# 53% PAE 32W Miniaturized X-band GaN HEMT Power Amplifier MMICs

Naoko Ono [1], Tomohiro Senju [2] Kazutaka Takagi [3]

*Core Technology Dept., Komukai Complex, Toshiba Infrastructure Systems & Solutions Corporation*
*1, Komukai Toshiba-cho, Saiwai-ku, Kawasaki 212-8581, Japan*
[1] nao.ono.vh@toshiba.co.jp
[2] tomohiro.senju.rf@toshiba.co.jp
[3] kazu.taka.yk@toshiba.co.jp

***Abstract* — We have developed a miniaturized high efficiency X-band power amplifier MMIC with 0.25 μm AlGaN/GaN HEMT on SiC technology. Class-F two-stage MMICs are designed and fabricated, and the chip size is 3.0 mm x 3.3 mm. The MMICs had an output power of 45.1 dBm (32.4W), a power added efficiency of 53.4% and an associated gain of 15.1 dB with a drain voltage of 36 V at 9.3GHz.**

**Index Terms — gallium nitride, MMIC, power amplifier, power added efficiency, X-band**

## I. Introduction

The gallium nitride (GaN) high electron-mobility transistor (HEMT) power amplifier (PA) MMICs have attracted much attention because the superior electrical characteristics of that compared with those of silicon (Si) devices and gallium arsenide devices, they are expected to be an excellent candidate for high power applications, such as X-band active electrically scanned array (AESA) systems for aircraft. The characteristics required for the GaN HEMT PA MMICs are compactness, high efficiency and high output power in terms of realization of small and low cost systems. Several high efficiency 10-43 W class GaN MMIC HPAs for X-band AESA systems have been reported [1]-[3].

In this paper, X-band GaN HEMT PA MMICs are presented. When designing of the MMICs, we focused on high efficiency and small size. The MMICs have class-F operation and the matching circuits are tuned to an efficiency optimum point. The chip size is shrunken as much as possible to achieve high power density PAs. The device technology and the design procedure of the class-F two-stage PA are explained in section II, and the measurement results are presented in section III. Finally, conclusions are given in section IV.

## II. Design

We designed an X-band two-stage PA MMIC which is based on the class-F configuration. The device used in the MMIC design was based on the AlGaN/GaN HEMT process of 0.25 μm gate length technology. The device exhibited a high-frequency performance of fmax ≥ 90 GHz for a monitor HEMT with a gate width of 4x100 μm, and had a breakdown voltage of greater than 100 V. It had a maximum drain current of 1 A/mm, and a power density of greater than 4 W/mm with a drain voltage ($V_{DS}$) of 30 V and a drain current ($I_D$) of 83 mA/mm.

The design target performance of the PA was set at an output power of above 44 dBm with a drain voltage of 30 V at 9.3 GHz. The GaN HEMT with a gate width of 300 μm had a saturation output power of 32 dBm. In the circuit design, the gate width of the HEMT unit cell for circuit was 600 μm, a total gate width for first stage was 600 μm x 2 cells and that for second stage was 600 μm x 8 cells. In order to get maximum efficiency, the load impedance of the circuit for fundamental frequency was set at efficiency optimum point with class-F operation.

High efficiency PAs are based on the careful control of the harmonic content of the voltage and current waveforms at the transistor terminals. An ideal class-F PA has an efficiency of 100 %. The even harmonics reactance are low and the odd harmonics reactance are high so that the drain voltage waveform is formed into a square wave shape and the drain current waveform is formed into a half sine wave shape. However practical PAs are influenced by the on-state resistance and the isolation between the input and the output port of the transistor, so that the efficiency is a little lower.

Although the concept of the class-F operation is generally applied to the output matching circuits, there are some reports that the concept is effective against the input matching circuits [4]. Therefore, our MMIC was applied the concept to both the input and the output matching circuits. Especially, the second and third harmonics are important for practical PA to achieve a high efficiency operation, because controlling higher than third order harmonics increases the circuit complexity without any necessary improvement of the performance [5],[6]. Thus the MMICs were designed considering up to third-order harmonics.

The resonator, which consists of a shunt capacitor and a strip-line short stub, was located in the output matching circuit for the second and the third harmonics to realize class-F operation. The distance between the drain terminal of the HEMT and the short edge of the stub was set at a quarter wavelength for the second harmonics, and the phase is adjusted by the line length of main transmission direction. The parallel circuit, which was composed of the resistor and the capacitor, was located near the gate of the HEMTs to stabilize the MMIC. All transmission line lengths in the MMIC are shorter than a quarter wavelength for fundamental frequency.

