Current Status and Future Outlook

Power Semiconductors: Current Status and Future Outlook

ONISHI, Yasuhiko* MIYASAKA, Tadashi* IKAWA, Osamu*

1. Introduction

Fuji Electric is committed to helping achieve a sustainable society through its energy and environment businesses. This goal is one of the core pillars of our management policy and is reflected in the promotion of SDGs in all corporate activities, including those involving the supply chain. This enables us to contribute to solving social and environmental issues such as global warming. These initiatives are allowing us to respond to the international community's goal of realizing an integrated economic, social and environmental framework to achieve a responsible and sustainable society.

In particular, one of Fuji Electric's environmental goals is to help realize a "low-carbon society." This involves improving the efficiency of the power electronics equipment used in various industrial and social infrastructure systems, while also enhancing the performance of the power semiconductor devices used to operate the power electronics equipment.

2. Fuji Electric's Power Semiconductors

Fuji Electric offers a diverse line-up of power semiconductor devices to meet the needs of various applications, as shown in Fig. 1.

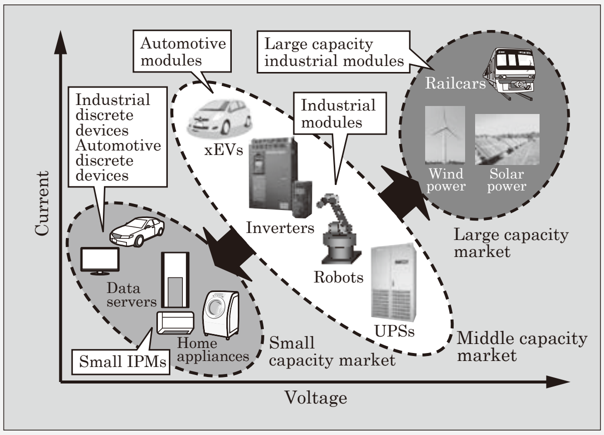

Fig.1 Application examples of Fuji Electric's power semiconductors

In the field of small-capacity equipment, we have developed and commercialized small-capacity intelligent power modules (IPMs)*1 for use in the motor drive systems of air conditioners and other home appliances; industrial-use discrete*2 insulated gate bipolar transistors (IGBTs)*3 for use in the power conversion of power conditioning systems (PCSs) and uninterruptible power systems (UPSs); and superjunction metal-oxide-semiconductor field-effect transistors (SJ-MOSFETs)*4 for use in the

* Electronic Devices Business Group, Fuji Electric Co., Ltd.

***1 IPM:**
This is an acronym for intelligent power module. It is a power module that incorporates a power semiconductor device, gate drive circuit and protection circuit. In addition to facilitating circuit design, the use of a dedicated gate drive circuit can maximize the performance of the power semiconductor device.

***2 Discrete:**
This type of power semiconductor device consists of a single IGBT or MOSFET, 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.

***3 IGBT:**
This is an acronym for insulated gate bipolar transistor. An IGBT is a high-voltage control device that has a gate insulated with an oxide insulated film. It has the same structure as MOSFET. It makes use of the strong points of MOSFET and bipolar transistors. Its bipolar operation means that it can make use of conductivity modulation, and as a result, it is able to achieve a high blocking voltage, low on-resistance and switching speed sufficient for use with inverters.

***4 SJ-MOSFET:**
The drift layer in vertical-power MOSFETs, where the drain and source electrodes are formed on opposite sides of the device, has conventionally been formed with a low-concentration n layer. In contrast, superjunction (SJ)-MOSFETs have a drift layer that consists of a periodic pn column structure. Compared with conventional MOSFETs, SJ-MOSFETs can be significantly improved in blocking voltage and specific on-resistance trade-off characteristics.

power conversion of other types of equipment. In particular, we are developing and commercializing SJ-MOSFET products not only for industrial applications, but also for automotive applications, such as the control units of engines, transmissions and brakes and the power conversion and control functions of xEV (electrified vehicle) chargers. In terms of automotive applications, we have developed and commercialized intelligent power switches (IPSs) that turn on and off the drive current of a hydraulic valve and other control devices in the powertrain, including the engine and transmission; pressure sensors for the gas pressure control units of gasoline-vehicle intake and exhaust systems; pressure sensors for the hydraulic pressure control units of engines, transmissions, power steering systems and brakes; and single-chip igniters for the ignition control units of gasoline engines. We have also developed and commercialized power ICs that control the switching power supplies of various electronic devices, including LED lighting.

