A Ka-band 22 dBm GaN amplifier MMIC*

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Abstract: A Ka-band GaN amplifier MMIC has been designed in CPW technology, and fabricated with a domestic GaN epitaxial wafer and process. This is, to the best of our knowledge, the first demonstration of domestic Ka-band GaN amplifier MMICs. The single stage CPW MMIC utilizes an AlGaN/GaN HEMT with a gate-length of 0.25 μm and a gate-width of 2 × 75 μm. Under $V_{ds} = 10$ V, continuous-wave operating conditions, the amplifier has a 1.5 GHz operating bandwidth. It exhibits a linear gain of 6.3 dB, a maximum output power of 22 dBm and a peak PAE of 9.5% at 26.5 GHz. The output power density of the AlGaN/GaN HEMT in the MMIC reaches 1 W/mm at Ka-band under the condition of $V_{ds} = 10$ V.

Key words: GaN; MMIC; AlGaN/GaN HEMT; amplifier; Ka band; CPW

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1. Introduction

Amplifiers based on AlGaN/GaN HEMTs (high-electron-mobility transistors) have attracted much attention in high-frequency, high-power microwave applications. This is because AlGaN/GaN HEMTs are of high breakdown voltage, high current density and high saturation velocity. At 4 GHz, the output power density of AlGaN/GaN HEMTs has reached 40 W/mm[1]. The maximum output power of a single HEMT has reached 100 W at 2 GHz[2]. In high frequency aspect, AlGaN/GaN HEMTs operating at the Ku-band, Ka-band (26.5–40 GHz)[3, 4], and even W-band (75–110 GHz)[5] have been demonstrated. At the Ka-band, the output power density has reached 10.5 W/mm[3] and the output power for a single HEMT has reached 8 W[4].

Great progress has also been made in the study of high frequency GaN amplifier MMICs. A Ka-band GaN amplifier MMIC, which includes two stages, and the last stage composed of two HEMTs, has a gain of 13 dB at 26–36 GHz. At 35 GHz, its maximum output power is 4 W and the peak PAE is 23%[6]. A W-band GaN MMIC with three stages has a gain of 17.5 dB and a saturated output power of 25 dBm[5].

The domestic study of AlGaN/GaN HEMTs and MMICs is mainly restricted to the C-band and X-band. We have done some work to improve the frequency characteristics of AlGaN/GaN HEMTs. Based on domestic epitaxial GaN wafers and process, the Ku-band[7] and Ka-band[8] AlGaN/GaN HEMTs have been implemented. At the Ka-band, the AlGaN/GaN HEMT, with a gate-length of 0.25 μm and a gate-width of 2 × 75 μm, exhibits f_T of 44 GHz and f_{max} of 120 GHz at $V_{ds} = 10$ V. At $V_{ds} = 30$ V, the HEMT has a f_T of 32 GHz and a f_{max} of 150 GHz[8].

In this paper, we have designed a Ka-band amplifier MMIC based on this AlGaN/GaN HEMT in CPW technology. The amplifier can operate at 26–27.5 GHz. It has a peak gain of 6.3 dB and a maximum output power of 22 dBm at 26.5 GHz. To the best of our knowledge, it is the first demonstration of domestic Ka-band GaN amplifier MMICs.

2. Amplifier MMIC design

Amplifier MMICs have their transistors, matched circuits and bias circuits fabricated on one wafer. Their performance is determined by the selected transistors, circuit structure and process. In this paper, we have designed a MMIC based on our Ka-band AlGaN/GaN HEMT and GaN process. The AlGaN/GaN HEMT has a gate-length of 0.25 μm and a gate-width of 2 × 75 μm. It has a saturated drain current of 1030 mA/mm. At the Ka-band, the MSG (maximum stable gain) is 10.5–11.5 dB[8].

To maximize the output power, amplifiers are usually power-matched. Yet restricted by measurement conditions, we haven't obtained the optimal load and source impedances for power match at the Ka-band[8]. So we have used a conjugate match based on the S-parameter of the HEMT. The S-parameter was obtained on wafer under the conditions of $V_{ds} = 30$ V and $V_g = -1.5$ V. To maintain the S-parameter, we have designed the MMIC in CPW (coplanar waveguide) technology. Compared with micro-strip circuits, CPW circuits are more complicated to design. Yet their fabrication needs fewer processing steps, such as thinning, back holing and back gilding. Moreover, CPW circuits can realize lower thermal resistance. By adopting a flip-chip structure, the heat can be removed through the utilization of thermal bumps at the ground plate (including the sources of the HEMTs). Cost savings of up to 40% have been reported for a coplanar flip-chip high-power amplifier[9].