## III. PERFORMANCE

The characteristics of the X-band GaN HEMT PA MMIC test samples were measured under a pulsed drain bias of 10% duty cycle and 100 μs pulse width to avoid thermal effects. It operated fundamentally with a drain voltage of 30 V and a total drain quiescent current of 500mA. Furthermore, the characteristics of the MMIC depending on the drain voltage were measured to know its ability. In order to demonstrate the superiority of the characteristics of the GaN HEMT compared with those of the GaAs HEMT, the characteristics of similar X-band GaAs HEMT PA MMICs as a typical GaAs example were added in the results.

Figure 1 shows photographs of an X-band PA MMICs. The chip size of the GaN HEMT MMIC is 3.0 mm x 3.3 mm and that of the GaAs HEMT is 3.6 mm x 3.6 mm. Figure 2 - 4 shows the measured output power, power added efficiency (PAE) and associated gain versus input power level of the PA MMICs. The GaN HEMT MMIC with a drain voltage of 30 V had an output power of 43.8 dBm (24.1 W), a PAE of 52.7 % and an associated gain of 13.8 dB with an input power of 30 dBm at 9.3GHz.

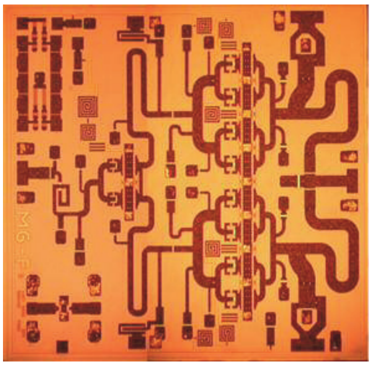
The GaN HEMT MMIC with a drain voltage of 36 V had an output power of 45.1 dBm (32.4 W), a PAE of 53.4 % and an associated gain of 15.1 dB with an input power of 30 dBm at 9.3GHz. The input power is set to obtain maximum PAE. The output power per unit chip area is important to grasp the ability of the PA MMIC. The GaN HEMT MMIC had an output power per unit chip area of 35.1 dBm/mm$^2$ (3.3 W/mm$^2$) with a drain voltage of 36 V.

Figures 5 and 6 show the measured output power and PAE versus frequency of the PA MMICs, respectively. The GaN HEMT MMIC with a drain voltage of 30 V had an output power of 41.3-44.0 dBm, a PAE of 43.3-53.1 % and an associated gain of 11.3-14.7 dB with an input power of 30 dBm in the frequency range of 8.8-9.8 GHz. The GaN HEMT MMIC with a drain voltage of 36 V had an output power of 43.4-45.3 dBm, a PAE of 48.5-53.8 % and an associated gain of 13.4-16.1 dB with an input power of 30 dBm in the frequency range of 8.8-9.8 GHz. These results show good agreement with the design target.

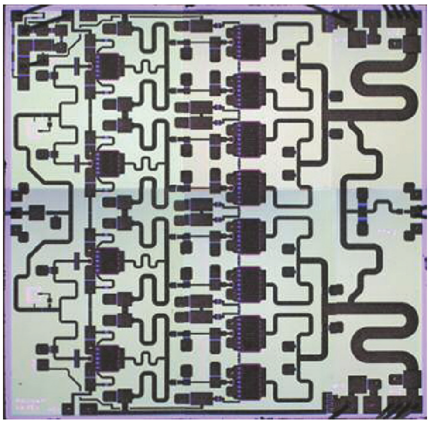
Table 1 shows the state-of-the-art X-band GaN HEMT PAs. From Table I, to our knowledge, one of the world's highest output power per area for X-band GaN MMIC PAs has been realized through this work.

## IV. CONCLUSION

We have developed a miniaturized X-band PA MMIC using 0.25 μm gate length AlGaN/GaN HEMT on SiC technology. Under pulsed bias condition with a drain voltage of 36 V at 9.3GHz, the MMIC achieved an output power of 45.1 dBm (32.4 W), a PAE of 53.4 %, an associated gain of 15.1 dB and an output power per unit chip area of 35.1 dBm/mm$^2$ (3.3 W/mm$^2$). It was confirmed that this newly developed MMIC is attractive for X-band AESA systems.



(a) GaN HEMT PA MMIC



(b) GaAs HEMT PA MMIC

Fig. 1. Photographs of an X-band PA MMICs.