In the field of medium-capacity equipment, we have developed and commercialized industrial-use IGBT modules for use in general-purpose inverters, servo motor control units for machine tools and robots, motor control units for commercial air conditioners, and power conversion units for UPSs. The demand for industrial-use power semiconductors is expected to grow as equipment and systems continue to be automated to improve productivity and alleviate labor shortages. In the field of automotive applications, we have developed and commercialized IGBT modules for use in the motor control units of xEVs. It is expected that the demand for automotive power semiconductors will grow in the future as many countries around the world shift from gasoline-powered vehicles to xEVs.

In the field of high-capacity equipment, we are contributing to the realization of zero emissions by developing and commercializing IGBT modules for use in the variable speed drive units of electrical rolling stock motors and for use in the power conversion systems of renewable energy power generation facilities, such as those for wind and mega solar. Furthermore, we have developed and commercialized silicon carbide (SiC)*5 power semiconductor devices as next-generation power semiconductors that achieve lower loss, higher blocking voltage and higher operating temperatures than conventional silicon (Si) devices.

3. Power Semiconductor Development Status

In this section, we will summarize some of Fuji Electric's latest achievements in the development of power semiconductors.

3.1 Enhanced withstand capability for xEV IGBT modules

The IGBT modules of xEVs play a key role in developing smaller, more efficient and reliable vehicles. One of the challenges in developing IGBT power modules for xEVs is to improve their withstand capability (I^2t capability). It is against this backdrop that we have recently developed an IGBT module for xEVs that improves I^2t capability by utilizing a reverse-conducting IGBT (RC-IGBT)*6 and by applying a packaging technology that uses a lead frame (LF) design[(1)], instead of conventional wire bonding, to connect to the circuit of the RC-IGBT surface electrodes (see Fig. 2).

In RC-IGBT modules, the IGBT and free wheeling diode (FWD)*7 regions are incorporated into a single chip. The heat generated by the FWD during FWD energization is dissipated throughout the entire region, including that of the IGBT. This lowers thermal resistance and improves I^2t capability compared to conventional FWDs[(2)].

I^2t protection also depends on the heat dissipation conditions. Therefore, we improved I^2t capability by using an LF design that increases the bonding area between the chip surface and the circuit. Compared with conventional wire-bonding based IGBT modules that consist of separate FWD and IGBT modules, our recently developed LF based RC-IGBT module improves I^2t capability by 160%,

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***5 SiC:**

SiC is a compound of silicon (Si) and carbon (C). It is characterized by a polymorphic multi-crystal 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 crystal structure. Since SiC possesses physical characteristics that are 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.

***6 RC-IGBT:**

This is an abbreviation for reverse-conducting IGBT. An RC-IGBT 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. Moreover, it facilitates IGBT module miniaturization and improved power density since it can reduce the number of chips in the module.

***7 FWD:**

This is an acronym for free wheeling diode. It is also referred to as a recirculation diode. An FWD is connected in parallel with the IGBT in the 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 FWDs. Since they are a bipolar type that also uses minority carriers, they can help reduce voltage drop during forward current flow. However, this will result in a larger reverse recovery loss.

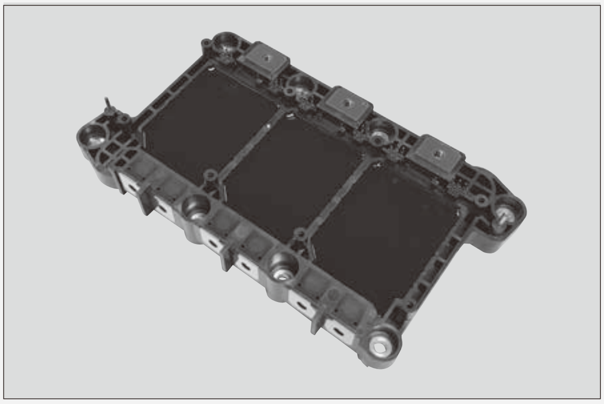

Fig.2 xEV module (newly developed product)

