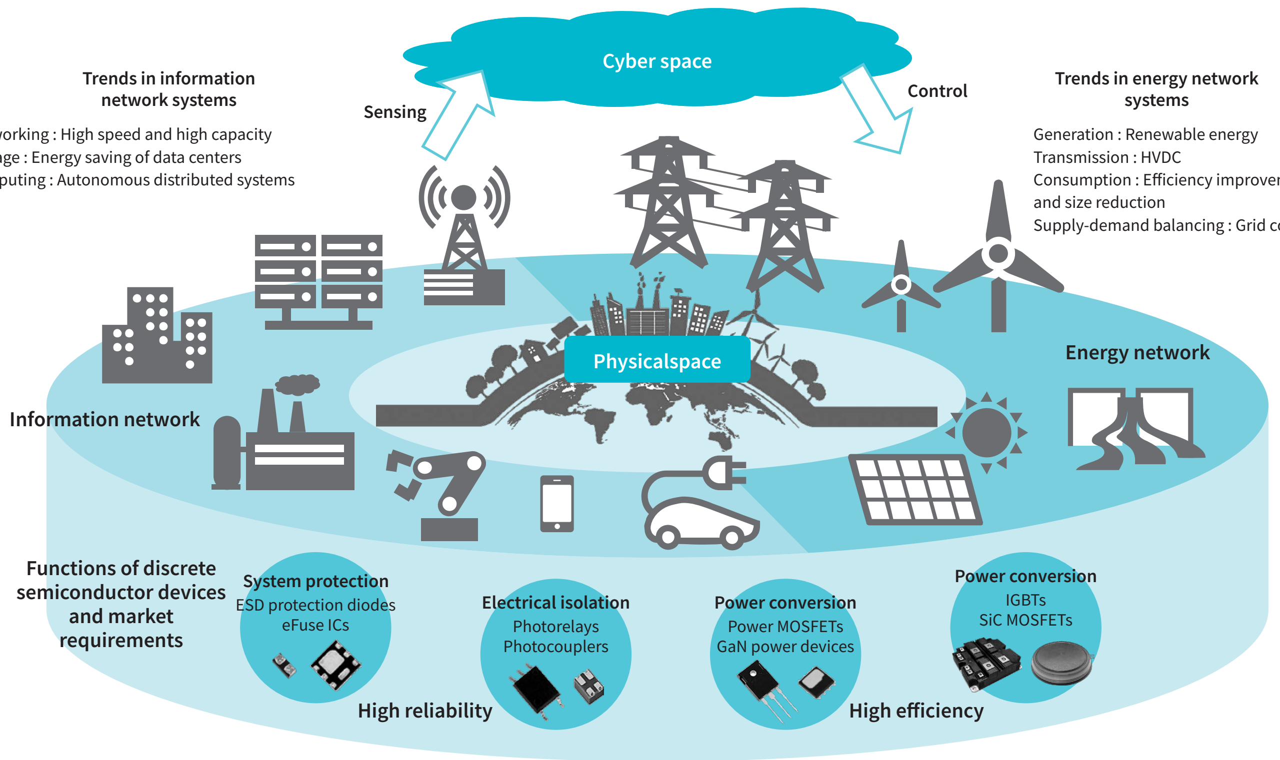
Latest Trends in and Future Outlook for Discrete Semiconductor Technologies

Severe global environmental and energy problems are driving demand for more effective utilization of electric energy in a broad range of fields including information and communication technology (ICT) systems, automotive and industrial systems, and electricity generation and transmission systems.
Toshiba Electronic Devices & Storage Corporation has been progressively developing and introducing a wide variety of discrete semiconductor products for electric energy conversion and protection applications ranging from small- to large-scale power systems, and is also making efforts to develop advanced technologies and commercialize products applying these technologies. We are committed to delivering various solutions to enable the efficient, stable, and secure handling of electric energy by means of our advanced discrete semiconductor technologies with the aim of realizing an energy-saving society.



