

GaN HEMTs for Wireless Communication

Seigo SANO*, Kaname EBIHARA, Takashi YAMAMOTO, Tomio SATO, and Naoyuki MIYAZAWA

Gallium nitride (GaN) high electron mobility transistors (HEMTs) have been widely used for high-power and high-frequency applications, such as cellular base stations, owing to their superior material properties. This paper describes the features and characteristics of the world's first commercialized GaN HEMTs. Specifically, it introduces our 400-W GaN HEMT Doherty amplifier for cellular base stations and 20-W broad band GaN HEMT for fixed wireless communications. For satellite communications and weather radars, we have also developed a high-power and high-reliability GaN HEMT. These GaN HEMTs contribute to the creation of small-form-factor, light-weight, and power-efficient transmitters for wireless communication.

Keywords: GaN HEMT, wireless communication, cellular base station, satellite communication, radar

1. Introduction

Gallium nitride (GaN) is expected to be applied to high-power and high-speed electronic devices because of its wide band gap and high saturated electron velocity compared to silicon (Si) and gallium arsenide (GaAs). We have been developing and commercializing gallium nitride high electron mobility transistors (GaN HEMTs*) on a silicon carbide (SiC) substrate, which has high heat dissipation, since 2000.⁽¹⁾

Figure 1 shows communication infrastructure networks. Based on fiber optic backbone networks as the core, there are wireless communication networks for cellular phone communication, communication between cellular phone base stations, and satellite communication, as well as optical networks for metro and access communication systems. Most wireless networks are built on microwave communication in the bands from 1 GHz to 30 GHz. GaAs and Si devices have been mainly used for power amplifiers in these networks. However, with the demand for higher outputs to support communication speed enhancement in recent years, GaN HEMTs, which have excellent high-power characteristics, have been receiving increasing attention. In radar systems for air traffic control, vessel moni-

toring, and weather observation, with the advent of GaN HEMTs, there is growing demand for replacing older vacuum tube systems.

This paper discusses the high-power GaN HEMT developed for wireless communication.

2. GaN-HEMT Technology

2-1 Material properties

Table 1 lists the material properties of the typical semiconductors used for microwave amplifiers. GaN has a saturated electron velocity (v_{sat}) two or more times faster than that of Si and GaAs, and a dielectric field strength (E_c) 10 times greater than that of Si and 7.5 times greater than that of GaAs. For comparison of the performance of high-frequency and high-power devices, the Johnson performance index, $v_{sat} \cdot E_c / 2\pi$, is used. Compared on this index, GaN is far superior to Si and GaAs, 27 times higher than Si and approximately 15 times higher than GaAs. This is the major reason why there are high expectations for GaN.

Table 1. Comparison of Material Parameters

	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
Dielectric 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 performance index based on the index of Si as 1	1.0	1.7	27

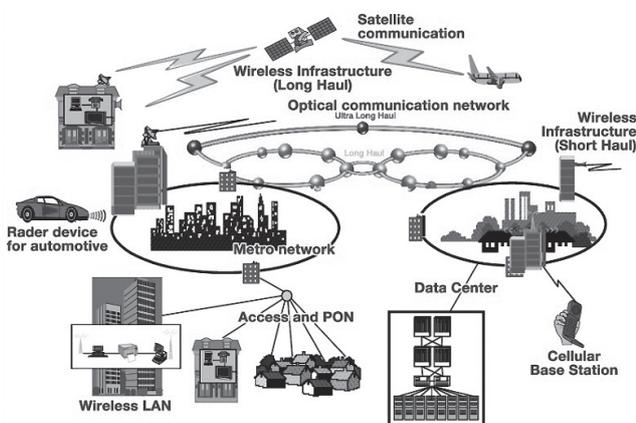


Fig. 1. Communication Infrastructure Networks

Figure 2 illustrates the relationship between the frequencies and output of amplification devices with different types of materials estimated from their physical properties. It also shows the ranges of power outputs

required for recent wireless communication networks. The figure indicates that GaN results in a superior device.

