Development of High Reliability GaN HEMT for Cellular Base Stations

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In the 3rd generation mobile communication systems such as W-CDMA, data traffic by cellular phones and other wireless tools has been steadily increasing. The data traffic is expected to further increase due to the wide spread use of smartphones and the introduction of WiMAX and LTE services that offer high-speed, high-capacity data transmission. A GaN (gallium nitride) HEMT (high electron mobility transistor) is suitable for the high-speed, high-power application owing to its excellent material properties. Although the actual products have been released for the cellular base station application, there are few reports studying the reliability of the GaN HEMT in detail. In this paper, we demonstrate the ruggedness and reliability of the GaN HEMT in several tests and describe the performance of the latest 500W-class asymmetric Doherty amplifier with the GaN HEMT.

Keywords: GaN HEMT, base station, reliability, ruggedness, amplifier

1. Introduction

In the 3rd generation mobile communication systems such as W-CDMA (Wideband Code Division Multiple Access), data traffic by cellular phones and other wireless devices has been steadily increasing. This data traffic is expected to further increase due to the wide spread use of smartphones and the introduction of WiMAX* (Worldwide Interoperability for Microwave Access) and LTE (Long Term Evolution) services that offer high-speed, high-capacity data transmission. Under these conditions, amplifiers used in base stations must exhibit high output power and high efficiency performance. However, it is difficult to meet these requirements with a Si-LDMOS (silicon laterally diffused metal oxide semiconductor) or GaAs FET (gallium arsenide field effect transistor).

A GaN HEMT (gallium nitride high electron mobility transistor) is suitable for the high-speed, high-power application in a wide bandwidth owing to its excellent material properties such as high breakdown voltage and high electron saturated velocity. Although the GaN HEMT has already been released for the cellular base station application, there are few reports[1] studying the reliability of this device in detail.

Thus far, we have shipped more than a million devices into the market since we successfully released the world's first GaN HEMT commercial products[2],[5]. The demand for the HEMT is expected to increase not only for use in base stations but also for terrestrial and satellite communications and radar devices[3].

In this paper, we demonstrate the ruggedness and reliability of the GaN HEMT in several tests and describe the performance of the latest 500W-class asymmetric Doherty amplifier with the GaN HEMT.

2. GaN Transistor

2-1 Material properties

Table 1 shows the key material parameters of major semiconductor materials used in high frequency applications. GaN has a saturated electron velocity (V_{sat}) twice as high as that of Si or GaAs, and a critical breakdown field (E_c) 10 times and 7.5 times larger than those of Si and GaAs. Additionally, JFOM (Johnson's figure of merit) of GaN is 27 times higher than that of Si and 15 times higher than that of GaAs. JFOM, expressed as $V_{sat} \cdot E_c/2\pi$, is a common benchmark for the performance of high frequency and high power devices.

Table 1. Material parameters comparison

	Si	GaAs	SiC	GaN
Band Gap (eV)	1.1	1.4	3.2	3.4
Saturated Velocity ($\times 10^7$cm/s)	1.0	1.3	2.0	2.7
Critical Breakdown Field (MV/cm)	0.3	0.4	3.0	3.0
Mobility (cm^2/V·s)	1300	6000	600	1500
Thermal Conductivity (W/cm·K)	1.5	0.5	4.9	1.5
Johnson's Figure of Merit (JFOM) versus Si	1.0	1.7	20	27

2-2 GaN HEMT structure

The epitaxial layers of the GaN HEMT grown on a semi-insulating SiC substrate are ideal for high power devices from a viewpoint of thermal management due to the good thermal conductivity of SiC. In addition, the additive effects of spontaneous polarization and piezo polarization, which are characteristic properties of GaN crystals, can generate 2DEG (two-dimensional electron gas) on the order of 10^{13}cm^{-2}. Therefore, the GaN HEMT promises more than 10 times higher output power than GaAs devices for the same gate width. The gate length is optimized to obtain sufficient power gain for the base station application.

In the early stage of GaN HEMT development, the control of gate leakage current is critical to ensure its reliability. The gate leakage current should be reduced to the order of 10^{-6} A/mm. We have achieved this low leakage current by processing GaN HEMT surfaces appropriately.

Figure 1 shows the drain current-voltage (I_{ds}-V_{ds}) characteristics, and **Fig. 2** shows the 3-terminal breakdown voltage of the GaN HEMT. Saturated drain current is 600 mA/mm at V_{gs} of +2.0 V, and breakdown voltage is 250 V at V_{gs} of -7.0 V. These characteristics of high saturated drain current and high breakdown voltage cannot be achieved with Si- or GaAs-based power devices, indicating the superiority of the GaN HEMT.

