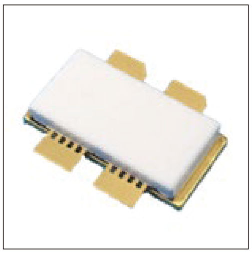


High-Power GaN HEMT for High-Frequency Amplifiers and Its Future Technologies

Kozo MAKIYAMA*, Shigeki YOSHIDA, and Ken NAKATA

Intelligent communication technology is an indispensable part of the infrastructure that supports modern society. In particular, wireless communication systems using high-frequency radio wave carriers have made remarkable progress in the last 30 years. In 2020, 5th-generation services started to realize high-data-rate transmission and low signal latency. The environments in which wireless communication networks operate have expanded to include the open sea and low earth orbit. To date, we have developed many kinds of commercial transmission devices for optical wired and wireless communications. We were the first company in the world to successfully mass produce and commercially ship Gallium Nitride high electron mobility transistors (GaN HEMTs), a key device for cell phone base stations, and have the top market share. This paper describes compound semiconductor devices represented by GaN HEMTs as well as novel crystal and device technology for discontinuous performance enhancement.

Keywords: mobile network, GaN HEMT amplifier, high-frequency high-power amplifier, epitaxial crystal, nitrogen (N) polarity

1. Introduction

We spend every day buried in a lot of information and communications. IoT technology, in which information devices and sensors are connected through the internet, is about to develop into a core technology in our daily lives. The progress in information and communication technologies, such as the internet, satellite broadcasting services, and cell phone services that began in the 1980s, had such a great impact that they changed our way of life. In particular, the internet and satellite broadcasting services that began in the late 1980s made it possible to instantly disseminate the same information worldwide, changing the structure of society and international relations.

2. Information and Communications in Society

As shown in Fig. 1, communication technology as a means of disseminating information is divided roughly into two categories: a wired communication network that uses optical fibers mainly and a wireless communication network that uses high-frequency radio waves.

Figure 2 shows the product families that are used actually for the above two networks. In an optical wired communication network using optical fibers, a metro/branch network is constructed with optical fibers and optical devices, and the communication speed of the backbone is being increased from 100 Gbps to 400 Gbps. Furthermore, in recent years, the demand for communications between data centers has been increasing, and high speed is also required for communications. We have developed a variety of optical transmission devices for optical wired networks, mainly optical fibers, and they have a large market share. A wireless communication network using radio waves consists mainly of a backhaul of a cellular phone (mobile wireless communication) service network and communications between the base station and terminals. For the above networks, devices for amplifiers

Fig. 1. Schematic illustration of wired and wireless communication systems

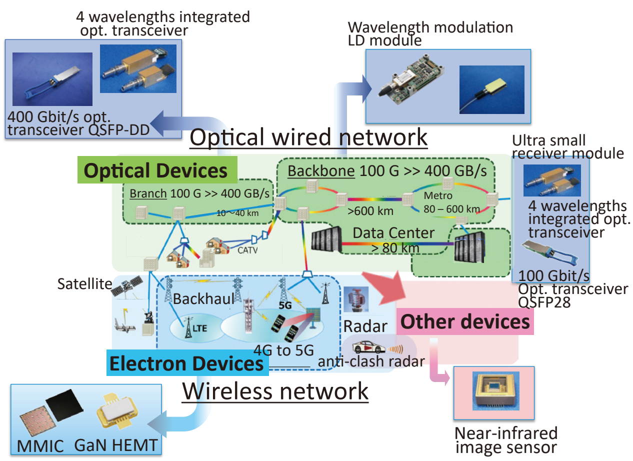


Fig. 2. Communication system and semiconductor transmission device

with high-power and high-frequency performances are indispensable.

In terms of data traffic, wired communications using optical fibers have been mainstream for conventional information and communications, but data traffic in wireless communication has exceeded that in wired communications with the explosive growth of mobile terminals.

This paper discusses the development of wireless communication technology, one of the technologies described above, and the compound semiconductor device technology that made the development possible.

