Professional Report

Power Semiconductor Devices Creating Comfortable Low-carbon Society

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OVERVIEW: Reducing CO_2 emissions recently has been an urgent issue to cope with the global warming. As the G8 leaders at the Hokkaido Toyako Summit in 2008 agreed to seek to share and adopt "the goal of achieving at least 50% reduction of global emissions by 2050" and the Japanese government set "the long-term goal of reducing 60 to 80% of emissions by 2050," there is a need for greater energy conservation and a switch to sustainable energy sources that do not use fossil fuels. Power electronics equipment and power semiconductor devices will be key for achieving these goals. Hitachi has been developing new power semiconductor devices, primarily through collaboration and cooperation with power electronics departments in the fields of power generation, rolling stock, automotive vehicles, industry, and consumer electronics. This report estimates the market size of the power semiconductor devices in a low-carbon society with a "halving of CO_2 emissions." It also describes Hitachi's latest technology of power semiconductor devices and the role of these devices in the future.

INTRODUCTION

THE problem of global warming is an important issue for the entire world. At the Hokkaido Toyako Summit held in July 2008, with respect to the goal of achieving at least 50% reduction of global emissions by 2050, the USA and seven other major nations (the G8) leaders agreed to seek to share and adopt it with all parties to the United Nations Framework Convention on Climate Change, including the BRIC nations (Brazil, Russia, India, and China), to also adopt this target[(1)]. Similarly, the government of Japan has proposed its Cool Earth Initiative and has announced its intention to "work toward establishing a low-carbon society that will be admired internationally with a long-term objective of reducing CO_2 (carbon dioxide)emissions by 60 to 80% of current levels by 2050 as Japan's contribution to the goal of halving total global emissions by 2050."[(2)]

In recent years, the concentration of CO_2 in the atmosphere has reached levels higher than any the Earth has experienced over the last 600,000 years (see Fig. 1). The major cause of this rise is the extensive use of fossil fuel since the industrial revolution and the IPCC (Intergovernmental Panel on Climate Change) Fourth Assessment Report released in 2007[(3)] predicted that by 2100 the mean global temperature could rise by up to 6.4°C and sea levels by up to 59 cm.

This article describes the expectations for power semiconductor devices in their role as key devices in power electronic equipment for achieving a low-carbon society with a halving of CO_2 emissions by 2050, and also looks at the potential market size. The article also looks at IGBTs (insulated gate bipolar transistors), a type of power semiconductor devices that has experienced annual growth of 19% in recent

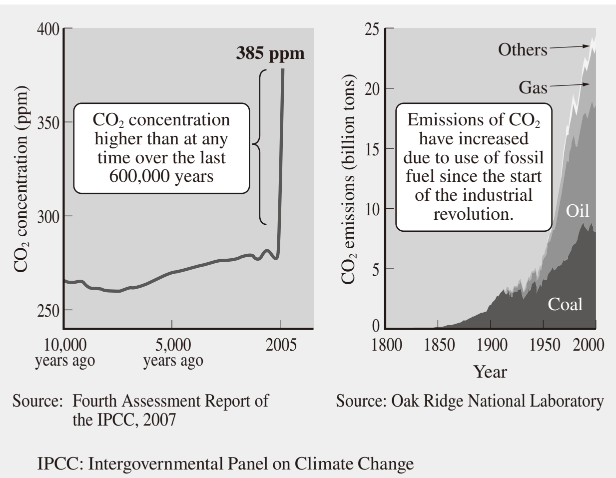


Fig. 1—Trend in CO_2 Concentration and CO_2 Emissions Due to Use of Fossil Fuel.
Use of fossil fuel has resulted in CO_2 concentrations higher than any the Earth has experienced over the last 600,000 years.

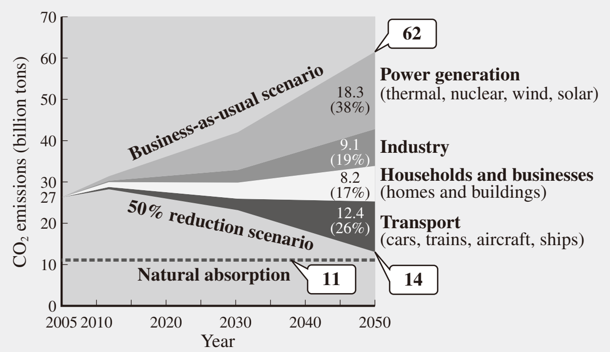
years and will clearly be essential in the move to a low-carbon society, giving an overview of the state of IGBT development at Hitachi and describing system applications.

POWER SEMICONDUCTOR DEVICES IN 2050

Expectations for Power Semiconductor Devices

Fig. 2 shows a scenario for reducing CO_2 emissions to half current levels by 2050. In its "Energy Technology Perspectives 2008[(4)]" publication, the International Energy Agency (IEA) calculates the size of reductions in each sector based on a "Blue Map scenario" that reduces CO_2 emissions by half, with a baseline "business-as-usual scenario" that assumes things will continue as they are used as a reference. As the business-as-usual scenario assumes CO_2 emissions will reach 62 billion tons by 2050, achieving the Blue Map 50% reduction scenario requires reducing this to 14 billion tons. The difference of 48 billion tons is the reduction to be achieved by 2050. As the global population is expected to rise to about 9.2 billion by 2050, this corresponds to annual emissions per person of 1.5 tons. As Japan currently has annual emissions of 10 tons per person, bringing this down to the global mean level of emissions per person requires a reduction of 85% by 2050. Also, even if the target of reducing emissions to 14 billion tons is achieved, this is still higher than the planet's natural capacity for CO_2 absorption of 11 billion tons per year, meaning that the concentration of CO_2 in the atmosphere will continue to rise, reaching 450 ppm.

