Al$_{0.3}$Ga$_{0.7}$N/Al$_{0.05}$Ga$_{0.95}$N/GaN Composite-Channel HEMTs with Enhanced Linearity

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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. Through channel engineering, 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 $\mu$m x 100 $\mu$m HEMT are kept near their peak values throughout the low- and high-current operating levels, a desirable feature for linear power amplifiers. Driven by W-CDMA signals with a center frequency of 2 GHz, an adjacent channel leakage ratio (ACLR) of less than –45 dBC was achieved with a power added efficiency (PAE) of 45% and a power density of 3.4 W/mm for composite-channel HEMTs (CC-HEMTs) grown on sapphire substrates, without using any linearization techniques.

Introduction

Wide bandgap AlGaN/GaN 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 metal-oxide-semiconductor (MOS) heterojunction field-effect transistors (8). It has been shown (3) that conventional AlGaN/GaN HEMTs require advanced linearization techniques such as digital predistortion to satisfy the adjacent channel leakage power ratio (ACLR) 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 undesirable 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 region of the III-nitride HEMTs for improved linearity.

In this paper, we propose and demonstrate a novel composite-channel HEMT (CC-HEMT) through channel engineering.

The CC-HEMT exhibits nearly-flat transconductance and cutoff frequencies at both low and high current operation levels --- the desirable feature for achieving high linearity. The CC-HEMTs also exhibit superior RF linearity, which is characterized through intermodulation measurement and ACLR measurement.

Device Structure and Fabrication

The composite channel HEMT structure, with the schematic cross section shown in Fig. 1, 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 10-nm carrier supplier layer doped at 3.5x10 $^{18}$ cm$^{-3}$, and a 2-nm undoped cap layer.

![Fig. 1. Cross-section of the CC-HEMT. Between the Al$_{0.3}$Ga$_{0.7}$N barrier and the GaN is a 6-nm-thick undoped Al$_{0.05}$Ga$_{0.95}$N layer with low Al composition (x=0.05).](image-url)

For the device fabrication, device mesa was formed using Cl$_2$/He plasma dry etching in an STS inductively coupled-plasma reactive ion etching (ICP-RIE) system. 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 seconds. Using on-wafer transfer length method (TLM) patterns, the ohmic contact resistance was typically measured to be 1.0 ohm-mm. Gate electrodes with 1 μm...
length were then defined by contact photolithography, Ni/Au e-beam evaporation and lift-off, subsequently. The devices have a source-gate spacing of $L_{sg} = 1 \mu m$ and a gate-drain spacing of $L_{gd} = 1 \mu m$. Finally, PECVD was used to deposit SiN for device passivation.

**Device Characterization and Discussion**

Although a widely accepted physical picture is lacking, 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 2DEG 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), resulting in the reductions in $G_m$ and gain. The conduction band profiles for a conventional and a composite-channel HEMT are plotted in Fig. 2. In a composite-channel HEMT structure, the inserted low Al composition AlGaN layer in the channel can effectively reduce the transverse E-field. Fig. 3 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. As a result, it is expected that the 2DEG is less affected by the interface, yielding higher mobility and transconductance at high current levels.

**Fig. 2.** Conduction band diagrams for conventional HEMT and CC-HEMT.

**Fig. 3.** The simulated vertical electrical field distribution in (a) conventional HEMT and (b) CC-HEMT. The peak value is reduced by 20% in CC-HEMT.
Fig. 6 and Fig. 7. All these parameters show much reduced bias dependence compared to their conventional counterparts.

Fig. 5. DC characteristics of CC-HEMT: (a) $I_{DS}$-$V_{DS}$ curve, the maximum current is about 900 mA/mm; (b) $I_{DS}$-$V_{GS}$ and $G_m$-$V_{GS}$ curve, the peak transconductance is about 150 mS/mm.

Large-signal load pull measurement was conducted on 100 µm-wide devices at 2GHz. A linear gain of 22 dB together with a power density of 3.4 W/mm and a PAE of 45% were obtained with a 25 V drain supply voltage, as shown in Fig. 8.

To characterize the linearity of the CC-HEMT, two-tone third order intermodulation (IM3) was measured and plotted in Fig. 9. An OIP3 of 33.2 dBm was obtained.
Driven by a W-CDMA signal centered at 2 GHz with a 4 MHz bandwidth and a 5 MHz channel spacing, the ACLR was measured and plotted in Fig. 10(a) along with the PAE. The CC-HEMT demonstrates state-of-the-art PAE of 45% with an ACLR of less than –45 dBc without the use of any linearization techniques. Compared with the baseline conventional HEMT, as shown in Fig. 10(b), the ACLR shows at least 7 dBc improvement in CC-HEMT.

Conclusions

A novel composite-channel HEMT with excellent linearity has been demonstrated on sapphire substrate. DC and RF measurements show flat transconductance and cutoff frequency within a wide bias range. These features favor the linear large-signal operation and are suitable for certain advanced wireless communication standards, such as W-CDMA.

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References