Power Semiconductors Contributing to Mobility and Energy Management

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1. Introduction

Global efforts toward achieving carbon neutrality by reducing carbon emissions are accelerating, and Japan and other countries around the world have established specific goals to reduce greenhouse emissions. Having included in our corporate philosophy our intentions to “contribute to prosperity,” “encourage creativity,” and “seek harmony with the environment,” Fuji Electric has established the “Environmental Vision 2050,” which aims to realize a “decarbonized society,” “recycling-oriented society,” and “a society that is in harmony with nature” through the spread and expansion of innovative clean energy technologies and energy-saving products, with our role in the realization of a sustainable society through energy and environment businesses as a pillar of our management policies.

In particular, the key to the realization of a decarbonized society is the expansion of vehicle electrification and the efficient use of electrical power, and power electronic equipment is indispensable in achieving these goals. As key devices for power electronic equipment, power semiconductors are becoming increasingly promising.

2. Fuji Electric’s Power Semiconductors

Fuji Electric develops a wide range of power semiconductors to address market demand. Figure 1 shows examples of the applications of Fuji Electric’s power semiconductors.

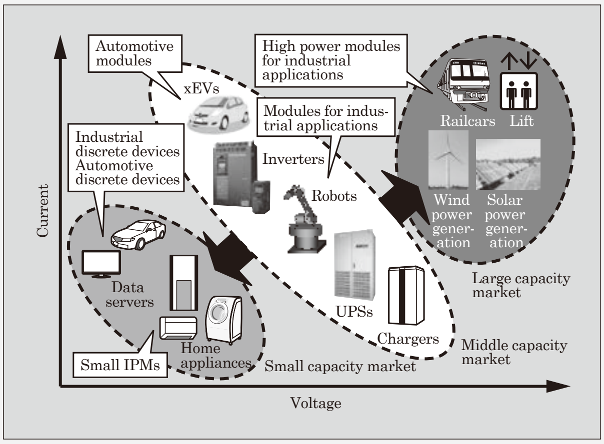

Fig.1 Examples of the application of Fuji Electric power semiconductors

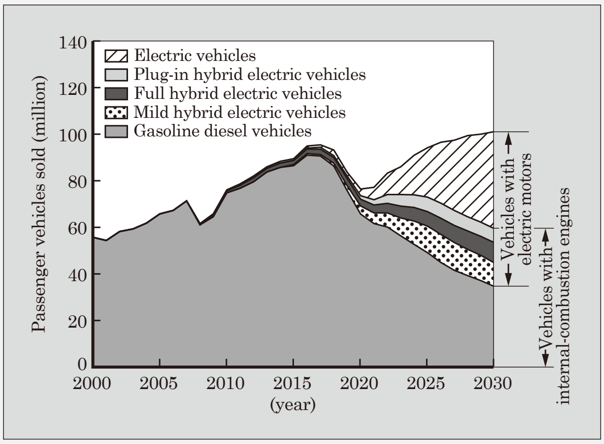

Fig.2 Estimated sales of passenger vehicles by power source (Prepared by Fuji Electric)

2.1 Automotive field

Figure 2 shows the expected global sales for passenger vehicles by power source. As indicated by this chart, sales of electric motor vehicles are expected to continue growing. Fuji Electric has been developing and expanding the mass-production of automotive insulated gate bipolar transistor (IGBT)*1 modules for motor control, as well as power semiconductor products for the power conversion control of chargers and DC power supplies.

However, internal combustion engines are expected to remain in use as a component of hybrid electric vehicles and others with a focus on environmental performance. For such applications, Fuji Electric develops and releases automotive products, including intelligent power switches (IPSs) used to perform on-off control of the driving current for the hydraulic valves in engines and transmissions, the intake and exhaust systems in gasoline engines, pressure sensors used for the hydraulic pressure control of transmissions, power steering and brak-

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ing mechanisms, and one-chip igniters used for ignition control of gasoline engines, and in this way, we contribute to the reduction of CO_2 emissions through efficient engine combustion and other achievements.

2.2 Industrial field

For industrial uses, Fuji Electric offers low, medium and high-power rating products.

