Gate-structure optimization for high frequency power AlGaN/GaN HEMTs*

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Abstract: The influence of gate-head and gate-source-spacing on the performance of AlGaN/GaN HEMTs was studied. Suggestions are then made to improve the performance of high frequency power AlGaN/GaN HEMTs by optimizing the gate-structure. Reducing the field-plate length can effectively enhance gain, current gain cutoff frequency and maximum frequency of oscillation. By reducing the field-plate length, devices with 0.35 μm gate length have exhibited a current gain cutoff frequency of 30 GHz and a maximum frequency of oscillation of 80 GHz. The maximum frequency of oscillation can be further optimized either by increasing the gate–metal thickness, or by using a τ-shape gate (the gate where the gate-head tends to the source side). Reducing the gate–source spacing can enhance the maximum drain-current and breakdown voltage, which is beneficial in enhancing the maximum output power of AlGaN/GaN HEMTs.

Key words: AlGaN/GaN HEMT; high frequency; gate structure; power
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1. Introduction

GaN-based materials exhibit high current density, high saturation velocity and high breakdown field. For this reason, AlGaN/GaN high-electron-mobility transistors (HEMTs) are being developed for high power and high frequency applications. In recent years, there has been great progress in high frequency power AlGaN/GaN HEMTs abroad. Ka-band, even W-band operations have been reported[1−3]. The output power at 40 GHz has reached 10.5 W/mm[1].

In theory, reducing gate length can enhance f_{T} (current gain cutoff frequency) and $f_{\max}$ (maximum frequency of oscillation). Yet the gate length of X-band AlGaN/GaN HEMTs has reached 0.3–0.4 μm, even 0.25 μm[4]. Gate lengths below 0.25 μm are still challenging for the domestic process, and deep submicron gates may cause serious short-channel effects such as threshold-voltage shift and soft pinch-off, high sub-threshold current and increased output conductance[5].

On the other hand, T-shape gates (include Γ-shape gates) are widely used for sub-micron gates. Such gate-structure can lower the gate-resistance because of its increased cross-section, and a gate-head on the drain side serving as a field-plate can increase the breakdown voltage. Yet the introduction of a gate-head also increases the parasitical gate-capacitances (C_{gs} and C_{gd}). It is known that low gate-resistance and low gate-capacitances are important for high frequency applications. So T-shape gates have a complicated influence on the performance of AlGaN/GaN HEMTs. In this paper, we compare the DC and RF performance of AlGaN/GaN HEMTs with different gate-structure parameters. The studied gate-structure parameters include gate–source spacing, gate-head length and gate-head location. It is indicated that the gate-head has a great influence on the frequency characteristics. By comparison, we drew some conclusions on optimization of the gate-structure for high frequency power AlGaN/GaN HEMTs.

2. Device structure and fabrication

The epitaxial wafer was provided by the Institute of Semiconductors of the Chinese Academy of Sciences. $Al_{0.25}Ga_{0.75}N$/AlN/GaN multilayers were grown on a sapphire substrate by MOCVD and the sheet resistance was 370 Ω/□. Ti/Al/Ni/Au for ohmic contact was deposited by evaporation, followed by rapid thermal annealing at 870 ℃for 50 s. The ohmic contact resistivity was 8.7×10^{-6} Ω·cm^2 measured by the four-probe method. Surface passivation was done using SiN (120 nm) film deposited by PECVD. A Ni/Au (40 nm/300 nm) gate with integrated gate-head was formed by the combined process of electron-beam lithography, dry-etch and evaporation. The actual gate length was measured to be 0.35 μm and the devices have a source-drain spacing of 4 μm and a gate-width of 75 μm. Figure 1 illustrates the devices' cross-section.

For convenience of comparison, the fabricated devices

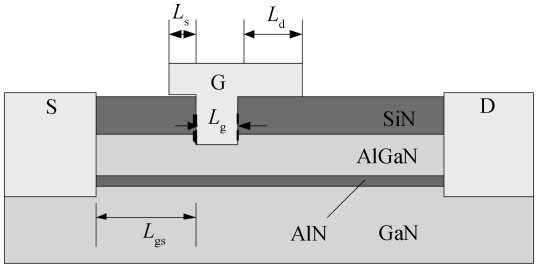

Fig. 1. Cross-section of the devices.

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Table 1. Five compared groups.

Group	L_d (μm)	L_s (μm)	L_{gs} (μm)
No. 1	0.2–1	0.2	1
No. 2	0.2	0.2–0.7	1
No. 3	0.2	0.7	1
	0.45	0.45	1
	0.7	0.2	1
No. 4	0.2	0.2	0.7–1.5
No. 5	0.2 or 0.7	0.2	2.3

were divided into five groups shown in Table 1. In the five groups, gate-head on the drain side (L_d), gate-head on the source side (L_s), gate-head location, and gate-source spacing (L_{gs}) are changed respectively. (The No. 5 group was specially added for breakdown-voltage comparison, because their breakdown voltage is degraded to the measurement range of our apparatus.) For each group, only one parameter was variable and each kind of device had members of no less than 5.

