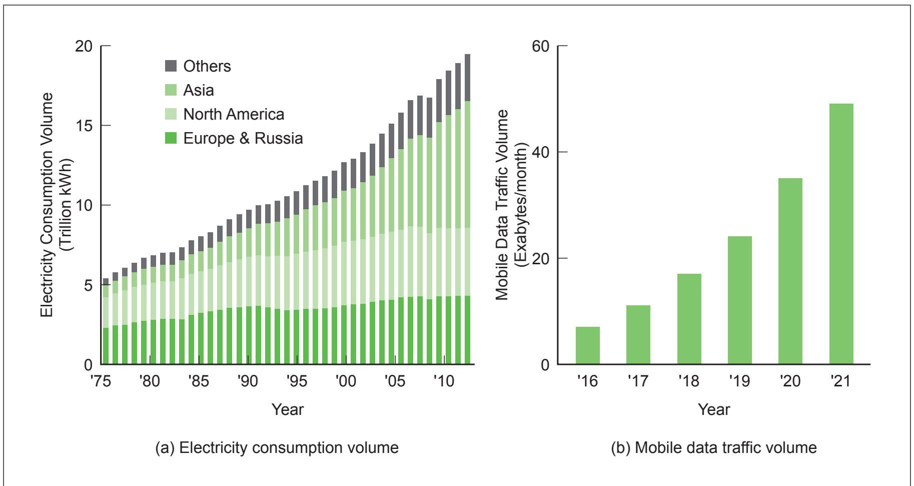
Trends in and Future Outlook for Semiconductor Devices with Enhanced Energy Efficiency

Among the issues that need to be addressed on a global scale are the growth in energy consumption and rise in carbon dioxide (CO_2) emissions. To conserve energy while meeting the increasing demand for electricity, it is necessary to improve energy efficiency at all stages from electric power generation to electricity consumption.
Toshiba Electronic Devices & Storage Corporation is promoting the development of various integrated circuits (ICs) and power devices as key parts in a broad range of fields, ranging from mobile, automotive, and other industrial applications to electric energy conversion equipment. We are making continuous efforts to supply such products in order to contribute to enhanced energy Efficiency

Electricity Demand and Effective Utilization

Along with economic growth and population growth, electricity consumption continues to increase worldwide, up 3.8-fold in the last 40 years (Figure 1(a))(1). The major increases in electricity consumption are occurring in Asia where many developing countries exist, as well as in other regions (e.g., the Middle East and Latin America), where economic growth and population growth are expected to continue into the future. Also, due to the development of the Internet and communication technologies together with the spread of smartphones and tablets, the amount of network traffic is also increasing explosively. By 2021, it is estimated that the mobile data traffic volume will be seven times as large as in 2016 (Figure 1(b))(2). As a result, the power consumption of network centers and terminals is rapidly increasing. In addition, the spread of hybrid and electric vehicles is also accelerating. For these reasons, it is clear that electric power demand will continue to increase.

Meanwhile, to address environmental and energy problems such as global warming, the shift from fossil energy to electric energy is accelerating, exemplified by the introduction of renewable energy such as solar, wind and hydroelectric power.



(Figure 1) : Worldwide trends in electricity consumption and mobile data traffic volume

However, it will not be possible to cope with this demand simply by increasing renewable energy generation.
Against this backdrop, attention is focusing on the concept of negawatts and negajoules, as they measure the effective utilization of electric energy and consequently indicate the same effect as an increase in electricity generation[3]. Specifically, conversion efficiencies of various electric energy from power generation to final consumption are improved by system control methods and power devices. Many IC design technologies and semiconductor components are employed to achieve this improvement.

In this article, the system trends toward effective use of electric energy and the semiconductor devices required for realizing these system trends are introduced.

