Chapter 3 Development of power devices

Section 1 Power Devices

Another important component of power electronic circuits is the semiconductor power device. Until now, the constraints imposed by power devices, such as switching speed and maximum operating temperature, have governed the entire system, but as power devices advance, these constraints are removed, placing higher demands on passive components, mounting technology, heat dissipation technology, and control technology. This chapter reviews the history of power device development and the progress of wide bandgap (WBG) semiconductor power devices, which have made significant progress in recent years.

1.1 The Dawn of Semiconductor Power Devices

Keyword: Semiconductor power device, Si diode, Si transistor, Bipolar transistor, Thyristor, GTO

Since the invention of the transistor in 1947 (actually, the junction-side bipolar transistor in 1948), the performance of semiconductor devices has improved year by year and their range of application has expanded rapidly. The vacuum tube, which had played a central role in electronics until then, was replaced by semiconductor devices, and semiconductor devices became electronic components that played a central role in wireless communications and information processing electronics. Meanwhile, as technological advances enabled semiconductor devices to achieve higher breakdown voltages and higher currents, the use of semiconductors in power conversion began to be considered. This was the advent of semiconductor power devices (power devices). Initially, germanium (Ge) was used, but later it was shifted to silicon (Si), and Si has occupied the leading position in power devices for the past 60 years up to the present.

The first power device to be commercialized was the rectifier diode. Until then, mercury rectifiers that used arc discharges in a vacuum were used for rectification. Compared to mercury rectifiers, which were fragile and required vacuum pumps and preheating, semiconductor rectifiers, which were immediately operable, compact, and robust, had an overwhelming advantage and were rapidly replacing them. Incidentally, the first Shinkansen bullet train (Series 0), which started service in 1964, used Si diodes with a withstand voltage of 800 A and 2500 V (1).

Derived from the junction bipolar transistor, the thyristor was developed by GE of the United States in 1957. It is a three-terminal device with gate terminals in addition to anode and cathode terminals. The trade name is Silicon Controlled Rectifier (SCR), and it is a device in which the diode transitions to a conducting state (arc) when current is applied to the gate terminal. When a rectifier circuit is configured with thyristors, the output voltage can be adjusted by adjusting the timing of triggering the thyristor (thyristor phase control method). The output voltage can now be adjusted continuously and electronically, whereas it was previously done step by step by switching the winding taps of the transformer. The thyristor's anode current must be set to zero to eliminate the thyristor's conduction state (arc quenching), but in the case of rectifier circuits, the voltage is automatically quenched when the input alternating current is zero. (1).

On the other hand, research on bipolar transistors with high current and high breakdown voltage has also progressed. Bipolar transistors have the advantage that they can be turned on and off at will according to the base current, since they conduct only when current flows through the base, and they were widely used in DC-DC converters and DC-AC converters (inverters). However, devices with a breakdown voltage of several kV are required for railroad and industrial equipment, and it has been difficult to switch these devices with bipolar transistors. As for thyristors, gate turn-off thyristors (GTO), which can turn off by drawing current from the gate terminal, were invented, and GTO thyristors were widely used, for example, in inverters of railroad vehicles, occupying a leading position until the late 1990s.

With the advent of these high-current, high-voltage rectifying and switching elements, the concept of freely converting and controlling electric power was born. This is power electronics. The origin of this concept is said to be an article written by GE's Storm in 1969 in the journal of the Institute of Electrical and Electronics Engineers (*IEEE) (IEEE Spectrum*). It is a new academic field that combines electrical equipment, semiconductor devices, and control in a trinity (2).

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1.2 Performance Indicators for Power Devices

Keyword: Switching operation, ON resistance, Withstand voltage, Off-state leakage, Dissipation, Heat generation, Maximum operating temperature

The essence of power electronics is to perform power conversion through the switching operation of semiconductor devices. In other words, the conduction and shutdown states of semiconductor devices are used. **Figure 3.1.2.** 1 shows the output characteristics of a typical transistor. In an analog amplifier circuit (Class A), the continuous state from point B to point D is used with point C of the load line as the bias point (operating point when no signal is present). Since a waveform faithful to the input signal is output, it is used to amplify analog signals. However, power loss equivalent to the terminal current × terminal voltage of the transistor, i.e., the area of the red rectangle in the figure, is regularly generated inside the trans istor even when there is no signal. However, the corresponding power loss is still generated in the transistor when a signal is input (during operation).

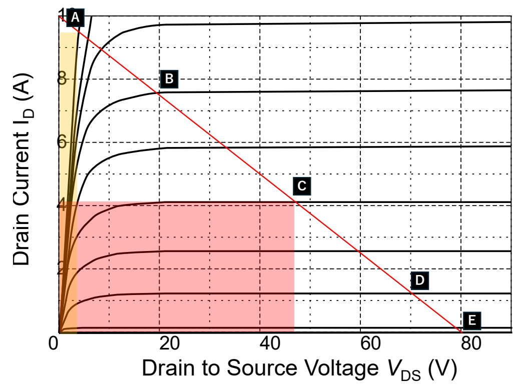

Figure 3.1.2.1 Difference in operating points of transistors in analog amplifiers and power

On the other hand, the power electronics circuit uses point A, which is completely on, and point E, which is completely off; at point E, the power loss is zero because the transistor is in a shutdown state; at point A, the transistor is conducting, and although there is loss due to conduction resistance (on resistance), as indicated by the orange rectangle in the figure, the power loss in the transistor is very small compared to the analog amplifier circuit. Compared to an analog amplifier circuit, the power loss in the transistor is very small. However, in the process of switching operation, the transistor must transition from A-B-C-D-E, and losses (switching losses) occur in this process.

The most important characteristics of power devices that perform switching operations are on-resistance (R_{on}) and breakdown voltage (V_b). On-resistance is the resistance in the conduction state, and the smaller it is, the better the power device with lower loss. The withstand voltage is the voltage at which current can be interrupted reliably. The basis of research and development of power devices is to minimize on-resistance while satisfying the withstand voltage required by circuit designers. In more detail, a small leakage current flows even in the off state. This is an off-state loss that must be minimized.

However, the current values used in power electronics circuits are orders of magnitude higher, ranging from tens of A to several kA, so the loss at point A in **Figure 3.1.2.1** is also quite large ($P_{\mathrm{loss}} = I^2\ R_{\mathrm{on}}$). As the temperature of semiconductors rises, the leakage current at off-state increases, and the heat generated by the leakage current causes the temperature to rise further, eventually leading to thermal runaway. The higher the upper temperature limit, the simpler the cooling system can be, which is a great advantage in system applications. Generally, in the case of Si power devices, the upper limit of use is 125 to 150 ℃ in terms of junction temperature (the temperature of the pn junction of the semiconductor device chip inside the package, not the temperature of the semiconductor device package). Considering the thermal resistance from the chip to the package, the package temperature must be maintained at several tens of degrees Celsius.

