

# A Ku band internally matched high power GaN HEMT amplifier with over 30% of PAE\*

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**Abstract:** We report a high power Ku band internally matched power amplifier (IMPA) with high power added efficiency (PAE) using  $0.3\ \mu\text{m}$  AlGaIn/GaN high electron mobility transistors (HEMTs) on 6H-SiC substrate. The internal matching circuit is designed to achieve high power output for the developed devices with a gate width of 4 mm. To improve the bandwidth of the amplifier, a T type pre-matching network is used at the input and output circuits, respectively. After optimization by a three-dimensional electromagnetic (3D-EM) simulator, the amplifier demonstrates a maximum output power of 42.5 dBm (17.8 W), PAE of 30% to 36.4% and linear gain of 7 to 9.3 dB over 13.8–14.3 GHz under a 10% duty cycle pulse condition when operated at  $V_{\text{ds}} = 30\ \text{V}$  and  $V_{\text{gs}} = -4\ \text{V}$ . At such a power level and PAE, the amplifier exhibits a power density of 4.45 W/mm.

**Key words:** Ku-band; AlGaIn/GaN HEMTs; IMPA; output power; PAE

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**PACC:** 7280; 7280E

**EEACC:** 1350F; 2560P; 1350H

## 1. Introduction

The use of solid state power amplifiers (SSPAs) in many radio communication systems, such as Ku band satellite communication systems, mobile cellular phone systems, etc, has increased significantly in recently years. The SSPA's higher reliability, smaller size, and enhanced performance have resulted in an increased popularity over its traveling wave tube amplifier (TWTA) counterparts. As a promising candidate for the next generation of microwave power devices, AlGaIn/GaN HEMTs have attracted much research interest due to the inherent advantages of their high voltage and high power density. Up to 11.2 W/mm pulsed power has been demonstrated from a  $150\ \mu\text{m}$  periphery device at 10 GHz<sup>[1]</sup>. 3.65 W/mm has also been demonstrated at 18 GHz from a  $0.35 \times 200\ \mu\text{m}$  E-mode AlGaIn/GaN HEMT<sup>[2]</sup>. At Ka band, a CW output power density of 5 W/mm has been obtained at 26 GHz<sup>[3]</sup>. Grown on a free-standing GaN substrate, instead of the SiC substrate used in previously reported devices, a  $150\ \mu\text{m}$  gate periphery AlGaIn/GaN HEMT has delivered a CW output power density of 9.4 W/mm at 10 GHz<sup>[4]</sup>. However, these impressive power densities were achieved only from small gate periphery devices. For practical applications, large gate periphery devices must be used in order to generate sufficient total output power levels.

In addition to the high power output of more than 10 W, high power added efficiency is also required, because power consumption becomes large with the output power and temperature radiation is a significant issue when handling such a high output power.

However, for high power operation with a large gate periphery HEMT in the Ku band and other higher frequencies,

many difficulties appear. For example, with the increase of device gate periphery, the device impedance decreases steadily in proportion to the total gate width, which makes the external matching network design very difficult. As the chip width becomes of the same order as the micro-strips in the matching circuits, it becomes difficult to feed a microwave signal uniformly to such a large transistor<sup>[5]</sup>. The parasitic effects of the connection wire and the encapsulation shell are also significant at high frequencies. In addition, the self-heating effect and the defect trapping effect in the large gate periphery devices will both be more profound<sup>[6, 7]</sup>. These problems have prevented the easy development of large gate periphery HEMTs for high power operation with external matching circuits at high microwave frequencies.

In this paper, we describe the application of internal matching techniques to the developed AlGaIn/GaN HEMTs at Ku band and its corresponding microwave performances. With a 4 mm-gate-width die, the amplifier exhibits a maximum output power of 42.5 dBm with a power-added efficiency of 30% to 36.4% over a frequency range of 13.8 to 14.3 GHz.

## 2. Device structure and fabrication

The schematic cross-section of the developed AlGaIn/GaN HEMTs is shown in Fig. 1. The epitaxial structure, including a 100 nm AlN nucleation layer, a  $2\ \mu\text{m}$  GaN buffer layer, a 2 nm AlN insertion layer, a 22 nm  $\text{Al}_{0.26}\text{Ga}_{0.74}\text{N}$  barrier layer and a 2 nm thin GaN cap layer, is grown on a semi-insulating 6H-SiC substrate by MOCVD. In order to increase the power density of the single HEMT chip, it is important to increase the maximum channel current and the drain breakdown voltage.

