Power Semiconductors: Current Status and Future Outlook

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1. Introduction

Energy consumption has been steadily increasing as populations and economies grow worldwide. In addition to measures for conserving energy, the use of renewable energies, such as photovoltaic power and wind power, has been expanding in an attempt to suppress CO_2 emissions and prevent global warming. Many countries have already declared their desire to completely ban the sale of gasoline powered vehicles in a few decades and been employing electric vehicles (xEV) as a means of reducing CO_2 and rapidly growing initiatives to achieve decarbonization.

Fuji Electric has been working on innovating energy technology for a long time. We have been contributing to the realization of a responsible and sustainable society by developing and commercializing power semiconductors as key devices in the power electronics products used in achieving energy stability and optimization.

2. Power Semiconductors and Application Examples

Figure 1 shows some application examples of Fuji Electric's power semiconductor products. Fuji Electric is developing power semiconductors to meet various needs. We offer power discrete devices*1 and small intelligent power modules (IPM)*2 for small capacity markets and power modules*3 for medium and large capacity markets, and they have industrial and automotive applications respectively. We are also developing products that use silicon (Si) and silicon carbide (SiC)*4 as materials for power semiconductor devices.

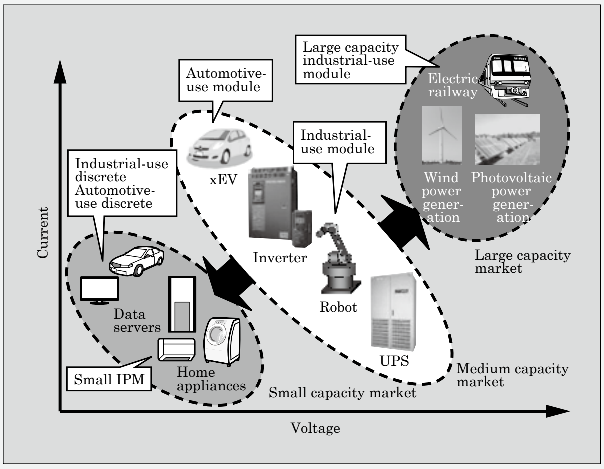

Fig.1 Examples of Fuji Electric power semiconductor product applications

It is important to adopt designs that ensure long-term reliability for power semiconductors. This includes not only semiconductor chip design, but also package electrical design, heat dissipation design, insulation design, and the design guarantees initial characteristics over a certain period of time. Fuji Electric has repeatedly innovated technologies

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***1: Power discrete device**

This power semiconductor device consists of a single IGBT or MOSFET power semiconductor device, or a circuit referred to as a 1-in-1 in which the device is supplemented with a diode inserted in an inverse parallel manner. The shape is generally determined by the pin layout and it adopts a package such as TO-220 or TO-3P. It is used in small capacity PC power supplies, uninterruptible power systems, LCD displays and small motor control circuits.

***2: IPM**

Abbreviation for intelligent power module. This is a power module that incorporates a power semiconductor device, drive circuit and protection circuit. Circuit design can be facilitated and the performance of the power semiconductor device can be maximized by using a dedicated drive circuit.

***3: Power module**

This is a package in an easy-to-use form that is created by routing multiple power semiconductors, corresponding to diode and transistor based applications, to construct an electrical circuit. It is referred to as a 1-in-1, 2-in-1, 6-in-1 or likewise, depending on the number of devices in the module (usually an IGBT + inverse parallel connected FWD). A module mounted with a drive circuit for controlling the power semiconductor device is called an intelligent power module (IPM).

as it develops power semiconductors that meet the requirements of high functionality, large capacity, and eco-friendliness.

In this chapter, we will provide an overview of the power semiconductor products developed by Fuji Electric.