In summary, the main performance indicators of power devices are on-resistance, breakdown voltage, off-state leakage, maximum operating temperature, and switching loss. (In addition, short-circuit withstand voltage, avalanche withstand voltage, etc. are also included, but are omitted here.)

1.3 Unipolar and bipolar devices

Keyword: Thyristor, Bipolar transistor, Bipolar device, Unipolar device, Vertical power MOSFET

Thyristors and bipolar transistors have been the switching elements of power electronics for some time. Initially, bipolar transistors were responsible for devices with breakdown voltages of several hundred volts, and thyristors were responsible for breakdown voltages of 600 V and higher. These devices are called bipolar devices because both electrons and holes are involved in the conduction operation of the device.

On the other hand, there are unipolar devices (also called many-carrier devices) in which only one carrier (typically the electron) is involved in the conduction operation of the device. Field-effect transistors (FETs) are unipolar devices in their normal mode of operation, especially metal-oxide-semiconductor field-effect transistors (MOSFETs), in which the gate terminals are insulated from the current path (source and drain terminals) through an oxide film. The oxide film technology and microfabrication technology cultivated in Si integrated circuits have been incorporated to create a vertical device structure with a current path from the front surface to the back surface of the chip, and power MOSFETs have been developed as power device elements, especially those with low breakdown voltages of 300 V or lower. The power MOSFET rapidly spread as a low-voltage device, especially at 300 V or lower.

A cross-sectional view of a power device called a vertical power MOSFET (DMOSFET) is shown in **Figure 3.1.3.1**. In practice, this structure is placed periodically in the device chip plane to lower the resistance. When V_{gs} is equal to or greater than the threshold voltage, the transistor turns on. An electron channel is formed at the MOS interface, forming an electron pathway from the n-type source region, MOS electron channel, n-type drift layer, to the n-type substrate, resulting in a conducting state between the source and drain. The voltage holding layer is the neutral state of the n-type semiconductor, and electrons of the same density as the donor density are transported by the drift. (This is why it is called the drift layer.)

On the other hand, when V_{gs} is below the threshold voltage, no carriers are induced at the MOS interface and do not contribute to conduction. The embedded n^+ source region becomes irrelevant for operation and can be viewed as a reverse-biased pn junction between the p-type well region and the n-type drift layer to which the source electrode is connected. This pn junction blocks the source-drain interface. MOSFETs are used so that the drain side is positive, but when the drain side is negative, this pn junction acts as a diode. MOSFETs inevitably form a body diode due to their structure.

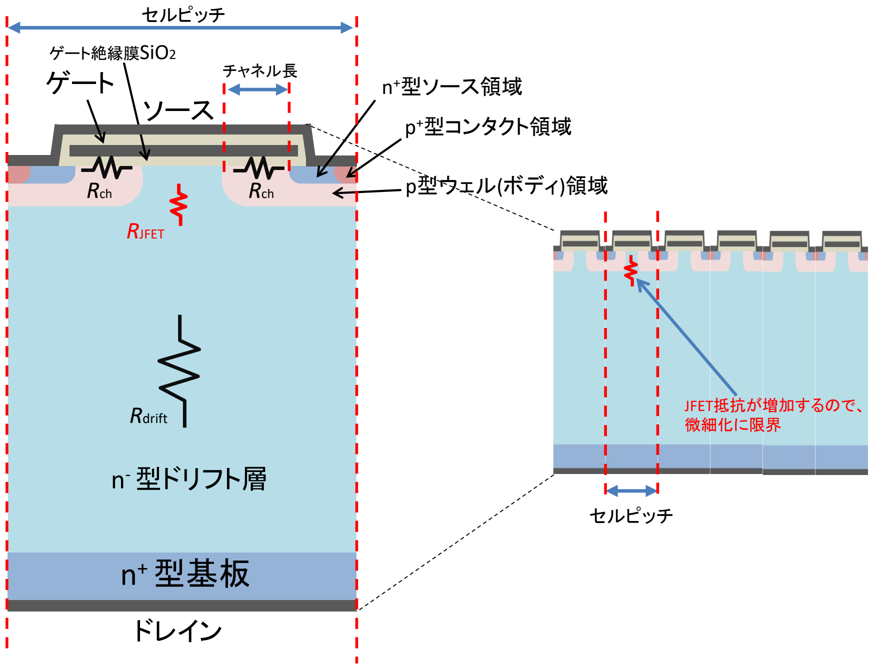

Figure 3.1.3.1 Structural Diagram of a Vertical Power MOSFET

The advantage of unipolar devices is fast operation. Since a large number of carriers are quickly transferred by an external electric field, on/off operation can be performed at high speed. On the other hand, to maintain breakdown voltage, the depletion layer region during off-state operation must be greatly expanded. Therefore, it is necessary to reduce the carrier density and thicken the depletion layer (called the breakdown voltage maintenance layer or drift layer). The voltage holding layer is added to the on-resistance as a series resistance of the device when the device is on. In actual power MOSFETs, there are various parasitic resistance components such as source electrode resistance, JFET area resistance in the narrowed area sandwiched between p-type wells on both sides, substrate resistance, drain electrode resistance, etc. However, if the design is well done, the ON resistance is basically the sum of the channel resistance of the MOSFET (R_{ch}), which is responsible for switching , and the drift layer resistance (R_{drift}), which is responsible for maintaining breakdown voltage.

On the other hand, bipolar devices can significantly reduce the resistance of the breakdown voltage maintenance layer by two to three orders of magnitude by actively utilizing the carrier injection state (conductivity modulation phenomenon in which electrons and holes become densely populated to neutralize carrier injection). In exchange, however, the switching operation becomes much slower. This is because when switching from on to off, conduction continues for a while due to the huge amount of carriers accumulated in the conductivity modulation region. The time required to completely switch from the on to off state limits the operating frequency of power electronics circuits using bipolar devices. In addition, large switching losses occur during the switching process due to unintended conduction states. Since the product of the switching loss and the operating frequency results in a loss per unit time, the available switching frequency is further limited by the prevention of thermal runaway (a heat dissipation problem). For example, the limit for thyristors with high breakdown voltage is several hundred Hz, and the limit for bipolar transistors is several tens of kHz.

Thus, in the second stage of power electronics, until the 1980s, power MOSFETs were used as switching devices for low withstand voltage, bipolar transistors for medium withstand voltage when switching speed was required, and thyristors for high withstand voltage otherwise.

