High-Efficiency L-Band 200-W GaN HEMT for Space Applications

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We have developed a high-efficiency L-band 200-W GaN HEMT for space applications. Incorporating two 100-W dies, the GaN HEMT achieves a PAE of 71% and DE of 74.6% at 1.58 GHz in CW operation, demonstrating world-class efficiency in this product range. In a space qualification test conducted under high temperature and RF overdrive conditions, this GaN HEMT showed excellent performance, satisfying all the reliability and lifetime requirements for space applications. This paper describes the feasibility of an SSPA using the GaN HEMT, which will contribute to a reduction in the size and weight of satellites.

Keywords: GaN HEMT, high efficiency, high output, satellite applications, space qualification test (SQT)

1. Introduction

There has been growing demand for efficient, high-output power amplifiers due to the increase in satellite applications such as navigation systems and satellite communications.

Conventionally, travelling wave tube amplifiers (TWTAs) have been widely used to attain high output power in applications that require an output of at least 50 W in the L-band*[1] or higher frequency bands. Recently, gallium nitride high electron mobility transistors (GaN HEMTs)*[2] have been used as solid state power amplifiers (SSPAs) to attain high output power that cannot be generated by conventional gallium arsenide field effect transistors (GaAs FETs).*[3] SSPAs are increasingly expected to replace TWTAs.

Meanwhile, efforts are under way to develop all-electric satellites powered by electric propulsion engines. Accordingly, the need for SSPAs will increase to help reduce the size and weight of satellites.

This paper introduces our highly efficient (74.6%), high-output (200 W), and highly reliable L-band GaN HEMT that has been developed as a feasible solution to replace TWTAs.

2. GaN HEMT Technology

2-1 GaN HEMT structure

The cross-sectional structure of our GaN HEMT is shown in Fig. 1. The field plate structure relaxes the electric field and attains high withstand voltage characteristics. However, this structure increases the parasitic capacitance and leads to decreased efficiency.[1]

The dimensions were optimized to attain high withstand voltage and high efficiency at the same time. A via hole that penetrates the silicon carbide (SiC) substrate was provided at the source for grounding.

Other structures shown in Fig. 1 were designed to provide sufficient reliability in satellite applications.

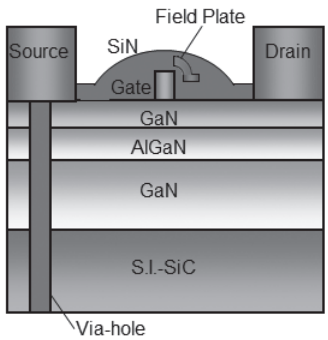

Fig. 1. Cross section of the GaN HEMT

2-2 Basic characteristics of GaN HEMTs

Figure 2 shows the RF characteristics of a basic unit transistor (gate width: 2.25 mm) that were measured using the load pull*[4] technique under the pulse condition (width: 12 μs, duty: 10%) at 1.58 GHz.

The output power (Pout), gain (Gain), power-added efficiency (PAE), and drain efficiency (DE) are plotted in this figure. In the measurement, the load impedance for the

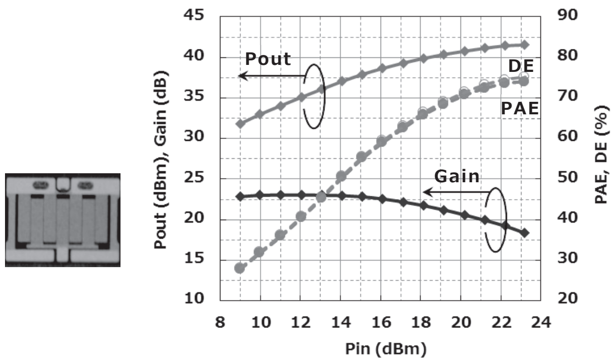

Fig. 2. RF characteristics of a basic unit transistor

fundamental frequency and second harmonic frequency was adjusted at the point where the output was balanced with efficiency. As shown in this figure, the drain efficiency of about 75% was attained with the output of 41.5 dBm.

The left panel in Fig. 3 shows the contours for the maximum Pout/PAE for the fundamental frequency and the right shows the phase for maximum efficiency of the second harmonic. In the circuit design, these impedances were scaled for the actual die gate width and used as the reference load.

