A Ku-band high power density AlGaN/GaN HEMT monolithic power amplifier*

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Abstract: A high power density monolithic power amplifier operated at Ku band is presented utilizing a 0.3 μm AlGaN/GaN HEMT production process on a 2-inch diameter semi-insulating (SI) 4H-SiC substrate by MOCVD. Over the 12–14 GHz frequency range, the single chip amplifier demonstrates a maximum power of 38 dBm (6.3 W), a peak power added efficiency (PAE) of 24.2% and linear gain of 6.4 to 7.5 dB under a 10% duty pulse condition when operated at $V_{ds} = 25$ V and $V_{gs} = -4$ V. At these power levels, the amplifier exhibits a power density in excess of 5 W/mm.

Key words: Ku-band; AlGaN/GaN HEMTs; power amplifier; monolithic; power density

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1. Introduction

With the rapid development of wireless communication, high power monolithic microwave and millimeter wave power amplifiers (PAs) have become more and more important in many applications, such as phase array radar, electronic warfare systems, and point-to-point wireless communication systems. Recently, AlGaN/GaN high electron mobility transistors (HEMTs) have attracted great attention due to the outstanding material properties of GaN[1]. The advantages associated with these materials include high breakdown fields, high peak electron and saturation drift velocities, and very high sheet charge densities at the interface resulting from a large conduction band offset, which results in high power densities. So for a certain power request, the chip size could be greatly reduced, yielding great potential for low cost. The importance of these devices for power amplifier technology is growing rapidly and already changing the rules for solid state power amplifier design and application.

Over the years, there have been significant efforts to improve the GaN HEMT process in order to attain a higher power level of different communication bands such as X, Ku and Ka band monolithic power amplifiers[2–9]. In an early publication, Masuda[2] presented a 10 W distributed MMIC power amplifier realized using a 0.25 μm GaN HEMT production process. Over 6–18 GHz, it achieved a power added efficiency of 18%. Darwish[3] developed a 4 W Ka band power amplifier for millimeter wave antenna application with a 1.2 mm output periphery. Bettdi *et al.*[4], reported an X band 50 W high power amplifier for a multi-domain T/R module using eight 1 mm gate width transistors for the final stage and four similar transistors for the first stage.

In this paper, we have demonstrated a high power Ku band power amplifier with 1.25 mm gate periphery GaN based HEMTs fabricated using 0.3 μm AlGaN/GaN HEMT technology on SI 4H-SiC substrate. Because of the potential instability of the amplifier, an on-chip parallel RC network is used at the gate of the transistor and barely affects the output power of the transistor. In addition, this network can also be used to create a frequency dependent loss. Biased at $V_{ds} = 25$ V, $V_{gs} = -4$ V, the amplifier attains a very high output power of 6.3 W (38 dBm), a power added efficiency (PAE) of 24.2% and linear gain of 7.5 dB at 14 GHz under on-wafer pulse measurement with a 10% duty cycle. Over 12–14 GHz, the amplifier exhibits a flat power frequency response with a fluctuation of less than 0.3 dBm. This paper will present details of the design approach, process and measured performance of this monolithic power amplifier.

2. Device and process technology

The 0.3 μm × 1.25 mm periphery AlGaN/GaN HEMT device is grown by metal organic chemical vapor deposition (MOCVD) on a 2-inch semi-insulating 4H-SiC substrate. The 2-inch diameter GaN HEMT wafer exhibits a low average sheet resistance of 300 Ω/□ with the resistance un-uniformity as low as 1.5%. The device structure shown in Fig. 1 consists of a 100 nm AlN nucleation layer, 2 μm undoped GaN, a 2 nm AlN insertion layer, 22 nm undoped $Al_{0.26}Ga_{0.74}N$ and a 2 nm GaN cap layer. Ti/Al/Ni/Au metallization is used to form drain–source ohmic contacts by electron beam evaporation. Device isolation is performed by ion implantation. Recessed gate etching is performed by dry etching technology and then 0.3 μm gate length Schottky gates with a field plate are formed by electron beam lithography. The gate metallization was realized using electron beam evaporated Ni/Au. The surface passivation layer adopts a SiN dielectric grown by plasma-enhanced chemical vapor deposition (PECVD). The source pads are directly grounded by back side via hole and the back side of the