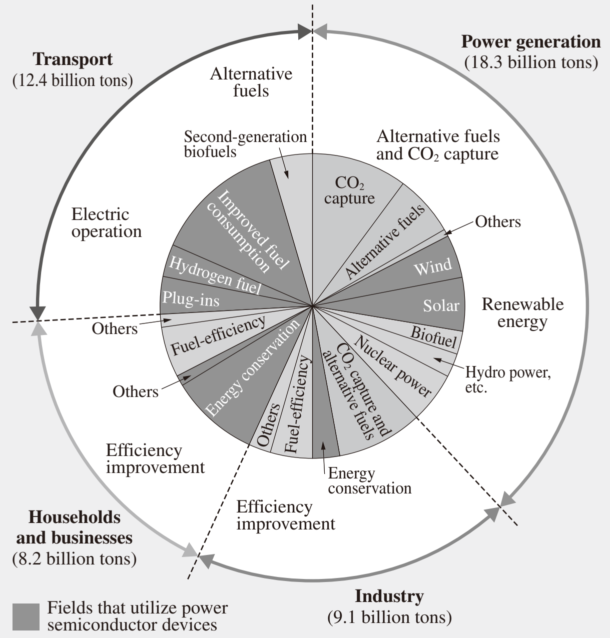
Fig. 3 shows calculations by the IEA of how much of a reduction can be excepted from different technologies in each sector to achieve an overall reduction of 48 billion tons. Possibilities in the field of electricity generation include use of alternative fuels and CCS (CO_2 capture and storage), and switching to other sources of energy such as renewable energy sources (wind and solar power) or nuclear power, etc. In factories, homes, and offices, saving energy by improving the efficiency of industrial plant, consumer appliances, and other equipment is an important issue. In the transport sector, it will be necessary to switch cars and other vehicles over to running on electric power. This will involve not only hybrid vehicles, but also requires the widespread adoption of electric vehicles, fuel cell vehicles, and other electrically operated vehicles with excellent fuel consumption. Many of these changes will require the development of technology and the additional cost of achieving



Source: Produced by author based on IEA Energy Technology Perspectives 2008 and other sources

IEA: International Energy Agency

Fig. 2—Scenario for Halving CO_2 Emissions by 2050 Broken Down by Sector.
Achieving CO_2 emissions of half the current level requires a reduction of 48 billion tons compared to the level of emissions that would result if no action is taken (business-as-usual scenario).



Source: Produced by author based on IEA Energy Technology Perspectives 2008

Fig. 3—Breakdown by Sector of Reduction Amounts and Methods for Achieving Halving of CO_2 Emissions by 2050.
The main sectors in which power semiconductor devices are used include renewable energy sources such as wind and solar power generation, plug-in hybrids and other automotive applications, and energy-saving home appliances and industrial equipment that use inverters. These sectors on their own provide a total of 21.7 billion tons in reductions or 45% of the total of 48 billion tons of reductions required to halve CO_2 emissions.

the 50% reduction scenario has been estimated at 45 trillion dollars by 2050. This represents an annual cost of 1.1 trillion dollars or 1.1% of global GDP (gross domestic product).

An indication that power semiconductor devices will play a particularly important role in achieving the 50% reduction scenario can be seen from the fact that the reduction in CO_2 emissions to be delivered by sectors that utilize power semiconductor devices total 21.7 billion tons, or 45% of the 48-billion-tons reduction needed for this scenario, even when only counting the major sectors which include switching the electricity supply to renewable energy sources such as wind and solar power, the transport sector which includes plug-in hybrids, electric vehicles and other types of vehicle, and energy-saving home appliances and industrial equipment that use inverters.

Power Semiconductor Device Market Size in 2050 and World in 2050

This section considers how many power semiconductor devices will be required to achieve the 50% reduction scenario and estimates the market size based on the IEA report. It also looks ahead to consider what social infrastructure, lifestyle, and other changes would result from this 50% reduction scenario.

Fig. 4 shows the changes in power generation sources associated with the 50% reduction scenario and how much power each source would supply. Under the business-as-usual scenario, it is estimated that the growth of emerging nations would result in global electricity demand in 2050 expanding to 50 trillion kWh or 2.7 times the current level. Under the 50% reduction scenario it is assumed that almost all the CO_2 produced by the use of fossil fuel for power generation would be captured and that there would need to be a substantial shift toward power sources such as nuclear power or renewable energy sources such as solar and wind. The quantity of electricity generated from solar, wind, and other renewable power sources would reach 10 trillion kWh which is more than eight times Japan's total annual power production of 1.2 trillion kWh. The estimated market size for the power semiconductor devices required for the conversion equipment associated with these renewable power sources is about one trillion yen per year for solar power generation and about 0.3 trillion yen per year for wind power generation. Achieving the 50% reduction scenario also requires an improvement in energy efficiency of approximately 15% and it is estimated that the size of the power semiconductor device market for