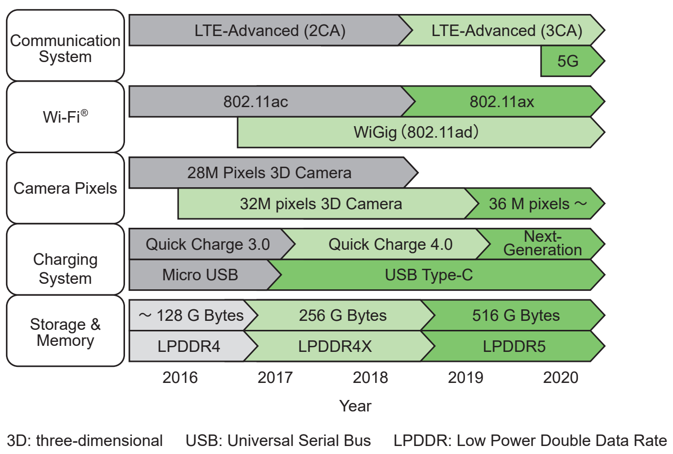
System trends

For effective use of electric energy, improvements in system performance are accelerating, and the requirements for semiconductor devices are becoming more demanding. In this section, system trends and requirements for semiconductor devices are described in three major application segments: 1) mobile/OA, 2) automotive/industrial, and 3) power conversion.

Mobile / OA field

Mobile devices, typified by feature phones and smartphones, are rapidly evolving in functionality and added value, in addition to the growth in the number of units shipped.

In terms of the communications standard, Long Term Evolution (LTE)-Advanced is now widespread, enabling much higher-speeds and large-capacity communications compared to third-generation (3G) systems. Techniques such as carrier aggregation (CA) that combines multiple frequencies to increase total data rate and the arrival of 5th-generation (5G) systems in 2020 will encourage widespread adoption of ultra-high-speed communications, as depicted in Fig. 2.
In addition, complementary metal-oxide-semiconductor (CMOS) sensors will increase the pixel count and data throughput. Battery capacity will increase together with fast-charging methods, and the storage and memory devices will increase in both capacity and data transfer rate. In response to such trends, power supply ICs will not only require high-current load capability but also improvement of the noise removal performance to keep up with the finer fabrication processes of the system ICs, high-speed transient load response to suppress fluctuations in output voltage, and improved efficiency of the power supply IC itself.



(Figure 2) : Trends in specifications of mobile devices

In the future, along with the advances in the Internet of Things (IoT), new applications such as those using wearable devices and sensor arrays will be created. New ICs and associated control techniques for achieving higher power efficiencies will be required.

For OA equipment, the international Energy Star program, launched in 1995 as a global energy saving standard, has spread to nine countries and regions. In addition to office equipment such as computers, printers, multifunction copiers, and their external power sources, television sets, air conditioners, lighting fixtures, etc. are also included in the list of equipment targeted for certification. Compliance criteria are set for each product group, and low-loss properties of ICs and power devices are required.

Automotive / Industrial field

To improve the energy utilization rate, there is strong demand for higher efficiency and downsizing of the power supply for industrial equipment including automotive in-vehicle equipment, servers and network equipment.

For automobiles, new developments are underway focusing on (1) the environment (reduction of CO_2 emissions), (2) energy saving (fuel economy), and (3) preventive safety (traffic accident prevention). In order to satisfy these demands, reliance on electronic control units (ECUs) capable of very advanced control is increasing (Table 1).

In response to these system trends, for automotive power semiconductor devices, which are the key components of the power supplies, reduction of dissipation loss and downsizing on a continuous basis are essential. In particular, low-voltage power metal-oxide-semiconductor field-effect transistors (MOSFETs) for motor control and electronic switching and intelligent power devices (IPDs) equipped with protection units will be needed to improve the performance.

Meanwhile, for industrial equipment, 80 PLUS is one of the industry standards that measure power conversion efficiency, and there are grade classifications according to performance. Helped by this standard, the number of high-efficiency models is increasing for servers and power supplies for network equipment.

Looking inside the power supply by functional block, the rectifying circuit uses a diode, the power factor correction (PFC) circuit uses a high-voltage MOSFET and a diode, and the direct current(DC)-DC converter section is composed of a high-voltage and a low-voltage MOSFET. These devices all require low internal power dissipation and high heat dissipation properties.