HVDC : High Voltage Direct Current ESD : Electrostatic Discharge MOS : Metal-Oxide Semiconductor
MOSFET : MOS Field-Effect Transisto GaN : Gallium Nitride IGBT : Insulated-Gate Bipolar Transistor SiC : Silicon Carbide

Overview : Toshiba discrete semiconductor products underpinning energy-saving society

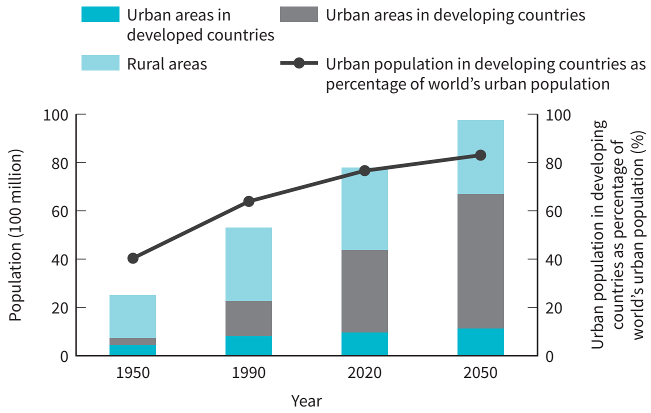
1. Introduction

The growing world population and the concentration of population in urban areas are compounding environmental and energy problems. A 2018 United Nations (UN) report(1) estimates that the world's population will increase more in urban areas than in rural areas, with the proportion of the population living in cities with more than 300 000 inhabitants projected to increase to roughly 68% by 2050. The urban population growth is forecast to occur mostly in developing countries (**Figure 1**). Population growth will exacerbate the current environmental and energy problems in developing countries that rely on fossil fuels as the main sources of energy. Local energy-saving efforts do not suffice to solve these problems.

In 2015, the UN Sustainable Development Summit adopted the Sustainable Development Goals (SDGs), calling for joint action by both developed and developing countries to combat climate change and tackle social issues. The success of the SDGs will depend on the ability to increase the ratio of renewable energy such as solar photovoltaic and wind energy (**Figure 2**)(2). whereas the ever-increasing power consumption in urban areas, electric power resources are projected to migrate to rural or outlying areas. Under these circumstances, it is necessary to further increase energy utilization efficiency by means of spatiotemporal power management and energy sharing. The progress of cyber-physical system (CPS) technologies will enable the intertwining of physical and cyber spaces, transcending all kinds of borders across systems, buildings, cities, regions, and even countries. To realize an energy-saving society, CPS-based information and energy networks will play an important role in handling electric energy in a highly efficient, stable, and secure manner.

Toshiba Electronic Devices & Storage Corporation provides an extensive portfolio of discrete semiconductor devices suitable for electric energy conversion and protection applications ranging from small- to large-scale power systems comprising these networks. We are committed to delivering solutions based on cutting-edge discrete semiconductor technologies that will help improve the efficiency and reliability of systems and thereby contribute to the realization of an energy-saving society see Overview diagram.

This report describes the trends in systems for efficient use of electric energy as well as the trends in semiconductor devices that support the realization of such systems.

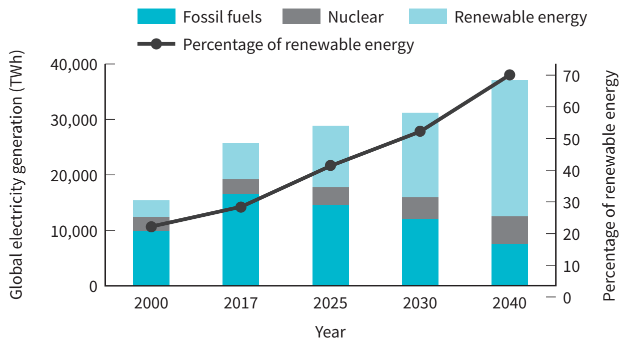


Urban areas : Cities with more than 300 000 inhabitants

* Based on "World Urbanization Prospects : The 2018 Revision" (1) from the United Nations

Figure 1. Global trends in urban population of industrial and developing countries

Urban areas in developing countries will drive the world's population growth.