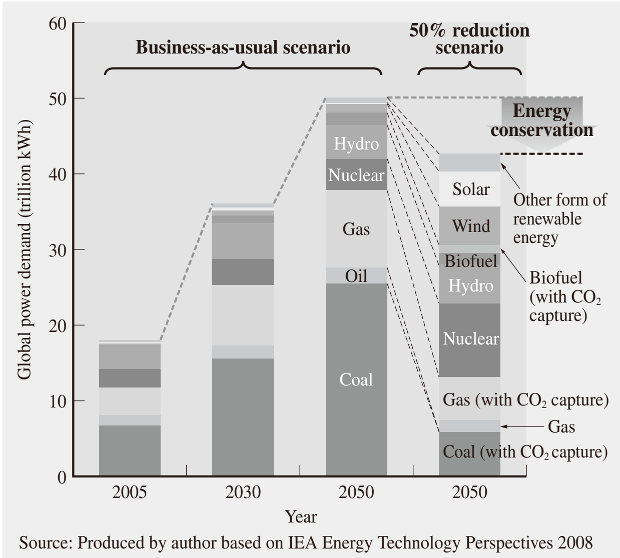
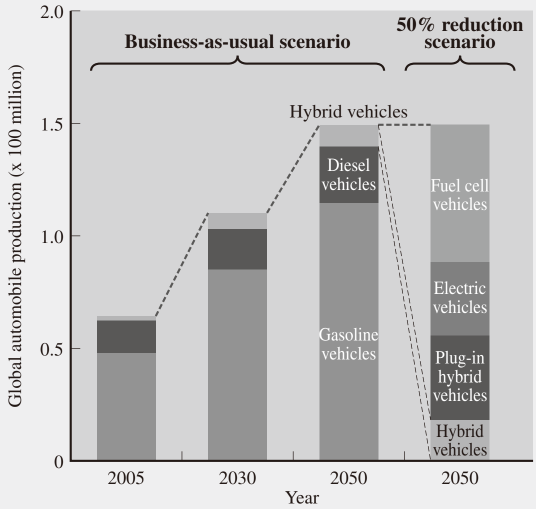


Fig. 4—Changes in Sources of Electric Power to Halve CO_2 Emissions by 2050.
Achieving the 50% reduction scenario will require the capture of almost all the CO_2 produced by the burning of fossil fuels to generate electricity and a major shift in the sources of electric power toward renewable energy such as solar and wind power, nuclear power generation, and other similar power sources. Energy efficiency savings of approximately 15% are also required.

this sector would be about 2.6 trillion yen per year.

Fig. 5 shows the production of the global automotive industry and the extent to which vehicles would need to switch to electric operation under the 50% reduction scenario. To achieve the 50% reduction scenario, almost all conventional gasoline- and diesel-powered vehicles that run on fossil fuels will need to be replaced with vehicles that use electric power which are anticipated to include plug-in hybrids, electric vehicles, and fuel cell vehicles. Achieving the widespread adoption of such vehicles will require lower costs to bring prices down to market levels, but many issues remain to be resolved for each of these vehicle types and different scenarios are possible in which fuel cell vehicles dominate or electric vehicles dominate, for example. In either case, electrically operated vehicles will be essential to achieving the 50% reduction scenario and the vehicles will require inverter control of acceleration and deceleration. The size of the market for power semiconductor devices in the automotive sector that will result from a shift to electrically operated vehicles has been estimated at about 5.1 trillion yen per year. Elsewhere in the transport sector, it is anticipated that use of inverters will grow in trucks, buses, trains, construction machinery, and ships in order to achieve fuel economy and energy efficiency, and



Source: Produced by author based on IEA Energy Technology Perspectives 2008 and other sources

Fig. 5—Shift to Electrically Powered Vehicles to Halve CO_2 Emissions by 2050.
Achieving the 50% reduction scenario will require that almost all vehicles change to electric operation. Vehicles such as hybrids that still use an internal combustion engine will be fueled by second-generation biofuels.

that this market will have an annual value of at least 1 trillion yen.

Summing the above figures gives a total market size for power semiconductor devices under the 50% reduction scenario of around 10 trillion yen per year. This is roughly ten times the current market size of about 1 trillion yen and indicates ongoing annual growth of approximately 5.6%.

The author has also attempted to predict what sort of world would be likely to result under the 50% reduction scenario described above. For example, designing homes to minimize total energy use the way they are designed for resistance to earthquakes would mean insulating them to such a high degree that a single air conditioner would be enough to provide heating and cooling, and installation of photovoltaic cells would be a matter of course. In the garage, the electrically operated family car would store enough electricity to power the home for several days and the car's battery, or other similar device, would be used to smooth the power output of the photovoltaic cells. In the event of an emergency, the ability of the home to generate its own electricity until assistance arrives would prove useful. Also, the energy-saving home appliances that are already standard in Japan would be in widespread use around the world, having become even more efficient due to advances in inverters, electric motors, and other components and able to create comfortable living spaces that are precisely controlled. Most cars, trucks, buses, and trains would be powered via an inverter that achieves a quiet in-vehicle environment, is able to recover energy when braking, and is capable of providing smooth starting and acceleration while emitting almost no exhaust gases. For society as a whole, optimized energy-efficient operation can be achieved within and between regions and the electricity grid made more reliable by fusing electricity and information networks.