2.1 Power module products (Si)

In the field of power module products, small IPMs are used in household appliances, such as air conditioners, and in the small capacity applications of inverters and servos. The demand for energy savings is also increasing in the applications that small IPMs are targeted at. For example, air conditioners are required to exhibit low noise characteristics in Europe and other countries in order to meet the standards related to energy consumption efficiency and comply with EMC standards for preventing radio wave interference. To meet these energy-saving demands, Fuji Electric has commercialized a 2nd-generation small IPMs[(1)-(3)]. In addition, we have developed a line-up of 650-V/50-A, 75-A products based on this 2nd-generation small IPMs that is capable of being used in applications typified by large air conditioners and industrial-use inverters.

For medium capacity industrial applications such as inverters, robots and uninterruptible power systems (UPS), we have developed the "X Series" as a line-up of the latest modules and IPMs that uses 7th-generation chip technology and packaging technology[(4),(5)].

In the medium capacity, we have also commercialized modules and IPMs for xEV, such as hybrid electric vehicles and electric vehicles[(6)]. IGBT*[5] modules are key components in the inverters used to control xEV motors. In addition to reducing loss to achieve efficient use of battery power, it is also important to achieve miniaturization, weight savings and capacity gains since mounting space is limited in engine rooms. To meet these requirements, we have developed 3rd generation high-power direct liquid cooling modules[(7)-(9)] for automotive applications that are equipped with RC-IGBTs*[6]. In addition to this 3rd-generation direct liquid cooling technology, we have developed large-capacity automotive modules that make use of lead frame technology instead of conventional wiring for the main circuit wiring in order to achieve further miniaturization and high reliability[(10),(11)]. In addition, in the field of temperature sensing for overheating protection, we have made use of on-chip temperature sensors instead of conventional negative temperature coefficient (NTC) thermistors in the development of on-chip sensors-integrated IGBT modules for xEV motor drives that seek to achieve miniaturization, weight savings and enhanced current capacity.

We have developed X-Series high-capacity modules to meet the demands of further miniaturization and increased efficiency in power conversion equipment[(12)]. Moreover, we have been developing hybrid modules suitable for electric railways that secure a higher degree of efficiency and reliability by employing new packages that utilize low-loss SiC-SBDs*[7] instead of an FWDs*[8(13)].

In order to use IGBT in applications characterized by frequent and repeated acceleration and deceleration, such as xEV, it is necessary to adopt a design that sufficiently takes into consideration power loss and temperature rise in the complex operation patterns related to the lifetime and reliability of the equipment.

Fuji Electric has released an IGBT simulator

***4: SiC**

SiC is a compound of silicon (Si) and carbon (C). It is characterized by a multi-crystal polymorph such as 3C, 4H and 6H. It is referred to as a wide-gap semiconductor with a band gap of 2.2 to 3.3 eV depending on the structure. Since it has physical properties advantageous to power devices, such as high dielectric breakdown voltage and high thermal conductivity, it is contributing to the development of devices characterized by high withstand voltage, low loss and high temperature operation.

***5: IGBT**

Abbreviation for insulated gate bipolar transistor. The gate has the same structure as MOSFET. It is a voltage control device that has a gate insulated with an oxide insulating film. It makes use of the strong points of MOSFET and bipolar transistors. It can make use of conductivity modulation because of its bipolar operation. As a result, it is able to achieve the high switching speed, high withstand voltage and low on-state resistance required by inverter applications.

***6: RC-IGBT**

Abbreviation for reverse-conducting IGBT. This device integrates an IGBT and FWD, which are used together as a pair, on a single chip in the module. It exhibits excellent heat dissipation characteristics since the IGBT and FWD operate in alternation, and it facilitates IGBT module miniaturization and improved power density since it can reduce the number of chips in the module.

***7: SBD**

Abbreviation for Schottky barrier diode. This is a diode characterized by a rectifying action that makes use of a Schottky barrier formed through metal and semiconductor bonding. Its excellent electrical characteristics have made it an object of study in the application to SiC-SBD based FWD. Compared with P-intrinsic-N (PiN) diodes that also use of a small number of carriers, SBD diodes, which operate only with a large number of carriers, speed up reverse recovery and reduce reverse recovery loss.

