Highly Linear Al$_{0.3}$Ga$_{0.7}$N–Al$_{0.05}$Ga$_{0.95}$N–GaN Composite-Channel HEMTs

Jie Liu, Yugang Zhou, Rongming Chu, Yong Cai, Kevin J. Chen, Member, IEEE, and Kei May Lau, Fellow, IEEE

Abstract—We report an Al$_{0.3}$Ga$_{0.7}$N–Al$_{0.05}$Ga$_{0.95}$N–GaN composite-channel HEMT with enhanced linearity. By engineering the channel region, i.e., inserting a 6-nm-thick AlGaN layer with 5% Al composition in the channel region, a composite-channel HEMT was demonstrated. Transconductance and cutoff frequencies of a 1 × 100 𝜇m HEMT are kept near their peak values throughout the low- and high-current operating levels, a desirable feature for linear power amplifiers. The composite-channel HEMT exhibits a peak transconductance of 150 mS/mm, a peak current gain cutoff frequency of 30 GHz, and a peak power gain cutoff frequency (f_{max}) of 12 GHz. For devices grown on sapphire substrate, maximum power density of 3.38 W/mm, power-added efficiency of 45% are obtained at 2 GHz. The output third-order intercept point (OIP3) is 33.2 dBm from two-tone measurement at 2 GHz.

Index Terms—AlGaN–GaN, channel engineering, composite channel, high-electron mobility transistors (HEMTs), linearity.

I. INTRODUCTION

WIDEd gap AlGaN–GaN high-electron mobility transistors (HEMTs), with their high-power handling capability at high frequencies, are emerging as the promising candidates for RF and microwave power amplifiers used in next generation wireless base stations [1]–[4]. The 3G wireless communication systems, such as W-CDMA/UMTS, impose stringent requirement for the linearity of the power amplifiers due to the large dynamic range in the variable envelop of the modulation signals. As a result, recently, there have been intensive activities in characterizing the linearity of conventional AlGaN–GaN HEMT [3], [5]–[7] and MOS heterojunction field-effect transistors [8]. It has been shown that conventional AlGaN–GaN HEMTs require advanced linearization techniques such as digital predistortion to satisfy the adjacent channel power ratio requirement for W-CDMA standard. To reduce the burden of the linearization techniques, it is necessary to optimize the HEMT epilayer structure for improved linearity. One desirable feature with regard to the linearity is the significant reduction of transconductance (G_m) and gain at high current levels [4]. Some groups are investigating ways of improving the linearity by using field-plate [9] and modifying the access resistance [10]. However, there have been limited activities in engineering the channel part of the III-nitride HEMTs for improved linearity.

In this letter, we propose and demonstrate a novel composite-channel HEMT (CC-HEMT) that offers enhanced linearity. The CC-HEMT features a thin layer (6 nm) of AlGaN layer with low-Al composition (5%) inserted in the channel region to form the major part of the active channel. A minor channel is formed in the GaN layer at the Al$_{0.05}$Ga$_{0.95}$N/GaN hetero-interface. The major channel is closely coupled to the minor channel to form a composite channel. Nearly flat transconductance and cutoff frequencies are achieved at both low and high current operation levels—the desirable feature for achieving high linearity.

II. DEVICE STRUCTURE AND FABRICATION

The composite channel HEMT structure, with the schematic cross section and conduction band diagram shown in Fig. 1(a) and (b), was grown on (0001) sapphire substrates in an Aixtron AIX 2000 HT system. After initial desorption at 1200 °C, a GaN nucleation layer was grown at 550 °C, followed by a 2.5-μm-thick unintentionally doped GaN buffer layer. Then the major channel layer, a 6-nm-thick AlGaN layer with 5% Al composition, was grown followed by the AlGaN barrier layer...
with 30% Al composition. The barrier layer consists of a 3-nm undoped spacer, a 21-nm carrier supplier layer doped at $2 \times 10^{18}$ cm$^{-3}$, and a 2-nm undoped cap layer. Room-temperature Hall measurements of the structure yield an electron sheet density of $1.3 \times 10^{13}$ cm$^{-2}$ and an electron mobility of 950 cm$^2$/Vs. Device active regions were defined using mesa etching by ICP-RIE (inductively coupled plasma reactive ion etching). It is followed by the source/drain ohmic contacts formation by a rapid thermal annealing of e-beam evaporated Ti–Al–Ni–Au at 850 °C for 30 s. Using on-wafer transfer length method patterns, the ohmic contact resistance was typically measured to be $1.0 \Omega \cdot$mm. Gate electrodes with 1-μm length were then defined by contact photolithography, Ni–Au e-beam evaporation and liftoff, subsequently. The devices have a source/gate spacing of $L_{sg} = 1$ μm and a gate/drain spacing of $L_{gd} = 1$ μm. Finally, PECVD was used to deposit SiN for device passivation.