Although the world envisaged by this 50% reduction scenario represents an energy revolution to rival the industrial revolution and faces many technical challenges including cost, it also provides an opportunity to establish a sustainable society and create a prosperous lifestyle that is in harmony with nature. The investment required to achieve this is estimated by the IEA to be equivalent to 1.1% of global GDP[4].

DEVELOPMENT OF IGBTS AT HITACHI AND SYSTEM APPLICATIONS

System Power Devices and HiGT Concept

The power semiconductor devices used in the sectors referred to above can withstand voltages of several hundred volts to control power supply voltages of 100 V or more, and currently most of these devices are IGBTs. Development of IGBTs started at Hitachi in 1986 and has grown along with the departments in the Hitachi Group that are responsible for system products, and this parallel development of devices and systems has led to the development of new techniques. To maximize the benefits to the system, the approach sometimes is to focus on improving the IGBT characteristics and at other times is to get the best performance from the IGBTs by considering the system specifications themselves. For this reason, Hitachi uses the term "system power device" to refer to power semiconductor devices.

Fig. 6 shows the basic concept of HiGT (high-conductivity IGBT)[5, 6] which is a feature of Hitachi IGBTs. Low-loss IGBTs can be produced by applying LSI (large-scale integration) design rules to the design of conventional IGBTs to achieve higher output current density and lower on-state voltage (voltage drop in the IGBT) when operating close to the rated current. Unfortunately, the disadvantage of this approach is that it makes the devices more prone to failure because it increases the saturation current and prevents the suppression of over-current when a fault occurs. In contrast, the key concept behind HiGT is to

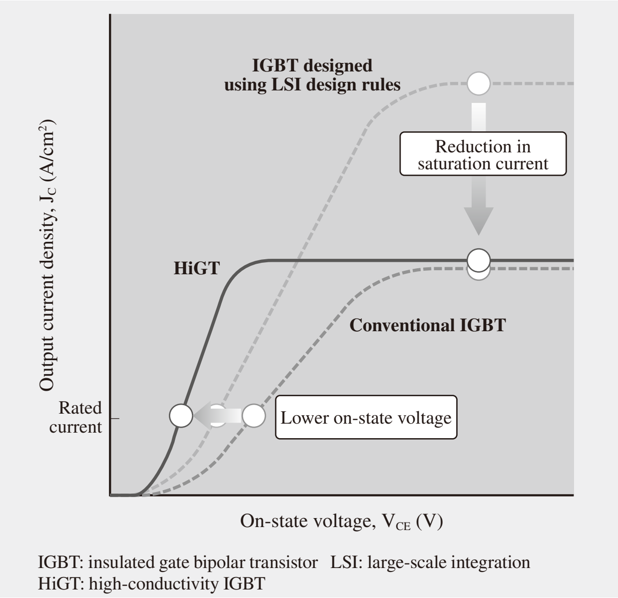


Fig. 6—Basic Concept of HiGT.
The HiGT concept is to increase resistance to breakdown during over-current by minimizing the saturation current density while also reducing the on-state voltage and achieving low losses by increasing the output current density when operating close to the rated current.

combine low losses with a high short-circuit capability by keeping the saturation current density to a level similar to a conventional IGBT while also increasing the output current density when operating close to the rated current to reduce the on-state voltage. One way to implement this concept is to revise the scaling rules for IGBTs[7] and this has been done for all Hitachi IGBTs. The following section describes the state of IGBT development based on example system applications.

Applications in Trains

The first application by Hitachi of IGBTs to trains was a 2,000-V 300-A IGBT module developed in 1992 which was the first such module to be produced anywhere in the world[8] [see Fig. 7 (a)]. At that time, GTOs (gate turn-off thyristors) were used as the power semiconductor devices in inverter-driven trains. However, IGBTs were already available for industrial applications in modules up to the 1,400 V class. In order to utilize IGBTs in trains, Hitachi developed a highly reliable module that could withstand the repeated acceleration and deceleration between stations and an IGBT chip with the ability to withstand voltages of 2,000 V that was required to use the high-voltage overhead wires. An IGBT inverter fitted with these modules was installed for the first time in the world in an 03 series train[9] on the Hibiya Line of Tokyo Metro Co., Ltd. (Tokyo Underground Railway Company previously known as the Teito Rapid Transit Authority) which entered commercial operation during 1993 [see Fig. 7 (b)]. The IGBT inverter was 40% smaller and lighter than previous GTO inverters and its noise level was 15 dB lower. Also, the maximum loss per trainset was reduced by 60% and the new inverter opened up the scope of applications for IGBTs in the railway industry. Further enhancements were made to the module and its consistency when produced in volume was improved by adopting a module substrate with a coefficient of thermal expansion that was low and also close to the coefficient of thermal expansion of the silicon used in the IGBT chip[10]. Module structures that use this low-expansion substrate subsequently became the de facto international standard for the railway industry and are still in wide use. They are also used in some hybrid vehicles.

The hybrid drive system[11] on the Kiha E200 Type[12] trains of the East Japan Railway Company generates electricity by running a diesel engine at its optimum RPM (revolutions per minute) [see Fig. 7 (c)]. The resulting AC (alternating current) voltage is converted to DC (direct current) in a converter

(a) World-first high-reliability IGBT module for trains (2,000 V, 300 A)
(b) This Hibiya line train was the first in the world to feature an IGBT inverter.
(c) This train with a hybrid drive system was the first in the world to enter commercial operation.
(d) This CTRL train was the first to be supplied to the UK by a Japanese manufacturer.