3. Development in Wireless Communication Technology

3-1 High electron mobility transistor (HEMT)

In wireless communications using high-frequency radio waves, semiconductor devices with excellent high-frequency and high-power performances are required to achieve high data rates. A high electron mobility transistor (HEMT)*[1], which was developed in 1980 by Dr. Mimura at then Fujitsu Laboratories Ltd. It is the key device that supports today's wireless communications. As shown in Fig. 3, the region where electrons are generated (doping or polarization) is separated from the region where electrons transport, and the two-dimensional electron gas (2DEG)*[2] generated at the dissimilar junction interface (heterojunction interface) is not scattered by impurities, allowing the electrons to travel at high speed. The former feature reduces noise generated by transistors, while the latter improves high-frequency signal amplification performance.

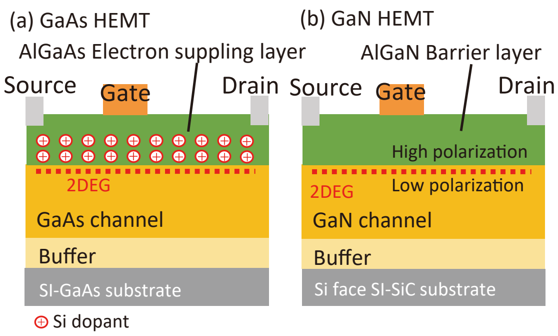


Fig. 3. Conceptual figures of HEMTs

3-2 Satellite communication (start of satellite broadcasting)

As described above, a HEMT operates at an extremely low noise and high frequency. Therefore, this transistor is suitable as a low-noise detector that amplifies weak radio waves from satellites. The low-noise property of this transistor was used for a satellite television dish antenna. With this new technology, the size of dish antennas, which used to be more than 1 m, was reduced to about 30 cm. As a result, they could be installed on the balconies of many houses and they quickly became popular. Thus, at the beginning of the development of the HEMT, it attracted attention mainly as a weak signal receiver.

3-3 Mobile wireless communications

Today, a HEMT is recognized as a device for high-frequency high-power amplifiers, as typified by a GaN HEMT*[3]. Figure 4 shows the communications standards, communication speeds, and semiconductor devices mainly used for each generation.

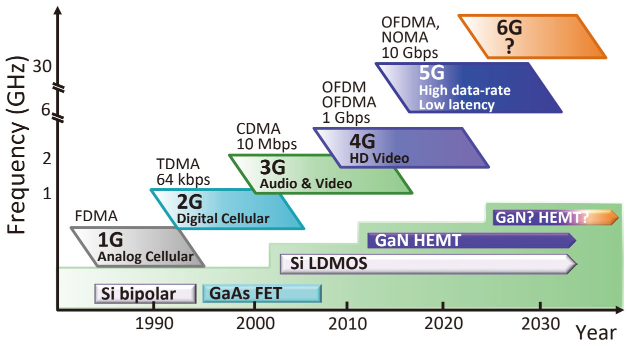


Fig. 4. Evolution of mobile communication system and base station semiconductor device

In the 1990s, at the stage of transition from the first generation (1G), which was based on analog systems, to the second generation (2G), which enabled data communications, the cell phone era began. Individuals became able to carry their own communication terminals instead of car phones that were popular at that time. In and after 2G, GaAs having excellent high-frequency characteristics was adopted as a base station amplifier. In addition, for the third generation (3G) system, which enables audio and video reproduction using mobile terminals, a code-division multiple access (CDMA) system was used to enable high-speed communications at 10 Mbps. Si lateral-diffused metal-oxide semiconductor (LDMOS) was the first base station amplifier in this generation, but with the shift to high-band carrier frequency during the second half of 3G and the fourth generation, a GaN HEMT having excellent high-frequency high-power characteristics was adopted for the first time. In 2007, our company (a manufacturing company with the current name of Sumitomo Electric Device Innovations, Inc. (SEDI)) succeeded in the commercialization of GaN HEMT for the first time in the world. In addition to the advantageous features described above, the GaN HEMT was superior to amplifiers comprising a GaAs HEMT or Si LDMOS in power density and power efficiency. The benefits gained from the use of a GaN HEMT, which are schematically shown in Fig. 5, are described below.

