A 4.69-W/mm output power density InAlN/GaN HEMT grown on sapphire substrate*

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Abstract: We report high performance InAlN/GaN HEMTs grown on sapphire substrates. The lattice-matched InAlN/GaN HEMT sample showed a high 2DEG mobility of 1210 $cm^2/(V{\cdot}s)$ under a sheet density of 2.6×10^{13} cm^{-2}. Large signal load-pull measurements for a (2 × 100 μm) × 0.25 μm device have been conducted with a drain voltage of 24 V at 10 GHz. The presented results confirm the high performances reachable by InAlN-based technology with an output power density of 4.69 W/mm, a linear gain of 11.8 dB and a peak power-added efficiency of 48%. This is the first report of high performance InAlN/GaN HEMTs in mainland China.

Key words: InAlN/GaN; HEMT; output power density; metal-organic chemical vapor deposition
DOI: 10.1088/1674-4926/32/12/124003 **PACC:** 7280E

1. Introduction

The academic and industrial progress of AlGaN/GaN high-electron-mobility transistors (HEMTs) for high-frequency and high-power application have been reported[1, 2] recently, which have been already successfully demonstrated in AlGaN/GaN HEMTs with power densities up to 41.4 W/mm at 4 GHz of depletion-mode and 3.65 W/mm at 18 GHz of enhancement-mode[3, 4]. With many important characteristics for high power application, such as a high breakdown field, high sheet charge density and the excellent chemical and thermal stability, AlGaN/GaN heterostructures have shown a promising potential as a power device. However, problems remain for millimeter-wave applications，such as high access resistances, unreliable passivation and short channel challenges associated with the fabrication of deep sub-micrometry gate length devices. In the following it will be shown that the electrical performance can still be improved further by substituting the AlGaN barrier by InAlN.

The performance of a GaN-based HEMT would be improved by use of InAlN/GaN material system, as InAlN with an In composition of about 17% is lattice-matched to GaN[5]. The high Al-content places the InAlN alloy closer to AlN than the AlGaN alloy used in AlGaN/GaN HEMTs. AlN has a Curie temperature, well above 1000 ℃, indicating higher chemical/thermal stability than an AlGaN/GaN heterostructure.

Another important feature is InAlN-alloys' spontaneous polarization, InAlN/GaN heterostructures have lower strain and can give rise to a 2-D electron gas with up to 4×10^{13} cm^{-2} carrier density compared to 2.5×10^{13} cm^{-2} for AlGaN/GaN heterostructures[6]. Thus, a thinner InAlN barrier layer should allow the achievement of millimeter-wave devices with lower access resistances, higher current densities and thus better power performance than AlGaN/GaN HEMTs.

This paper presents our results obtained from a study of InAlN/GaN heterostructures grown on sapphire substrates and the optimization of the technological process. Epitaxial growth and device processing are first described. The crystal quality of InAlN/GaN heterostructures was analyzed by high resolution X-ray diffractometry (HR-XRD), atomic force microscopy (AFM) and transmission electron microscopy (TEM). Finally, pulsed DC and load-pull measurements were conducted.

2. Epitaxial growth and device processing

Epilayers were deposited on 2 inch c-plane sapphire substrates in a low-pressure metal-organic chemical vapor deposition (LP-MOCVD) system. The growth was initiated by a low temperature GaN nucleation layer, followed by a 2-μm-thick undoped GaN buffer layer, using TMG and NH_3 as Ga and N precursors, H_2 as carrier gas. A 100-nm-thick InAlN barrier layer was grown for the In content measurement. The studied heterostructures consist of the GaN layer followed by a 1-nm-thick AlN spacer layer and a 13-nm undoped InAlN layer with an In content of about 17%. Figure 1 shows the structure and energy band diagram of the InAlN/GaN HEMT.

The HEMT device fabrication first consisted of ohmic contacts obtained by rapid thermal annealing of a Ti/Al/Ni/Au multilayer at 850 ℃ for 30 s under nitrogen ambient. We obtained a contact resistance of 0.6 Ω·mm by TLM measurements. Ni/Au Schottky contacts with a T gate technology were achieved by e-beam lithography with a length of 0.25 μm.