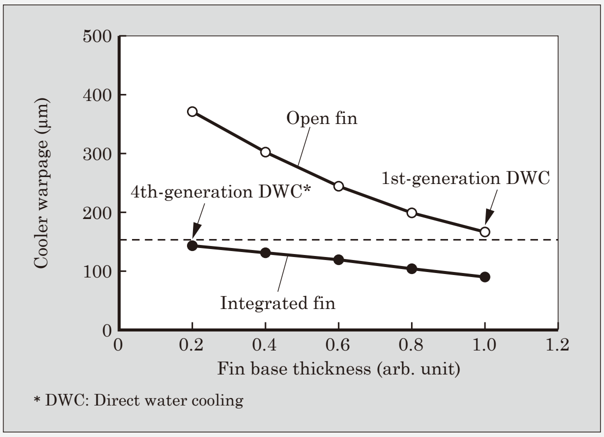

Fig.3 Warping of element-model based cooling unit in terms of fin base thickness

resulting in a highly reliable IGBT module for xEVs (Refer to "Enhanced Over-Current Capability of IGBT Modules for xEVs" on page 198).

3.2 Direct water cooling technology for xEV power semiconductor modules

The inverter units used to control xEV motors need to be installed in confined spaces. This means that they must be compact and flexibly support various installation configurations, while also being lightweight and efficient to achieve better fuel efficiency. To meet these needs, companies have been actively developing new integrated machinery and electric systems that incorporate motors, inverters and gearboxes with the aim of significantly improving the efficiency and cost of the latest electrification systems. Fuji Electric has also developed and commercialized a direct water cooling power module that uses a lightweight and highly workable aluminum cooling unit. The module provides the compactness, slimness, and reliability required by these new types of systems[(3),(4)].

In 1st-generation direct water cooling structures, the fin base of the cooling unit occupied 36% of the total thermal resistance. Thermal analysis simulations revealed that this was inhibiting the structure's heat dissipation performance. The structure's thermal resistance and the module's overall thermal resistance can be improved by simply reducing the thickness the fin base by up to 20%. However, the fin base requires some degree of thickness to ensure the rigidity of the cooler so that it can suppress thermal deformation due to temperature changes in the module. To achieve our goal, we developed a integrated fin that incorporates a heat sink and water jacket. This structure can easily suppress the deformation of the cooling unit compared to conventional structures that adopt a non-integrated open fin design. Figure 3 shows the warping of the cooling unit in terms of its fin base thickness. The integrated fin can reduce warpage to approximately 150 μm or less even when the fin is 20% thinner than that of a conventional open fin. This reduces the thermal resistance of the fin base, while maintaining its rigidity.

Assuming the same warpage of the cooling units, the integrated fin exhibits greater reliability, since its thermal cycling capability is at least twice that of the open fin. (Refer to "Direct Water Cooling Technology for Power Semiconductor Modules for xEVs" on page 201).

3.3 "F5202H" 5th-generation IPS for automotive applications

An IPS is a product that integrates a vertical power MOSFET, used for the output stage, and a horizontal power MOSFET, configured for the control and protection circuits, on a single chip. We recently developed the "F5202H" as an AMP equipped IPS that contributes to reducing the size and improving the heat dissipation of electronic control systems. We utilized 5th-generation IPS device processing technology to reduce the size of the chip by 45% compared with conventional products, while maintaining the same basic performance. This allows it to be mounted in a compact small outline non-leaded (SON) package with excellent heat dissipating characteristics, enabling it to reduce the package footprint by 45% and thermal resistance by 80%.

Figure 4 shows the appearance and internal structure of the F5202H compared with the conventional product[(5)]. It has the following features that enable it to contribute to the miniaturization of electronic control systems:

(a) Miniaturizes control and protection circuits while maintaining the same basic performance.
(b) Uses a small, high heat dissipating SON package.
(c) Integrates a high-precision operational amplifier to enable highly accurate load current monitoring.
(d) Comes with a maximum junction tempera-