3. DC characteristics

It is known that the maximum RF output power of a transistor operating at A-class can be estimated by $P_{out\_max} = \frac{V_{br} I_{DSS}}{8}$, where V_{br} is the breakdown voltage, I_{DSS} is the maximum drain current. So increasing I_{DSS} and V_{br} is critical for power transistors.

Measurements for the five groups indicated that I_{DSS} and transconductance (g_m) increase when L_{gs} was reduced. Yet such DC characteristics do not obviously alter, if L_d, L_s, or the gate-head location is changed. Figure 2 shows the I_{DS}–V_{DS} characteristic for two kinds of HEMTs with different L_{gs} and Figure 3 shows their transconductance (g_m) and I_{DS}–V_g characteristics. The HEMTs with L_{gs} = 0.7 μm exhibit I_{DSS} of 719 mA/mm and maximum g_m of 301 mS/mm. Yet the ones with L_{gs} = 1.5 μm exhibit I_{DSS} of 655 mA/mm and g_m of 273 mS/mm.

Some studies have proved that large gate field-plate (L_d) and large gate–drain spacing (L_{gd}) can increase the breakdown voltage (V_{br})[6, 7]. In this work, most devices exhibited V_{br} of 100 V or over, which exceeded the measurement range of our apparatus. Only the devices of group No.5, which have L_{gd} of 1.4 μm (i.e. L_{gs} = 2.3 μm), exhibited a breakdown voltage lower than 100 V. Among these devices, the ones with L_d = 0.2 μm exhibited a breakdown voltage of 62 V, and the others with L_d = 0.7 μm exhibited a breakdown voltage of 74 V.

4. Frequency characteristics

Experiments also indicated that the frequency characteristics of AlGaN/GaN HEMTs are greatly influenced by gate-head lengths and gate-head location. Yet reducing the gate–source spacing does not enhance f_T and f_{max} as expected. This is because reducing L_{gs} also increases the gate capacitance which balances the increased g_m[8].

The gate with a gate-head tending to the drain side is called a Γ-shape gate. Such gates are widely used in power AlGaN/GaN HEMTs because the gate-head can serve as a field-plate which can increase the breakdown voltage. Fig. 4 shows the RF-gains for devices with different field-plate lengths (group No. 1). It can be seen that h_{21} (current gain) and

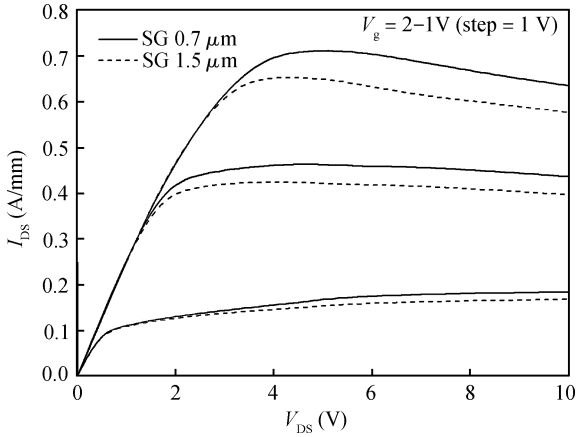

Fig. 2. I_{DS}–V_{DS} characteristic for devices with L_{gs} = 0.7 μm and L_{gs} = 1.5 μm respectively.

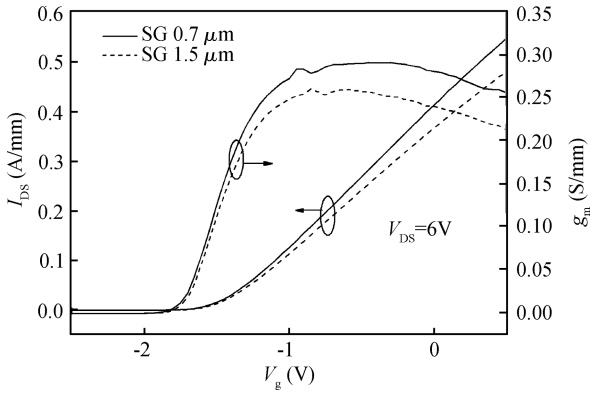

Fig. 3. Transconductance (g_m) and I_{DS}–V_g characteristics for devices with L_{gs} = 0.7 μm and L_{gs} = 1.5 μm respectively.