GaN HEMT amplifiers have high efficiency and generate a relatively small amount of heat, making it possible to downsize the heat sink. These features led to a significant reduction of 50% in power consumption, 60% in volume, and 70% in weight of the amplifiers when compared with conventional Si LDMOS. The accelerating introduction of remote radio head (RRH), which can be installed on the rooftops of buildings and other structures due to its reduced volume and weight, resulted in a significant increase in the installed number of fourth-generation (4G) base stations. In

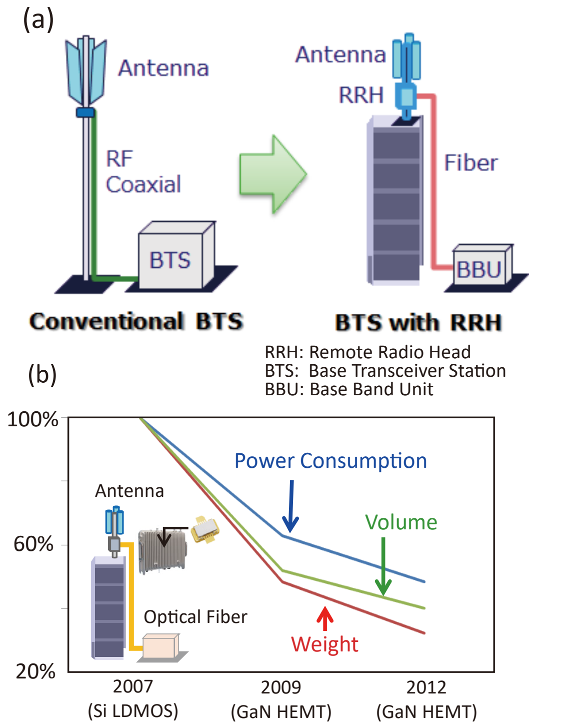


Fig. 5. Effect of the use of GaN HEMT amplifier for reducing the volume, weight, and power consumption of base station unit

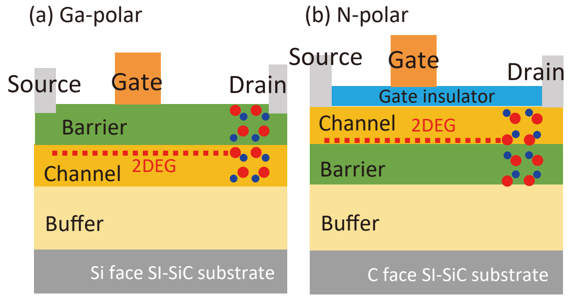
conjunction with this, demand for GaN HEMT amplifiers in Japan and overseas increased significantly. In the fifth generation (5G) systems, which achieve a further higher data rate (10 Gbps) and lower latency, GaN HEMTs are still used as the devices for base station amplifiers after their high-frequency characteristics and signal amplification quality are improved. The market demand for 5G systems is not yet mature, and the semiconductor devices to be used in these systems are still under development. According to our view, the applications that fully utilize the performance specified in the 5G standard have not yet matured enough on the user side. Similarly, for the sixth generation (6G) systems that will use terahertz waves for wireless communication for the first time, the development of semiconductor devices will face a large barrier since it is difficult to achieve high output power and high frequency at the same time in order to cover poor permeation of radio waves.

4. R&D on Next-generation Devices for Amplifiers

4-1 N-polar GaN HEMT

The GaN HEMT that has been discussed above is a Ga-polar HEMT in which Ga atoms are lined up on the surface of the semiconductor crystal (see Fig. 6 (a)). Technologies have been developed to further increase the power output density, to make the operation frequency further higher, and to suppress the transient response caused by traps inside the crystal. In parallel with continuous improvement of the performance of Ga-polar GaN HEMT as one of our commercial products, we started in 2020 the development of a nitrogen (N) polar GaN HEMT*4, which was not an extension of the previous technological improvements. As shown in Fig. 6 (b), a N-polar GaN HEMT in which nitrogen (N) atoms are lined up on the surface of the semiconductor crystal has the potential of bringing out a technological innovation that is discontinuous from conventional technologies in terms of physical property.

