ARTICLES

Journal of Semiconductors
(2024) 45, 012501
doi: 10.1088/1674-4926/45/1/012501

11.2 W/mm power density AlGaN/GaN high electron-mobility transistors on a GaN substrate

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Abstract: In this letter, high power density AlGaN/GaN high electron-mobility transistors (HEMTs) on a freestanding GaN substrate are reported. An asymmetric Γ-shaped 500-nm gate with a field plate of 650 nm is introduced to improve microwave power performance. The breakdown voltage (BV) is increased to more than 200 V for the fabricated device with gate-to-source and gate-to-drain distances of 1.08 and 2.92 μm. A record continuous-wave power density of 11.2 W/mm@10 GHz is realized with a drain bias of 70 V. The maximum oscillation frequency (f_{max}) and unity current gain cut-off frequency (f_t) of the AlGaN/GaN HEMTs exceed 30 and 20 GHz, respectively. The results demonstrate the potential of AlGaN/GaN HEMTs on freestanding GaN substrates for microwave power applications.

Key words: freestanding GaN substrates; AlGaN/GaN HEMTs; continuous-wave power density; breakdown voltage; Γ-shaped gate

Citation: Y S Hu, Y G Wang, W Wang, Y J Lv, H Y Guo, Z R Zhang, H Yu, X B Song, X Y zhou, T T Han, S B Dun, H Y Liu, A M Bu, and Z H Feng, 11.2 W/mm power density AlGaN/GaN high electron-mobility transistors on a GaN substrate[J]. *J. Semicond.*, 2024, 45(1), 012501. https://doi.org/10.1088/1674-4926/45/1/012501

1. Introduction

AlGaN/GaN high electron-mobility transistors (HEMTs) have attracted much attention in high-power microwave applications, benefitting from the high breakdown electric field, high electron mobility and velocity. The research into AlGaN/GaN HEMTs mainly focuses on the heteroepitaxy on SiC, sapphire, or Si substrates[1–4]; however, many threading dislocations will be introduced. The threading dislocation densities are always above 1×10^8 cm^{-2}[5]. The high threading dislocation densities will lead to a large leakage current[6] and diffusion of a large amount of metal along the dislocation[7], reducing the reliability and lifetime of the AlGaN/GaN HEMTs[8]. The threading dislocation densities in AlGaN/GaN heterojunction epitaxy on freestanding GaN substrates can be reduced to 10^7 cm^{-2}[9], circumventing this problem.

Unfortunately, there are many impurities, such as O and Si, at the regrowth interface between the epitaxial GaN layer and the substrate, which will give rise to a parallel conduction channel and increase the leakage current in the HEMTs on the GaN substrate. Various techniques have been developed to circumvent this problem. The proposed approaches mainly include Fe-doping[10, 11], Mg-doping[12], Be-doping[13], C-doping[14, 15], p-AlGaN back barrier[16], H_2 *in-situ* etching in an NH_3 atmosphere[11], and so on. Based on these techniques, HEMTs on freestanding GaN substrates have been reported[14, 17–23]. The first HEMT on freestanding GaN substrates was reported in 2000[24]. The results were comparable to that on SiC substrates, while microwave-related data were not reported. The highest maximum frequency of oscillation (f_{max}) is 171 GHz, realized by AlN/GaN HEMT[22]. The record output power density is around 10 W/mm@10 GHz, which is achieved by AlGaN/GaN HEMTs on a GaN substrate in 2004[21].

In the present research, the HEMTs were fabricated on $Al_{0.25}$GaN/GaN heterostructures on a GaN substrate. The growth conditions were similar to those used elsewhere[25], while an Mg-doping layer was also introduced to suppress the Si impurity at the regrowth interface. The asymmetric Γ-shaped 500-nm gate with a field plate of 650 nm was introduced to increase the BV and output power density of our fabricated devices[26, 27]. The BV is increased to above 200 V, while the drain bias is increased to 70 V during the continuous-wave power measurements. Meanwhile, the fabricated devices maintain high associated gain and operating frequency, benefiting from small gate length and a gate-to-source distance. The out power density of 11.2 W/mm@10GHz is realized with our fabricated devices, which is the highest value.