CTRL: Channel Tunnel Rail Link

Fig. 7—World-first IGBT Module for Trains and Example Trains Fitted with IGBTs.
The world's first train using an inverter fitted with IGBTs was introduced by Tokyo Metro Co., Ltd. on its Hibiya Line. Following trials in 1992, the train entered commercial operation in 1993. The hybrid drive system used on the Kiha E200 Type trains of the East Japan Railway Company stores power generated by the diesel engine in lithium batteries and uses it to drive electric motors. Hitachi Class 395 trains for the CTRL (Channel Tunnel Rail Link) commenced operation in December 2009.

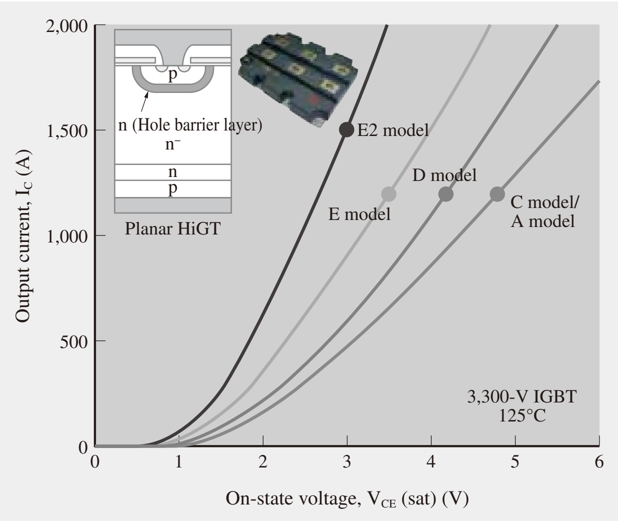


Fig. 8—Use of Planar HiGT to Reduce On-state Voltage in 3,300-V Modules.
The latest planar HiGT is used as the IGBT chip in the E2 model 3,300-V 1,500-A HiGT module. Planar HiGT reduces the on-state voltage and increases the output current through the use of a flat (planar) MOS (metal-oxide semiconductor) gate structure on the surface of the silicon and a hole barrier layer that improves electric conductivity, while still keeping to the HiGT concept.

that uses IGBTs and the energy is stored in lithium batteries. This energy is then converted back to AC by an inverter (which also uses IGBTs) and used to drive the electric motor. Compared to conventional diesel engines, use of a hybrid drive system results in lower fuel consumption (-10%), lower noise (-30 dB), and lower emissions of nitrogen oxides and particulate matter (-60%). The system has also been used on long-distance high-speed trains and a system fitted to an existing HST (high-speed train)[(13)] has completed operational trials in the UK.

More recently, the supply of rolling stock for the CTRL[(14)] in the UK, the birthplace of the railway industry, can be seen as recognition of the many years of experience that Hitachi has built up in Japan with various types of rolling stock, including high-speed trains like the Shinkansen, and the quality and reliability of its leading-edge railway technology and other capabilities, this being the first such order to be received by a Japanese manufacturer [see Fig. 7 (d)].

Fig. 8 shows the improvements in the characteristics of 3,300-V IGBT modules which are mainly used in trains. In the 15 years since producing the world's first 2,000-V IGBT module to be installed in a train, Hitachi has worked to produce devices that can withstand higher voltages and carry higher currents with lower losses. The E2 model 3,300-V 1,500-A HiGT module features the latest planar HiGT chip. Planar HiGT features a flat (planar) MOS (metal-oxide semiconductor) gate structure on the surface of the silicon and uses a hole barrier layer to improve modulation of conductivity while keeping to the HiGT concept. This reduces the on-state voltage and losses while increasing the output current.

Although high-voltage and high-current IGBT modules have in the past mainly been developed for use on trains, they have also recently started to be used not only in heavy industrial applications such as in the steel industry but also in other applications such as wind power generation, construction machinery, and ships. Technology developed for railways is expanding into social infrastructure systems in tandem with power electronics technology.

Applications in Hybrid Vehicles

The highly reliable design techniques that Hitachi established for railway applications are now being used in inverter systems for hybrid vehicles and Hitachi is working to develop these techniques further to satisfy the requirements for reliability and low cost that are characteristic of the automotive market. Fig. 9 shows a HiGT module for use in hybrid vehicles and a driver IC (integrated circuit) with a high drive capacity and advanced functions that has been commercialized for use in high-output IGBT modules for strong hybrid vehicles (hybrids able to run on battery power alone). Unlike trains, use of water cooling is a natural choice for automobiles as most already have a water cooling system for the engine which includes a radiator. The HiGT module has water cooling fins on its underside (base) which allow direct cooling using water from the radiator. Because this configuration does not require the use of heat-conducting grease, the resulting thermal resistance is approximately 25% lower than on indirect cooling systems in which the cooling fins are separate from the module. In addition to lowering the temperature of the IGBT chip and improving module reliability, this helps make the inverter smaller because it allows a higher mounting density[(15)].