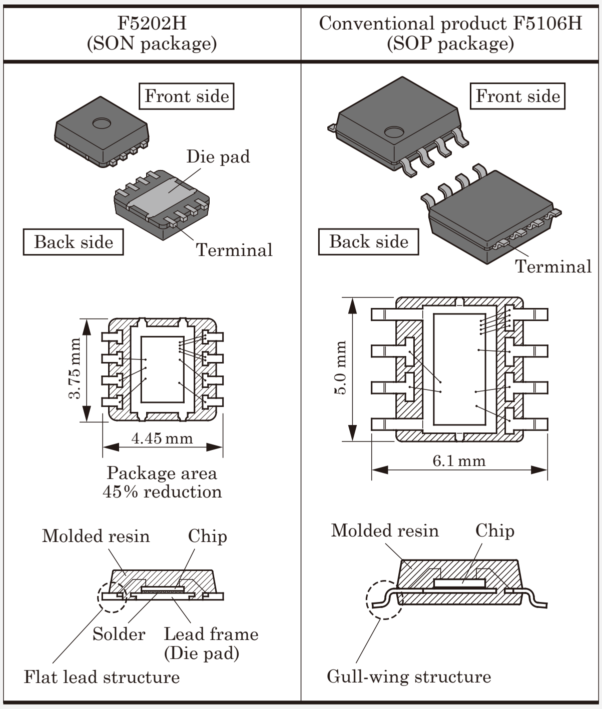

Fig.4 Comparison of package appearance and internal structure

ture T_{vj} rating of 175 °C, allowing for long-term operation in high-temperature environments.

(Refer to "'F5202H' 5th-Generation Intelligent Power Switch for Automotive Applications" on page 206)

3.4 7th-generation "X Series" 1,200-V/2,400-A RC-IGBT module for industrial applications

Fuji Electric has commercialized its 7th-generation "X Series" as a line-up of IGBT modules that makes breakthroughs in chip and packaging technologies. The line-up achieves higher power density by lowering IGBT module loss and improving reliability[6]. Moreover, we have also developed an RC-IGBT, which integrates an IGBT and FWD on a single chip, allowing it to minimize the number of chips and the overall chip area, while also reducing generated loss[7],[8]. 7th-generation "X Series" RC-IGBT modules for industrial applications (hereinafter, "X Series" RC IGBT) combine the chip and packaging technologies of 7th-generation X Series IGBT modules with the technology of RC-IGBT modules to achieve even higher power density. We recently added to the line-up a 1,200-V/2,400-A rated PrimePACK™*3+ that comes equipped with an RC-IGBT module.

The X Series chip technology has significantly reduced collector-emitter saturation voltage $V_{CE(sat)}$.

* PrimePACK™: A trademark or registered trademark of Infineon Technologies AG.

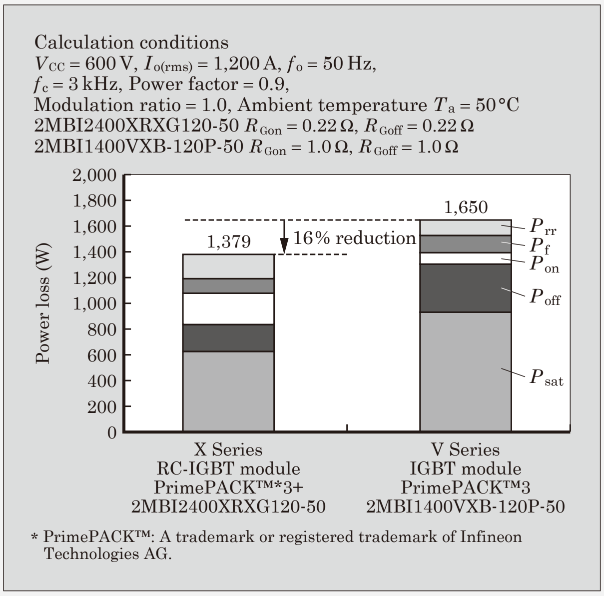

Fig.5 Comparison of "X Series" and "V Series" power dissipation

Furthermore, by using the most advanced thin wafer processing technology, we were able to improve the trade-off relationship between the saturation voltage and switching loss. As a result, the module achieves a 16% reduction in power loss compared with conventional products (see Fig. 5).

