Improvement of power performance of GaN HEMT by using quaternary InAlGaN barrier

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Abstract—High power performance InAlGaN/GaN HEMT as a candidate for high power and high frequency amplifiers has been demonstrated versus the conventional AlGaN/GaN HEMT by using the same device processes. Comparing with its conventional AlGaN/GaN counterpart, the InAlGaN/GaN device exhibits a much larger output current density of 1.94 A/mm due to its higher 2DEG density of 2.0×10¹³ cm⁻² by using a thin quaternary InAlGaN barrier layer, and almost twice as large as f₁ of 142 GHz and fₘₐₓ of 203 GHz. Through measurements of large-signal characteristics at frequency of 34 GHz and biased at 10 V, the InAlGaN/GaN device shows a high output power density of 2.75 W/mm, which is about 87% increase in comparison with that of its AlGaN/GaN counterpart with an output power density of 1.47 W/mm.

Index Terms—InAlGaN/GaN, HEMT, output power, T-shaped gate.

I. INTRODUCTION

GaN-based high electron mobility transistors (HEMTs) are widely used for high power and high frequency amplifiers due to its excellent material characteristics, such as high breakdown electric field, high electron saturation velocity, etc. [1,2]. Benefiting from these properties, GaN HEMTs can provide a larger output power density at high operating frequency than other semiconductor devices such as silicon MOSFETs and GaAs-based heterostructure devices [1]. With development in GaN HEMT technology, RF power performance of conventional AlGaN/GaN HEMTs has been fully excavated and is approaching the limit of their material structures. On the one hand, the maximum output power of the device is limited by its maximum drain current and breakdown voltage. In order to further improve the output power density at the same working voltage, the drain current density must be increased. The maximum drain current density is dependent on the sheet concentration of two dimensional electron gas (2DEG) generated at the interface of AlGaN barrier and GaN channel layers by spontaneous and piezoelectric polarizations. However, for a conventional AlGaN/GaN HEMT, the sheet density of 2DEG is usually below 1.3×10¹³ cm⁻², which hinders the improvement of its output power. On the other hand, increasing the concentration of 2DEG can improve the device’s drain current density, so as to increase its transconductance. A thinner barrier layer can improve the capability of gate modulation, so as to increase its transconductance and suppress the short channel effects. The improvement of transconductance and the suppressing of the short channel effects contribute to the improvement of the frequency performance. Hence, in order to increase the device’s frequency performance, a thinner barrier layer that can produce a high concentration of 2DEG is needed [3,4]. However, the conventional AlGaN barrier layer has a critical thickness of at least 10 nm to provide a sufficient concentration of 2DEG, which hinders the improvement its frequency performance [5,6].

Increasing Al composition in AlGaN barrier can not only improve the concentration of 2DEG, but also reduce the critical thickness of barrier layer. In this case, the AlGaN/GaN HEMT can obtain a higher output current density by using a thinner barrier layer, which can further improve its output power density and operating frequency. However, when Al composition in AlGaN barrier is too large or directly using AlN as barrier, the crystal lattice mismatch between Al(Ga)N barrier and GaN becomes critical, which severely deteriorates the crystal quality of heterostructures and even makes the epitaxial films suffer from cracks after growth [7,8]. The InAlN barrier has been proposed to solve these problems [9,10]. InAlN with In composition of 18% is lattice-matched to GaN and it can provide an almost double concentration of 2DEG comparing with the conventional AlGaN/GaN heterostructures [11-13]. However, alloy immiscibility in InAlN growth has been found and indium pits on the surface are hard to be eliminated [14,15]. These severe problems have impeded the acquisition of high quality InAlN materials.

Fortunately, it has been found that InAlGaN quaternary alloy is much more miscible than InAlN and hence high quality InAlGaN materials can be acquired. The concentration of 2DEG and the strain between InAlGaN and GaN can be controlled by modulating the In and Al compositions [8,16]. By using proper In and Al compositions, 2DEG with high concentration in InAlGaIn heterostructures can be obtained even using a thin barrier layer [8,17].
In this work, high power InAlGaN/GaN HEMT with In and Al compositions of 0.05 and 0.75 has been demonstrated versus the conventional AlGaN/GaN HEMT and the advantages of InAlGaN/GaN heterostructure have been investigated. The InAlGaN/GaN heterostructure shows a much higher concentration of 2DEG by using a thin InAlGaN barrier layer. The two type HEMT devices were fabricated by using the same device processes, including a technique of 0.1 μm T-shaped gate encapsulated with low-κ BCB. Direct current (DC), small-signal and large-signal characteristics of the two type devices have been specifically analyzed. We find that the InAlGaN/GaN device achieves a substantially improvement in frequency and output power thanks to its much higher concentration of 2DEG and thinner barrier. It indicates that InAlGaN/GaN HEMTs are of great promising for high power and high frequency applications.

II. DEVICE FABRICATION

The InAlGaN/GaN and AlGaN/GaN HEMT structures were grown on 3 inch semi-insulator SiC substrates by metal organic chemical vapor deposition. The material structures from bottom to top, include a GaN buffer layer, a 1 nm AlN interlayer and a barrier layer, as shown in Fig. 1. For the InAlGaN/GaN HEMT, a 7 nm InAlGaN layer with In and Al compositions of 0.05 and 0.75, respectively, is used as the barrier layer. The conventional AlGaN/GaN HEMT employs a 12 nm AlGaN barrier layer with Al composition of 0.3. Room temperature Hall measurements indicate the sheet concentration and mobility of 2DEG are $2.0 \times 10^{13} \text{ cm}^{-2}$ and 1500 $\text{cm}^2 \text{V}^{-1} \text{s}^{-1}$ for the InAlGaN/GaN structure with a sheet resistance of 208 $\Omega/\square$. For the conventional AlGaN/GaN structure, the density of 2DEG is $1.0 \times 10^{13} \text{ cm}^{-2}$ with mobility of 2000 $\text{cm}^2 \text{V}^{-1} \text{s}^{-1}$, resulting in a sheet resistance of 312 $\Omega/\square$.