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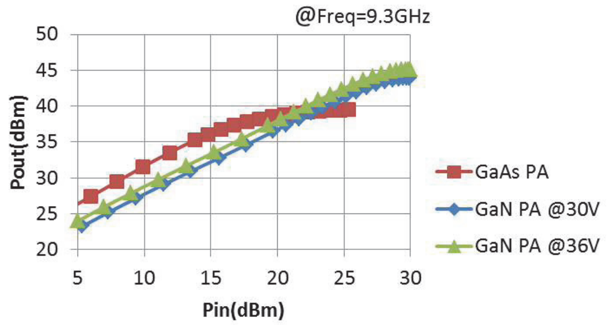


Fig. 2. Measured output power vs. input power level of the PA MMICs.

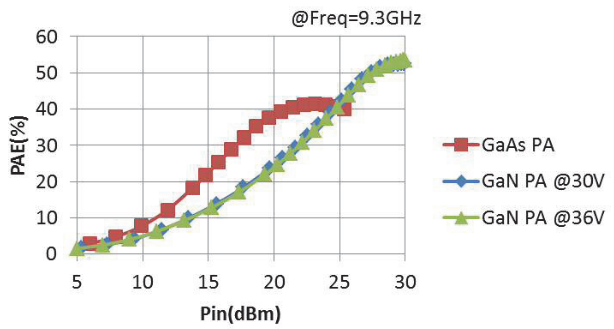


Fig. 3. Measured PAE vs. input power level of the PA MMICs.

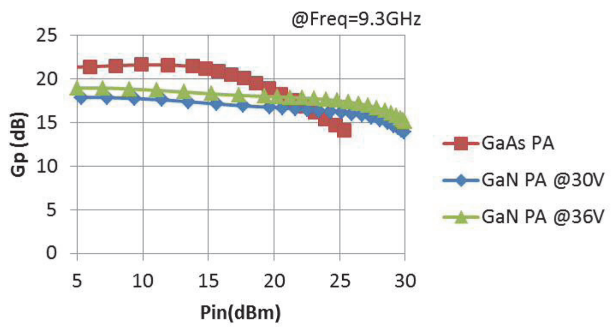


Fig. 4. Measured associated gain vs. input power level of the PA MMICs.

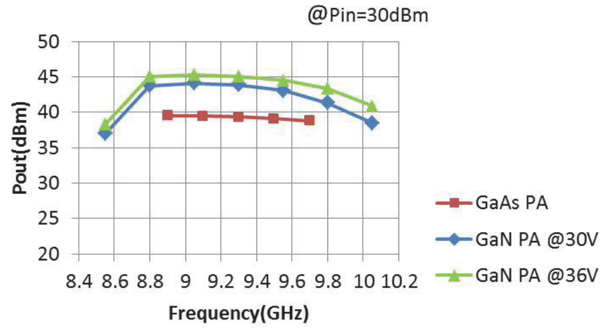


Fig. 5. Measured output power vs. frequency of the PA MMICs.

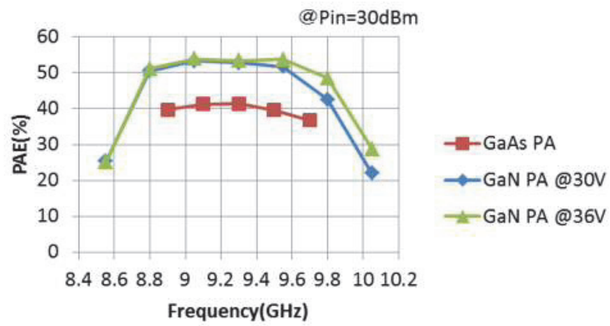


Fig. 6. Measured PAE vs. frequency of the PA MMICs.

TABLE I
State-of-the-art X-band GaN HEMT PAs

| Ref. | Technology | $P_{out}$ (W) | PAE (%) | $G_p$ (dB) | Area ($mm^2$) | $P_{out}$/Area ($W/mm^2$) | MMIC/ IMFET |
|---|---|---|---|---|---|---|---|
| This work | GaN HEMT (0.25μm) | 32.4 | 53.4 | 15.1 | 9.9 | 3.27 | MMIC |
| [1] | GaN HEMT (0.25μm) | 43.0 | 52.0 | 16.3 | 18.0 | 2.39 | MMIC |
| [2] | GaN HEMT | 31.6 | 43.5 | 14.5 | 18.7 | 1.70 | MMIC |
| [3] | GaN HEMT | 20.0 | 46.0 | 20.0 | 16.0 | 1.25 | MMIC |
| [4] | GaN HEMT (0.15μm) | 30.0 | 58.6 | 12.2 | 87.0 | 0.34 | IMFET |