The significant feature of N-polar GaN HEMTs as devices for amplifiers is that electrons are structurally confined in the channel without being spread in the buffer direction, as shown in the simulation results in Fig. 7 (a).



● represents Ga atom. ● represents N atom. The atom arrangement is nothing more than the conceptual representation of the arrangement atoms inside the crystal, and the position and number of atoms in the cross section have no meaning.

Fig. 6. Difference between Ga-polar HEMT and N-polar HEMT

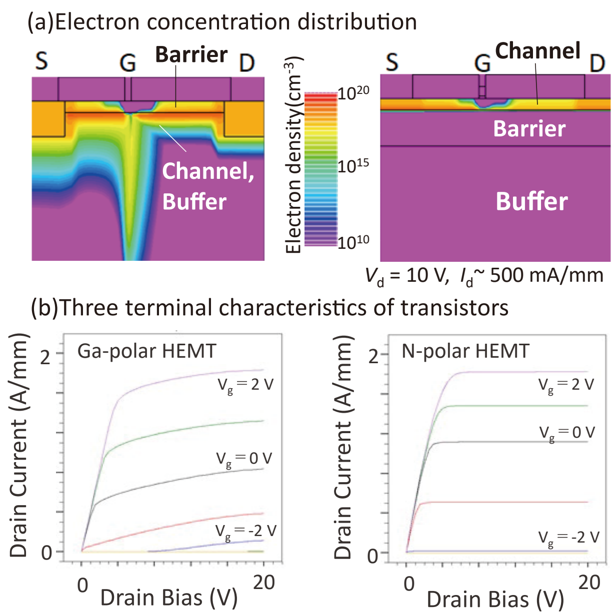


Fig. 7. Calculation of electron distribution and characteristics prediction by simulation

Due to this feature, N-polar GaN HEMTs improve the linear-saturation characteristics of the transistor, reduce the drain conductance*5 as the simulation results in Fig. 7 (b) show, and lower drain conductance improves the maximum power gain cut-off frequency (f_{max}). Figure 8 shows a comparison of Ga-polar drain conductance and N-polar drain conductance based on the measurement of a prototype device. This feature will improve the transient response characteristics of the device by blocking the effects of residual electron traps in the buffer region.

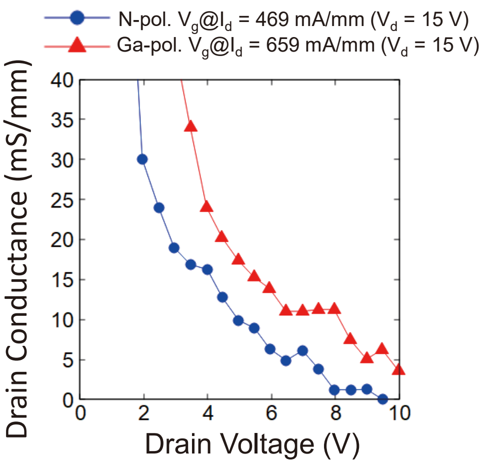


Fig. 8. Measurement-based comparison of Ga-polar and N-polar HEMTs in terms of drain conductance

4-2 Development of process with mass production

As described above, N-polar GaN HEMTs are promising as devices that further increase output power density, operate at a higher frequency, and reduce transient response due to GaN HEMT-specific trapping. However, an N-polar GaN crystal, in which nitrogen atoms are lined up on the semiconductor crystal surface, is not resistant to acid, alkali solution, or plasma irradiation treatment and damages the crystal to degrade its electrical properties. In contrast, these treatments have little effect on Ga-polar GaN HEMT crystals. To overcome the above-described shortcoming of N-polar GaN HEMTs, we redesigned and reengineered the conventional Ga-polar GaN HEMT mass production process and succeeded in fabricating a prototype of N-polar GaN HEMT using mass production facilities.