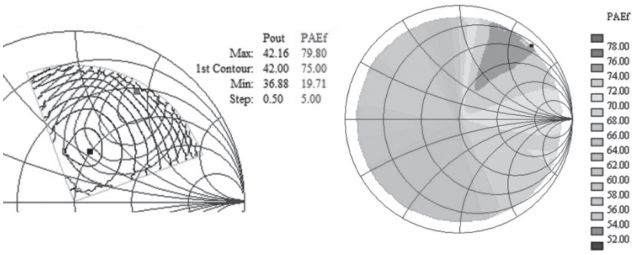

Fig. 3. Load pull measurement results of fundamental frequency (left) and second harmonic (right)

3. Development of a 200 W GaN HEMT

3-1 Device design

To attain the 200 W output, the gate width for the 100 W GaN HEMT was determined based on the load pull measurement result shown in Fig. 3, and it was decided to use two 100 W GaN HEMTs in parallel, each with a gate width of 24 mm. The die layout is shown in Fig. 4.

The 1.5 GHz band, which is mainly used for navigation and mobile communication satellites, was selected for the operation frequency. This relatively low frequency increased the size of the matching circuit, making it difficult to attain perfect matching to 50 Ω in the package.

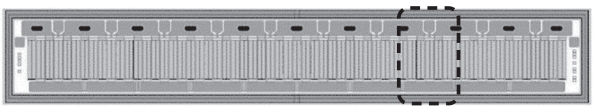

Fig. 4. 100 W GaN HEMT die layout

Accordingly, the package was designed to attain partial matching (15–30 Ω), and the 50 Ω matching was attained using an external matching circuit. In the circuit design, an accurate small signal model of the basic unit transistor (gate width: 2.4 mm, see Fig. 4) was extracted.

The output load impedance of the fundamental frequency and second harmonic for the large signal characteristics was extracted by the load pull measurement to match the circuit load with the maximum efficiency point. In terms of the second harmonic for the input, it is well known that the maximum efficiency point is close to the short circuit impedance (180°).[2]

Thus, regarding the basic frequency on the input side, the load was adjusted to the maximum gain point derived from the source pull measurement. The second harmonic was adjusted to the impedance close to the short circuit impedance.

4. 200 W GaN HEMT Evaluation Result

4-1 RF characteristics

Photo 1 shows the internal circuit of our 200 W GaN HEMT, and Photo 2 shows an evaluation board equipped with an external matching circuit. The overall size of the package is 24 mm × 17.4 mm. The input and output matching circuit in the package is formed on an alumina and highly dielectric substrate.

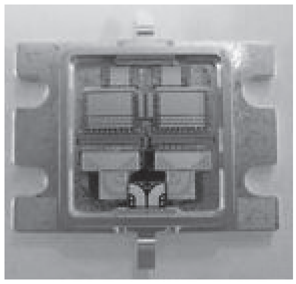

Photo 1. Internal circuit of the L-band 200 W GaN HEMT

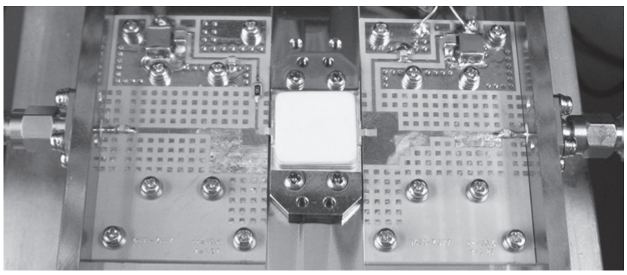

Photo 2. Evaluation board for the L-band 200 W GaN HEMT

The output power, DE, PAE, and gain characteristics during CW operation (frequency: 1.58 GHz, case temperature [Tc]: 45°C) are shown in Fig. 5. The figure indicates the saturation output of 53.2 dBm (210 W), linear gain (GL) of 18.3 dB, PAE of 71%, and DE of 74.6%.

Figure 6 shows the frequency characteristics of output power and PAE. The output is at least 52.8 dBm, and the PAE is at least 69% in the 50 MHz bandwidth. The output power and power-added efficiency were also measured at low temperature (Tc = −40°C) and high temperature (Tc = 85°C), but no oscillations or spurious signals,*5 etc. were observed. The operation was confirmed to be stable.

