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Power Devices

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Technical Reports

Precis

Mitsubishi Electric power modules which employ the latest chip and package technology realize ideal PE systems thanks to their high quality, low loss, excellent noise performance.

Overview

Author: *Hidenori Nishihara**

Latest Technology Trends and Prospects for Power Modules

In view of dwindling reserves, rising prices and the greenhouse gases produced by combustion, fossil fuels are rapidly being replaced by electricity in all sectors. Power electronics (PE) technologies are essential for converting power, and power devices are a vital part of this. Mitsubishi Electric Corporation provides a wide variety of power modules ranging from 100 watts to several megawatts by combining optimum semiconductor chips (e.g., IGBTs) and packaging technologies. These power modules are supplied to applications including agricultural, household, industrial, automotive, electric railway, and electric power sectors.

To satisfy the diversifying requirements for power modules of PE devices, Mitsubishi Electric has released the latest 7th Generation silicon (Si) and silicon carbide (SiC) chip technologies. We have combined this chip technology with the latest packaging technology to reduce the size and weight of modules, increase efficiency and package density, while also reducing electro-magnetic interference (EMI) and improving functionality.

Mitsubishi Electric power modules are ideal for high-reliability, high-efficiency PE systems thanks to their high quality, low loss, excellent noise performance, and simple user assembly.

**Senior General Manager, Power Device Works*

RC-IGBT Chip Technology for White Goods

Authors: *Tetsuo Takahashi** and *Takuya Yoshida***

1. Introduction

Today, power devices are used for various types of equipment such as industrial machinery, electric vehicles, and consumer appliances (e.g., air conditioners and refrigerators). Many of the main power devices currently used have IGBTs and FWDs, and their performance continues to be enhanced. The RC-IGBT, which combines an IGBT and FWD, is an example of development aiming at higher performance.

It is difficult to improve the performance of the RC-IGBT because the characteristics of both the IGBT and FWD must be taken into account simultaneously. However, the size of the chip can be reduced, so it is a key device for reducing the size and energy consumption of the latest power modules.

This paper introduces the second-generation RC-IGBT for consumer products and describes how its characteristics were significantly improved using Mitsubishi Electric Corporation's latest technologies.[1]

2. Structure of RC-IGBTs for Consumer Products and Applied Technologies

2.1 Basic structure of the RC-IGBT

The structure of the RC-IGBT consists of an IGBT and an FWD integrated into one chip. There is a trade-off relationship between the performance of the IGBT and FWD and fabrication cost.

The next section describes the technologies applied to the RC-IGBT for consumer products to improve its performance and suppress the cost at the same time.

2.2 Structure of the RC-IGBT and applied technologies

Table 1 lists the technologies of the latest second-generation RC-IGBT.

2.2.1 Optimization of the area ratio of the FWD region

The area ratio of the FWD region – the first item in the table above – is an important parameter that affects the power loss in the IGBT and FWD when each one is functioning. Figure 1 shows the dependency of the forward voltage drop (V_F) and the reverse recovery current (I_{rr}) on the FWD area ratio as an example.

As shown in Figure 1, V_F is in a trade-off relationship with I_{rr}, so the area ratio is optimized to minimize the total power loss depending on the application.

2.2.2 Review of the structure of the FWD

Generally, the FWD needs to be optimized in consideration of the forward voltage drop and reverse recovery characteristics as mentioned earlier.

To improve the characteristics of FWDs, the structure of the second-generation RC-IGBT is designed such that the current does not concentrate in a certain spot, which results in avoiding a rapid increase in the reverse recovery current and forward voltage drop.

2.2.3 Improvement of the layout of the IGBT and FWD

The layout of the second-generation RC-IGBT was designed such that heat is dispersed in the chip as much

Table 1 Design concept of the second-generation RC-IGBT

Item	Technology	Purpose
1	Optimization of the area ratio of the FWD region	Reduce the power loss.
2	Review of the structure of the FWD	Improve the trade-off between V_F and recovery.
3	Improvement of the layout of the IGBT and FWD	Optimize the heat radiation from FWDs.
4	Thinning of wafers	Reduce the power loss using the seventh-generation process.
5	Manufacturing method without lifetime control (Selectable depending on the application)	Reduce the variation in the characteristics and cost.

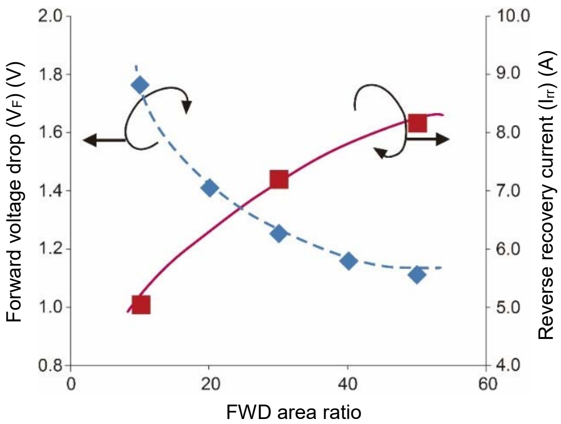

Fig. 1 FWD area ratio dependence of V_F and I_{rr}

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as possible. Figure 2 illustrates the layout of the IGBT and FWD. By dividing the FWD region in which the current is concentrated into small sections in the design, the temperature rise at a certain spot in the FWD can be reduced. Figure 3 shows the dependency of the reverse recovery current (I_{rr}) and surge forward current (I_{FSM}) on the size of the FWD for the same FWD area ratio. The figure shows that optimizing the size can significantly improve the I_{FSM}, which is an index of the FWD's current-carrying capacity, without significantly increasing the I_{rr} that affects the power loss.

Optimally dividing the FWD region greatly improved the FWD's heat dissipation in the second-generation RC-IGBT.

2.2.4 Thinning of wafers

CSTBT[2] technology using the seventh-generation IGBT process in which wafers are made very thin was applied to the RC-IGBT for consumer products. This greatly improved its characteristics.

2.2.5 Manufacturing method without lifetime control

To reduce the cost and characteristic variation, a structure without lifetime control was applied to a wide carrier frequency range by comprehensively improving the characteristics. A structure with lifetime control was used for the section on the high-speed side to satisfy various applications of consumer products.

3. Characteristics of RC-IGBTs for Consumer Products

3.1 Characteristics of the chip

The characteristics of the second-generation RC-IGBT combined all technology mentioned before were greatly improved compared to those of previous-generation devices.

Figure 4 shows the trade-off characteristics between the collector-emitter saturation voltage (V_{CEsat}) and the turn-off loss (E_{off}) in IGBT mode. Figure 5 shows the trade-off relationship between the forward voltage drop (V_F) and the recovery loss (E_{rr}) in FWD mode. Both characteristics were greatly improved compared to the previous-generation RC-IGBTs.[3]

Figure 6 compares the loss in inverters for products, which was normalized by the effective area of the chip (Tj = 125°C, fc = 5 kHz). The loss in the new structure was reduced to approximately one-third that of the previous structure.