In addition, the "X Series" RC-IGBT module uses RC-IGBT technology and a high heat dissipating insulating substrate to substantially reduce thermal resistance and realize a higher current rating than conventional products using the same package size. Moreover, the module uses a high heat-resistant silicone gel to raise the maximum junction temperature to 175 °C and ensure high reliability during continuous operation (Refer to "7th-Generation 'X Series' 1,200-V/2,400-A RC-IGBT Modules for Industrial Applications" on page 211).

3.5 Line-up expansion of 2nd-generation 1,200-V All-SiC modules

The characteristics of Si-based power semiconductor devices are approaching the theoretical limit of their material properties. For this reason, SiC is attracting attention as a next-generation semiconductor material that can go beyond the limits of Si in terms of miniaturization and efficiency.

In 2017, Fuji Electric commercialized an All-SiC 2-in-1 module[9] with a rated capacity of 1,200 V/400 A. The module utilized a fully molded package that incorporated a 1st-generation SiC-MOSFET chip with a trench gate structure.

To expand the product line-up, we developed an All-SiC 2-in-1 module using a standard Si-IGBT module package [W108 × D62 (mm)] in order to ensure external shape and terminal arrangement compatibility. This newly developed All-SiC module

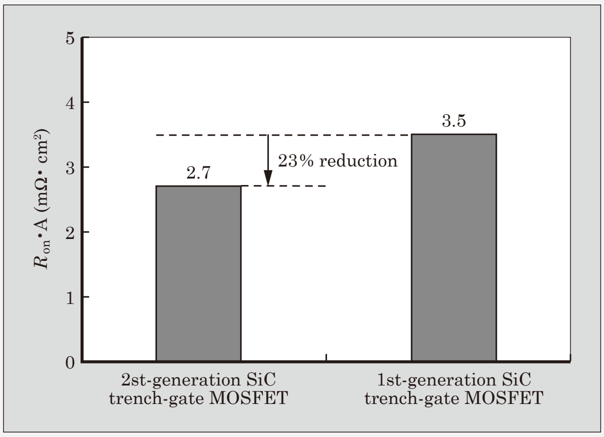

Fig.6 Comparison of the $R_{on}{\cdot}A$ for a 2nd-generation SiC trench gate MOSFET and 1st-generation SiC trench MOSFET

uses a laminated structure for the main terminal to reduce internal inductance.

Figure 6 shows a comparison of the specific on-resistance $R_{on}{\cdot}A$ for a 1,200-V 2nd-generation SiC trench gate MOSFET and 1st-generation SiC trench MOSFET. The 2nd-generation SiC trench gate MOSFET utilized smaller design rules for the cell pitch. This enabled it to reduce $R_{on}{\cdot}A$ by 23% and achieve lower conduction loss compared to the 1st-generation MOSFET.

We used simulations to confirm that the newly developed All-SiC module reduces inverter generated loss by 59% at a carrier frequency of f_c = 5 kHz and 63% at f_c = 20 kHz compared with the Si-IGBT module under the output current condition of $I_{O(rms)}$ = 200 Arms. This indicates that All-SiC modules equipped with 2nd-generation SiC trench gate MOSFETs will achieve lower generated losses, allowing for higher densities and capacities. Furthermore, the module's higher switching frequency makes it possible to use smaller passive components, which can facilitate the development of smaller power electronics equipment (Refer to "1,200-V 2nd-Generation All-SiC Modules" on page 216).

3.6 7th-generation "X Series" IGBT-IPM based on the compact "P644" package

An IPM is a high-performance IGBT module that integrates an IGBT gate drive circuit and protection circuit in an IGBT module consisting of an IGBT and FWD.

In order to achieve further miniaturization, higher efficiency, and higher power output in power conversion systems, we expanded our lineup of "X Series" IPMs[10] that apply 7th-generation chip and packaging technologies. In particular, we developed an IP that incorporates a brake circuit based on the industry's smallest class "P644" package, as shown in Fig. 7.

