

Outlook for GaN HEMT Technology

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It is expected that the high electron mobility transistor (HEMT) using gallium nitride (GaN) as its wide band gap semiconductor will be applied in diverse, green ICT systems because of its high efficiency. The GaN HEMT utilizes high-density two-dimensional electron gas (2DEG) accumulated in the boundary layer between GaN and AlGaIn through their piezoelectric effect and natural polarization effect. This makes it possible to realize a low on-state resistance (R_{on}). Combined with a high breakdown voltage, the GaN HEMT indicates a superb performance as a power device. After the development of GaN HEMT technology started for power amplifiers of mobile base stations, it was expanded to a radar sensor application. Further expansion of its application is expected in the field of power conversion, in equipment such as server power systems. While the development of GaN HEMT technology has been promoted, focusing on "high output power" conventionally, further advantages such as high efficiency and low energy consumption have been attracting much attention in recent years. In this paper, the outlook for GaN HEMT technology is described in terms of its contribution to energy saving.

1. Introduction

Commercialization of gallium nitride (GaN) is observed in various areas including LED lighting and green-colored lights of traffic signals. Also in terms of electronic devices, application of high electron mobility transistors (HEMT) using GaN in the field of green ICT systems is considered very promising. Fujitsu Laboratories is a forerunner in the development of HEMT, globally. The development of compact-size antennas for broadcasting satellites by Fujitsu gathered public attention in the 1980s and Fujitsu has been a leader in this technology area since then. The basic configuration of GaN HEMT is shown in **Figure 1**. GaN HEMT utilizes high-density two-dimensional electron gas (2DEG) accumulated in the boundary layer between GaN and AlGaIn through their piezoelectric effect and natural polarization effect. This makes it possible to realize a low on-state resistance (R_{on}) as its transistor characteristic. Combined with a high breakdown voltage as its wide band gap semiconductor, GaN HEMT shows a superb performance as a power device.

High-frequency GaN HEMT is an indispensable

component for power amplifiers for transmission of wireless communication systems and radar systems, which need high-output-power and high-efficiency performance. For instance, mobile base stations require high-output and high-efficiency power devices of a 100 W class. To achieve power in the order of 100 W, a parallel configuration of multiple devices is needed if conventional GaAs MESFET or Si LD-MOSFET is used. On the other hand, thanks to its high-output-power performance, GaN HEMT can achieve 100 W or higher with just a single device, making high-efficiency and power-saving power amplification possible.

Recently, GaN HEMT R&D has been expanding to power conversion electronics. Their operation frequency is less than several ten MHz in contrast to the GHz operation of high-frequency power amplifiers. While the development of GaN HEMT has been promoted, focusing on "high output power" conventionally, its focus is shifting to further advantages such as high efficiency and low energy consumption.

In this paper, the contribution of GaN HEMT technology is described in terms of energy saving.

2. High-efficiency operation

To operate a transistor circuit with high efficiency, it is ideal if either the current or voltage that runs during the transistor operation can be made zero at any time. Then, the product of current and voltage (i.e., the power consumption of the transistor) becomes zero, and you can achieve 100% operation efficiency. However, in reality, there is always a finite value of resistance, R_{on} , during the on-state of the transistor so the power consumption cannot become zero. Besides, parasitic capacitances of transistors make instantaneous switching impossible and cause a power loss. Compared to the silicon (Si) transistors widely used in amplifiers and switching power systems, GaN HEMT shows a lower power loss during the on state (on-state power loss) with low R_{on} based on high-density 2DEG.

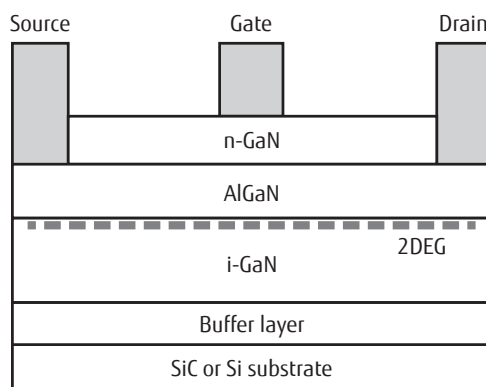
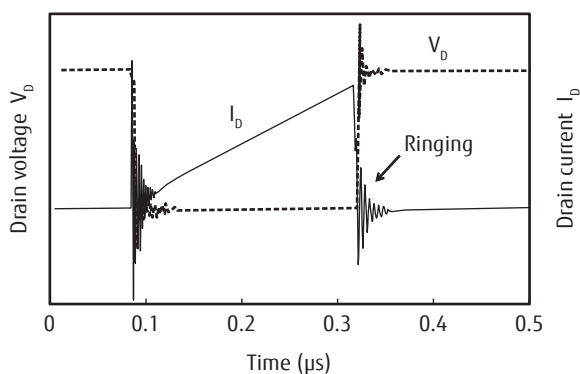
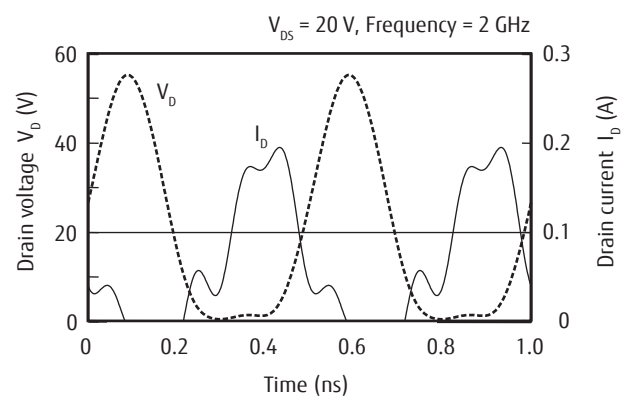


