Consideration of Design Strategy of GaN HEMTs for Base Stations

Ken KIKUCHI* and Hiroshi YAMAMOTO

In recent years, gallium nitride high-electron-mobility transistor (GaN HEMT) amplifiers with high efficiency have been adopted due to the increasing demand for downsized and low-power-consumption base stations. In 5G networks, where further improvement in network capacity and data rates is required, the presence of GaN HEMTs is expected to grow further due to their advantages in broadening the bandwidth of amplifiers. This paper describes the characterization and analysis method for the current source of GaN HEMTs that we are working on to develop the GaN HEMT amplifiers for base stations. We newly adopted a large-signal low-frequency measurement that enables evaluation under conditions close to the actual radio frequency operation, to explore design guidelines for GaN HEMTs. In addition, we analyzed the effect of gate voltage clipping in class-F and inverse class-F operation, which is known as a method for improving the efficiency of amplifiers by using a large-signal model to figure out the limiting factor of efficiency.

Keywords: GaN, HEMT, large-signal model

1. Introduction

In recent years, gallium nitride high-electron-mobility transistor (GaN HEMT*1) amplifiers with high efficiency have been adopted due to the increasing demand for downsized and low-power-consumption base stations. The market demand for base station amplifiers, especially for their low cost, has led to the use of silicon laterally diffused metal oxide semiconductor (Si-LDMOS) transistors with its superior price-performance ratio. However, along with the growing demand for compact and low-power base stations, LDMOS transistors have been increasingly replaced with GaN HEMTs, which have superior efficiency characteristics. In the fifth-generation mobile communications (5G) market, where services are now beginning to be introduced, there is a need for further improvements in data transmission capacity and speed. Therefore, it is strongly expected that the presence of GaN HEMTs, which is advantageous for its broadband characteristics, will increase.

Sumitomo Electric Industries, Ltd. has been engaged in research and development of GaN HEMT since 2000, and we became the first company in the world to start mass production in 2006. Since then, we have been a leader in the GaN HEMT market.(1)–(3) In order to lead the market, a variety of technologies are required for product development. The technical framework of GaN HEMT development is broadly divided into the following four categories, as illustrated in Fig. 1.

① Crystal growth
② Device process
③ Circuit design/implementation
④ Power amplifier verification

Sumitomo Electric's GaN HEMT products for base station amplifiers are brought to market in the form of packaged discrete devices with GaN HEMT dice. To meet market requirements, we are working on improving reliability and cost reduction, as well as developing new technologies to improve the transistor's characteristics at each framework. This paper describes our novel characterization and analysis techniques to explore design guidelines for GaN HEMTs and improve their performance.

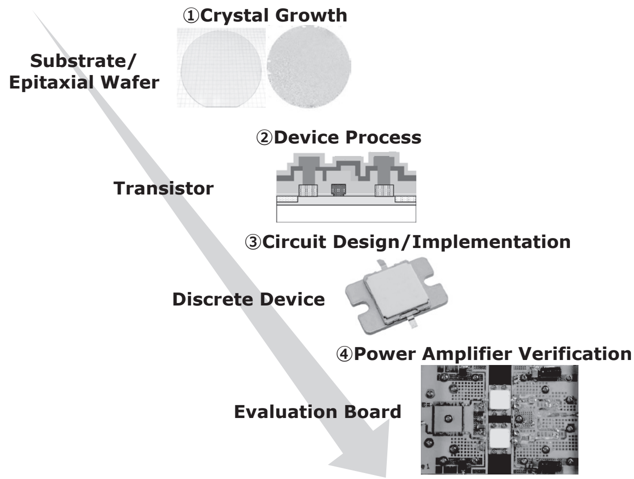

Fig. 1. Technical framework of GaN HEMT development

2. GaN HEMT Amplifier for Base Stations

2-1 Transistor technology

Table 1 shows the key material parameters of the major semiconductors used in microwave transistors.(4) The saturated electron velocity (V_{sat}) of GaN is twice or more higher than that of silicon (Si) and gallium arsenide (GaAs). The critical breakdown field (E_c) of GaN is 10 times and 7.5 times higher than Si and GaAs, respectively. As a result of these features, GaN HEMTs enable high power-density than Si-LDMOS. Consequently, the drain source capacitance (C_{ds}) per output power is much smaller for GaN than for Si-LDMOS, making it possible to realize a high-power and high-efficiency amplifier with low loss at high frequencies. Moreover, when compared with the same output power, GaN HEMT amplifiers can be smaller than Si-LDMOS amplifiers because of the high-power density. Furthermore, our GaN HEMTs are grown on a silicon carbide (SiC) substrate with high thermal conductivity, which is advantageous in terms of thermal management of high-power devices.