4-3 Epitaxial technology for 4-inch N-polar GaN HEMT

A compound semiconductor device differs from Si devices in that its performance is largely dependent on crystal (epitaxial) growth technology. Different from Si and other single crystal/single-element crystals, GaAs and InP have a cubic sphalerite-type structure and GaN has a hexagonal wurtzite-type structure, and they are compounds composed of two to four elements. In the case of GaN HEMT, for example, band engineering can be used to form a HEMT structure by heterojunction of GaN and AlGaN.

With the aim of developing next-generation products, we have developed a technology that can fabricate the above-described N-polar GaN HEMT using metal-organic chemical vapor deposition*[6] that can treat substrates of up to 6 inches in design. In the conventional technology, a large amount of impurities are taken in the device buffer region as residual carriers, which act as electroconductive substances. It is also difficult to suppress the formation of hillocks on the crystal surface (crystal defects). The newly developed crystal growth technology significantly reduces the concentration of impurities, thereby allowing the use of hillock-free crystal structures (see Fig. 9 and Photo 1).

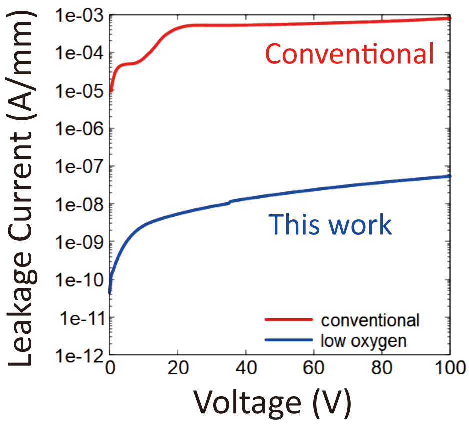


Fig. 9. Effect of impurity intake suppression technology for leakage current suppression in device isolation region

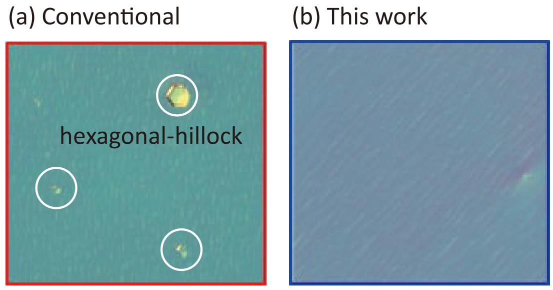


Photo 1. Reduction of hillock by new crystallization technology

4-4 Challenge to the development of new MIS technology

In this N-polar GaN HEMT development work, a new gate-insulating film*[7] technology was newly developed. The metal-insulator-semiconductor (MIS) structure used in the development is a laminate structure of a metal (gate electrode metal), insulator (gate insulating film), and semiconductor. It is also called an insulated gate because of its electrical characteristics. The MIS structure is also called a metal-oxide-semiconductor (MOS) structure when the gate-insulating film is an oxidized film. After the 1980s, the development of MOS FETs and MIS HEMTs using GaAs, as well as Si MOSFET, had been actively performed. However, it was difficult to fabricate a device that operated properly. This was attributable to the effects of traps mainly at the interface between a compound semiconductor, such as GaAs, and the gate-insulating film. For this reason, Schottky barrier junction gate electrodes, in which the gate metal material is directly formed on the semiconductor surface, have been used for compound semiconductor devices. On the other hand, N-polar GaN HEMTs had a physically unavoidable problem in that the gate leakage current increases because the gate electrode is located on the GaN channel, where highly concentrated 2DEG accumulates as shown in Fig. 6 (b).