2. Device structure and fabrication

The new heterostructure was grown on a GaN substrate with metal-organic chemical vapor deposition (MOCVD). The heterostructure from top to bottom was a 2-nm GaN, a 18-nm $Al_{0.25}Ga_{0.75}N$, a 1-nm AlN, a 500-nm GaN channel layer, a 1.5-μm Fe-doping GaN, and a 500-nm Mg-doping GaN, as shown in Fig. 1(a). The 2DEG density and mobility were 1.0×10^{13} cm^{-2} and 1950 cm^2/(V·s), respectively. The device fabrication was commenced with mesa isolation by dry etching. The metal for source/drain was Ti/Al/Ni/Au multi-layer metal,

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Received 28 JULY 2023; Revised 4 SEPTEMBER 2023.

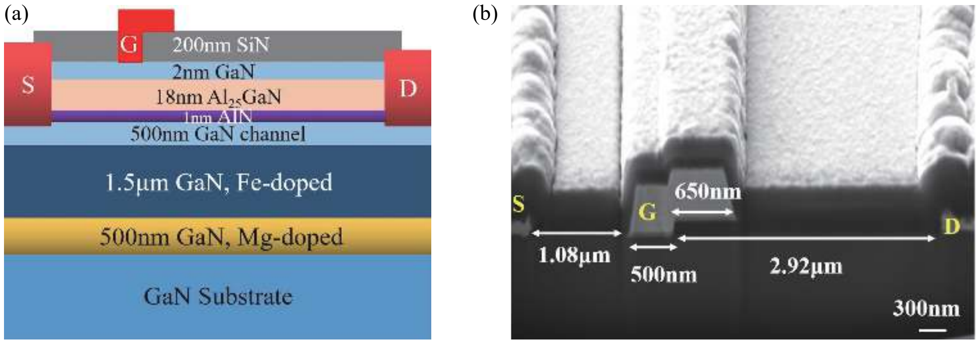

Fig. 1. (Color online) (a) Schematic cross-section of the AlGaN/GaN HEMT on a GaN substrate and (b) the SEM image of the Γ-shaped gate.

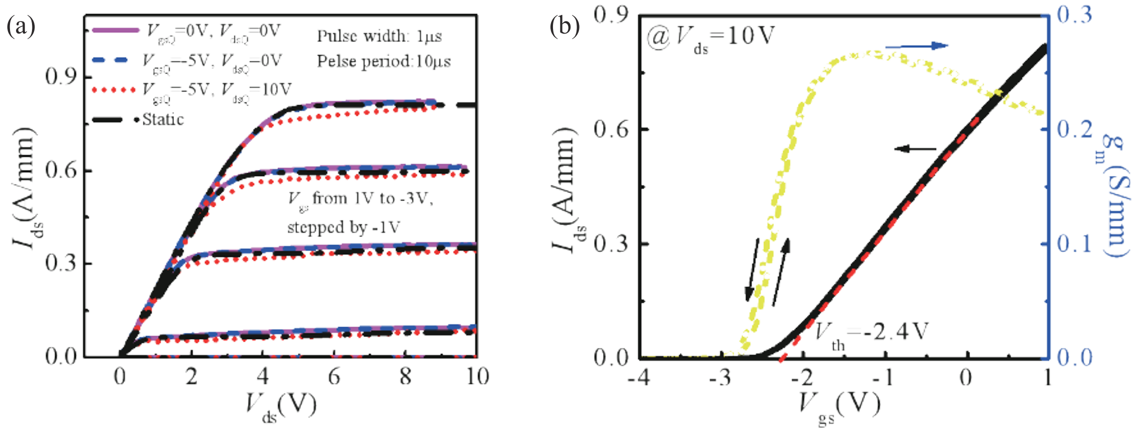

Fig. 2. (Color online) (a) Static and pulsed current–voltage curves. (b) Double transfer characteristics of the AlGaN/GaN HEMTs on a GaN substrate.