We develop and release low-power rating products, including intelligent power modules (IPMs)*2 used for driving the motors of electrical appliances such as air conditioners. We also develop and release discrete*3 IGBTs mainly used for power conversion equipment, such as low-power rating power conditioning systems (PCSs) and uninterruptible power systems (UPSs). Furthermore, we develop and release power ICs for controlling the switching power supplies of LED lighting and other electronic equipment.

In the medium-power rating product field, we develop and mass-produce industrial IGBT modules to be used in general-purpose inverters, machine tools, servo motor control for robots, motor control for business-use air conditioners, and power conversion equipment in UPSs for data centers. In this field, the demand is expected to rise as investments are made in automation to address labor shortages and improve productivity.

In the high-power rating product field, we develop and release IGBT modules for power conversion equipment for renewable energy generation, including wind power and mega solar, and variable speed drives for motors in railcars.

In addition to these products, Fuji Electric develops and releases silicon carbide (SiC)*4 devices, which are next-generation power semiconductors with better characteristics compared with existing silicone (Si) devices, such as low loss, high breakdown voltage, and high temperature operation.

3. The State of Power Semiconductor Development

This chapter showcases Fuji Electric's latest achievements in the development of power semiconductors.

3.1 Packaging technologies that achieve high power density in IGBT modules for xEVs

Automotive IGBT modules used for controlling the driving motors of electrified vehicles (xEVs) must be made compact enough to fit in limited spaces and also require higher power density to meet the demand for higher output. As a result of efforts to develop the semiconductor devices and packaging technologies required to achieve higher power density in power modules, Fuji Electric has developed an industry-leading, ultra-compact IGBT module for xEVs, the "M677" made for 100-kW class inverters as a key component of xEV power trains (see Fig. 3).[(1),(2)] To achieve reduced size and increased output power, we have equipped the M677 with a 7th-generation reverse conducting IGBT (RC-IGBT)*5, and in order to reduce conduc-

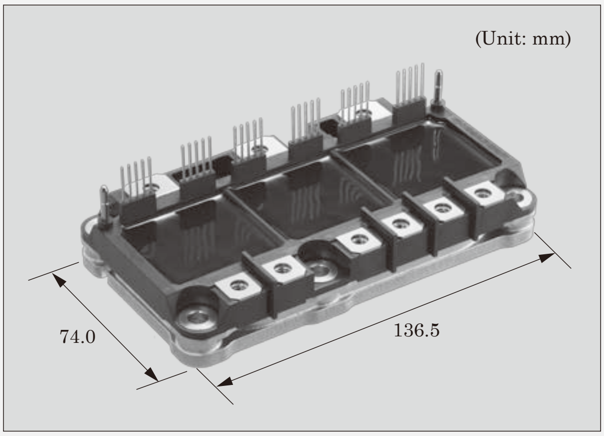

Fig. 3 "M677" IGBT module for xEVs

***1 IGBT**

IGBT is an initialism for insulated gate bipolar transistor. It is a voltage controlled device with a gate that is insulated with an oxide insulation layer, the gate structure of which is the same as that of MOSFETs. It makes use of the advantages of MOSFETs and bipolar transistors. Its bipolar functionality enables the use of conductivity modulation, and it features both high switching speed and high-voltage resistance and low on-state resistance, which are sufficient for inverter applications.

***2 IPM**

IPM is an initialism for intelligent power module. These power modules have built-in driver circuits and protection circuits in addition to power semiconductor components. In addition to reducing the burden of circuit design, the use of dedicated drive circuits maximizes the performance of the power semiconductor components.

***3 Discrete**

The word discrete is used to describe power semiconductor devices that consist of a single power semiconductor IGBT or MOSFET or a circuit called a 1 in 1, in which diodes are inserted in anti-parallel configuration. Pin layouts are determined for general purpose uses, with variations such as TO-220 and TO-3P. These devices are used to control circuits of small capacities, including PC power supplies, uninterruptible power systems, liquid crystal displays, and small motors.

