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Fabrication of AlGaN/GaN Fin-Type HEMT Using a Novel T-Gate Process for Improved Radio-Frequency Performance

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ABSTRACT To increase the radio-frequency (RF) performance of AlGaN/GaN-based fin-type high electron mobility transistors (HEMTs), a novel T-gate process was developed and applied to fabricate a device with high RF performance. In a single lithography process, the applied T-gate process shows a technique for forming a T-gate using the reactivity difference of several photoresists. The fabricated device has a steep fin width (W_{fin}) of 130 nm, a fin height (H_{fin}) of 250 nm, and a gate length (L_G) of 190 nm. The device exhibits a low leakage current (I_{off}) of 6.6×10^{-10} A/mm and a high I_{on}/I_{off} current ratio of 4.7×10^8. Moreover, the fabricated device achieved a high cut-off frequency (f_T) of 9.7 GHz and a very high maximum oscillation frequency (f_{max}) of 27.8 GHz. The f_{max} value of the proposed device is 138% higher than that of GaN-based fin-type HEMTs without T-gate.

INDEX TERMS FinFET, Gallium compounds, nanofabrication, nanolithography, high electron mobility transistor, T-gate, E-beam lithography, maximum oscillation frequency.

I. INTRODUCTION

With a high resistance and wide band gap, GaN is considered to be the most suitable material for developing power devices and radio-frequency (RF) devices [1]–[4]. AlGaN/GaN high electron mobility transistors (HEMTs) in particular have been extensively used for high-power and RF devices because of the high-density two-dimensional electron gas (2-DEG) obtainable from the AlGaN/GaN heterojunction [5]–[8]. Generally, HEMTs based on the AlGaN/GaN heterojunction are manufactured with a planar structure. However, because of its structural characteristics, the planar HEMT has low gate controllability, demonstrating a high leakage current and subthreshold swing (S). To address this issue, many researchers are currently focusing on developing the fabrication of a fin structure to improve the leakage current characteristics and S characteristics. Over the past few years, AlGaN/GaN-based fin-type devices have been developed to achieve improved electrical performances in terms of, for example, better on-state current (I_{on}) and high-power characteristics [9]–[12]. For example, J. H. Seo *et al.* studied a Al(In)N/GaN heterojunction-based fin-type HEMT [13] with a focus on the I_{on} characteristics; however, the RF characteristics of GaN-based fin-type HEMTs demonstrate very low RF performances with high parasitic capacitance and gate resistance. For determining the RF performance of a device, there are two typical criteria: cut-off frequency (f_T) and maximum oscillation frequency (f_{max}). For fabricating high-speed devices, the gate length must be short, which causes the gate electrode resistance to become very large and leads to a decrease in f_{max} [14]. Therefore, it is necessary to apply T-gate to ensure high speed operation and RF performance

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of the device at the same time. The previously announced T-gate process is formed through several lithography processes. However, there is a disadvantage that the process is complicated and costs are increased [15]–[17].

Therefore, in this study, we developed a novel process technique to form a T-gate with single lithography process that can be applied to FinFET structure. The fabricated device has very high f_{max} due to the low gate-resistance (R_G) of T-gate.

II. DEVICE FABRICATION

Using metal organic chemical vapor deposition (MOCVD), AlGaN/GaN heterostructures were grown on a sapphire (0001) substrate. The grown epitaxial layer consists of a 2 μm thick high-resistance GaN (HR-GaN) buffer layer, a 50 nm thick GaN channel layer, a 25 nm thick $Al_{0.25}Ga_{0.75}N$ layer, and a 2 nm thick undoped GaN cap layer. The grown AlGaN/GaN epi has a 2-DEG density of 8×10^{12} cm^{-2}, an electron mobility of 1700 cm^2/V·s, and a sheet resistance of 450 Ω/sq. Firstly, 300 nm MESA etching was performed for device-to-device isolation, which was performed using a TCP-RIE. Then, a 100 nm of SiO_2 hard mask layer was deposited, and a fin width (W_{fin}) of 130 nm and a fin length (L_{fin}) of 2 μm were patterned using electron beam (e-beam) lithography. Subsequently, SiO_2 etching through the BOE solution was performed to lift out the portion to be etched, and after removing e-beam photo resist using acetone, and then etched to a depth of 200 nm using TCP-RIE. After fins are formed, treatment is performed at 90 °C for 3 minutes using 5 % concentration tetramethylammonium hydroxide (TMAH) solution on the sidewalls of the fins.