which was fabricated by electron-beam evaporation. However, realizing low ohmic resistance of $Al_{0.25}GaN$/GaN heterostructures on the GaN substrate is much harder than heterostructures on other substrates, because of the lower threading dislocation densities[9]. Therefore, a low-power inductively coupled plasma (ICP) etching process at source/drain regions was undertaken before ohmic metal evaporation[28, 29]. The radio frequency (RF) generator power, inductively coupled plasma generator power and etching time were set to 10 W, 180 W, and 1 min, separately. A ohmic resistance of 0.8 Ω·mm was realized after being annealed at 860 °C in nitrogen. The surface was passivated with 200-nm silicon nitride (SiN). The SiN in-gate region was removed by the ICP dry etching process. To reduce the damage caused by the dry etching process, a high-temperature annealing process (450 °C in nitrogen for 5 min) was taken after SiN etching. An Ni/Au asymmetric Γ-shaped gate was formed by electron-beam lithography, which is closer to the source contact. The width and lengths of the single gate is 75 μm and 500 nm, respectively. The gate field plate was 650 nm, as shown in Fig. 1(b). The distances from gate to source and from gate to drain were 1.08 and 2.92 μm, respectively.

3. Results and discussion

The output characteristics of the AlGaN/GaN HEMTs on the GaN substrate is illustrated in Fig. 2(a). The total current collapse is around 4.3%, and the gate lag is around 0.1%. The maximum drain current is 816 mA/mm, and the maximum transconductance is 264 mS/mm. In addition, the surface state is well suppressed, as reflected where the maximum deviation of transconductance is only 0.8%.

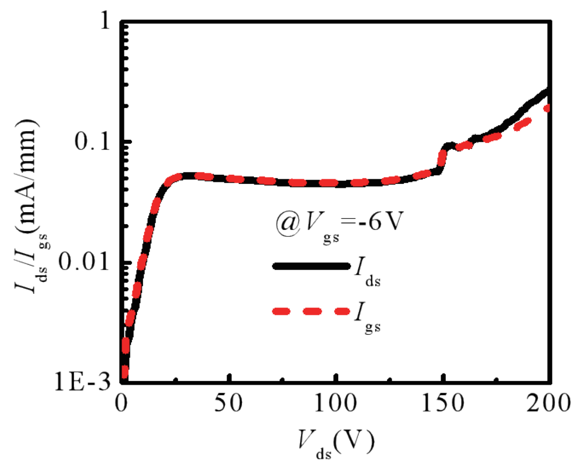

Fig. 3. (Color online) 3-terminal breakdown characteristic of the AlGaN/GaN HEMT on a freestanding GaN substrate.

The 3-terminal breakdown characteristic of the AlGaN/GaN HEMT on the GaN substrate is displayed in Fig. 3. The judgment basis for BV is that the drain leakage current rises to 1 mA/mm[30, 31]. Benefiting from the low threading dislocation densities, the homogeneous epitaxial AlGaN/GaN HEMT on the GaN substrate can achieve high BV[13, 32]. To realize these advantages, the asymmetric gate (larger distance of gate–drain) and the gate field plate are introduced. High breakdown voltages exceeding 200 V (200 V is the limit to our test system) have been realized in the fabricated devices (Fig. 3).

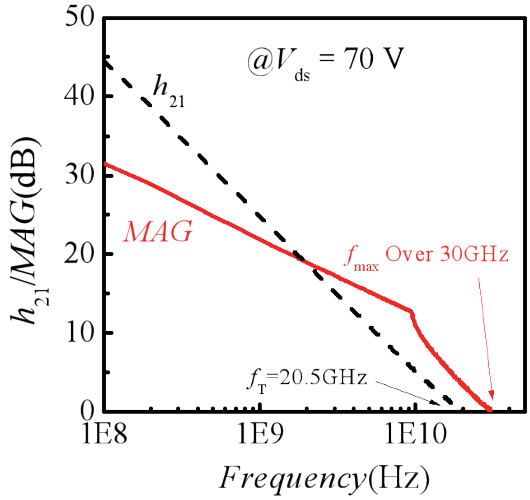

Fig. 4. (Color online) Small-signal radio frequency performance of the AlGaN/GaN HEMT on a GaN substrate.