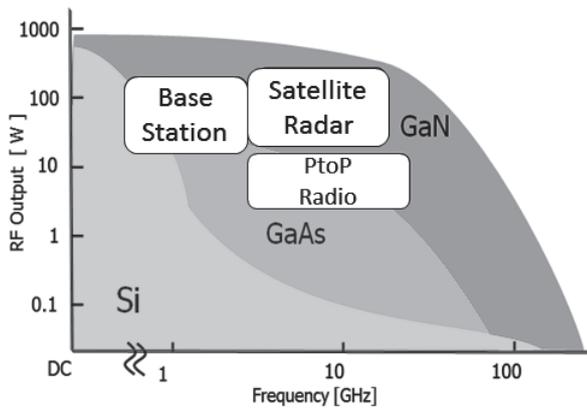


Fig. 2. Relationship between Material Properties and Amplifier Outputs

2-2 Structure and basic characteristics of GaN HEMT

Figure 3 shows the cross-section of a GaN HEMT. GaN can form large band discontinuity by hetero junction with AlGaIn and a high-density two-dimensional electron layer appears on its junction interface. In addition, using the characteristics of GaN crystals, it is possible to realize a high electron density due to spontaneous and piezo polarizations of the nitride semiconductor, enabling the GaN HEMT to drive very high current densities. To achieve even higher breakdown voltage characteristics, a field plate structure has been adopted to alleviate electric field-induced effects. For the support substrate, a highly heat conductive silicon carbide (SiC) substrate is used, and for the purpose of obtaining power amplification gains appropriate for each type of communication networks, the electrode structure, including gate strength, has been optimized.

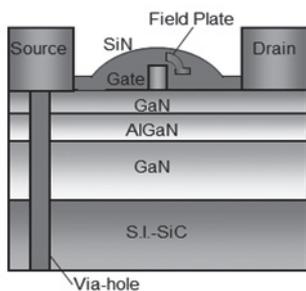


Fig. 3. Cross-Section of a GaN HEMT

Figure 4 shows an example of drain current vs. drain voltage (I_{ds} - V_{ds}) characteristics of a GaN HEMT. The saturated drain current when $V_{gs} = +2.0$ V is 1.1 A/mm, demonstrating a high current capacity. In addition, the three-

terminal breakdown voltage (BV_{dsx}) at pinch-off is 290 V. During high-frequency operation, the maximum source-drain voltage needs to be three times or more as high as the operating voltage. Our GaN HEMT has a sufficiently high breakdown voltage for an operating voltage of 50 V.

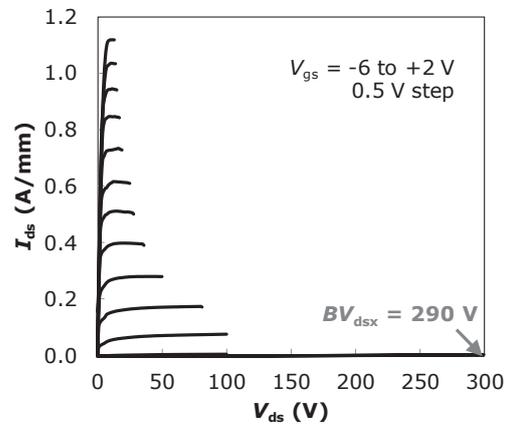


Fig. 4. I_{ds} - V_{ds} Characteristics of the GaN HEMT

The mean time to failure (MTTF) of our GaN HEMT is shown in Fig. 5. It was calculated from the result of a high-temperature operating test. The MTTF of one million hours was realized at a channel temperature of 200°C.

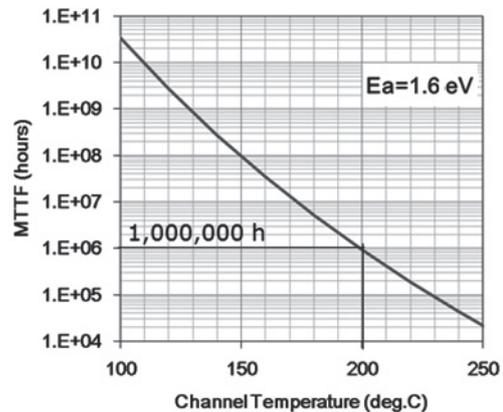


Fig. 5. MTTF of the GaN HEMT

3. GaN HEMT for Cellular Base Stations

Currently, 4th-generation (4G) cellular communication systems are in operation, using the L-band with a range of around 1 GHz to 3 GHz. To achieve high-speed communication, digital demodulation is used to transmit signals. Therefore, a power amplification device with an output exceeding the actual antenna power by approximately 6 to 10 dB is required. Since the average antenna power of a general cellular base station is approximately 40 W, the saturated output power of the power device needs to

be 400 W. In addition, because of the demand for a power amplification method with low power loss at average outputs, the Doherty amplification method is widely used. This method was proposed by W.H. Doherty of AT&T Bell Laboratories in 1936. As shown in Fig. 6, a Doherty amplifier comprises a class AB main device and a class C peak device both operating in parallel. The efficiency peaks at the power point 6 dB backed off from the saturated output power.