1.4 Insulated Gate Bipolar Transistor

Keyword: IGBT, Conductivity modulation

In the mid-1980s, a revolutionary device appeared in Si power devices. It was the insulated gate bipolar transistor (IGBT). This device is a combination of a MOSFET and a bipolar transistor, and has the advantage that it can be easily turned on and off by driving the voltage of the isolated gate of the MOSFET, while in the on-state state, low on-resistance is achieved by using conductivity modulation of the bipolar device. Although a prototype IGBT device was proposed around 1978, its practical use was impossible because of latch-up caused by parasitic thyristors due to the npnp structure contained inside. In 1982, Baliga et al. first demonstrated a device similar to today's IGBTs. Later, in 1984, Nakagawa et al. of Toshiba Corporation invented a structure that does not latch up, which attracted attention as a new device worthy of actual use , and research and development progressed worldwide. This is considered to be the origin of the current Si IGBTs [(1)].

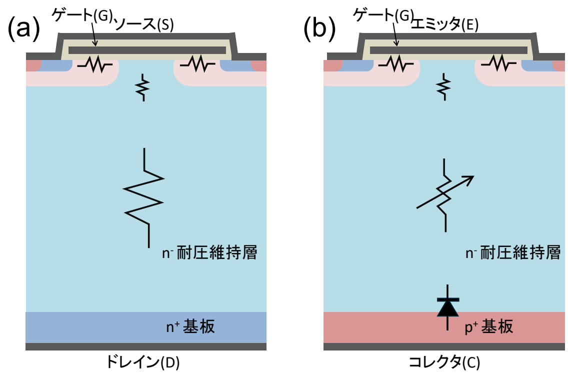

Figure 3.1.4.1 Basic structure of (a) MOSFET and (b)

Figure 3.1.4.1 shows the basic structure of a MOSFET and an IGBT. When a voltage above the threshold voltage is applied to the gate, electrons are supplied through the channel. On the other hand, the pn junction between the substrate and the breakdown voltage maintenance layer is forward biased, and holes are supplied from the substrate. Electrons are supplied from the channel to cancel out the positive charge due to hole injection, and there are almost the same number of electrons and holes in the voltage maintenance layer, and their density increases significantly from the original donor density. This is conductivity modulation.

In the 2000s, IGBTs with very high performance at 600 V to 3.3 kV breakdown voltage were realized, and the standard power electronic devices were Si MOSFETs up to 600 V, IGBTs from 600 V to 3.3 kV, and GTO thyristors for higher voltage. In addition , research and development of IGBTs has progressed, and IGBTs with a withstand voltage of 6.5 kV are now in practical use [(2)].

Si IGBTs are excellent devices, but they have the problem of slow switching speed because they are bipolar devices. There is a trade-off between switching speed and the effect of conductivity modulation. If defects are intentionally introduced into the semiconductor and the recombination speed is increased, the switching speed is increased, but the effect of conductivity modulation, or on-resistance reduction, is weakened. IGBTs have been developed that are appropriately tuned for the switching frequency of power electronics circuits; the available switching frequency of IGBTs is limited to a few tens of kHz at most due to losses. This switching frequency is responsible for the characteristic squeaking sound in electric vehicles.

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1.5 Unipolar limit

Keyword: Breakdown voltage, breakdown voltage, avalanche breakdown, breakdown field strength, band gap, characteristic on-resistance, unipolar limit

Consider a semiconductor pn junction diode. When a forward voltage is applied, the current rises above the diffusion potential and the diode becomes energized. On the other hand, when a reverse voltage is applied, only a very small leakage current flows. However, as the reverse voltage is increased, breakdown occurs at a certain point and a large current flows. This voltage is called breakdown voltage or withstand voltage (withstand voltage).

There are two types of breakdown mechanisms: Zener breakdown and avalanche breakdown. Avalanche breakdown originates from a process called impact ionization, in which carriers accelerated by an electric field collide with each other in the depletion layer, and the energy of the collision generates an electron-hole pair. Consider the case of an electron entering from the left side of the depletion layer. This electron undergoes impact ionization several times in the depletion layer and M_{n} times in size when it leaves the depletion layer. This is called avalanche multiplication. When impact ionization occurs, a hole is produced in the depletion layer. These holes travel in the depletion layer in the opposite direction, and may cause impact ionization in the process. When a certain critical point is exceeded, the generation of electrons and holes in the depletion layer continues indefinitely ($M_{\mathrm{n}} \to \infty$). This situation is called avalanche destruction. Avalanche multiplication is expressed by the following equation

$$1 - \frac{1}{M_{\mathrm{n}}} = \int_0^W \alpha_{\mathrm{n}}(x) \exp\left[-\int_x^W \left(\alpha_n(x') - \alpha_p(x')\right)\mathrm{d}x'\right]\mathrm{d}x \qquad (3.1.5.1)$$

Here α_{n}, α_{p} is the impact ionization coefficient of electrons and holes at each location in the depletion layer (multiplication by the unit distance traveled), and W is the depletion layer width. The integral of the right-hand side is called the ionization integral, and the avalanche multiplication is reached when this integral value is 1.

The impact ionization coefficient is a function of the electric field strength. Although it varies slightly depending on the depletion layer width and field strength distribution, avalanche breakdown generally occurs when the maximum field strength in the depletion layer exceeds a certain value. This field strength is called the breakdown field strength and is an indicator of the avalanche breakdown resistance of semiconductor materials. Impact ionization cannot occur unless the carriers are accelerated by the electric field and obtain a kinetic energy sufficiently larger than the band gap, which is why it is suddenly less likely to occur when the band gap increases. As a result, the breakdown field strength increases with the band gap. As described below, the band gap of GaN and SiC is about 3 times larger than that of Si, but their breakdown field strength is about 10 times larger than that of Si.

Whether it is a MOSFET, IGBT, or thyristor, the pn junction supports off-state isolation. The design of a power device begins with the design of the pn junction to achieve the desired breakdown voltage. The thickness of the n-type drift layer is secured and the doping density of the drift layer is reduced so that the maximum field strength of the pn junction is less than the breakdown field strength of the semiconductor at the desired breakdown voltage. On the other hand, in the on-state, the n-type drift layer is a resistive component. This is the reason why there is a trade-off between increasing the breakdown voltage and increasing the on-resistance (loss).

Assuming that the n-layer (voltage holding layer) is thick enough, the electric field distribution in the depletion layer will be in the shape of a right triangle (green in the figure). If the maximum electric field strength is E_{cr} and the desired dielectric breakdown voltage is V_{B}, the required depletion layer width is $W = 2V_{\mathrm{B}}/E_{\mathrm{cr}}$. The thickness of the n-layer should be the minimum necessary to eliminate unnecessary resistance, so it should be adjusted to this maximum depletion layer width.