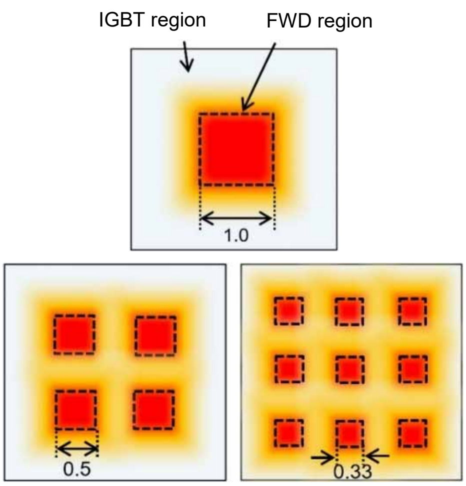

Fig. 2 Design concepts of FWD layout: optimizing the thermal distribution

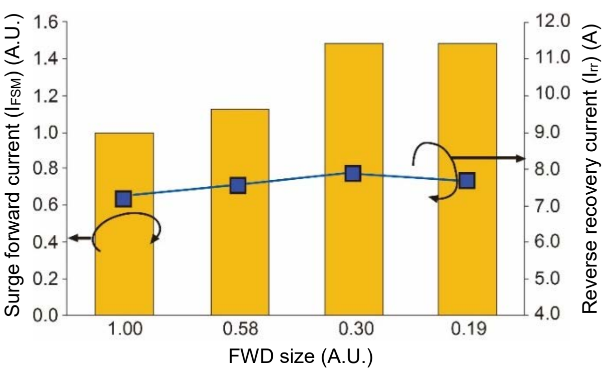

Fig. 3 FWD size dependence of I_{FSM} and I_{rr}

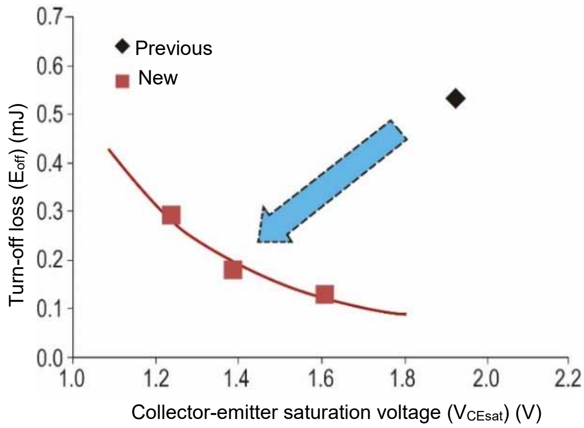

Fig. 4 Trade-off relationship between V_{CEsat} and E_{off}

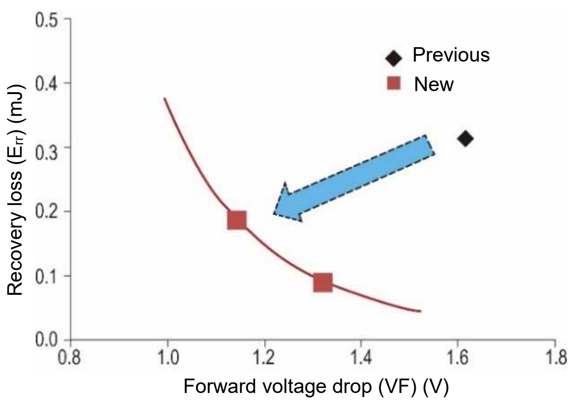

Fig. 5 Trade-off relationship between V_F and E_{rr}

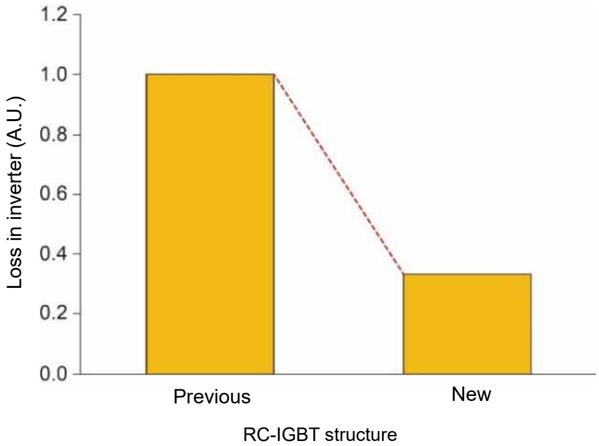

Fig. 6 Comparison of total inverter loss between previous RC-IGBT and second-generation RC-IGBT

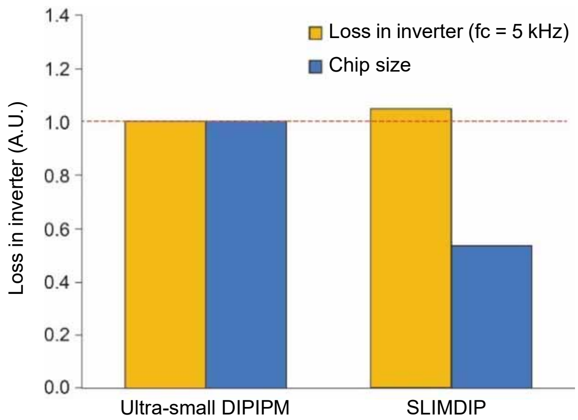

Fig. 7 Comparison of total inverter loss and chip size between the latest DIPIPM and SLIMDIP

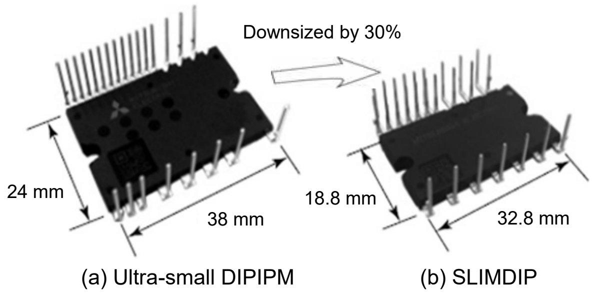

Fig. 8 Photograph of the latest DIPIPM and SLIMDIP

3.2 Characteristics of products

The module size of the SLIMDIP series with the second-generation RC-IGBTs was greatly reduced.[4]

Figure 7 shows the ratio of the loss in the inverter between an ultra-small DIPIPM for which an IGBT and FWD are separately mounted and a SLIMDIP module of the same current rating along with the ratio of the area occupied by the mounted chips. The region occupied by the chip in the SLIMDIP module was reduced to approximately half compared to the ultra-small DIPIPM, thus allowing the power module to be approximately 30% smaller (Fig. 8).

4. Conclusion

The power loss in 600V RC-IGBTs developed for consumer products was reduced to approximately one-third compared to the previous-generation devices and the size of the chip was reduced to approximately half. This reduction has led to commercialization of the SLIMDIP with a 30% smaller package.

We are presently developing the third-generation RC-IGBT with improved characteristics. We will continue contributing to the advancement of power electronics and the realization of an energy-saving society through the technical development and commercialization of devices.

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Development of Package Structure for High-Temperature Operation

Author: *Kenta Nakahara**

1. Introduction

In recent years, power electronics that efficiently convert electric energy have been applied to an increasing number of sectors such as the consumer electronics, industrial, electric railway, automobile, PV power generation, and wind power generation sectors, aiming at environmental protection and an energy-saving society. Among such power electronics devices, power modules work an important role of controlling electric currents. Therefore, power loss during operation and the package size need to be reduced while achieving high power density. Accordingly, silicon carbide (SiC) is expected to be used for next-generation power devices. SiC devices can operate faster than conventional silicon (Si) devices and their power loss is smaller, so the properties of power modules can be remarkably improved. In addition, SiC devices can operate at high temperatures, so reducing the package size can reduce the size of the power modules and the units on which they are mounted.[1)]

We improved the heat resistance of various parts (e.g., bonding and sealing agents) and developed new processes in the course of developing the packages, which improved the reliability of bonding when applying high temperature cycling, in particular, and extended the bonding lifetime. These improvements have realized high-quality, highly reliable packages. We have used such technologies to develop high-temperature operation packages for which the chips' operation temperature (Tjop) is 175°C or higher.

2. Structure of High-Temperature Operation Packages

Figure 1 shows the main structure (diagram) of the newly developed power module. As the structure of the new package type that is expected to operate at high temperatures (175°C or higher), a heat-resistant substrate is bonded to the surface of a baseplate with heat-resistant solder. A chip is bonded to the surface of the heat-resistant substrate using Ag sintering. An electrode on top of the chip is connected to the pattern on the substrate with a wire (e.g., Al). Another electrode, which provides electric connection to the outside, is connected to the pattern on the heat-resistant substrate by ultrasonic (US) bonding. A case is fitted to the baseplate. The inside of the case is filled with a heat-resistant sealing material.[2)]

The Ag sinter bonding, heat-resistant substrate, heat-resistant solder material, and US bonding technology for electrodes as elemental technologies for packages that enable high-temperature operation are introduced next.

3. Elemental Technologies for Packages

3.1 Ag sinter bonding technology

Assuming that the chips will be operating at high temperatures, there is a limit due to the properties of the soldering material used as bonding under the chips. Therefore, a new bonding material and process for such material are required. We developed a sinter bonding

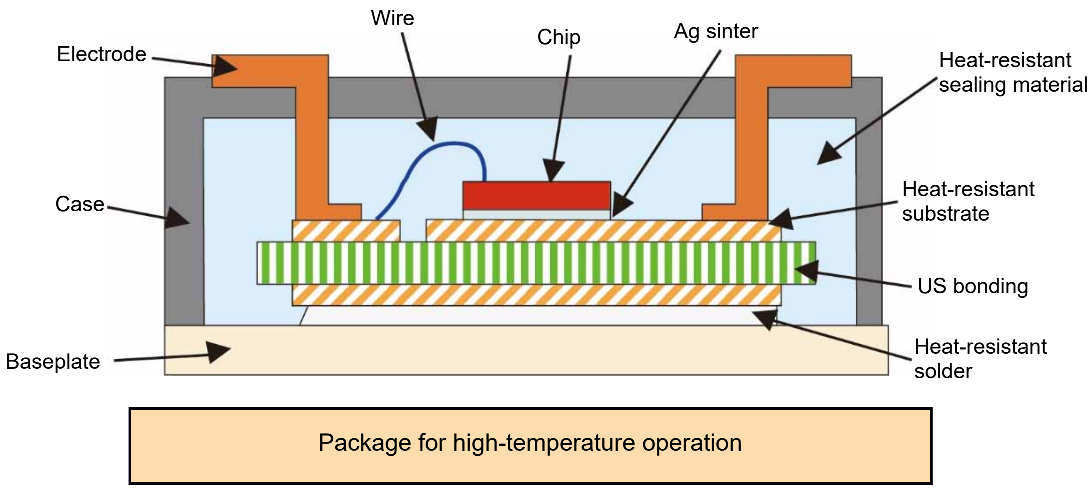

Fig. 1 Main structure of new package

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process using Ag particles, which ensures excellent heat resistance and high quality.[3] In the Ag sinter bonding process, multiple chips can be mounted and can be bonded at once. Therefore, the chips for the new package type can be made smaller than those of the conventional package type. We considered increasing the density in the arrangement of 4×3 chips by batch bonding. Figure 2 shows a scanning acoustic tomography (SAT) image after batch bonding by Ag sintering. Figure 3 shows the cross section of the bonding. The SAT image and the cross section show no voids or cracks at the bonding, so the bonding condition is good. As a result, for the new package type, the density of chips is increased by Ag sintering and the quality of bonding is high.

