

S-band 600 W and X-band 200 W High-Power GaN HEMTs for Radar Transmitters

Naoyuki MIYAZAWA*, Makoto NISHIHARA, Kunihiro USAMI, Makoto AOJIMA and Takashi YAMAMOTO

High output power gallium nitride (GaN) high electron mobility transistors (HEMTs) have been developed for S-band and X-band radar applications. The fully internally matched S-band GaN HEMT exhibits a minimum output power of 600 W, a minimum power gain of 12.8 dB, and a drain efficiency (DE) of 60% at 2.7–2.9 GHz for radar applications such as an air traffic control radar. The fully internally matched X-band GaN HEMT exhibits a minimum output power of 200 W, a minimum power gain of 9 dB, and a power-added efficiency (PAE) of 38% at 8.5–9.8 GHz for radar applications such as a marine radar and weather radar. The output power of these GaN HEMTs is the highest in the market, contributing to reduction in the size, weight and power consumption of radar transmitters.

Keywords: GaN HEMT, S-band, X-band, radar, high output power

1. Introduction

In recent years, active industrial efforts have been directed towards the development of internally matched GaN high-electron-mobility transistors (HEMTs^{*1}) for radar transmitter applications in aviation surveillance, ship surveillance, and weather observation systems. S-band^{*2} radar is used to meet advanced aviation surveillance requirements at airports. X-band^{*3} weather radar allows for the detection of local weather change such as torrential rain. Demand for these radar systems is expected to grow in the future.

Output power requirements of these radar systems are in the order of several tens of kilowatts. Hence, vacuum tube devices, such as magnetrons and klystrons, have been traditionally used in most of these systems because of their high output power capability and cost effectiveness. However, the service life, or replacement cycle, of vacuum tube devices is short, ranging from 6 to 12 months, thereby increasing the running cost. Another problem with vacuum tubes is that they tend to interfere with other nearby wireless communication systems operating at mutually close frequencies because vacuum tubes operate at a high noise level and a wide bandwidth. For these reasons, there is an increasing demand for high-power solid-state devices. As an alternative to vacuum tubes, solid-state devices have excellent long-term reliability and noise characteristics.

Compared with gallium arsenide field effect transistors (GaAs FETs)^{*4} which have been used as solid-state devices, GaN HEMTs deliver higher power and have a higher gain owing to the superior material properties of GaN. Consequently, they are attracting great interest as solid-state devices suitable for radar and other high-power systems. Furthermore, there is an increasing demand for wide-band amplifiers that offer design convenience. Characterized by high input/output impedance, GaN HEMTs enable amplifiers to operate in a wide band as well as at high output power.

Sumitomo Electric Industries, Ltd. commercialized the world's first GaN HEMT for mobile phone stations, which

received the Minister of Education, Culture, Sports, Science and Technology (MEXT) Award of the Japan Techno-Economics Society Technology Management & Innovation Awards in 2013.⁽¹⁾ On the foundation of these technologies,⁽²⁾ the company has also strived to raise the output power of internally matched GaN HEMTs designed for high-power applications, with the aim of further expanding the market for GaN HEMT.⁽³⁾⁻⁽⁸⁾ This paper presents the results of these numerous efforts—S-band and X-band GaN HEMT products that feature output power capability of the world's highest class.

2. GaN HEMT Technology

2-1 Material properties

Table 1 lists the properties of the principal semiconductor materials used in gigahertz-band (1 gigahertz = 10⁹ hertz) high-frequency amplifiers and other similar devices. The saturated electron velocity (V_{sat}) of GaN is at least twice higher than those of Si and GaAs. The breakdown field strength (E_c) of GaN is 10 times and 7.5 times higher than the E_c of Si and GaAs, respectively. Johnson's figure of merit is used to compare the performance of high-frequency, high-power devices. Using saturated electron velocity and breakdown field strength, Johnson's figure of merit is expressed as follows: $V_{sat} \cdot E_c / 2\pi$. In terms of

Table 1. Principal properties of semiconductor materials

	Si	GaAs	GaN
Band gap (eV)	1.1	1.4	3.4
Saturated electron velocity ($\times 10^7$ cm/s)	1.0	1.3	2.7
Breakdown field strength (MV/cm)	0.3	0.4	3.0
Electron mobility ($\text{cm}^2/\text{V}\cdot\text{s}$)	1300	6000	1500
Thermal conductivity ($\text{W}/\text{cm}\cdot\text{K}$)	1.5	0.5	1.5
Johnson's figure of merit (Si = 1.0)	1.0	1.7	27

Johnson's figure of merit, GaN is approximately 27 and 15 times higher than Si and GaAs, respectively, indicating overwhelming superiority.