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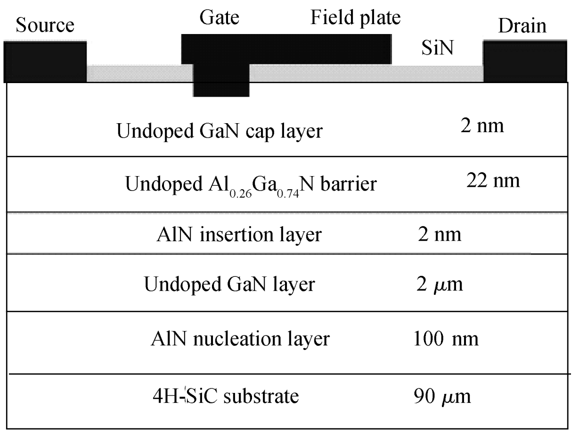

Fig. 1. Schematic cross section of the fabricated AlGaN/GaN HEMT.

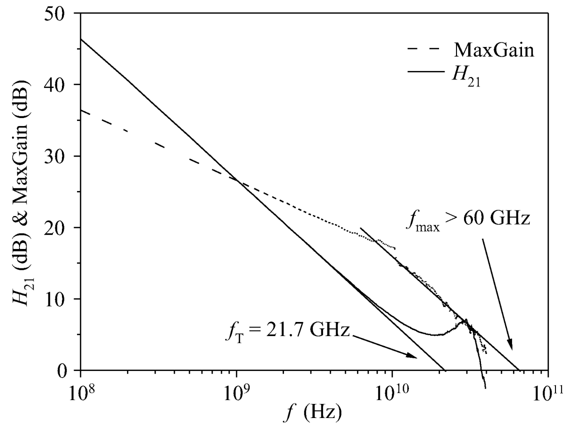

Fig. 2. Small signal characteristics of the AlGaN/GaN HEMT.

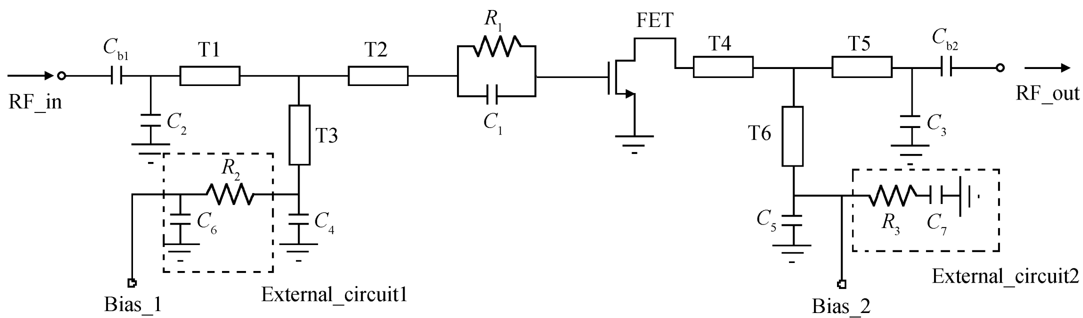

Fig. 3. Schematic diagram of the GaN HEMT MMIC power amplifier with external circuits at bias networks.

device is thinned down to 90 μm by mechanical polishing in order to reduce thermal resistance. The AlGaN/GaN HEMT exhibits a saturated drain current density of 1 A/mm and a maximum transconductance of 307 mS/mm. Small signal measurements show a cutoff frequency of 21.7 GHz and a maximum oscillation frequency of over 60 GHz at the drain bias of 25 V as shown in Fig. 2. At the designed centre frequency of 14 GHz, the MAG of the device is still greater than 12 dB, so it is used to realize this power amplifier.

