GaN Device for Highly Efficient Power Amplifiers

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Fujitsu has been developing gallium nitride high electron mobility transistors (GaN-HEMT) for small transmitter amplifiers for Long Term Evolution (LTE) base stations. The use of GaN-HEMT in highly efficient transmitter amplifiers has attracted much attention because of its high breakdown voltage characteristics. High-efficiency amplifiers with high gain are needed to decrease the power consumption and size of base stations. This paper describes the development of high-power GaN-HEMT operating at high voltage for LTE base stations. First, we introduce the advantages of GaN-HEMT in terms of its physical properties and GaN-based power amplifiers. Then, issues to be solved in the early developing stage of GaN-HEMT are focused on and the current status is described. Efficiency data of power amplifiers are shown. Finally, the future outlook is discussed in detail.

1. Introduction

In Japan, as smartphones are becoming more and more widespread, there are urgent needs to improve the channel capacity and communication speed of mobile wireless communication systems. The provision of Long Term Evolution (LTE) mobile wireless communication systems has started and the future commercialization of next-generation LTE systems has come into sight.

Base stations, which are the key to mobile wireless communication systems with a higher capacity and faster speed, are essentially required to make systems easy to install and reduce maintenance costs. To meet these requirements, they require technologies for reducing the size and power consumption.

This paper presents the characteristics and background to the development of high-power transmitter amplifier technology. Fujitsu has successfully commercialized this technology for the first time in the world by using gallium nitride high electron mobility transistor (GaN-HEMT) as a key technology to realize lower power consumption (higher efficiency). The future outlook on the GaN-HEMT business is also discussed.

2. Physical properties of GaN

GaN is used for blue and white LEDs that are adopted in lighting and are characterized by a low power consumption and long operating life. A comparison between the physical properties of GaN and conventional semiconductors is shown in **Table 1**. As compared with the conventional semiconductors such as silicon (Si) and gallium arsenide (GaAs), GaN is less prone to electric field breakdown, which allows it to operate at a high voltage. Si devices are used in the existing base station systems and the operating voltage of the high-power amplifiers is 28 V, which is lower than the base station system power voltage of 48 V. This means the base station systems use circuits to convert the power voltage. If the base stations can reduce the amount of power voltage conversion performed, it will be possible for them

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Table 1
Comparison of physical property of GaN with other materials.

Material	Breakdown electric field (MV/cm)	Heat conductivity (W/cm/K)	Traveling electron density (/cm^2)	Mobility (cm^2/Vs)	Saturated electron speed (cm/s)
Si	0.3	1.5	Up to10^{12}	1300	1×10^7
GaAs	0.4	0.5	Up to10^{12}	2000-4000 (MESFET)	1.3×10^7
SiC	3.0	4.9	Up to10^{12}	600	2×10^7
GaN	3.0	1.5	Up to10^{13}	1500 (HEMT)	2.7×10^7

High breakdown voltage High-voltage operation
High-current-density operation High-temperature operation
High-speed operation High-efficiency operation

to reduce their size and power consumption.

GaN has a wide band gap and high breakdown electric field, which allows it to operate at a high voltage. GaN with a high breakdown voltage has the possibility of realizing amplifiers that operate at a high voltage of 50 V and give the advantage of reduced loss during power voltage conversion.

GaN also has physical properties that make it suitable for high-speed and high-efficiency operation because of the high electron mobility and electron speed. While high-power operation has the problem of heat generation, silicon carbide (SiC) has a higher heat conductivity than gold and characteristically dissipates heat well. Hence we use it as a substrate to address this problem. That is, GaN satisfies the physical property conditions to offer high-voltage operation and high-power performance.

3. GaN-HEMT structure and development issues

HEMT is a field-effect transistor that makes use of the fact that the electrons generated in a junction between semiconductor materials with different band gaps travel at a higher speed than in the conventional semiconductors. HEMT was developed by Fujitsu in 1980 by using GaAs, a compound semiconductor, for the first time in the world. It is now widely in use as infrastructure technology that supports an IT society such as satellite receivers, mobile phone handsets, navigation systems that use the GPS and wide-area wireless access systems.

