GaN HEMT Technology for Environmentally Friendly Power Electronics

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Gallium nitride (GaN) is a type of compound semiconductor material called a wide-bandgap semiconductor that has already found practical use as an LED light source. A high electron mobility transistor (HEMT) made of GaN features low operating resistance and a high breakdown voltage, which makes it promising as a next-generation power semiconductor that can raise the efficiency and miniaturize diverse types of power and energy equipment. GaN HEMTs have already been put to use as transmission power amplifiers in high-frequency wireless communication systems and radar systems. Coupled with the recent establishment of technology for manufacturing GaN HEMT structures having high breakdown voltages (600 V and greater) on a Si substrate using large-diameter, low-cost wafers, the development of high-efficiency power electronics equipment as switching power supplies in data servers and personal computers is progressing at a rapid pace. At Fujitsu Laboratories, we are moving forward with research and development of switching power supplies using GaN HEMTs for application to future information and communications technology (ICT) products. An AC adapter using Fujitsu's GaN HEMT technology was recently praised for its high performance and contributions to the environment, and for this achievement, Fujitsu was awarded the Grand Prize of the 26th Global Environment Award. This paper describes the design technology for applying GaN HEMT technology to switching power supplies and reports on the contributions of this technology to energy savings.

1. Introduction

Gallium nitride (GaN) is a compound semiconductor material commonly called a wide-bandgap semiconductor that has already found practical use as a light source in LED lighting and decorative illumination. Additionally, as GaN features a high breakdown voltage[1),2)] and high electron saturation velocity compared with Si semiconductor, there has been extensive research on the practical application of GaN to high-speed switching devices and high-frequency amplifiers.[3)] A typical GaN structure of electronic and electrical components is used in high electron mobility-transistors (HEMTs).[4),5)]

Fujitsu has been a world leader in HEMT technology since its invention by Fujitsu Laboratories in 1979, which led to the development of HEMT-based compact antennas for receiving satellite broadcasts in the 10-GHz band. Compared with super junction (SJ) metal–oxide–semiconductor field-effect transistors using Si (SJ Si MOSFETs), HEMTs made of GaN (GaN HEMTs) feature an exceptionally high carrier density of $5–10\times10^{12}$ cm^{-2}. They can therefore achieve a true on-state resistance (R_{on}) (described below) of 1/5 to 1/10 that of Si, making it easy to achieve a power device capable of high-speed operation with a high breakdown voltage.

Figure 1 compares GaN with silicon carbide (SiC), Si MOSFETs, and SJ Si MOSFETs in terms of the relationship between the R_{on} of a semiconductor electronic device and the breakdown voltage. The higher theoretical limit for GaN suggests that GaN HEMTs are more promising than other types of semiconductor as an electronic device that can achieve a high breakdown voltage and low R_{on}.[6)] These characteristics are driving the practical use of GaN HEMTs as a power amplifier for transmitters in such applications as GHz-band wireless communications and radar systems.

It has recently become possible to manufacture

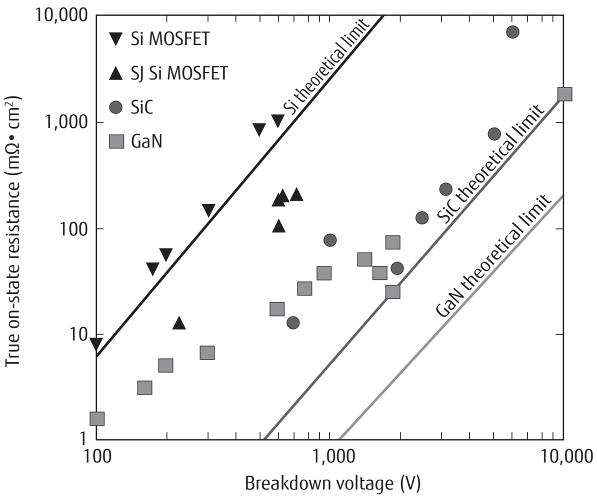


Figure 1
Performance comparison of semiconductors.

GaN HEMT structures having high breakdown voltages (600 V and greater) on a Si substrate using large-diameter, low-cost wafers.[7] This has led to the application of GaN HEMTs to power electronics equipment such as high-output switching power supplies that must operate at several hundred volts and higher. The use of GaN HEMTs will contribute to the development of green ICT systems in the not too distant future. At the same time, calls are being made for even greater energy savings as a countermeasure to global warming, and required reductions in power consumption are increasing yearly.