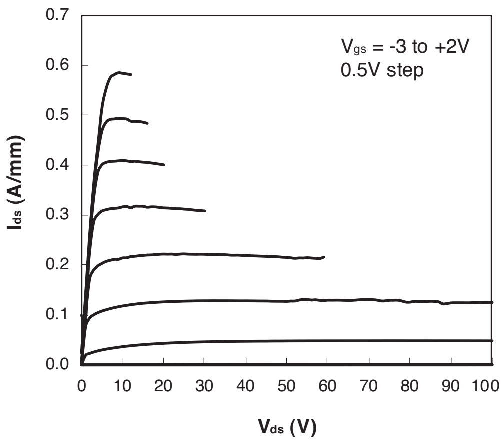

Fig. 1. Drain current-voltage characteristics of GaN HEMT

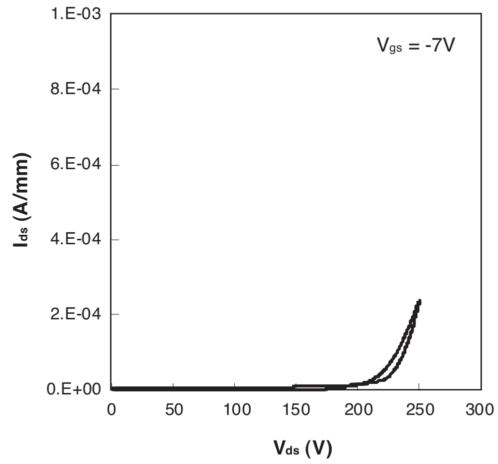

Fig. 2. 3-terminal breakdown voltage of GaN HEMT

3. Ruggedness and Reliability

3-1 Area of safe operation

When it comes to product reliability, long term reliability characterized by MTTF (Mean Time To Failure) is the focus. However, for the commercialization of the GaN HEMT, ruggedness is also important to be operated under various RF conditions.

To estimate the maximum drain-source voltage (Vds) under RF operation, we simulated a drain-source voltage waveform in an inverse class-F operation used for a high efficiency amplifier. **Figure 3** shows the simulation results at gain compression output power of 5 dB (P5dB) with Vds of 50 V and frequency of 2.1 GHz. The peak drain-source voltage was estimated to be around 160 V. For an inverse class-F operation, a 3-terminal breakdown voltage of over 160 V is required, and thus, the 3-terminal breakdown voltage of the GaN HEMT, which is 250 V, is sufficient to cope with a simulated peak drain-source voltage as shown in **Fig. 2**.

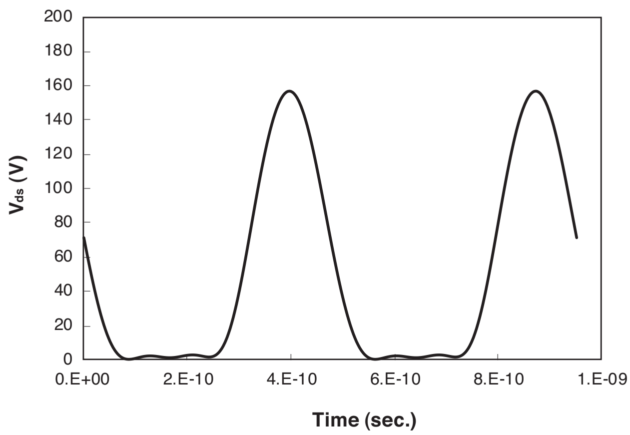

Fig. 3. The waveform of simulated drain-source voltage (V_{ds}) in inverse class-F operation at P5dB

Semiconductor transistors can be damaged by thermal breakdown or electric field breakdown, if the bias condition of RF operation is beyond the ASO (Area of Safe Operation). Therefore, it is important for the GaN HEMT to have a large ASO for high-power and high-temperature operation.

Figure 4 shows the simulation load line in an inverse class-F operation and the ASO at 200°C, which is a guaranteed channel temperature generally required for a high power amplifier used in a base station. The load line was simulated with V_{ds} of 50 V and output power of P5dB. The ASO was evaluated by the pulsed DC measurement to prevent an unexpected increase in the channel temperature. As shown in **Fig. 4**, the GaN HEMT achieved a 3-terminal breakdown voltage of 220 V at 200°C, which is sufficiently high for the expected peak drain voltage of 160 V, and the simulation load line was well inside of the ASO.

