Development of GaN HEMT for Microwave Wireless Communications

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High-power broadband devices are increasingly required for microwave wireless communication such as terrestrial and satellite communication over 6 GHz (e.g., C-band). Thus far, GaAs devices have been used in these communication systems, however, the properties of GaAs are insufficient to meet the high-power broadband requirements. To address this challenge, we have focused on the superior physical properties of GaN. Based on our GaN high electron mobility transistor (HEMT) technology for cellular base stations (e.g., L/S-band), we have developed a GaN HEMT applicable for the C-band, which is commonly used for microwave wireless communication. This paper summarizes the characteristics of the GaN HEMT and a 20 W-class internally-matched broadband device equipped with the GaN HEMT.

Keywords: GaN HEMT, microwave, wireless, amplifier, broadband

1. Introduction

Gallium Nitride (GaN) devices are desirable for the application of high-power and high-speed operation electron devices because of their excellent properties such as large energy band gap and high saturated electron velocity. We have already developed and produced GaN HEMTs*1 on SiC substrate targeting the frequency range of L/S-band mainly for the amplifier used in cellular base stations. The operating frequency is up to 3.5 GHz.

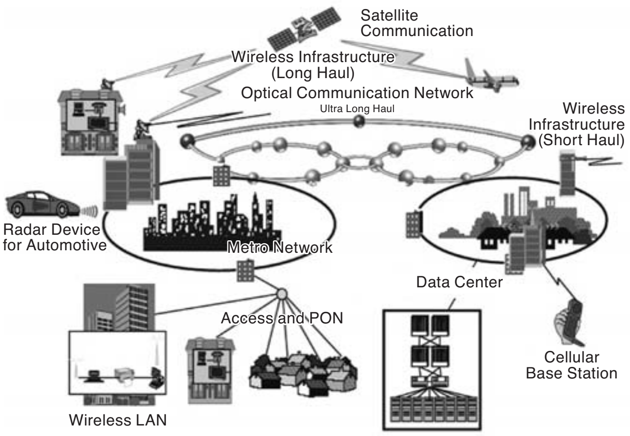

Fig. 1. Present communication infrastructure network

Figure 1 shows a schematic illustration of the present communication infrastructure network. In this figure, microwave wireless communication indicates terrestrial and satellite communication, whose operating frequency band is mainly from 6 GHz to 16 GHz. Thus far, GaAs devices have been used in these communication systems.

As an example of 20 W-class GaAs devices, in order to cover a broadband frequency range from 6 GHz to 16 GHz, more than 8 versions of GaAs devices are required, because the conventional GaAs devices have very narrow band performance of approximately 1 GHz bandwidth at 10 GHz.

In contrast, the high-power device using GaN HEMTs accomplished 60 W radio frequency (RF) output power in 1 GHz bandwidth[1]. Hence, the GaN HEMT has superior characteristics in high power and broadband capability than GaAs devices. In addition, the broadband performance of the GaN HEMT permits on-time delivery and stock reduction of the communication systems. This is because, although the actual frequency range of the system depends on each carrier company as well as each country, shared use of a single broadband GaN HEMT device type leads to simplified stocking for various systems.

In this paper we summarize the performances of the GaN HEMT developed for microwave wireless communication and the 20 W-class broadband GaN device.

2. GaN Transistor

2-1 Material properties

Table 1 shows the key material parameters of the major materials used in high frequency applications. Compared to GaAs, GaN has two times higher saturated elec-

Table 1. Material parameter comparison

	Si	GaAs	SiC	GaN
Band Gap Energy: E_g (eV)	1.1	1.4	3.2	3.4
Critical Breakdown Field: E_c (MV/cm)	0.3	0.4	3.0	3.0
Mobility: μ_e ($cm^2/V \cdot s$)	1300	6000	600	1500
Thermal Conductivity: κ ($W/cm \cdot K$)	1.5	0.5	4.9	1.5
Saturated Velocity: V_{sat} (10^7cm/s)	1.0	1.3	2.0	2.7
Johnson's Figure of Merit (JFOM) $V_{sat} \cdot E_c/2\pi$ vs GaAs	0.57	1	11.5	15.5

tron velocity (V_{sat}) and 8 times larger critical breakdown field. Additionally, Table 1 shows Johnson's figure of merit (JFOM), which is commonly used in benchmarking of high frequency and high power devices. JFOM is expressed as $V_{sat} \cdot E_c / 2\pi$. As shown in the table, JFOM of GaN is 15 times higher than that of GaAs. Furthermore, the GaN HEMT grown on the SiC substrate is ideal from a viewpoint of the thermal management for high power devices, because SiC has better thermal conductivity than GaAs.