In February 2016, the United States Department of Energy (DOE) raised the efficiency standards for external power supplies such as AC adapters, reflecting increasingly severe electrical power regulations.[7] Achieving high efficiency in all sorts of electronics equipment has consequently become an issue of concern. Additionally, as mobile phones, smartphones, and tablets become increasingly popular, there is increasing demand for highly efficient and miniature AC adaptors used to charge those devices. Against this background and with the aim of making a contribution to the environment, we have undertaken the development of highly efficient and miniature power supplies using GaN HEMTs. An AC adapter that we developed using this technology has already been praised for its high performance and contributions to the environment, and for this achievement, Fujitsu was awarded the Grand Prize of the 26th Global Environment Award (see Appendix).

In this paper, we report on the design technology developed by Fujitsu for applying GaN HEMTs to power electronics equipment and switching power supplies in particular and on the contributions of GaN HEMTs to energy savings.

2. Factors behind high-efficiency operation of GaN HEMTs

In switching power supplies using a transistor as a switching element, an ideal state with no operating loss in the switching element is one in which either the current flowing in the element or the applied voltage is zero, which means that the product of current and voltage is zero. In reality, however, there is a series of resistance components in the electrodes (drain, gate, and source) making up the transistor, that is, in the switching element. In particular, parasitic resistance that cannot be eliminated arises between the drain and source electrodes when current flows. Additionally, the amount of current flowing in a switching element depends on the electron concentration of the transistor and is therefore finite, which results in the true on-state resistance.

As a result of this parasitic resistance component and true on-state resistance, the voltage across the switching element when current flows is non-zero, generating a power loss. This is called "on-state loss." There is also parasitic capacitance between electrodes that cannot be physically eliminated, and this, combined with parasitic resistance, causes the temporal rate of change in the current and voltage during switching to be finite. As a result, the product of current and voltage is non-zero, generating a power loss. This is called "switching loss."

The main electrical characteristics of cascode-type GaN HEMTs and Si MOSFETs are compared in **Table 1**. Although their maximum rated currents I_{max} are essentially the same, the on-state resistance of GaN HEMTs is approximately half that of Si MOSFETs. Next, looking at inter-electrode capacitances C_{iss}, C_{oss}, and C_{rss} and at the gate charge storage Q_g, which are parameters related to switching loss, we see that those of GaN HEMTs are only about one-fifth those of Si MOSFETs with the exception of output capacitance. These differences in electrical characteristics result in different pulse

Table 1
Main electrical characteristics of GaN HEMTs and Si MOSFETs.

	Threshold voltage V_{th} (V)	On-state resistance R_{on} (mΩ)	Drain/Source breakdown voltage (V)	Max. rated current I_{max} (A)	Input capacitance C_{iss}* (pF)	Output capacitance C_{oss}* (pF)	Feedback capacitance C_{rss}* (pF)	Gate charge storage Q_g* (nC)
GaN HEMTs	2	100	600	20.0	450	140	13	14
Si MOSFETs	3	190	600	20.7	2,400	60	70	87

*V_{ds} = 600 V

response characteristics.

A schematic diagram of a measurement system used to evaluate the pulse response characteristics of a transistor is shown in **Figure 2 (a)**. In this system, the power supply voltage V_{DD} is set to 400 V, and the load resistance is set to 25 Ω. The results of measuring the pulse response characteristics of GaN HEMTs and SJ Si MOSFET are shown in **Figure 2 (b)**. The solid and broken lines represent the drain voltage waveform and current waveform, respectively. The triangular areas under the points where these waveforms intersect correspond to switching loss. It can be seen that the GaN HEMT switching loss is very small compared with of the SJ Si MOSFET one.

The switching characteristics are compared in **Table 2**. GaN HEMTs have a switching time 1/4–1/6 and a switching loss 1/3–1/8 those of Si MOSFET. With low on-state resistance and switching loss, GaN HEMTs are well suited for achieving even higher levels of efficiency in power electronics equipment.[8),9)]

Table 2
Switching characteristics of GaN HEMTs and Si MOSFETs.

	GaN HEMTs	Si MOSFETs
On time (ns)	7.0	41.5
Off time (ns)	7.5	30.5
On loss (μJ)	5.6	45.4
Off loss (μJ)	13.7	46.9

3. High-efficiency operation testing

To evaluate efficiency in actual power electronics equipment, we mounted and evaluated a GaN HEMT on a power factor correction (PFC) circuit. A schematic diagram of this single-switch PFC circuit and a photo of the prototype PFC circuit are shown in **Figures 3 (a)** and **(b)**, respectively. In this circuit, the switching frequency of the control IC is set to 680 kHz, which is approximately ten times the conventional figure, and the output power is controlled using electronic load equipment connected to the output. In this way, we evaluated the relationship between output power and efficiency.