Next, let us consider the donor density. From Gauss's law $\mathrm{d}E/\mathrm{d}x = e\,N_{\mathrm{d}} / \epsilon_{\mathrm{s}}$, the donor density to achieve such an electric field distribution can be determined. Here, ϵ_s is the dielectric constant of the semiconductor. the resistance of the n-layer is expressed as $R_{\mathrm{on}}\,A = W/(e\,N_{\mathrm{d}}\,\mu_{\mathrm{n}})$, where the mobility of electrons μ_{n}, and the cross-sectional area A. Eliminating W and N_{d} from the above equation, we obtain

$$R_{\mathrm{on}}A = \frac{4\,V_B{}^2}{\varepsilon_{\mathrm{s}}\,\mu_{\mathrm{n}}\,E_{\mathrm{cr}}{}^3} \qquad (3.1.5.2)$$

The on-resistance ($R_{\mathrm{on}}A$) normalized by the element area A is called the characteristic on-resistance.

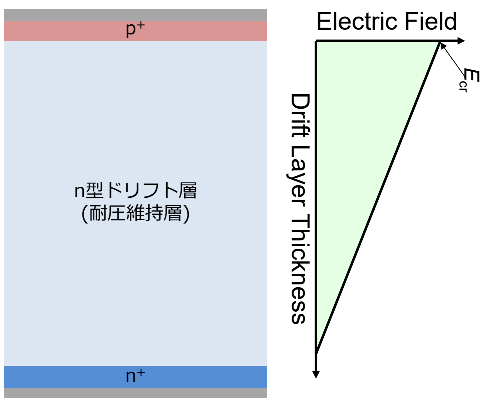

Figure 3.1.5.1 Electric field distribution in a p+n

As can be seen from this equation, when the semiconductor material is fixed, the on-resistance increases with the square of the breakdown voltage, as shown in **Figure 3.1.5.2**. In reality, since the value obtained here is for the drift layer resistance, the MOS channel resistance and various other parasitic resistance components are added. It is called unipolar limit.

If devices of 1200 V required for electric vehicles and 3300 V used in railroads are to be realized, the resistance of unipolar limits becomes too high for Si. Therefore, bipolar devices (thyristors and IGBTs) that can take advantage of conductivity modulation by carrier injection are used, but as mentioned above, there is a price to pay in exchange for the reduction of conduction loss by conductivity modulation: large switching loss (limitation of the operable frequency).

As can be seen from the unipolar limit equation, the breakdown field contributes to the reduction of on-resistance to the power of 3. WBG semiconductors have a breakdown field strength 10 times greater than that of Si, while the mobility and dielectric constant of WBG semiconductors are not much different from those of Si. Therefore, considering devices with the same breakdown voltage, unipolar devices with low switching loss can reduce on-resistance to 1/1000 of that of Si. This is the reason why WBG semiconductors are expected to be the next generation power devices and have been studied intensively since the late 1990s.

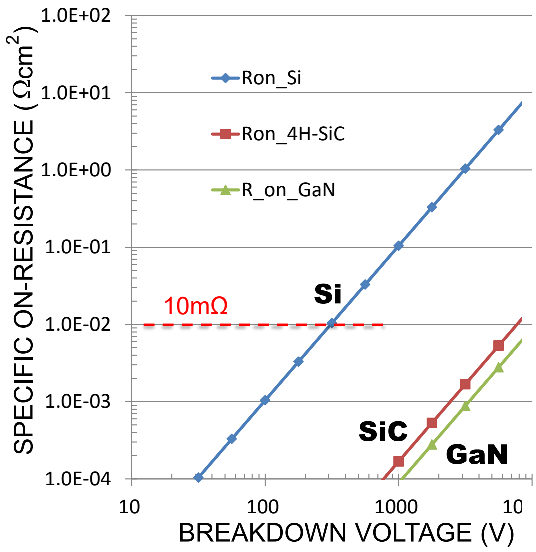

Figure 3.1.5.2 Unipolar Limits of Various

Section 2 Wide bandgap semiconductor power devices

2.1 Wide bandgap semiconductor materials

Keyword: Wide band gap (WBG) semiconductor, SiC, GaN, Ga_2O_3, Diamond, AlN, Cutoff characteristics, Leakage current

Among semiconductor materials, those with band gaps (forbidden bandwidths) exceeding 3 eV are called wide bandgap (WBG) semiconductors, and the physical properties of Si, gallium arsenide (GaAs), and typical WBG semiconductors are shown in **Table 3.2.1.1**.

WBG semiconductors have various properties related to their large band gap. From the viewpoint of electronic devices, the true carrier density of WBG semiconductors is several tens of orders of magnitude smaller than that of Si and GaAs at room temperature. In addition, the breakdown field strength is more than 10 times larger than that of Si and GaAs. **Figure 3.1.5.2** shows the calculation of the unipolar limit described in the previous section, which indicates that SiC and GaN can reduce the on-resistance to 1/300 to 1/500 of that of Si for devices of the same breakdown voltage. The cutoff characteristic (leakage current) of electronic devices is related to the true carrier density, and the leakage current of Si and GaAs increases at temperatures of 150~200 ℃, making them unfeasible as devices. In principle, however, the device can be operated with low leakage current even at high temperatures. The high breakdown field also provides an overwhelming performance advantage when used as high-power high-frequency (microwave to millimeter-wave band) transistors and power switching devices.

In addition, WBG semiconductors are chemically very stable due to the strong bonding strength between atoms, which makes defect formation due to irradiation less likely. Taking advantage of this, research and development of devices for use in chemically harsh environments and radiation-resistant devices are underway. However, the reverse side of this chemical stability is the difficulty of crystal growth and device fabrication processes, but through many years of research, the technology has gradually been established, and today, various devices using GaN and SiC are widely used in the world.

Among WBG semiconductors, those with a band gap exceeding about 5 eV are called ultra-wide gap (UWBG) semiconductors. Although there are some issues such as difficulty in controlling conductivity in addition to the difficulty of crystal growth and device fabrication processes, UWBGs are being studied as materials that offer even higher performance (and lower characteristic on-resistance) than WBGs. Typical materials include diamond (C), gallium oxide (Ga_2O_3), and aluminum nitride (AlN).