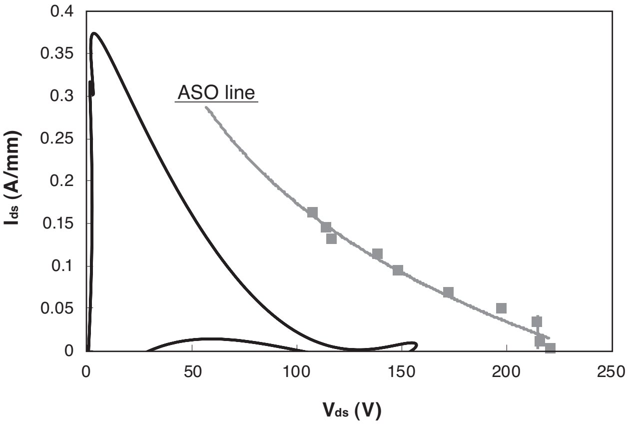

Fig. 4. Simulated load line and ASO line at 200°C

3-2 Ruggedness

To maximize the RF performance of the GaN HEMT, we generally evaluate its performance under the best matched load impedance condition, however, it is very important to prepare for operation under mismatched load impedance conditions such as high VSWR (voltage standing wave ratio). We carried out a ruggedness test with a VSWR of 10:1 using a load pull setup in CW (continuous wave) operation. The test results showed no damages or failures in its properties.

To confirm further ruggedness, we carried out an RF step stress test at up to P13dB. The results of the RF step stress test are shown in **Fig. 5**. We confirmed no property failures or significant degradation in the output power.

The results of the VSWR ruggedness test and the RF step stress test show that our GaN HEMT has sufficient ruggedness for a wide range of RF stress.

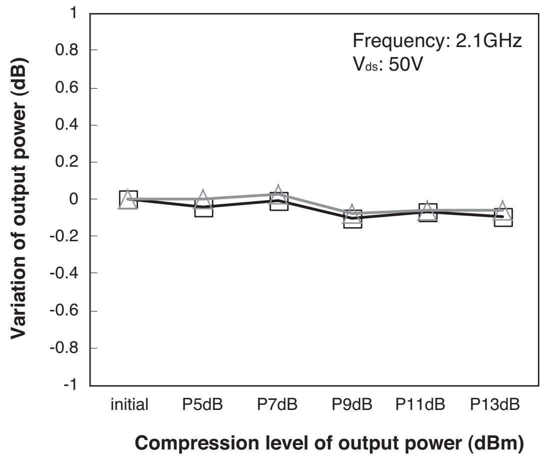

Fig. 5. RF step stress test results

3-3 Long-term reliability

We also carried out an operating life test of the GaN HEMT at high temperatures. In order to determine activation energy (E_a), the test was conducted at temperatures (T_{ch}) of 250°C, 275°C, 300°C, and 315°C. E_a was estimated to be 1.6 eV and MTTF was to be 1.07×10^6 hours (approximately 122 years) at T_{ch} of 200°C as shown in **Fig. 6**.

Furthermore, the failure rate of our GaN HEMT, which was calculated based on field return products, was less than 5 FITs (Failures In Time). These results indicate that our GaN HEMT has excellent long-term reliability.

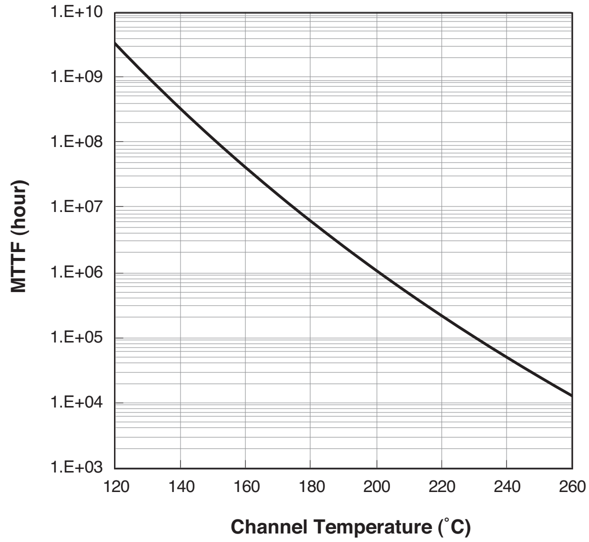

Fig. 6. Estimated MTTF

4. 2.6 GHz High Power GaN HEMT Device

We have developed a 500W-class asymmetric Doherty amplifier by combining 300W- and 200W-class GaN HEMTs. A top view of the asymmetric Doherty amplifier is shown in **Photo 1**. **Figures 7 and 8** show the power characteristics of this asymmetric Doherty amplifier at 2.6 GHz frequency band. We obtained a saturated output power of 57.3 dBm (537 W), a linear gain of 13.5 dB, and a drain ef-