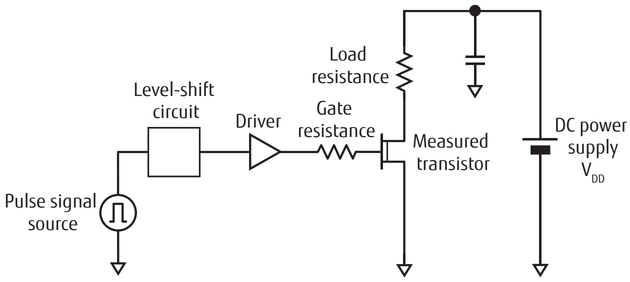
As show in **Figure 3 (c)**, the difference in efficiency between the GaN HEMT and an SJ Si MOSFET was only 0.5–1 points for low output power (up to approx. 100 W). However, for high output power, where the effects of switching loss are greater, the difference widened and became very large (up to approx. 5 points) at 500 W. In other words, despite a switching frequency approximately ten times that of conventional devices, a GaN HEMT can achieve high efficiency even at high output.[9),10)] These results point to GaN HEMTs becoming a power device that can raise the efficiency of power electronics equipment. This technology has been used to develop a 2.5 kW output PFC for servers.[10)]

4. Miniaturization of power electronics equipment

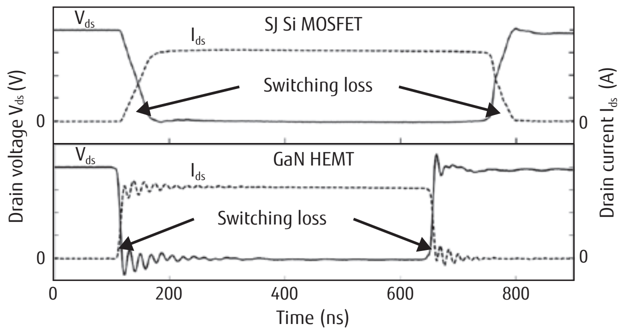
As described above, a GaN HEMT is a device that can achieve high efficiency even at a high switching frequency. Increasing the switching frequency enables equipment to be miniaturized.

One factor determining size in power electronics equipment originates in the coil components such as transformers. Many reactance components such as capacitors and coils are used in power electronics equipment, and the impedance of such components depends on the operating frequency. Raising the frequency even for a component with small characteristic values can result in achieving the required impedance. That is, raising the switching frequency enables device miniaturization.

Mobile terminals such as mobile phones, smartphones, and tablets have become increasingly popular in recent years, and up to approx. 2.1 billion units are now in operation globally. These devices are frequently