3. Results and discussion

The In content of InAlN was measured by HR-XRD. Figure 2 shows the symmetric (002) ω–2θ and the asymmetric

* Project supported by the National Natural Science Foundation of China (Nos. 60890192, 60876009).
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Received 23 May 2011, revised manuscript received 21 June 2011

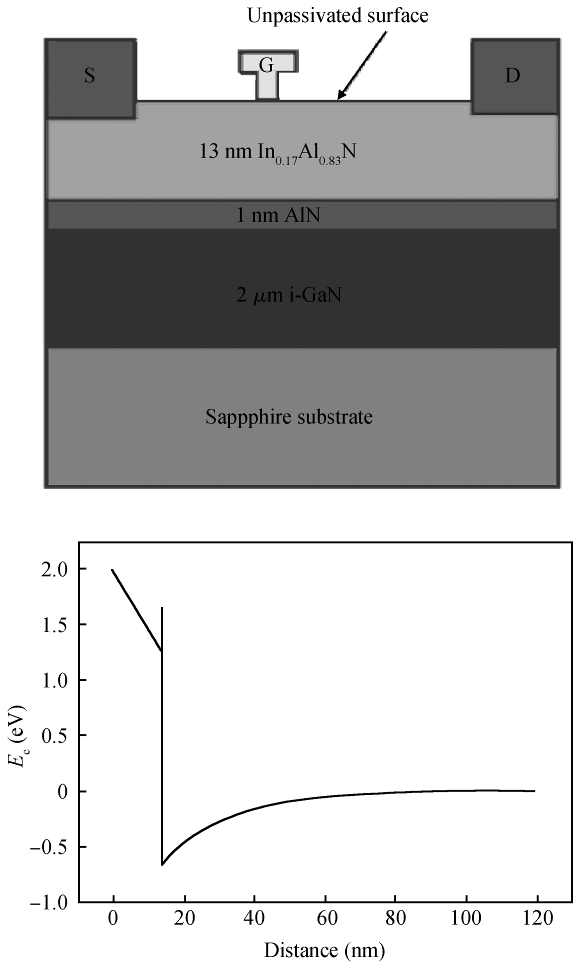

Fig. 1. Structure and energy band diagram of a schematic InAlN/GaN HEMT.

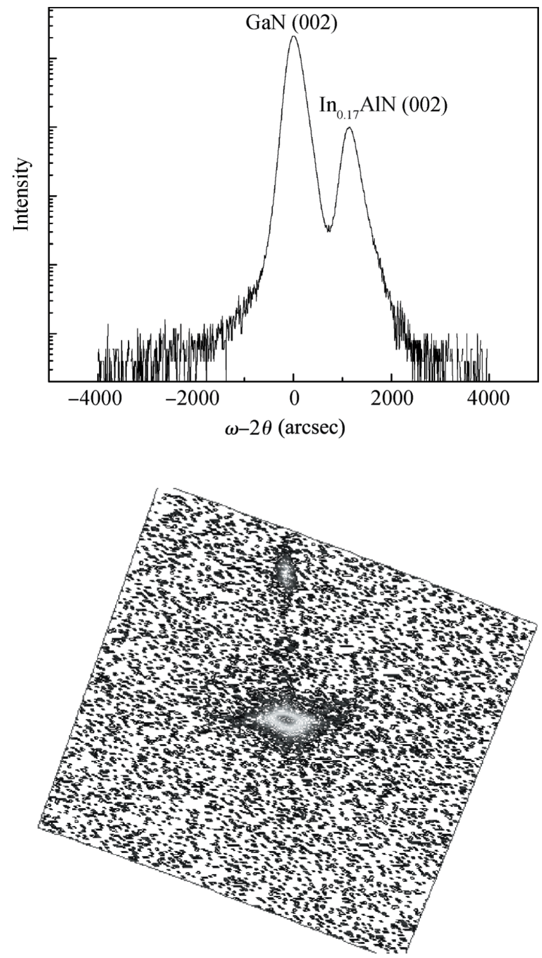

Fig. 2. HR-XRD ω–2θ (002) curve and RSM (105) mappings of $In_{0.17}AlN$/GaN.

(105) RSM measurements for a sample grown under optimized conditions. HR-XRD measurements reveal the indium content and structural quality of the InAlN barrier layer with respect to the GaN buffer. A high structural quality of the layer and interface is reflected in this measurement. The results indicate an In content of 17%, a homogeneous indium distribution, a sharp interface and pseudomorphic growth. This is also confirmed by AFM and TEM measurements: smooth surfaces and a sharp interface are shown in Figs. 3 and 4. Clear atomic steps with a RMS (5 $\times$ 5 μm^2) of 0.426 nm can be observed. Figure 4 illustrates a cross-sectional micrograph measured by TEM, suggesting the coherent and abrupt InAlN/GaN interface.