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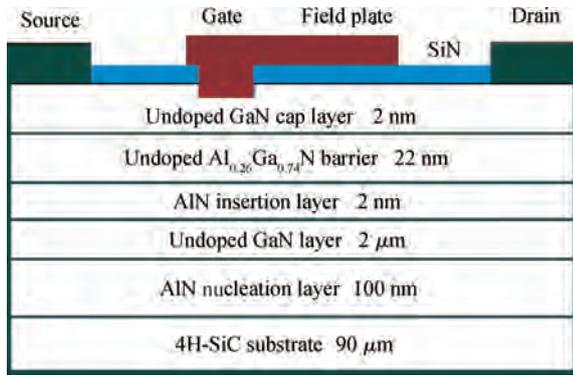


Fig. 1. Schematic cross section of the developed AlGaIn/GaN HEMTs.

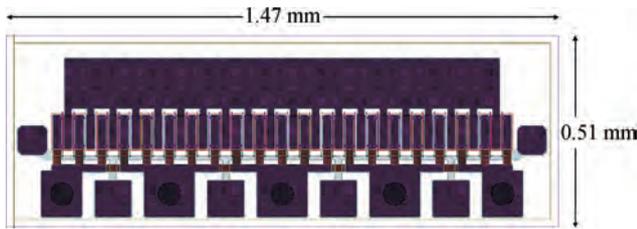


Fig. 2. Photograph of the developed AlGaIn/GaN HEMT with a gate width of 4 mm. Chip size:  $1.47 \times 0.51 \text{ mm}^2$ .

In this study, a field plate and a recessed gate are employed during the AlGaIn/GaN HEMT processing to improve device performance. Details for the device fabrication were previously reported<sup>[8, 9]</sup>.

A top view of the fabricated AlGaIn/GaN HEMT is shown in Fig. 2. The total gate width is 4 mm with 40 gate fingers. While the source–drain spacing is  $4 \mu\text{m}$  and the gate spacing is  $30 \mu\text{m}$  with a unit gate finger width of  $100 \mu\text{m}$ . The chip size is  $1.47 \times 0.51 \text{ mm}^2$ . Air bridges and via holes are formed to reduce the parasitic capacitance and inductance. To reduce thermal resistance, the SiC substrate is thinned to  $90 \mu\text{m}$ .

### 3. Device performance

The DC characteristics and on-wafer  $S$  parameters used for the amplifier design are measured with a 1 mm gate-periphery device, which is fabricated on the same wafer and then scaled to provide approximate results for a 4 mm gate periphery device. The DC tests show that the small gate device exhibits a maximum transconductance of 307 mS/mm and more than 80 V drain-to-source breakdown voltage ( $V_{br}$ ), with a saturation current of 1 A/mm. These values are high enough to ensure safe operation with more than 30 V drain voltage. In addition, the small signal measurements show a cutoff frequency ( $f_T$ ) of 31.6 GHz and a maximum frequency of oscillation ( $f_{max}$ ) of over 60 GHz at the drain bias of 30 V, as shown in Fig. 3.

### 4. Matching circuit design

The circuit schematic of the internally matched AlGaIn/GaN HEMTs is shown in Fig. 4. The HEMTs consist of 4 unit cells. The gate periphery of the unit cell is 1 mm. Based on the empirical methodology<sup>[10, 11]</sup>, the internal matching cir-

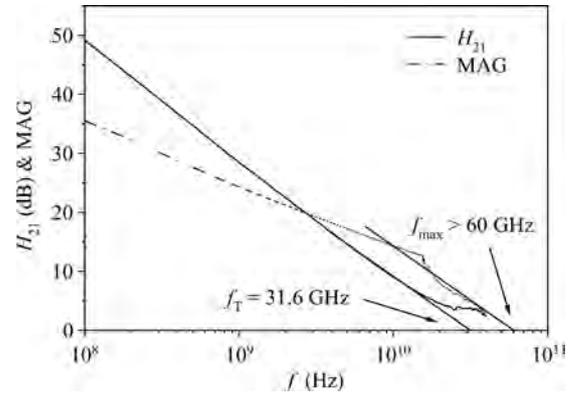


Fig. 3. Small signal characteristics of 1 mm gate periphery AlGaIn/GaN HEMTs.

cuits are designed to achieve high output power characteristics using a small equivalent circuit in combination with focus microwave load pull measurements performed for the unit cell. As the optimum load impedance shifts significantly as a function of the input drive level, large signal matching is required for the output network. While there is little variation of input impedance, conjugate matching could be used for the input network to realize a good input return loss.