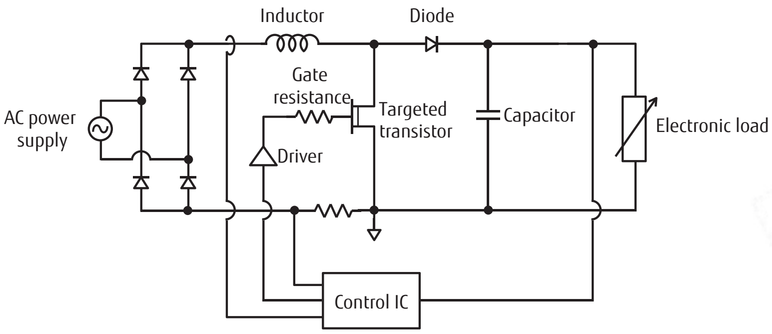


(a) Pulse-response-characteristics evaluation circuit

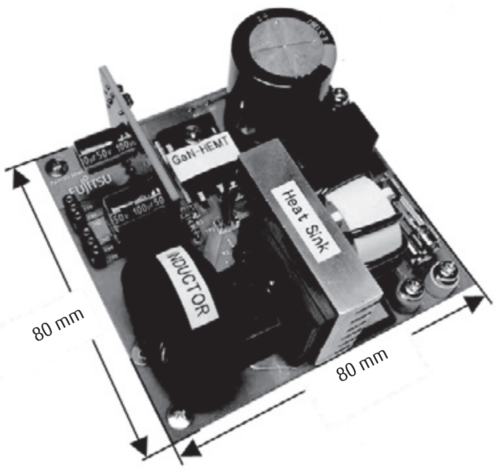


(b) GaN HEMT and SJ Si MOSFET pulse response characteristics

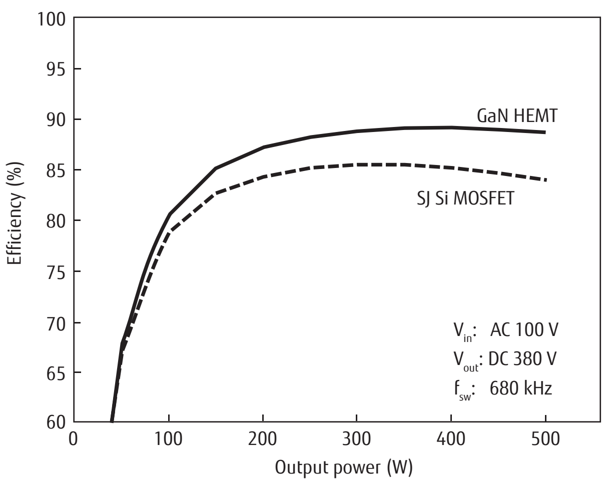
Figure 2
Comparison of pulse response characteristics.



(a) Single-switch PFC circuit for evaluating loss characteristics



(b) Prototype PFC circuit



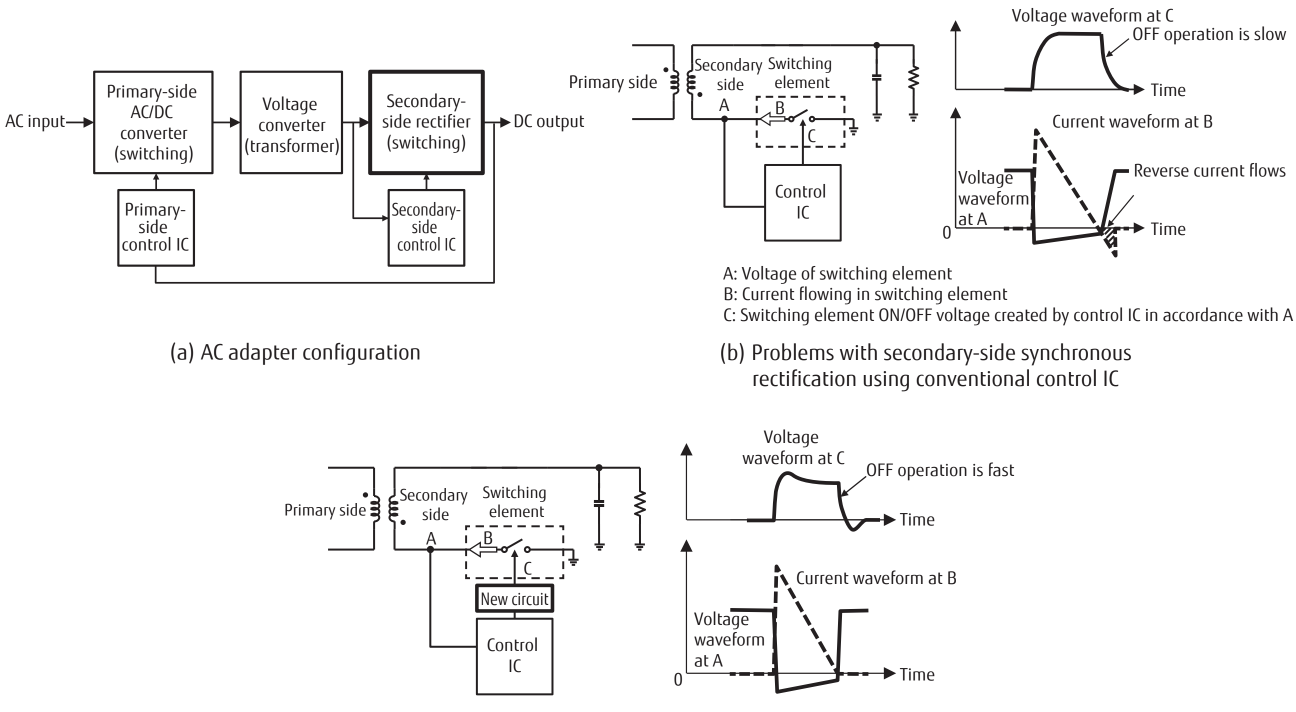
(c) Comparison of efficiency characteristics

Figure 3
Single-switch PFC circuit for evaluating loss and efficiency characteristics.

used so much that their batteries become drained, resulting in an increasing number of users carrying around AC adapters or battery packs for charging purposes. While typical AC adaptors for low-power equipment (up to approx. 5 W) are conveniently small, those for higher power equipment (10 W or higher) are typically larger and heavier. The use of a GaN HEMT makes it possible to achieve a 10-W-class AC adapter with a size equivalent to that of 5-W-class products while improving efficiency. Using a GaN HEMT, we have achieved the world's smallest and most efficient AC adaptor having an efficiency of 87% and a volume of only 15.6 cc with an output of 12 W, which is sufficient even for tablets.[12)]

As shown in **Figure 4 (a)**, an AC adapter, acting as a switching system, takes in AC voltage and outputs DC voltage for powering the connected device. It generates stable DC voltage through the use of a transformer and a switch that periodically turns current ON and OFF. The circuit block from the AC input to the transformer is called the primary side (AC/DC converter), and that from the transformer to the DC output is called the secondary side (rectifier). We used a synchronous rectification system with the aim of achieving low loss.