***8: FWD**

Abbreviation for free wheeling diode. It is also referred to as a circulation diode. This device is connected in parallel with the IGBT in power conversion circuits of inverters, and is responsible for recirculating the energy stored in inductance to the power supply side when the IGBT is turned off. PiN diodes are mainstream for Si based FWD. Since it is a bipolar type that also uses a small number of carriers, the voltage drop during forward current flow can be reduced. However, this will also result in a larger reverse recovery loss.

that is available free of charge on our website to calculate power loss and temperature in IGBT modules[14]. It has been updated to enable characteristics such as the temperature dependence of loss, which is a characteristic more closely reflects actual situations.

2.2 Power module products (SiC)

SiC is expected to proliferate as a next-generation power semiconductor material. Since SiC has about 3 times the band gap and thermal conductivity of Si, it has very few thermally excited carrier and thus can diffuse generated heat more easily, thereby contributing to high-temperature operation. Moreover, it also has the benefit of reducing loss.

In order to reduce the switching loss of power semiconductors, it is effective to replace IGBT with MOSFET*9. However, increase in the conduction loss of a Si-MOSFET is the problem we have to work on. SiC has a dielectric breakdown electric field strength approximately 10 times that of Si, and thereby exhibits that a high withstand voltage can be secured even in devices that are thinner. Furthermore, it also has the benefit of reducing conduction loss because heavy doping can be done at the drift layer. Therefore, by utilizing SiC-MOSFET for the switching element, it is possible to reduce loss in power conversion equipment to a greater extent than can be done using Si-IGBT. By taking advantage of the superiorities of high operation temperature, low loss, and high withstand voltage exhibited in these types of SiC devices, it is possible to achieve miniaturized, high power density modules.

Fuji Electric is developing small and medium capacity products to which a low-inductance high-output packaging technology is applied to derive these superiorities from SiC devices. Furthermore, we are also developing large capacity products such as power distribution equipment.

We are confident that our modules with SiC trench gate MOSFETs have world-class low-loss characteristics[15],[16]. In order to achieve further improvement, we have developed an application technology for halo structure vertical SiC trench gate MOSFET that suppresses the short channel effect[17]. This development was conducted as part of a project of the joint research body Tsukuba Power Electronics Constellation (TPEC).

As mentioned in Section 2.1, we have developed products that utilize 7th-generation chip technology and packaging technology using Si that can be applicable to medium capacity industrial fields such as inverters, robots and UPS. Demand is increasing for power conversion equipment with further miniaturization and efficiency using high carrier frequency regions for power conversion. To meet this demand, Fuji Electric has developed high-speed hybrid modules that combine high-speed IGBTs and SiC-SBDs capable of lowering loss in high carrier regions of 20 kHz or higher.

2.3 Power discrete, power ICs, pressure sensors

In recent years, the use of the Internet of Things (IoT), big data and artificial intelligence (AI) has been increasing the amount of data used worldwide. As a result, UPSs for servers and data centers have been becoming more efficient. In addition, there has been increasing demand for high-efficiency power conditioning systems (PCSs) that convert DC to AC to use renewable energies such as photovoltaic power generation. Fuji Electric has been developing discrete IGBTs that achieve high efficiency for UPS and PCS. We have also recently developed the "XS Series" as a line-up that improves the $V_{CE(sat)}$ responsible for steady-state loss as well as switching loss compared with previous "High-Speed W Series" products[18].

Against the backdrop of fuel efficiency and exhaust gas regulations, the number of pressure sensors for automotive applications has been increasing. In intake systems, pressure sensors are used to highly control the air and fuel mixture ratio in order to improve fuel efficiency. In exhaust systems, pressure sensors are used to highly control the amount of gas recirculated after combustion in order to clean the exhaust gas. Pressure sensors are also used to detect fuel leaking from a tank. Fuji Electric has developed pressure sensors for these types of applications for low pressure[19],[20]. The demand has also been greatly increasing for high-pressure sensors for brakes, transmissions and hydraulic control of engine oil. Fuji Electric improved its 5th-generation automotive high-pressure sensors for conventional engine oil pressure applications and has developed 6.5th-generation automotive pressure sensors that ensure accuracy under the high temperature environments accompanying engine downsizing.