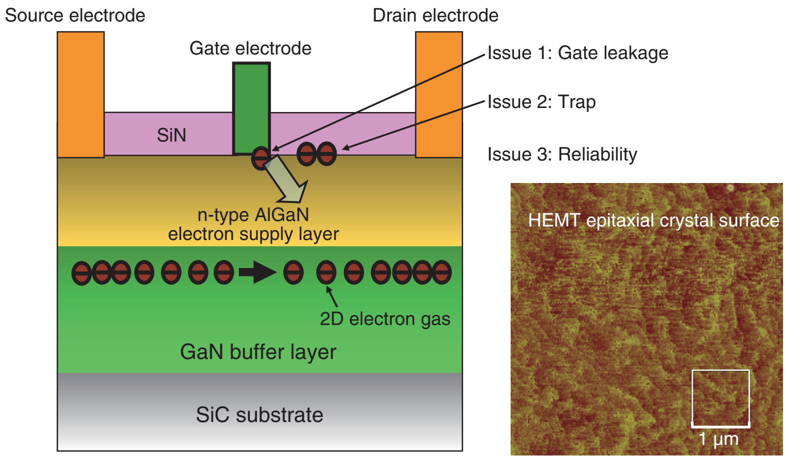
A HEMT structure that uses GaN [**Figure 1 (a)**] is characterized by the lamination of two different layers of GaN and aluminum gallium nitride (AlGaN) and the use of 2D electron gas (traveling electrons) generated in the junction for operation. The HEMT structure can obtain higher current density than field-effect transistor structures used in Si- and GaAs-based devices. This is because GaN has a piezoelectric effect due to spontaneous and piezoelectric polarizations, which generates a strong electric field inside. For this reason, ten times as much 2D electron gas can be generated as compared with the conventional compound semiconductor materials such as GaAs and the current density increases. Accordingly, higher-power and higher-efficiency operation than is offered by the conventional transistors can be expected. Based on these points, amplifiers that use GaN are regarded as promising next-generation high-power amplifiers.

At the beginning of the development in early 2000s, however, actual high-voltage operation with the HEMT structure as shown in Figure 1 (a) brought the following problems to light.

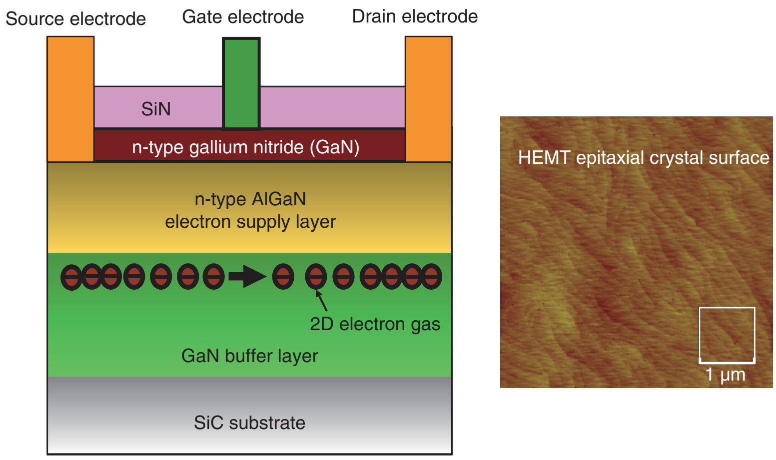
1) The gate electrode generates a large leakage current (gate leakage), which is not supposed to run.
2) During high-frequency high-power operation, traveling electrons are trapped in the device and the on-resistance increases (current collapse).
3) A sudden breakdown or power performance deterioration is observed if power is supplied for an extended period of time.

Because of these reasons, sufficient performance as a high-voltage operation transistor was not achieved and stable reliability could not be obtained.

One factor in this is the surface topology



(a) Conventional GaN-HEMT structure



(b) Recessed-ohmic surface-charge-controlled GaN-HEMT structure

Figure 1
GaN-HEMT structures and surface topology.

(atomic force micrograph) shown in Figure 1 (a). The surface has cracks reminiscent of the Grand Canyon.

4. GaN-HEMT development technologies

Figure 1 (b) shows the structure of the transistor developed to solve the issues mentioned in the previous section. To improve the surface topology and suppress the gate leakage, the focus has been placed on controlling the junction between the GaN-HEMT and gate electrode. Accordingly, we have proposed a surface-charge-controlled structure, in which a conductive GaN layer with n-type doped in it is used for the surface of the HEMT structure.[1] As shown in the photo of the surface in Figure 1 (b), the proposed structure has successfully prevented cracks in the surface. The concept is totally different from the high-density surface layer to improve the ohmic characteristics, which is used for the conventional GaAs-based devices: even if the impurities are doped, high-density electrons do not exist but are completely depleted.