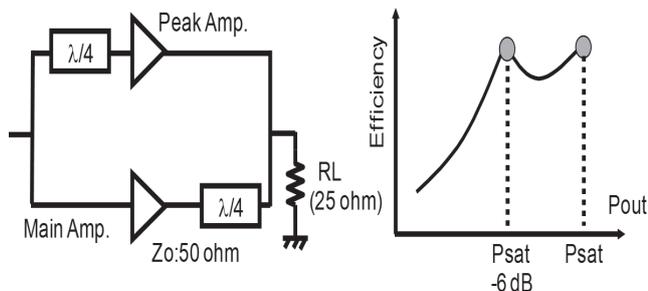


Fig. 6. Outline of the Doherty Amplification Method

An asymmetric Doherty amplification method is also discussed to support operation at power back-off of 6 dB or more.⁽²⁾ Photo 1 is a photo of an EGN21C210I2D GaN HEMT with a saturated output power of 200 W developed for cellular base stations. Photo 2 shows a Doherty amplifier using this device. Table 2 lists the major characteristics of the Doherty amplifier. It has achieved a saturated output power of 400 W and a high efficiency of 54% at a 6 dB



Photo 1. Exterior View of the EGN21C210I2D GaN HEMT
(Size: 12.9 mm × 21.0 mm)

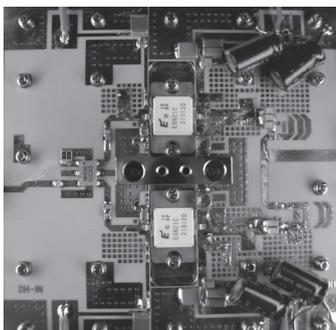


Photo 2. Exterior View of the Doherty Amplifier

Table 2. Characteristics of the Doherty Amplifier Using EGN21C12D GaN HEMTs

Item	Characteristics	Unit
Frequency	2.11 to 2.17	GHz
Drain power voltage	50	V
Saturated output power	56 (400)	dBm (W)
Gain at 6 dB back-off power	16	dB
Efficiency at 6 dB back-off power	54	%

back-off power. Our GaN HEMTs are used for many base stations in and outside Japan, contributing to the miniaturization and power saving of those stations.

4. GaN HEMTs for Point-to-Point Radio

The communication through the wireless network between cellular base stations discussed in Section 3 is called point-to-point radio. Since it uses microwaves with a range of approximately 6 to 28 GHz, it is also called terrestrial microwave communication. Signals are digitally modulated. Multivalued modulation systems have been used to support the 4G cellular communication in recent years. For this purpose, high-power and high-linearity amplification devices are required. This is why demand is shifting from conventional GaAs FETs*2 to higher-power GaN HEMTs.⁽³⁾

Photo 3 shows the exterior view of the package of SGK5872-20A, a 20-W GaN HEMT device. Table 3 lists its major characteristics. In addition to a GaN HEMT, the package contains a matching circuit formed on a ceramic substrate, to match the impedance of 50 ohms of an external circuit. A GaN HEMT features broadband characteristics by high-voltage operation. The GaN HEMT has an

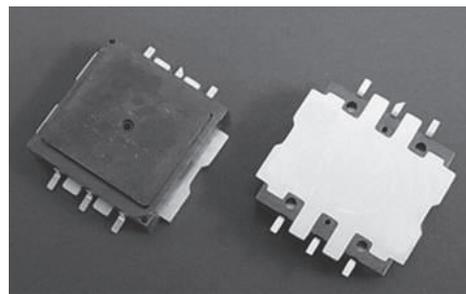


Photo 3. Exterior Views of the SGK5872-20A GaN HEMT
(Left: front side; right: rear side; size: 12.9 mm × 13.0 mm)

Table 3. Characteristics of SGK5872-20A

Item	Characteristics	Unit
Frequency	5.85 to 7.2	GHz
Drain power voltage	24	V
Saturated output power	43 (20)	dBm (W)
Efficiency at the saturated output power	41	%
Small signal gain	12	dB

operating frequency range twice or more as wide as that of a GaAs FET when operated at 24 V, which is more than twice higher than the operating voltage of the GaAs FET, 10 V. This feature realizes operation in a frequency range of 5.85 to 7.2 GHz, and the 6 GHz and 7 GHz bands. Moreover, the adoption of an SiC substrate has achieved a low thermal resistance, enabling surface mounting, which has not previously been implemented. This device has realized the miniaturization and cost reduction of communication equipment.