Figure 2 illustrates a schematic cross-sectional structure of a GaN HEMT. The GaN/aluminum gallium nitride (AlGaN) heterojunction forms large band discontinuity, and a highly concentrated two-dimensional electron gas is generated at the interface. Additionally, high electron density is achieved originating from the spontaneous and piezoelectric polarization of the nitride semiconductor, thereby making very-high-current driving possible. Moreover, a field plate structure is adopted for mitigating the electric field around the gate electrode.

Table 1. Material parameters comparison

	Si	GaAs	SiC	GaN
Bandgap (eV)	1.1	1.4	3.3	3.4
Saturated electron velocity ($\times 10^7$ cm/s)	1.0	2.0	2.0	2.5
Critical breakdown field (MV/cm)	0.3	0.4	3.0	3.0
Thermal conductivity (W/cm・K)	1.5	0.5	4.9	2.1

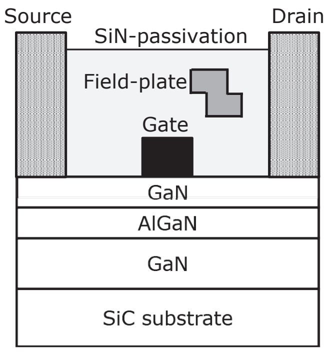

Fig. 2. Schematic cross-sectional structure of GaN HEMT

2-2 Circuit technology

Figure 3 illustrates a simplified equivalent circuit of a GaN HEMT amplifier. In a discrete device used in a base station system, transistors are mounted in a package with input and output terminals, and a matching network consisting of bond wires and capacitors is placed on both sides of the transistor. The matching network is designed to improve the efficiency. In recent years, waveform engineering, which is based on shaping transistor voltage and current waveforms, has attracted much attention to circuit designers of high-efficiency power amplifiers.(5)

Based on the power balance considering current and voltage waveforms at the current source of the transistor,

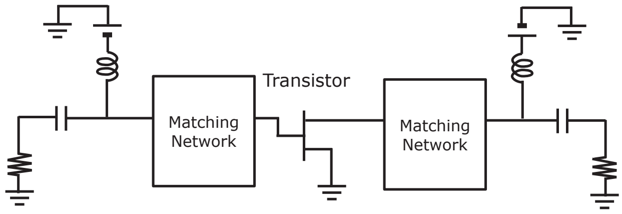

Fig. 3. Simplified equivalent circuit of a GaN HEMT amplifier

two design guidelines for the matching network to improve the efficiency of the amplifier are known as follows;

1 Power consumption by the overlap of current and voltage waveforms is reduced to zero.
2 Power consumption by the harmonic termination is reduced to zero.

A high-efficiency amplifier can be built by designing the matching network following these guidelines, i.e., by shaping current and voltage waveforms. The methods used for this purpose are grouped into several modes as operation classes determined according to bias conditions and harmonic termination conditions. In this section, we explain class-F and inverse class-F amplifier, which are commonly used in high-efficiency GaN HEMT amplifiers.

Both class-F and inverse class-F amplifiers are based on a class-B amplifier. The class-B amplifier has a sinusoidal drain voltage waveform and a half-sinusoidal drain-current waveform. In this setting, all harmonics are short terminated, where voltage harmonics are zero. Hence, the power consumption due to harmonics referred to in condition 2 becomes zero. Consequently, in the class-B amplifier, efficiency decreases due to current-voltage overlaps referred to in condition 1. To improve the efficiency, the drain voltage is controlled to exhibit a squared waveform in class-F, while the drain current exhibits a half-sinusoidal waveform, as in class-B. Figure 4 illustrates voltage and current waveforms of class-B and class-F. As shown in the figure, for the class-F amplifier, the squared waveform and half-sinusoidal waveform are used to achieve zero waveform overlap for the above-mentioned high efficiency condition 1, and the power consumption of the harmonics is reduced to zero by setting the even-order voltage of the harmonics to zero (the load terminated short) and the odd-order current to zero (the load to be terminated open) for condi-