***4 SiC**

SiC is a compound of silicon (Si) and carbon (C). There are a variety of SiC polymorphic crystal structures, such as 3C, 4H, and 6H, and the compound is known as a wide gap semiconductor with bandgaps of 2.2 to 3.3 eV. Due to its high electric breakdown voltage and heat conductivity, it is useful for power devices, and it is increasingly being used to produce devices that feature high breakdown voltage, low loss, and high-temperature operation.

tion loss, we reduced the Si wafer thickness and optimized the surface structure. As a measure to address the tendency for the internal temperature to rise in conjunction with the reduction of thermal capacity caused by the reduced chip volume, we use copper lead frames, which have higher heat dissipation properties than conventional aluminum wires. This results in a 40% improvement compared with the predecessor product in terms of the short-circuit failure energy that damages the chip due to thermal runaway attributable to, for example, leak current.

Moreover, we confirmed that this package is sufficiently resistant to electromigration, which has the potential to cause increases in wiring resistance and thermal resistance if the module is used in high power density or high temperature environments. (Refer to page 175, "Package Technology for achieving High Power Density in IGBT Modules for xEVs").

3.2 Line-up expansion of the 2nd-generation 1,700-V All-SiC modules

Since the power electronic equipment used in 690-V AC motor drives and railcars operate at a DC bus voltage of 900 to 1,100 V, there is demand for power semiconductors rated at 1,700 V. In addition, higher DC bus voltages are required in the renewable energy sectors, including solar and wind power generation, to improve power generation efficiency and reduce costs.[3] For use in industries in which high withstand-voltage power semiconductors are sought, Fuji Electric previously developed a 1,700-V All-SiC module equipped with a 2nd-generation SiC trench gate metal-oxide-semiconductor field-effect transistor (MOSFET)[4], and has now added a newly developed product to this line-up.

Compared with the 3-level NPC circuit configured with the predecessor 1,200-V Si-IGBT, the 2-level circuit configured with the newly developed 1,700-V All-SiC module has achieved a 69% reduction in the total loss when applied to power electronic equipment with a DC bus voltage of 1,100 V (see Fig. 4). In addition to the expected high efficiency, switching from a 3-level circuit configuration to a 2-level one can reduce the number of power semiconductor devices, which is expected to increase the reliability of power electronics equipment and reduce costs.

SiC-MOSFETs are capable of much faster switching than Si-IGBTs, but have the disadvantage of causing high surge voltages during high-speed switching due to the wiring inductance inside the module. For the All-SiC module, the new product in the line-up, we have reduced the wiring inductance by 24% by changing the internal structure[4], but the Si-IGBT can be replaced with this product easily because its external shape and terminal layout are still compatible with the 7th-generation "X Series" IGBT's 2-in-1 package "M276" (Refer to page 180, "Line-Up Expansion of 2nd-generation 1,700-V All-SiC Modules").

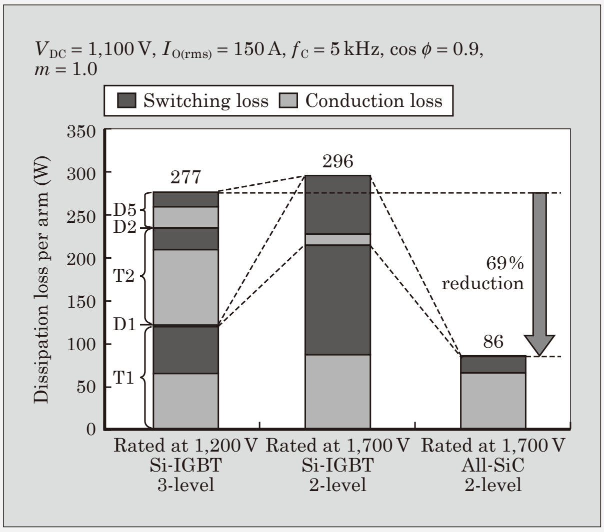

Fig.4 Loss comparison with 3-level and 2-level circuits

3.3 Line-up of compact 7th-generation IGBT-IPMs with RC-IGBTs

As the adoption of factory automation and communication devices including mobile phones has become more widespread in recent years, the demand for servo systems used for industrial robots, machine tools, and other applications has increased. Space saving is a critical requirement for such devices, and to achieve this, the size of the power semiconductors used in these devices must also be reduced, the key to which is high temperature operation and low loss. In addition, they are required to be highly reliable to prevent sudden malfunctions.