Switching power supplies of 75 W or more used

***9: MOSFET**

Abbreviation for metal-oxide-semiconductor field-effect transistor . This voltage control device is a type of field-effect transistor that has a gate insulated with an oxide insulating film. It is the most common structure in LSI. Its unipolar operation enables operation at high speeds, but it is used as a low withstand voltage, high frequency device since on-state resistance rises according to withstand voltage. In contrast to planar gate MOSFET where the gate is located on the surface of the device and the channel is parallel to the surface of the device, trench gate MOSFET are characterized by the gate being embedded in a groove formed on the device and the channel perpendicular to the surface of the device.

in electronic devices must be equipped with a power factor correction (PFC) circuit that suppresses harmonic current in accordance with the international standard IEC 61000-3-2. In order to achieve energy savings, PFC circuits are continuously required to reduce standby power and improve efficiency at light loads. To meet these requirements, Fuji Electric has developed 4th-generation critical mode PFC control ICs[21] that exhibit less standby power and higher efficiency at light loads than previous 3rd-generation critical mode PFC control ICs.

3. Power Semiconductor Development Status

In this chapter, we will provide an overview of the development status of Fuji Electric power semiconductors. For details, please refer to the subsequent papers in this journal.

3.1 2nd-generation small IPM 650 V/50 A, 75 A series

Fuji Electric has been developing small IPM products that integrate the power devices and control ICs necessary for inverter circuit configurations that require energy savings and low noise characteristics. In 2015, we launched the 2nd-generation small IPM (2G-IPM) series rated at 600 V/10 to 30 A, which uses X-Series IGBT chip technology. This series achieves lower loss than conventional products, expands maximum operating temperature T_{vjop} from 125 °C to 150 °C and enhances overcurrent detection and overheating protection functions[2]. In addition, we have added to this a line-up of 650-V/50-A, 75-A products which are mainly applicable to large air conditioners and industrial-use inverters (see Fig. 2). In order to ensure the same level as conventional products had, the products were designed to suppress the heat generation that accompanies allowable current expansion and reduction in the internal stress that accompanies package size enlargement (refer to "Line-Up of 2nd-Generation Small IPM with 650 V / 50 A, 75 A" on page 181).

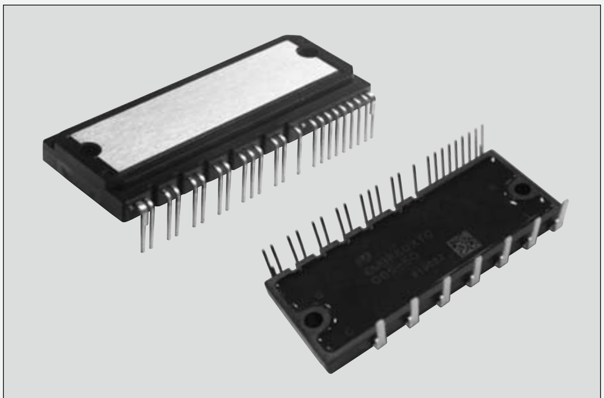

Fig.2 Small IPM (650 V/50 A, 75 A)

3.2 On-chip sensor-integrated IGBT module for xEV motor drive applications

Fuji Electric has developed products that make use of technologies of RC-IGBT chips and cooler integrated structures that meet the needs of low loss, miniaturization, weight-savings and large capacity for automotive modules[7]-[10]. We have also developed on-chip sensor integrated IGBT modules to meet the demand for further miniaturization. Conventionally, NTC thermistors were arranged near the chip as temperature sensors for overheating protection. However, an on-chip sensor integrated IGBT module, incorporating a temperature sensor diode on the power semiconductor chip, can monitors chip temperature accurately. Compared with NTC thermistors, it is possible to increase allowable current by 13% reducing the safety margin of various characteristics that affect the thermal design features such as device characteristic variation and package thermal resistance variation. A comparison of the allowable current of an automotive IGBT module equipped with an on-chip temperature sensor and an NTC thermistor at a switching frequency of 8 kHz is shown in Fig. 3. The figure shows that modules equipped with an on-chip temperature sensor can be miniaturized more than modules equipped with a conventional NTC thermistor, provided that the allowable current is the same (refer to "On-Chip Sensor Built-In IGBT Modules for Driving xEV Motors" on page 186).