The GaN epitaxial wafer has a thickness of 300 μm and a relative dielectric coefficient of about 6.7. All CPW transmission lines in this MMIC have a characteristic impedance of 50 Ω. According to our process parameters, the center conductor of the CPW line is 46 μm wide and the gap between it and the ground plate is 15 μm. The amplifier has been designed at

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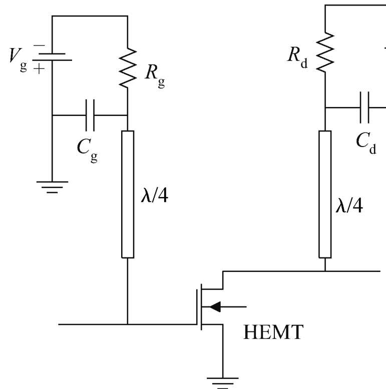

Fig. 1. Bias and stabilizing circuit of input and output.

32 GHz. The biases are fed in by one-forth-wavelength CPW transmission lines, which have a length of 1.2 mm. Simulation indicated that the transistor with a bias circuit was not stable ($K < 1$) at 8.5–33 GHz, so it was necessary to add a stabilizing circuit.

The common stabilizing method is to add a series RC-net at the gate of the transistor. Yet this may cause two problems for the Ka-band circuit. First, the HEMT has an MSG of only 11 dB at 32 GHz. A series RC-net can seriously decrease the gain. Second, the MIM capacitance, with dielectric material of SiN, was only used at the X-band or lower in our previous study. Its frequency characteristics are not known at the Ka-band, so it is risky to use such capacitances as matching components. The bias and stabilizing circuit of the amplifier are shown in Fig. 1. C_g and C_d are the decoupling capacitances. Two 3 Ω resistances, R_g and R_d, are added to the input and output circuits, respectively, as stabilizing components. The resistance at the drain side can decrease the PAE (power added efficiency). Yet in this design, the static drain current is no more than 60 mA under the conditions of $V_{ds} = 30$ V and $V_g = -1.5$ V. So the power consumed on the resistance is less than 11 mW. Simulation with ADS indicated that the circuit of Fig. 1 is absolutely stable.

After adding the bias and stabilizing circuit, conjugate load impedance of $11.0 + j71.8$ Ω and conjugate source impedance of $2.84 + j0.13$ Ω can be obtained by simulation. The matching circuit is composed of series and shunt CPW transmission lines. The source is matched to $2.84 + j0.13$ Ω and the load matched to $11.0 + j71.8$ Ω. Figure 2 is the whole circuit diagram. The maximum gain is 9.1 dB at 32 GHz.

A MMIC layout was drawn in a 'momentum' environment of ADS software, which can carry out electromagnetic simulation. The layout was simulated and adjusted to meet the design targets. The final simulated S-parameter is shown in Fig. 3. Simulation indicates that the MMIC layout has good performance at 31–33 GHz. The maximum gain is 8.1 dB at 31.5 GHz, which is 1 dB lower than that of the schematic circuit. This is due to the loss of the passive components. The amplifier is absolutely stable across the whole frequency.

3. MMIC fabrication

The MMIC amplifier was fabricated on a two inch GaN epitaxial wafer, which was provided by the Institute of Semiconductors of the Chinese Academy of Sciences. As shown in Fig. 4, $Al_{0.2}Ga_{0.8}N/AlN/GaN$ multilayers were grown on a SiC substrate by MOCVD and the sheet resistance was 370 Ω/□.

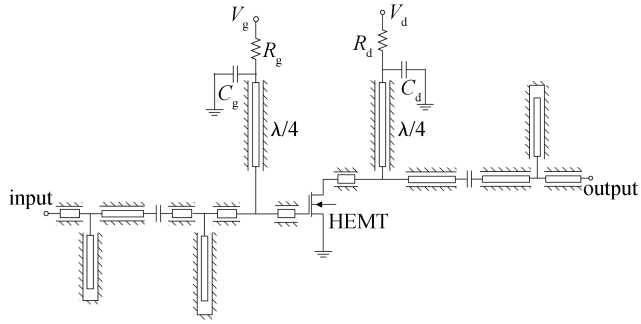

Fig. 2. CPW amplifier circuit diagram.