Table 3.2.1.1 Physical properties of various semiconductors

	Si	GaAs	4H-SiC	GaN	β-Ga2O3	Diamond	AlN
Contraband Width (eV)	1.12	1.42	3.26	3.42	4.5	5.5	6.0
electron mobility (cm^2/Vs)	1350	8000	1180	1480	200	4500	300
Saturation drift velocity (cm/s)	1×107	1×107	2×107	2×107	1.5×107	1.5×107	2×107
breakdown field (MV/cm)	0.3	0.4	3	3	>7	>10	>10
dielectric constant	11.8	13.1	10.3	10.4	10.2-12.4	5.7	8.5

2.2 SiC Vertical MOSFET

Keyword: SiC MOSFET, switching loss, rise voltage, merit, system level effect, MOS channel mobility

Si IGBTs are excellent devices, but they have several drawbacks compared to Si MOSFETs. The first is the aforementioned switching losses. Another disadvantage is the static characteristics of the device: IGBTs contain a pn junction in the current path (forward biasing the pn junction is essential for conductivity modulation), so the rising voltage of the pn junction is always a factor in the on-state losses. **Figure 3.2.2.1** shows a comparison of the on-state output characteristics of commercially available Si MOSFETs and Si IGBTs: the MOSFETs show a linear rise in current from 0 V, while the IGBTs show a rise from around 0.8 V, about the diffusion voltage of Si. At high currents (30 A), the IGBTs have the advantage of greatly reducing the resistance of the breakdown voltage maintenance layer due to conductivity modulation, so the IGBTs have a loss 1/3 that of the MOSFETs. (In reality, the current value is several times higher than this, so the loss is even smaller.) On the other hand, at current values as low as 2.5 A, IGBT losses are higher due to the loss of the rising voltage, which is twice that of MOSFETs. In the case of electric vehicles (EVs), this loss can be a problem because the vehicle is operated at a relatively low current value for long periods of time during constant-speed driving.

Using SiC, a WBG semiconductor, the resistance of the drift layer (characteristic on-resistance of unipolar limit) can be reduced to about 1/300 of that of Si, as mentioned above; with Si, a MOSFET structure is realistic up to about 600 V, but with SiC, it is realistic up to around 3~10 kV. The MOSFET structure can achieve low ON-resistance (resistance equivalent to Si MOSFET 300 V breakdown voltage), eliminating the need to use IGBTs; MOSFETs can also operate at high speeds, significantly reducing switching losses (or enabling higher frequencies). Furthermore, the available temperature range can be expanded, resulting in system advantages due to the simplification of the cooling system.

The benefits of replacing Si IGBTs with SiC MOSFETs (as well as other WBG semiconductor MOSFETs), the system-level effects, and the associated new research needs are summarized in **Figure 3.2.2.2**.

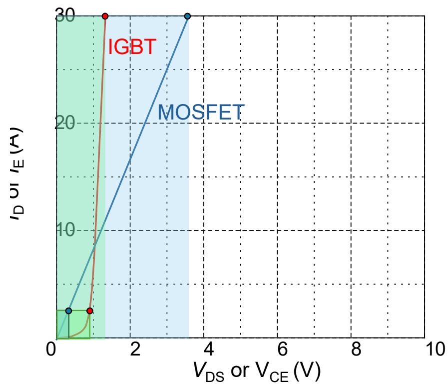

Figure 3.2.2.1 Comparison of output characteristics of Si MOSFET (blue line) and Si IGBT (red line) when on

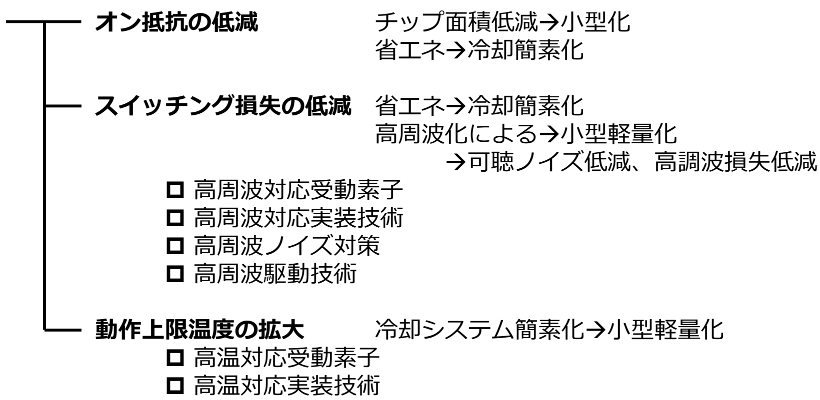

Figure 3.2.2.2 Benefits and system-level effects of transitioning from Si IGBTs to SiC MOSFETs, and associated research needs

Since the late 1990s, research and development of SiC power MOSFETs has progressed.[1,2] In 2010, ROHM started mass production of SiC power MOSFETs ahead of the rest of the world. In addition, Mitsubishi Electric Corporation installed SiC inverter modules on the Tokyo Metro Ginza Line, and the power MOSFETs not only offer the above-mentioned merits, but also greatly reduce operating power consumption by enabling power regenerative braking over a wide speed range due to reduced power loss during power conversion, and reduce brake maintenance costs by reducing the burden on mechanical brake systems. This was the starting point for the subsequent application of SiC to rolling stock [3]. SiC MOSFETs are used in the Yamanote Line and the latest Shinkansen (N700S series).

In the case of SiC, it is said to be difficult to increase the MOS channel mobility; the mobility of several tens cm^2/Vs is secured by MOS interface nitridation, etc. and the channel resistance is reduced by further miniaturization of the gate structure (multiple parallelization of channels). However, the ratio of channel resistance to drift resistance is larger in devices with a voltage of less than 2 kV, and even if the breakdown voltage is lowered below 1 kV, the on-resistance does not drop much, making it difficult to compete with Si MOSFETs below 400 V. The SiC MOSFETs have made it possible to use fast-switching MOSFET devices up to about 3.3 kV, which is a very big impact in the power electronics field. This has had a very large impact on the power electronics field.

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2.3 SiC Super Junction MOSFET

Keyword: Superjunction structure, Superjunction, SJ MOSFET

Even with SiC, the resistance of the voltage holding layer becomes negligible at voltages above 3.3 kV. Another method to reduce the resistance of the voltage holding layer is the superjunction (SJ) structure [1] shown in **Figure 3.2.3.1**. This method utilizes the periodic structure of the pn junction (perpendicular to the electric field) as the breakdown voltage maintenance layer; the entire SJ structure is depleted to support the breakdown voltage, and the doping region contributes to electrical conduction several to ten times higher than normal when on. （For SiC, there is room for SiC SJ MOSFETs in the 3.3~20kV range. However, the switching characteristics deteriorate a little when using the SJ structure (bipolar like IGBTs). (However, the switching characteristics deteriorate slightly with the SJ structure (not as significantly as in bipolar devices such as IGBTs). In Japan, research and development of SiC SJ MOSFETs has been conducted as a national project (Strategic Innovation Program (SIP) of the Cabinet Office), and device resistance with even lower on-resistance than the SiC unipolar limit has been reported [2].