IGBT-intelligent power modules (IPMs), which are IGBT modules equipped with a control IC for driving the IGBT gate as well as a protection function, have highly reliable diverse applications, such as numerical control (NC) machine tools, robots, and elevators.

To achieve low power dissipation, the 7th-generation IGBT-IPM[5]-[8], which is the newest generation of IGBT-IPMs, employs 7th-generation chip technology, in which the IGBT trench gate structure is made finer and the drift layer is made thinner

***5 RC-IGBT**

RC-IGBT is an initialism for reverse-conducting IGBT. They are components that integrate the IGBT and FWD into a single chip. The IGBT and FWD sections operate alternately, resulting in excellent heat dissipation and reducing the number of chips in the module, leading to smaller IGBT modules and higher power density.

through the use of thin wafer processing technology, as well as a new control technology for driving the IGBT gate. Furthermore, it can operate under high temperatures due to 7th-generation packaging technology, which includes high heat resistant gel and highly reliable solder. In order to meet the demand for further size reduction and high reliability, we have added products that make use of RC-IGBT chips to 7th-generation IGBT-IPM line-up. The RC-IGBT chip combines the IGBT chip and the free wheel diode (FWD)*6 chip on a single chip.

Reduction of package size is now possible with the use of the RC-IGBT, which has reduced the total chip footprint by 33% compared with the 6th-generation IGBT-IPM, which is configured with independent IGBT and FWD chips. In addition, 7th-generation chip technologies and a new control technology have reduced power dissipation by approximately 7% compared with the 6th-generation IGBT-IPM. With the reduction in chip footprint and power dissipation, the newly developed compact package "P639" has reduced the footprint of the copper base, which dissipates chip heat by 33% compared with the predecessor, and has thereby reduced the package's area by 27%. Furthermore, the ΔT_{vj} power cycling lifetime, which is a typical lifetime characteristic of power modules, has also increased through the use of the RC-IGBT. The predecessor 6th-generation IGBT-IPM has the IGBT and FWD alternately repeating heating and cooling, whereas the RC-IGBT integrates the IGBT region and the FWD region into one chip, and therefore, the temperature change ΔT_{vj} of the entire chip is smaller than that of the independent chips. Because of this, power cycling lifetime ΔT_{vj} in relation to the junction areas' wear-out failure caused by temperature changes is estimated to be approximately 10 times longer than that of the 6th-generation model during operation at an output frequency of 1 Hz.

As an example, if the predecessor "P629" used in a 60-mm width back-fin type servo amplifier is replaced by the newly developed P639, the servo amplifier's casing can be reduced in width to the order of 46.5 mm, which is a reduction of approximately 20% (see Fig. 5) (Refer to page 185, "Line-Up of Compact 7th-Generation IGBT-IPMs with RC-IGBTs").

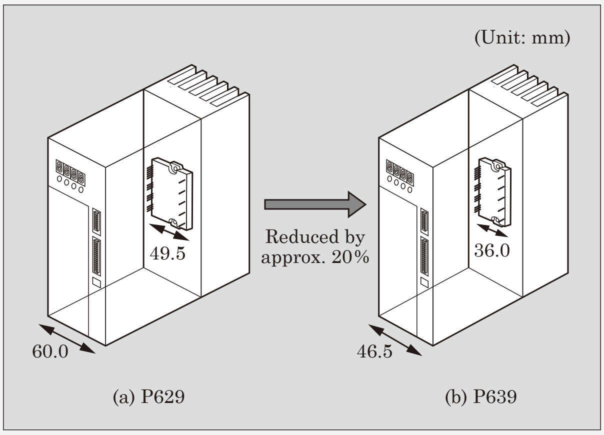

Fig.5 Schematic diagram of a back-fin type servo amplifier

3.4 3.3-kV 7th-generation "X Series" IGBT chip technology

High-speed rail vehicles emit far less CO_2 than airplanes, which achieve the same function of long-distance transport. For this reason, in recent years, the introduction of high-speed rail has been increasing not only in Japan but also around the world. Railway vehicles use IGBT modules to drive their motors. To reduce CO_2 emissions, IGBT modules require further reductions in power loss. In addition, to reduce the power consumption of high-speed trains themselves, the weight reduction of the vehicles and their on-board equipment is important and requires IGBT modules that can facilitate the size and weight reduction of the system.