* Based on "World Energy Outlook 2018" (2) from the International Energy Agency(IEA)

Figure 2. Global trends in power generation by type of energy source

Renewable energy will provide baseline power in scenarios designed to achieve the Sustainable Development Goals.

2. System trends

2.1 Information networks

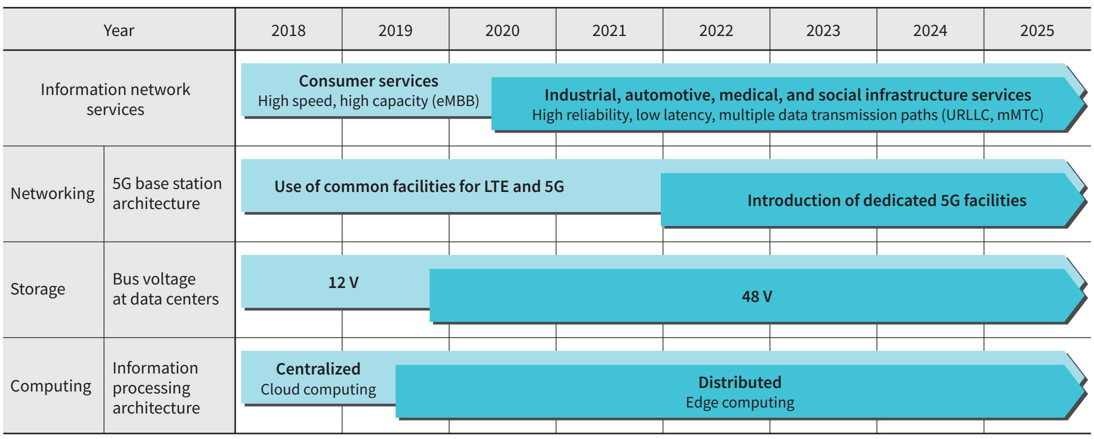
In contemporary society, the steady growth of mobile data traffic is driving an increase in the amount of energy consumed by data communication. Previously, information and video content constituted a large proportion of the data exchanged among information, communication, and consumer systems on a network. However, with the recent progress of the Internet of Things (IoT), the roles of information networks are expanding to include the coordination of the functions and services for a wide range of systems, including automotive and industrial equipment. The progress of the information network at the heart of this transformation is supported by the evolving system technologies for networking, storage, and computing shown in **Figure 3**[(3)].

In the field of networking, there are high expectations for fifth-generation (5G) cellular network systems, which will provide faster connections, more capacity, higher reliability, lower latency, and greater number of connected devices . Since the link distance and transmitter power are constrained by the 5G radio characteristics, a 5G network requires dozens more base stations than a Long-Term Evolution (LTE) network. Therefore, smaller receiver/transmitter units and antenna facilities with lower power consumption are necessary for mobile network operators. Furthermore, 5G networks for automotive, industrial, and medical applications impose stringent reliability and redundancy requirements.

In the field of storage, an increasing number of data centers are migrating to a 48 V power delivery system in order to save energy and reduce costs. Since the electric current that passes through a 48 V power line is theoretically one-fourth the current that passes through a 12 V power line, the transmission loss through a power line can be reduced by increasing its bus voltage from 12 V to 48 V. An increase in the efficiency of 48 V power supply units is essential for the dissemination of this technology.

In the field of computing, a distributed computing paradigm called edge computing is attracting plenty of attention. It brings data computation closer to the edge of an information network where users are located, thereby reducing the workload required for communication, computation, and storage. In the future, integrated platforms that combine the functions of cloud and edge computing will become pervasive.