5. GaN HEMTs for Satellite Ground Stations

Satellite communication is the two-way communication with a communications satellite launched into space. It involves a satellite ground station (hub station) and small stations called very small aperture terminals (VSATs) as the subscribers. The carrier frequencies are usually 14 GHz and 30 GHz. Since the ground station needs to handle high output power, vacuum tubes called traveling wave tubes (TWTs) are often used. However, since the advent of GaN HEMTs, the vacuum tubes have been replaced with those high-reliability solid-state devices.

Photo 4 is the exterior view of SGK1314-60A, a newly developed 14 GHz-band GaN HEMT. Table 4 indicates its major characteristics.



Photo 4. Exterior View of the SGK1314-60A GaN HEMT (Size: 12.9 mm × 21.0 mm)

Table 4. Characteristics of SGK1314-60A

Item	Characteristics	Unit
Frequency	13.75 to 14.5	GHz
Drain power voltage	24	V
Saturated output power	48 (60)	dBm (W)
Efficiency at the saturated output power	32	%
Small signal gain	8.5	dB

6. GaN HEMTs for Satellites

In addition to the power amplification device for ground communication described above, the power amplification devices for satellites are being changed from TWTs to GaN HEMTs. GaAs FETs, which are also solid-state devices, were previously commonly used. However, GaN HEMTs have realized output power that cannot be achieved by GaAs FETs. With the spread of mapping applications for onboard navigation systems and smartphones, the use

of satellite communications will expand further. Moreover, all-electric satellites propelled electrically are currently under study. There are high expectations for GaN HEMTs, which will enable further downsizing and weight reduction of satellites.

Photo 5 is the internal circuit of an L-band 200-W internal matching type GaN HEMT. To attain miniaturization, alumina substrates are used for the input and output, and a matching circuit is located on a highly dielectric substrate. Figure 7 shows the output power, drain efficiency, power addition efficiency, and gain characteristics in continuous operation at a frequency of 1.58 GHz and a case temperature (T_c) of 45°C. The device has achieved a saturated output power of 53.2 dBm (210 W), linear gain of 18.3 dB, power addition efficiency of 71%, and drain efficiency of 74.6%, all of which indicate the highest performance in the world.

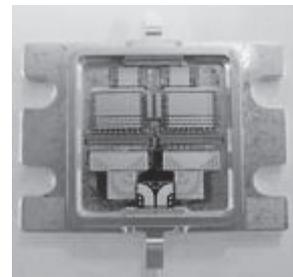


Photo 5. Internal Circuit of an L-Band 200-W GaN HEMT

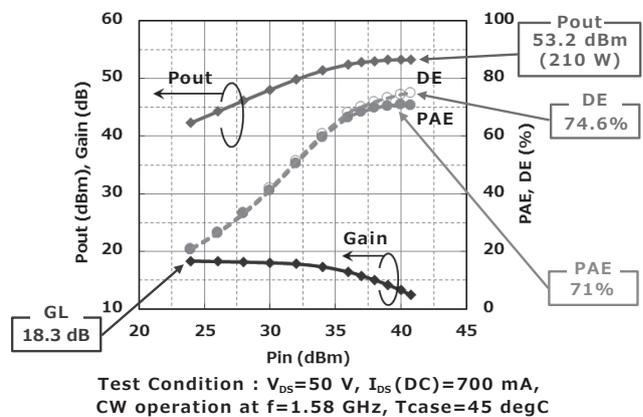


Fig. 7. Power Characteristics of an L-Band 200-W GaN HEMT

The devices for satellite require very high reliability. In order to check long-term reliability, we conducted a space qualification test (SQT) on a satellite using the GaN-HEMT technology according to a standard space qualification procedure established based on the MIL-PRF-19500 world standard. Radiation resistance is another important factor for application in space. A single event effects (SEE*) radiation test as illustrated in Table 5 was performed to confirm that our GaN-HEMT technology maintains sufficient reliability even under high radiation.⁽⁴⁾

Table 5. Single Event Effects (SEE) Test (RF Operation Test)

Radiation species	¹³² Xe
Energy [MeV]	650
Fluence [pcs/cm ²]	Up to 3 × 10 ⁵
Flux [pcs/cm ² /sec]	Up to 3000
LET** (Si) [MeV/(mg/cm ²)]	66.3
Drain voltage V _{ds}	Up to 53 V
Drain current I _{ds} (DC)	250 mA
Output level	Up to 4 dB gain compression point