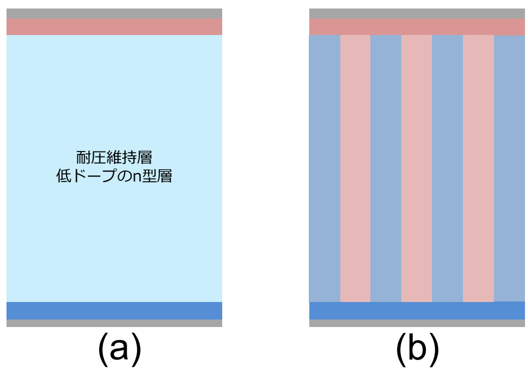

Figure 3.2.3.1 (a) normal bonding and (b) super-jointed structure

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2.4 SiC Bipolar Devices

Keyword: SiC IGBT, pin diode

For 20 kV-class devices used in power transmission and distribution systems, the characteristic on-resistance becomes large even with the SiC SJ structure, and unipolar devices are becoming more and more difficult to use. One way is to use ultra-wide gap semiconductors such as AlN and Ga_2O_3, which have even lower ON-resistance and higher breakdown field strength, but another way is to fabricate bipolar devices using SiC. SiC is an indirect transition semiconductor, and if good quality crystals are prepared, high conductivity modulation effect due to long carrier lifetime can be realized. SiC IGBTs have been vigorously studied in a national project (Funding Program for World-Leading Innovative R&D on Science and Technology (FIRST), Cabinet Office, Government of Japan), and n-channel SiC IGBTs with 16 kV breakdown voltage have been reported [(1)]. Although the differential on-resistance is greatly reduced by conductivity modulation, the pn junction of WBG semiconductors has a band gap at the rise time (3.2 V for SiC and GaN), resulting in large losses at low currents, as described for Si IGBTs. In addition to IGBTs, prototypes of pin diodes and thyristors have been reported for SiC. AlN and other materials are nonsense because the rise voltage is too large. In addition, GaN is a direct transition semiconductor, and sufficient conductivity modulation cannot be expected at high breakdown voltage (thick breakdown voltage maintenance layer), so SiC is the only WBG bipolar device material.

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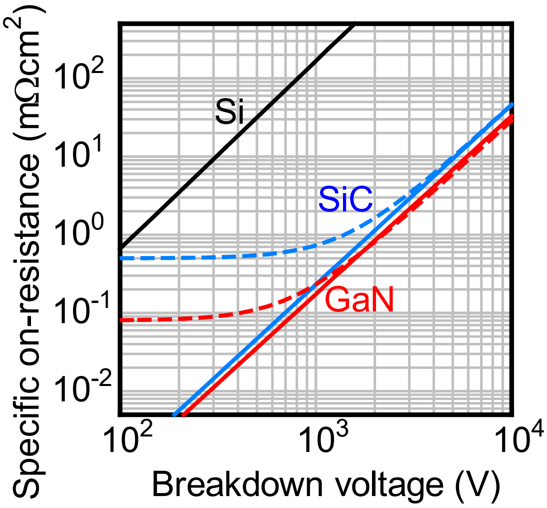
2.5 GaN Vertical MOSFETs



Keyword: Mobility, On-resistance, Gate capacitance, Fast switching, GaN diode, GaN vertical MOSFET, GaN wafer

Next, I will discuss GaN. Although AlGaN/GaN horizontal HEMT power devices preceded GaN in terms of development history, the vertical GaN MOSFET with a device structure similar to that of SiC is described here. As shown in **Table 3.2.1.1**, the physical properties of GaN are similar to those of SiC, and like SiC, it is a material system that can realize low ON-resistance MOSFETs. [(1)]. On the other hand, research on GaN has been lagging behind, but in recent years, fairly accurate data on dielectric breakdown have been reported [(2)]. Although the true mobility of GaN was unknown, it has become clear that the mobility, which was previously thought to be around 1200 cm2/Vs, can reach 1480 cm2/Vs when very high-purity crystals are fabricated and evaluated [(3)]. (Very recently, results exceeding 1600 cm^2/Vs were reported at an international conference.) Using these data to calculate the unipolar limit, a 20~30% reduction in on-resistance is expected compared to SiC.

Comparing SiC, for which power MOSFETs are already in mass production, and GaN, which is still in the research and development stage, the 20~30% resistance reduction effect alone may seem unattractive, but the story changes when considering the entire device. As mentioned earlier, the on-resistance of a power MOSFET is the sum of the on-resistance of the breakdown voltage maintenance layer and the resistance of the MOS channel, and while it is difficult to improve the MOS channel mobility of SiC, GaN has reported very high mobility of over 200 cm^2/Vs, even though there are still few research groups worldwide. **Figure 3.2.5.1** shows the on-resistance considering the sum of MOS channel resistance. below 2 kV, especially below 1.2 kV, the MOS channel resistance becomes rather dominant. By increasing the channel mobility by a factor of 3 to 4, the improvement in channel mobility is directly reflected in the on-resistance in this voltage range. At this breakdown voltage, GaN has the potential to reduce on-resistance to 1/2 to 1/3 of that of SiC, which is an attractive advantage.

Figure 3.2.5.1 Withstand voltage vs. on-resistance in a vertical MOSFET that also takes channel mobility (channel resistance) into account (dotted line)

<2kV or lower, the channel resistance becomes more dominant than the drift resistance as a percentage of the characteristic ON resistance.

This resistance reduction can be viewed in a variety of ways, including

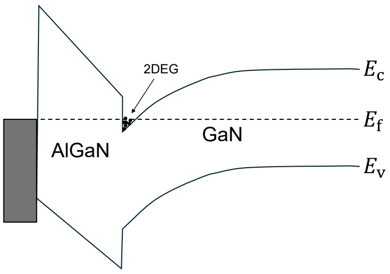
1. If a smaller chip area is required to achieve the same on-resistance, more chips can be obtained from the same wafer, resulting in cost reduction. On the other hand, since the same amount of heat is generated by smaller chips, the heat generated per area will be larger, requiring technological innovation in heat dissipation technology.
2. If the same on-resistance can be achieved with a smaller chip, the gate capacitance is proportional to the chip area for the same structure, enabling high-speed switching. Smaller gate capacitance reduces the gate drive, which enables higher switching speeds, lower switching losses, and higher switching frequencies. In order to achieve higher switching frequencies, mounting technologies such as reducing wiring inductance and improving the high-frequency characteristics of passive components will be required.
3. Looking at the internal structure of the device, if the channel resistance is small, there is no need to make the channels smaller and denser [(4)]. Since gate capacitance is proportional to channel density, it is possible to reduce gate capacitance further with the same chip area. Although some of the benefit of reduced on-resistance is lost, the combination of 2. and 3. is expected to enable a significant increase in high frequency for SiC MOSFETs. Although it is difficult to achieve ultrahigh speed like the horizontal GaN HEMT described below, it is possible to raise the switching frequency from a few MHz, which is becoming difficult for SiC MOSFETs, to 6.78 MHz or 13.56 MHz in the industrial science and medical (ISM) band.