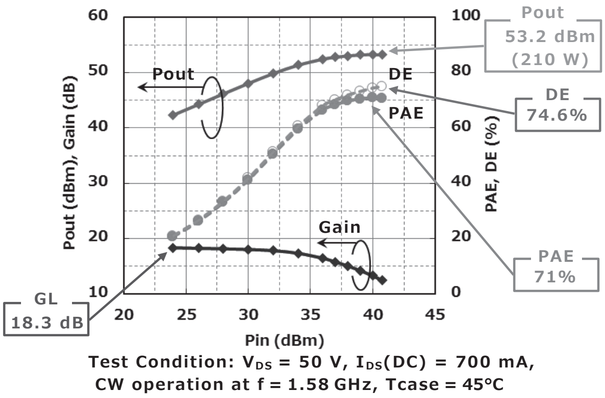

Fig. 5. RF characteristics of the L-band 200 W GaN HEMT

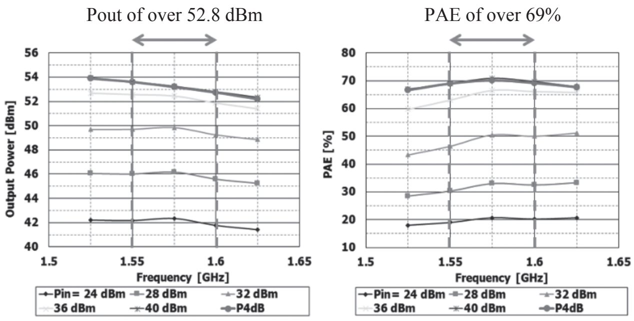

Fig. 6. RF frequency characteristics of the L-band 200 W GaN HEMT

4-2 Thermal design and verification result

Thermal design is another important factor because the GaN HEMT is intended for CW operation. Since our GaN HEMT is formed on a SiC substrate (see Fig. 1), the size of the substrate is a main parameter determining the thermal resistance (Rth).(3)

Figure 7 shows the results of an experiment to determine the correlation between the GaN die size (equivalent to the SiC size) and thermal resistance; the figure indicates an excellent correlation.

We designed a 100 W GaN HEMT die measuring 6.0 mm × 0.86 mm to provide appropriate thermal resistance to maintain maximum reliability under CW operation. The expected thermal resistance was 1.1°C/W.

The measured thermal resistance of the 200 W GaN HEMT was 0.6°C/W, which was very close to the expected value. The estimated channel temperature (Tch) of the 200 W GaN HEMT at 1.58 GHz (during RF operation) was calculated by:

$$Tch = (PDC^{*} + Pin - Pout) \times Rth + Tc = 136°C$$

*PDC: Direct current power supplied from the bias power source

Here, the case temperature (Tc) is 85°C (maximum temperature expected for satellite applications). The 200 W GaN HEMT proved to be highly reliable at the channel temperature of 136°C, as demonstrated by the result of a reliability test as described in the next section.

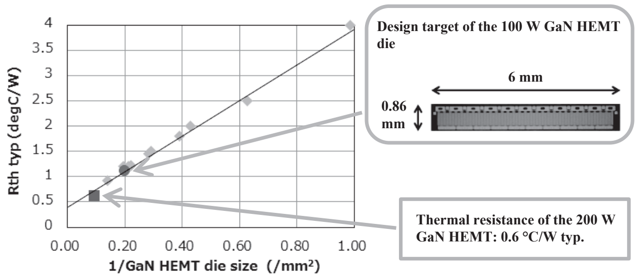

Fig. 7. Correlation between the GaN HEMT die size and thermal resistance

5. Reliability Test

5-1 Space qualification test (SQT)

We conducted a space qualification test (SQT) on the GaN HEMT in accordance with the standard space qualification procedures established based on MIL-PRF-19500, a global standard.

Table 1 lists the life test and environmental test items for the SQT (except for radiation hardness test items).

In terms of the life test, the long-term reliability was verified based on the DC high temperature operating life test (DC HTOL), RF high temperature operating life test (RF HTOL), and RF step stress test.

Table 1. Space qualification test (SQT)

Category	Test item	
Life test	DC HTOL (V_{DS} = 60 V, Tch = 250, 275, 300, 315°C) RF HTOL (V_{DS} = 55 V, Tch = 270, 290, 310°C, P4dB) RF step stress (V_{DS} = 60 V, Pin = P3dB ~ P13dB, Two hours each)	
Environmental test	Thermal environment	Thermal shock Temperature cycle
	Mechanical environment	Shock and vibration Constant acceleration

In terms of the environmental test, satisfactory results were obtained from the thermal environment (thermal shock, temperature cycle) and mechanical environment (shock, vibration, constant acceleration) tests.