(Table 1) : Trends in requirements for automotive

			2015～2020	2020～2025	2025～2030
Circumstance	Fuel Economy Regulations	EU	130 g/km	95 g/km	70 g/km
		USA	15.1 km/L	→	23.2 km/L
		Japan	18.6 km/L	20.3 km/L	→
Safety & Comfort	Automatic Brake		deployment Collision Avoidance (EuroNCAP)	Combined with Autonomous Driving	
	Autonomous Driving		Level2 (Partial)	Level 3 (Conditional)	Level 4 (Advance)
	Head lamp		LED Head lamp		LaserHeadlamp
Average Number of ECU mounted			≒ 20 units	≒ 30 units	≒ 35 units

EU : European Union
EuroNCAP : European New Car Assessment Programme
LED : Light Emitting Diode

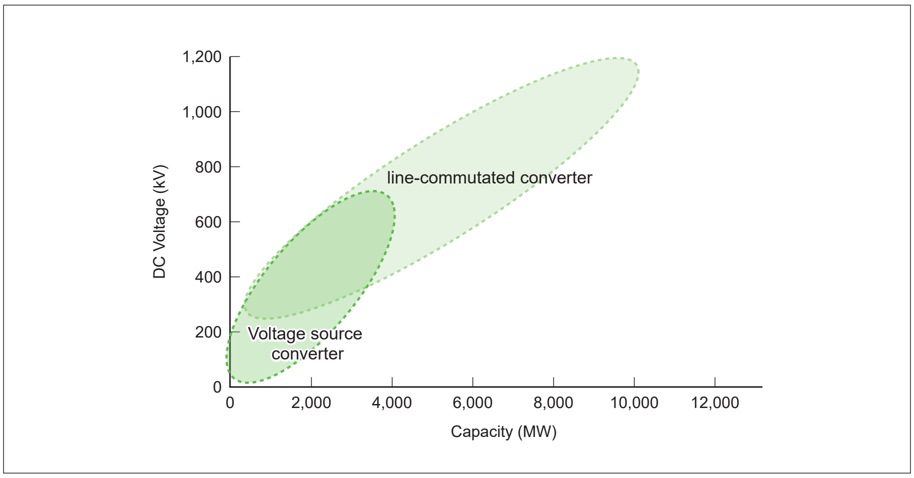
Power conversion field

In order to meet the increasing electric power demand, it is necessary to increase the amount of power generated as well as the effective utilization of electric energy. The power conversion system plays the role of connecting this power generation and utilization. For transmitting and distributing large amounts of electric power, the demand is for large-capacity systems. For medium-sized power systems, such as for alternative energy systems and railway systems, the needs for miniaturization and higher efficiencies are driving the advances in technology.

Among them, high-voltage direct current transmission (HVDC) is a system suited to large-capacity, long-distance transmission, from large-scale power plants to large cities and for grid interconnection using submarine cables. Practical applications are expanding throughout the world. In Japan, HVDC systems such as the Hokkaido-Honshu connection and the Kii Channel are in operation. Furthermore, a concept of interconnecting large-scale renewable power generation facilities between continents, including those for offshore wind power generation, solar power in desert areas, and solar thermal power generation, has been proposed.

The connection of HVDC and existing alternate current (AC) grid systems requires large-capacity AC-DC converters with high voltage (several hundred kV class), using semiconductor switches to convert from AC to DC and from DC to AC. Traditionally, a line-commutated converter using a thyristor as a semiconductor switch has been mainstream for the AC-DC converter, but the necessity of installing supplementary equipment such as power compensators and harmonic filters that require extra space has been a problem. Therefore, voltage source converters incorporating a large power self-extinction device such as an injection-enhanced gate transistor (IEGT) have attracted attention in recent years, and their adoption is increasing, mainly in China, as replacements for line-commutated HVDCs (See Fig. 3).

In addition to transmission and distribution, another area where remarkable progress is being made is electric railways. In this field, there is strong demand to reduce the volume and mass of equipment. It is important to reduce the loss of power devices, increase the operating frequency, and miniaturize the peripheral components. Practical implementations of silicon carbide (SiC) semiconductors are starting, exploiting their superior material properties, such as high critical electric field strength, and high thermal conductivity.