The electric field distribution in the device has been calculated by a device simulation. The results showed the conventional structure has a region with a very high electric field strength near the gate electrode. This electric field concentration is the cause of the gate leakage. With the present surface-charge-controlled structure developed, no concentration of electric field occurs near the gate electrode, which raises hopes for a reduced gate leakage.

The present development does not have easily-oxidizable aluminum in the semiconductor surface and may suppress current collapse due to electron traps in the semiconductor surface.

The GaN-HEMT transistor developed by the authors has been grown by the metalorganic vapor phase epitaxy (MOVPE) process. For the substrate, SiC, which has high heat conductivity, has been used. The MOVPE process has been adopted to grow a GaN buffer layer, n-type AlGaN electron supply layer and n-type GaN cap layer on the SiC substrate in order. To reduce the ohmic contact resistance, recessed ohmic technology has been used, in which the n-type GaN cap layer is removed from the ohmic electrode portions and the ohmic electrodes are formed on the AlGaN electron supply layer. To increase the power gain, the gate length has been specified to be 0.5 µm and a semiconductor passivation layer of silicon nitride (SiN) has been formed on the GaN surface.

The technologies above successfully lead to suppress the gate leakage and current collapse and improve the reliability.

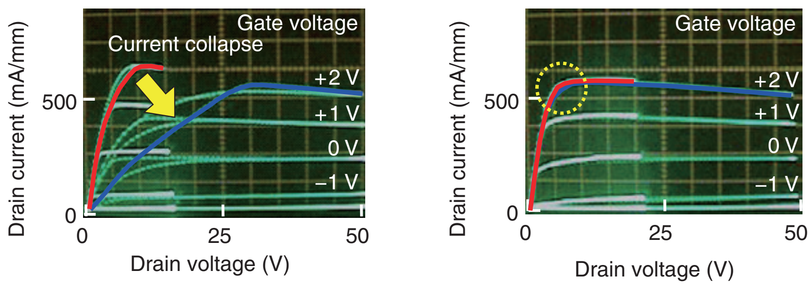
The gate leakage can now be reduced to 1/1000th of the conventional structure or less and any sudden breakdown can be prevented as well.

The improvement of the current collapse is illustrated in **Figure 2**. It shows current-voltage curves with the measurements taken at 100 Hz using a curve tracer. Figure 2 (a) is a diagram of the conventional structure and Figure 2 (b) shows the structure developed by the authors. Figure 2 (b) shows a rapid rise in the drain current with reference to the drain voltage, indicating suppressed increase of the on-resistance.

Regarding power supply for an extended period of time, the variation in power characteristics has been successfully suppressed by improving the quality of the GaN buffer layer. This has allowed GaN-HEMT to be commercialized for the first time in the world.[2)]

5. GaN-HEMT amplifier

The advantages of using GaN-HEMT as amplifiers are shown in **Table 2**. The optimum impedance is higher than conventional devices as a result of increasing the operating voltage, which facilitates matching in the circuit. In addition, easier harmonic processing allows for greater efficiency. Furthermore, a size reduction can be achieved because of the lower heat generation.



(a) Operation with conventional structure (b) Operation with present structure developed

Figure 2
I-V curves of GaN-HEMT.

Table 2
Advantages of GaN-HEMT amplifier.

Physical property	Advantage of HEMT	Advantage of amplifier
• High breakdown voltage	• High-voltage operation • High load impedance • Good linearity	• Easy harmonic processing (higher efficiency) • Low matching loss • Simplified voltage conversion
• Wide band gap	• High-temperature operation	• Small, lightweight cooling system
• High heat conductivity • High current density	• High-voltage operation • Small chip size	• Small, lightweight amplifier

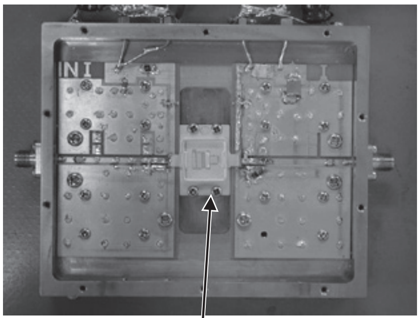


Figure 3
GaN-HEMT power amplifier.

