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Advanced Gate Technologies for State-of-the-art $f_T$ in AlGaN/GaN HEMTs

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Abstract

In this paper, the lower-than-expected frequency performance observed in many AlGaN/GaN high electron mobility transistors (HEMTs) has been attributed to a significant drop of the intrinsic small-signal transconductance ($g_{m}$) with respect to the intrinsic DC $g_{m}$. To reduce this $g_{m}$-collapse and improve high frequency performance, we have developed a new technology based on a combination of vertical gate-recess, oxygen plasma treatment, and lateral gate-etch which has allowed us to fabricate AlGaN/GaN HEMTs with a record current-gain cutoff frequency ($f_T$) of 225 GHz for a gate length ($L_g$) of 55 nm, and 162 GHz for an $L_g$ of 110 nm.

Introduction

GaN-based high electron mobility transistors (HEMTs) have emerged as one of the prime candidates for solid-state power amplifiers at frequencies above 30 GHz. A great deal of the excitement about its prospect comes from the unique combination of high electron velocity ($v_{\text{peak}} \approx 2.5 \times 10^7 \text{ cm/s}$) and high breakdown electric field ($\approx 3.3 \text{ MV/cm}$) [1, 2]. In spite of the recent progress in maximum operating frequency [3, 4], there are still important issues that need to be overcome to further extend operating frequencies of GaN HEMTs to mm-wave ranges (30-300 GHz). One of the biggest challenges in mm-wave GaN HEMTs is that the typical frequency response of these devices, as measured by the current-gain cutoff frequency ($f_T$), is lower than what the intrinsic material properties predict. Several hypotheses have been proposed to explain the lower-than-expected frequency performance. Some of them include short-channel effects in scaled devices [5] and degradation of the gate modulation efficiency by interface defects and traps [6]. However, it is still not clear what is primarily limiting high frequency performance of GaN HEMTs and more understanding is needed to identify solutions to this problem.

This paper shows for the first time that the drop in the intrinsic small-signal transconductance ($g_{m}$) with respect to the intrinsic DC $g_{m}$ can largely degrade the frequency performance of AlGaN/GaN HEMTs. To mitigate this $g_{m}$-collapse, we found the interface between the gate metal and the AlGaN surface needs to be carefully passivated. Also, it is well known that harmonious scaling of vertical and lateral dimension of the gate is important to maximize frequency performance. In this regard, we have developed a new gate technology including vertical gate-recess, oxygen plasma treatment, and lateral gate-etch which enable us to achieve state-of-the-art $f_T$ in AlGaN/GaN HEMTs.

Process Technology

Fig. 1 shows the cross-section of an AlGaN/GaN HEMT fabricated in this work. Device fabrication began with mesa isolation using a Cl$_2$/BCl$_3$ plasma-based dry etch. A new recessed ohmic contact metallurgy based on alloyed Si/Ge/Ti/Al/Ni/Au (2/2/20/100/25/50 nm) contacts was used to reduce both ohmic contact resistance (by 55 %) and surface roughness of the contacts (by 83 %) over conventional non-recessed Ti/Al/Ni/Au ohmic contacts (Fig. 2). It should be noted that a smooth ohmic surface is very important to increase processing yield and reproducibility of the gate lithography, especially for short source-to-drain distances (< 2 μm). Fig. 3 summarizes the gate technology used in this work. Sub-micron gates were patterned by 30-keV electron-beam lithography on a single ZEP resist layer. The patterned ZEP layer was coated by a thin layer of Al$_2$O$_3$ deposited by atomic layer deposition. A deposition temperature of 80 °C was used to prevent the reflow of the ZEP. Then a low power gate recess was applied using Cl$_2$/BCl$_3$-based electron cyclotron resonance reactive ion etching (ECR-RIE). In some devices, the gate recess was followed by an oxygen plasma treatment to the AlGaN surface. It should be highlighted that the remaining Al$_2$O$_3$ sidewalls play an important role to protect the ZEP layer from the oxygen plasma, preserving the original gate length defined by the lithography. After the oxygen plasma treatment, a Ni/Au (10/70 nm) metal stack was deposited for the gate contact and, finally, a selective Ni etching was performed to further reduce the physical gate length.