Fuji Electric has developed the 3.3-kV SiC hybrid high power module (HPM), which combines the newest-generation "X Series" IGBT and a Schottky barrier diode*7 (SiC-SBD), thereby achieving significant reductions in power loss.[9]

The newly developed 3.3-kV X-Series IGBT chip (X-IGBT) has a more optimized surface structure and a thinner n^- drift layer, which, compared with the predecessor product, results in a 1.0 V reduction in collector-emitter saturation voltage $V_{CE(sat)}$ at rated current, which is an indicator of conduction loss.

Figure 6 shows the relationship between the turn-off loss E_{off} and $V_{CE(sat)}$. With the X-IGBT, $V_{CE(sat)}$, when compared at the same E_{off}, has been

***6 FWD**

FWD is an initialism for free wheeling diode. It is also called a reverse-conducting diode. This component is connected parallel to an IGBT in power conversion circuits, such as inverters, and are responsible for returning the energy stored in the inductance to the power supply side when the IGBT is turned off. P-intrinsic-N (PiN) diodes are used mainly for Si FWDs. They are bipolar diodes that also use minority carriers, and therefore, they enable the reduction of voltage drop during forward current flow, but they also cause larger reverse recovery losses.

***7 SBD**

SBD is an initialism for Schottky barrier diode. They are diodes with rectifying action that uses the Schottky barrier created by the junction of a metal and a semiconductor. Due to their excellent electric characteristics, studies on their application in FWDs for SiC-SBDs are underway. In comparison with PiN diodes that also use minority carriers, SBDs operate with majority carriers only, and have faster reverse recovery speed and lower reverse recovery loss.

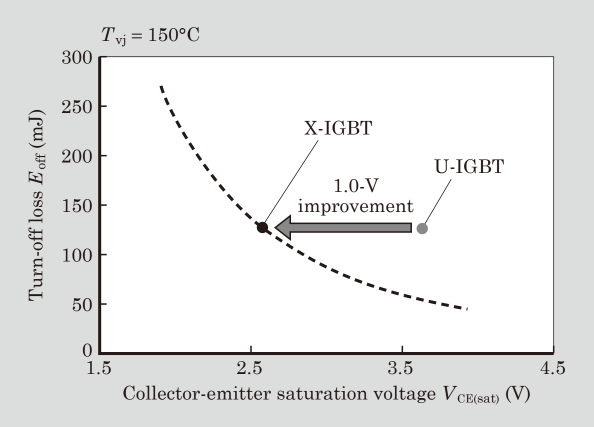

Fig.6 Relationship between the turn-off loss and the collector-emitter saturation voltage

reduced by 1.0 V compared with the predecessor product. In addition, the finer surface structure improved the control performance with gate resistance dv/dt, di/dt during turn-on, resulting in improvements in turn-on loss E_{on}.

The 3.3-kV SiC hybrid HPMs equipped with this IGBT are employed in high-speed rail vehicles that are now in commercial service, and the IGBT is contributing to reductions in power consumption of high-speed rail vehicles and the size and weight reduction of equipment (Refer to page 190, "3.3-kV 7th-Generation "X Series" IGBT Chip Technology").

3.5 "FA8C00 Series" of 7th-generation PWM power supply control ICs

Energy-saving requirements for switching power supplies used in electronics are growing stricter, and in particular, improvements in power conversion efficiency for low loads are urgently required as the use of networks expands and more systems are in constant operation. In emerging economies, slow progress in infrastructure development causes commercial power supply (AC power supply) voltage to fluctuate frequently. This causes high voltages in the AC power supply, and damages to power supply units that occur when the input voltage range of power supply units is exceeded have become a problem. Moreover, there is an urgent demand to reduce the number of components in power supplies in response to the continued need for low cost electronic equipment.

Fuji Electric has recently developed the "FA8C00 Series," which can further improve power conversion efficiency at low loads on power supply systems compared with its predecessor[10], support high AC input voltages, and reduce the number of power supply components. Table 1 shows a functional overview of the FA8C00 Series.