Figure 1
GaN HEMT basic configuration.



(a) GaN HEMT for switching power supply



(b) GaN HEMT for high frequency amplifier

Figure 2
Waveforms of drain voltage and drain current.

The power loss at switching between the On state and Off state is also low based on low parasitic capacitances. These two characteristics make it possible for GaN HEMT to operate with lower power consumption than conventional Si transistors. In power electronics applications, GaN HEMT is considered very promising as an electronic component for a switched-mode power device. The issue to be addressed in this application is the "ringing" that occurs during the switching due to its high-speed response property [Figure 2 (a)]. It is imperative to suppress this ringing, which is a cause of unnecessary power consumption. Meanwhile, in high-frequency amplifier applications of several hundred MHz or higher, the device should be operated with high efficiency by controlling a load impedance so that the product of current and voltage of the transistor becomes zero. For instance, in the case of the inverse class-F operation, where the load impedance is tuned to be infinite at even harmonic frequencies of the signal frequency (fundamental frequency) while it is tuned to be zero at odd harmonic frequencies, the waveform of transistor drain current becomes rectangular and that of the drain voltage becomes half-wave rectified [Figure 2 (b)]. Because the waveform of the drain current is rectangular and the peak current level is low, it is possible to reduce power consumption and voltage drop due to transistor R_{on} or resistance in the feed line. This makes it possible to realize excellent efficiency. On the other hand, the transistor should have high breakdown voltage because the peak value of the drain

voltage may become three times as high as the DC supply voltage (V_{DS}). Because a high breakdown voltage is one of the superior characteristics of GaN HEMT, it is an ideal electronic component for high-efficiency operation. Comparing the switching waveforms reveals that an overlap of current and voltage remains in high-frequency amplifiers where the efficiency remains at approx. 70% normally, while it is possible to achieve 90% or higher in the switch-mode power supply.

3. High-frequency GaN HEMT technology

As examples of high-frequency GaN HEMT monolithic microwave integrated circuits (MMIC) technology, a 10 GHz one-chip transceiver and a 6–18 GHz wide-band MMIC amplifier are explained below.

Recent wireless communication systems and sensing systems use various frequency resources and their transceivers are composed of different devices respectively. If a communication chip that integrates the functions of such transmitter and receiver is developed, the system size and power consumption can be reduced. To handle high-output-power transmitter signals and weak receiver ones on a single chip simultaneously, it is essential to efficiently switch between the transmitter signal and receiver signal with minimum loss while preventing the transmitter signals from interfering with the receiver signals. It was difficult to meet both these requirements with conventional technologies.

Our innovative transmitter/receiver switch using GaN HEMT can address this issue. Despite its compact size (1.8 mm × 2.4 mm), the device achieved the highest performance in the world with a transmission loss as low as 1.1 dB in the range of 0–12 GHz. Drastic size and weight reductions (1/10 or less) were achieved compared to the conventional transmitter/receiver switch system using a magnetic substance.

Further, the transistor is shielded against unnecessary signal radiation through arranging ground via holes around the transistor, and unnecessary signal interference was suppressed by appropriately arranging signal wiring based on 3D electromagnetic simulation. These innovations have ensured stable operation of a high-output-power circuit without causing erroneous oscillation. Using these technologies, a single-chip transceiver MMIC was developed on a pilot basis (Figure 3). In this device, a transceiver switch, a

transmitter amplifier and a receiver amplifier are integrated. While realizing an output of 6.3 W in the 10 GHz band, the chip size could be miniaturized successfully to 3.6 mm × 3.3 mm, which is 1/10 of the conventional devices using multiple chips.¹⁾