(Figure 3) : Trends in capacity of high-voltage direct current (HVDC) transmission systems

Trends in semiconductor devices

So far we have discussed system trends in the three fields of mobile/OA, automotive/ industrial, and power conversion. From here onward, we describe the progress of various ICs and power devices that are the key components for realizing these systems.

Power supply IC trend

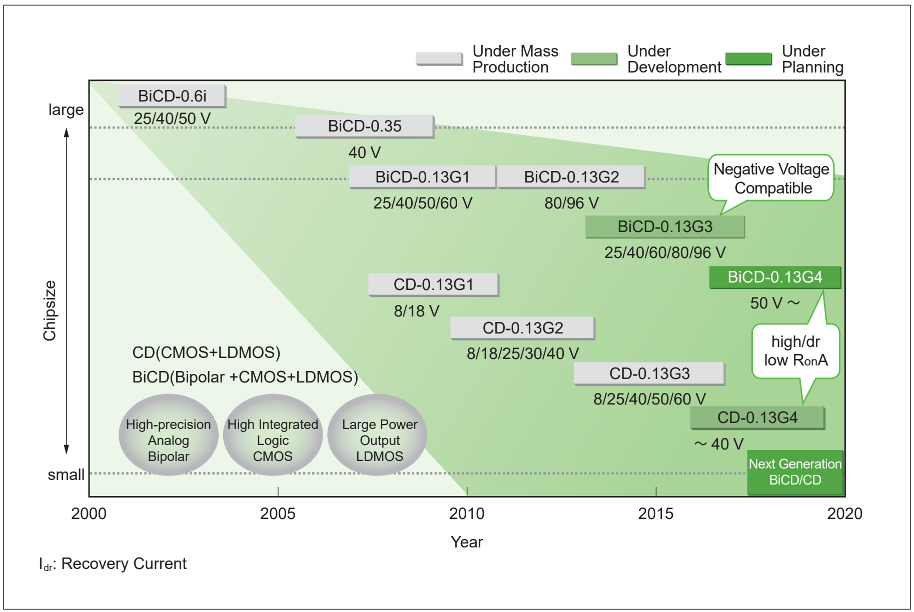
For power devices designed for mobile supplies, low-loss properties to reduce their own internal power consumption are required. This power consumption is largely proportional to the product of the current flowing through the output MOSFET and the input-output (drain-source) voltage, which is lost as heat. In order to reduce this power dissipation, it is necessary to reduce the static loss (ON resistance) of the output MOSFET.

It is standard practice to increase the size of the MOSFET, which increases the parasitic capacitance associated with the gate, not only making the device more susceptible to oscillation and degrading the noise removal performance, but also sacrificing the high-speed load transient response characteristics. To counter these problems, increases in both area for noise suppression and drive current for higher-speed response are needed.

Process and device improvements to reduce the on-resistance ($R_{on}A$) per unit area are being pursued.

On the other hand, for analog power devices designed for office automation (OA) equipment, IC processes for different device structures and mixed-process fabrication techniques will be required according to the various end applications. Toshiba Electronic Devices & Storage Corporation has developed two types of process platforms: BiCD (bipolar + CMOS + LDMOS (lateral double diffused MOS)) - 0.13 and CD (CMOS + LDMOS) - 0.13 . The BiCD - 0.13 process incorporates LDMOS, bipolar transistors, and various analog elements based on a 0.13 μm CMOS process. The CD - 0.13 process dispensed with the bipolar transistors and thereby increased cost competitiveness. In accordance with various product requirements, we are trying to increase the variation of withstand voltage, expand the device lineup, and improve the performance with each process generation (Figure 4).

Currently, we are considering the next-generation IC process. By reducing the $R_{on}A$ and increasing the output power of the LDMOS, the internal heat dissipation is substantially reduced and the power loss is minimized.