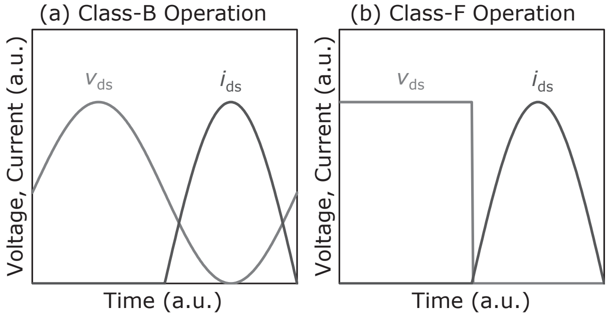

Fig. 4. Current and voltage waveforms: (a) class-B amplifier and (b) class-F amplifier

tion 2, thereby achieving a theoretical efficiency of 100%. The inverse class-F amplifier swaps the voltage and current waveforms of the class-F amplifier. The theoretical drain efficiency achieves 100% as in the class-F amplifier.

2-3 Designing a high-efficiency amplifier

As mentioned above, a high-efficiency amplifier requires improvements both in the GaN HEMT structure and process as a semiconductor device and in the matching network maximizing the performance of GaN HEMT itself. For this purpose, it is necessary to evaluate the characteristics of GaN HEMTs and to analyze the limiting factors for efficiency in radio frequency (RF) operation. Chapters 3 and 4 discuss current source evaluation of GaN HEMTs using large-signal low-frequency measurements and the analysis of efficiency-limiting factors at various operating classes using a large-signal model.

3. Current Source Evaluation by Large-Signal Low-Frequency Measurements

This chapter demonstrates current source evaluation of GaN HEMT by using large-signal low-frequency (LSLF) measurements.[(6)]

Recently, the LSLF measurement was proposed as a technique of evaluating load lines and time-based current and voltage waveforms under realistic RF operations.[(7),(8)] In this technique, characterization of the current source is enabled in the equivalent circuit of the GaN HEMT shown in Fig. 5, since the measurement frequency of 2 MHz allows the reactance component in the transistor to be ignored. Thus, it becomes possible to evaluate the effects of electron traps*2 specific to GaN HEMT on the current source, more directly than conventional *I-V* measurements.

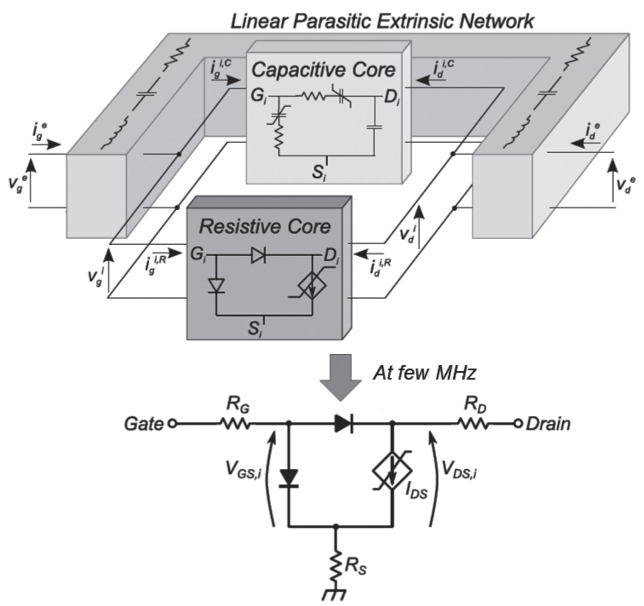

Fig. 5. Principle of LSLF measurements[(9)]

Firstly, Fig. 6 shows the measured load lines under class-B operation. The graph plotted with a dashed line was obtained from conventional pulsed *I-V* measurements. Voltage stress conditions in the pulsed *I-V* measurement were set as follows: V_{gq} = −5 V, V_{dq} = 50 V. Load lines obtained by LSLF measurements show an increase in on-resistance, compared with the pulsed *I-V* measurement results. Secondly, Table 2 compares RF characteristics measured at 4.4 GHz corresponding to the band in that the amplifier is actually used and RF characteristics obtained by LSLF measurements. In both measurements, the output load is set to the optimal condition for the output power. The saturated output power and efficiency of both are close to each other, indicating that the LSLF measurement is consistent with the practical RF operation.