The foregoing system trends require further enhancement of various power devices. For power devices for power supply applications, it is necessary to reduce power loss and enhance heat dissipation in order to increase the system efficiency. Also, power devices for communications infrastructure applications require size reduction and an extended operating temperature range. In addition, the need for high-reliability networks is driving demand for transient-voltage suppression (TVS) diodes, eFuse ICs, and other protection devices as well as for isolation devices that



eMBB : enhanced Mobile Broadband
URLLC : Ultra-Reliable and Low Latency Communications
mMTC : massive Machine Type Communication

* Based on "Future Outlook for Core Technologies for Realizing 5G Communication 2020"[(3)] from Fuji Chimera Research Institute, Inc.

Figure 3. Trends in information network technologies

The progress of information networks is supported by evolving system technologies for networking, storage, and computing.

provide electrical isolation between communication systems.

2.2 Energy networks

An increased uptake of renewable energy is indispensable for increasing the electricity output without impacting the environment. As power plants are installed in areas far from densely populated urban areas, the construction of power transmission networks proceeds. In addition, new initiatives include power management based on supply-demand forecasting using big data and artificial intelligence (AI).

Figure 4 shows the trends in the progress of energy networks, which is supported by the evolution of system technologies for the generation, transmission, consumption, and supply-demand balancing of electric energy[(2)(4)].

As regards power generation, the ratio and the amount of renewable energy in the energy mix are predicted to increase in the years ahead. Large-scale offshore wind farms are becoming increasingly common in Europe and other regions. Offshore wind farms are expected to be non-intermittent and reliable sources of a great amount of energy. Moreover, hundreds of large wind turbines can be installed over an extensive offshore area, unconstrained by the availability of land.

It is necessary, however, to establish power transmission infrastructure first since it is unavailable in many of the areas suitable for wind power generation. In order to increase the electricity output and reduce the operation and maintenance costs, wind farm facilities will be scaled up to support multi-megawatt plants while IoT technology will progress to support smart maintenance.

In the field of power transmission, the efficiency and capacity of power conversion, transmission, and distribution systems will be increased so as to send the generated electricity to consumers more efficiently. In particular, high-voltage direct-current (HVDC) transmission is becoming increasingly common around the world as a means of long-distance high-power transmission. Since HVDC provides higher transmission efficiency than alternating current and facilitates the power interchange across regions, it is highly compatible with renewable energy grids. The AC-DC converter, a main component of the HVDC system, incorporates high-power semiconductor devices capable of handling high voltage and power. In China and elsewhere, conventional thyristor-based line-commutated converters have recently been replaced by self-commutated converters reliant on injection-enhanced gate transistors (IEGTs) or other self-turn-off devices.

In the field of energy consumption, system power efficiency will continue to improve for energy saving while system size will shrink

Year		2018	2019	2020	2021	2022	2025	2030 and beyond
Generation	Percentage of renewable energy (SDGs)	25 %					38 %	>50 %
	Amount of wind power generated (per wind turbine) (Place of installation)	5 MW (onshore)			8 MW (offshore)		10 MW (offshore)	12 MW (offshore)
Transmission	Amount of power transmitted through HDVC link(per system)	3 GW	5 GW				8 GW	
	HVDC Percentage of self-commutated converters	50 %					65 %	70 %
Consumption	International standard requiring increase in i nverter efficiency IEC 60034-30)	IE2*1 : High Efficiency IE3 : Premium Efficiency					IE4 : Super-Premium Efficiency	
Supply-demand balancing	Stable supply of electricity through supply-demand balancing			Real-time energy supply-demand forecasting and control using IoT, AI, and big data I Virtual Power Plant (VPP) technology				

*1 : IE code. Efficiency class specified by IEC 60034-30. There are four classes from IE1 to IE4.
*2 : Based on "World Energy Outlook 2018 from the International Energy Agency (IEA)"[(2)] and "Toshiba's Approaches to Green Energy Aggregation Service Contributing to Stabilization of Power Systems" by Kosakada M., et al[(4)].

