All-SiC Module Packaging Technology

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ABSTRACT

We applied the All-SiC (silicon carbide) module with new package structure to mega solar power conditioning sub-system (PCS), achieving 98.8% energy conversion efficiency and resulting in energy conservation. Key technologies are 3-dimensional wiring using Cu pins with power board instead of conventional Al wiring and full-mold structure using the thermosetting epoxy resin. These technologies lead to small package size, low inductance, and high reliability. We have optimized the package design to bring out the intrinsic performances of SiC device. Resin flow analysis and its visualization methods are carried out to design molding process, resulting in the full mold structure with free air void.

1. Introduction

Public interest in environmental issues such as global warming is increasing year by year, and worldwide society demands less greenhouse gas emissions representative of CO_2. Meeting such a need requires the active utilization of renewable energies and greater energy saving of power electronics equipment. In general, power semiconductors play a key role in the power conversion system of power electronics products. Silicon (Si) devices, which are the conventional mainstream, have undergone various breakthroughs and gradually approach its physical limit. Regarding this background, silicon carbide (SiC) devices, which are the next-generation semiconductors enabling even less power dissipation, are raising expectations for their contribution toward energy saving.

Fuji Electric has developed an All-SiC module using SiC metal-oxide-semiconductor field-effect transistors (SiC-MOSFETs) and SiC Schottky barrier diodes (SiC-SBDs) and using it to a power conditioning subsystem (PCS) for mega solar power plants. This paper describes the packaging technology of the All-SiC module.

2. Features of New Package

In order to achieve more efficient power conversion of high-capacity photovoltaic power generation as mega solar power plants, Fuji Electric started mass production of mega solar PCSs that employ All-SiC modules in 2014. Figure 1 shows the external appearance of the mega solar PCS, its built-in power unit and the All-SiC module. It uses the All-SiC module in voltage boosting circuit and achieves a high efficiency of 98.8% to save energy. Further efforts have been made to reduce the size and weight of the equipment[1].

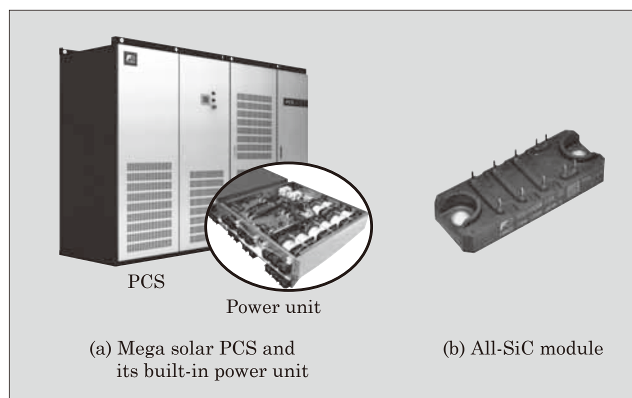

Fig. 1 Mega solar PCS and All-SiC module

Figure 2 shows cross-sectional structures of the new package used in the All-SiC module and the conventional package used in a silicon insulated-gate bipolar transistor (Si-IGBT) module. Table 1 shows the comparison of the typical characteristics of these modules. The new package contains small size SiC chips connected in parallel. In order to flow large current through wiring on the chip, we applied 3-dimensional wiring with Cu pins and a power substrates instead of aluminum wires. For the size advantage, the footprint is reduced to approximately 40% compared with the conventional module. This miniaturization achieved by 3-dimensional wiring effectively reduces the inductance less than a quarter of the conventional one. Additionally, thermal resistance is decreased approximately a half of conventional module by using a ceramics insulating substrate consisting of a high-thermal-conductive ceramics substrate (Si_3N_4) bonded with thick copper plates and by adopting a structure without metal base[2][3]. Furthermore, the use of