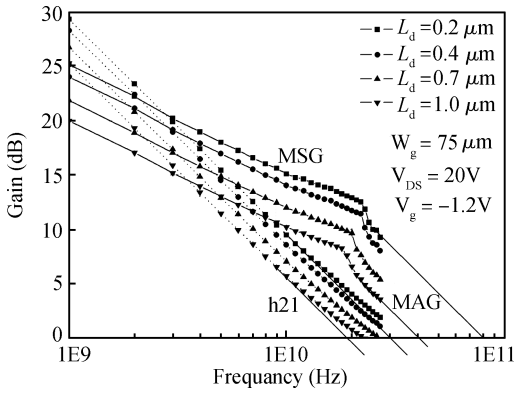

Fig. 4. Small-signal RF-gains of devices with different field-plate lengths.

MSG/MAG (maximum stable gain/maximum available gain) increase with reduced field-plate length. At 8 GHz, the device with L_d = 1.0 μm has MSG of 11.1 dB. If the length is reduced to 0.2 μm, the MSG reaches 16.0 dB. Moreover, the turning frequency from MAG to MSG also increases. This redounds to enhance gain at high frequency. At 30 GHz, the MAG is about 2.7 dB for the former, and is 8.5 dB for the latter. Figure 5 shows f_T, f_{max} and MAG for devices with different field-plate lengths.

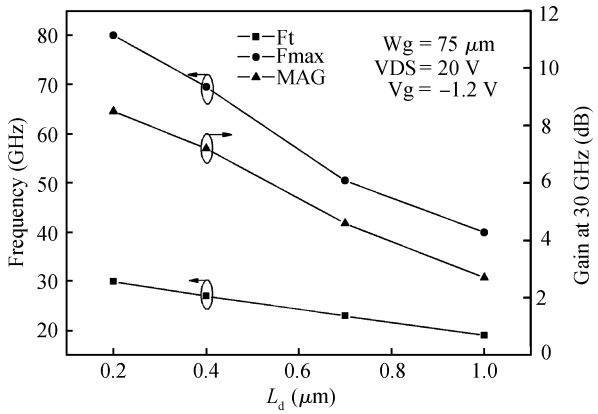

Fig. 5. f_T, f_{max} and MAG of devices with different field-plate lengths.

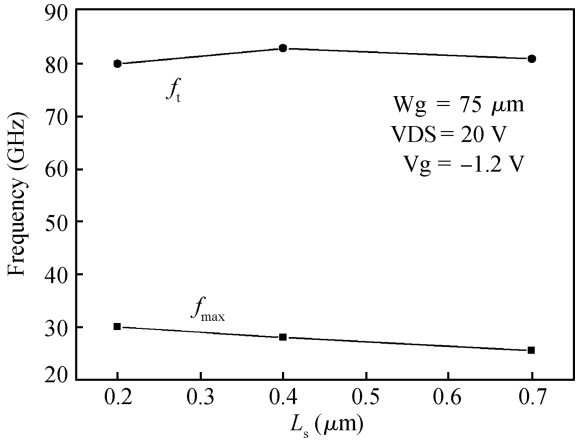

Fig. 6. f_T, f_{max} of devices with different L_S.

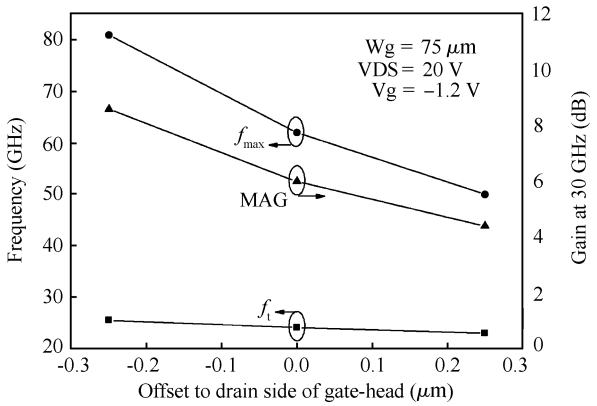

Fig. 7. f_T, f_{max} and MAG for devices with different gate-head locations (or gate shapes).

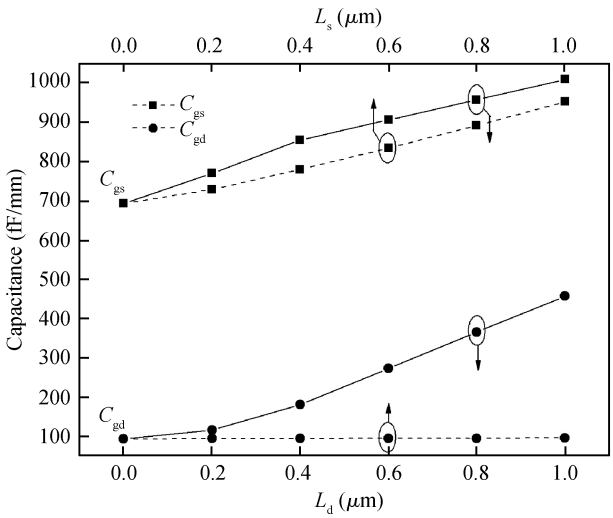

Fig. 8. Simulated relations of gate capacitances versus L_d and L_s respectively.