Depending on the cross-sectional direction, because GaN has a different TMAH etching rate, an anisotropic etching process using this property was used to produce a fin with steep sidewalls [13]. After that, remove the remaining SiO_2, a Ti/Al/Ni/Au stack was deposited and a source/drain ohmic contact was formed using rapid thermal annealing.

After forming the source/drain ohmic contacts to form the T-gate the three kinds of photoresists (PRs) were coated in the order of PMMA, co-polymer, ZEP, and E-spacer, as shown in Fig. 1(b). Depending on the material, the PR was stacked to take advantage of the difference in responsiveness to e-beam. As shown in Figs. 1(c) and 1(d), following the PR coating, the line (foot patterning) and the area (head patterning) dose were simultaneously applied to form a T-gate via a single lithography process. During the process, the intensity of the line dose determines the T-gate foot length (gate length) and the area dose determines the head depth. Finally, as shown in Fig. 2(c), a Ni/Al stack of the gate with a foot length (L_{Foot}) of 190 nm and a head length (L_{Head}) of 470 nm was formed. Nickel in the foot region forms a Schottky junction with AlGaN due to its high workfunction (5.04 ∼ 5.35 eV), preventing gate leakage and increasing the threshold voltage. Aluminum was selected as the head material for fast deposition speed, cost reduction and reduced gate resistance due to low resistivity. Fig. 2(a) presents a schematic of the fabricated AlGaN/GaN fin-type HEMT structures with the T-gate, while Fig. 2(b) presents a scanning electron microscope (SEM) image of a fabricated device.

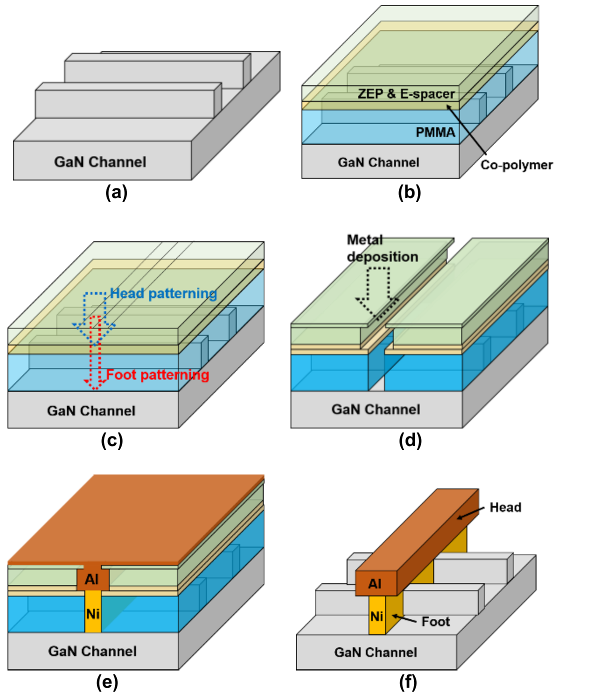

FIGURE 1. Schematic of the process flow for the T-gate on the fin structure. (a) AlGaN/GaN epitaxial layer grown via MOCVD and 3D fin structure formation. (b) Three-step e-beam resist layers coat. (c)–(e) one-step e-beam patterning and metal deposition process. (f) Lift-off and T-gate with fin structure formation.

