High linearity and high power performance with barrier layer of sandwich structure and Al$_{0.05}$GaN back barrier for X-band application

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Abstract
The high power and linearity performance of GaN-based HEMT for X-band application was achieved using the barrier layer of sandwich structure and Al$_{0.05}$GaN back barrier. The AlGaN-sandwich-barrier can modulate polarization-graded field for more flat transconductance profile under the high drain bias. Only about 7.5% current collapse (CC) occurs for drain quiescent bias of 40 V. Due to the Al$_{0.05}$GaN back barrier, the three-terminal off-state breakdown voltage (BV$_{PD}$) of 260 V and a very small drain-induced barrier lowering (DIBL) of 2.7 mV V$^{-1}$ is achieved. The AlGaN sandwich barrier combined with Al$_{0.05}$GaN back barrier device exhibits a high current-gain cutoff frequency $f_T$ of 42 GHz@$V_{DS} = 10$ V, and a high power-gain cutoff frequency $f_{MAX}$ of 130 GHz@$V_{DS} = 60$ V. Load-pull measurement at 10 GHz revealed a saturated power density of 7.3 W mm$^{-1}$ was achieved with an associated PAE of 29.2% and Gain of 10.6 dB. Two-tone measurement at 10 GHz showed an OIP3 of 38 dBm and a corresponding linearity figure-of-merit OIP3/$P_{DC}$ of 4.5 dB. These results demonstrate the great potential of AlGaN-sandwich -barrier/GaN/Al$_{0.05}$GaN HEMTs as a very promising alternative to high power and high linearity X-band power amplifier.

Keywords: high power and linearity GaN-based HEMT, barrier layer of sandwich structure, Al$_{0.05}$GaN back barrier, two-tone linearity, graded barrier

(Some figures may appear in colour only in the online journal)
from the device-level due to its low system-level cost [7]. In order to reduce nonlinearity from device-level, researchers proposed a field-plated gate-recessed structure AlGaN/GaN HEMTs [8] for improving the device linearity characteristics. Gao et al. utilized the double-hump feature in the transconductance-gate voltage curve with PZT-gated AlGaN/GaN/MIS-HEMTs [9] to design high linearity devices. Recently, GaN-based Fin-HEMTs [10, 11] offered flat $g_m$ and high normalized current density for GaN-based device linearity improvement. Based on Fin-HEMTs structure, large signal linearity enhancement was achieved by device-level Vth engineering for transconductance compensation [12]. However, these methods will bring extra capacitance (e.g. field plate capacitance, PZT-gated capacitance and side wall capacitance) and limit high frequency performance. Based on epitaxial structure design, 3D channel with compositionally graded AlGaN barrier [13] and a composite 2D–3D channel with InGaN sub-channel [14] were achieved for transconductance and power linearity improvement. However, lower barrier height of AlGaN layer leads to larger gate leakage in 3D channel and poor quality of InGaN sub-channel and buffer demonstrates the severe current collapse. In this paper, the degradation of mobility slows down by optimizing the E-field profile under high E-field and thus we improve the trans-conductance nonlinearity of GaN device. Table 1 shows the comparison of the best device level reported values of linearity figure of merits (LFOM).

In this work, we demonstrate the 10 GHz load-pull and large signal two-tone linearity measurements of AlGaN-sandwich-barrier/GaN/Al$_{0.05}$GaN HEMTs. The AlGaN sandwich barrier allowed for a flatten of the high electric field peak and high quality Al$_{0.05}$GaN back barrier allowed for better 2DEG confinement. No significant current collapse was observed under 500 ns pulse measurements at 40 V drain bias. A deep Class-AB microwave performance with a maximum power density of 7.3 W/mm$^{-1}$, an OIP3 of 38 dBm for 100 µm width device and a corresponding OIP3/PDC of 4.5 dB at 10 GHz from load-pull and two-tone measurements was demonstrated. It is also believed to be the best power performance while keeping high OIP3/PDC under the high drain bias for X-band application. It shows that our proposed device will effectively alleviate the contradictions between the power peak and linearity of GaN-based amplifier.