To solve this problem, we set about developing a high-breakdown-voltage/high-dielectric HfSiOx using the atomic layer deposition method.[(1)-(3)] For this HfSiOx, an ultra-thin multilayer laminate structure of HfOx and SiOx is deposited, and then post-deposition annealing is performed to progress the reformation of the mixing/atomic bond. Figure 10 shows the measurement results for the dielectric constant and breakdown voltage of an HfSiOx film fabricated on a Ga-polar GaN HEMT. The developed HfSiOx gate insulating film achieved a relative dielectric constant of 13.5 and a breakdown voltage of 8.5 MV/cm. Compared with those of silicon nitride (SiN) gate insulating films used in our previous studies of N-polar GaN HEMT, the relative dielectric constant was about 2 times higher and the breakdown voltage was about 1.2 times higher. Meanwhile, the HfSiOx interfacial charge density of Ga-polar GaN HEMT was estimated to be about 10^{11} cm^{-2} eV^{-1} by a simplified evaluation method. In the next step, we will verify this density of the HfSiOx gate insulating film fabricated on an N-polar GaN HEMT by using a high-precision measurement method.

As described above, the technology for gate-insulating films is still under development. However, the basic electrical characteristics of gate insulating films and the output characteristics of the prototype device described below show the possibility of realizing MIS structure compound semiconductor devices that have been difficult to realize until today. This technology is attracting attention as our unique technology from the viewpoints of reducing gate leakage, stabilizing input impedance, and improving device reliability.

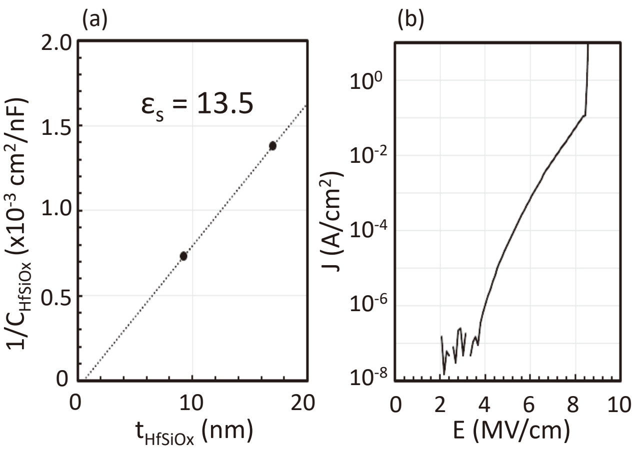


Fig. 10. Measurement results for the relative dielectric constant and breakdown voltage of HfSiOx film

4-5 Electrical characteristics of fabricated N-polar GaN HEMT

As described above, we have succeeded in fabricating a prototype of N-polar GaN HEMTs using facilities compatible with the mass-production of 4-inch devices. The fabricated GaN HEMTs are shown in Photo 2. The output characteristics of the GaN HEMT are shown in Fig. 11. The fabricated device achieved a high power density (8.09 W/mm), which was as high as that achieved by a competing institute in its earlier study. In our R&D, we could develop a group of elemental technologies that can overcome the physical property limits associated with the structural features of conventional Ga-polar GaN HEMTs, and we also integrated these technologies.

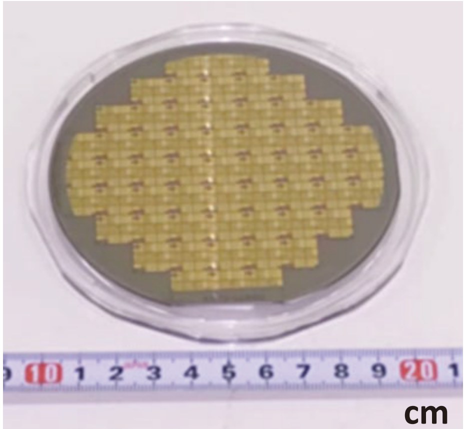


Photo 2. N-polar GaN HEMTs fabricated on a 4-inch SiC substrate using mass production facilities