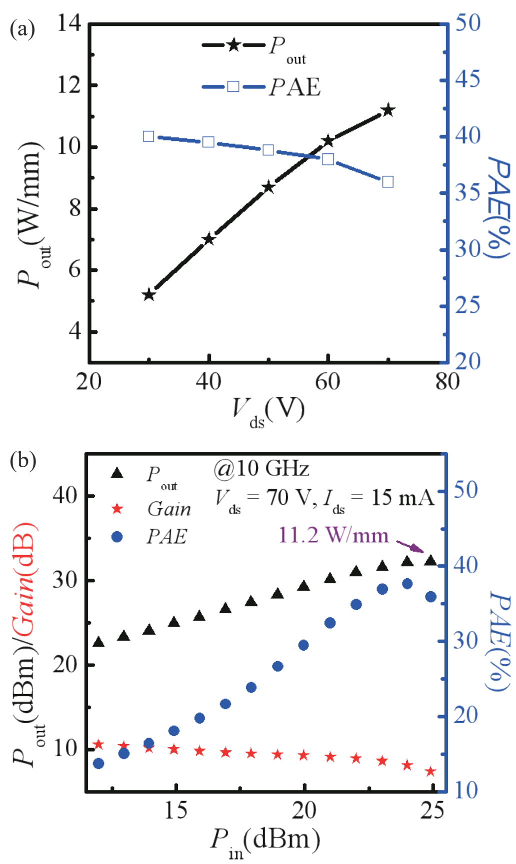

Fig. 5. (Color online) Large-signal performance of the AlGaN/GaN HEMTs on a GaN substrate. (a) The CW output power and PAE vs. V_{ds}. (b) The large-signal performance and PAE vs. P_{in}.

Fig. 4 is the radio frequency small-signal characteristics of the fabricated AlGaN/GaN HEMT. The frequency was varied from 100 MHz to 30 GHz in 50-MHz increments during on-wafer measurements. The f_{max} of 20.5 GHz and f_{max} over 30 GHz are realized, as shown in Fig. 4.

The continuous-wave (CW) power was measured by the load–pull system. The gate width of the measured device is 2 × 75 μm. The device was operated in Class AB mode, while the drain bias was biased at 30, 40, 50, 60, and 70 V. The CW output power was increased from 5.2 to 11.2 W/mm,

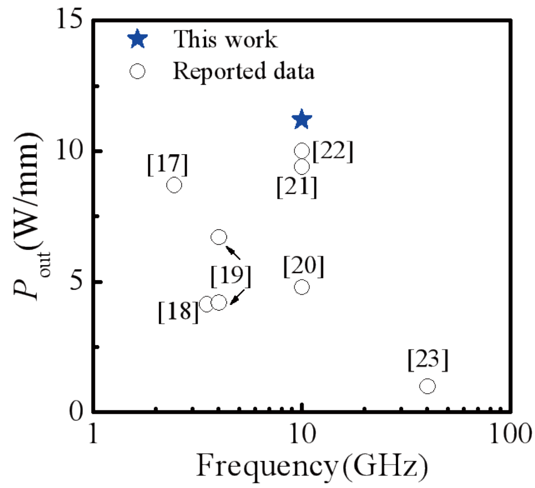

Fig. 6. (Color online) Plot of P_{out} vs. frequency for our devices against reported AlGaN/GaN HEMT on a GaN substrate from reported results[17−22].

with the drain bias increasing from 30 to 70 V, as illustrated in Fig. 5(a). The large-signal performance with drain based of 70 V was shown in Fig. 5(b). The CW output power peak was 11.2 W/mm, while the power-added efficiencies (PAE) is just 36%. The value of PAE is a bit low, which can be improved by reducing contact resistance and gate length.

The output power densities of our device and other similar reported devices are benchmarked (Fig. 6). The output power density of 11.2 W/mm for our device represents a record value among all reported references.

4. Conclusion

In summary, X-band AlGaN/GaN HEMT on a GaN substrate with high power density has been investigated. The BV over 200 V is realized by introducing the asymmetric gate and gate field plate. The working voltage of the drain electrode is increased to 70 V during the microwave output power measured. A continuous-wave power density reaches a record value of 11.2 W/mm@ 10 GHz. However, the PAE is as low as 36%, which may be caused by large ohmic resistance and gate length. The techniques of Si ion implantation in the source/drain regions and use of a small gate will be introduced to solve this problem, improving PAE and microwave output power. Moreover, the measured f_{max}/f_t of our fabricated device exceeds 30 GHz/20 GHz. The results of our fabricated device demonstrate the potential of AlGaN/GaN HEMT on a GaN substrate for microwave power applications.

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