The in situ SiN/AlGaN-sandwich-barrier/GaN/Al$_{0.05}$GaN hetero-structure layers were grown at Xidian University on a 3-inch SiC substrate using metal organic chemical vapor deposition. The HEMT hetero-structure comprises of a 1.5 μm un-doped Al$_{0.05}$GaN buffer, 100 nm GaN channel layer, 1 nm AlN layer, 26 nm AlGaN sandwich barrier (3 nm top Al$_{0.3}$GaN barrier, 20 nm graded AlGaN barrier and 3 nm bottom Al$_{0.5}$GaN barrier). The bottom Al$_{0.9}$GaN barrier can provide higher 2DEG confinement and stronger polarization effect. The middle linear graded AlGaN barrier (Al mole fraction ranged from 40% to 20%) and the top Al$_{0.3}$GaN barrier can modulate polarization-graded field for flatter transconductance profile. Hall measurements showed a carrier density of $1.3 \times 10^{13}$ cm$^{-2}$ and an electron mobility of 1800 cm$^2$ V$^{-1}$ s$^{-1}$. The sheet resistance is approximately 270 Ω$^{-1}$ at RT. Device processing started with Ti/Al/Ni/Au source/drain electrodes, and then annealed at 830 °C for 30 s in a N$_2$ environment in order to form the ohmic contacts. A measured contact resistance was 0.4 Ω mm. Device was isolated by planar selectively implanted isolation. A SiN layer of 120 nm thick plasma-enhanced chemical vapor deposition (PECVD) was deposited to provide a passivation. An opening in SiN for gate foot was defined by electron beam lithography followed by CF$_4$ dry etching of the SiN layer. Then, Ni/Au e-beam evaporation and lift-off were carried out subsequently to form the gate electrodes. All devices in this letter have a gate length of 0.2 µm, a gate overhang above the FP SiN layer of 0.5 µm, a gate width of 2 × 50 µm, a gate-source spacing of 1.0 µm, and gate-drain spacing of 3.3 µm.

Figures 1(a) and (b) show the schematic of a scaled 200 nm gate length field-plate (FP) GaN-based HEMT with an AlGaN-sandwich-barrier (SWB) and an AlGaN normal barrier (NB), respectively. The HEMT structure contains gate region and access region. Generally, as for microwave application, the access region was much larger than gate region. Then, the electric field (E-field) distribution under gate region and access region would be uneven. From the E-field simulation results, the SWB can improves the non-uniformity of the E-field distribution along the channel direction to some extent (figures 1(c) and (e)) and extend E-field region under both low and high drain bias condition (figures 1(c) and (d)) compared with the NB structure (figures 1(e) and (f)) where the E-field region was concentrated under the gate and showed a peak increase between the gate and drain. What’s more, when the drain bias increased from 10 V to 60 V, the increase of the E-field was higher for the NB structure, especially under the gate region near the drain side.

To further study the effect of SWB on the E-field extension, the E-field distribution along the gate length direction for SWB and NB structure were shown in figures 1(g) and (h), respectively. The variation of E-field distribution along the gate for SWB structure was smaller than that for NB structure. According to Monte Carlo evaluations of the electron transport in AlGaN/GaN hetero-structures presented by Li et al [15], the saturation drift velocity would degrade at the high E-field and further cause the degradation of the channel mobility. In this work, since the variation of the E-field value for SWB structure was smaller than that for NB structure due to the wider electric field extension, the change of saturation drift velocity was also smaller for SWB structure. That is to say, the degradation of channel mobility was reduced due to the wider electric field extension. Then in the view of the transconductance ($g_m$), which equals to the following expression [16]:

$$g_m(V_G) = \frac{dI}{dV_G} \frac{d\omega}{dV_G} d\omega = \frac{e\varepsilon_{zz} W v_{sat}}{\omega(V_G) \left[ 1 + \eta \int_0^V v_{sat} N_{pad} dV \right]^2} \tag{1}$$
where $W$ is the gate width, $\omega$ is the depletion depth, $a$ is the channel thickness, $N_{pol}$ is the polarization charge, and $\eta \equiv \frac{L_S}{\mu N_{ch} V_D}$ where $L_S$ is length of the source region and $\mu$ is the electron mobility in the 2-DEG. As discussed above, the flat profile of $\mu$ leads to a flat $\eta$ and make contribution to a flatter $G_m$ especially at high E-field. Therefore, such wider electric field extension at the high drain bias can effectively reduce E-field peak and can suppress the fluctuation of

