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High Frequency AlGaN/GaN T-gate HEMTs on Extreme Low Resistivity Silicon Substrates

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Abstract

This work demonstrates high frequency AlGaN/GaN HEMTs grown on a 200-mm diameter extremely-low-resistivity (ELR) (2.5 mΩ·cm) silicon substrate. With a gate length of 0.1-μm, the short-circuit current gain cutoff frequency f_T, maximum oscillation frequency f_{max}, and maximum transconductance $g_{m,\,max}$ of 27 GHz, 71 GHz and 247 mS/mm can be achieved, respectively. The obtained high frequency performance is among the best reported to date for the GaN HEMTs on such low resistivity silicon substrates.

1. Introduction

GaN-based high electron mobility transistors (HEMTs) on the silicon substrate have become the most promising candidate for power amplifiers in 5G wireless communication systems. To take the advantage of large wafer diameters with reduced cost, GaN HEMT grown on large size low-resistivity (LR) ($\rho < 10$ Ω·cm) silicon substrates with a diameter up to 150 mm was reported [1]. Also, the passive components, such as inductors, coplanar waveguides and transmission line, were realized on LR ($\rho < 40$ Ω·cm) Si substrates [2-4]. Compared with the typically used high-resistivity substrate for RF applications, the LR substrate exists a better mechanical strength with lower cost. However, growing a high insulating GaN buffer layer and fabricate high frequency devices on a large diameter Si wafer still faces significant challenges. In addition, the parasitic effects introduced from the LR substrate could be severe for high frequency applications. In this work, 100-nm T-gate GaN HEMTs on 200-mm diameter ELR Si (111) (2.5 mΩ·cm), insulated by a 5.5-µm Carbon doped buffer layer, are realized and characterized. The realized 100-nm gate length transistors in this work have achieved f_T and f_{max} of 27 GHz and 71 GHz, respectively.

2. Device design and fabrication

The AlGaN/AlN/GaN HEMTs were grown on a 1000 µm thick 200 mm diameter P-type ELR Si substrate (provided by Global Wafers Co., Ltd.), as shown in Fig. 1. The wafer consists of a 5.5-µm Carbon doped layer for achieving highly resistive GaN buffers [5], followed by a 300 nm GaN channel and 1 nm AlN interlayer. Then, about 25 nm $Al_{0.23}GaN$ barrier layer was grown. Finally, a 2-nm GaN layer is used to prevent aluminum from oxidizing on the AlGaN surface. The electron mobility and the sheet carrier concentration are over 1800 cm^2/V and 9×10^{12} cm^{-2}, respectively, which results in a 392 Ω/□ sheet resistance.

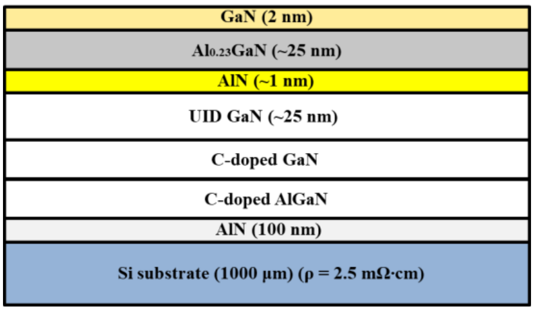


Fig. 1 Cross-sectional view of the AlGaN/AlN/GaN HEMTs grown on the extremely-low resistivity silicon substrate.

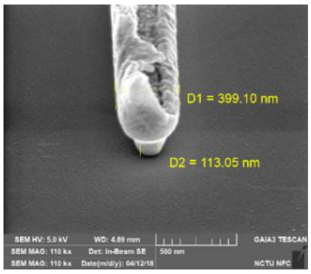
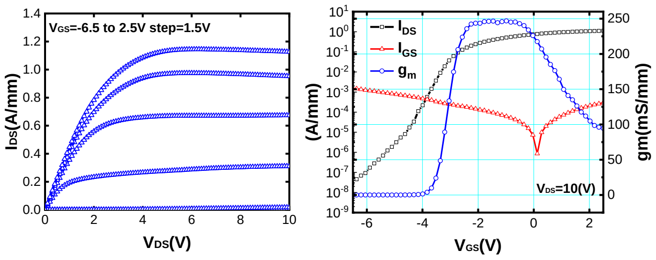


Fig. 2 FIB micrograph of T-gate for the fabricated GaN HEMT.

The manufacturing process started from mesa and uses Cl_3/BCl_3 mixed gas with an etching depth of approximately 150 nm using a Reactive Ion Etching (RIE) system. After mesa isolation, the source/drain was recessed to a depth of 20 nm to reduce the ohmic contact resistance, and then Ti/Al/Ti/Au (25/125/45/55 nm) was deposited by thermal evaporation, followed by rapid thermal annealing at 800 °C for 30 s in N_2 ambient and lift-off process. The bilayer photoresist PMMA/copolymer was coated by E-beam lithography system to define a T-shaped gate, followed by a Ni/Au (30/360 nm) deposition and lift-off process. The sample was then immersed in dilute HCl: H_2O (1:8) for 50 s, followed by soaking in deionized water for 10 s. A 25-nm SiN_X layer was deposited by PECVD at 300 °C, and CHF_3/O_2 mixed gas RIE etching for via. Finally, the Ti/Au (30/400 nm) pad for RF measurement was deposited.