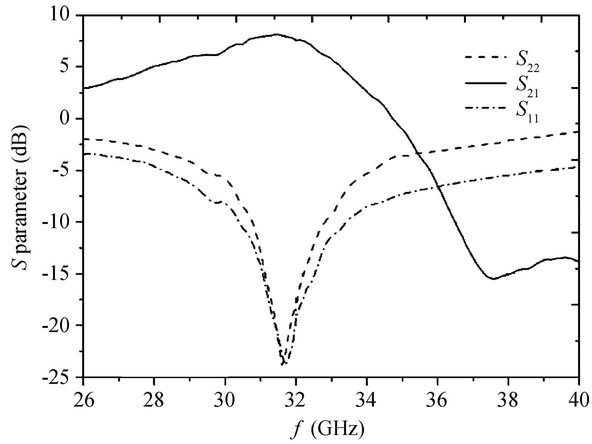

Fig. 3. Electromagnetic-simulation result of the MMIC layout.

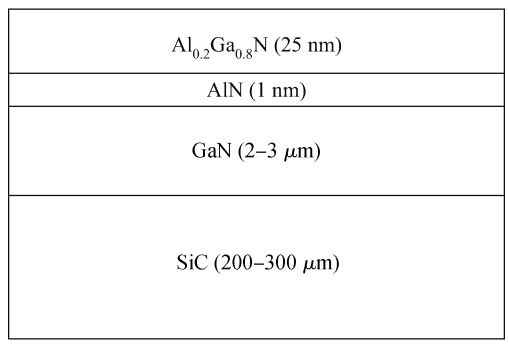

Fig. 4. Structure of the GaN epitaxial wafer.

The MMIC was fabricated in the GaN processing line of the Institute of Microelectronics of the Chinese Academy of Sciences. The process was similar to that of the AlGaN/GaN HEMT[7]. The main processes included photoetching, evaporating Ti/Al/Ni/Au and rapid thermal annealing to form ohmic contact; surface passivating with SiN, electron-beam lithography, dry-etch, photoetching and evaporating Ni/Au to form T-shape gate; then metalizing, second passivating, and electroplating followed to complete the MMIC.

Figure 5 is a photo of the completed amplifier MMIC. Two test HEMTs and two capacitances besides the MMIC are

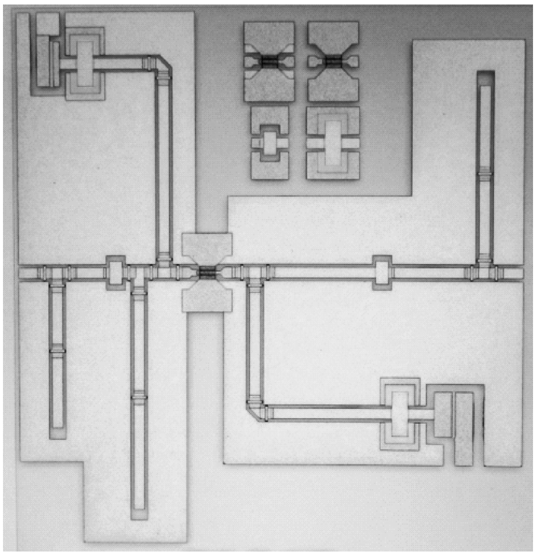

Fig. 5. Photo of the Ka-band GaN amplifier MMIC.

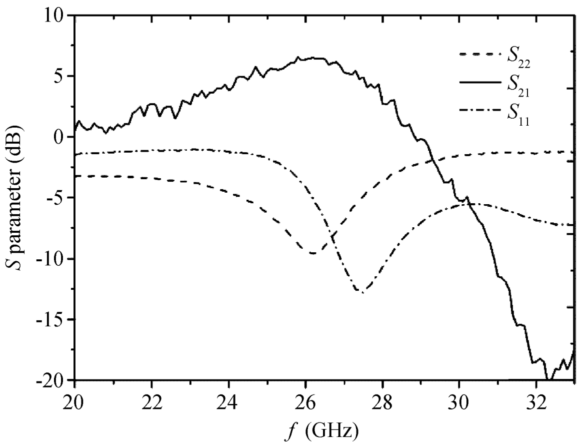

Fig. 6. S-parameters of the actual amplifier MMIC.

used to verify the performance of discrete devices. The whole MMIC is 2.26×2.36 mm^2 in size.

4. Circuit performance

Measurements indicated that the amplifier MMIC had better gain and return-loss characteristics at $V_{ds} = 10$ V instead of $V_{ds} = 30$ V. As shown in Fig. 6, the amplifier exhibits better S-parameters at 26–27.5 GHz and a peak gain of 6.38 dB at 26.5 GHz. Compared with the simulated results (Fig. 3), the measured results have a similar curve-shape of the S-parameter, yet it is 5 GHz lower in frequency and 1.7 dB lower in gain. Such deviations may arise from the following factors:

(1) The gate-head was formed by photoetching, which was about 0.2 μm larger than the previous one. A larger gate-head causes a larger parasitic gate-capacitance, which degrades the frequency characteristics of the HEMT.