**Figure 1.** A schematic diagram of (a) AlGaN-sandwich-barrier/GaN/Al$_{0.05}$GaN HEMTs and (b) AlGaN/GaN/Al$_{0.05}$GaN HEMTs, (c) low-electric field distribution and (d) high-electric field distribution of AlGaN-sandwich-barrier/GaN/Al$_{0.05}$GaN HEMTs, (e) low-electric field distribution and (f) high-electric field distribution of AlGaN/GaN/Al$_{0.05}$GaN HEMTs, Electric field profile along the channel direction of (g) AlGaN-sandwich-barrier/GaN/Al$_{0.05}$GaN HEMTs and (h) AlGaN/GaN/Al$_{0.05}$GaN HEMTs.
channel mobility for the flatter \( G_m \). Moreover, in the view of the SWB structure design, it has a middle linear graded AlGaN barrier, then considering the \( N_{pol} \) expression [16]:

\[
qN_{pol} \equiv -\nabla \cdot \mathbf{P} = -\left( \varepsilon_z u_{cz} + \frac{P_0}{z} \right) \varepsilon_z.
\] (2)

From the above polarization charge equation, we can obtain that a linear graded AlGaN barrier produces a uniform polarization charge profiles [16], which will make the depletion depth \( \omega \) change gradually with the gate voltage, resulting a relative flat \( \omega \), this also improve the \( G_m \) linearity. Then, as to improve the power linearity, the ratio of the level of third-order sideband power to the level of fundamental power should be small. It is noted that the ratio is proportional to [17]

\[
\frac{d^2 I}{dV^2} = \frac{G_m''}{G_m}.
\] (3)

Since a flat \( G_m \) cause a small \( G_m'' \), resulting a small ratio and improve the power linearity.

The linear-scale transfer characteristics of AlGaN-sandwich-barrier/GaN/Al\(_{0.05}\)GaN HEMTs with different drain voltage are plotted in figure 2(a). The maximum saturation current at \( V_{GS} = 2 \) V was 1130 mA mm\(^{-1}\) and maximum extrinsic transconductance \( (G_m) \) of 280 mS mm\(^{-1}\) was obtained. With the increase of drain voltage, the saturation current and transconductance peak deteriorate significantly. However, the decrease of transconductance with the increase of gate voltage turns to be suppressed at high drain bias due to E-field extension as discussed above. This is accompanied by a very small DIBL of 2.7 mV V\(^{-1}\) in the sub-threshold characteristics (figure 2(b)).

Figure 3(a) shows the DC and pulsed drain-current versus drain voltage characteristics of AlGaN-sandwich-barrier/GaN/Al\(_{0.05}\)GaN HEMTs. The quiescent bias conditions for the measurement is \( V_{GS0} = -8 \) V and \( V_{DS0} = 40 \) V. It is clear that there is no significant drain CC (only about 7.5%) due to high quality of \textit{in situ} SiN passivation and buffer layer. The off-state three-terminal breakdown characteristics of AlGaN-sandwich-barrier/GaN/Al\(_{0.05}\)GaN HEMTs are shown in
The three-terminal $BV_{DS}$ of 260 V is achieved at a drain leakage current of 1 mA mm$^{-1}$ due to the strong electron confinement of Al$_{0.05}$GaN back barrier (inset of figure 3(b)).

The small-signal measurements were conducted using Keysight E8363 network analyzer. The system was calibrated using a short-open-load-through calibration standard. Figure 4(a) shows the gate voltage dependence values of $f_T$ and $f_{max}$ in AlGaN-sandwich-barrier/GaN/Al$_{0.05}$GaN HEMTs. It shows most $f_{max} > 30$ GHz and $f_T > 20$GHz for most of the gate bias region. And a peak $f_T$ and $f_{max}$ of 42 GHz and 65 GHz were obtained bias at $(V_{GS} = -3.8 \text{ V, } V_{DS} = 10 \text{ V})$. According to the above discussion results of figure 1, the wider E-field extension at the high drain bias will lead to flatter mobility and flatter Gm. The intrinsic cutoff frequency ($f_T$) can be calculated by the following equation [17]:

$$f_T = \frac{G_m}{2\pi (C_{gs} + C_{gd})}$$

(4)

where $C_{gs}$ and $C_{gd}$ are gate-source and gate-drain capacitance.