Hall measurements at room temperature reveal a sheet carrier density of 2.6 $\times$ 10^{13} cm^{-2}, a sheet resistance of 210 $\Omega/\Box$ and a mobility of 1210 $cm^2/(V\cdot s)$. Such high electron mobility is obtained by using an optimal quality of AlN spacer and InAlN barrier. The sheet carrier density is about twice as high as the typical AlGaN/GaN epitaxy layers.

DC measurements were performed on 2 $\times$ 100 μm transistors with 0.25 μm length gate. The unpassivated device shows almost current-collapse free at a positive gate bias, as shown in Fig. 5. The maximum drain current density at $V_{GS} = +2$ V is close to 1.6 A/mm in a reproducible way (1.56 A/mm for the presented device), which is to our knowledge beyond the highest drain current density of any AlGaN/GaN HEMT structure, especially for samples fabricated on sapphire substrates. We can expect even higher current densities by improving the thermal management and reducing trap effects. Pulsed experi-

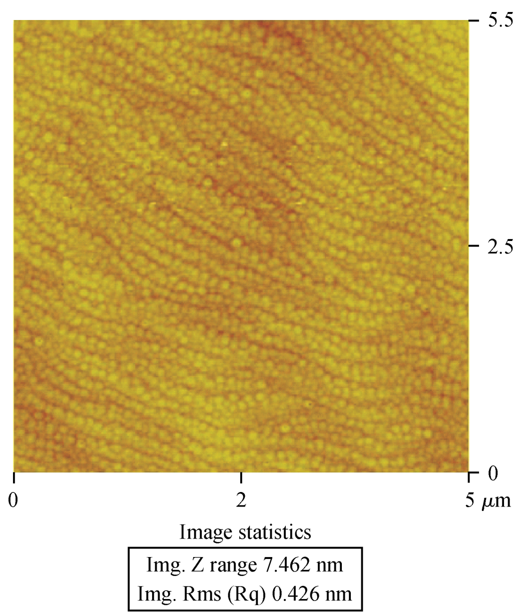

Fig. 3. Image of InAlN/GaN heterostructure surface by AFM.

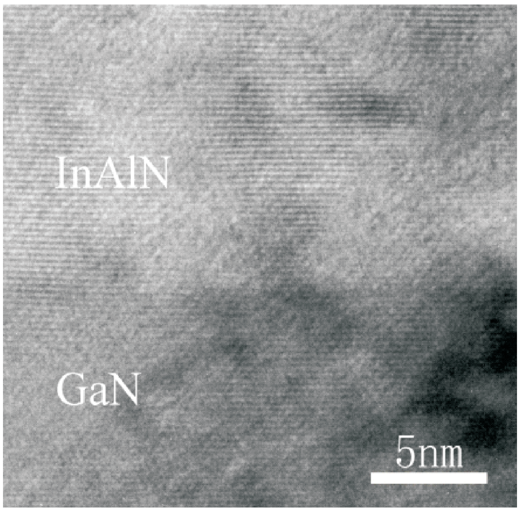

Fig. 4. Images of InAlN/AlN/GaN heterostructures by TEM.

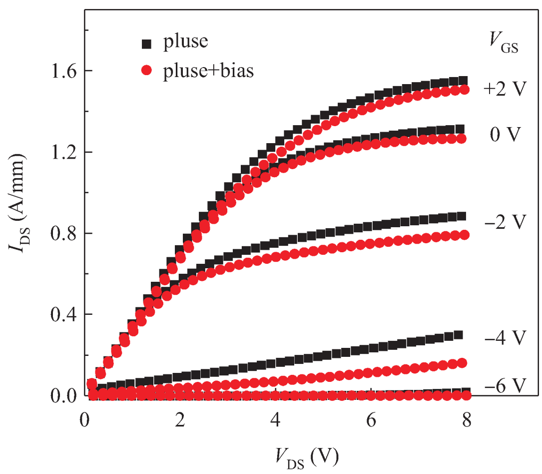

Fig. 5. Pulse DC characteristics of unpassivated InAlN/ GaN HEMT.

ments were performed in a routine 16 μs pulse and 500 μs duty cycle. All quiescent bias points (V_{DS0}, V_{GS0}) are chosen in order to simultaneously eliminate the thermal and trap effects and to reveal the gate and drain lag effects: ($V_{DS0} = 0$ V, $V_{GS0} = 0$ V) and ($V_{DS0} = 12$ V, $V_{GS0} = -6$ V). The peak transconductance is 286 mS/mm at $V_{GS} = -3$ V. In the case of unpassivated AlGaN/GaN HEMTs, a significant current collapse is observed under pulsed gate and drain conditions due to AlGaN surface charging effects. A much lower current dispersion was observed in our case, although these devices were still unpassivated, indicating a relatively stable surface in the case of the AlInN barrier material.