2-2 Basic characteristics of GaN HEMT

This section presents an example of the characteristics of the GaN HEMT that we developed for X-band product applications. The gate length was adapted to an optimal length to achieve sufficient gain in the X-band. Figure 1 shows a plot of the drain current versus drain voltage ($I_{ds} - V_{ds}$). This GaN HEMT exhibited high current capacity, with saturated drain current value of 1.1 A/mm at $V_{gs} = +2.0$ V. Additionally, the drain-to-source breakdown voltage BV_{dsx} reached 290 V under pinch-off conditions. Existing studies reported that during radio-frequency (RF) operation, the drain-to-source voltage could exceed three times the operating voltage.⁽⁹⁾ The drain-to-source breakdown voltage of the GaN HEMT is sufficiently higher than the operating voltage of 50 V.

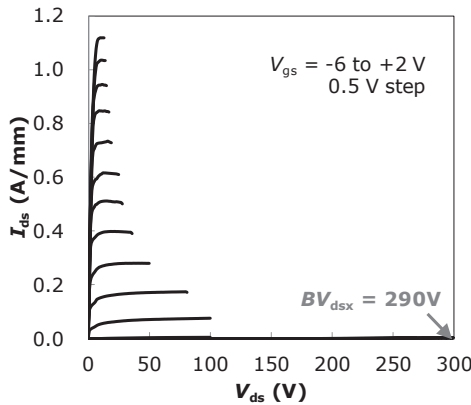


Fig. 1. $I_{ds} - V_{ds}$ characteristics of newly developed X-band GaN HEMT

2-3 Reliability of GaN HEMT

The mean time to failure (MTTF) of the newly developed X-band GaN HEMT is shown in Fig. 2. The results of

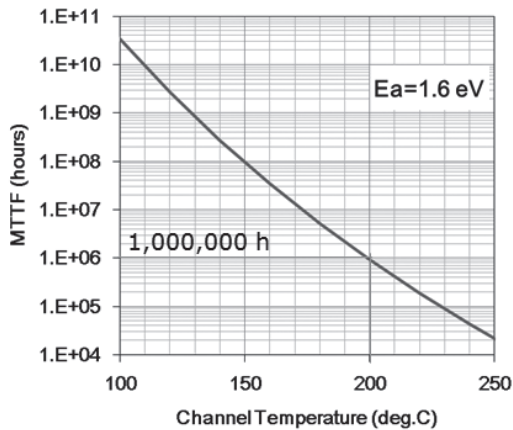


Fig. 2. MTTF of newly developed X-band GaN HEMT

a high-temperature operating test conducted using unit transistors were used to plot the graph. At a channel temperature of 200°C, the MTTF was 1,000,000 h.

3. Development of Internally Matched GaN HEMT

3-1 Target specifications

To achieve increased output power in comparison with our previous products (S-band 320 W and X-band 120 W), it was necessary to give due consideration to factors such as the thermal design of the transistor, pulse conditions, and package size.

Sumitomo Electric's reliability index for its GaN HEMT products is an MTTF figure of 1,000,000 h. To achieve this goal, the transistor channel temperature of the GaN HEMT must be reduced to 200°C or below. During pulse operation, the transistor channel temperature reaches a peak at the end of an RF pulse, as schematically shown in Fig. 3. The transistor channel temperature increases with a larger pulse width (PW) and higher duty cycle (DC). Hence, pulse conditions must be taken into consideration when designing a high-power device.

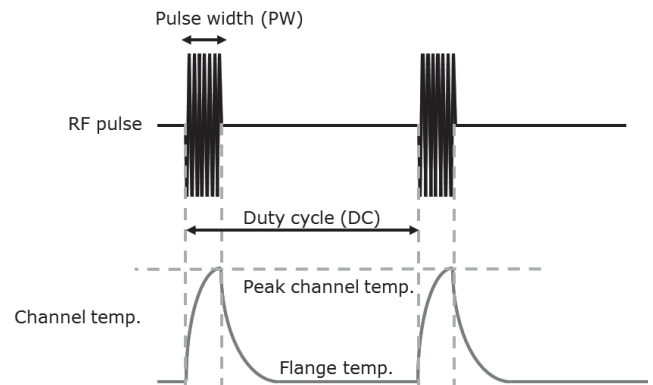


Fig. 3. Schematic diagram of relationships between RF pulse and channel temperature

Meanwhile, radar systems may use various transmission pulse width and duty cycle conditions depending on the distance to the target to be detected and the target size. For the maximum practical pulse conditions that would meet virtually any customer requirements, we selected $PW = 200 \mu s$ and $DC = 10\%$ for the S-band, and $PW = 100 \mu s$ and $DC = 10\%$ for the X-band at a flange temperature of 75°C. Furthermore, the frequencies selected were the 2.7–2.9 GHz portion of the S-band often required for air traffic control radar, and the 8.5–9.8 GHz portion of the X-band to cover ship and weather radar applications.