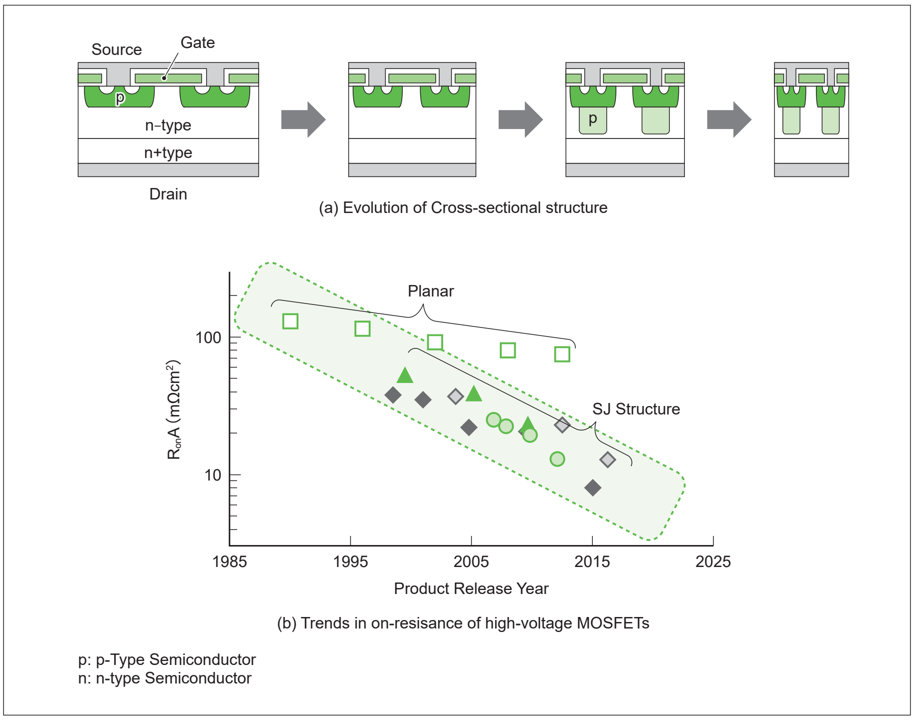
(Figure 4) : Roadmap of processes applied to analog power ICs produced by Toshiba Electronic Devices & Storage Corp.

Power MOSFET trend

Power MOSFETs are used for small-capacity systems from several tens of watts to several kilowatts and are suitable for applications where priority is given to downsizing of the systems, such as power supplies. They are classified either as low-voltage MOSFETs or high-voltage MOSFETs, depending on whether the withstand voltage is lower or higher than around 200 V.

To achieve high efficiencies, both low conduction losses and low switching losses are required. Therefore, $R_{on}A$ is used as a figure-of-merit for achieving low on-resistance even for small chip area in the same manner as for the IC devices.
Normally, the power MOSFET employs a vertical structure, and $R_{on}A$ basically consists of the channel resistance of the surface MOS section and the drift resistance at the center of the device structure. The drift resistance increases with the withstand voltage. Therefore, in low-voltage MOSFETs, the channel resistance portion of $R_{on}A$ dominates and is large. By employing the same process technologies used in LSIs and memory devices, a fine surface planar gate was formed. In addition, a trench gate structure was employed to further the fine process, and a high-density gate structure was realized(5).

In the high-voltage MOSFET, in the same manner as for the low-voltage MOSFET, the advanced process technologies were applied to miniaturize the surface planar gate. In addition, in order to reduce the drift resistance that accounts for the majority of the $R_{on}A$ component, a superjunction (SJ) structure forming a periodic P-type layer within the drift layer was employed, and these improvements are ongoing (Fig. 5(a))(6). Through these efforts, the $R_{on}A$ has been reduced to 1/10 in 15 years for low-voltage MOSFETs and to 1/10 in 20 years for high-voltage MOSFETs (Fig. 5(b))(7). If this trend continues, the theoretical limit for silicon devices will be reached. Therefore, devices based on new materials such as gallium nitride (GaN), which have the potential to substantially reduce $R_{on}A$, are being considered (see column).