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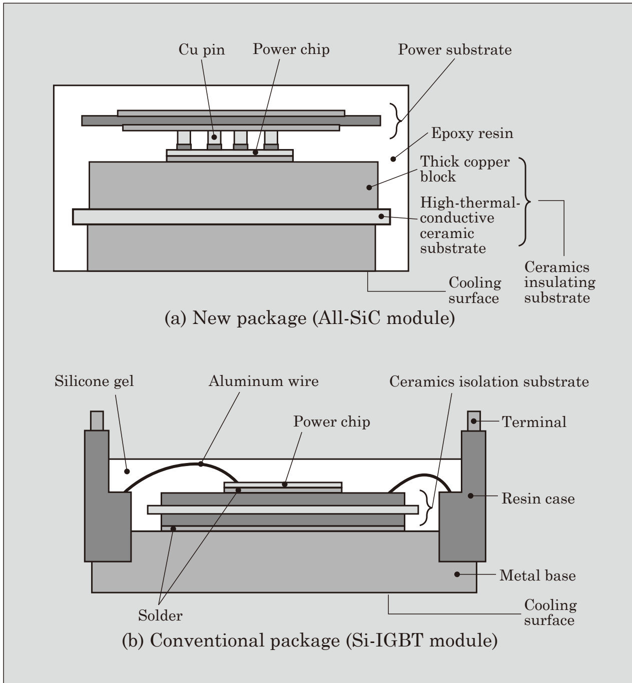

Fig. 2 Cross-sectional package structure

Table 1 Comparison of typical characteristics between the new and conventional packages (Relative comparison at 1,200-V/100-A rating)

Package characteristics	Conventional package	New package
Thermal resistance (K/W)	0.469	0.209
Inductance (nH)	52	12
Footprint	1	0.42

epoxy resin for the molding resin improves reliability. Molding technology ensures the isolation of the chips and ceramics substrate and also suppresses the distortion of joint area between the chips and Cu pins. Adopting transfer mold forming for this epoxy resin molding eliminates the need for a conventional resin case, leading to miniaturization and productivity improvement. In the new package structure, the epoxy resin is the key component that determines the performance of the module.

3. Package Structure Design

3.1 Internal wiring structure

The SiC-MOSFET allows faster switching compared with the conventional Si-IGBT. To bring out advantage of the ability, it is necessary to reduce surge voltage that increases in proportion to the switching speed and this make it crucial to reduce the inductance of internal wiring.

The new package has achieved miniaturization by adopting 3-dimensional wiring that uses Cu pins and a power substrate as shown in Fig. 2(a). This decreases the wiring distance and reduces self-inductance. Furthermore, we attempted to reduce the inductance

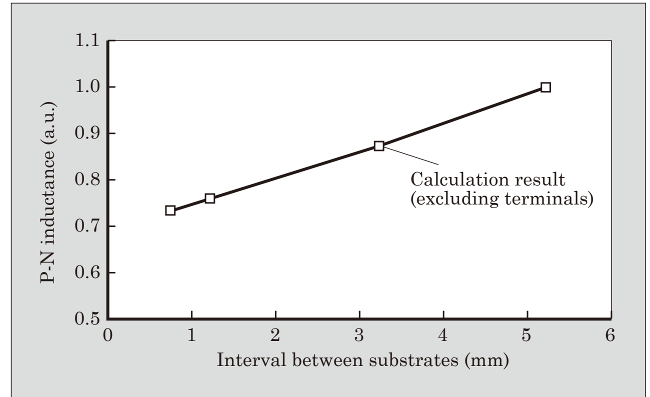

Fig. 3 Relationship between the substrate interval and inductance

further by arranging the power substrate and ceramics insulating substrate in parallel and by connecting the wiring to make the change in the current (di/dt) occur in the opposite directions[(4)]. In this structure, the closer the 2 substrates are positioned, the more the inductance decreases as shown in Fig. 3. Consequently, we set the interval as narrow as possible on the condition that it does not affect the insulation performance or assembly work. As a result, the P-N inductance of the new package is less than 25% (approx. 12nH) compared with the conventional package.

Since a mega solar PCS handles large current, multiple All-SiC modules are connected in parallel. In this case, the inductance is inversely proportional to the number of modules. This is more advantageous for high-speed switching than the conventional case where a smaller number of large-capacity modules were used.

3.2 Molding structure

A full-mold structure with thermosetting epoxy resin can relief the stress inside the module. In the view of reliability, stress is occurred at joint areas of the chip. Molding can cover surrounding of the chip and other joint areas, and distortion is eased[(5)]. This effect improves the power cycle capability at ΔT_j = 150 °C by 20 times or more compared with the conventional package[(6)].