3.2 Heat-resistant substrates

Previously, aluminum nitride (AlN) ceramic was used for our substrates. We considered heat-resistant substrates to which silicon nitride (Si_3N_4) ceramic was applied as a new material. A thermal cycle test was carried out to evaluate the heat resistance. In the test, the temperature of AlN and Si_3N_4 substrates was changed from −40°C to 175°C (⊿T = 215 K) to see how cracks would progress at the ceramic sections and joints with the patterns on the substrates. As shown in Fig. 4, a crack progress to the ceramic section of the AlN substrate, but no cracks appeared on the Si_3N_4 substrate even after 600 cycles, so Si_3N_4 substrates have high reliability and excellent heat resistance.

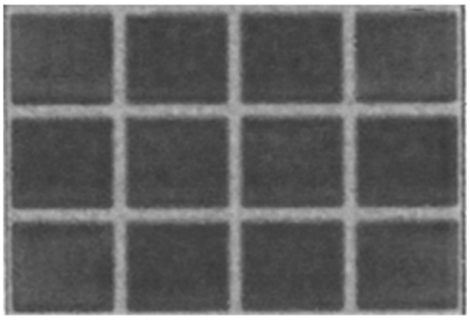


Fig. 2 SAT image of batch bonding using Ag sintering

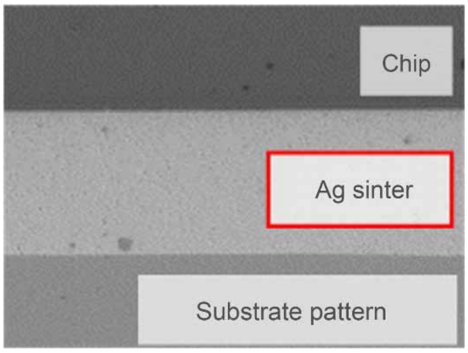
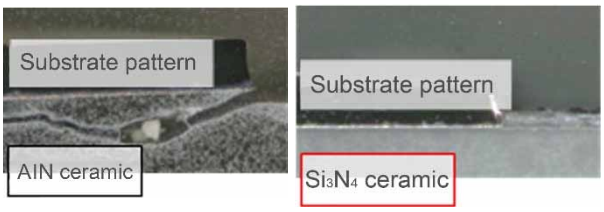


Fig. 3 Cross section of Ag sintering layer



(a) AlN substrate (b) Si_3N_4 substrate

Fig. 4 Cross section of substrate after temperature cycling test

3.3 Heat-resistant soldering material

The soldering material used to bond a substrate to a baseplate should remain free of cracks at the joint in order to continue dissipating the heat generated by the chip to the baseplate. Therefore, we considered using a highly durable and heat-resistant RoHS soldering material. Table 1 lists the basic elements of such heat-resistant solder. Multiple elements were added to the solder depending on the mechanical properties of substrates and baseplates to be bonded in order to extend the bonding lifetime. The selected soldering material was used to bond the Si_3N_4 substrate and baseplate mentioned in Section 3.2. A thermal cycle test in which the temperature was changed from −40°C to 175°C (⊿T = 215 K) was carried out to see if a crack would form at the solder joint. As a result, no cracks appeared at the joint after 600 cycles, which shows that the material can be used as heat-resistant solder (Fig. 5).

Table 1 Main materials of heat-resistant solder and their effects

Material	Melting temperature	Effect
Sn	231.9°C	-
Sb	630.5°C	Improved mechanical strength
Cu	1083.0°C	Improved creep property

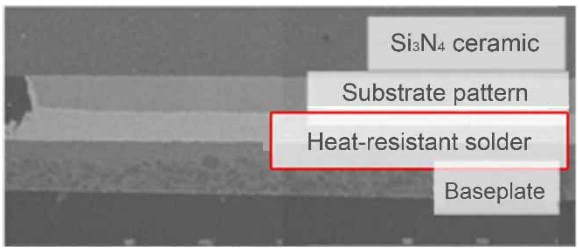


Fig. 5 Cross section of solder junction layer after thermal cycle test

3.4 US bonding technology for electrodes

In the past, the electrode used for electric connection with the outside was bonded with solder to the pattern on a heat-resistant substrate for energization. However, as the power density increases, heat generated due to the electrode's resistance also increases and so the temperature at the joint between the electrode and the pattern on the substrate increases. Therefore, the bonding lifetime at high-temperature cycles needs to be secured. We started using an ultrasonic (US) bonding technology to bond the electrodes and the substrate patterns to extend the bonding lifetime. Wiring by US bonding has eliminated the solder that existed between the electrodes and substrate patterns in the previous bonding; directly bonding the electrode and pattern can enhance the bonding strength. It has been confirmed that the bonding lifetime of the electrode and substrate can be extended for high-temperature cycling.

4. Conclusion

We have been developing elemental technologies for packages to allow high-temperature operation of power modules. Table 2 lists the new technologies introduced in the new package type to enable high-temperature operation. This paper described the technologies related to Ag sinter bonding, heat-resistant substrates, heat-resistant soldering material, and US bonding of electrodes. We believe that designing innovative packages and developing materials and production processes are important to commercialize power modules that operate at high temperatures in addition to the technologies introduced in the present report.

Table 2 Difference between new package and conventional one

Component	Conventional package	New package
Chip DB	Solder	Ag sinter
Substrate	AlN ceramic	Si_3N_4 ceramic
Substrate DB	Solder with Pb	Heat-resistant solder
Electrode-Substrate bonding	Solder	US (Ultrasonic)
Seal[3]	Conventional material	Heat-resistant material

Note: DB is die bonding.

To contribute to energy conservation and environmental protection, we will accelerate the development of next-generation high-quality power modules that operate at high temperatures and continue working to commercialize such modules based on our elemental technologies and mass production technologies for power module packages.

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Packaging Technologies Using Epoxy Resin Sealing

Author: *Hiroyuki Harada**

1. Introduction

Companies around the world must contribute to reducing environmental impact and achieving a low-carbon society. Along with the advances made in industrial equipment, electric railways, and automobiles, the development of power modules to be mounted onto such machines has also been accelerating. Therefore, we have further improved our packaging technologies, including heat resistance and insulation properties, to ensure the stable performance and high reliability of the power modules.

This paper introduces the epoxy resin sealing packaging technology that was adopted for the NX-type models of our T-Series seventh-generation IGBT modules for industrial applications and our J1-Series power semiconductor modules for automobiles.

2. Characteristics of the structures

2.1 Characteristics of the package structures

Figure 1 shows the appearance of the packages for the NX-type models of the T-Series seventh-generation IGBT modules for industrial applications and the J1-Series power semiconductor modules for automobiles.

As shown in Fig. 2, the conventional structure consists of a metal baseplate and ceramic insulating substrate combined with silicone gel sealing. The characteristics of the structure of the NX-type models of the industrial T-Series are an insulated metal baseplate having high heat dissipation and insulation properties, and DP resin made from epoxy resin as the sealing material. In addition, adopting DP resin reduced the risk of mismatches between the linear expansion coefficients

Fig. 1 Packages for power modules

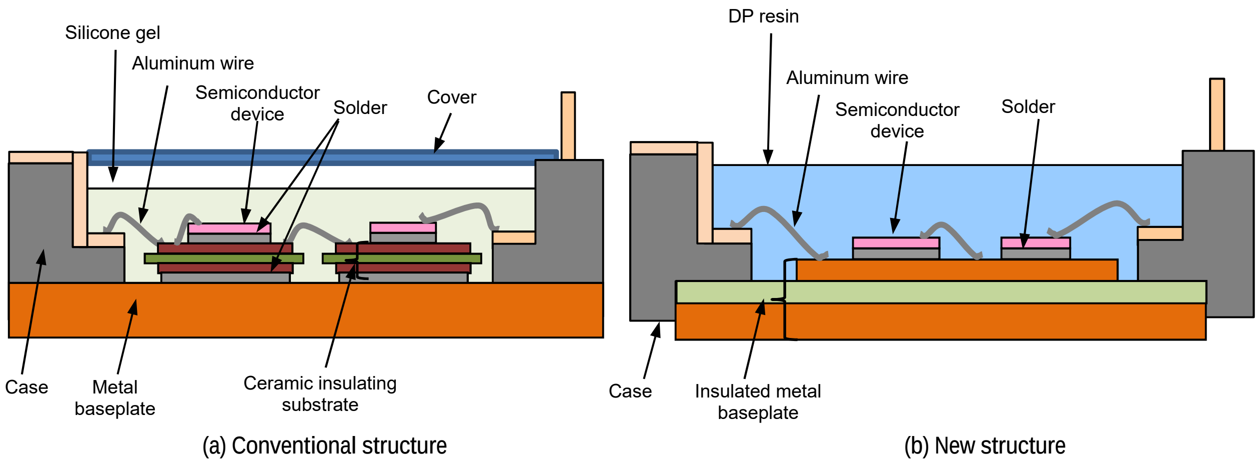

Fig. 2 Cross section of T-Series NX type

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of the components, which improved the resin's resistance to separation during thermal cycles.(1)