In this paper, we call the gate where the gate-head tends to the source side a τ-shape gate. Figure 6 shows the f_T, f_{max} of HEMTs with different L_s (group No. 2). Compared with Fig. 5, it can be seen that L_s has less influence on the frequency than L_d. With L_s reduced, f_T increases. But f_{max} does not vary much, and a peak value even occurs at L_s = 0.4 μm. This indicates that the gate-resistance and gate-capacitance are optimized for f_{max} at this point. The devices with L_s = 0.2 μm have smaller parasitical gate-capacitances and higher f_T than the ones with L_s = 0.4 μm, yet their f_{max} is lower. The only explanation is that the former has too high a gate-resistance which results from the reduction of the gate cross-section. Both reducing L_d and reducing L_s will cause cross-section reduction. So increasing the gate-metal thickness is necessary, if gate-head length is reduced by much.

Either the Γ-shape gate or τ-shape gate can be considered as a special T-shape gate. The only difference is their gate-head location. Figure 7 shows f_T, f_{max} and MAG of devices with different gate-head locations. The horizontal axis is the offset to drain side of the gate-head, compared with the normal T-shape gate. It can be seen that moving the gate-head from the drain side to the source side can enhance f_T, f_{max} and MAG. The three kinds of gates have equal gate-resistance, yet the τ-shape gate exhibits better frequency characteristics.

L_d and L_s can cause parasitical gate-capacitances. We have used a finite-element two-dimensional simulator (Silvaco Atlas) to investigate the gate capacitances for devices illustrated in Fig. 1. In one simulation, L_s was set to 0, and L_d varied from 0 to 1 μm. In another simulation, L_d was set to 0, and L_s varied from 0 to 1 μm. Figure 8 shows the relations of gate capacitances versus L_d and L_s respectively. With L_s increasing, C_{gs} increases and C_{gd} nearly keep constant. Yet with L_d increasing, both C_{gs} and C_{gd} increase. We believe this is due to the field-plate function of the L_d part. When L_d increases, the electric field beneath the gate-foot decreases, so the depletion-mode region reduced, which makes C_{gs} also increase. The simulations indicate that L_d has greater effect on both C_{gs} and C_{gd} than L_s. This can explain why reducing L_d can improve frequency characteristics more effectively than reducing L_s.

5. Gate-structure optimization

So far the implementation of gate lengths below 0.25 μm is still challenging for the domestic process of AlGaN/GaN HEMTs. Moreover, such deep sub-micron gates may cause serious short channel effects[5]. So it is significant to improve the frequency characteristics by optimizing the gate-structure.

From the above experiments, we can make suggestions to improve the frequency characteristics of AlGaN/GaN HEMTs.

By reducing the gate-field-plate length, the gain, f_T and f_{max} can be effectively enhanced. Yet reducing the gate-field-plate reduced the gate cross-section. The gate-resistance will increase, which can limit the enhancement of f_{max}. So if the gate-field-plate is reduced by much, it is preferable to increase the gate-metal thickness.

L_s has less influence on the frequency characteristics than L_d. Increasing L_s can reduce the gate resistance. So f_{max} can also be optimized by using a τ-shape gate, except to increase the gate-metal thickness.

Either reducing the gate field-plate or using a τ-shape-gate improves the frequency characteristics at the expense of degrading the breakdown voltage (the τ-shape gate also has a small gate field-plate). Increasing the gate-drain spacing can enhance the breakdown voltage of AlGaN/GaN HEMTs. When the source-drain spacing is fixed, it is preferable to locate the gate as near the source side as possible (i.e. reducing the gate-source spacing). Moreover, reducing the gate-source spacing can also enhance the maximum drain current. So reducing the gate-source spacing is beneficial to enhancement of the maximum output power of AlGaN/GaN HEMTs.

6. Conclusion

We have studied the DC and RF performance of AlGaN/GaN HEMTs with different gate-structures. From the results, we have made suggestions to improve the performance of high frequency power AlGaN/GaN HEMTs by optimizing the gate-structure. Reducing the field-plate length can effectively enhance gain, f_T and f_{max}. f_{max} can be further optimized either by increasing the gate-metal thickness, or by using a τ-shape gate (a gate where the gate-head tends to the source side). These approaches for improving frequency characteristics are especially significant when difficulties exist with reducing the gate length. In order to enhance the maximum output power, it is preferable to reduce the gate–source spacing, which can enhance the maximum drain-current and breakdown voltage.

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