1,200-V driver IC[(16)] has a maximum capacity of 10 A for driving the gate on the IGBT module and is suitable for high-capacity inverters in strong hybrid vehicles fitted with electric motors in the 100-kW class. A single driver IC can drive both the upper and lower arm IGBTs for one phase module and the functions on the IC include a deadtime generation function and various protection circuits. By continuously monitoring and controlling the operation of the upper and lower

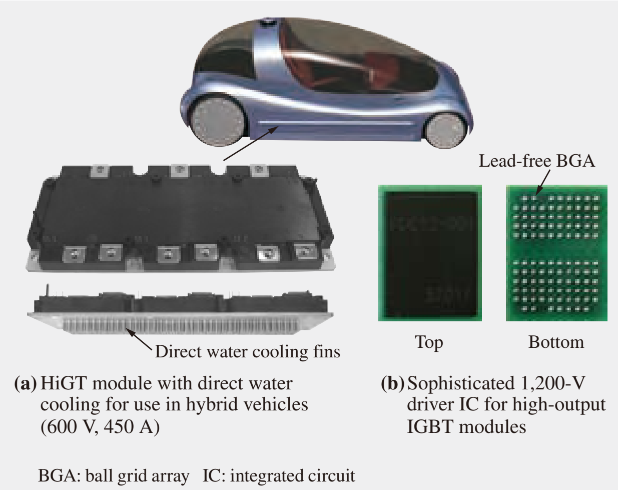


Fig. 9—HiGT Module and Driver IC for Hybrid Vehicles.
This 600-V 450-A HiGT module is fitted with three sets of trench HiGTs (one per phase). The module has fins on the underside that allow direct water cooling with a thermal resistance that is approximately 25% lower than the indirect water cooling used previously. The driver IC integrates the drive circuit for one phase with a maximum output of 10 A and features deadtime generation and soft gate functions as well as various protection functions. The IC is provided in a lead-free BGA package suitable for installation in systems where space is limited.

arm IGBTs, the IC can prevent the upper and lower IGBTs from being turned on simultaneously and short-circuiting the power supply. By generating the deadtime in the IC, this time can be shortened to achieve smoother motor operation. The driver IC also has a soft switching function. Switching the IGBTs smoothly and with low losses helps minimize over-voltage and heat generation in the IGBTs. Protection functions that guard against over-current, over-temperature, and low-supply voltage are also incorporated to ensure that the inverter can operate safely and reliably.

Hitachi has developed a new SOI (silicon-on-insulator) high-voltage IC to integrate these numerous functions and allow higher mounting densities and also a new lead-free BGA (ball grid array) package with multiple chips including the power MOSFETs (metal-oxide-semiconductor field-effect transistors) used as the output buffers.

Fig. 10 shows a comparison between the output characteristics of the trench HiGT used in the HiGT module shown in Fig. 9 with those of previously developed IGBT series models. The A series high-speed IGBTs developed in the late 1980s were used in step-up converters in air conditioners. Use of a step-up converter increases the torque generated by a permanent magnet synchronous motor when operating at the high end of its speed range and Hitachi developed an energy-efficient air conditioner capable of producing warm air at 80°C even during winter which went into commercial production in 1990. This was the original version of Hitachi's current line of PAM (pulse amplitude modulation) air conditioners. Applications of the S series and GS/GR series modules with low on-state voltage that were developed subsequently included industrial systems and elevators.

Trench HiGTs have a MOS gate with a trench structure and use interspersed gates with floating potential p layers. Selectively interspersing gates not only achieves the HiGT concept of minimizing the saturation current, it also reduces gate capacitance making the device easier to drive. Meanwhile, use of the floating p layer encourages electron injection, increasing electrical conductivity and reducing the on-state voltage (loss). The adoption of features such as low-loss trench HiGTs and a directly cooled module with low thermal resistance allows the construction of inverters for hybrid vehicles that combine small size with high output.

In this way, synergies can be enhanced by extending these new technologies developed for use in hybrid vehicles to applications in other fields.

Applications in Air Conditioners

Hitachi has also developed high-voltage ICs for small electric motors that integrate the associated peripheral circuits as well as the IGBTs and diodes (see

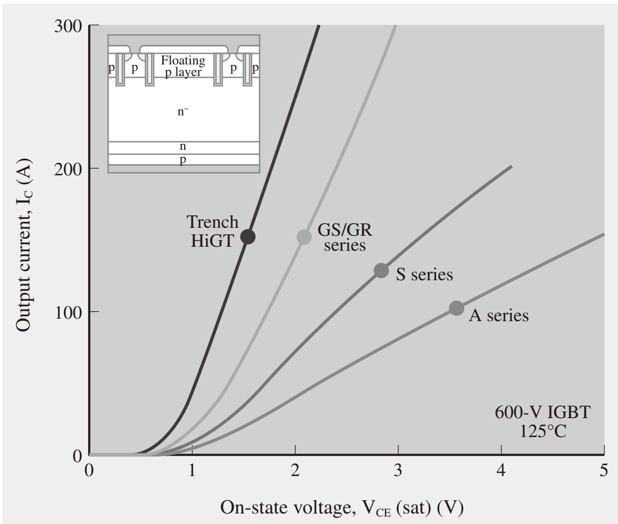


Fig. 10—High Output and Low On-state Voltage Achieved Using Trench HiGTs.
As both the on-state voltage and switching losses on trench HiGTs have been reduced by approximately half compared to the A series, inverter losses have also been roughly halved.