3. Circuit design

The matching circuit of the amplifier is designed to achieve high power characteristics by using a small signal equivalent circuit with on-wafer measured S-parameter integrated with load pull measurement for optimal load impedance at 14 GHz by Focus Microwave load pull measurement system.

The schematic diagram and corresponding photograph of the fabricated MMIC for the completed power amplifier are shown in Figs. 3 and 4, respectively. The dimension of the chip is 2.66 × 1.37 mm^2. The design is achieved by adopting a proper matching network and using both lumped and distributed elements[10, 11].

To design the power amplifier, the output matching network, which transfers maximum output power from the GaN FET to the 50 Ω system, is designed first. To restrain the harmonic components and improve linearity, as well as to attain high power, a low pass Π type impedance transformer network is employed, where the short microstrip line T4 for connection is considered. The RF shorted shunt stub T6 also acts as a bias line to provide DC current. It is set to 83 μm width to achieve high current handling capability, while the rest of the microstrip lines on the main RF path are set to 58 μm width in order to have a compact area. In the input matching network, a low pass filter is also employed and, in addition, as the power device is potentially unconditional, a carefully chosen on-chip RC parallel stabilization network was placed in the input of the transistor, which is absorbed into the impedance matching network. Even though the resistive loading R_1 at the input would deteriorate the noise performance, the shunt resistor is necessary for practical microwave operation. The gate bias line is also set to 58 μm width as ultra low current flows through it. DC decoupled MIM capacitors, C_{b1} and C_{b2}, are placed besides the RF input and output pads which reduce their lossy effect on

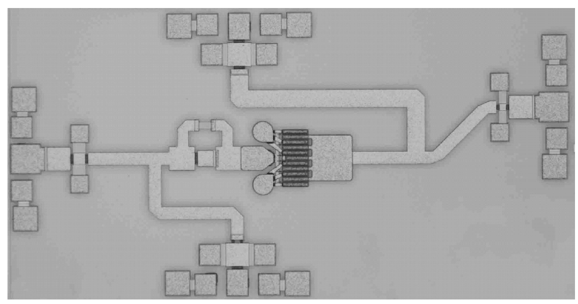

Fig. 4. Photograph of a 12–14 GHz MMIC power amplifier with a chip size of 2.66 × 1.37 mm^2.

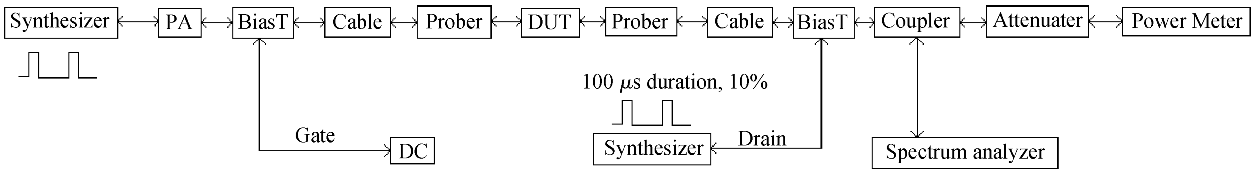

Fig. 5. On-wafer RF pulse-power measure test set.

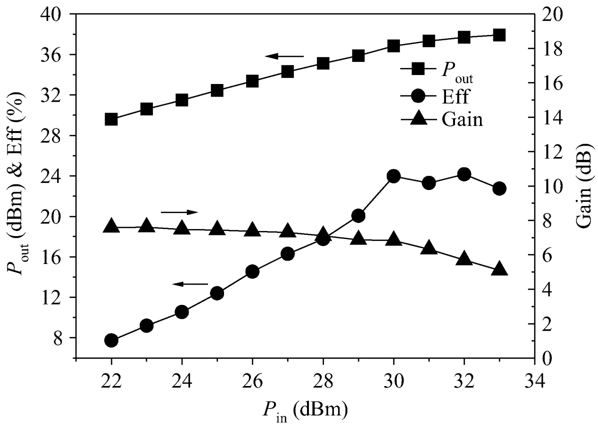

Fig. 6. On-wafer pulse power measurements for 1.25 mm gate width MMIC power amplifier at 14 GHz with 100 μs duration when biased at $V_{ds} = 25$ V and $V_{gs} = -4$ V.