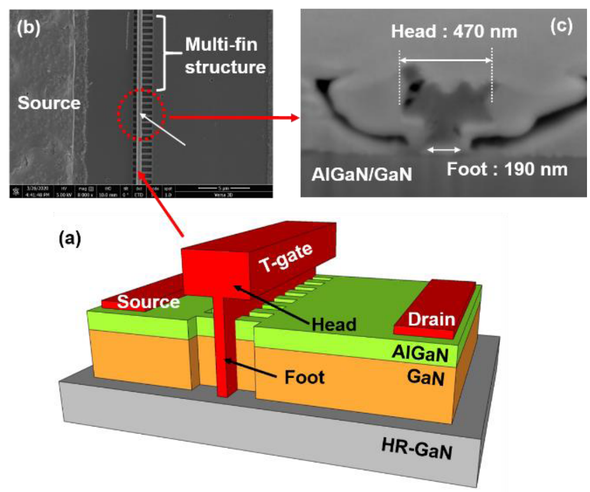

FIGURE 2. Device structure (a) 3D schematic illustration of the fabricated devices. (b) A bird's-eye SEM image of a fabricated fin with a T-gate structure. (c) Cross-sectional SEM image for T-gate with a foot of 190 nm and a head of 470 nm.

III. DEVICE CHARACTERISTICS AND DISCUSSION

Fig. 3 shows the I_{DS}-V_{GS} transfer characteristics of the proposed AlGaN/GaN fin-type HEMT with an L_G of 190 nm. The L_G is the same L_{Foot} as above. The fabricated device had

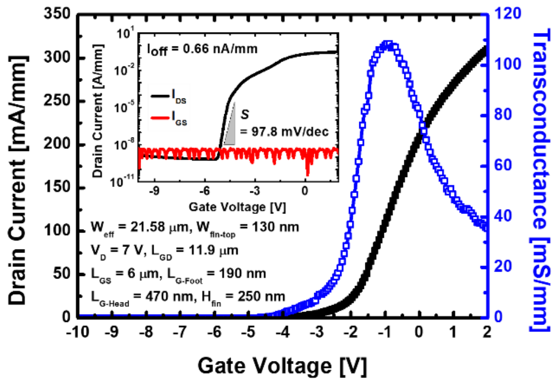

FIGURE 3. I_{DS}-V_{GS} **transfer characteristics of the fabricated AlGaN/GaN fin-type HEMT with a T-gate under** $V_{DS} = 7$ **V. The inset shows the** I_{DS}-V_{GS} **transfer curves and gate leakage current on a logarithmic scale.**

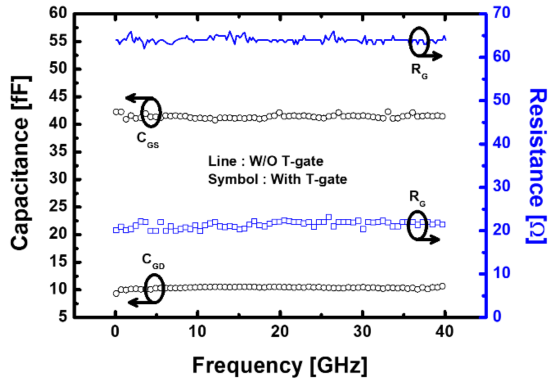

FIGURE 4. **Frequency dependence of the extracted capacitances (**C_{GS} **and** C_{GD}**) and gate resistance (**R_G**).**

a gate to source length (L_{GS}) of 6 μm, and a gate to drain length (L_{GD}) of 11.9 μm, while the T-gate head had a length of 470 nm.

Furthermore, the fabricated device had a W_{fin} of 130 nm, a fin height (H_{fin}) of 250 nm, a fin to fin distance of 400 nm, a L_{fin} of 2 μm, and a fin number of 166. Both I_{on} and transconductance (g_m) were normalized by the effective gate width (W_{eff} = 130 nm× 166 = 21.58 μm). The measured results for the I_{on} and g_m are 310 mA/mm and 108 mS/mm, respectively.