(2) The structure of the GaN epitaxial wafer is not consistent with the previous one.

(3) The GaN process is not mature. The process accuracy and stability need to improve.

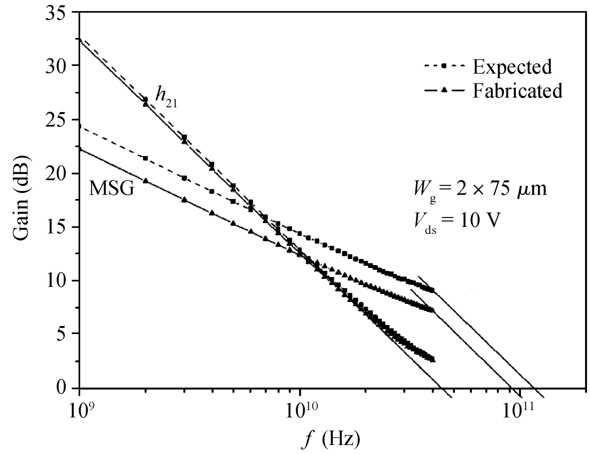

Fig. 7. Difference between the HEMT in the MMIC and the previous one.

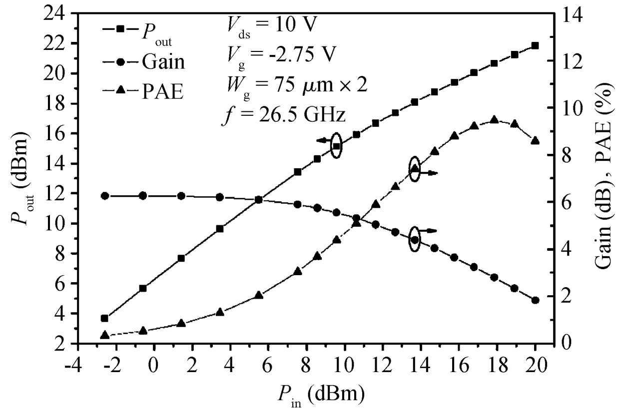

Fig. 8. Power characteristics of the MMIC at 26.5 GHz.

(4) The loss of MIM capacitance. High-Q capacitances are required in the Ka-band circuits. Yet restricted by the measurement conditions, the Q-factor of SiN MIM capacitances at the Ka-band have not been obtained.

(5) The accuracy of the simulation software. The simulation software used in this paper is momentum of ADS. It can conveniently combine with the simulation of a circuit diagram, yet its accuracy is not very good at the Ka-band[10].

The frequency characteristics of the HEMT in the MMIC are compared with those of the previous one[8] in Fig. 7. The MSG of the former is 2 dB lower than the latter. The f_{max} is decreased from 120 to 91 GHz, yet the f_T is decreased only a little. This is in accordance with the fact that the gate head of the T-shape gate is enlarged[11]. Because the frequency characteristics of the HEMT degrade, the amplifier MMIC also degrades.

The RF-power characteristics of the MMIC were measured under $V_{ds} = 10$ V and continuous-wave operating conditions at 26.5 GHz. As shown in Fig. 8, the linear gain is 6.3 dB, the maximum output power is 22 dBm (158 mW) and the peak PAE is 9.5%. The ultra low PAE is mainly due to the fact that the drain voltage is only 10 V.

In our previous study, we demonstrated Ka-band AlGaN/GaN HEMTs[8]. However, restricted by the measurement conditions, the maximum output power at the Ka-band was not obtained. Now, we can deduce that the output power of the HEMTs at the Ka-band is over 1 W/mm (158 mW/150 μm) under the condition of $V_{ds} = 10$ V. Supposing V_{ds} is 30 V, it is expected that the output power density at the Ka-band can reach over 3 W/mm.

5. Conclusion

In this paper, we have designed and fabricated a Ka-band GaN amplifier MMIC based on the domestic GaN epitaxial wafer and process. The amplifier has an operating bandwidth of 1.5 GHz. It exhibits a linear gain of 6.3 dB, a maximum output power of 22 dBm and a peak PAE of 9.5% at 26.5 GHz. To the best of our knowledge, this is the first demonstration of domestic Ka-band GaN amplifier MMICs. It also proves that the AlGaN/GaN HEMT utilized in the MMIC has an output power density of 1 W/mm at the Ka-band under the condition of V_{ds} $= 10$ V.

Compared with the simulation results, the amplifier MMIC degrades in gain and operating frequency. For future Ka-band GaN MMIC fabrication, it is necessary to improve the consistency of the GaN epitaxial wafer, the stability of the process and the accuracy of the layout simulation.

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