In order to improve power conversion efficiency at low loads, a conventional method of reducing MOSFET switching losses has been employed by performing burst operation, in which continuous switching operation and switching stoppage are repeated. To further improve power conversion efficiency in this operation, it is effective to optimize the output pulse width to match the power supply to avoid generating output pulses for driving MOSFETs with narrow widths. With the addition of a function to set the minimum output pulse width according to the power supply, the FA8C00 Series can now improve power conversion efficiency at low loads.

Table 1 "FA8C00 Series" function overview

Item	Conventional product	FA8C00 Series
Minimum output pulse width select function	Not provided	Available
Maximum applied voltage of the high AC input voltage terminal	650 V	710 V
IC output voltage clamp function	Not provided	Available (16 V)
External regulator	Required	Not required (8 parts reducible.)

In addition, we have improved the start-up device used in the internal circuit of the high voltage AC input terminal (VH terminal) for utility power connection. Increasing the rated maximum input voltage of the device to 710 V has allowed it to prevent the breakdown caused by the fluctuation of the AC power source.

On the other hand, the rated voltage of the gate terminal of MOSFETs driven by the power supply IC is 20 to 30 V, and applying a higher voltage can damage the MOSFETs. To prevent this, the previous product required an external regulator circuit to limit the VCC terminal's voltage, which is the power supply voltage of the driver circuit for driving the MOSFET, to 20 V or below. In the new series, the FA8C00, the function of clamping the output terminal's voltage inside the IC has been incorporated so that the gate voltage output from the IC is regulated at 16 V even if the VCC terminal's voltage exceeds 30 V. This improvement has eliminated the need for an external regulator circuit and facilitated the reduction of power supply parts (Refer to page 194, "'FA8C00 Series' 7th-Generation PWM Power Supply Control ICs").

3.6 Auto-zero amplifier technology for IPS

Fuji Electric has been developing and releasing IPSs[11],[12], which are current drive devices to operate the solenoid valves for controlling automotive transmission systems. The size reduction of IPSs and the integration of peripherals into one chip are measures that can reduce the size of electronic control unit (ECU) boards, thereby providing vehicles with more interior comfort. Improvements in the current detection accuracy of IPSs can improve fuel efficiency. When the IPS and the shunt resistor for current detection, which has been previously placed separately, are integrated into a single chip, the Joule heat generated by the shunt resistor causes the chip temperature to rise. The remedial suppression of this rise in chip temperature requires the shunt resistance to reduce to one-fourth of the conventional value. Although accommodating the resistance reduction while maintaining the input current-amplifier output voltage characteristics requires the increase of the differential gain of the amplifier to four times the conventional gain, this measure causes the disadvantage of increased amplifier output errors and worsened current detection accuracy. To resolve this, we have developed the auto-zero amplifier technology that self-corrects the offset voltage at specified intervals.

Figure 7 shows the evaluation results of an actual device using an auto-zero amplifier. In this evaluation, we set the gain to be 32 times, which is four times greater than the conventional amplifier, considering the need to reduce the shunt resistor's resistance to one-fourth the conventional resistance. To the amplifier input, we applied a load current of 1 A and a voltage that allows the shunt resistance to be one-fourth the conventional resistance. Under these conditions, we conducted an evaluation of current detection accuracy within the temperature range of −40 °C to +175 °C. The target value for current detection accuracy was set to be ±3.1% or lower, which is the same as 5th-generation IPSs(13). The results showed that it met the target specification of the 5th-generation IPS despite the fact that we set the gain to be 32 times, which is four times greater than with the conventional amplifier.

This suggests that the mounting footprint of ECU boards can be expected to be reduced while preserving a current detection accuracy that is equivalent to the conventional level (Refer to page 199, "Auto-Zero Amplifier Technology for Intelligent Power Switches").