As can be seen from the above equation, the flatter $G_m$ leads to the flatter $f_T$ at the high E-field. Moreover, the maximum oscillation frequency ($f_{max}$) is proportional to $f_T$ and can be approximately equal to as follows:

$$f_{max} = \frac{f_T}{2\sqrt{R_s + R_g + R_d} + 2\pi f_T R_g C_{gd}}$$

(5)
where $R_s$, $R_t$, $R_{ds}$, and $R_i$ are the gate resistance, intrinsic resistance, source-drain resistance and source resistance, respectively. Then a flatter $f_t$ also leads to the flatter $f_{\text{max}}$. Figure 4(b) shows the drain voltage dependence values of $f_t$ and $f_{\text{max}}$ in AlGaN-sandwich-barrier/GaN/Al0.05GaN HEMTs. It shows almost constant $f_t$ (the same trend with $G_m$) and a significant increase $f_{\text{max}}$ with the increase of drain voltage. The peak $f_{\text{max}}$ of 130 GHz is achieved at $V_{DS} = 60$ V. From figure 4(c), the extension of drain potential significantly narrowed with the increase of drain voltage. The reduction of drain potential extension corresponds to an increase of depletion region width between drain and gate, resulting a reduction of $C_{gd}$. From equation (5) the decrease of $C_{gd}$ makes contribution to $f_{\text{max}}$ improvement. Therefore, the high performance of $f_t$ and $f_{\text{max}}$ corresponding a wider gate swing and a significant increase $f_{\text{max}}$ at $V_{DS} = 60$ V make our proposed device play an important role in high linearity and high power X-band RF application.

Continuous wave RF power measurement was performed at 10 GHz using a Maury load-pull system. The drain bias was 60 V. The gate was biased at pinch-off voltage for the deep Class-AB operation. Both input and output matching were tuned for optimum PAE. A saturated power density ($P_{\text{sat}}$) of 7.3 W mm$^{-1}$ was achieved with an associated PAE of 29.2% and Gain of 10.6 dB (figure 5(a)). Two-tone intermodulation distortion measurements were performed without using harmonic tuners at 60 V bias. The fundamental frequency was at 10 GHz and 2nd tone was at 10.01 GHz. Figure 5(b) shows the performances from the two-tone measurement, where $P_{\text{1,0}}$ is the power in one of the fundamental tones, IM3 is the level of one of the third order distortion products, and IMD3 is the ratio between them. The OIP3 was calculated to be 38 dBm, which corresponds to the LFOM OIP3/$P_{\text{DC}}$ of 4.5 dB. Normally, the high drain bias leads to the high DC power consumption ($P_{\text{DC}}$) and lower LFOM. However, the transconductance linearity contributes to better OIP3 and high quality AlGaN back barrier contributes to lower $P_{\text{DC}}$ at high drain bias. Therefore, both high power performance and excellent LFOM under high drain bias can be achieved in this work. To the best of our knowledge, this is the first reported OIP3/$P_{\text{DC}}$ of 4.5 dB@10 GHz at 60 V bias and 7.3 W mm$^{-1}$ power density. Figure 6 shows comparison of device level LFOM and maximum power density [13, 14, 18, 19]. Both the power density and LFOM performance are improved by AlGaN sandwich barrier and AlGaN buffer optimization.

In this work, high power and linearity of AlGaN-sandwich-barrier/GaN/Al0.05GaN HEMTs for X-band application is reported. A peak power of 7.3 W mm$^{-1}$ was achieved with an associated PAE of 29.2% and Gain of 10.6 dB at 10GHz. An excellent OIP3 of 38 dBm and OIP3/$P_{\text{DC}}$ of 4.5 dB are firstly achieved at 60 V drain bias. The excellent power and LFOM performance of AlGaN-sandwich-barrier/GaN/Al0.05GaN HEMTs made a solid foundation for development of high power and linearity device design.

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