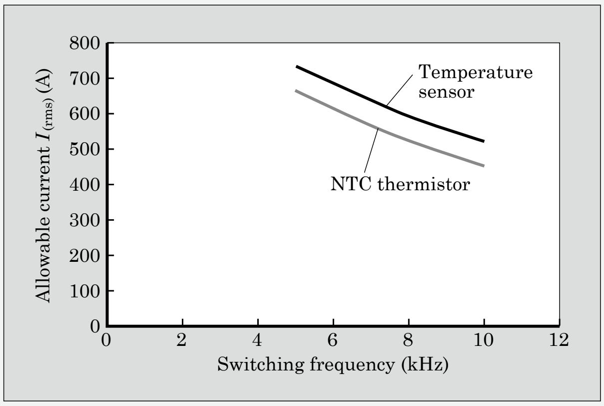

Fig.3 Automotive IGBT on-chip temperature sensor and NTC thermistor allowable current

3.3 Simulator based IGBT module generated loss, temperature and lifetime estimation

Fuji Electric has released software that is available free of charge on its website to simulate generated loss and semiconductor chip temperature when incorporating a Fuji Electric IGBT product into a power electronics system such as an inverter. We have recently released Ver. 6, which comes with newly added functionality. Ver. 6 supports 3-level circuits and commonly used PWM*10 methods. In

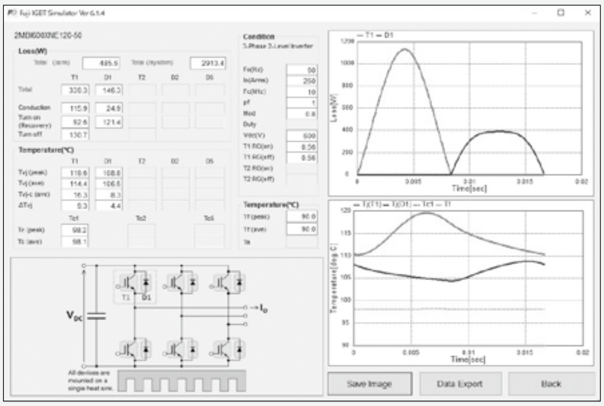

Fig.4 IGBT Simulator Ver. 6 operation screen example (calculation of steady-state loss)

previous version's loss calculations were performed assuming a uniform junction temperature T_{vj} of 125 °C. However, in Ver. 6, we incorporated a calculation function that takes into account T_{vj} dependency, thereby making simulations more realistic. Compared with commercially available circuit simulators, it is more user friendly and makes it easy to obtain results with the same level of accuracy as the commercially available circuit simulators show. It also newly supports applications such as automotive modules, which are characterized by complex output and T_{vj} fluctuations. Figure 4 shows the operation screen of IGBT Simulator Ver. 6 (refer to "Estimation of Power Losses, Temperatures and Power Cycle Lifetime for IGBT Modules by Using IGBT Simulator" on page 199).

3.4 Trench gate MOSFET equipped 3.3-kV All-SiC module for distribution equipment

Since September 2014, Fuji Electric has been participating in the "Demonstration Project for Constructing a Next-Generation Distributed Energy Electric Power Network" launched by New Energy and Industrial Technology Development Organization (NEDO). In this project, we have been developing next-generation voltage regulators (distribution equipment) and applicable control systems that use SiC power semiconductors in order to support the expanded use of renewable energies such as photovoltaic power generation, and maintain and improve our international competitiveness in the electric power equipment and systems industry. So far we have successfully developed 3.3-kV All-SiC 200-A 1-in-1 module for next-generation distribution equipment[22]. In order to further reduce the size and weight of distribution equipment, we have developed modules that expanded rated