A failure mode (i.e., decreased gain) was observed in both DC HTOL and RF HTOL. The calculated activation energy (Ea) is 2.10 eV for DC HTOL and 2.21 eV for RF HTOL. Ea of DC HTOL was very close to that of RF HTOL. Thus, the failure modes of DC HTOL and RF HTOL were considered to be identical.

The DC HTOL and RF HTOL results and the Arrhenius plot derived from the life test are shown in Figs. 8 and 9, respectively. The mean time to failure (MTTF) at the channel temperature of 200°C is projected to be 2.34×10^{7} hours (2,671 years) for DC HTOL and 1.18×10^{7} hours (1,347 years) for RF HTOL. This MTTF is sufficient for satellite applications whose service life is typically 15 years. As discussed above, the estimated channel temperature when the 200 W GaN HEMT is operated is 136°C, and the MTTF is 5.71×10^{10} hours. The reliability is sufficiently high.

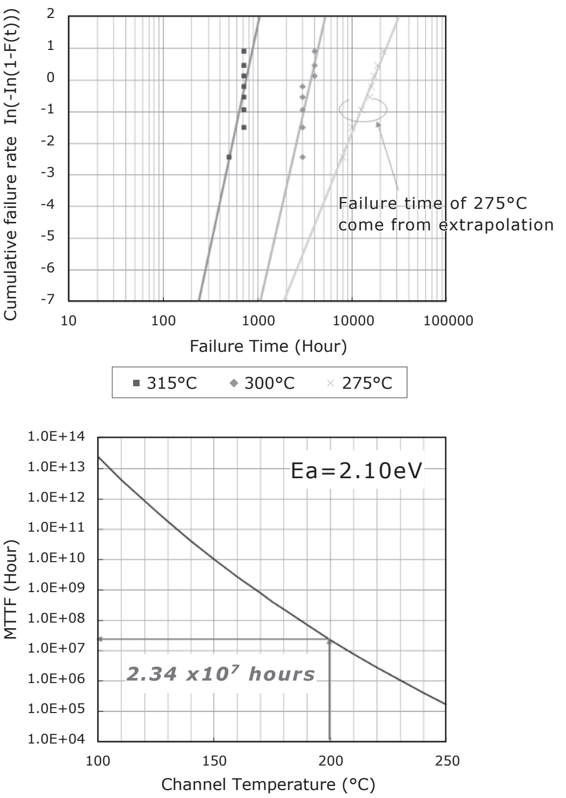

Fig. 8. Weibull distribution (top) and MTTF (bottom) of DC HTOL

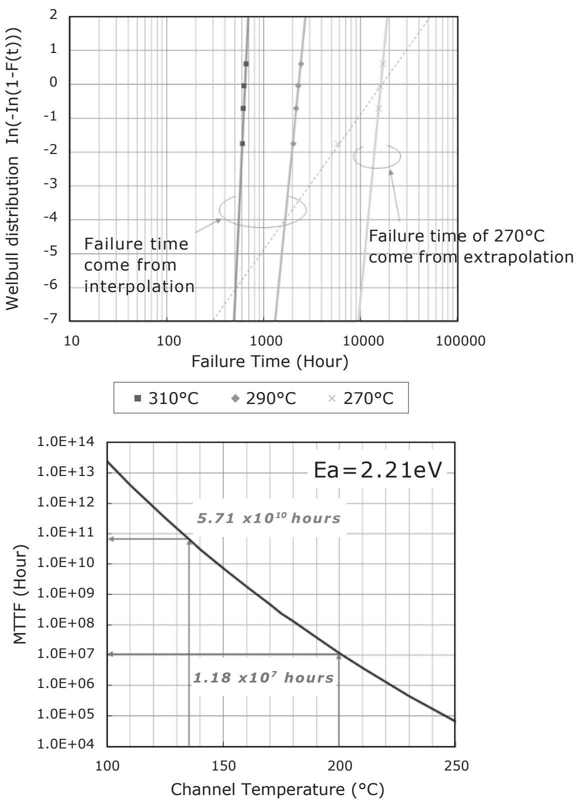

Fig. 9. Weibull distribution (top) and MTTF (bottom) of RF HTOL

5-2 Radiation hardness test

Radiation hardness is also an important factor for applications in space. Three types of radiation test are commonly used: single event effect (SEE),*6 total ionizing dose effect (TID),*7 and proton beam irradiation.[4] We conducted an SEE test that was considered to be most important for the GaN HEMT.