Furthermore, the latest generation of high-efficiency GaN HEMT technology was used to minimize the increase in transistor channel temperature by reducing power consumption. Moreover, on the basis of the results of a transistor load-pull test^{*5} of the basic unit, power added

efficiency targets of 60% and 40% were set for the S- and X-bands, respectively, for devices matched at the required frequencies.

In addition to these operating and power consumption conditions, the thermal resistance of the package selected and the mountable die size led to the setting of minimum output power targets of 600 W and 200 W for the S- and X-bands, respectively, operating at 50 V.

3-2 GaN HEMT die design

To achieve the output power targets, dies were formed with transistor gate widths of 74.5 μm and 14.4 μm , respectively, for the S- and X-bands. These two dies were arranged for parallel operation. The gate finger lengths were minimized to ensure sufficient gain in the operating frequency segments. The die sizes were 6.00 \times 0.86 mm for the S-band and 5.38 mm \times 0.76 mm for the X-band.

3-3 Matching circuit design

For both the S- and X-bands, matching circuits were designed using model transistors of the basic unit and the load-pull results. The internal circuits of the S-band 600 W GaN HEMT are shown in Fig. 4. Matching was achieved by an inductor and a ceramic capacitor using bonding wires. The output powers from the two dies were combined by a $\lambda/4$ Wilkinson impedance transformation to provide wideband capability. The package size was 24.0 \times 17.4 mm, excluding leads.

Figure 5 depicts the internal circuits of the X-band 200 W GaN HEMT. To improve the uniformity of the phases of input and output signals to/from each transistor unit as necessitated by higher frequencies of the X-band compared to the S-band, an electromagnetic field simula-

tion was performed. Then, the internal circuits were divided into four segments. A low-pass matching network was allotted to each segment for 4-2-1 in-phase power division/combination. The package size was 24.0 \times 17.4 mm, excluding leads.

4. Performance of Internally Matched GaN HEMT

4-1 RF characteristics

The RF characteristics of the S-band 600 W GaN HEMT are plotted in Fig. 6. The device achieved the minimum output power target of 600 W by a sufficient margin. Meanwhile, the GaN HEMT reached 59% power added efficiency, almost achieving the target performance.

Figure 7 shows the RF characteristics of the X-band 200 W GaN HEMT. The device's output power was sufficient to meet the minimum 200 W target. The power added efficiency of this GaN HEMT was 38%, which is very close to the target performance.

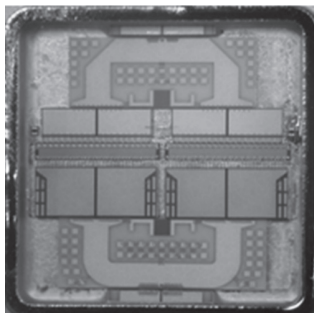


Fig. 4. Internal circuits of S-band 600 W GaN HEMT

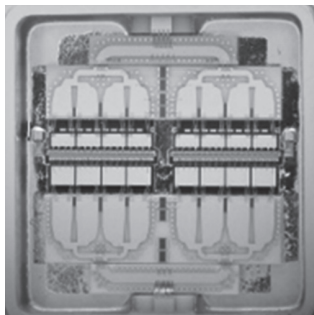
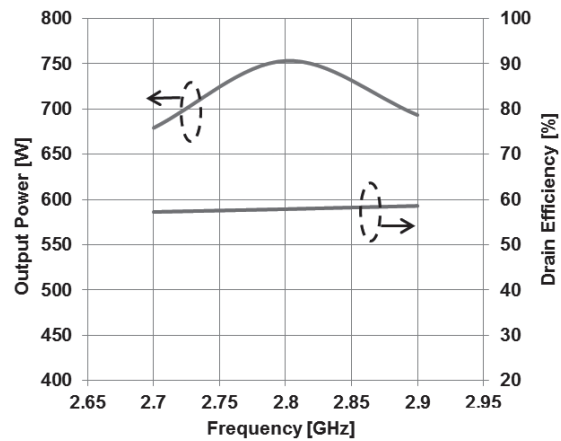
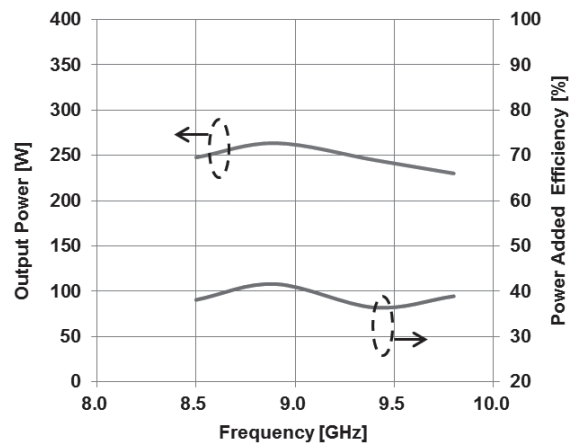