Figure 4. Trends in energy network technologies

Progress of energy networks is supported by evolving technologies for generating, transmitting, consuming, and adjusting the supply of energy.

for space saving. For example, many countries are standardizing efficiency classes for industrial motors and inverters based on the International Electrotechnical Commission (IEC) 60034-30 standard with a view to establishing legal regulations. In the automotive field, as hybrid and electric vehicles become increasingly common, the use of in-vehicle electronics and electroactuation is expanding at an accelerating pace so as to reduce the environmental impact, save energy, enhance safety, and provide access to information infrastructure. Railway train manufacturers have begun using silicon carbide (SiC) power devices to reduce the size and weight of power conversion units since SiC devices are superior in terms of low power loss, high-frequency switching, high-temperature capability, and high-voltage tolerance.

In the field of supply-demand balancing, efforts to enhance the power utilization efficiency are underway, including coordination among an information network and a power grid controller as well as real-time supply-demand forecasting using IoT technology.

High-power semiconductor devices are major components of power conversion systems. In response to the ongoing system trends, it is necessary to further reduce the power loss, increase the breakdown voltage, and enhance the reliability of high-power semiconductor devices and thereby increase their capacity.

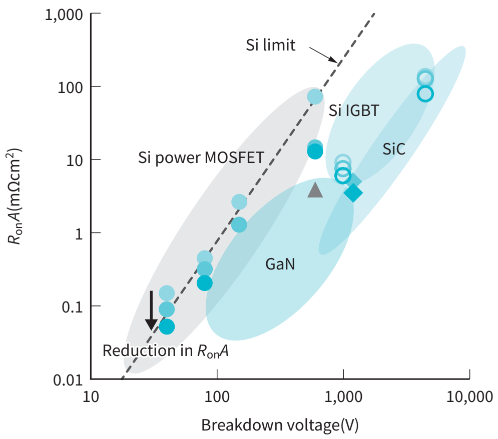
3. Trends in discrete semiconductor devices

The previous section has described the trends in systems to manage the ever-increasing amounts of information and electricity output and improve energy utilization efficiency. In these systems, discrete semiconductor devices perform power conversion to handle electric energy efficiently while providing protection and electrical isolation to ensure stable and safe operation. The following subsections discuss the technological development for our discrete semiconductor devices.

3.1 Various types of discrete semiconductor devices

Power devices perform power conversion in various equipment and systems. They are designed according to system requirements to handle several tens of volts to several thousands of volts. Different types of devices and semiconductor materials are utilized, depending on the voltage handled. **Figure 5** shows the breakdown voltage and specific on-resistance ($R_{on}A$) of typical power devices. Power devices approach the ideal switch as their breakdown voltage increases and $R_{on}A$ decreases. Silicon (Si) power metal-oxide-semiconductor field-effect transistors (MOSFETs) are utilized in the 900 V or lower voltage region for home appliances, office equipment, information devices, and communication systems. We have continually improved the $R_{on}A$ and other electrical characteristics of Si power MOSFETs. Nowadays, gallium nitride (GaN) power devices are also becoming available with lower $R_{on}A$ than that of conventional Si power MOSFETs. In addition, in the 600 V and higher voltage region, Si insulated-gate bipolar transistors (IGBTs) play an important role in hybrid vehicles, railway electronics, and power transmission and distribution systems. In recent years, we have also been developing SiC power MOSFETs in this voltage region, which are already commercialized for railway and other applications.

Highly reliable energy equipment and systems are required to realize an energy-saving society. To realize such energy systems, it is essential to reduce the loss of power devices for power conversion applications while improving the performance of devices that provide protection and electrical isolation. For example, TVS diodes are used to protect edge computers from electrostatic discharge (ESD). We have been successively reducing the capacitance of TVS diodes to support the ever-increasing signal speed. In addition, we have released eFuse ICs, an enhanced variant of conventional load switch ICs, that provide high-speed short-circuit protection in the event of an overcurrent condition. Optical isolation devices such as photocouplers or photorelays are used for applications that transfer data or require electric isolation between two circuit domains with a substantial voltage difference. We have also been reducing the size and increasing the current capacity of optical isolation devices.



