Self-Aligned-Gate GaN-HEMTs with Heavily-Doped $n^+$-GaN Ohmic Contacts to 2DEG


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Abstract

We report record DC and RF performance obtained in deeply-scaled self-aligned-gate GaN-HEMTs with heavily-doped $n^+$-GaN ohmic contacts to two-dimensional electron-gas (2DEG). High density-of-states of three-dimensional (3D) $n^+$-GaN source near the gate mitigates "source-starvation" resulting in a dramatic increase in a maximum drain current ($I_{d_{\text{max}}}$) and a transconductance ($g_m$). 20-nm-gate D-mode HEMTs with a 40-nm gate-source (and gate-drain) distance exhibited a record-low $R_{on}$ of 0.23 $\Omega \cdot$mm, a record-high $I_{d_{\text{max}}}$ of >4 A/mm, and a broad $g_m$ curve of >1 S/mm over a wide range of $I_{ds}$ from 0.5 to 3.5 A/mm. Furthermore, 20-nm-gate E-mode HEMTs with an increased $L_{sw}$ of 70 nm demonstrated a simultaneous $f_T$/$f_{\text{max}}$ of 342/518 GHz with an off-state breakdown voltage of 14V.

Introduction

Deeply-scaled E/D-mode GaN-HEMTs with an unprecedented combination of high-frequency and high-breakdown characteristics offer practical advantages in circuit applications such as sub-millimeter-wave power amplifiers, ultra-linear mixers, and increased output power digital-to-analog converters. During the last few years, through innovative device scaling technologies GaN-HEMT cutoff frequencies have been significantly increased - almost doubled - while maintaining Johnson figure of merit ($JFOM$) breakdown performance [1]. It is reported that in deeply-scaled FETs highly-doped source/drain (S/D) can significantly improve device performance by enhancing electron supply in the source [2,3]. Regrown $n^+$-GaN ohmic contacts have been shown to be one of viable technologies to reduce parasitic access resistances [4,5]. However, much attention has not been paid to an important role of heavily-doped S/D contacts in mitigating "source-starvation" which limits present GaN-HEMT performance. In this paper, we, for the first time, have developed self-aligned-gate GaN-HEMTs with regrown $n^+$-GaN S/D in direct contact with the 2DEG near the gate, and demonstrate dramatically enhanced DC and RF characteristics in conjunction with engineering of the lateral device dimensions.

Device design

Fig. 1 illustrates a technology cross-section featuring (i) a laterally-scaled self-aligned-gate, (ii) vertically-scaled depletion and enhancement-mode AlN/GaN/AlGaN double-heterojunction (DH) HEMT epitaxial structures as detailed in Fig. 2, and (iii) heavily-doped $n^+$-GaN ohmic contacts regrown by MBE. A high 2DEG density ($n_s$) of 1.2(D)/1.1(E)×10$^{13}$ cm$^{-2}$ and a high electron mobility ($\mu$) of 1200(D)/1250(E) cm$^2$/V·s were measured after surface passivation with SiN. Heavily-Si-doped $n^+$-GaN ohmic layers (7×10$^{19}$ cm$^{-3}$, 50 nm) laterally contact to 2DEG in the GaN channel. A Pt/Au gate is then self-aligned to the $n^+$-GaN ohmic contacts by enhancing electron supply in the source [2,3]. Regrown $n^+$-GaN ohmic contacts have been shown to be one of viable technologies to reduce parasitic access resistances [4,5]. However, much attention has not been paid to an important role of heavily-doped S/D contacts in mitigating "source-starvation" which limits present GaN-HEMT performance. In this paper, we, for the first time, have developed self-aligned-gate GaN-HEMTs with regrown $n^+$-GaN S/D in direct contact with the 2DEG near the gate, and demonstrate dramatically enhanced DC and RF characteristics in conjunction with engineering of the lateral device dimensions.

Fig. 1. Deeply-scaled self-aligned-gate double-heterojunction (DH) HEMT with heavily-doped regrown $n^+$-GaN ohmic contacts to the 2DEG in the GaN channel.

Fig. 2. Vertically-scaled (a) D-mode and (b) E-mode DH-HEMT epitaxial structures.

Fig. 3 compares two regrown $n^+$-GaN ohmic structures: (a) A regrown $n^+$-GaN ohmic layer directly contacts to the 2DEG, where electrons are supplied from the 3D $n^+$-GaN source to the 2DEG near the gate (3D-2D). (b) An $n^+$-GaN ohmic layer was regrown on top of the (Al)GaN/AlN barrier layers as reported in our previous paper [1], where electron are...
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We report record DC and RF performance obtained in deeply-scaled self-aligned-gate GaN-HEMTs with heavily-doped n+-GaN ohmic contacts to two-dimensional electron gas (2DEG). High density-of-states of three-dimensional (3D) n+-GaN source near the gate mitigates source-starvation, resulting in a dramatic increase in a maximum drain current ($I_{d_{max}}$) and a transconductance ($g_m$). 20-nm-gate D-mode HEMTs with a 40-nm gate-source (and gate-drain) distance exhibited a record-low Ron of 0.23 Ω·mm, a record-high $I_{d_{max}}$ of >4 A/mm, and a broad $g_m$ curve of >1 S/mm over a wide range of $I_{d}$ from 0.5 to 3.5 A/mm. Furthermore, 20-nm-gate E-mode HEMTs with an increased $L_{sw}$ of 70 nm demonstrated a simultaneous $f_T/f_{max}$ of 342/518 GHz with an off-state breakdown voltage of 14V.