Figure 3 shows a cross section of the J1-Series power semiconductor module for automobiles. In the structure of the J1-Series, a ceramic insulating substrate is combined with a radiating fin, which enhances the cooling performance. The direct lead bonding (DLB) structure in which a metal frame is directly bonded to a semiconductor device with solder was adopted to improve the current-carrying capability and to reduce the wiring resistance and inductance. In addition, using DP resin as sealing resin makes the module structure as reliable as transfer-molded power modules (T-PMs) with the DLB structure. The three-phase inverter circuit configuration in which three 2-in-1 circuits are arranged was packaged into a single package to achieve a 6-in-1 circuit.(2)

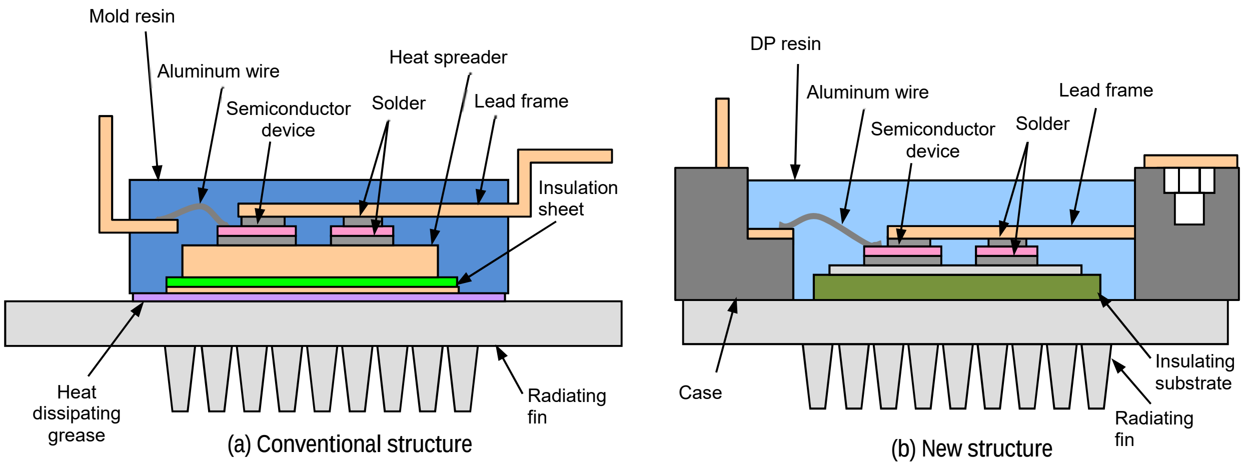
2.2 Characteristics of the resin sealing technology

The package structure and components of power modules vary depending on the application, so appropriate resin sealing based on the performance of the package is required. There are three types of resin sealing: mold resin sealing using solid epoxy resin used for transfer molding, silicone gel sealing used for sealing of general case type modules, and DP resin sealing using liquid epoxy resin. The characteristics vary between the resin technologies (Table 1).

In mold resin sealing, the reliability of the power module is high thanks to sealing by transfer molding. However, an expensive mold is required, making it difficult to change the module structure. In addition, the productivity of sealing large modules deteriorates since there is a limit to the size of molds.

For silicone gel sealing, the heat resistance and insulation performance are excellent. Since silicone gel has a low viscosity, it is easy to fill the narrow gap. However, its heat resistance and reliability will need to be improved in the development of future power modules.

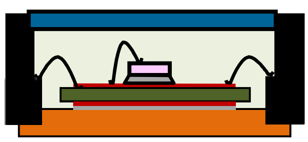
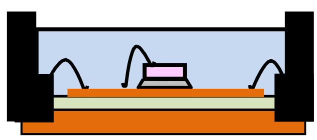
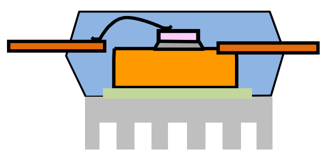
DP resin sealing, which uses liquid epoxy resin, solves such problems with sealing technologies. DP resin sealing does not require molds and its resistance to moisture permeability is high compared to silicone gel. It is considered that DP resin sealing could reduce the deterioration of solder materials at the bottom of semiconductor devices as a result of thermal cycles. These factors suggest that DP resin sealing can achieve



(a) Conventional structure (b) New structure

Fig. 3 Cross section of J1-Series

Table 1 Comparison of resin sealing technology

	Case type module		Transfer molding
	Silicone gel sealing	DP resin sealing	Mold resin sealing
Structure			
Reliability	Reliable	Highly reliable	Highly reliable
Larger package size	Possible	Possible	Not sufficiently possible
Linear expansion coefficient	High	Low	Low
Elastic modulus	Low	High	High

high reliability even under severe service environments. Meanwhile, its resin viscosity and elastic modulus are high, so it is difficult to fill the narrow-gap sections. The influence on separation and module warp caused by stress due to differences between the linear expansion coefficients of various components must be taken into account. Therefore, the optimum resin material design and sealing processes are important. These are discussed in detail in Chapter 3.

3. Packaging technology with resin for sealing

3.1 DP resin material design

DP resin consists of mainly epoxy resin, a ceramic filler, and various additives (e.g., flame retardant). We have developed materials with the optimum resin characteristics for each module type.

For the J1-Series for automobiles, the module structure includes a ceramic insulating substrate, so a DP resin type with a low linear expansion coefficient matching the ceramic's linear expansion coefficient had to be selected. The resin's linear expansion coefficient can be adjusted by changing the amount of filler to be added to the resin, as shown in Fig. 4. However, as the amount of filler increases, the resin viscosity also increases, thereby decreasing the liquidity. Regarding the liquidity of the resin, the liquid limit (viscosity) at which the resin can be filled even in the narrow-gap sections in modules at a high filling factor was calculated from a basic evaluation. We have identified the amounts of filler to be added (range) where the liquidity is excellent and have developed a DP resin that satisfies the required resin characteristics.

3.2 DP resin sealing process technology

Resin sealing in which the resin can be filled in the narrow-gap sections at high density requires the optimum filling processes based on determined resin characteristics. In recent years, power modules have become smaller and the density has become higher. The DLB structure and other types of structures have also been applied. These trends have resulted in an increasing number of module sections with narrow gaps of 1 mm or less. Therefore, optimization of the resin filling processes has become even more important. Regarding the processes, we filled resin under optimum conditions that were determined through evaluation, and achieved high-quality resin sealing at high density.

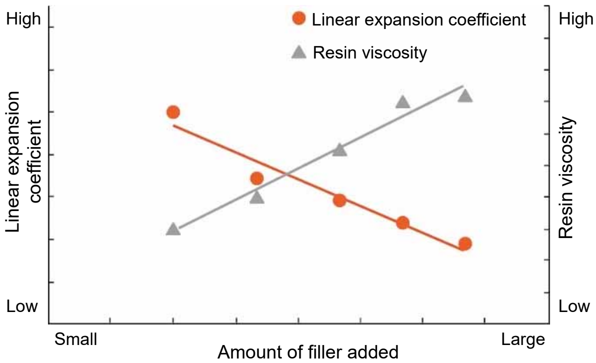
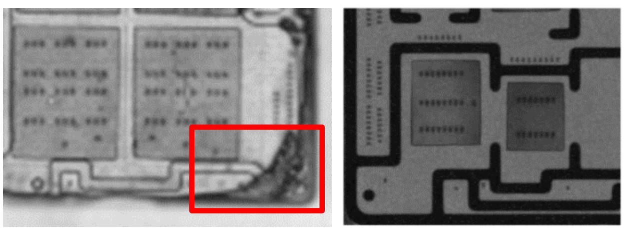
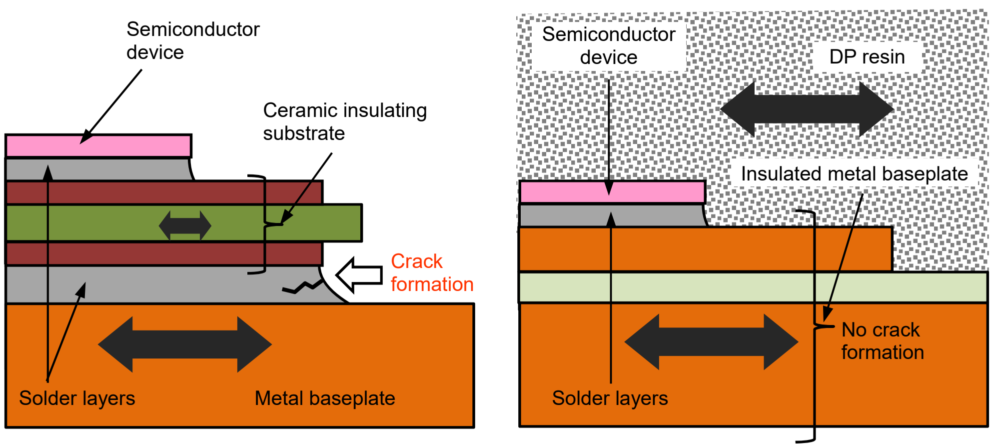


Fig. 4 Relationship between linear expansion coefficient and resin viscosity with respect to filler amount



(a) Silicone gel sealing structure (b) DP resin sealing structure

Fig. 5 Cross section of substrate after thermal cycle test



(a) Silicone gel sealing structure (b) DP resin sealing structure

Fig. 6 Cross section of each sealing structure

3.3 Reliability test

The conventional structure in which silicone gel sealing was applied for a ceramic insulating substrate and the new structure in which DP resin sealing was applied for an insulated metal baseplate (NX-type model of the T-Series for industrial applications) were tested in a thermal cycle test (−40°C ↔ 125°C). Figure 5 shows scanning acoustic tomography (SAT) images after 600 cycles. Figure 6 illustrates the cross sections of the two types of sealing structures (diagrams).[3]

On the silicone gel sealing structure, as the thermal cycle test proceeded, a crack advanced slightly from the end of the solder layer in the lower section of the ceramic insulating substrate. On the other hand, the DP resin sealing structure has no solder joint layer between the baseplate because an integral-type substrate is used, so no component degradation was seen after the thermal cycle test. For both structures, no degradation was observed on the solder joint layers in the lower sections of the semiconductor devices after the thermal cycle test.