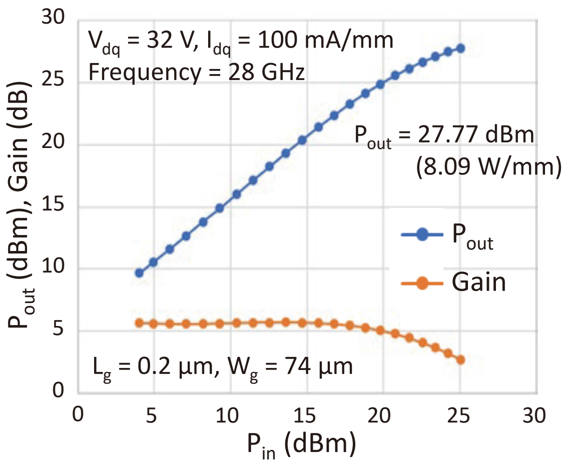


Fig. 11. The output power characteristics of a fabricated N-polar GaN HEMT

5. Future Challenges

As described above, the demand for communication services, both wired and wireless, is increasing rapidly. Our society cannot sustain itself without information and communication systems. However, these network systems consume an enormous amount of power. Table 1 shows an excerpt from the future network-related electricity demand forecasts issued by the Japan Science and Technology Agency's Social Scenario Research Project for Realization of a Low Carbon Society. Although this is a worst-case forecast, the power consumption of mobile networks will increase dramatically and will raise a serious problem when viewed from society's overall power consumption.

Table 1. Electricity demand by information networks

(TWh / year)	2018	2030
Entire Network exclude data center	490	2400
Base station for Mobile network	280	1970
Energy consumption ratio of mobile network (%)	57	82

From the viewpoint of power consumption, improved power efficiency of GaN HEMTs is required for base stations. In addition, research is being carried out to introduce GaN HEMTs into mobile terminals. Overseas companies are developing the most advanced GaN HEMTs, which are 20% more efficient than Si amplifiers and 6% more efficient than GaAs amplifiers.(4)

So far, we have discussed the devices used for wireless communications. Our society has become affluent with the expansion/diversification of electronic devices and the services that use them. However, the power consumption of society as a whole is increasing steadily. Global R&D is being carried out with an eye on reducing power consumption. For example, conventional large, low-efficiency power supply adapters are being replaced with high-efficiency, compact products using GaN. In addition to Si IGBTs, SiC-based FETs have begun to be used in power conversion devices that are essential for EVs. These are important basic technologies for realizing a low-carbon society.

6. Conclusion

In this paper, the information and communication systems that are currently indispensable for our daily lives and economic activities, as well as various semiconductor devices that support these systems, were explained. In addition, the transition of mobile wireless communications from the first to the sixth generations was discussed. Furthermore, N-polar GaN HEMT, a cutting-edge technology we are developing for commercialization, was explained as the latest technological development.

Finally, the power problem was mentioned as a future challenge. In this field, global companies are investing a lot of resources to rapidly promote technological innovations. As a result, many electronic devices are being refreshed. With the aim of further development, we will seize this business trend.

7. Acknowledgment

The development of the N-polar GaN HEMT described in this paper is based on results obtained from the “Research and Development Project of the Enhanced Infrastructure for Post-5G Information and Communication System” JPNP20017, commissioned by the New Energy and Industrial Technology Development Organization (NEDO).

Technical Terms

*1 High electron mobility transistor (HEMT): A field-effect transistor composed of a compound semiconductor heterojunction. It is excellent in high-frequency and low-noise characteristics.

*2 Two-dimensional electron gas (2DEG): Electrons that are formed near the hetero-interface of HEMT. Its motion in a direction normal to the device surface is restricted. It has very high mobility.

*3 GaN HEMT: A HEMT composed mainly of the heterojunction of AlGaN and GaN. It is used as a high-power device due to the high electron concentration resulting from the high polarization of AlGaN and the high breakdown voltage of GaN.

*4 N-polar GaN HEMT: A HEMT with a structure in which atom arrangement and heterojunction are inversed when compared with a commonly used Ga-polar HEMT.

*5 Drain conductance: An index that can indicate the superiority or inferiority of the saturation characteristics of a transistor. The smaller this value is, the more suitable it is for high-frequency amplifiers.

*6 Metal organic chemical vapor deposition: A process that makes it possible for crystals to grow in a gas phase in a thermal equilibrium state using metal-organic compounds.

*7 Gate insulating film: A film that insulates a semiconductor surface and gate metal. It has been considered difficult to fabricate this film on a compound semiconductor.

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