The fabricated AlGaN/GaN fin-type HEMT demonstrated performances with the subthreshold swing (S) of 97.8 mV/dec at maximum slope, the off-state current (I_{off}) of 6.6 × 10^{-10} A/mm, and the I_{on}/I_{off} current ratio of 4.7 × 10^8 as shown in the inset of fig. 3. This excellent off-state performance demonstrated that the channel was completely blocked by the electric field of the gate covering the fin structure and that the HR-GaN layer had fewer defects.

Furthermore, the TMAH solution was used to reduce the plasma etch damage on the fin sidewalls. It has been reported that, to create a clean surface, the TMAH solution process considerably reduces surface leakage currents by eliminating the defects on the GaN surface [7], [18]. As a result, the fabricated device showed low gate leakage current characteristics as can be seen in the inset of figure 3.

Fig. 4 shows the extracted gate-to-source capacitance (C_{GS}), gate-to-drain capacitance (C_{GD}) and R_G by using previously published RF models [14]. The extracted parameter values of the device with T-gate are as follows: C_{GS} = 41.4 fF; C_{GD} = 10.35 fF; g_m = 2.85 mS and R_G = 21.8 Ω. The fabricated device with T-gate show a significantly lower R_G compared to 64 Ω of the device without T-gate. The f_T and f_{max} were calculated using the extracted parameters. The calculated f_T and f_{max} were 8.8 GHz and 32 GHz, respectively. The results show similar values to the measurement results shown in fig. 5. The formula used for the calculation is follows:

$$f_T = \frac{g_m}{2\pi\,(C_{GS} + C_{GD})} \tag{1}$$

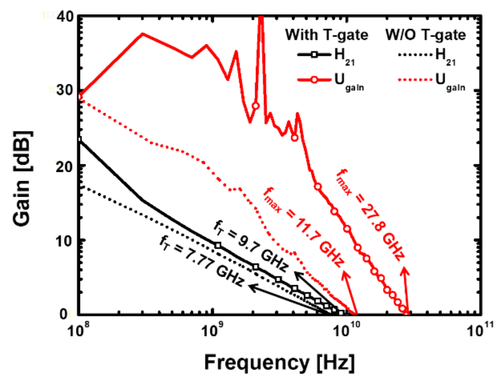

FIGURE 5. **Measured** f_T **and** f_{max} **characteristics of fabricated devices with and without T-gate.**

$$f_{max} = \frac{f_T}{\sqrt{4R_G\,(g_{DS} + 2\pi f_T C_{GD})}} \tag{2}$$

where g_{DS} means the source-drain conductance. Fig. 5 shows the measured current gain ($|H_{21}|$) and the unilateral power gain (U_{gain}) of the with and without the fabricated device. Depending on whether T-gate is applied or not, f_T is 9.7 GHz and 7.77 GHz, respectively, and there is no significant difference.

However, f_{max} showed a large difference between 27.8 GHz and 11.7 GHz, respectively. The f_{max} value of the fabricated device was 138% higher than that of GaN-based fin-type HEMTs without T-gate, because of the low R_G due to T-gate.

IV. CONCLUSION

The AlGaN/GaN fin-type HEMT was fabricated using a novel T-gate process technique. To apply the T-gate process to fin-type HEMT, the e-beam lithography has been adapted in the stacked multiple PRs (PMMA, co-polymer and ZEP). The T-gate was formed via a single lithography process by applying the optimized PR thickness and the line/area dose of the e-beam. The formed T-gate had a L_{Foot} of 190 nm (= L_G) and a L_{Head} of 470 nm. The fabricated device has I_{off} = 6.6 × 10^{-10} A/mm, indicating very low I_{off} characteristics.

In terms of RF characteristics, both f_T and f_{max} were 9.7 GHz and 27.8 GHz, respectively. The f_{max} was 138 % higher than GaN-based fin-type HEMTs without T-gate.

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