For the silicone gel sealing structure, the linear expansion coefficient of the ceramic insulating substrate is relatively close to that of the semiconductor device, so the stress on the solder joint layer is not so high. On the other hand, for the DP resin sealing structure, the difference between the linear expansion coefficient of the semiconductor device and that of the insulated metal baseplate is large, so the stress applied to the solder joint layer is high. However, the high-modulus DP resin with excellent adhesiveness covering the solder joint layer may have reduced the stress working on the solder joint layer.

In addition, the results of a power cycle test showed that the power cycle life of the new structure is equal to or longer than that of the conventional structure. This is further evidence of the high reliability of the resin sealing technology using DP resin sealing.

4. Conclusion

For the NX-type models of our T-Series seventh-generation IGBT modules for industrial applications and our J1-Series power semiconductor modules for automobiles, DP resin sealing using epoxy resin was adopted in place of silicone gel sealing which was mainly used in the conventional case type modules, thus improving the reliability of the power modules. We will accelerate the development of the next-generation power modules by improving the performance of the sealing technologies, including materials and production processes, to contribute to an energy-saving society.

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Relaxing Thermal Stress by Using SLC Technology and New PC-TIM

Authors: *Koichi Masuda** and *Yoshitaka Otsubo**

1. Introduction

Solid cover (SLC) technology is applied to the structure of the LV100 (Fig. 1) to reduce the thermal stress. In addition, combining the SLC technology with a new type of phase change (PC)-thermal interface material (TIM), which has a high thermal conductivity, has made it possible to further enhance performance. The characteristics of the LV100 and the new PC-TIM are described below:

(1) The SLC technology increases the capacity and chip mounting area.
(2) Changes in the shape of the baseplate (warps) due to temperature changes are reduced.
(3) The new type of PC-TIM has high thermal conductivity and high heat resistance.
(4) The SLC technology combined with the new PC-TIM reduces the thermal resistance.

2. SLC technology

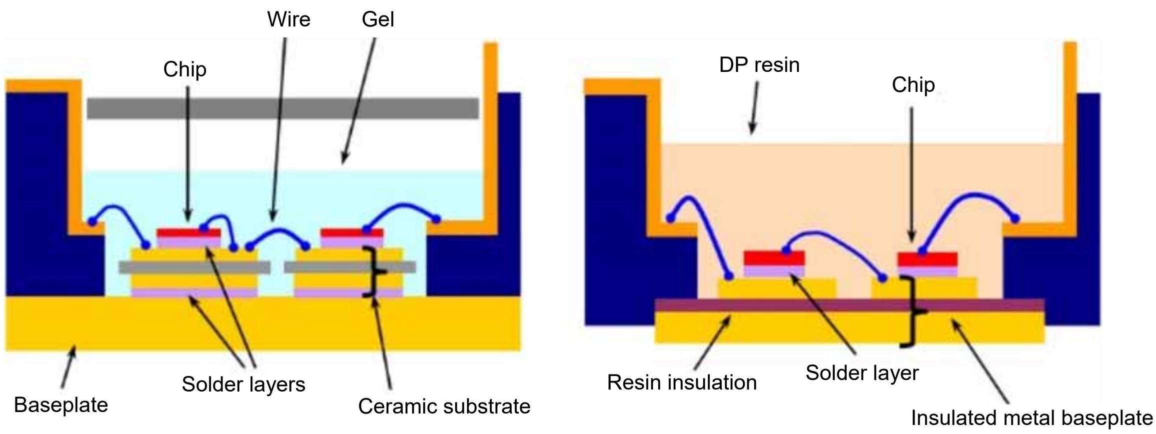
Figure 2 shows schematic drawings comparing the structure with the conventional technology that uses a “conventional structure” and the structure with the SLC technology that uses an integrated substrate with resin insulation. Table 1 lists the features of the SLC technology for large-capacity modules. The adopted SLC technology increased the capacity and power density of the LV100 for industrial applications.

For power modules in the conventional structure, in cases when the rated current exceeds 1,000 A, the ceramic substrate must be divided into multiple sections to prevent cracking of the substrate. On the other hand, when the SLC technology is applied, there is no need to divide the substrate, so the area of the metal pattern on the substrate can be larger. As shown in Fig. 3, the pattern area of the industrial LV100 was increased by

Fig. 1 LV100

Table 1 Features of SLC technology

#	Item	Advantage
1	Integrated substrate	Enlarges the chip mounting area
2	Optimization of the constituent materials’ linear expansion coefficients	Reduces the thermal stress due to differences between the materials’ linear expansion coefficients
3	Resin insulation material with high thermal conductivity	Reduces the thermal resistance



(a) Conventional structure

(b) SLC technology

Fig. 2 Comparison of structures

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approximately 20% for the outline size of the LV100. Also, an undivided single substrate made it possible to reduce the area of the terminal joints, which allowed a further increase in the area ratio of the chip mounting section on the surface of the metal pattern. The increased chip mounting area can reduce the thermal resistance and increase the output from modules compared to the conventional structure.

In addition, in the SLC technology, the thermal expansion coefficients of the constituent materials have been optimized. The ceramic substrate and the solder under the substrate are eliminated and materials with similar thermal expansion coefficients are used to compose a module, which improves the heat cycle

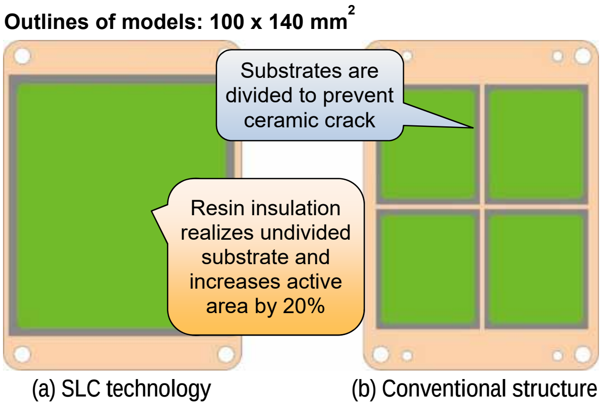

Fig. 3 Comparison of active area for Cu pattern

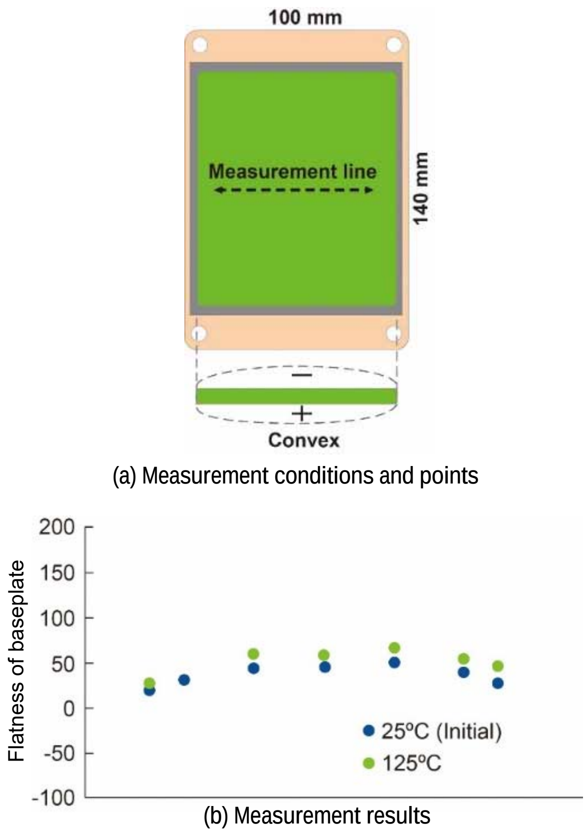

Fig. 4 Measurement results for baseplate flatness

resistance.(3) Figure 4 shows the measured flatness of a baseplate in relation to temperature changes. Even for the LV100 with a large baseplate area, the SLC technology reduces the displacement of the baseplate due to temperature changes. This reduction of displacement improves the pumping-out resistant and makes it possible to reduce the thickness of the heat radiation materials, such as silicone grease and PC-TIM.