(Figure 5) : Trends in cross-sectional structure and on-resistance of high-voltage MOSFETs

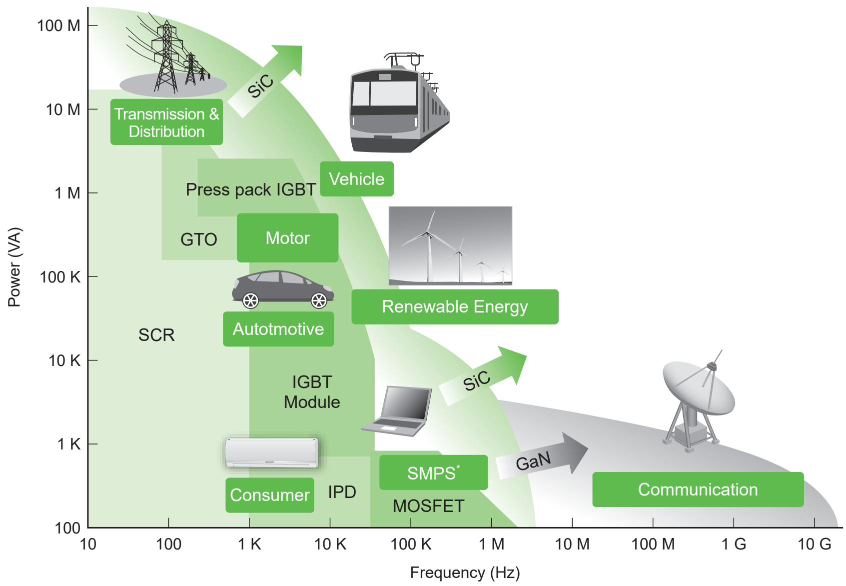
IGBT trends

Low loss (low on-state voltage drop), high breakdown capability, high-temperature operation, and high reliability are important characteristics of high-power devices for conversion systems. Insulated-gate bipolar transistors (IGBTs) have been widely used as self-turn-off elements that address these requirements. The IGBT is a bipolar device that combines a MOS gate structure with a diode structure. For high-capacitance applications, compared with a unipolar

Semiconductor components used for the conversion of electric energy

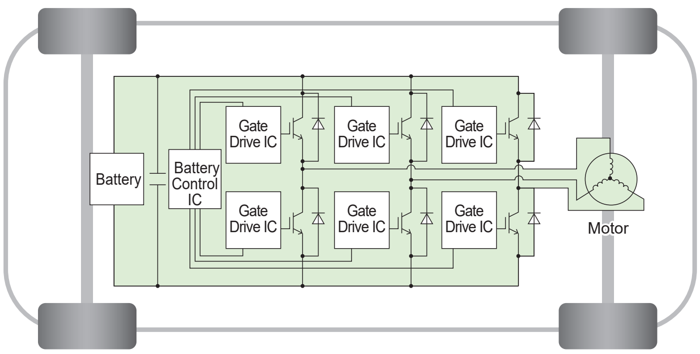
Electric energy is generated at the power plant and undergoes various conversions, such as voltage and AC/DC, before it reaches its various applications, such as home appliances, electric cars, and trains.
For example, electricity flowing through a wire extending from a power plant is several kV to several tens of kV AC, whereas the electricity supplied from a house or a building's wall outlet is 100 V or 200 V AC or thereabouts, and a microcomputer embedded in a smartphone or a household appliance operates with several volts DC. Therefore, it is necessary to convert electric power before consumption by the final application, where the conversion and control functions are handled by the power electronics. Electric energy is temporarily stored in coils, capacitors and other storage devices, and converted using semiconductor switches to the required voltage, waveform (DC or AC), etc.
The semiconductor switch used here is called a power device. Power devices differ in withstand voltage and other device characteristics depending on the voltage applied during conversion. In general, the larger the power being handled, the larger the conversion loss, so a bipolar device such as an IGBT having a low on-state voltage is used as the switching device at low switching frequencies. When the energy is small, priority is given to downsizing of the system, and unipolar devices such as power MOSFETs are used at high switching frequencies (Fig. A).