Figure 3 shows an amplifier with a GaN-HEMT chip of 36 mm in the gate width mounted in a package and fixture adjustment provided. It has succeeded in efficiently amplifying W-CDMA signals for third-generation mobile phone base stations, which is the most important condition of operation for practical use, and showed characteristics of 174 W output with 63 V operation.[3),4)] With a push-pull amplifier with two of these chips used in parallel, the maximum output of 250 W has been obtained with 50 V operation using W-CDMA signals.[2)] A distortion compensation circuit using digital pre-distortion (DPD) was also adopted.[5)] With its high load impedance, GaN-HEMT well accommodates distortion compensation and is capable of providing efficiency of 40% in single-end average power operation. By making use of these base technologies, an amplifier offering efficiency of 50% in average operation can now be realized.[6)]

6. Future of GaN-HEMT

Figure 4 shows a future roadmap of the market for GaN-HEMT-based devices for respective frequencies. The base station applications mainly of the 2 GHz band have been commercialized and turned into business based on the technologies developed by the authors. Further efficiency improvement will be demanded for base station applications in the future. GaN-HEMT, which is capable of harmonic processing, can be applied to various amplifier circuit forms and easily supports a wider bandwidth. For that reason, it is regarded as a promising key technology of next-generation amplifiers.

Development into other bandwidths is also expected. One possibility is applying HaN-HEMT to high-frequency band amplifiers including those operating at the millimeter-wave frequency.[7)] As shown in Table 1, this is an amplifier application that takes advantage of the high speed of GaN and expected uses include long-distance wireless communications for disaster situations and in mountains.

In addition to amplifier applications, there are also high expectations for application to switching transistors for high-efficiency power supply in the kHz to MHz range.[8)] This is because of advantages mainly including the ease with which the breakdown voltage can be improved, thanks to the physical properties as shown in Table 1, and the characteristic high switching speed of the HEMT structure. For example, reducing the power consumption and size of the power supply such as PC AC adapters is among the expected effects. In the future, use as transistors at the core of electric vehicles and photovoltaic power generation, which require high-efficiency power supply, is anticipated.

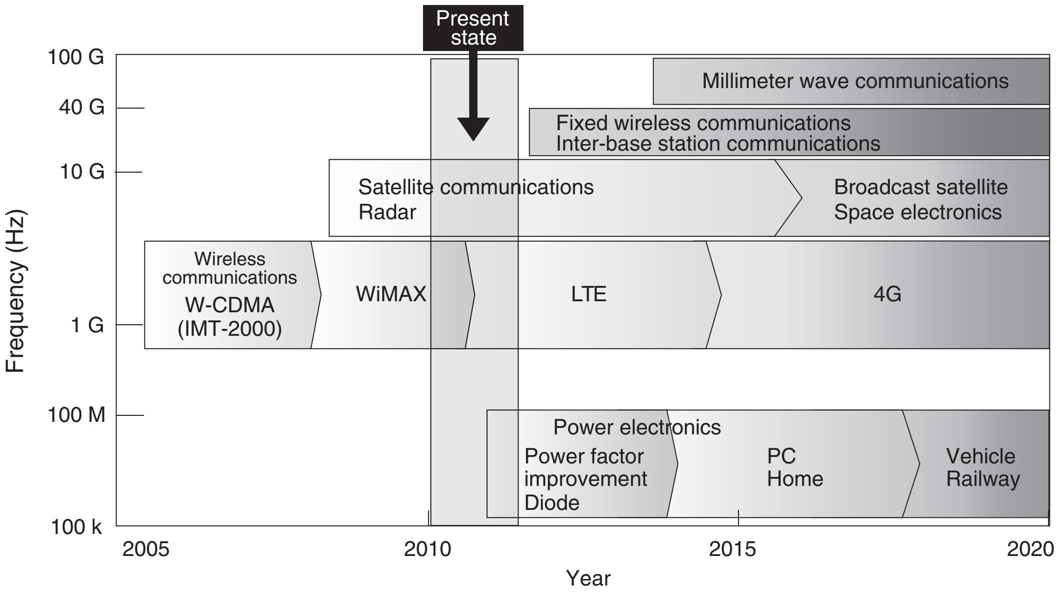


Figure 4
Future prospects for GaN-HEMT.

Many power supply units are used in base stations and GaN-HEMT is estimated to be in use for devices other than amplifiers in base stations in the future.

7. Conclusion

The authors have developed a surface-charge-controlled structure that uses a conductive n-type GaN layer and achieved the suppression of gate leakage and current collapse. As a result, high-power characteristics of 250 W with 50 V operation have been successfully realized before the rest of the world. In addition, the authors have worked on improving the performance from the perspective of the physical properties of GaN, succeeded in verifying reliability for the first time in the world and commercialized GaN-HEMT before others. Based on the results above, GaN-HEMT can now be mass-produced for LTE base stations.

From now on, the authors intend to further accelerate the development of GaN-HEMT with a view to expanding to bandwidths other than base station applications.

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