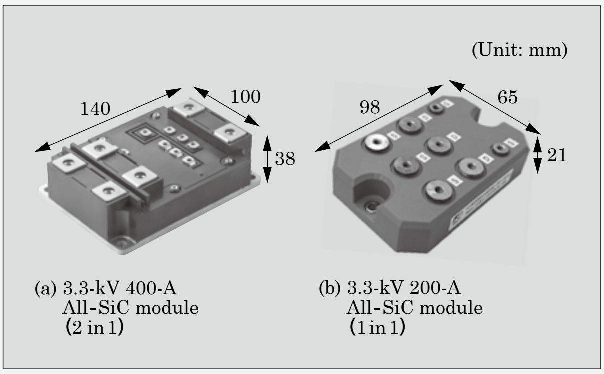

Fig.5 3.3-kV All-SiC module

capacity to 400 A (see Fig. 5). The use of the SiC trench gate MOSFET significantly reduced generated loss when compared with conventional SiC planar-gate MOSFET. The footprint size has been reduced by 45% compared with previous 200-A 1-in-1 modules that have an equivalent circuit configuration (4 units required) (refer to "3.3-kV All-SiC Module with Trench-Gate MOSFETs for Electric Distribution Equipment" on page 190).

3.5 High-speed hybrid modules combining high-speed IGBTs and SiC-SBDs

Fuji Electric has developed high-speed hybrid modules that reduce loss in high frequency regions that are characterized by a switching frequency of 20 kHz or higher, as required by power conversion equipment in the renewable energy field. The products contain combinations of high-speed IGBTs suitable for high-speed switching and low loss SiC-SBDs. The products are compatible with conventional Si modules with 2-in-1 circuit configurations having the same package as that of the conventional Si modules. Figure 6 shows the inverter generated loss simulation results for a distributed small capacity PCS equipped with a high-speed 1,200-V/200-A hybrid module that utilizes an M276 package. Compared with X Series Si modules, total generated loss can be reduced by approximately 50%. Moreover, the rate of reduction increases at high switching frequencies. It can contribute to high efficiency operation and miniaturization through the high-frequency operation of the inverter (refer to "High Speed Hybrid Modules Combining High Speed IGBTs with SiC-SBDs" on page 176).

3.6 SiC-MOSFETs achieving high threshold voltage and low on-state resistance with halo structure

Fuji Electric has been contributing to energy savings of power electronics equipment by develop-

***10: PWM**

Abbreviation for pulse width modulation. It is a power control method that uses switching elements. Given a DC input, it changes output by varying the on-state time width while repeatedly powering on and off at a constant frequency. It is generally used when converting DC to AC with an inverter.