In the development of GaN vertical MOSFETs, it is very important to consider circuit design and application fields that can take advantage of these advantages in order to differentiate them from SiC. In the ultimate form, the AlGaN/GaN heterostructure, which is unique to GaN, can be applied to the channel section, where the mobility of the two-dimensional electron gas induced at the AlGaN/GaN interface can reach nearly 2000 cm^2/Vs, more than 20 times higher than the channel mobility of SiC, depending on the structure. The above advantages become even more pronounced. On the other hand, there is a strong desire for [an] insulated gate structure for MOS from the circuit system side, and INNOPEL is studying a hybrid MOS structure with an AlN intermediate layer [(5)] or an AlGaN composition gradient layer [(6)] at the MOS interface as a hybrid of MOS and heterostructure. Although there are some issues to be solved, such as control of threshold voltage and verification of reliability, high channel mobility of several hundred cm^2/Vs has been reported.

INNOPEL is also developing GaN diodes, and is fabricating Junction Barrier Schottky diodes using ion implantation to reduce leakage current in the reverse direction as in SiC [(7)]. At the beginning, ion implantation technology was still in its infancy and devices with good characteristics could not be fabricated, but recently, devices with characteristics that match computer simulations have begun to be produced. With a relatively small rise voltage of 0.9 V, these devices have the potential to be attractive for circuit applications.

An important technology for the practical application of GaN vertical MOSFETs is the manufacturing technology for large-diameter, high-quality GaN wafers. There are various approaches to this, but Japan is currently the world leader in GaN wafer fabrication. Mitsubishi Chemical Corporation has the world's leading-edge technology for mass synthesis using the ammonothermal method, and has established a pilot production line in Muroran, Japan, in collaboration with Japan Steel Works (JSW) under a national project (NEDO). (8) Although mass production of 4-inch diameter is underway, it is said to be technically feasible to further increase the diameter. The amonothermal method grows several hundred thick crystals at the same time, and mass production is expected to be possible and cost will come down in the future as mass production technology advances.

Research on GaN vertical MOSFETs began in Japan and the U.S. around 2013, but it was still in the R&D phase, just before commercialization. However, joint research between various experts and industry has made great progress in the MOS technology and ion implantation technology mentioned above, which are the most important key technologies in the INNOPEL project. It is no exaggeration to say that Japan is leading the world in GaN vertical MOSFET technology. However, in order to further clarify the advantages of GaN over SiC, research on MOS and ion implantation is needed. If the power of domestic academia is concentrated and industry-academia collaboration is achieved within a few years, and the technology is then transferred to industry for commercialization ahead of the world, it is possible to build a supply chain and ecosystem in Japan, from GaN wafers to epitaxial growth, process technology, devices, passive components, circuit systems, and applied equipment. A domestic supply chain and eco-system can be established.



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2.6 Horizontal GaN HEMT

Keyword: High electron mobility transistor, HEMT, High frequency device, Field plate structure, Ultra-fast switching, Horizontal power device, USB charger, Hybrid power IC

GaN was initially studied as a material for blue light-emitting diodes and laser diodes, but it was also studied as a material for high power GaAs-based high-frequency transistors because of its high breakdown field strength. In the course of this research, it was discovered that a high density of two-dimensional electron gas can be induced at the interface without donor addition to the barrier layer (AlGaAs), which was required for GaAs-based transistors. and piezoelectric polarization of GaN and AlGaN. The extremely large polarization enables a channel electron density of 1013 cm^{-2}, which is nearly 10 times higher than that of Si-based and SiC MOS structures, and by properly designing and fabricating the heterostructure, a channel electron mobility of over 1000 cm^2/Vs can be realized, resulting in a HEMT with extremely low channel resistance. Due to the high breakdown field strength of GaN, high breakdown voltage can be obtained even when the gate is miniaturized for higher frequencies, and high-power transistors in the microwave (GHz) band can be realized.

(a) (b)

Figure 3.2.6.1 (a) Energy band diagram of AlGaN/GaN and (b) Schematic di[...]nsistor

The development of GaN HEMTs for high-frequency devices progressed, a[...] devices began to be considered around the year 2000. The reason for this is that the voltage resis[...] by maintaining the distance between the gate and drain electrodes, and devices with a voltage [...] the electric field concentration at the edge of the gate electrode, such as a field plate, can be succ[...]mparison of GaN vertical and horizontal power devices.

Table 3.2.6.1 Comparison of GaN vertical and horizontal power devices

	GaN Vertical Power Devices	GaN Horizontal Power Devices
Area utilization efficiency and high current	◎	×
High withstand voltage	◎	△
avalanche resistant	◎	×
high speed switching	△	◎
Effect of crystal defects on devices	×	○

In vertical power devices, current flows over the entire crystal surface, with drain electrodes on the back surface and source electrodes on the front surface interconnected by bridges. Therefore, the entire crystal can be utilized, resulting in high area utilization efficiency and facilitating large currents. In the horizontal type, it is necessary to widen the gap between the gate electrode and drain electrode to ensure breakdown voltage. In addition, it is necessary to form source and drain electrodes on the surface, which requires an area other than the gate and gate-drain spacing that is essentially necessary for device operation, resulting in low area utilization efficiency. For higher breakdown voltage, as explained in the unipolar limit, the breakdown voltage can be increased in the vertical type by lowering the doping of the n layer (breakdown voltage maintenance layer) of the $p^{+}n$ junction and increasing the film thickness. In the horizontal type, the gate-drain spacing can be widened, but a complex field plate structure must be built in to mitigate the electric field concentration at the gate edge. This also greatly affects the device's breakdown resistance (avalanche resistance) when a voltage higher than the breakdown voltage is applied. In the vertical type, if the electric field concentration at the edge of the device is properly mitigated, the electric field will be uniform over the entire crystal surface, and the current will flow uniformly over the entire crystal surface when breakdown occurs. For a certain amount of energy (loss x time), the device can continue to be used without degradation. On the other hand, in the case of the horizontal type, the current concentrates in the high electric field area at the gate edge, which basically results in breakdown of the dielectric film, irreversibly destroying the device and making its continued use impossible. While this is not a problem in applications such as battery chargers, where safety will not be affected even if the device should break, it is difficult to use the device in applications where reliability is important, such as in in-vehicle inverters.

Although GaN horizontal power devices seem to be at a disadvantage up to this point, when considered against Si power devices, they have an overwhelming advantage at breakdown voltages below 1000 V due to their extremely small channel resistance. Since the channel resistance greatly surpasses that of Si MOS, GaN lateral power devices have an advantage even at low breakdown voltages of 100 V or lower.

