/(mA/mm)	V_{th}/V	$G_{m,max}$/(mS/mm)	I_{gleak}/(mA/mm)	V_{BR}/V
$L_G = 1$ μm	743	–3.69	161	33.0	117
$L_G = 3$ μm	665	–3.64	139	46.7	148
$L_G = 5$ μm	601	–3.63	126	44.6	147
$L_G = 8$ μm	521	–3.56	112	42.8	140
$L_G = 13$ μm	429	–3.49	96	43.6	142
$L_G = 20$ μm	342	–3.41	82	45.2	156

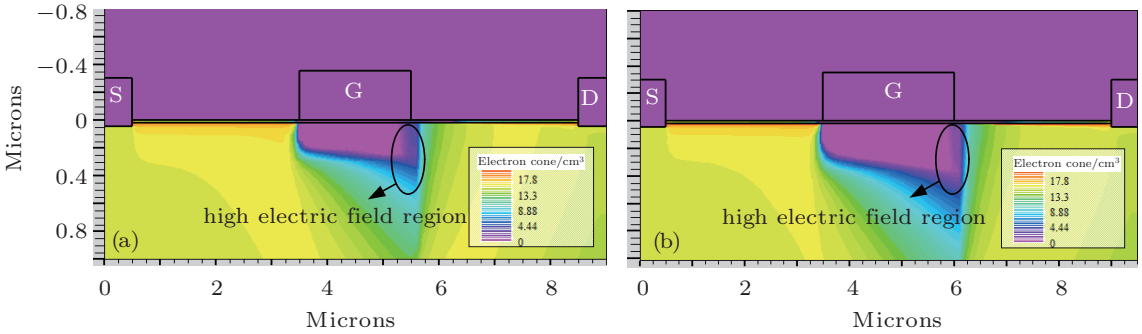


Fig. 7. (color online) Off-state logarithmic electron concentration distributions of the AlGaN/GaN HEMTs respectively with (a) $L_G = 2$ μm, $V_{DS} = 100$ V; (b) $L_G = 2.5$ μm, $V_{DS} = 100$ V.

4. Conclusions

In this work, the effects of gate length on breakdown voltage are investigated in AlGaN/GaN HEMTs. The value of V_{BR} for the HEMT with $L_G = 3$ μm is 148 V, which is 31 V higher than that for the HEMT with $L_G = 1$ μm. For the HEMT with $L_G = 3$ μm, the high electric field region is almost completely depleted, and it is difficult to inject the electrons from the source into the high electric field region. The gate length of 3 μm can alleviate the buffer-leakage-induced impact ion-

ization compared with the gate length of 1 μm, and the suppression of the impact ionization is the reason for improving the breakdown voltage. A similar suppression of the impact ionization exists in each of the HEMTs with $L_G > 3$ μm, and there is no obvious difference in breakdown voltage among the HEMTs with $L_G = 3$ μm–20 μm. Simulation results indicate that the gate length value in which buffer-leakage-induced impact ionization begins to be alleviated is in a range between 2 μm and 2.5 μm.

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