However, the issue with the full-mold structure is caused by the fact that materials with different linear expansion coefficients are molded together. When the package cured under elevated temperature is returned to normal temperature, internal stress is generated and warpage occurs in the entire module. It is necessary to keep the warpage as low as possible because it may increase stress or thermal resistance when the product is mounted on a cooling fin or cause a pump-out phenomenon*1 of the compound due to the temperature change during operation.

Figure 4 shows the results of the finite element method (FEM) analysis and actual measurement to examine the relationship between the warpage and the thickness of the main body (thickness of resin) of

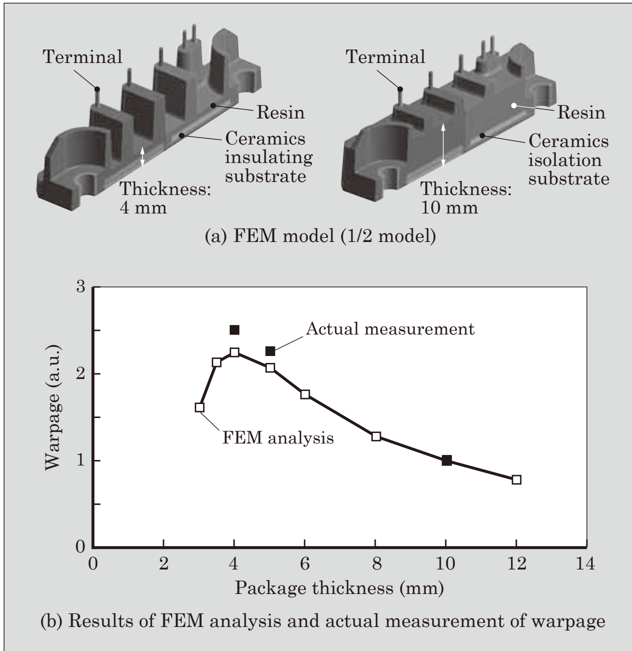

Fig. 4 FEM model of the new package and results of analysis and actual measurement of warpage

the new package excluding protrusions. The results indicate that the warpage becomes smaller when the package is either thicker or thinner than a certain thickness. This is probably caused by the fact that, in the region where the package is thin and dominated by the rigidity of the ceramics insulating substrate, the stress on the ceramics insulating substrate decreases with the decrease of the resin thickness, resulting in smaller warpage. On the other hand, in the region where the package is thick and is dominated by the rigidity of the resin, the rigidity of the resin increases further with the increase in the resin thickness so that the package is less affected by the ceramics insulating substrate, resulting in smaller warpage. In real-world situations, however, when the thickness of the ceramics insulating substrate, chip thickness and power substrate lamination are considered, the module would be manufactured in the region where the rigidity of the resin dominates. Consequently, it is effective to produce the All-SiC module with thicker epoxy resin to obtain low warpage module. In this case, it is important to optimize the resin thickness and inductance value because a thicker resin part requires a longer terminal to be extended outside, causing an increase in inductance. The insulation distance between the terminal and ground (creepage/clearance distance) must also be considered.

As a result, the internal structure of the module is designed to arrange most components on the cooling surface side. This is done to reduce inductance by arranging the power substrate and ceramics insulating substrate at a narrower interval and to suppress warpage by making the module thicker. When transfer mold forming is used for this high concentrated structure, the resin hardly flows smoothly and evenly inside the module. Therefore, it requires a mold process design based on an accurate recognition of the resin flow.

4. Mold Process Design

4.1 Simulation techniques and mold design

One of the concerns of the transfer mold forming of the new package is scattered voids (trapped air) and welds (sections where resin flows meet together) inside the module. These are caused by the deterrence of the flow. The chips, Cu pins and other internal components are rationale. The volatile filling speed at the narrow space and that at the other space can also generate voids and welds (resin flow junction part).

To understand this phenomenon, simulation of the resin flow was done. Figure 5 shows the simulation model and result of the resin flow. As a result of this, welding position, air trap and/or bubbles in the flowing resin was clarified by changing molding conditions. This result is reflected to the mold design.