However, as shown in **Figure 4 (b)**, synchronous rectification can actually increase loss depending on the shape of the control signal waveform output by the control IC. To align the timing of the secondary-side switching element that makes current flow with the ON/OFF operation of the primary-side switching element and to always turn current ON/OFF with appropriate timing in the GaN HEMT, adjustments must be made so that the slope of the control signal waveform output by the control IC is steep. The basic operation of the secondary-side control IC generates a voltage to control the ON/OFF operation of the switching element in line with the voltage of the switching element. However, the OFF operation is relatively slow because of the effects of high-speed operation, and as a result, reverse current is temporarily generated during the rise of the switching element voltage, thereby producing loss. As shown in **Figure 4 (c)**, we resolved this problem by inserting a circuit for controlling the timing between the control IC and GaN HEMT on the secondary side and for adjusting the waveform of the voltage generated by the control IC. This scheme suppresses the generation



(a) AC adapter configuration

(b) Problems with secondary-side synchronous rectification using conventional control IC

(c) Efficiency improvement with waveform shaping technology

Figure 4
High-efficiency technology for developed AC adapter.

of loss current during high-speed operation as would occur with the conventional configuration and outputs current with appropriate timing while taking advantage of the low operating resistance of the GaN HEMT.

The relationship between output power and efficiency is shown in **Figure 5 (a)** for two output powers: 5 W and 12 W. The transformer was optimized in accordance with the specified output power. The maximum efficiency for both was 87%, the world's highest for AC adapters of this type. A photograph of the AC adapter that we developed by applying this technology is shown in **Figure 5 (b)**.

5. Conclusion

In this paper, we described the design technology we developed for applying GaN HEMTs to power electronics equipment. Thanks to their low on-state resistance and superior high-speed switching performance as well as high breakdown voltage, GaN HEMTs can be used for achieving miniaturized, high-efficiency devices for wireless communications and power applications such as PFC circuits and AC adaptors.

Going forward, we intend to further develop GaN HEMT device technology including the GaN HEMT device itself, circuits that exploit its performance, and mounting methods. We will continue to make proposals on using GaN HEMTs to raise the value of ICT systems especially in fields that require energy savings and miniaturization such as machine-to-machine (M2M) communication via cloud networks and the Internet of Things (IoT) and in the environmental, chemical, and automobile industries. With GaN HEMT technology, Fujitsu aims to make a major contribution to solving energy-related problems and achieving a low-carbon society.

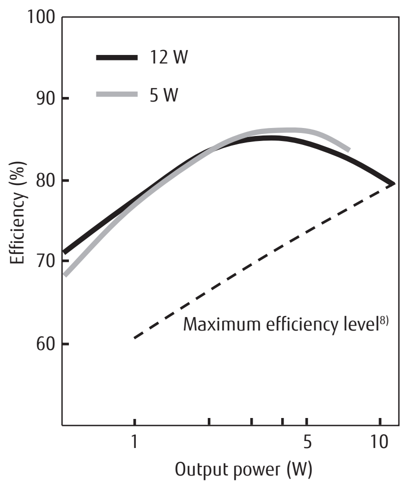
Appendix

In recognition of the highly evaluated technology introduced in this paper, Fujitsu was awarded the Grand Prize of the 26th Global Environment Award sponsored by the Fujisankei Communications Group in May 2017. The Global Environment Award recognizes companies and organizations that are actively involved in preventing global warming and preserving the environment to promote a harmonious coexistence between industrial development and the global environment.

- Global Environment Award (in Japanese)
  http://www.fbi-award.jp/eco/jusyou/
- Press release

Fujitsu Wins Grand Prize in 26th Global Environment Award-Recognized for development of the world's smallest and most efficient AC adapter (March 3, 2017)

http://www.fujitsu.com/global/about/resources/news/press-releases/2017/0303-01.html



(a) Efficiency characteristics

(b) AC adapter

Figure 5
Efficiency characteristics and appearance of AC adapter.

Award ceremony of the 26th Global Environment Award

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