The input and output matching are both realized with a pre-matching network and a series transmission line. The pre-matching network consists of a T type LC low pass filter, in which the connection bonding wire (labeled  $L_2/L_3$  in the schematic) between the HEMT device and matching network provides an additional inductive element. The other inductor in the network is also realized with a gold bonding wire of  $25 \mu\text{m}$  in diameter. The transmission lines, when used as series components for impedance transformation, have the advantages of low insertion loss and low cost, as compared to bulky inductors. For the same reason, the shunt capacitors in pre-matching networks are realized with microstrip structures on a high relative dielectric constant ( $\epsilon_r = 36$ ) substrate with a thickness of  $127 \mu\text{m}$ . This also helps to reduce the  $Q$  factor and improve the bandwidth of the circuit in a smaller size.

With the high levels of accuracy that can be achieved using quality test fixtures, the poor characterization of bonding wires becomes significant especially at high microwave frequencies<sup>[12]</sup>. For that reason, the input and output passive matching networks including the bonding wires are both modeled using Ansoft’s high frequency structure simulator (HFSS) CAD software according to the practical assembling technique. As shown in Fig. 5, it is a 3D model of the output matching network used for simulation. An initial simulation shows that the central frequency of the circuit shifted downwards. So it should be optimized to have good  $S$  parameters over the desired frequency range. This will greatly help to reduce the efforts in the assembling process afterwards. Figure 6 shows a top view of the final Ku band internally matched AlGaIn/GaN HEMT with package size of  $16.5 \times 9.7 \text{ mm}^2$ .

### 5. RF performance

The microwave performance of the internally matched single chip AlGaIn/GaN HEMT with a 4 mm total gate width is

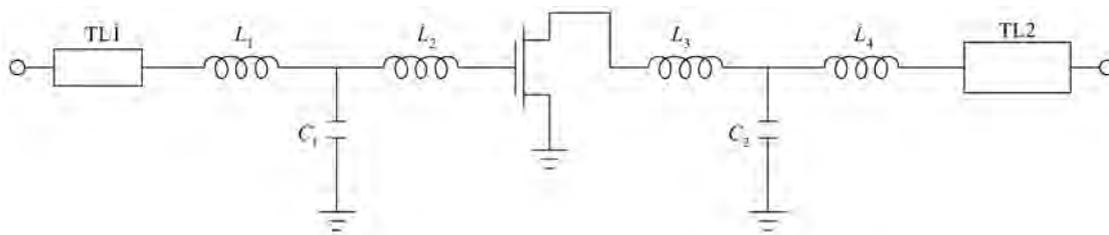


Fig. 4. Schematic of the internally matched AlGaIn/GaN HEMT amplifier.

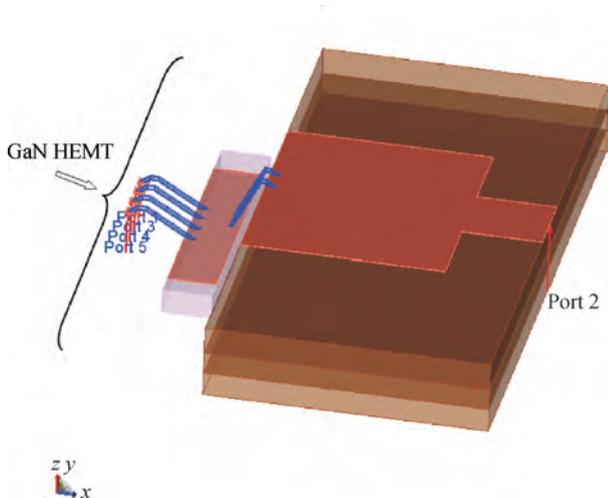


Fig. 5. Simulation model of the passive output matching circuit in HFSS.