Furthermore, the thermal conductivity of the resin insulation sheet was improved compared to the conventional sheet material used for our seventh-generation NX-type 1,200 V series. As shown in Table 2, the improvement in the sheet material's thermal conductivity reduced the thermal resistance by 6% while the isolation voltage was increased from 2.5 to 4.0 kV by increasing the thickness of the sheet.(4) Realization of the isolation voltage of 4.0 kV has made it possible to apply the SLC technology to 1.7 kV power modules. This sheet type with such high thermal conductivity has been used for the NX-type seventh-generation 1.7 kV system.

3. PC-TIM with high thermal conductivity and high heat resistance

To reduce thermal stress, it is important to improve the power module's heat dissipation and reduce the thermal contact resistance between the baseplate and the heatsink. We started applying the PC-TIM to the seventh-generation NX-type and std-type and are considering adopting a new type of PC-TIM for which the thermal conductivity and heat resistance have been improved. Table 3 compares the PC-TIM with the conventional specifications and those of the new type with high thermal conductivity and high heat resistance.

Table 2 Comparison of resin insulation sheets

Applied product	Resin insulation sheet	Withstand voltage	Ratio of thermal resistance (Rthj-c)*
Seventh-generation 1,200 V NX-type series, etc.	Conventional specifications	2.5 kV	1.0
Seventh-generation 1.7 kV NX-type series, industrial LV100, etc.	High thermal conductivity specifications	4.0 kV	0.94

Note: Thermal resistance ratio between the junction and the case for the same chip size

Table 3 Comparison of PC-TIMs

PC-TIM	Thermal conductivity [W/(m·K)]	Maximum service temperature (°C)
Conventional specifications	3.4	125
Specifications with high thermal conductivity and high heat resistance	4.0	150

The thermal conductivity of the new PC-TIM was improved to 4.0 W/(m·K) and can be used at 150°C. Figure 5 shows the results of evaluating the wet-spreading properties of the two types of PC-TIMs. The wet-spreading property has a trade-off relationship with the thermal conductivity based on the amount of filler content (Fig. 6 shows a conceptual drawing): when the thermal conductivity is improved, the wet-spreading property may decrease. To solve this, the constituent materials and filler diameter were optimized for the new PC-TIM, which improved the thermal conductivity without impairing the wet-spreading property.

Figure 7 shows the weight change rates of the two types of PC-TIMs in a high-temperature storage test at 150°C. For the specifications of high thermal conductivity and high heat resistance, the weight change rate at high temperatures was reduced by increasing the thermal decomposition temperature. This improvement allows the PC-TIM to be used at 150°C.

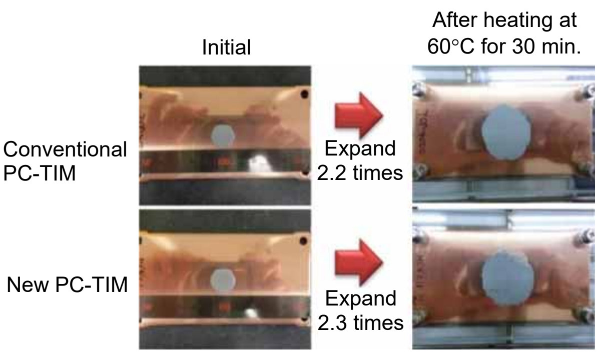

Fig. 5 Measurement results for wet-spreading property

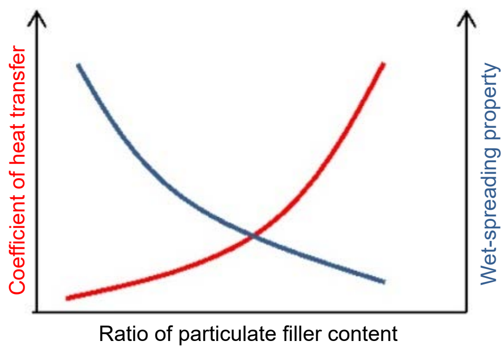

Fig. 6 Conceptual drawing of PC-TIM trade-off relationship

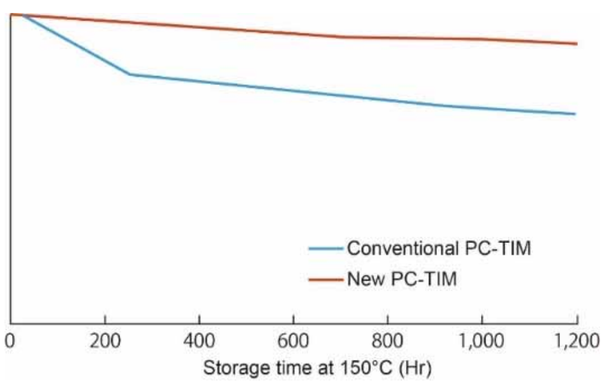

Fig. 7 Comparison results for weight change during storage test at 150°C

4. Reduction of thermal resistance

Combining the SLC technology with the new PC-TIM with high thermal conductivity and high heat resistance can reduce the thermal resistance. Table 4 shows the modelling conditions of the steady-state thermal analysis performed to check the heat dissipation. The outline size of the industrial LV100 was used for the analysis. For comparison, another model for which silicone grease was used as the heat radiation material with an Al_2O_3 substrate as the module structure was analyzed. In addition, the thickness of the heat radiation material in the SLC structure was decided at 50 μm because the displacement of the baseplate due to temperature changes was reduced. Figure 8 compares the thermal resistance of the two models calculated by the steady-state thermal analysis. The analysis results show that the thermal resistance of the model with the new technology is approximately half that of the model with the conventional technology. This demonstrates that the heat dissipation was improved by combining the new PC-TIM having high thermal conductivity and high heat resistance with the SLC technology.

Table 4 Conditions of thermal resistance calculation

Model	Structure	Heat radiation material*	Outline size (mm^2)
New technology	SLC structure	PC-TIM 4.0 W/(m·K) 50 μm	100 × 140
Conventional technology	Conventional structure (Cu baseplate + thin Al_2O_3 substrate)	Silicone grease 0.9 W/(m·K) 100 μm	

Note: The thickness of the heat radiation material is as recommended for each structure.

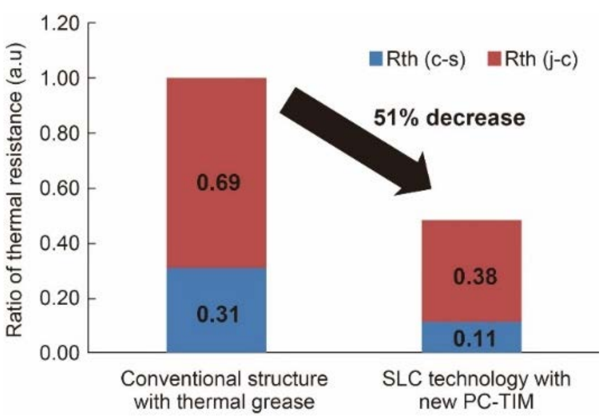

Fig. 8 Thermal resistance calculation results

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Optimized inverter design by DIPIPM+

Author: *Toru Ichimura**

1. Introduction

Mitsubishi Electric Corporation has commercialized the CIB-type insulated gate bipolar transistor (IGBT) module in which the power chips for the converter circuit, brake circuit, and three-phase inverter were integrated to meet various market demands. Mitsubishi has also commercialized the DIPIPM in which the power chips for the three-phase inverter and control ICs were integrated and transfer-molded. DIPIPM+ (DIPIPM plus) is a new type of power module that combines these two modules. The DIPIPM+ is an innovative power device that can reduce labor-intensive design work by engineers who develop inverters, while also reducing the size of the inverter equipment. A previous paper(1) discussed the performance of the DIPIPM+. This paper describes main features of DIPIPM+ about integration of power devices and control circuit and optimization of inverter system design brought by the appropriate structural characteristics (e.g. optimal terminal arrangement).

2. DIPIPM+

2.1 Internal structure

Figure 1 illustrates the block diagram of the DIPIPM+. As shown in the figure, the DIPIPM+ integrates main inverter circuit, which is three phase bridge connection by six pairs of IGBT and FWDi (free wheeling diode), brake circuit consists of series-connected IGBT and Diode, and three phase diode bridge for converter circuit.