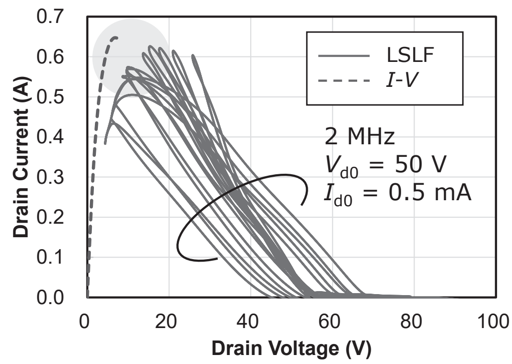

Fig. 6. Load lines obtained by LSLF measurements

Table 2. Comparison of RF characteristics

	Saturated output power	Saturated efficiency
2 MHz (LSLF)	8.0 W	62.3%
4.4 GHz	8.0 W	58.9%

The above-mentioned technique was used to compare the on-resistance of two types of GaN HEMT. Figure 7 presents the comparison results. For Types-A and Type-B, surface passivation conditions were intentionally changed, which resulted in a different electron trap condition. LSLF

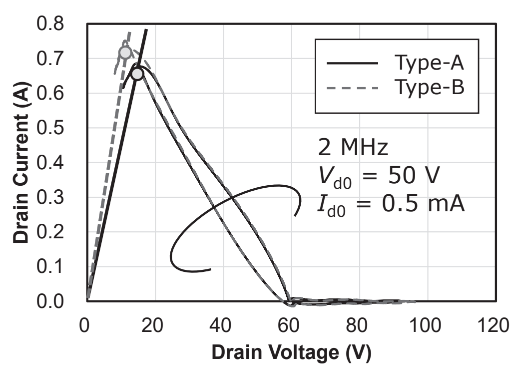

Fig. 7. Load line comparison

measurements shows that Type-B with optimized passivation condition reduces the on-resistance and increases the efficiency. Regarding efficiency, a similar trend was observed at 4.4 GHz, proving that LSLF measurements are useful as an evaluation technique for process technology development.

4. Analysis of Efficiency-Limiting Factors Using Large-Signal Model

This chapter describes the use of a large-signal model*[3] for analyzing efficiency-limiting factors in class-F and inverse class-F operations.[10]

Figure 8 illustrates the large-signal model of GaN HEMT used in the present study.

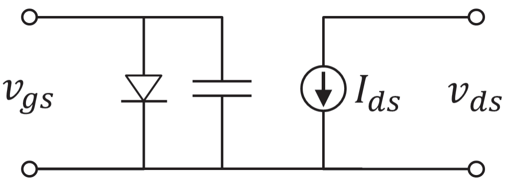

Fig. 8. Large-signal model of GaN HEMT

A simplified model is used here to analyze the effect of gate current through Schottky diode of a GaN HEMT on its efficiency, eliminating non-linear capacitance and other reactance. A simple transistor model by Cripps was adopted for the current source, as expressed below.[11]

$$I_{ds} = I_{max}\left(1 - \exp\left(-\frac{v_{ds}}{V_k}\right)\right) f(v_{gs}) \quad \cdots\cdots (1)$$

where I_{max} is the maximum drain current, v_{ds} is the drain-source voltage, and v_{gs} is the gate-source voltage. V_k, known as the knee voltage, is an indicator that defines the on-resistance. The function expressed as $f(v_{gs})$ was defined as follows, dividing the conduction characteristics of GaN HEMT into pinch-off, on-state, and saturation regions.

$$f(v_{gs}) = \begin{cases} 0, & v_{gs} < V_{th} \\ (v_{gs} - V_{th})/(V_{gsmax} - V_{th}), & V_{th} \le v_{gs} \le V_{gsmax} \\ 1, & V_{gsmax} < v_{gs} \end{cases} \quad \cdots (2)$$

where V_{th} is the threshold and V_{gsmax} is the maximum gate voltage.

Furthermore, the characteristics of the Schottky diode were defined as follows:

$$I_{gs} = \begin{cases} 0, & v_{gs} \le V_{gsmax} \\ I_0 \exp\left((-v_{gs} + V_0)\, q/kT - 1\right), & V_{gsmax} < v_{gs} \end{cases} \quad \cdots (3)$$

where I_0 and V_0 are both coefficients in the model.

In the model, two efficiency-limiting factors are considered: on-resistance, defined by V_k, and gate voltage clipping caused by the gate current flowing through the Schottky diode. The analysis aims to identify which is the dominant efficiency-limiting factor in class-F and inverse class-F operations.

Figure 9 presents the measured load line under inverse class-F and class-F operations. We also adjusted the parameters of our simplified model and show the I_{ds} curve (dotted lines in Fig.7).