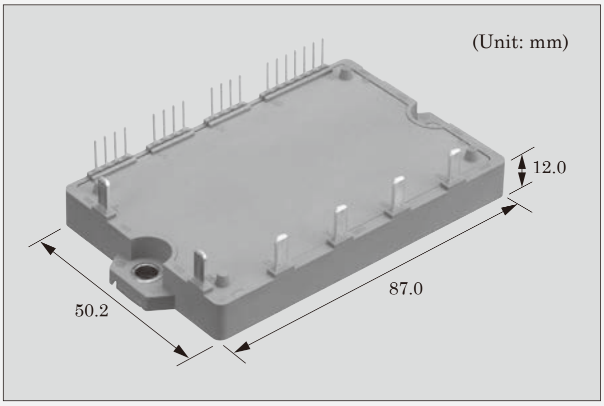

Fig. 7 External appearance of the "P644" X Series IPM

The X Series IPM P644 product line-up includes 650-V products with ratings of 50 A and 75 A, and 1,200-V products with ratings of 25 A and 35 A. The module footprint on the cooling unit is 12% smaller than the "V Series" IPM 7-in-1 "P636" package in the same rating range.

The X Series IPM substantially reduces generated loss compared to the V Series IPM. This was accomplished by thinning the drift layer through front-surface trench-gate structure miniaturization and thin wafer processing; utilizing 7th-generation chip technology[11] to improve the IGBT turn-off loss and conduction loss trade-off characteristics; and enhancing the gate drive circuit to reduce turn-on loss during switching. Furthermore, in order to enhance operation at high temperatures, the X Series IPM increases the maximum chip junction temperature T_{vjop} during continuous operation from 125 °C to 150 °C compared to the V Series IPM. This was accomplished by using high heat-resistant gel and highly reliable solder. The IPM also makes it possible for the IGBTs of braking components to operate independently during lower arm protective operation. This helps prevent overvoltage breakdown in the semiconductor devices. These technological enhancements give the X Series IPM P644 a smaller external shape and higher output current than the V Series IPM (Refer to "7th-Generation 'X Series' IGBT-IPM with 'P644' Compact Package" on page 221).

3.7 Line-up expansion of "XS Series" discrete IGBTs

There has been increasing demand to enhance the efficiency of the UPSs used for servers and data centers and the PCSs used for renewable energy applications. It is against this backdrop that Fuji Electric has been mass-producing and supplying XS Series discrete IGBTs having a blocking voltage of 650 V and 1,200 V, capable of improving the trade-off characteristics between conduction loss and switching loss and making UPSs and PCSs more efficient[12].

We recently enhanced the XS Series by develop-

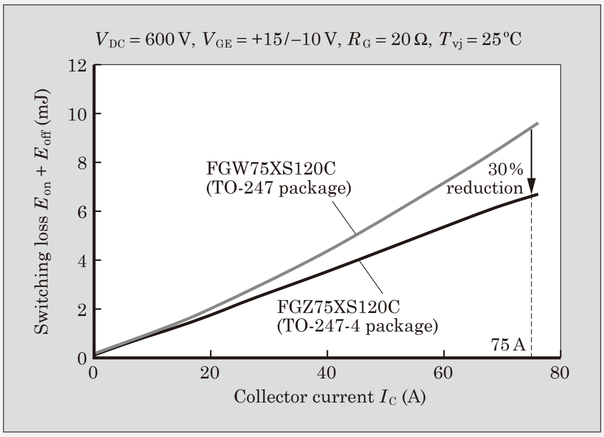

Fig. 8 Comparison of switching loss between the TO-247-4 package product and the TO-247 package product (I_C dependence)

ing a 1,200-V/75-A TO-247-4 package.

The IGBT chips used in this product series are based on 7th-generation X Series IGBTs. They feature a surface structure and FS layer optimized for UPS and PCS applications; a collector designed to suppress hole injection; and a thinner Si wafer. These improvements allow the product series to achieve better trade-off characteristics between conduction loss $V_{CE(sat)}$ and turn-off loss E_{off} than 6th-generation products[13].

As for the package, we utilized a TO-247-4 package, which is a conventional TO-247 package enhanced with a sub-emitter terminal. By incorporating the sub-emitter terminal and isolating the gate current from the collector current I_C, we were able to reduce the back electromotive force that was caused by applying collector current and emitter wiring inductance on the gate voltage during turn-on and turn-off. This enables the product to reduce its switching loss.