For the gate driving of the IGBTs in the inverter and brake circuits, ICs are connected to the circuits. The IC for driving the upper arms in the inverter circuit (high-voltage integrated circuit (HVIC)) has a high-voltage level shift circuit. The HVIC can receive control signals from the microcomputer (MCU) without an insulation element (e.g., photocoupler). It also has a protection function for control supply undervoltage (UV). The IC for driving the lower arms (low-voltage integrated circuit (LVIC)) has a circuit for driving the IGBTs as well as UV and short circuit (SC)

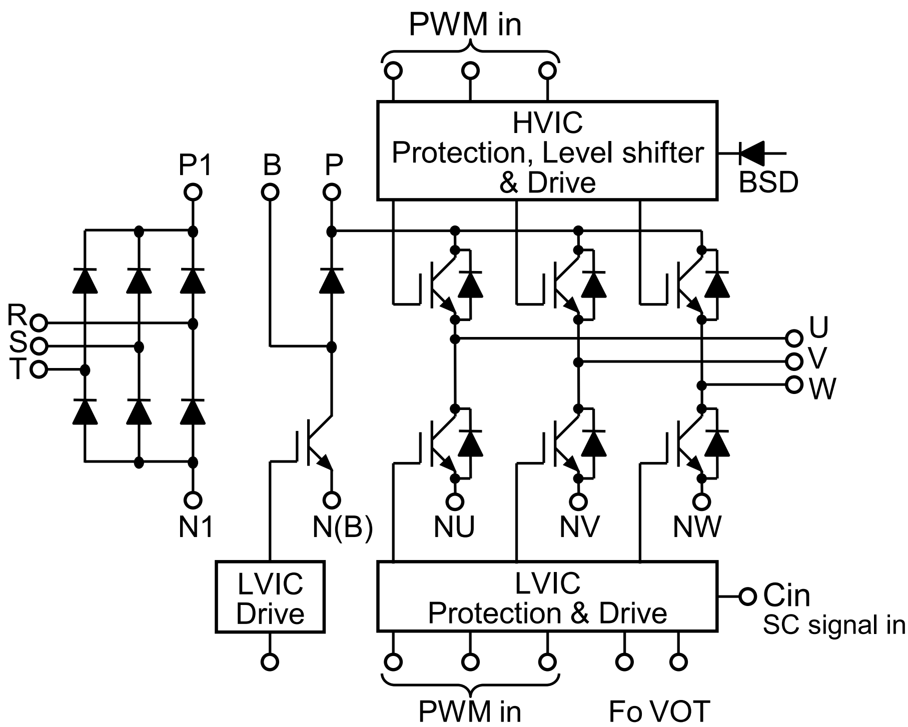

Fig. 1 Internal block diagram of DIPIPM+

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protection functions. For the SC protection, the lower arm IGBT is quickly shut off by inputting the voltage drop of the external resistor connected to the main circuit's lower arm emitter terminal at the time of an overcurrent. When the LVIC's protection function is activated, fault-out (FO) signal is output for external notification of an abnormality.

In addition, a function is provided that detects the temperature of the module with a thermal sensor on the LVIC and outputs it as analog voltage signal (voltage output of temperature (VOT) function).

2.2 Terminal arrangement

The DIPIPM+ has a well-configured terminal arrangement so that wiring on a printed circuit board (PCB) of the inverter equipment is easy and the assembled inverter equipment can work efficiently and stably for an extended period of time.

As shown in the external connection diagram in Fig. 2, the main circuit terminals (AC three-phase input, brake, and three-phase output terminals) are arranged in a line on the long side of the package so that they can be connected in the shortest distance to the terminal block of the inverter equipment. The terminals for connecting a smoothing capacitor and for control input/output are arranged in a line on the other long side.

3. Optimization of the DIPIPM+ Connection Circuits

3.1 Optimization of the DIPIPM+ main circuit wiring

The DIPIPM+ main circuit terminals have been arranged in accordance with the arrangement on the inverter equipment's terminal block for external connection, so the main circuit wiring on the PCB can be dramatically simplified compared to the conventional wiring using a CIB-type IGBT module (Fig. 3).

Figure 4 illustrates the wiring in which a DIPIPM is combined with a three-phase diode rectifier. Because the wiring is simpler, it has an advantage compared to the IGBT module shown in Fig. 3. However, it is obvious that the wiring on a PCB using the DIPIPM+ shown in Fig. 2 is the simplest because there are no cross wires.

Complicated main circuit wiring on a PCB including cross wires may be a main cause of insulation problems, noise, and many other problems. Therefore, simplifying the main circuit wiring maintains and improves the functions and performance of the inverter equipment. The simple terminal arrangement of the DIPIPM+ has the following advantages in main circuit wiring:

- The pattern wire length can be reduced;
- No jumper wire is required;
- Double-sided PCB can be used (no multilayer PCB is required);
- The creepage distance can be reduced and the dead space is significantly reduced; and
- These advantages greatly reduce the PCB size.

3.2 Optimization of the DIPIPM+ control circuit wiring

The DIPIPM+ has an LVIC that drives the brake circuit and an HVIC and another LVIC that drive the inverter circuit and that have the protection function. Their drive capability has been optimized to realize low radiation noise and low power loss, so the gate resistance does not