Fig. 11). Most of these are single-chip inverter ICs for use in the fan motors in the interior and exterior units of air conditioners. With an output of 1.5 A and rated for voltages up to 500 V, these high-voltage ICs can be used to implement inverter control for motors up to the 150-W class. Because their ability to withstand high voltages means the ICs can use high-voltage AC power in the 100 V to 200 V range directly without requiring a switching regulator to reduce the voltage, they feature high efficiency and small size. As a result, the ICs can be incorporated inside a motor, a practice that can transform a standard permanent magnet synchronous motor into an "inverter motor" capable of variable speed control. Hitachi led the world by developing the first generation of these single-chip inverter ICs[17], [18] in 1990 which was the first time IGBTs had been incorporated into an IC, but the market for the devices remained slow for some time. They only started to become more widely used after the Top Runner Program was introduced by the 1999 amendment to the Revised Energy Conservation Law in Japan.

Hitachi made further enhancements to these single-chip inverter ICs including also integrating an 8-bit microcomputer into the motor[19] to achieve even more efficient drive of permanent magnet synchronous motors, which already feature high efficiency. Using a microcomputer has reduced the power consumption of the motor by up to 15% (5 W) independently of any individual variation between motors. Hitachi also developed a technique for generating a current polarity signal for the motor output current, for the first time for small fan motors. By carefully controlling the phase difference between this signal and the position signal indicating the positions of the magnets, speed variations that cause noise can be suppressed to reduce the noise level of the motor by up to 35% (20 dB). The rated current of the IC was increased to 2 A to allow its use with fan motors in the package air conditioners used in offices and similar environments. Single-chip inverter ICs are also used in fan and pump motors for natural refrigerant heat pump water heater, gas water heaters, air purifiers, driers, and other equipment as well as in automatic doors where they help create comfortable living environments and spaces with energy saving and quiet. This combination of high-voltage IC and microcomputer is made possible by the fusion of power electronics technology from heavy electric machinery with motor control technology built up by Hitachi through its many years of experience in industrial, home appliance, and other applications.

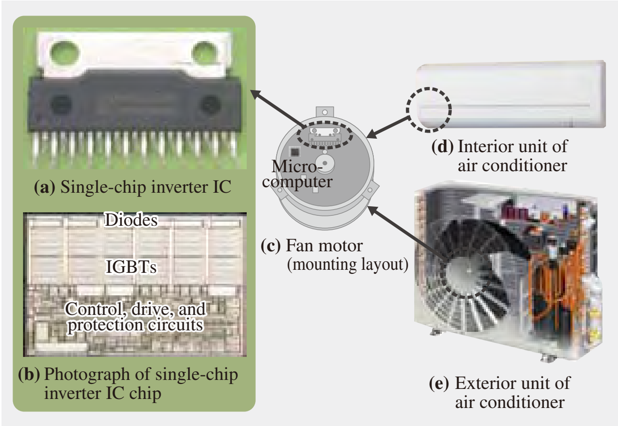


Fig. 11—Adoption of Inverter Control on Small Motors through Use of Single-chip Inverter ICs.
A single-chip inverter IC integrates IGBTs, diodes, and various other circuits to achieve energy efficiency and comfort by converting small motors like those used in the interior and exterior units of air conditioners to inverter control by mounting the IC inside the motor.

This use of inverter control even for small motors in pursuit of energy-efficiency and comfort can be thought of as characteristic of Japanese culture and, against a background in which there is a need for measures that commit all of our strengths to dealing with the problem of global warming, Hitachi regards it as a new type of value that Hitachi should take an active role in communicating to the world so that it is more widely adopted.

FUTURE OUTLOOK FOR POWER SEMICONDUCTOR DEVICES

Fig. 12 shows the results of pursing lower on-state voltages as part of the underlying concept of HiGT in comparison to conventional IGBTs. The figure also shows the relationship between the main applications for power semiconductor devices and their rated voltages. To operate, an IGBT requires a forward bias of approximately 1 V across the p-n junction as shown in Fig. 8, Fig. 10, and elsewhere and therefore achieving an on-state voltage of less than 1 V is difficult. This is because this value of 1 V is determined by the band gap energy which is a property of the silicon material. Whereas it is difficult to make any substantial improvement in the losses for a low-voltage IGBT in the 600-V range for which the on-state voltage is already close to 1 V, there remains scope for improvement for IGBTs in the high-voltage range such as 3,300-V models like the E2 module described earlier. Use of this technology is not limited to the high-voltage range only and it has also been extended to lower voltages

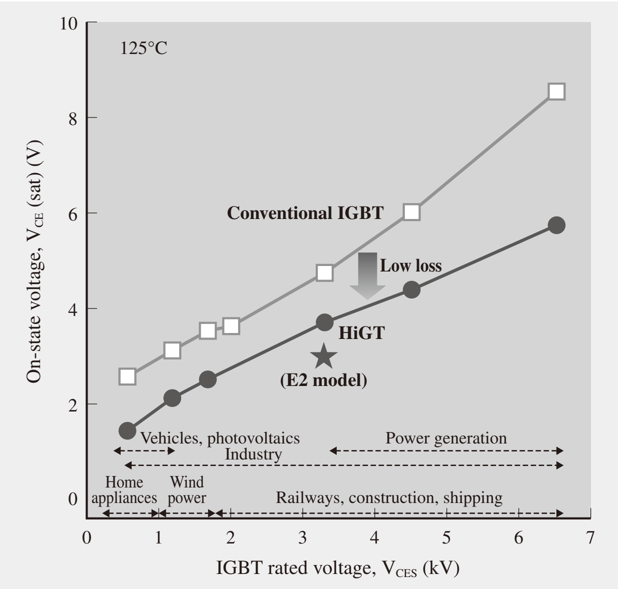


Fig. 12—Pursuit of Lower On-state Voltage Using HiGT.
Hitachi has been working to achieve low losses by reducing the on-state voltage across the entire range of voltage ratings based on the underlying concept of HiGT.