Figure 8 shows the I_C dependence of the switching loss of the TO-247-4 package product and TO-247 package product at a rating of 1,200 V/75 A. The switching loss (turn-on loss E_{on} + turn-off loss E_{off}) of the sub-emitter equipped TO-247-4 package was 30% lower than that of the TO-247 package at a rated current of 75 A (Refer to "'XS Series' Discrete IGBTs Line-Up Expansion" on page 227).

3.8 "FA1B00N" 4th-generation critical conduction mode power factor correction control IC

Switching power supplies are becoming more widely used as electronic devices become smaller and lighter. The harmonic current produced by switching power supplies can cause equipment and wiring facility operational failures and power factor degradation, while also increasing apparent power. To overcome these power supply harmonic current and power factor issues, it is common to use active filter type power factor correction (PFC) circuits. It is against this backdrop that Fuji Electric has commercialized ICs that control PFC circuits.

As energy savings is becoming increasingly important in electric equipment, PFC circuits are also being required to reduce their standby power and improve their efficiency over a wide range of load areas, including light loads.

In recent years, consumers have also been demanding more durable and less expensive electronic devices, such as LED lighting. This has additionally increased the demand for higher reliability and lower power supply costs in PFC circuits.

To meet these demands, we have developed the "FA1B00N" 4th-generation critical conduction mode (CRM) PFC control IC as a product that comes with enhanced protective functions and lower power supply costs, as opposed to our "FA5601N" CRM PFC control IC, which was designed to satisfy harmonic current regulations and is mainly used for LED lighting applications. Table 1 shows a comparison between the main functions of our recently developed FA1B00N and the conventional product.

Compared with conventional products, the FA1B00N includes a function to reduce overshoot at startup[14], a function to suppress PFC output voltage drop, and a function to protect against V_{CC} voltage overvoltage. Furthermore, we also improved the product's PFC output voltage control reference voltage V_{fb} accuracy and overcurrent detection voltage accuracy.

These enhancements have made it possible to reduce standby power, increase efficiency over a wide range of load areas including light loads, improve reliability and decrease power supply costs (Refer to "'FA1B00N' 4th-Generation Critical Conduction Mode Power Factor Correction Control IC" on page 231).

Table 1 Comparison of performance with conventional product

Item	FA1B00N	FA5601N
Turn-on timing detection	ZCD* winding	ZCD winding
Control method	On-width fixing control	On-width fixing control
Startup overshoot reduction function	Provided	Not provided
PFC output voltage reduction suppressing function	Provided	Not provided
Overvoltage protection for V_{CC} voltage	Provided	Not provided
V_{fb} reference voltage	2.5 V ± 1.0%	2.5 V ± 1.4%
Overcurrent detection voltage	0.65 V ± 2.0%	0.65 V ± 3.1%
Light load switching behavior	Maximum oscillation frequency limit	Maximum oscillation frequency limit

* ZCD: Zero current detection

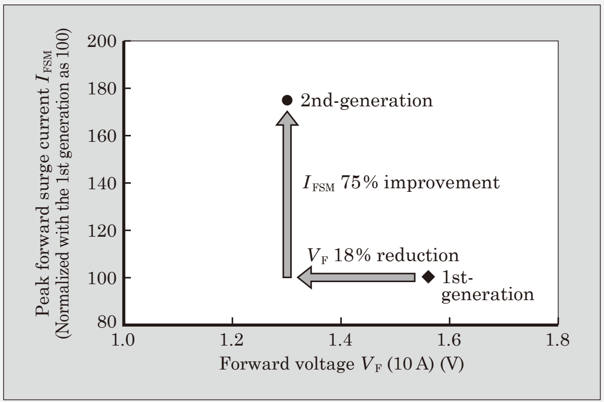

Fig.9 V_F-I_{FSM} characteristics in the 1st- and 2nd-generation 650-V SiC-SBDs

3.9 2nd-generation SiC-SBD

Fuji Electric has been mass-producing SiC-based Schottky barrier diodes (SBDs*8), planar gate MOSFETs and trench gate MOSFETs. These products are contributing to energy savings through their use in solar PCSs, industrial-use inverters and electrical rolling stock inverters.

We have recently developed a 2nd-generation SiC-SBD that has better operating characteristics and forward surge withstand capability than the 1st-generation product.