Figure 1. Schematic (left) and cross-section STEM image (right) of recessed AlGaN/GaN HEMT. The physical gate length, $L_g$, after lateral Ni-etch is 55 nm. The barrier thickness, $t_{\text{bar}}$, after vertical gate-recess is 17 nm (1 nm AlN spacer is included.).
Figure 2. Comparison between conventional (left) and recessed Si(2nm)/Ge(2nm)/Ti/Al/Ni/Au ohmic contacts (right). Both of them were alloyed at 820 °C. 55% smaller contact resistance ($R_C$) and 83% smoother surface roughness were observed for the new ohmic technology by TLM, AFM, and microscopy images (inset).

Figure 3. New gate technology developed in this work. 10 nm of ALD-Al$_2$O$_3$ sidewalls protects the gate length defined by e-beam lithography from the oxygen plasma treatment. After Ni/Au gate metal deposition, the bottom Ni layer was selectively etched to further reduce the physical gate length.

Effect of Oxygen Plasma Treatment

Fig. 4 shows a high-resolution TEM (HRTEM) image of the fabricated HEMTs at the interface between gate metal and the AlGaN surface, and Table 1 shows X-ray photoelectron spectroscopy (XPS) measurements of the AlGaN surface before and after the oxygen plasma treatment. The oxygen plasma forms a thin Ga$_2$O$_3$ layer and reduces the Carbon concentration at the AlGaN surface. This plasma treatment reduces the gate leakage current by two orders of magnitude and the interface trap density by 50% (Fig. 5) without degrading mobility and transconductance (Fig. 6). Important, the resultant HEMTs showed no degradation in intrinsically transconductance at high frequencies (i.e. no RF $g_m$-collapse) and exhibited 36% higher $f_T$ than the device without oxygen plasma treatment (Fig. 7). It is also noted that part of the $f_T$ improvement originated from the slightly higher mobility of the oxygen plasma-treated sample, as shown in Fig. 6.

Table 1. XPS measurement of the AlGaN surface after oxygen plasma treatment reveals the formation of a Ga$_2$O$_3$ layer and much lower carbon contamination at the surface than in the as-grown sample.

![Figure 4](image4.png) A cross-section HRTEM image of 55-nm gate length HEMTs at the interface between gate metal (Ni) and the AlGaN surface. 1 nm of Ga$_2$O$_3$ layer was confirmed in conjunction with XPS measurement shown in Table 1.

![Figure 5](image5.png) Subthreshold and $I_G$ characteristics (left) and $D_{it}$ (right) of AlGaN/GaN HEMTs with and without oxygen plasma treatment. $D_{it}$ was measured by the conductance method. The reverse-biased leakage current is two orders of magnitude lower and $D_{it}$ is 50% lower in oxygen plasma-treated samples. The slight increase in the gate-to-channel separation due to the Ga$_2$O$_3$ layer is responsible for the small shift of the threshold voltage ($\Delta V_T = 0.15$ V).

![Figure 6](image6.png) Drift mobility ($\mu_{Drift}$) as a function of the sheet carrier density (left) and $g_m$ characteristics (right) of non-recessed ($t_{bar} = 22$ nm) AlGaN/GaN HEMTs with and without oxygen plasma treatment. $\mu_{Drift}$ and $g_m$ are slightly higher in oxygen plasma-treated samples.
Figure 7. Intrinsic RF transconductance \( g_m,i \) of AlGaN/GaN HEMTs with and without oxygen plasma treatment. \( g_m,i \) is extracted from measured S-parameters in the range of 5 ~ 40 GHz. The inset shows \( f_T \) for both devices. The oxygen plasma-treated sample showed 36 % higher \( f_T \) by preserving \( g_m,i \), which drops without the treatment.