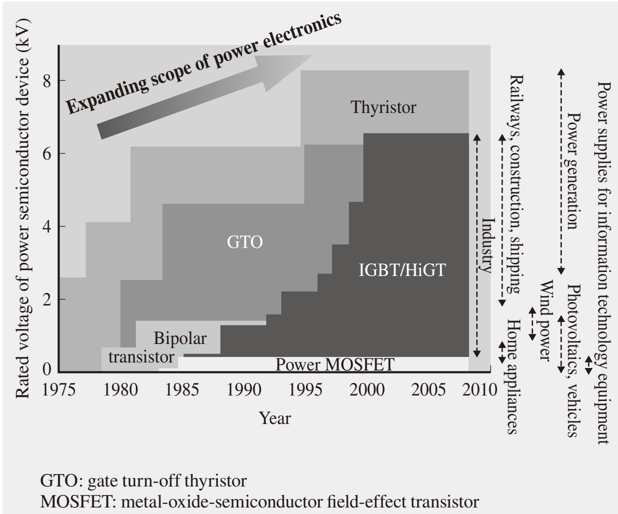


Fig. 13—Types of Power Semiconductor Device and Trend toward Higher Rated Voltages.
The range of applications for power electronics technology has grown as power semiconductor devices have become able to withstand higher voltages, and as IGBTs have become available with higher voltages and lower losses, IGBTs and HiGT have taken over from GTOs, bipolar transistors, and other devices to become the predominant type of power semiconductor device.

to help make inverters and other equipment smaller and more efficient by reducing losses, even if only slightly, and bringing these into wider use is essential to realizing an energy-efficient society.

Fig. 13 shows how the types and voltage ratings of power semiconductor devices have changed over time. As power semiconductor devices have improved their ability to withstand higher voltages, the range of applications for power electronics technology has also grown. Along with the development of IGBTs with higher voltages and lower losses in the 1990s, IGBTs and HiGT have suddenly taken over from GTOs, bipolar transistors, and other devices to become the predominant type of power semiconductor device. The scope of applications for IGBT and HiGT is wide, extending from home appliances in the low-voltage range where the devices must withstand voltages of only several hundred volts through to vehicles and 6,500-V power generation, railway, and heavy industry applications, and this has made these devices into an unprecedented “almighty” category of power semiconductor devices. The reason for this is not only the progress that has been made in making the devices able to withstand higher voltages, reducing losses, and other aspects of their performance, but also because IGBTs are close to being the ideal power semiconductor device with characteristics that include being robust, meaning they require little in the way of additional protection circuits, being easy to connect together in parallel to carry higher currents due to their preventing from current crowding, and being very easy to control because of their use of voltage-driven MOS gates.

However, it is also true that low-voltage IGBTs are approaching the limits of what is possible, as indicated in Fig. 12, and just as IGBTs superseded other device types such as GTOs and bipolar transistors, there is a need to find new types of power semiconductor device. In recent years, other semiconductor devices such as SiC (silicon carbide) and GaN (gallium nitride) have attracted attention as alternatives to silicon and the expectations for these are high, their having been the subject of extensive research and development which in some cases has reached the stage of commercialization. However, they still face a range of problems relating to crystal defects, production processes, and other factors and they are not yet capable of covering the wide range of applications shown in Fig. 13. It appears that enhanced IGBTs with low losses, low noise, and low cost will remain the mainstay for the time being. Another important factor is the use of total design that can get the maximum performance from IGBTs by working on development in parallel with the departments responsible for designing practical power electronics systems.

CONCLUSIONS

Following its Environmental Vision 2010 published in 2001 and its Environmental Vision 2015 published in 2006, Hitachi has also produced its long-term plan for preventing global warming entitled Environmental Vision 2025 on December 20, 2007, and it announced its intention to help reduce annual CO_2 emissions by 100 million tons by 2025 through Hitachi products and services. Power semiconductor devices are used in a wide application for saving energy and sustainable energy and already play an important role. To date, however, they have barely reached the starting gate.

As described in this article, a paradigm shift in the production and use of energy will be required over the next 40 years in order to achieve the 50% reduction scenario. Power semiconductor devices are directly involved in roughly half of the areas where the hoped-for 48 billion tons of reductions are to be found and the size of the market for these products is expected to increase 10-fold from its current level to reach 10 trillion yen per year in 2050. Further, the world envisaged under this 50% reduction scenario is not one of stifling frugality and poverty but rather a prosperous way of life that is in harmony with nature and in which can be seen a sustainable and pleasant low-carbon society.

Hitachi intends to continue developing even better "system power devices" and thereby to do what it can to realize this prosperous low-carbon society at the earliest possible date.

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