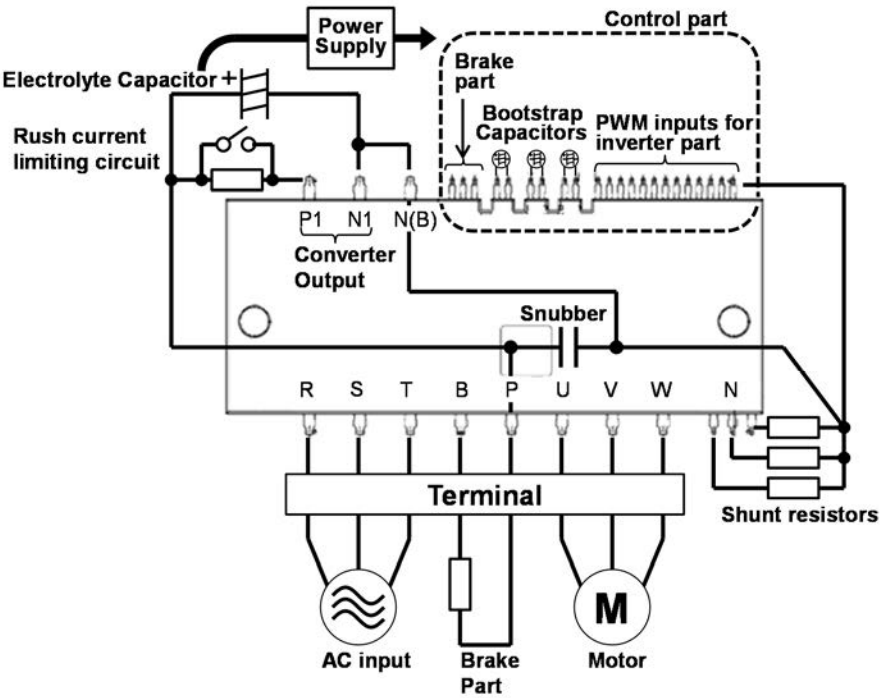


Fig. 2 External connection of DIPIPM+

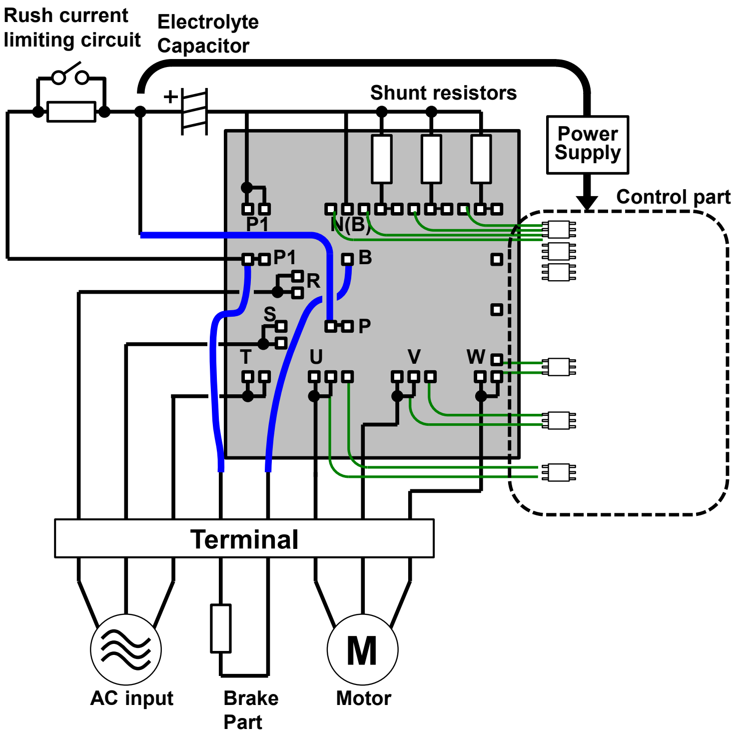


Fig. 3 External connection of CIB-type IGBT module

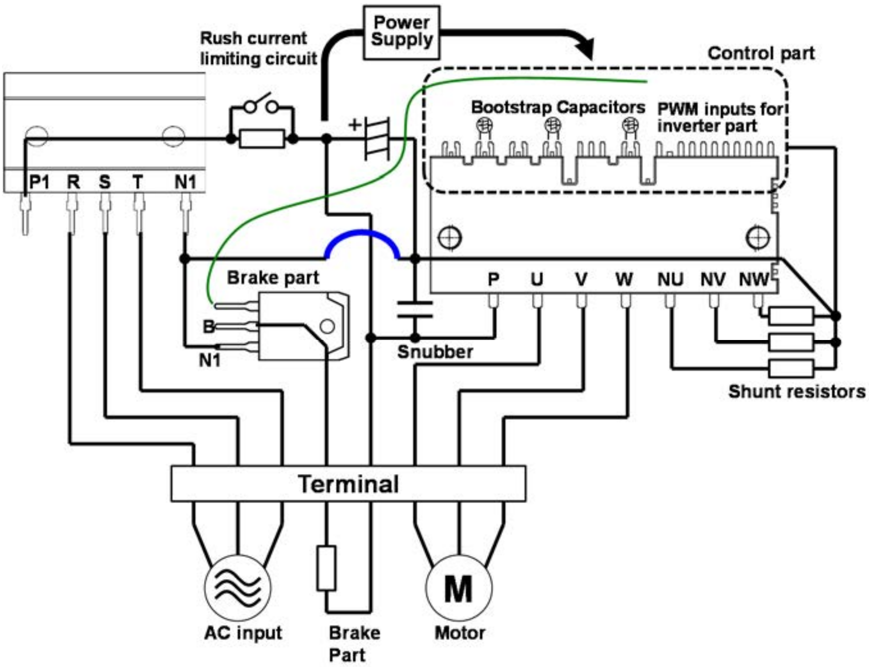


Fig. 4 External connection of DIPIPM and diode rectifier

need to be adjusted in the design of the control part. These control terminals taken out from the DIPIPM+ are concentrated on one side of the DIPIPM+. Shortening the wiring to the microcomputer that handles small signals can minimize the possibility of exposure to noise from the surrounding circuits, which makes it easier to improve the reliability of the inverter equipment.

3.3 Optimization of the control supply circuit

The electric potential of the power supply for driving the IGBTs on the inverter circuit's upper arms needs to be independent from that of other control supply.

For IGBT and similar modules, multiple transformer windings are provided to generate power supply. However, such power supply becomes larger due to the insulation between the transformer output terminals. In addition, attention is required for the insulation (e.g., isolation using a separator) in designing to ensure that a displacement current at the time of IGBT switching does not propagate to any other control supply via parasitic capacitance between the transformer windings.

Given the small power consumption of the Mitsubishi HVIC used for the DIPIPM+. a bootstrap circuit can be used for the power supply for driving the IGBTs on the upper arms. Thus, for the transformer, only a 15 V output for the inverter circuit and another power supply for the secondary side are required. This allows the design of transformer to be simple (e.g., laminated winding) (Fig. 5).

In addition, the DIPIPM+ has high-voltage bootstrap diodes (BSDs) for bootstrap circuits, so the power supply wiring on a PCB becomes simpler and its footprint can be smaller.

3.4 Optimization of the system cost

For the main circuit wiring on a PCB for inverter equipment, it is necessary to secure the pattern width based on the flowing current and the insulation distance based on the voltage. As the wiring is longer, the area of the PCB needs to be larger. A PCB can be downsized by multi-layering the boards. Generally, however, the price of a board increases as the number of layers increases. In addition, the transmission of noise via parasitic capacitance between the layers has a harmful influence.

Figure 6 illustrates example configurations of an inverter system using an IGBT module and of inverter equipment using the DIPIPM+. For the DIPIPM+ solution, the number of photocouplers can be reduced by connecting the motor control MCU and DIPIPM+ without isolation lines: a low-cost low-voltage digital isolator with a longer operating life can be used instead. Inputting the voltage drop of the shunt resistor to the MCU can reduce the number of current sensors. Inputting the divided the voltage drop to the DIPIPM+ can provide accurate protection at the time of a short circuit by the SC protection function. On the other hand, the desat method, which is generally proposed for the IGBT module solution, uses the power device's active region characteristics that are very close to the limit for breakage. In addition, a complicated design is required that takes into account operation delays during On/Off.

When considering an entire inverter system, the SC protection function of the DIPIPM+ can also work as protection against motor demagnetization, thus reducing the cost of the current detection circuit.

The aforementioned downsized power supply transformers and reduction of the main circuit wiring including jumper wires can improve the reliability and reduce the system cost significantly.

4. Conclusion

The improved performance of silicon power semiconductors has been approaching its theoretical limit, so expectations for silicon carbide (SiC) and other materials have been increasing. However, as power modules do not consist of only power devices, they can be further optimized including their structures.

We recognized the importance of the interfaces to PCBs through which power modules are implemented and have established the structure and terminal arrangement for realizing low-cost and highly reliable inverter systems and making best use of the power semiconductors in the DIPIPM+.

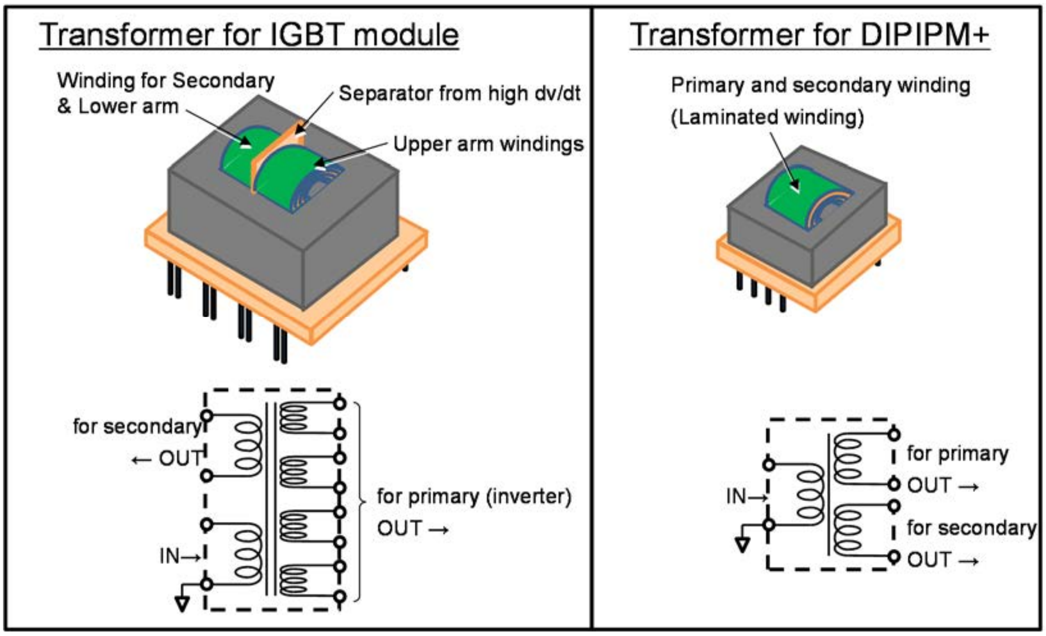
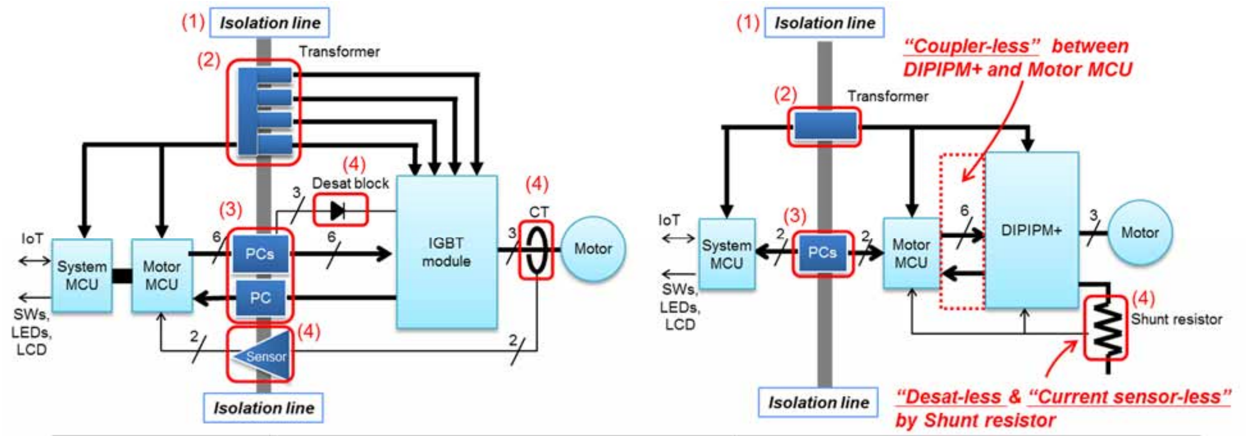


Fig. 5 Comparison of transformer for IGBT module and DIPIPM+



	IGBT module solution	DIPIPM+ solution
(1) Isolation line	Between IGBT module and Motor MCU	Between System MCU and Motor MCU
(2) Control power supply (Transformer)	Primary floating output x 4 + Secondary output x 1	Primary output x 1 + Secondary output x 1
(3) Photo coupler	High speed and high CMR photo coupler x 6 + Normal transistor photo coupler x 1	Digital isolator (bidirectional) (3.3V or 5V) x 1
(4) Current detection	Desaturation detection by high voltage and high speed diode for SC protection with Current feedback function by CT	Both SC protection and Feedback current detection by shunt resistor

Fig. 6 Comparison between IGBT solution and DIPIPM+ solution

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