Fig. 5. Internal circuits of X-band 200 W GaN HEMT



VDS=50 V, Pin=31.6 W, PW=100 μsec , DC=10 %

Fig. 6. RF characteristics of S-band 600 W GaN HEMT



VDS=50V, Pin=25 W, PW=100 μsec , DC=10%

Fig. 7. RF characteristics of X-band 200 W GaN HEMT

4-2 Test setup

Figure 8 illustrates the test fixture of the X-band 200 W GaN HEMT. The external circuits were simply composed of 50 Ω lines and $\lambda/4$ bias lines resulting from the 50 Ω fully internal matching.

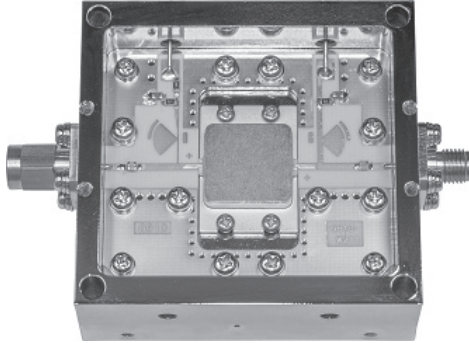


Fig. 8 Test setup for X-band 200 W GaN HEMT

4-3 Channel temperature verification

Figure 9 plots the channel temperature obtained using a transient thermal analysis system for the X-band 200 W GaN HEMT. The test results revealed a sufficiently low peak channel temperature of 150°C observed under the following conditions: PW: 100 μ s; DC: 10%; and flange temperature: 75°C.

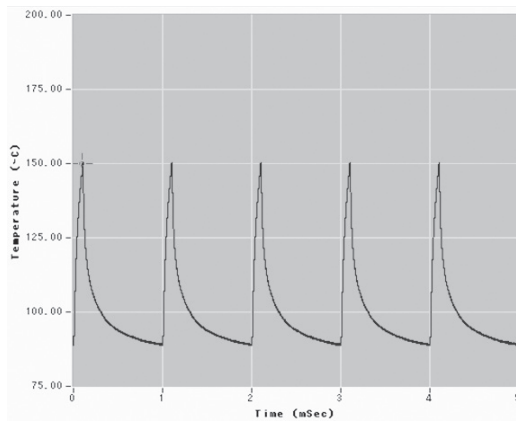


Fig. 9. Channel temperature evaluated with transient thermal analysis system

5. Conclusion

Table 2 summarizes the evaluation results for the newly developed, internally matched S-band 600 W and X-band 200 W GaN HEMTs. Various types of surveillance radar and weather observation radar are expected to evolve and come into wider use in the future. With these radar systems, expectations are high that the use of solid amplifier devices will improve their long-term reliability and reduce their size. This paper described the development of

internally matched GaN HEMTs that deliver the industry's highest level of output power in the S- and X-bands. Sumitomo Electric continues to work on the development of GaN HEMT technology and products to meet the demands for high-frequency, high-power devices.