The SEE test was conducted under two different conditions: RF operation under the normal bias condition (Condition A) and pinch-off with no RF signal input (Condition B). The details of the test are shown in Table 2.

The GaN HEMT showed no failures under Condition A. The safe operating area (SOA) was attained under Condition B (see Fig. 10). The GaN HEMT burnt out at VDS = 195 V or more, which is at least three times the value of VDS = 50 V and sufficient for normal operation. These results demonstrate that our GaN HEMT offers sufficient reliability against radiation.

Table 2. Single event effect (SEE)

Condition A: During RF operation

Source	^{132}Xe
Energy [MeV]	650
Fluence [piece/cm^2]	~ 3×10^5
Flux [piece/cm^2/sec]	~ 3000
LET*8 (Si) [MeV/(mg/cm^2)]	66.3
Drain voltage V_{DS} [V]	~ 53
Drain current I_{DS} (DC) [mA]	250
Output level	Gain compression point (up to 4 dB)

Condition B: Pinch-off operation, no RF input

Source	^{132}Xe	^{124}Xe
Energy [MeV]	650	420
Fluence [piece/cm^2]	~ 3×10^5	
Flux [piece/cm^2/sec]	~ 3000	
LET (Si) [MeV/(mg/cm^2)]	66.3	67.7
Drain voltage V_{DS} [V]	~ 225	
Gate voltage V_{GS} [V]	-6	

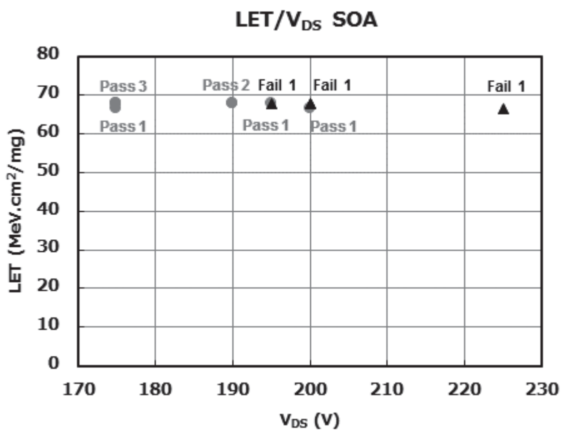

Fig. 10. Safe operation area by SEE without RF input

6. Conclusion

We have developed a highly efficient 200 W GaN HEMT that attains a DE of 74.6% at 1.58 GHz under CW operation. SSPAs using this GaN HEMT are expected to achieve the highest level of efficiency among L-band 200 W-class amplifiers. This GaN HEMT design features thermal resistance settings to ensure sufficient reliability at the maximum case temperature and maximum CW power. We verified that our GaN HEMT passes the SQT (life and environment) and radiation hardness test (SEE) and is sufficiently reliable for use in space. Based on these results, we have demonstrated the feasibility of the GaN HEMT SSPA for satellite applications.

Technical Terms

∗1 L-band: L-band refers to the 1–2 GHz bandwidth in the microwave frequency classification. It is used for various applications such as navigation (e.g., GPS) and mobile communication by communication satellites.

∗2 High electron mobility transistor (HEMT): A transistor that uses two-dimensional electrons induced at the semiconductor junction interface. A HEMT can form a channel with high electron density that is hardly affected by impurity scattering.

∗3 Gallium arsenide field effect transistor (GaAs FET): A GaAs FET is suited to amplifying high frequencies (e.g., microwaves) because electrons can move almost five times faster than in silicon.

∗4 Load pull: Load pull is a method for evaluating large signal characteristics. The characteristics are evaluated while changing the impedance matching condition using a variable mechanical impedance device (a tuner).

∗5 Spurious signals: Spurious signals refer to unnecessary signal components other than input signals or specified frequency components that are included in signals output from an amplifier, etc.

∗6 Single event effect (SEE): An effect that causes temporary malfunctions or permanent failures when ionization generates a high density charge on a semiconductor device due to the incidence of one high energy particle (e.g., proton, heavy ion).

∗7 Total ionizing dose effects (TID): Electrons and electron holes are generated by cosmic radiation. Electron holes accumulate in the insulating materials of the integrated circuits and change the device characteristics gradually, resulting in deterioration of characteristics and failure. TID is also called cumulative dose effect.

∗8 Linear energy transfer (LET): LET indicates the energy of particles acting on matter (per unit volume density, per unit distance).

References

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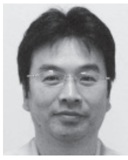

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