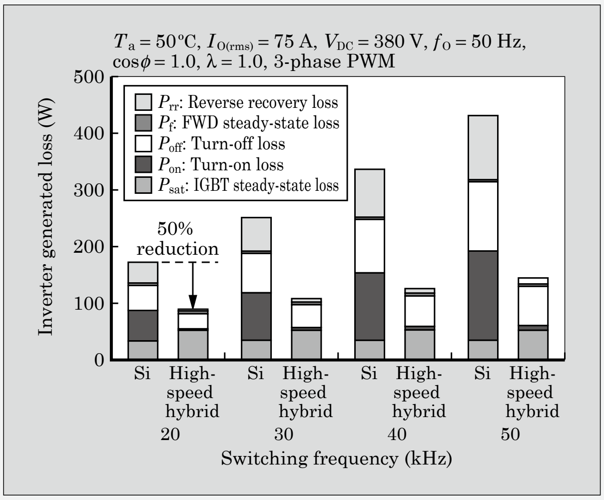

Fig.6 Simulation based comparison of inverter generated loss

ing and commercializing SiC-MOSFET equipped compact and lightweight PCS[23] and mega solar PCS[24]. Power semiconductor modules play an important role in these products. In order to reduce loss, we have been developing modules that utilize trench-gate MOSFETs in place of conventional planar gate MOSFETs[15]. As a measure to further reduce loss, we have recently developed a technology to apply the halo structure used with Si horizontal MOSFET to vertical trench MOSFET. It reduces the on-state resistance that contributes to low loss while maintaining a high threshold voltage. Figure 7 shows the relationship between on-state resistance and threshold voltage. Channel shortening is an effective way to reduce on-state resistance. However, in conventional structures, threshold voltage drops significantly due to the shortened channel, thereby making it susceptible to malfunction (short channel effect). In order to avoid the short channel effect, we applied a halo structure and verified that on-state resistance could be reduced at a high threshold voltage (refer to "SiC-MOSFET with High Threshold Voltage and Low On-Resistance Using Halo Structure" on page 195).

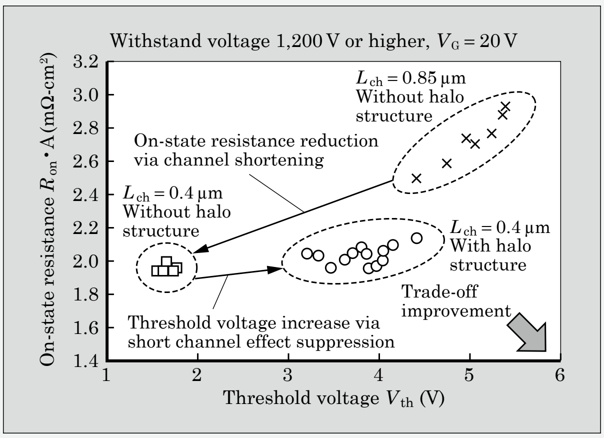

Fig.7 Effect of applying halo structure in trench gate SiC-MOSFET

3.7 "XS Series" 650-V discrete IGBT

Fuji Electric has developed the "XS Series" 650-V discrete IGBT. This product can be widely used for the power circuits of industrial equipment and the PFC circuits of switching power supplies for UPSs and PCSs, demand for which has been increasing accompanying social trends including increased data usage worldwide and the development of renewable energies. Compared with the conventional "High-Speed W Series[18]", these modules improve the trade-off between on-voltage and switching loss and meet the demand for low loss. Figure 8 shows the results of measuring efficiency when using the XS Series with a UPS composed of a 3-level inverter I-type circuit as an application example. The UPS output capacity was 3 kW, and IGBT switching frequency was 4 kHz. Compared with the High-Speed W Series, the XS Series improves efficiency by up to 0.12 points in all load regions (refer to "XS Series 650-V Discrete IGBTs" on page 211).

3.8 6.5th-generation automotive high-pressure sensors

High pressure sensors used for measuring engine oil pressure are required to ensure accuracy at high temperatures due to the higher density mounting accompanying engine downsizing implemented to improve fuel efficiency in automobiles. By optimizing the diaphragm diameter, thickness and position of the gauge resistor, Fuji Electric has successfully developed a 6.5th-generation automotive high-pressure sensor that improves output characteristic linearity and circuit temperature characteristics, while ensuring accuracy at high temperatures (see Fig. 9). As a result, the accuracy guaranteed temperature is increased to 150 °C, while that of the previous 5th-generation products is 125 °C (refer to "6.5th-Generation Automotive High Pressure Sensors" on page 215).