7. GaN HEMTs for Radars

The output power required for radar transmitters used for aircraft monitoring, vessel monitoring, and weather observation is several kW to several tens of kW. These applications are mainly served by vacuum tube devices including magnetrons and klystrons that can perform high-power operation. However, vacuum tubes have disadvantages such as limited reliability, high noise levels, and wide occupied bandwidths that tend to result in interference with other wireless communication systems using similar frequencies. For these reasons, solid-state GaN HEMTs have been drawing attention.⁽⁵⁾

Photo 6 is the test fixture of a GaN HEMT for a radar. Table 6 gives the major characteristics of an S-band 600-W GaN HEMT for air traffic control and a GaN HEMT for an X-band weather observation radar that can detect local weather fluctuations.

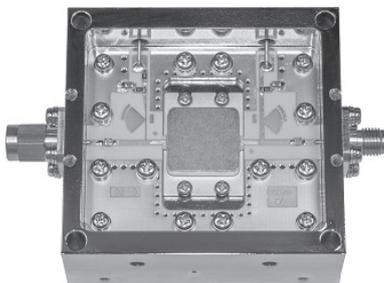


Photo 6. Photo of a Mounted GaN HEMT for a Radar

Table 6. Major Characteristics of GaN HEMT for Radars

Item	S-Band 600W SGK2729-600H-R	X-Band 200W SGK8598-200A-R
Drain voltage (V _{ds})	50 V	50 V
Pulse width	200 μsec	100 μsec
Duty cycle	10%	10%
Frequency (entire range)	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 addition efficiency (PAE)	59%	38%

With the world's highest level of characteristics, these devices are used in many radars.

6. Conclusion

Our GaN HEMTs, which had been researched and developed since 2000, have finally entered the commercialization phase. In recent years, they have been widely used in various types of wireless communication equipment such as cellular base stations. This paper has mainly introduced the features of our high-power GaN HEMTs and their high-frequency characteristics. We received a "Ministry of Education, Culture, Sports, Science and Technology Award" of the "2nd Management of Technology/Innovation Award" in 2013 for these development efforts.⁽⁶⁾

Technical Terms

- *1 High electron mobility transistor (HEMT): A transistor using two-dimensional electrons induced on a semiconductor junction interface. It can form a high electron density channel less affected by impurity scattering.
- *2 Gallium arsenide field effect transistor (GaAs FET): A field effect transistor made of gallium arsenide. Since compared with silicon, electrons can move nearly five times faster through this material, this device is suitable for the amplification of high frequency signals such as microwaves.
- *3 Single event effect (SEE): An occurrence of a temporary malfunction or permanent failure caused by the entry of a single high-energy particle (proton, heavy ion, etc.) into a semiconductor device, which generates high-density electric charges by ionization.

References

- (1) H.Sano et.al, "A 40W GaN HEMT Doherty Power Amplifier with 48% Efficiency for WiMAX Applications," 2007 IEEE Compound Semiconductor Integrated Circuit Symposium Digest
- (2) H.Deguchi et.al, "A 2.6GHz Band 537W Peak Power GaN HEMT Asymmetric Doherty Amplifier with 48% Drain Efficiency at 7dB BO," 2012 IEEE MTT-S Int. Microwave Symposium Digest
- (3) S.Mizuno et.al, "A 5.9-8.5GHz 20Watts GaN HEMT," 2010 Asia-Pacific Microwave Conference
- (4) H.Yoshikoshi et.al, "Radiation Hardness Tests for Space Qualified X-band AlGaIn/GaN HEMTs," 2015 Reliability of Compound Semiconductor Workshop
- (5) K. Kikuchi et.al, "An 8.5-10.0 GHz 310 W GaN HEMT for Radar Applications," 2014 IEEE MTT-S Int. Microwave Symposium Digest.
- (6) URL
http://global-sei.com/news/press/14/prs010_s.html

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

S. SANO*

• General Manager, Sumitomo Electric Device Innovations, Inc.



K. EBIHARA

• Senior Manager, Sumitomo Electric Device Innovations, Inc.



T. YAMAMOTO

• Senior Manager, Sumitomo Electric Device Innovations, Inc.



T. SATO

• Senior Manager, Sumitomo Electric Device Innovations, Inc.



N. MIYAZAWA

• Senior Manager, Sumitomo Electric Device Innovations, Inc.