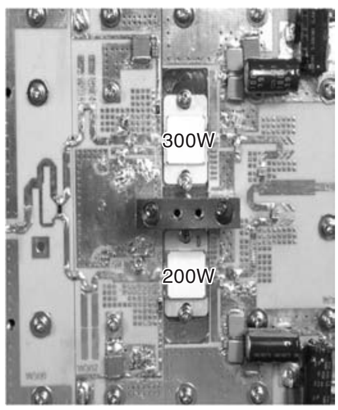

Photo 1. Top view of 500W-class asymmetric Doherty amplifier

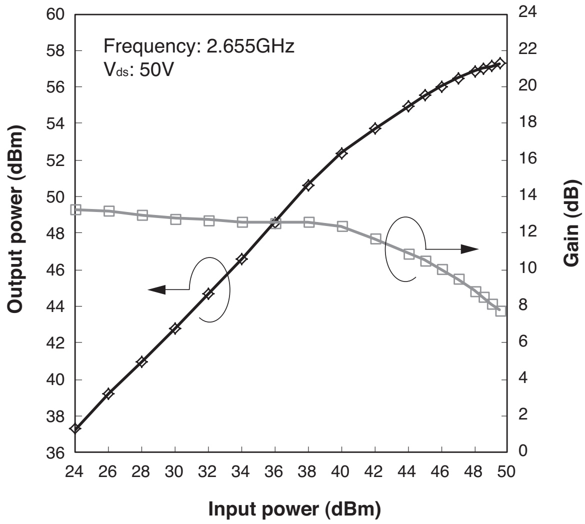

Fig. 7. Output power and gain characteristics of asymmetric Doherty amplifier

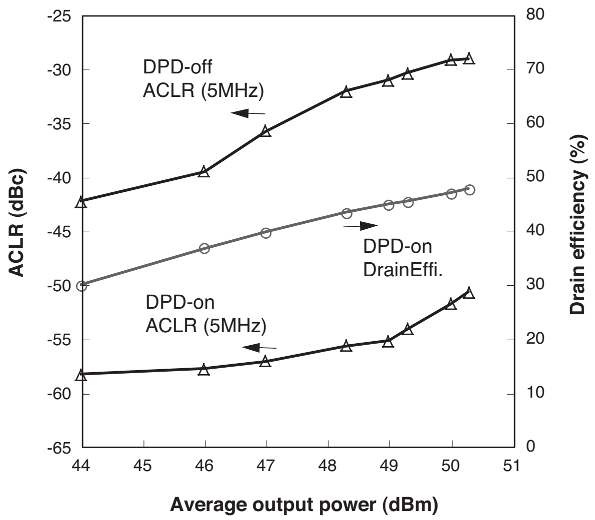

Fig. 9. ACLR and drain efficiency characteristics of asymmetric Doherty amplifier

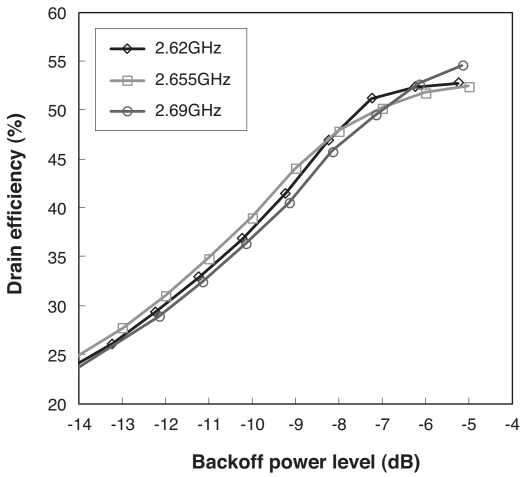

Fig. 8. Drain efficiency characteristics of asymmetric Doherty amplifier

ficiency of over 50% at 7 dB back-off output power.

The key performance factors of a power amplifier used in a cellular base station are high efficiency and high linearity, which have been a traded-off. In these days, DPD (Digital Pre-Distortion) techniques are frequently used to compensate for signal distortion caused by high efficiency amplifiers. **Figure 9** shows ACLR (Adjacent Channel Leakage Ratio) and drain efficiency characteristics when W-CDMA signals are input under the DPD operation. In order to investigate the adaptability of the Doherty amplifier to the DPD techniques, a commercially-available DPD test system was employed. A drain efficiency of 48% and a well-linearized ACLR of -50.6 dBc were achieved at the average output power of 50.3 dBm (107 W), which is a 7 dB back-off output power.

These results show the superiority of our GaN HEMT for the next generation base station systems which require high frequency, wide bandwidth, high output power and low power consumption.

5. Conclusion

Amplifiers used in base stations are required to be capable of high-frequency, power-saving operation at a wide bandwidth. A GaN HEMT transistor is suitable for use in cellular base stations and other wireless systems, owing to its excellent material properties. However, for the commercialization of the GaN HEMT, its reliability and quality needed to be thoroughly tested.

In this paper, we have demonstrated the ruggedness and reliability of the GaN HEMT, as well as the superiority of our 500W-class asymmetric Doherty amplifier at 2.6 GHz frequency band. We intend to accelerate GaN HEMT development even more for WiMAX, LTE and the other wireless communication systems.

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