The power devices are switched by applying an input signal to the gate electrode. To generate this gate input signal, a gate driver IC is required for each power device. Also, a control signal for operating the gate driving IC in a timely manner is output from the control IC (Fig. B). As can be seen, many semiconductor devices are used in power electronics systems to convert electric energy.



GTO: Gate Turn-Off Thyristor UPS: Uninterruptible Power System SCR: Thyristor
*SMPS: Switch mode devices

(Figure A) : System & Power Devices using Electric Energy

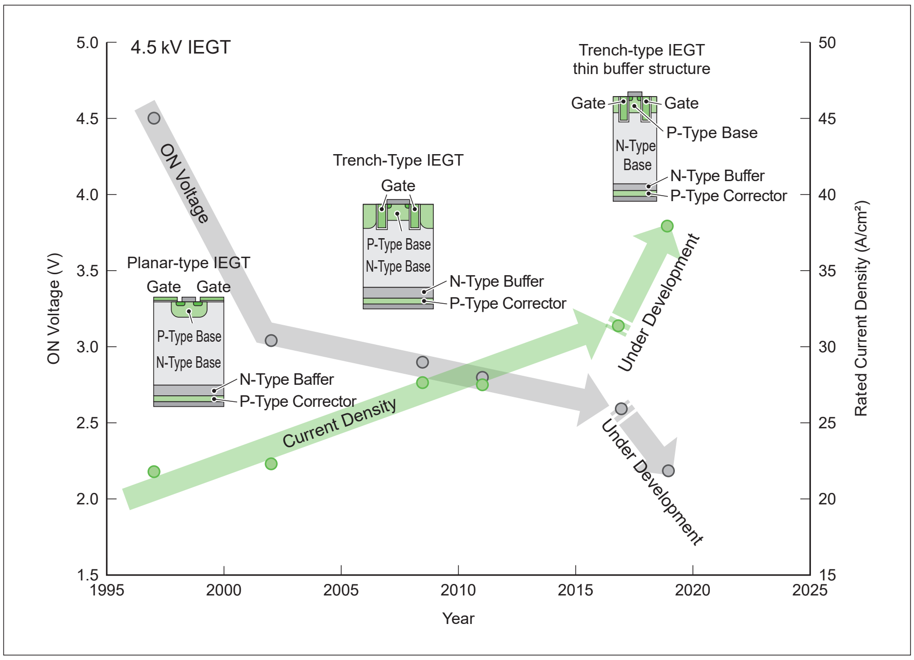


(Figure B) : Power Devices and Drive ICs for electric motor for electric car

MOSFET, a significantly low on-state voltage can be achieved. A low on-state voltage is realized by means of conductivity modulation by injecting holes from the P-type collector layer formed on the back substrate to lower the resistance of the N-type drift layer while maintaining high breakdown voltage under off-state.

We have introduced high-power, low-loss devices by employing an injection enhancement (IE) structure and improving the performance. The IE structure suppresses the hole outflow from the emitter side, increases the carrier density, and achieves a low on-voltage. For a 4.5 kV-class element used in power conversion, the IE effect was improved by modifying the conventional planar gate structure to a trench type and at the same time optimizing the layout of the P-type base. In addition to improving these cell structures, we optimized the collector structure on the backside of the device and the junction-termination structure for achieving high blocking voltage, thereby raising the turn-off capability and increasing the current density rating (Fig. 6).

Si-IEGTs with a withstand voltage rating of 4.5 kV or more are still in mainstream use in the area of high-power conversion systems, and development continues to improve performance. Meanwhile, for rolling stock systems where there is a strong need for device miniaturization, SiC power devices having high switching speeds unattainable with bipolar devices are starting to appear. We are currently developing SiC-MOSFETs .



(Figure 6) : Trends in performance of high-voltage injection enhanced gate transistors (IEGTs)

Conclusion

To promote energy conservation, the development of power electronics that contributes to highly efficient electric energy usage together with the technological progress of associated key IC and power devices is important and indispensable. With the advances in the sophistication and diversification of applied systems, we will accurately identify these trends and continue to provide timely solutions that match these market needs.

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