Many conventional wireless systems including aircraft radars use multiple frequency resources and devices for each frequency band. However, if a single amplifier can cover a wide frequency range, then energy saving, size miniaturization and weight reduction of radar systems or wireless communication systems can be realized. In the case of aircraft radars, the system is switched among multiple bands as below: C band (4–8 GHz) suitable for rainy weather conditions; and X band (8–12 GHz) and Ku band (12–18 GHz) where objects can be measured with high accuracy. If there is a single amplifier covering the range from the C band to the Ku band, a multiple-unit configuration becomes obsolete and system downsizing as well as energy saving is achieved. In the conventional system, an amplifier circuit comprised of a parallel connection of multiple GaAs transistors is used. While the output power level can be increased by increasing the number of transistors, this results in larger wiring loss due to prolonged circuit wiring. Therefore, it is difficult to cover the bandwidth up to 18 GHz with a system using GaAs amplifiers.

By developing a circuit of power divider and combiner with a super-wide bandwidth on a semiconductor substrate, an output power level of as high as 12.9 W could be realized in a wide bandwidth (6–18 GHz) in a GaN HEMT MMIC technology. The figure of 12.9 W is twice that achieved by the conventional approach.²⁾ Further, by developing a receiver amplifier using GaN

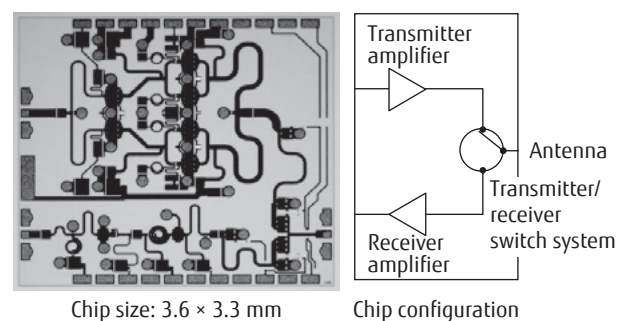


Figure 3
GaN single-chip transceiver MMIC for 10 GHz band.

HEMT, the highest level of performance in the world could be realized with a signal gain of 16 dB and noise figure of 2.3–3.7 dB with a size as small as 2.7 mm × 1.2 mm in the 3–20 GHz range. Besides, a high-output-power, compact size transceiver module was developed by using MMICs with the aforementioned properties (**Figure 4**). While miniaturizing the transceiver module size to 12 mm × 30 mm, 10 W output in a wide bandwidth (6–18 GHz) was realized.³⁾ By using this technology, multiple frequencies can be used with just a single transceiver module. System integration is promoted for radar and wide-band communication systems where multiple frequencies are used, and miniaturization, weight reduction and energy saving of the system will become possible.

4. Power GaN HEMT technology

Because the Power GaN HEMT shows a lower R_{on} and the switching speed is faster compared to the conventional Si power devices, it is expected to improve power conversion efficiency and contribute to system miniaturization. Specifically, if the switching frequency for the power supply can be set to a range that exceeds 1 MHz from the conventional range of less than several hundred kHz, miniaturization, weight reduction and energy saving of capacitor and magnetic components such as transformers and inductors will be achieved.

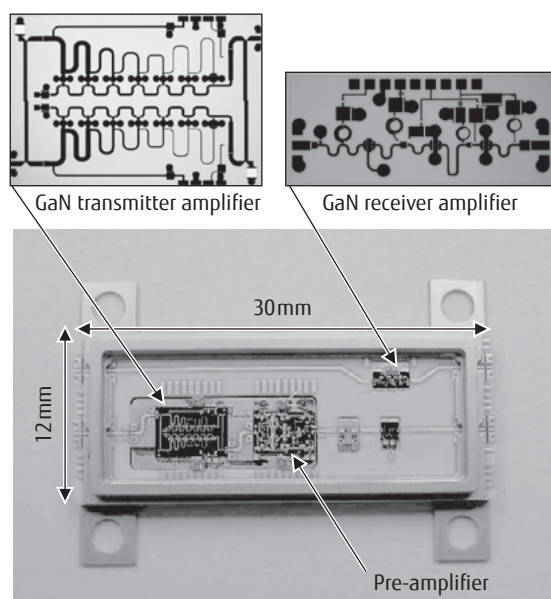


Figure 4
GaN HEMT transceiver module for wide band.

R_{on} of power GaN HEMT can be reduced by applying a positive voltage on the gate electrode to increase the 2DEG density. However, in the above-mentioned high-frequency GaN HEMT configuration, its gate positive voltage is limited to as low as about 2 V, because a Schottky barrier junction is adopted (i.e., a gate metal electrode is formed directly on the semiconductor) and its large gate leakage current. To overcome this issue, an insulated gate configuration was developed, where a dielectric insulation layer is inserted between the interface of the gate metal and the semiconductor. As a result, a gate voltage higher than 2 V could be applied and a low R_{on} characteristic could be achieved. In addition, tolerance for high peak voltage of the unexpected ringing could be improved at switching operation.