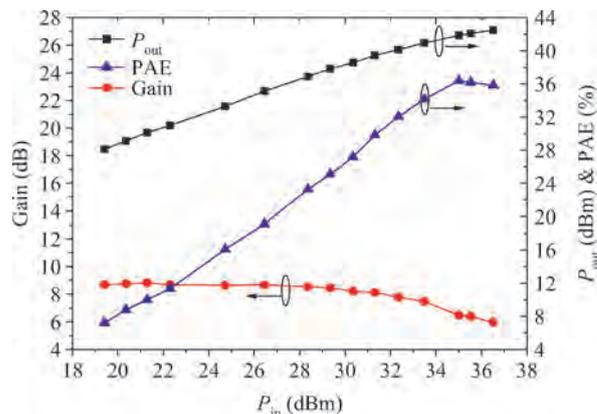


Fig. 7. Measured power characteristics of the developed internally matched 4 mm AlGaIn/GaN device at 13.9 GHz under pulse condition.

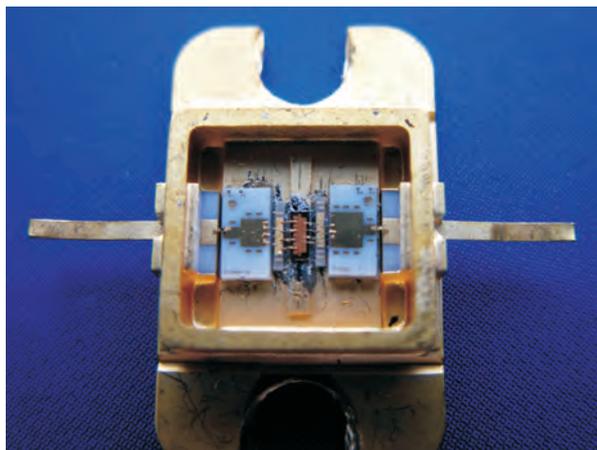


Fig. 6. Top view of the internally matched AlGaIn/GaN HEMT with package size of  $16.5 \times 9.7 \text{ mm}^2$ .

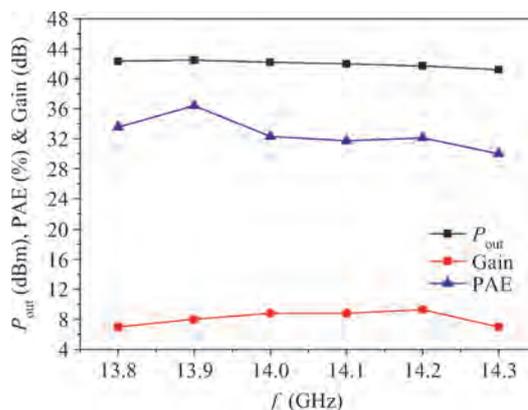


Fig. 8. Frequency responses for the developed internally matched amplifier over a frequency range of 13.8 to 14.3 GHz under a drain bias of  $V_{ds} = 30 \text{ V}$ .

described in this section.

The internally matched amplifier is tested in a test fixture using RF pulse power measurement at a drain bias voltage of 30 V. Figure 7 shows the RF power performances of the packaged amplifier under a pulsed condition at a duty cycle of 10% with a pulse width of  $10 \mu\text{s}$  at 13.9 GHz. At that frequency, the drain current is 250 mA and the measured output power reaches 42.5 dBm with 8.7 dB linear gain and 36.4% of PAE. At such a power level and PAE, the power density reaches 4.45 W/mm. This is more than ten times higher than its GaAs

counterpart<sup>[13]</sup>, which means that GaN can potentially attain a higher power output with other higher microwave performance indicators such as small size and a low noise figure at the same time.

Figure 8 shows the frequency response of the linear gain, power output and PAE of the internally matched amplifier. At the frequency range of 13.8 to 14.3 GHz, the PAE is over 30% and the variation of the power level is less than 1 dB.

## 6. Conclusion

In this paper, a Ku band high power internally matched AlGaIn/GaN HEMT with over 30% of PAE has been devel-

oped using the 3D-EM simulator of the high frequency structure simulator (HFSS). With a 4 mm-gate-periphery die, the developed amplifier delivers a maximum output power of 42.5 dBm with a variation of less than 1 dB and a PAE of 30% to 36.4% over a frequency range of 13.8 to 14.3 GHz. At this power level and PAE, 4.45 W/mm power density is obtained.

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