III. DEVICE CHARACTERISTICS AND DISCUSSION

To profile the carrier distribution in the composite-channel HEMT, capacitance–voltage (C–V) measurement was carried out on a Schottky diode with Schottky contact formed on top of AlGaN barrier and the ohmic contact to the channel serving as the other electrode. The carrier distribution profile along with the C–V characteristics are plotted in Fig. 1(c). It is observed that the main channel is located at the Al$_{0.3}$Ga$_{0.7}$N–Al$_{0.65}$Ga$_{0.35}$N interface, but with more carriers spreading away from this interface indicating the strong coupling between the two channels at the two hetero-interfaces.

The dc $I_{DS} - V_{GS}$, $I_{DS} - V_{DS}$ and $G_m - V_{GS}$ characteristics of CC-HEMT and conventional HEMT are plotted in Fig. 2. For the CC-HEMT, the pinch-off voltage is $-6$ V. The off-state drain breakdown voltage is larger than 60 V. The maximum drain current is about 900 mA/mm and the maximum $G_m$ is about 150 mS/mm, slightly lower than 175 mS/mm, which was normally achieved in our conventional baseline AlGaN–GaN HEMTs. This indicates that the inserted low Al composition AlGaN layer only results in small degree of mobility degradation. The most important feature for CC-HEMT is that the $G_m$ is quite flat after the onset and remains close to its peak value at high current levels, a desirable feature for linear operation of the large-signal power amplifiers. At the maximum drain current ($V_{GS} = 1$ V), $G_m$ of 120 mS/mm was obtained on CC-HEMT, a 20% drop from its peak value, which is much lower than that of conventional HEMT, which is about 40%. On-wafer S-parameters measurements were conducted on 1 × 100 μm composite-channel HEMT and conventional HEMT. Current gain and power gain cutoff frequencies, $f_T$ and $f_{max}$, are extracted from the measured S-parameters and plotted in Fig. 3. Relatively flat $f_T$ and $f_{max}$ were obtained for CC-HEMT from low to high current levels, while the conventional HEMT shows significant drop at high current levels. Large-signal load-pull measurement was carried out using Maury’s MT982B01 tuners. Tuning for maximum output power ($P_{out}$) at 2 GHz, a $P_{out}$ of 3.38 W/mm and a peak power-added efficiency (PAE) of 45% was obtained, as shown in Fig. 4(a). Using two-tone signals at 2 GHz with a 1-MHz separation, third-order intermodulation (IM3) was measured and plotted in Fig. 4(b). An output third-order intercept point (OIP3) of 33.2 dBm was obtained.

Without a widely-accepted model, one possible dominant factor for the $G_m$ and gain reduction at high current levels in conventional AlGaN–GaN HEMT is the large transverse electric-field (E-field) **perpendicular** to the channel and the barrier/channel interface at the high current levels. Strong piezoelectric and spontaneous polarization, together with the modulation doping in the barrier layer, create sharp band bending at the heterojunction interface, resulting in the large transverse E-field. This strong field will push the two-dimensional electron gas closer to the interface when the electrons are traveling laterally from the source to drain, and enhances the scattering of the electrons at the hetero-interface. The stronger scattering degrades the electron mobility [11]. In a composite-channel HEMT structure, the inserted low Al composition AlGaN layer in the channel can effectively reduce the

---

**Fig. 2.** DC characteristics of CC-HEMT and conventional HEMT. (a) $I_{DS} - V_{GS}$ characteristics. (b) $I_{DS} - V_{GS}$ and $G_m - V_{GS}$ characteristics.

**Fig. 3.** Cutoff frequencies ($f_T$ and $f_{max}$) for 1 μm × 100 μm CC-HEMT and conventional HEMT with $V_{GS}$ varying from pinch-off to 1 V. Source-to-drain voltage $V_{DS}$ is fixed at 10 V.
transverse E-field. Fig. 5 plots the simulated transverse E-field distribution in a composite-channel HEMT and a baseline conventional HEMT at zero gate bias, which corresponds to high current level operation. A 20% reduction in the peak vertical E-field can be obtained by inserting a 6-nm-thick Al$_{0.05}$Ga$_{0.95}$N layer in the channel, indicating a less sharp band bending in the CC-HEMT. Compared to merely reducing the E-field by implementing an AlGaN barrier with lower Al composition, the CC-HEMT incorporates the minor channel at the Al$_{0.05}$Ga$_{0.95}$N–GaN interface to compensate the reduced carrier density in the main channel. Furthermore, the coupling between the major and minor channel also pulls the carrier distribution away from the barrier/channel interface, which leads to reduced scattering.

IV. CONCLUSION

A novel composite-channel Al$_{0.2}$Ga$_{0.8}$N–Al$_{0.05}$Ga$_{0.95}$ N–GaN HEMT with excellent linearity has been demonstrated on sapphire substrate. DC and RF measurements show that transconductance and cutoff frequencies can be maintained near their peak values from low to high current levels. These features favor the linear large-signal operation and are suitable for advanced 3G wireless systems such as W-CDMA/UMTS.

REFERENCES