2-2 AlGaN/GaN HEMT structure

A heterojunction of AlGaN and GaN has large energy band offsets and makes AlGaN/GaN interface generate high-density two-dimensional electron gas (2DEG). In addition, the additive effects of spontaneous polarization and piezo polarization, characteristic properties of GaN, can combine to form on the order of 10^{13}cm^{-2} of 2DEG density. Therefore, the AlGaN/GaN HEMT can drive very high current. The GaN HEMT can also be operated by high voltage because the critical electric field of GaN is 8 times higher than that of GaAs. The GaN HEMT promises more than 10 times higher power than GaAs devices.

Unlike the GaN HEMT for cellular base stations, the GaN HEMT for microwave wireless communication requires high frequency operation. Therefore, we have optimized the wafer process and electrode structure, especially refinement structure of gate length. We achieved the high frequency performance of 27 GHz of ft[*2] in gate length of 0.35 µm.

2-3 Transistor performance

Figure 2 shows the drain current-voltage (Ids-Vds) characteristics of the fabricated GaN HEMT with gate length of 0.35 µm. The GaN HEMT has a saturated drain current (Imax) of about 680 mA/mm at a gate voltage of +2.0 V and the pinch off voltage of -2.5 V. In addition, the GaN HEMT has a high breakdown voltage of 170 V, which is sufficient value for 24V operation. The loadpull measurement[*3] results are shown in **Fig. 3**. The GaN HEMT shows good performance of saturated output power of 3 W/mm and PAE[*4] of 53% under power matching at frequency of 8 GHz.

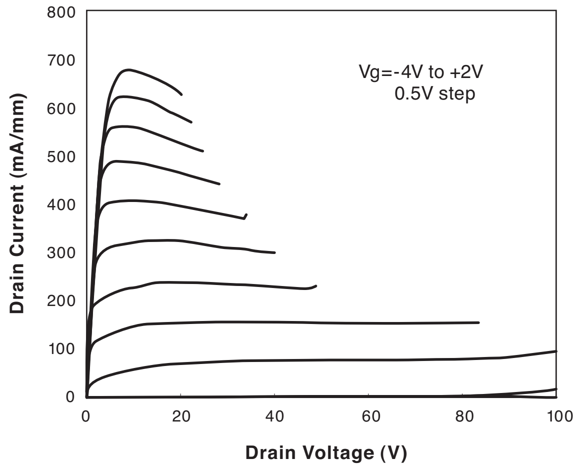

Fig. 2. Drain current-voltage characteristic of GaN HEMT

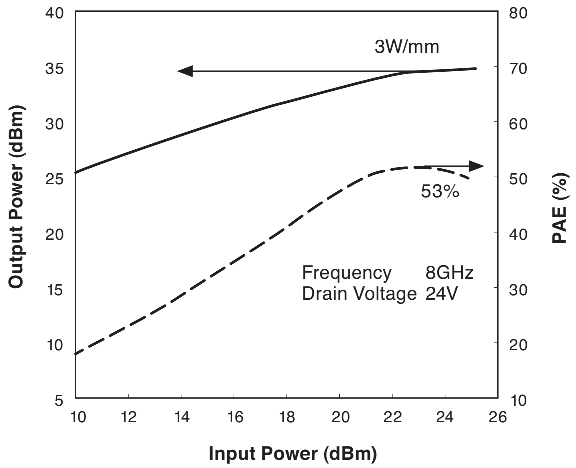

Fig. 3. Loadpull measurement results of GaN HEMT (power match)

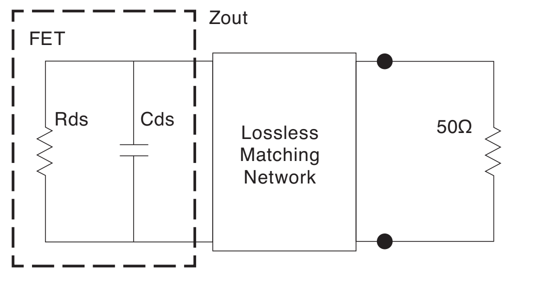

Fig. 4. Output side equivalent circuit of FET and matching circuit

3. C-band 20W-class Internally-Matched Broadband GaN Device

3-1 Limiting factors of broadband impedance matching

When the broadband matching of impedance is attempted, there are two possible limiting factors to be considered: Q-factor and output impedance (Zout) of a transistor. The former, theoretically investigated by Fano[(2)], gives gain-bandwidth-matching restriction for the ideal case of lossless matching network. The latter, arising from the finite number of filter elements[(3)], gives a relationship between impedance-transformation ratio and fractional bandwidth at a certain attenuation condition of a filter.