Al_2O_3 with a wide band-gap property was adopted as a material for the gate insulation layer, and the atomic layer deposition (ALD) method is used for layer formation. The ALD method is an approach to obtain a flat and uniform insulation layer by controlling layer thickness at an atomic-layer level. Because the conventional compound semiconductors such as GaAs or InP have a large amount of electron traps on the interface between the insulation layer and semiconductor, it is very difficult to adopt an insulated gate configuration such as Si MOSFET. On the other hand, while GaN shows relatively few interface traps, it is still inadequate to adopt an insulated gate configuration. The interface trap impacts the stability of voltage that turns on GaN HEMT (V_{th}). When the gate voltage is applied to positive, electrons are trapped in the interface between the insulation layer and the semiconductor, which results in shifting of V_{th} .⁴⁾ We discovered that the main factor of this V_{th} shifting is the AlOH impurities in Al_2O_3 and Ga oxide in Al_2O_3 /GaN interface. By removing these substances, it was possible to reduce the V_{th} shifting to 0.25 V from about 2 V.⁵⁾

Reducing the production cost is also an important factor for power GaN HEMT commercialization. In concerted efforts with Fujitsu Semiconductor, we have developed a GaN-on-Si technology that allows cost reduction by adopting a large diameter Si substrate. Especially, we have developed an epitaxial growth technique of high-quality GaN on a 6-inch Si substrate as well as an optimal electrode configuration that can suppress R_{on} elevation at switching operation. A prototype power supply circuit was developed for an

evaluation of the developed power GaN HEMT and successful results were obtained in a power conversion efficiency exceeding those of the conventional Si power devices. Further, the server power supply system developed by Nakao et al., installing power GaN HEMTs in its power-factor-correction (PFC) circuit,⁶⁾ demonstrated a high output power operation up to 2.5 kW (**Figure 5**). The total efficiency level with an input of AC 230 V and output of DC 12 V reached 94.3% at its peak. These achievements make the high-power GaN HEMT a promising solution for green ICT system applications. Further, a contribution to the low carbon society may be expected by using this technology for power conditioners used in photovoltaic power generation, air conditioner power supplies and so forth.

5. Future prospects

In addition to the miniaturization and energy saving of the above-mentioned wireless communication and power conversion systems, the use of technologies based on GaN HEMT is expected to cover wider areas in future. While no reference is made in this paper, expansion of this technology in the machine-to-machine (M2M) field is expected through the use of cloud networking based on various sensing functions. In the area of sensing technology, diverse applications are being examined including those in environment

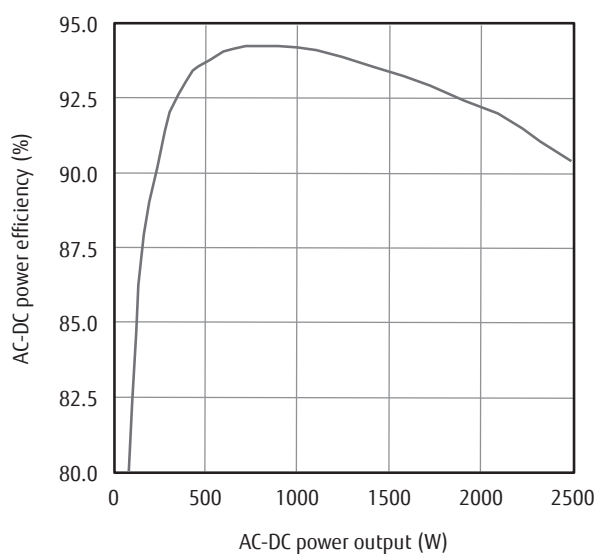


Figure 5
Output and efficiency characteristics of server power system integrating high-power GaN HEMT.

research, biotechnology and structural analysis by positive use of high-speed, high-sensitivity characteristics of the GaN HEMT. Through penetration in the M2M and ICT fields, GaN HEMT is expected to make a great contribution in new areas by supporting the intelligent social infrastructure from the device level. A smart city system, vehicle/traffic systems, food industry, logistics, agriculture, healthcare/welfare industries, environment systems and education systems are some examples where this technology is expected to make a contribution.

6. Conclusion

In this paper, the frontier of GaN HEMT technology in high-frequency amplifier and power conversion applications was reported while focusing on its advantage of "energy saving." Because of its low on-state resistance and high-speed switching performance, GaN HEMT has a possibility to miniaturize device size and minimize power consumption with low cost through further sophistication of the GaN HEMT technology and promotion of circuit development that maximizes these advantages. This will open up a bright future for this technology in novel fields. We are committed to realize a low carbon society by making proposals to improve values of various ICT systems by using this device.

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