* The data point marked by ▲ is an excerpt from reference (5).

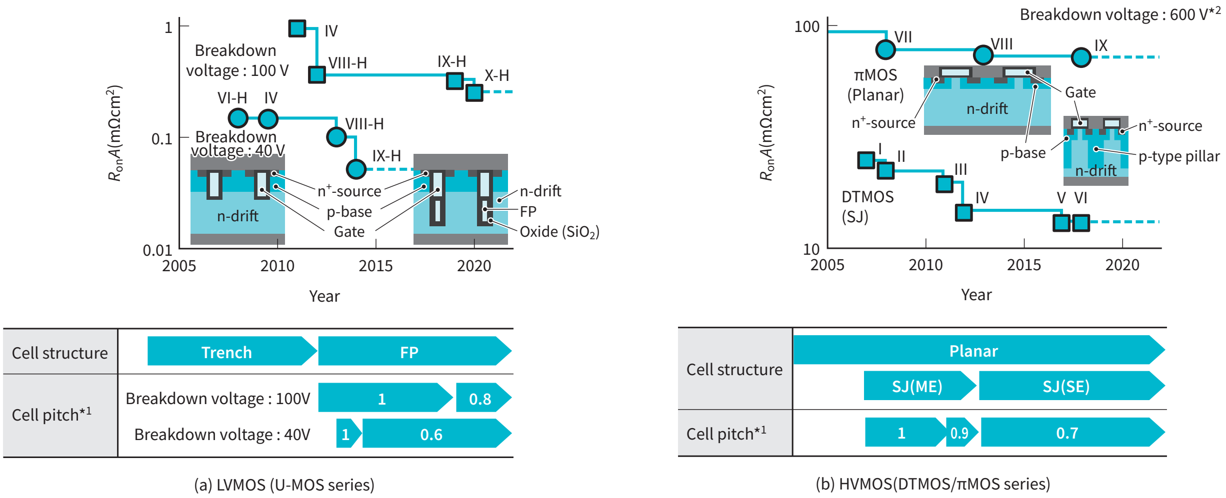
Figure 5. Relationship between breakdown voltage and specific on-resistance ($R_{on}A$) of various types of power devices

The higher the breakdown voltage and the lower the 13 $R_{on}A$ value, the more closely power devices approach the ideal switch. The dashed line in the above figure is called the Si limit, which represents the theoretical limit of $R_{on}A$ achievable with one-dimensional Si devices.

3.2 Si power MOSFETs

Si power MOSFETs are broadly divided into low-voltage MOSFETs (LVMOS) and high-voltage MOSFETs (HVMOS) at a breakdown voltage of 200 to 300 V. **Figure 6** shows the $R_{on}A$ values of and major technological trends in Si power MOSFETs. It shows the transitions of the LVMOS (U-MOS) series of 40 V and 100 V MOSFETs as well as HVMOS (πMOS and DTMOS) series of the 600 V planar and superjunction (SJ) MOSFETs. In early generations of Si power MOSFETs, channel resistance accounted for a large proportion of $R_{on}A$. To reduce their $R_{on}A$, we mainly increased the channel density by reducing the cell pitch[(6)]. Consequently, in thesubsequent generations of Si power MOSFETs, the drift layer resistance accounted for a dominant proportion of $R_{on}A$. To reduce its resistance, we then developed new device structures, including trench field plate (FP)[(7)] and SJ[(8)] structures. Since the dopant concentration and the thickness of the drift layer are generally determined by the breakdown voltage, the drift layer resistance has a lower limit called the Si limit as highlighted by the dashed line in Figure 5. We have overcome this limit, however, by increasing the dopant concentration of the drift layer without compromising the breakdown voltage. This was made possible by the charge compensation effects of buried electrodes in the case of the FP structure and that of the p-type semiconductor in the case of the SJ structure. As a result, we have succeeded in reducing the $R_{on}A$ of 100 V LVMOS by more than two-thirds and roughly halving the $R_{on}A$ of 600 V SJ-HVMOS over the last ten years.