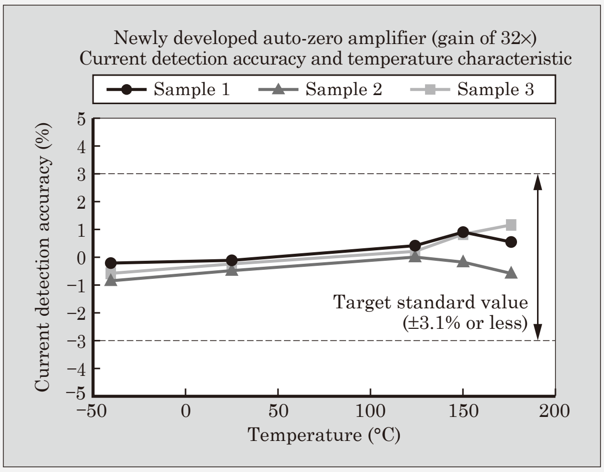

Fig.7 Evaluation results of an actual device using an auto-zero amplifier

3.7 Trench SBD-integrated SiC-MOSFET to suppress bipolar degradation

SiC has a higher breakdown electric field than Si and is capable of reducing the resistance of devices if the drift layer, which holds voltage, is made thinner and higher in carrier concentration. This means that it can contribute to loss reduction in power conversion equipment. Furthermore, SiC, which also has high heat conductivity and a wide band gap, enables devices to operate under high temperatures, allowing cooling systems to be simplified. With this advantage, it plays a role in the size and weight reduction of power conversion equipment.

On the other hand, loss is increased due to the increase in on-state voltage (bipolar deterioration) when current flows to the body diode functioning as the reverse-conducting device of the SiC-MOSFET. To counter this problem, we considered the integration of the SBD and MOSFET into one chip (trench SBD integration) as the bipolar deterioration suppression method.

In a Tsukuba Power-Electronics Constellations (TPEC) project, Fuji Electric has established the technology for forming a trench SBD in SiC trench gate MOSFETs. In the case of built-in trench SBDs, if trench SBDs are formed planarly between trench gates, the cell pitch must be wider than in conventional SiC trench-gate MOSFETs, resulting in increased conduction loss. In the project, we managed to form a trench SBD in the conventional SiC trench gate MOSFET, thereby achieving SBD integration without widening the cell pitch. In addition, narrower cell pitch caused less bipolar degradation and suppressed the loss increase.

Figure 8 shows the amount of change ΔV_F versus applied forward current density. In the graph, ΔV_F increases due to the bipolar current in the case of device B, which has a larger cell pitch, whereas

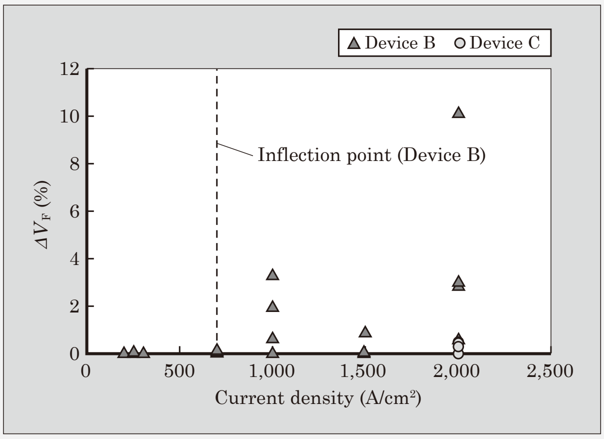

Fig.8 ΔV_F versus applied forward current density in the case of device C, which has a relatively narrower cell pitch, bipolar deterioration is suppressed, demonstrating that ΔV_F does not increase before a current density of 2,000 A/cm^2, which is the upper limit of the power supply system used. We also confirmed that bipolar deterioration can be suppressed stably regardless of the epitaxial substrate's threading basal plane dislocation (BPD) density (Refer to page 204, "Trench SBD-Integrated SiC-MOSFET To Suppress Bipolar Degradation").

4. Postscript

The above is a summary of Fuji Electric's latest developments in the field of power semiconductors. Since its foundation, Fuji Electric has pursued innovation in energy and environmental technologies, making a wide range of contributions to the world in such fields as industrial and social infrastructure and automobiles. Above all, power electronics is a field of technology that drives the rapidly growing efforts toward energy saving, decarbonization, and other environmental solutions. Power semiconductors are key devices in the field of power electronics, and by continuing to innovate the technology, Fuji Electric will continue to contribute to the creation of a responsible and sustainable society.

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