(a) (b)

Fig. 3 (a) Measured DC I_{DS}-V_{DS} characteristics of the 100-nm AlGaN/GaN HEMT on ELR Si substrate ($W_G = 2 \times 12.5\ \mu$m) with a good pinch-off and high output resistance. (b) Transfer characteristics at V_{DS}=10 V.

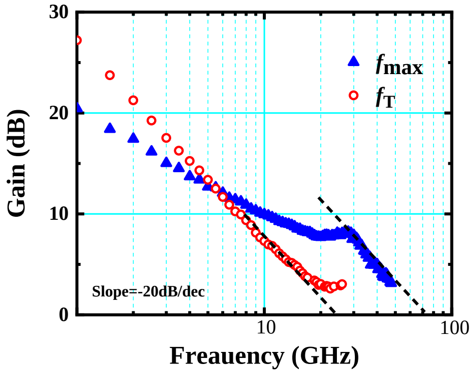


Fig. 4 Measured frequency response of the fabricated GaN HEMT on the ELR Si substrate at V_{DS} = 10V and V_{GS} = -3.5V. The extracted f_T and f_{max} are 27 GHz and 71 GHz, respectively.

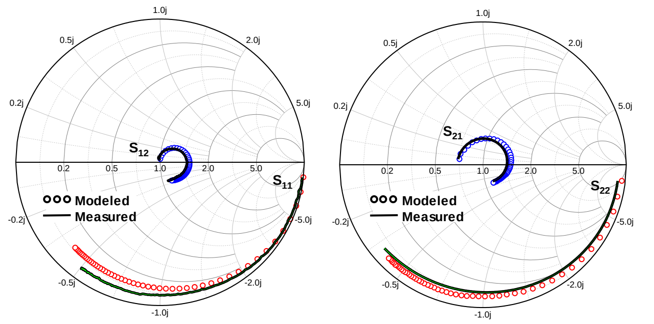


Fig. 5 Measured and modeled frequency response of the fabricated GaN HEMT at V_{DS} = 10V and V_{GS} = -3.5V. The extracted f_T and f_{max} are 27 GHz and 71 GHz, respectively.

3. Results and Discussion

The DC *I-V* characteristics of this work were measured by an Agilent B1500A semiconductor device analyzer. The T-shaped gate with a 0.113 µm footprint and 0.4 µm head was captured by FIB, as shown in Fig. 2. Fig. 3(a) and 3(b) show the DC I_{DS}-V_{DS} and transconductance characteristics. The smaller source-drain distance combined with low ohmic contact resistance allow a low ON-resistance of 2.4 Ω·mm, which was extracted at V_{GS} = 2.5V. The maximum drain current density ($I_{D,\ max}$) of 1.144 A/mm at V_{GS} = 2.5 V and peak extrinsic $g_{m,\ max}$ of 247 mS/mm at V_{GS} = -1 V can be obtained. Note that the short channel effect is not obvious and good pinch-off (I_{on}/I_{off} ~ 3×10^5) can be achieved, which can be mainly attributed to the improved gate control over the channel by improving the aspect ratio between the gate length and the optimized AlGaN barrier thickness.

The small-signal high frequency measurements were performed using the Agilent N5245A PNA-X network analyzer. Fig. 4 shows the measured results of the device at the bias of V_{GS} = -3.5 V and V_{DS} = 10 V. With the open pad de-embedding procedure, the f_T and f_{max} up to 27 GHz and 71 GHz are obtained by extrapolating with a slope of -20 dB/decade. During the parameter extraction and modeling process, it was found that the heterojunction of low-resistivity silicon substrate plays an important role for the device frequency response due to the two-dimensional electron gas (2DEG) at the interface. The parasitics exist at the interface between substrate and GaN result in an RC pole, which significantly limited the f_{max} [6]. Fig. 5 presents the measured and modeled results by the equivalent circuit including the substrate network. A good agreement can be obtained between the measured and modeled results.

4. Conclusions

This work successfully demonstrated the high frequency 0.1 µm AlGaN/GaN HEMTs with T-shaped gate on an extremely low resistivity Si substrate (2.5 mΩ·cm). The measured f_T, f_{max} and $g_{m,\ max}$ are 27 GHz, 71 GHz and 247 mS/mm respectively. The achieved high frequency performance are among the best compared with previously reported results for the GaN HEMTs on low resistivity silicon substrates.

Acknowledgements

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