HEMT devices were fabricated on the two type material structures simultaneously. Ohmic contact patterns were defined by photolithography with drain-to-source distance of 2 μm. Ti/Al/Ni/Au metal stack was deposited by electron-beam evaporation. After lift-off, Ohmic contacts were achieved by rapid annealing at 840 °C under nitrogen atmosphere. Subsequently, device isolation was realized by using B⁺ ion implanting. T-shaped gates with gate-length of 0.1 μm were defined by using a method of bi-layer electron-beam resist lithography. Ni/Au metal stack was deposited as gate metals. After the gates were fabricated, the devices were passivated with a thin Si₃N₄ layer deposited by plasma-enhanced chemical vapor deposition to reduce current collapse. Finally, low-κ BCB was used to encapsulate the T-shaped gates, which can protect the gates and make the devices compatible with the processes of MMIC fabrication without significant increase in parasitic gate capacitance.

III. RESULTS AND DISCUSSION

On-wafer measurements of DC and S-parameters of the two type devices with gate width of 2 × 100 μm were carried out by using an Agilent 8510B network analyzer at room temperature. Fig. 2 gives their DC output characteristics. The gate voltage is applied from -7 V to 2 V with a step of 0.5 V. The maximum drain current is 1.94 A/mm for the InAlGaN/GaN device at gate bias of 2 V, which is much larger than 1.12 A/mm from the conventional AlGaN/GaN device owing to its higher sheet concentration of 2DEG.

![Fig. 2. I_D-V_D output characteristics of the InAlGaN/GaN (a) and AlGaN/GaN (b) devices. The gate bias for the top curve is 2 V and the step of gate bias from bottom to top is 0.5 V.](image)

Fig. 3 shows transfer characteristics of the two type devices at drain bias of 10 V. The InAlGaN/GaN device has a slightly larger negative threshold voltage of -4.5 V than the conventional AlGaN/GaN device due to its high concentration of 2DEG. The peak transconductance of the conventional AlGaN/GaN device is 347 mS/mm, whereas the InAlGaN/GaN device exhibits a significantly increased transconductance of 506 mS/mm owing to its thinner barrier layer and much higher concentration of 2DEG.
S-parameters of the devices have been measured from 100 MHz to 40 GHz. On-wafer open and short patterns are used to de-embed pad parasitic capacitances and inductances. Small signal characteristics are converted from the measured S-parameters, as the results shown in Fig. 4. Current gain cut-off frequency $f_T$ and maximum frequency of oscillation $f_{\text{max}}$ are respectively obtained by extrapolating the measured data of $|h_{21}|^2$ and MAG with a slope of -20 dB per decade. The $f_T$ and $f_{\text{max}}$ of the conventional AlGaN/GaN device are 75 GHz and 126 GHz, whereas the InAlGaN/GaN device demonstrates a much larger $f_T$ of 142 GHz and $f_{\text{max}}$ of 203 GHz. On the one hand, the sheet resistance of InAlGaN/GaN structure is only 208 $\Omega/\square$, which is 33.3% lower than that of the AlGaN/GaN structure. The significantly reduced sheet resistance brings in low access resistances, i.e., low parasitic source and drain series resistances, which contributes to the improvement in frequency performance of the InAlGaN/GaN device. On the other hand, using thinner InAlGaN barrier layer can effectively improve the gate control capability and transconductance, so as to improve the device’s $f_T$ and $f_{\text{max}}$ by increasing its small signal gains.

On-wafer large-signal characteristics have been measured at drain bias of 10 V and frequency of 34 GHz in continuous wave mode by load-pull setup. The measured results of the two type devices are shown in Fig. 5. A maximum output power of 27.41 dBm (550 mW) has been obtained for the InAlGaN/GaN device with associated PAE of 33.6% and gain of 7.88 dB. The output power density is calculated as 2.75 W/mm. For the conventional AlGaN/GaN device, the output power is 24.7 dBm (295 mW) with associated PAE of 36.81% and gain of 7 dB, showing an output power density of 1.47 W/mm. Owing to its large dynamic range of operating current, the InAlGaN/GaN device demonstrates a quite high output power density, which is about 87% increase in comparison with that of the AlGaN/GaN device at the same working voltage.

IV. CONCLUSION

High power performance InAlGaN/GaN HEMT has been demonstrated versus the conventional AlGaN/GaN HEMT by using the same 0.1 $\mu$m T-shaped gate technique. Owing to its high sheet concentration of 2DEG, the maximum drain current of the InAlGaN/GaN device has been improved significantly from 1.12 A/mm to 1.94 A/mm in comparison with its AlGaN/GaN counterpart. Further, the InAlGaN/GaN shows a much higher $f_T$ of 142 GHz and $f_{\text{max}}$ of 203 GHz than the AlGaN/GaN device with $f_T$ of 75 GHz and $f_{\text{max}}$ of 126 GHz due to its substantially increased transconductance and reduced
parasitic resistances. Using load-pull measurements, the InAlGaN/GaN device also achieves a high output power density of 2.75 W/mm, which is about 87% increase in comparison with that of the AlGaN/GaN device at the same working voltage. These outstanding characteristics of the InAlGaN/GaN device indicate that using quaternary InAlGaN barrier is a promising approach to fabricate GaN-based HEMTs for high power and high frequency applications.

REFERENCES