As shown in **Fig. 4**, the drain-to-source capacitance (Cds) of a FET is connected in parallel with the drain-to-source resistance (Rds). Output parameters of the GaN HEMT and GaAs FET of 20 W-class are summarized in **Table 2**. Here, the impedance transformation ratio (r) is

Table 2. 20W-class device parameter comparison

	Cds (pF)	Rds (Ω)	Cds*Rds (psec)	Zout (Ω)	Transformation ratio: r (50/Zout)
GaN HEMT	0.9	57	51	5.5	9.1
GaAs FET	8.4	4.9	41	0.7	71

defined as 50/Zout. According to Fano[3], smaller product of Cds and Rds, which is related to the Q-factor, means broader bandwidth characteristics. Estimated Rds*Cds of GaAs is smaller than that of GaN, and therefore, it seems GaAs has a more broadband property than GaN. However, it cannot be in reality because Fano's theory is based on an ideal network with an infinite number of elements. Actual matching networks are usually formed by two or three stage filters.

Estimated fractional bandwidth against the impedance transformation ratio with two-stage Chebyshev filter is shown in **Fig. 5**. Impedance transformation ratio of the GaN HEMT (r = 9.1) is quite small compared with that of GaAs FET (r = 71). As a result of this difference, the estimated fractional bandwidth of the GaN HEMT is 70%, while that of the GaAs FET is 40%. Consequently, the GaN HEMT has superior characteristics in broadband matching capability compared to the GaAs FET. This main factor is that the GaN HEMT has larger RF power density than the GaAs FET, and therefore, the GaN HEMT can have smaller gate-width than the GaAs FET.

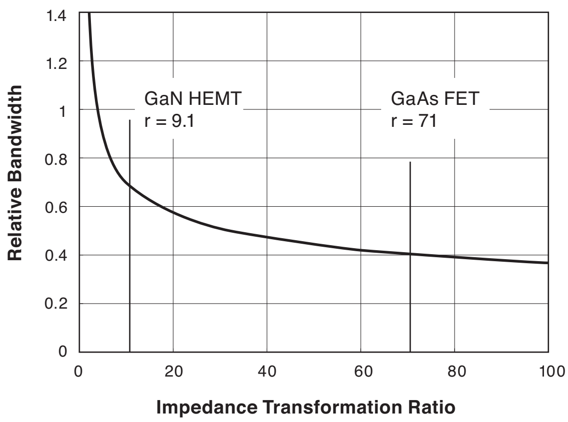

Fig. 5. Relationship of impedance transformation ratio and relative bandwidth (two-stage filter elements)

3-2 Performance of GaN device

Photo 1 shows an inner view of the internally-matched broadband GaN device that we have developed. The device consists of a single die of GaN HEMT with 12 mm gate periphery together with internal matching circuits in a package. The design of the internal matching circuits is based on an empirical methodology and the circuits are optimized to achieve high gain characteristics ranging from 5.9 GHz to 8.5 GHz. The input matching network consists of three stages of impedance transformer. The output matching network consists of two stages of Chebyshev type impedance transformer.

Figure 6 shows the measured S-parameters. The small signal gain (S21) is about 14 dB from 5.0 GHz to 8.5 GHz. The measured output power and PAE against the input power at 7.2 GHz with continuous wave signals are shown in **Fig. 7**. The GaN device attains more than 20 W (43 dBm)