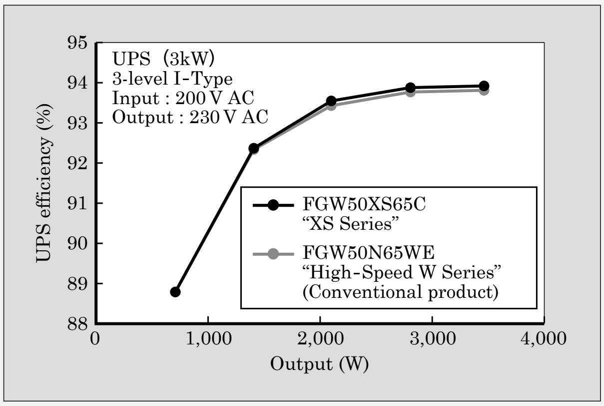

Fig.8 UPS efficiency when applying an "XS Series" 650 V discrete IGBT

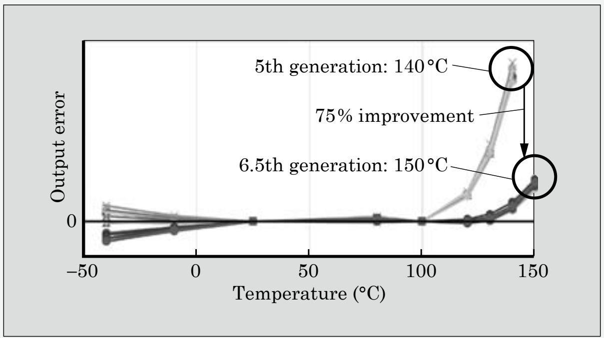

Fig.9 Output error temperature characteristics in 6.5th-generation automotive high-pressure sensors

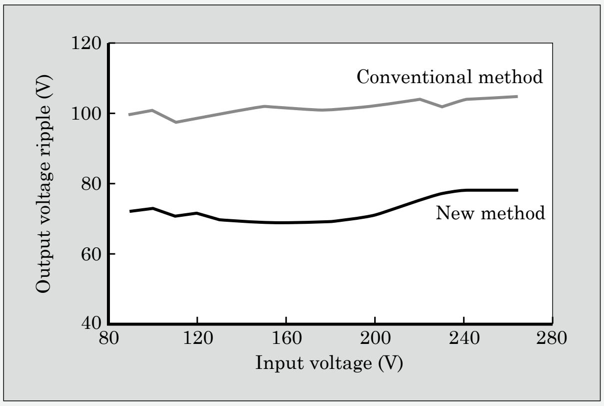

Fig.10 Output voltage ripple comparison (smoothing capacitor: 15 μF)

3.9 "FA1B00 Series" 4th-Generation critical conduction mode, power factor correction control ICs

Switching power supplies are widely used with electronic equipment since they can achieve greater miniaturization, a lighter weight and higher efficiency than conventional linear power supplies. The harmonic current of switching power supplies leads to operation failure and power factor degradation in equipment and distribution facilities, as well as an increase in apparent power. Therefore, power source harmonic current is regulated by the international standard IEC 61000-3-2. Active filter type PFC circuits are widely used to eliminate harmonic current induced power factor problems. Fuji Electric has commercialized ICs that control PFC circuits, thereby contributing to reducing the cost and improving the energy savings of switching power supplies. Fuji Electric has developed the "FA1B00 Series" 4th-generation critical mode PFC control IC, which enables highly efficient power control during light loads and standby. This product is the successor to the "FA1A00 Series" 3rd-generation critical mode PFC control IC. The PFC control IC can comply with power source harmonic current regulations and miniaturize the output capacitor of the PFC circuit. In addition, it makes use of a newly conceived control method that suppresses output voltage ripple and reduce power source harmonic current. The new method can suppress output voltage ripple to 70% of that of conventional methods over the entire input voltage range (see Fig. 10). Basic characteristics such as efficiency and power factor are the same as conventional methods, but in addition, it satisfies power source harmonic current characteristics. It also reduces output voltage ripple with the new control method and miniaturizes smoothing capacitors, which have large footprints in the PFC circuit (refer to "FA1B00 Series 4th-Generation Critical Conduction Mode, Power Factor Correction Control ICs" on page 205).

4. Postscript

Fuji Electric has continuously pursued innovation of energy technologies on the basis of its management policy of "contributing to the realization of a responsible and sustainable society through innovation of electric and thermal energy technologies." Power electronics are a driving force behind meeting the increasing demand for energy savings, decarbonization and environmental conservation. Through our technological innovation in power semiconductors, key devices in this field, we are contributing to the achievement of a sustainable society.

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