4.2 Resin flow visualization

In order to improve mass production quality and productivity, it needs to optimize the mold design and process conditions. This modulation needs to consider factors of the air vent operation and the flow and elimination behavior of bubbles that cannot be calculated by

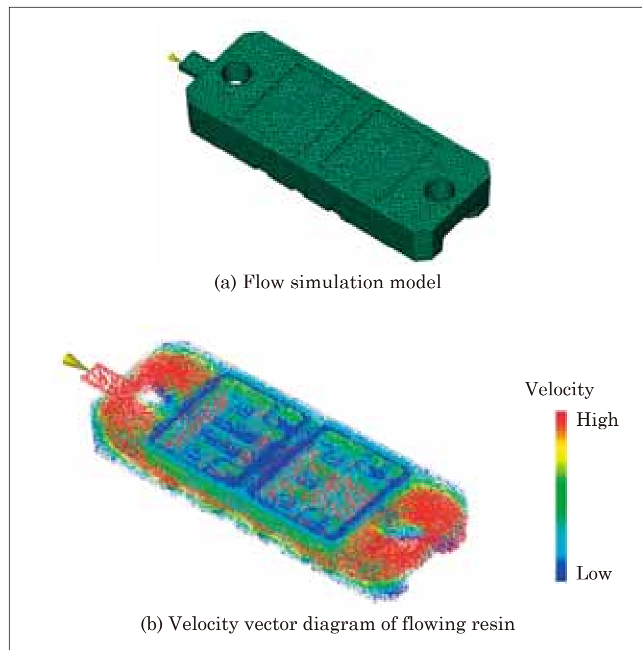

Fig. 5 Resin flow simulation

*1: Pump-out phenomenon: Phenomenon where the compound between the module and cooling fin is pushed out of the space due to repeated deformations of the package caused by temperature changes during operation, resulting in an increase of thermal resistance

simulation.

Therefore, molding visualization is done by using experimental glass plate as shown in Fig. 6. As a result of this, it is successful to avoid the air trap and welds by arranging an air vent, optimizing the gate shape and modulating the flow conditions including speed, temperature and pressure. For example, Fig. 6(b) illustrates the process in which the void generated by the air trapped near the mounting hole is pushed down to the inside of the ring and disappears. It is hard to understand the resin flow behavior by simulation.

As described above, both of the simulation and practical visualization of the resin flow are important for accurately understanding the mechanism of the void. These technologies are used to develop mold process design techniques that are applied to the mold design and molding conditions. At the result, it is able to achieve the All-SiC module in a full-mold structure.

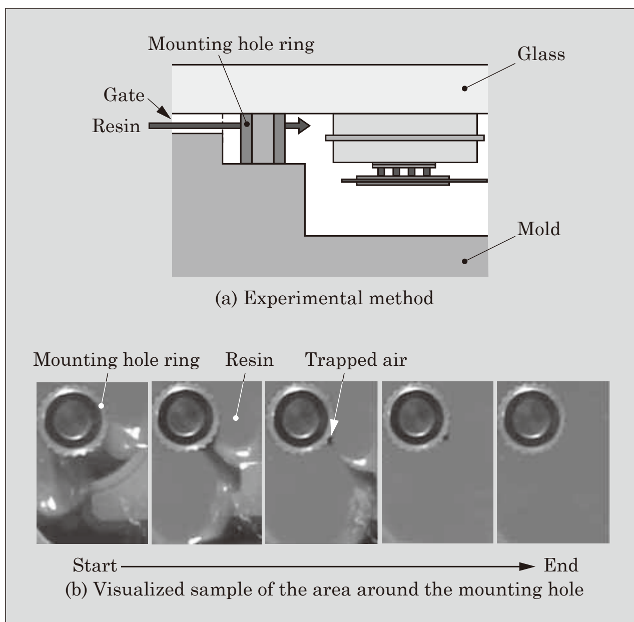

Fig. 6 Experiment of resin flow visualization

5. Postscript

This paper describes the packaging technology of the All-SiC module. For the design of the All-SiC package, not only structure design but also mold process design using simulation and practical visualization of resin flow are important.

We continue to contribute to developing the power electronics technologies and realizing a low carbon society through developing small- to large-capacity modules and broadening their application to various power electronics.

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