The small signal S-parameter of 2 × 100 μm gate width and 0.25 μm gate length HEMT was measured between 0.5 to 50 GHz in the probe tips. Extrinsic cut-off frequencies have been extracted $f_T = 34$ GHz and a maximum oscillation frequency $f_{max} = 40$ GHz (Fig. 6) extrapolated from the current gain H_{21}, where the condition is $V_{GS} = -4$ V and $V_{DS} = 8$ V.

Unlike the commonly used AlGaN/GaN structures, we did not note any limitation due to the aspect ratio. Indeed, in our case a gate-to-channel distance of only 13 nm is used while typical AlGaN-barrier thicknesses are about 25 nm. This will

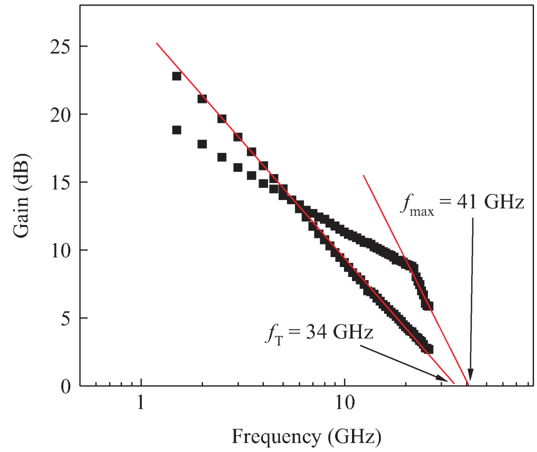

Fig. 6. Extrinsic current gain cut-off frequency of InAlN/GaN HEMT.

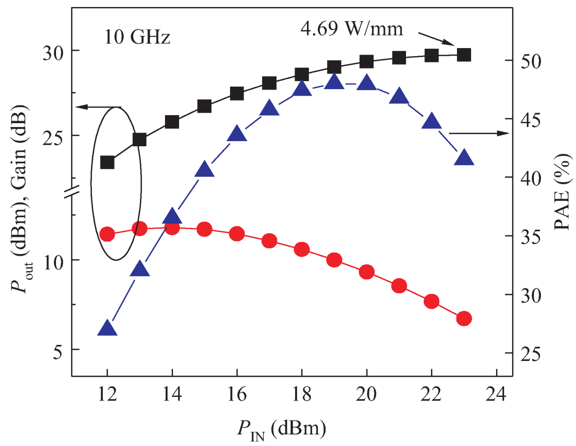

Fig. 7. Large-signal characteristics of InAlN/GaN HEMT measured at 10 GHz.

allow for obtaining high transconductances (> 400 mS/mm), low output conductances and high gain at mm-wave frequencies for sub-100 nm gate lengths. Recently, the state of the art cut-off frequency (205 GHz) of a GaN-based structure was reached using a 3 nm $In_{0.15}AlN$ barrier thickness and a 55 nm gate length[7].

Large signal measurements realized on 2 × 100 μm transistors confirmed the high potentiality of the devices, as shown in Fig. 7. Devices were characterized at 10 GHz in CW using a load-pull system with passive tuners. DC bias conditions were $V_{DS} = 24$ V and $V_{GS} = -3.7$ V, then the quiescent current was $I_q = 11$ mA. Measurements performed show an output power density of 4.69 W/mm, a linear gain of 11.8 dB, and a peak power-added efficiency of 48%. The presented results confirm the high performances reachable by InAlN based technology.

4. Conclusion

In conclusion, we report the high performance obtained from InAlN/GaN HEMT materials and devices grown and fabricated on sapphire substrates. We achieved a high quality material with the mobility is 1210 cm^2/(V·s). A power density of 4.69 W/mm with 48% PAE at 10 GHz in CW was obtained with 2 × 100 μm transistors. The cutoff frequency f_T

$= 34$ GHz at 0.25 μm gate length. This result strengthens the performance projections for InAlN-based technology as a potential successor of AlGaN/GaN HEMTs for microwave and millimeter-wave power applications.

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