DC and RF Characteristics

Fig. 8 shows the DC characteristics of one of the fabricated AlGaN/GaN HEMTs with \( L_g \) of 55 nm, gate-to-channel distance (\( t_{bar} \)) of 17 nm, and source-to-drain distance (L_{SD}) of 1 \( \mu \)m. The device exhibited excellent pinch-off, a low knee voltage of 2 V, and a high peak transconductance of 500 mS/mm. The RF performance of the same device was characterized from 0.5 to 40 GHz (Fig. 9). The network analyzer was calibrated with a short-open-load-through (SOLT) standard and the calibration was verified by insuring that both S12 and S21 of the through standard are less than \( \pm 0.01 \)dB and that both S11 and S22 are less than -45 dB within the measured frequency range after the calibration. On-wafer open and short structures were used to de-embed the effect of parasitic pad capacitances and inductances. A record \( f_T \) of 225 GHz was obtained by extrapolating \( |h_{21}|^2 \) with a slope of -20 dB/dec using a least-square fit. For comparison, the highest \( f_T \) reported so far in nitride transistors was 190 GHz in 6-nm barrier AlGaN/GaN HEMTs with 60-nm gate length [3]. \( f_T \) was linearly increased from 205 GHz to 225 GHz by reducing source-to-drain distance from 2 \( \mu \)m to 1 \( \mu \)m. Devices with an \( L_g \) of 110 nm and the same \( t_{bar} \) of 17 nm showed an \( f_T \) of 162 GHz and this higher \( f_T \times L_g \) product (17.8 GHz\( \mu \)m when \( L_g = 110 \) nm vs. 12.4 GHz\( \mu \)m when \( L_g = 55 \) nm) is due to the improved gate aspect ratio in the longer gate length devices. The relatively low \( f_{max} \) values in our devices are mainly due to the large gate resistance (\( R_g \)).

The small-signal equivalent circuit of these devices was carefully extracted following ref. [7] and confirmed by matching their S-parameters with measured S-parameters using Advanced Design System (ADS) software simulations. The electron velocity was calculated from the internal gate capacitances and intrinsic transconductance as a function of \( L_g \). Internal gate capacitances (\( C_{gs,i} \), \( C_{gd,i} \)) without external gate fringing capacitances (\( C_{gs,ext} \), \( C_{gd,ext} \)) were obtained from the scaling behavior of extracted \( C_{gs} \) and \( C_{gd} \) (Fig. 10). The electron velocity monotonically increased with reducing \( t_{bar} \), resulting in \( f_T \) improvement (Fig. 11). Also, in the devices with lower \( t_{bar} \), we observed less roll-off in \( v_e \) and \( f_T \) when scaling \( L_g \), indicating that the short-channel effects are mitigated as the devices are vertically scaled. Fig. 12 and Fig. 13 benchmark the frequency performance of the devices obtained in this work against previous data in the literature.
Figure 10. Method to calculate electron velocity. The internal gate capacitances, $C_{gs,i}$ and $C_{gd,i}$ are extracted from the scaling behavior of extracted $C_{gs}$ and $C_{gd}$ (left). The intrinsic electron velocity ($v_e$) is calculated from $C_{gs,i}$, $C_{gd,i}$, and $g_{m,i}$ at a given $L_g$ following the equation of intrinsic delay, $\tau_{int}$ (right).

Figure 11. Calculated $v_e$ (left) and measured $f_T$ (right) as a function of $L_g$ for different $t_{bar}$. The $v_e$ and $f_T$ drop as reducing $L_g$ is mainly due to $g_{m,i}$ roll-off. This drop can be mitigated by reducing $t_{bar}$, which increases the aspect ratio of the gate ($L_g/t_{bar}$) and reduces short-channel effects.

Figure 12. Evolution of $f_T$ in GaN HEMTs for the past 15 years. A state-of-the-art frequency performance is reported in this work.

Figure 13. The benchmark of the $f_T\cdot L_g$ products with data found in the literature as a function of aspect ratio. It is important to keep the aspect ratio > 5 to avoid strong short-channel effects (SCE).

Our future work is focused on more aggressive scaling on both lateral and vertical dimensions of the HEMT and investigating origin of RF $g_{m,i}$-collapse.

Conclusions

In summary, we have demonstrated AlGaN/GaN HEMTs with outstanding frequency performance. In particular, $L_g=55$ nm devices exhibit a record $f_T$ of 225 GHz. To achieve this high $f_T$, we combined a scaled geometry with a novel oxygen plasma treatment to simultaneously improve short-channel effects and RF $g_{m,i}$-collapse. This new technology increases the electron velocity in GaN HEMTs by 40 % and uncovers the unsurpassed potential of GaN transistors for very high frequency applications.

References


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