Our next step is to reduce drive, switching, and reverse recovery losses while continually reducing $R_{on}A$ through process scaling. Power MOSFETs are widely used for power supply applications. We will contribute to reducing system size and power loss by



n⁺ : highly doped n-type semiconductor
ME : multi-epitaxial process

*1 : Normalized such that the cell pitch of early generation is equal to one
*2 : Device with a breakdown voltage of 650 V in the case of the DTMOS V and VI generation

Figure 6. Trends in $R_{on}A$ of and technologies for Si MOSFETs

In order to reduce on-resistance, we adopted an FP structure instead of a trench structure and reduced the cell pitch for LVMOS while adopting an SJ structure instead of a planar structure and reducing the cell pitch using single-epitaxial (SE) process for HVMOS.

enhancing the performance of power MOSFETs.

3.3 Si IGBTs

Insulated-gate bipolar transistors (IGBTs) combine the controllability advantage of MOSFETs and the high-current and low on-state voltage characteristics of bipolar transistors. IGBTs have a region called n-drift to increase the breakdown voltage. When electrons are injected from the MOS gate on the top side of the device and holes are injected from the p-type collector region on the back side, conductivity modulation occurs in the n-drift region, causing a decrease in on-state voltage.

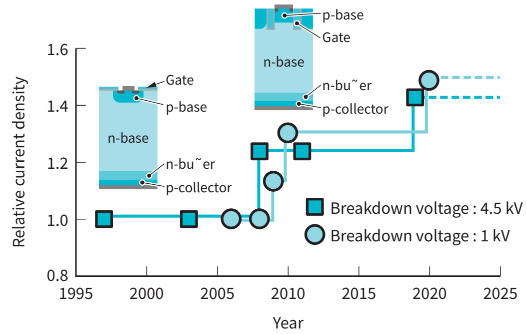
Current density is one of the electrical characteristics that represent the performance of Si IGBTs. **Figure 7** shows the trends in the current density of 4.5 kV IEGTs for HVDC applications and 1 kV IGBTs for home appliance applications. We have successively increased the current density of IGBTs through the improvement of the injection enhancement (IE) effect, wafer thinning, and the optimization of the IGBT backside structure. Since a freewheeling diode (FWD) is commonly placed in parallel with the IGBT, we have released a variant of an IGBT called a reverse-conducting IGBT (RC-IGBT) that integrates an FWD into the IGBT device to further increase the current density. Furthermore, we have been working on high-accuracy simulation technology and model-based development in order to reduce development time.

3.4 Wide-bandgap semiconductor power devices

In recent years, power devices fabricated using SiC, GaN, and other wide-bandgap semiconductor materials have been used in practical applications.

SiC (4H-SiC[*1]) has roughly 2.9 times as wide a bandgap and roughly 10 times as high breakdown electric field as Si. As compared with Si power MOSFETs, SiC, in principle, makes it possible to reduce the drift layer thickness by a factor of 10 while increasing the drift dopant concentration by a factor of 100. As a result, SiC power MOSFETs can be designed to exhibit $R_{on}A$ two orders of magnitude lower than that of Si power MOSFETs.

(*1) One of the polytypes of SiC. The number 4 represents the four-bilayer stacking periodicity. The letter H indicates hexagonal symmetry.