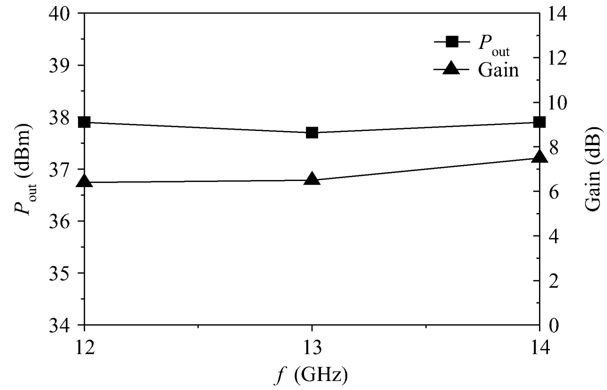

Fig. 7. Measured output power and linear gain versus frequency at the frequency range of 12–14 GHz when the input power is set to about 32 dBm.

the matching network. The decouple capacitors are designed to 2.5 pF. However, it may in fact be greater due to the process variation, which is a positive effect for our design.

In order to suppress instabilities, external circuits with discrete resistors (R_2 & R_3) and capacitors (C_6 & C_7) can be used to enhance low-frequency oscillation cancellation. The shunt capacitors C_6 and C_7 can also be used to remove ripple waves of the bias power supply, which is enhanced by on-chip bypass shunt MIM capacitors (C_4 & C_5).

Finally, the electrical network needs to be converted to a layout. The conversion to a layout introduces a parasitic component as well as a coupling effect, so electromagnetic simulation using Agilent's Momentum are performed to improve the design of the tuning circuits. The GSG pads are considered in the EM simulation for calibration when operating on-wafer pulse measurements.

4. Power amplifier performance

The power amplifier is tested on-wafer from 12–14 GHz using an on-wafer RF pulsed-power measure test set, as shown in Fig. 5.

For on-wafer pulse-power amplifier testing, the DC drain current pulse is set to 100 μs duration with a 10% duty cycle. This prevents excessive device heating during circuit tests. On-wafer pulse measurements also allow for high-volume testing of MMIC power amplifiers without having to dice and mount chips in fixtures.

The measured power and gain of the power amplifier versus input power at 14 GHz are shown in Fig. 6. It can be observed that the GaN-FET amplifier developed here attains a saturated output power of 38 dBm at about a 2 dB gain compression point with linear gain of 7.5 dB and a PAE of 24.2% under the bias condition of $V_{ds} = 25$ V, $V_{gs} = -4$ V. For this 1.25 mm periphery amplifier, the power density can achieve more than 5 W/mm, which means that it shows great potential for attaining higher power at smaller sizes.

A typical frequency response of the power amplifier is shown in Fig. 7 for P_{out} and gain with 32 dBm input power. In the frequency range of 12–14 GHz, the amplifier exhibits an output power of 6.3 W (38 dBm) with ΔP of 0.3 dB and associated linear gain of 6.4 to 7.5 dB.

5. Conclusion

In this paper, we have reported a Ku-band high power density MMIC power amplifier fabricated using a 0.3 μm AlGaN/GaN HEMT production process on 4H SIC substrate. The developed amplifier with a single 1.25 mm gate periphery device delivers 38 dBm (6.3 W) output power with 24.2% PAE and 7.5 dB linear gain at 14 GHz. In addition, over the 12–14 GHz frequency range, the amplifier has power flatness between 37.7 and 38 dBm. In this power level and PAE, an above 5 W/mm power density is available. So, it shows great potential for attaining more power at smaller sizes with AlGaN/GaN HEMT devices.

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