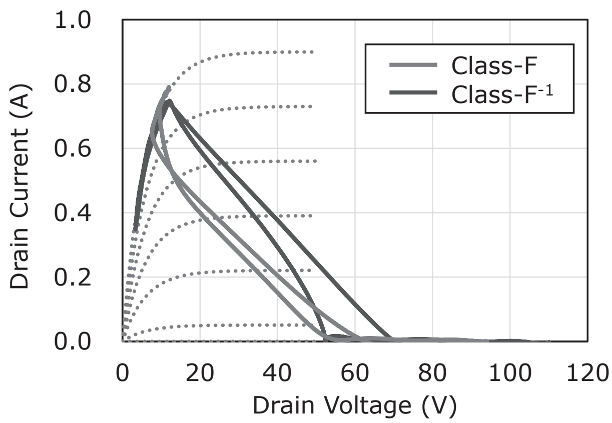

Fig. 9. Measured load lines in saturated region with the optimum impedance for output power under class-F operation (dashed line) and inverse class-F operations (solid line). Dotted lines indicate fitted Ids-curve obtained by the simplified model

Next, this model was used to analyze the effects, on efficiency, of gate voltage clipping caused by the gate current flowing through the Schottky diode. Figure 10 provides the simulation results of the output load dependency of the efficiency in class-F and inverse class-F. The output load was set to be optimal relative to the output power. For these operation classes, the plot is overlaid with and without including the gate current I_g flowing through the Schottky diode (I_g = 20 mA). For the class-F operation shown in Fig. 10 (a), the efficiency tended to be independent of the presence of the gate current. This result suggests that, in class-F operation, the efficiency-limiting factor is the on-resistance defined by V_k. In contrast, in inverse class-F operation, the efficiency tended to decrease when the gate current was present, as presented in Fig. 10 (b). This result proves that the efficiency-limiting factor in the inverse class-F operation is the gate current flowing through the Schottky diode.

Based on these analyses, design guidelines for GaN HEMTs are closely related to the operating class of the amplifiers. In general, it is necessary to design a GaN HEMT suitable for a feasible circuit configuration under the constraints of size and other passive devices, or in other words, the operating class. For example, when realizing a class-F amplifier, the limiting factor on its efficiency is the on-resistance. For GaN HEMTs, it is important to focus on improving the performance of the current source by reducing the resistance component. On the other hand, in the case of inverse class-F amplifier, the efficiency is limited by the gate current. Therefore, improvements related to processes such as gate electrode formation and surface treatment are required to reduce the gate current. Thus, the large-signal model provides a significant advantage in that it allows us to comprehensively examine design guidelines for improving amplifier characteristics from both the GaN HEMT and the circuit perspective.

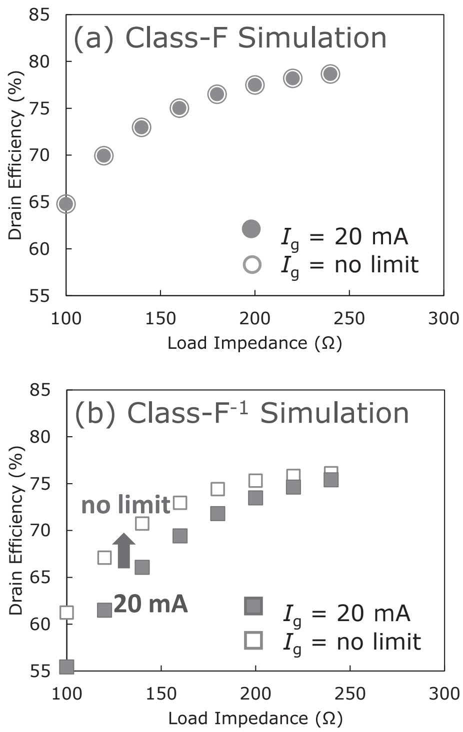

Fig. 10. Simulation results of the output load dependency of the efficiency in class-F and inverse class-F

5. Conclusion

For the improvement of GaN HEMT amplifiers for base station, this paper described the evaluation of current sources for GaN HEMTs using LSLF measurements and analyzing of the efficiency-limiting factors for GaN HEMTs in various operating classes using a large-signal model. We continue to develop GaN HEMT technologies and products to meet the demand for high efficiency amplifiers for high-speed wireless communications.

Technical Terms

*1 High-electron-mobility transistor (HEMT): A transistor that uses two-dimensional electron gas induced at the semiconductor junction interface. HEMTs can be used to form high-electron-density channels less susceptible to impurity scattering.

*2 Electron trap: The charging and discharging of electrons at a constant rate in semiconductor devices caused by crystal defects and impurities.

*3 Large-signal model: For circuit elements such as transistors and diodes, the response to voltage and frequency is expressed as a function or equivalent circuits. The model allows to be calculated in a circuit simulator.

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