**Subject Terms**

supplied from the 2DEG source to the 2DEG channel (2D-2D).

**Results and Discussion**

An access resistance \( R_{ac} \), defined as a total resistance from the ohmic metal to the edge of the gate, of 0.101 \( \Omega \cdot \text{mm} \) is the lowest value ever reported in GaN-HEMTs (Fig. 4). Resistance components of \( R_{ac} \) are shown in Fig. 4, which were extracted from a TLM test structure, contactless sheet resistance measurement, and dependence of device on-resistance \( R_{on} \) on \( L_g \) (Fig. 5). The regrown interface resistance \( R_{int} \) between the \( n^+ \)-GaN and the 2DEG is only 0.026 \( \Omega \cdot \text{mm} \), reaching its theoretical limit \([-h/(2q^2 n_s^{1/2}) = 0.036 \Omega \cdot \text{mm}] \) [6]. More importantly, this new approach not only reduces \( R_{ac} \) but also increases flexibility in a material choice of GaN-HEMT epi structures since the \( R_{ac} \) is independent of the barrier materials as is the case for the conventional approach. Fig. 6 and Fig. 7 compare DC characteristics of 60-nm D and E-mode HEMTs with 3D-2D and 2D-2D contacts. Reduced \( R_{on} \) by -18\% (-19\%) for D (E)-mode device is a result of the reduced \( R_{ac} \). \( I_{d_{max}} \) is dramatically increased by +34\% (+45\%) for D (E)-mode device due to an increase of \( g_m \) at high \( I_d \). This result clearly illustrates that typical \( g_m \) roll-off at high \( I_d \) observed in previous devices is due to the limited electron supply from the source, i.e., "source-starvation." 20-nm-gate D-mode HEMTs with \( L_{sw} = 40 \) nm exhibited a record-low \( R_{on} \) of 0.23 \( \Omega \cdot \text{mm} \), a record-high \( I_{d_{max}} \) of >4 A/mm, and a broad \( g_m \) curve of >1 S/mm over a wide range of \( I_d \) from 0.5 to 3.5 A/mm (Fig. 8). Fig. 9 shows a peak \( g_m \) of E-mode HEMTs as a function of \( L_g \) for various \( L_{sw} \), indicating that the closer the \( n^+ \)-GaN/2DEG interface is to the gate, the more efficiently electron are supplied from the 3D \( n^+ \)-GaN source. The record-high \( g_m \) of 2.2 S/mm was measured for a device with \( L_g/L_{sw} = 40/50 \) nm.
While the shorter gate-source distance \((L_g)\) enhances the electron supply, the longer gate-drain distance \((L_{gd})\) increases breakdown voltage and reduces output conductance \((g_d)\) and gate-drain capacitance \((C_{gd})\). Off-state breakdown voltage \((BV_{off})\) increased linearly with increasing \(L_{sw}\) with a slope of 3.25 MV/cm, close to the critical field of GaN (~3.4 MV/cm) (Fig. 10). Drain induced barrier lowering (DIBL) for sub-50-nm gate lengths \((L_g)\) improved significantly with increasing \(L_{sw}\) owing to an increased gate to drain electrostatic isolation (Fig. 11), leading to a lower \(g_d\) due to suppression of the "short-channel-effect." A balanced device design with \(L_g/L_{sw} = 20/70\) nm in the E-mode HEMTs resulted in a simultaneous \(f_T/f_{max} = 342/518\) GHz with a \(BV_{off}\) of 14 V. This record-high \(f_{max}\) is attributed to the decreased \(g_d\) and \(C_{gd}\) due to the increased gate-drain distance together with a high \(g_m\) enabled by the new 3D \(n^+\)-GaN source contact to the 2DEG (Fig. 12). Fig. 13 shows good scaling behavior of \(f_T/f_{max}\) with \(L_g\) down to 20 nm. As a result of proportional device scaling and enhanced electron supply in self-aligned-gate...
Fig. 14. Comparison of extrinsic peak $g_m$ vs. $V_{th}$ with the state-of-the-art results reported for GaN-HEMT technology.

Fig. 15. Proportional device scaling and enhanced electron supply in deeply-scaled self-aligned-gate GaN-HEMTs successfully resulted in a record $f_T$ and $f_{max}$ exceeding an average cutoff frequency of 400 GHz.

GaN-HEMTs, enhanced peak $g_m$ in excess of 2 S/mm (Fig. 14) and an average cutoff frequency $[= (f_T f_{max})^{1/2}]$ of >400GHz were obtained (Fig. 15).

**Conclusion**

Heavily-doped $n^+$-GaN S/D contacts to the 2DEG in deeply-scaled self-aligned-gate GaN-HEMTs were demonstrated for the first time. The new technology was shown to effectively mitigate “source-starvation,” resulting in a significant enhancement in $R_{on}$, $I_{max}$, $g_m$, and $g_m$ linearity. An $R_{on}$ of 0.23 $\Omega$mm, an $I_{max}$ of >4 A/mm with a broad $g_m$ curve of >1 S/mm over a wide range of $V_{gs}$, was obtained in 20-nm D-mode HEMTs with $L_{sw} = 40$ nm. In conjunction with lateral device size optimization for a reduced $g_d$ and $C_{gd}$ as well as an increased $BV_{gd}$, a record $f_{T}/f_{max}$ of 342/518 GHz was obtained in 20-nm HEMTs with a $JFOM$ of 4.8 THz·V.

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**Reference**