In terms of switching characteristics, the depletion layer in horizontal power devices expands laterally, and after the depletion layer expands, the gate electrode and drain electrode are spatially isolated from each other. This significantly reduces gate capacitance and enables ultra-fast switching. (This is thanks to the wasted area.) Ultra-fast switching speeds of not only several MHz but also tens to hundreds of MHz are possible. This will enable the development of a new area that is completely different in dimension from the 100~200 kHz of conventional power electronics.

The tolerance of crystal defects is mentioned: GaN contains high-density through-dislocations when grown heteroepitaxially on heterogeneous substrates such as Si and SiC. In the case of vertical epitaxial growth, the through-dislocation is in the direction where the electric field is applied during the off state, and the leakage current becomes large due to the through-dislocation, resulting in problems such as a decrease in breakdown voltage. In the vertical case, it is necessary to use a high-quality GaN substrate for homoepitaxial growth. On the other hand, in the case of the horizontal type, the electric field at off-state and the through-dislocation are orthogonal to each other, and the device characteristics do not deteriorate much even if there is a through-dislocation. This enables devices to be mass-produced at low cost using inexpensive, large-area Si and sapphire substrates.

Due to the above characteristics, especially the mass producibility mentioned in the last section, research on GaN horizontal power devices has been booming since the 2000s, and in 2010, International Rectifier (IR) of the United States succeeded in commercializing a 300 to 600 V. These transistors had the advantages of low ON-resistance and high-speed switching, but lacked reliability information (accumulation), were not easy to use because their characteristics differed greatly from those of Si MOSFETs, and had weak killer applications. applications.

A major turning point was the high-power USB charger: the establishment of the Power Delivery standard, which allows USB Type-C to flexibly distribute large amounts of power, increased the need for USB chargers of 60 to 100 W. While Si power devices would have increased the size of the charger, the use of GaN horizontal power devices The use of GaN horizontal power devices, however, has enabled chargers that are less than half the size of Si power devices, thanks to a significant improvement in switching frequency, which reduces the size of the capacitors and inductors required, as well as the conduction loss due to low on-resistance. This convenience has made it popular, and GaN (horizontal power device) USB chargers have become a popular product in just a few years since their appearance in 2021.

The power IC is thought to have been the technological key to the spread of this technology. Hybrid power ICs have been developed that combine the control circuits (Si integrated circuits) of GaN HEMTs, which are difficult to master, in the same package, allowing users to design power electronics circuits as an ideal switching unit. The GaN HEMTs used inside themselves were quite capable of high performance around 2015. This is an important example of how the pursuit of power device performance alone will not work, as providing ease of use will determine whether the device business is successful or not.

GaN horizontal power devices are capable of switching at several hundred to several MHz with ease. Since the majority of power electronics modules are composed of passive components, the ability to reduce the size of passive components through higher frequency will enable a significant reduction in size and weight. The field of specialty is portable battery chargers, for which miniaturization and weight reduction are strongly required. Currently, on-board chargers (OBCs) for electric vehicles are being developed around the world, and since OBCs are used only for charging, the smaller the volume and weight of the OBC in the vehicle, the better. The OBC also has a high tolerance for failure, since even if it should break, it will only be because it was not charged the next morning and will not cause fatal problems such as stopping the vehicle while in operation. As described above, there are great expectations for GaN horizontal power devices, but as they become higher frequency and smaller (higher density), the requirements for passive components and heat dissipation technology will increase, so it will be important to develop technologies that can meet these requirements.

In the case of hybrid power ICs, problems such as the inductance of the connection between the Si chip and the GaN power device will arise if the frequency is further increased. A chip integrating a GaN control circuit and a GaN power device is currently under consideration. Various studies are also underway for the drive system. However, in the several-MHz range, it will be necessary to integrate control circuits and power devices in a hybrid manner, as is currently being done with GaN horizontal power devices.

A detailed survey and analysis of GaN power devices, especially horizontal devices, was conducted in 2021 by the Japan Patent Office (JPO) in its Technology Trend Survey. Please refer to that report (1). Incidentally, a survey on GaN power devices was also conducted in FY 2008 (2). It should be noted that the status (key players) of GaN horizontal power devices has drastically changed between FY 2008 and FY 2021.

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Section 3 Summary

The transition from power devices using Si to those using wide bandgap semiconductors will not only lower on-resistance (compared with the same structure and breakdown voltage), but will also add new values such as "high switching speed" and "high temperature operation. The most promising wide bandgap semiconductors are SiC and GaN, both of which have made considerable progress in technological development. Their physical properties (band gap, breakdown field strength, and electron mobility, which are especially important in power devices) are similar. In terms of voltage holding layer resistance, GaN and SiC are 1/300 to 1/500 that of Si, and GaN is expected to be 20 to 30% smaller than SiC. On the other hand, SiC and GaN are in a competitive relationship in power MOSFETs, but considering that GaN has a larger MOS channel mobility, GaN has an advantage in terms of on-resistance in devices with breakdown voltages from several hundred to 3.3 kV, and it is also possible to improve switching speed by shifting part of the on-resistance reduction in design. AlGaN/GaN horizontal power devices are unique new devices that have not existed in conventional power devices, and new developments are expected, especially taking advantage of their overwhelming switching speed. The overall status of power device R&D is summarized in **Figure 3.3.1.1.**

It is extremely important to develop passive components and mounting technology that can take advantage of fast switching speeds and high temperature operation. For example, even if the power device itself can withstand high temperatures, the mounting technology may limit the available temperature, and the heat generated by the power device may raise the temperature of the surrounding passive components and limit the temperature limit of the passive components. In addition, to take advantage of high-speed switching, it is important to develop capacitors with low ESR and inductors with excellent high-frequency characteristics.

conventional

Si MOSFET Low withstand voltage (~600V) Fast switching (hundreds of kHz)

Si SJ MOSFET Medium withstand voltage (600~1.2 kV) Switching is rather slow

Si IGBT medium voltage (600~6.5 kV) High speed (tens of kHz) compared to thyristors
Si thyristor High withstand voltage (3.3 kV~) Low speed (<1 kHz)

present

SiC MOSFET Medium to high voltage (900 V~10 kV) Fast switching (100 kHz) Railway, automotive, renewable energy
AlGaN/GaN HEMT Low to medium voltage (~1.2 kV) Ultra-fast switching (~50 MHz) AC adapter

near future

SiC SJMOSFET High withstand voltage (3.3kV~10kV) Slightly sacrificed switching speed (~ several tens kHz) (nearing commercialization)
GaN MOSFET Medium to high voltage (600 V~3.3 kV), low ON-resistance, fast switching (MHz) (R&D progress)
SiC IGBT High withstand voltage (10~20 kV) High speed (~ tens kHz) compared to thyristor (R&D progress)

Figure 3.3.1.1 Current Status of Power Device R&D

［Jun Suda］