Breakdown voltage : 4.5 kV	Cell structure	Planar → Trench → Trench IE effect optimization
Breakdown voltage : 1 kV	Cell structure	Trench → Fine pitch trench IE effect optimization
	Diode	Separate chip → Integrated on same chip (RC-IGBT)

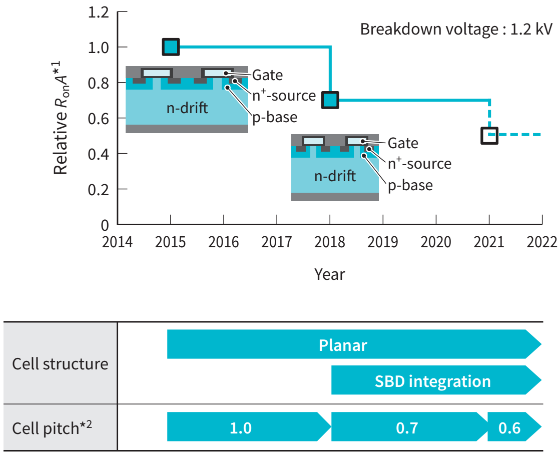
Figure 7. Trends in current density of and technologies for Si IGBTs

In order to increase the current density, we have adopted trench technology, optimized the IE e˜ect, employed wafer thinning technology to reduce on-state voltage, utilized other peripheral technologies, and integrated a diode on the same chip.

Therefore, SiC allows the application area of unipolar devices to expand into the high-voltage region for which IGBTs, a type of bipolar device, have been conventionally required. Consequently, SiC power MOSFETs can be switched at high frequency and help reduce the size of a system, including peripheral components.

Figure 8 shows the trends in the $R_{on}A$ of and the technologies for our SiC power MOSFETs. Although SiC power MOSFETs have lower channel electron mobility than Si power MOSFETs, we have successively reduced channel resistance and thereby $R_{on}A$ by improving the device process[9] and increasing the channel density through a reduction in cell pitch. In addition, when a pn diode present between the drain and source of an SiC power MOSFET is forward-biased, a bipolar operation occurs, causing bipolar degradation[10]. This is a phenomenon in which a diode's forward voltage and a MOSFET's on-resistance (R_{on}) increase as the energy generated by the recombination of electrons and holes causes stacking faults to expand into the SiC epitaxial layer. We have solved this problem by integrating a Schottky barrier diode (SBD) in an SiC MOSFET. Our SiC power MOSFETs incorporating the foregoing technologies are currently utilized for railway inverters in Japan. We will continue to improve device structures and device processes to further improve the performance of SiC power MOSFETs.

As is the case with SiC, GaN has a wide bandgap—roughly three times as wide as that of Si. GaN is a promising candidate as a material for high-voltage power devices capable of high-speed switching because a high-electron-mobility transistor (HEMT) structure can be formed on the heterojunction between GaN and aluminum gallium nitride (AlGaN). Since large-diameter epitaxialwafers (epiwafers) on a silicon substrate can be used for lateral devices, the use of epiwafers combined with a planar gate structure helps reduce the gate charge, making it possible to reduce gate drive and switching losses. However, there are several challenges to be solved for GaN power devices to achieve normally-off operation. To overcome these challenges, we are currently developing devices that combine a GaN power device and a Si MOSFET in a cascode structure as well as MOS devices with an aluminum nitride (AlN) layer. The high-speed operation of GaN power devices is expected to help increase the switching frequency of power supply circuits, thereby reducing system size.



*1 : $R_{on}A$ of only MOS cell portion. Base year 2015 = 1.0
*2 : Cell pitch of MOS cells. Base year 2015 = 1.0

Figure 8. Trends in $R_{on}A$ of and technologies for SiC power MOSFETs

We have reduced $R_{on}A$ by reducing the cell pitch while improving device reliability by integrating an SBD on the MOSFET chip.

4. Conclusion

As the amounts of information and electricity generated are expected to continue increasing, it is essential to improve energy utilization efficiency in order to solve environmental and energy problems. We will contribute to the realization of an energy-saving society by developing discrete semiconductor devices for various applications in a timely manner.

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