Compared with the 1st-generation SiC-SBD, the 2nd-generation SiC-SBD comes with an optimized Schottky junction that improves V_F by 3%, an optimized junction barrier Schottky (JBS) structure[15] and drift layer that improves drift resistance, and a thinner device thickness of approximately 33% that reduces substrate resistance. These enhancements reduced V_F by 18% and improved conduction loss.

Figure 9 shows the forward voltage V_F to forward surge withstand capability I_{FSM} characteristics of a 650-V SiC-SBD. Compared to the 1st-generation product, the 2nd-generation SiC-SBD reduces V_F (10 A) by 18%, increases I_{FSM} by 75%, and achieves lower loss and higher reliability. We started developing discrete products that use this SBD device in FY2020[16].

3.10 1.2-kV SiC superjunction MOSFET

To reduce characteristic on-resistance $R_{on} \cdot A$ in SiC-MOSFETs, it is necessary to reduce drift layer resistance, since it occupies a large portion of total MOSFET resistance. In recent years, there have been endeavors to use the parasitic diodes (body diodes) of MOSFETs as recirculation diodes. There has also been interest in the recovery characteristics of body diodes.

In light of these circumstances, Fuji Electric has been working to develop a SJ structure[17] that can effectively reduce drift layer resistance without impacting blocking voltage.

We created prototypes of a standard SiC-SJ-MOSFET (SiC-SJ), SiC narrow pitch SJ-MOSFET (SiC-narrow SJ pitch), and SiC-non-SJ-MOSFET (non-SJ) for comparison at a blocking voltage of 1.2 kV. Compared with the SiC standard SJ structure, the SiC narrow pitch SJ structure had a 50% thinner p-column width and a higher n-column concentration. The prototype MOSFETs were assembled using a TO-247 package. They were evaluated against each other in terms of their static characteristics and body diode recovery characteristics.

As for static characteristics, we evaluated the forward I-V characteristics by setting the gate voltage to 0 V at room temperature and at 175 °C. Figure 10 shows the $R_{on} \cdot A$ temperature dependence. $R_{on} \cdot A$ for the standard SiC-SJ-MOSFET and SiC narrow pitch SJ-MOSFET was lower than that of the SiC-non-SJ-MOSFET, resulting in a lower temperature dependence as well. Furthermore, the SiC narrow pitch SJ-MOSFET had the lowest $R_{on} \cdot A$ at 175 °C. This indicated to us that the resistance of the SiC-SJ-MOSFET could be further reduced by increasing the n-column concentration and narrowing the pitch. This enabled us to improve other static characteristics (blocking voltage and body diode I-V characteristics) and body diode recovery characteristics, thereby facilitating use in inverter circuit applications.

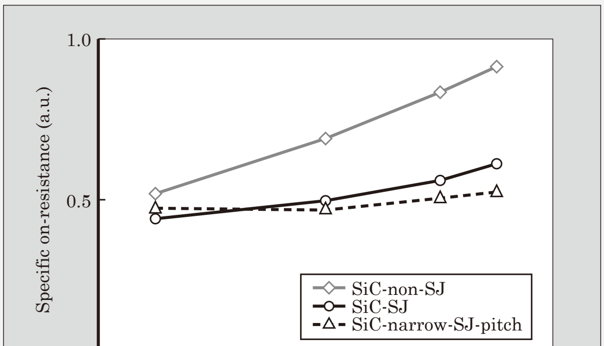

Fig.10 Characteristic on-resistance temperature dependence

***8 SBD:**

This is an acronym 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 minority carriers, SBDs, which operate only with majority carriers, speed up reverse recovery and reduce reverse recovery loss.

This research was conducted in a project undertaken with the joint research body Tsukuba Power Electronics Constellations (TPEC) (Refer to "1.2-kV SiC Superjunction MOSFETs" on page 237).

4. Postscript

In this paper, we described some of Fuji Electric's latest achievements in the development of power semiconductors. Fuji Electric has been engaged in innovating energy technologies since its founding and carries out its management policy based on the core pillar of "innovating electric and thermal energy technologies that contribute to realizing a responsible and sustainable society." In this regard, power electronics technology is playing a crucial role in addressing increasingly important environmental issues such as achieving energy savings and a low-carbon society. We are committed to innovating power semiconductor technologies, since they are key devices used in power electronics and can contribute to achieving a sustainable society.

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