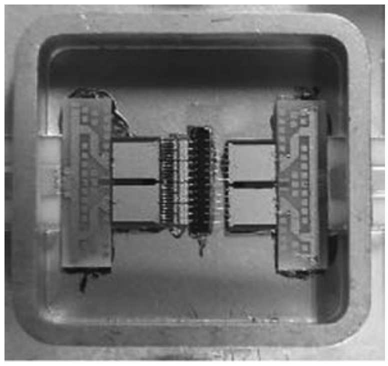

Photo 1. Inner view of 20W-class internally-matched broadband GaN device

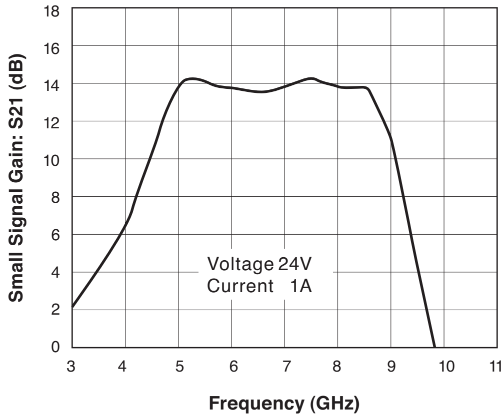

Fig. 6. Small signal characteristics of 20W-class GaN device

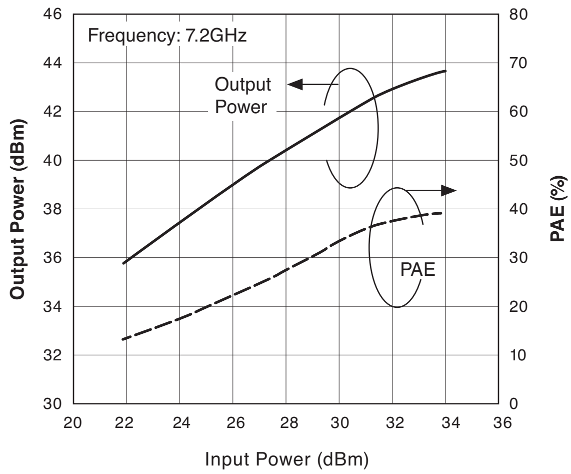

Fig. 7. Large signal characteristics of 20W-class GaN device

saturated output power and about 40% PAE. **Figure 8** shows the measured power performance as a function of frequency compared with our commercially available GaAs FET products[4], indicated as a dotted line. The GaN device, indicated as a solid line, exhibits excellent perform-

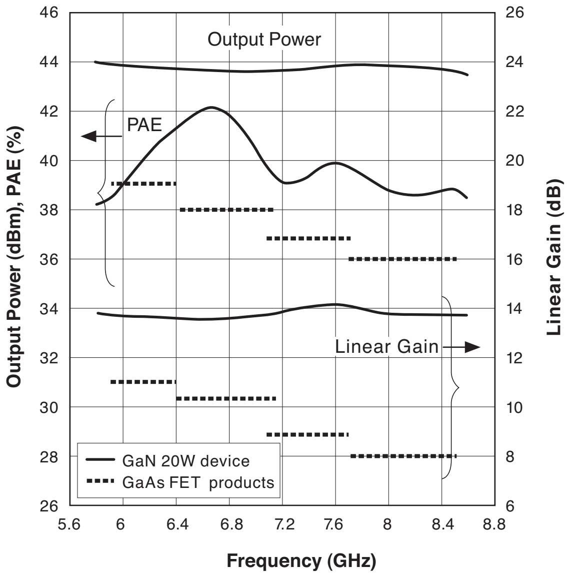

Fig. 8. Broadband performances of 20W-class GaN device

ance of the saturated output power of 43 dBm (20 W), PAE of about 40%, and the linear gain of 13.5 dB over the wide frequency range from 5.9 GHz to 8.5 GHz. In the 20 W-class, an internally-matched broadband GaN device realized the frequency band of four GaAs products with the one GaN device(5). In addition, PAE of the GaN HEMT attained 3 point and linear gain was 5.5 dB higher than that of the GaAs FET at 8.5 GHz.

4. Conclusion

We have developed a higher frequency operation GaN HEMT for microwave wireless communication by refinement of device structure, based on our GaN HEMT technology established for cellular base stations. The 20 W-class internally-matched broadband GaN device realized the frequency band for four GaAs products by one GaN device, taking advantage of high-power and broadband property of the GaN HEMT. We plan to continue the development of the GaN HEMT for microwave wireless communication and efficiently produce devices employing the superior features of the GaN HEMT.

Technical Term

*1 HEMT : High Electron Mobility Transistor
One of the field effect transistors, incorporating a junction between two materials with different band gaps as the channel instead of a doped region. The channel has few collisions with impurities, and is formed with high electron density.

*2 ft : transition frequency
An index showing the high-frequency performance of a transistor. It is also known as current gain cutoff frequency, or the gain-bandwidth product.

*3 Loadpull measurement
One of the evaluation methods of the large signal RF characteristics. This method uses mechanically variable impedance adjustment equipment called "tuners," and can evaluate characteristics in various impedance matching conditions.

*4 PAE : Power Added Efficiency
An index for rating the efficiency of a power amplifier that takes into account the effect of the gain by the amplifier.

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