Table 2. Evaluation results of internally matched GaN HEMTs

Characteristic	S-band 600 W	X-band 200 W
Drain Voltage, V_{ds}	50 V	50 V
Pulse Width	200 μ s	100 μ s
Duty Cycle	10%	10%
Frequency	2.7–2.9 GHz	8.5–9.8 GHz
Saturated Output Power, P_{sat}	680 W	250 W
Power Gain, G_p	13.2 dB	10.0 dB
Power Added Efficiency (PAE)	59%	38%

Technical Terms

- *1 High-electron-mobility transistor (HEMT): A transistor that uses two-dimensional electron gas induced at a semiconductor joining interface. HEMTs form a high-electron concentration channel, relatively free of the effects of impurity scattering.
- *2 S-band: According to frequency-based designation, the S-band refers to the 2–4 GHz portion of microwaves. The S-band is used for various applications including mobile communications and wireless LAN. The 2.7–3.5 GHz portion is assigned to various types of radar. Compared with the X-band, the S-band is more widely used for long-distance observation purposes, including aviation surveillance. Aviation surveillance radar uses frequencies from 2.7 to 2.9 GHz worldwide.
- *3 X-band: The 8–12 GHz segment of microwaves is called the X-band according to frequency-based designation. Owing to its short wavelengths, which allow antennas to be small, the X-band is assigned to various types of radar, along with satellite and other types of wireless communications. These include ship surveillance and weather observation radar, for which the 8.5–9.8 GHz portion is used globally.
- *4 Gallium arsenide field effect transistor (GaAs FET): This transistor is suitable for amplifying microwaves and other high frequencies because it allows electrons to move approximately five times faster than silicon FETs.
- *5 Load-pull test: The load-pull test is a method of evaluating large signal characteristics. Using an impedance control unit known as a tuner, the load-pull test performs characteristics evaluation under varied impedance matching conditions.

References

- (1) http://www.sei.co.jp/news/press/14/prs010_s.html
- (2) K. Inoue, S. Sano, Y. Tateno, F. Yamaki, K. Ebihara, N. Ui, A. Kawano, H. Deguchi, "Development of Gallium Nitride High Electron Mobility Transistors for Cellular Base Stations," SEI technical review, No. 71, pp.88-93 (October 2010)
- (3) T. Yamamoto, E. Mitani, K. Inoue, M. Nishi, and S. Sano, "A 9.5-10.5GHz 60W AlGaIn/GaN HEMT for X-band High Power Application," Proc. Eur. Microw. Integr. Circuits Conf., pp. 173-175, Munich, Germany (October 2007)
- (4) M. Nishihara, T. Yamamoto, S. Mizuno, S. Sano, and Y. Hasegawa, "X-band 200W AlGaIn/GaN HEMT for high power application," Proc. Eur. Microw. Integr. Circuits Conf., pp. 65-68, Manchester, UK (October 2011)
- (5) S. Mizuno, F. Yamada, H. Yamamoto, M. Nishihara, T. Yamamoto, and S. Sano, "A 5.9-8.5GHz 20 Watts GaN HEMT," Proc. Asia-Pacific Microwave Conf., pp. 123-126, Yokohama, Japan (December 2010)
- (6) K. Kikuchi, M. Nishihara, H. Yamamoto, S. Mizuno, F. Yamaki and T. Yamamoto, "A 65 V operation high power X-band GaN HEMT amplifier," Proc. Asia-Pacific Microwave Conf., pp. 585-587, Sendai, Japan (November 2014)
- (7) K. Kikuchi, M. Nishihara, H. Yamamoto, S. Mizuno, F. Yamaki, T. Yamamoto and S. Sano, "An 8.5-10.0 GHz 310 W GaN HEMT for Radar Applications," IEEE MTT-S Int. Microwave Symp. Dig., pp. 1-4, Tampa, USA (June 2014)
- (8) K. Kikuchi, M. Nishihara, H. Yamamoto, S. Mizuno, F. Yamaki, and T. Yamamoto, "An X-band 300-W class High Power GaN HEMT Amplifier for Radar Applications," SEI technical review, No. 81, pp.40-44 (October 2015)
- (9) F. Yamaki, K. Inoue, M. Nishi, H. Haematsu, N. Ui, K. Ebihara, A. Nitta, and S. Sano, "Ruggedness and Reliability of GaN HEMT," Proc. Eur. Microw. Integr. Circuits Conf., pp. 328-331, Manchester, UK (October 2011)

Contributors The lead author is indicated by an asterisk (*).

N. MIYAZAWA *

- Senior Manager, Electron Devices Division, Sumitomo Electric Device Innovations, Inc.



M. NISHIHARA

- Electron Devices Division, Sumitomo Electric Device Innovations, Inc.



K. USAMI

- Electron Devices Division, Sumitomo Electric Device Innovations, Inc.



M. AOJIMA

- Manager, Electron Devices Division, Sumitomo Electric Device Innovations, Inc.



T. YAMAMOTO

- Senior Manager, Electron Devices Division, Sumitomo Electric Device Innovations, Inc.

