

Packaging Technologies for SiC Power Modules

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ABSTRACT

Wide bandgap materials such as silicon carbide (SiC) and gallium nitride (GaN) are attracting attention as materials for next-generation power semiconductor devices. Fuji Electric is currently developing new packaging technologies to take full advantage of SiC devices. Compact and highly reliable power modules with low thermal resistance and high-temperature operating capability can be realized by replacing aluminum wire bonding, solder joints and silicone gel encapsulating structures with copper pin connections, silver sintering joints and epoxy resin molding structures. Improved performances of prototype all-SiC modules and SiC diode modules with new packaging technologies have been evaluated.

1. Introduction

Recently, power modules have been widely used in industrial, consumer products and hybrid and electric vehicle applications. As the performance of Si devices used in the power modules is approaching its theoretical limits, wide bandgap (WBG) devices such as silicon carbide (SiC) and gallium nitride (GaN) are attracting attention. WBG devices have some advantages such as higher dielectric breakdown voltage, lower loss, higher switching and higher temperature operation capability compared to Si devices.

This paper introduces new packaging technologies that take full advantage of the features of WBG devices, especially SiC devices.

2. Features and technology of SiC Power Module Package

Fuji Electric is presently evaluating SiC metal-oxide-semiconductor field-effect transistors MOSFETs and SiC Schottky barrier diodes (SBDs) to be implemented in SiC modules. New packaging technology introduced in this paper can also be applied to other SiC devices such as SiC insulated gate bipolar transistors (IGBTs).

Figure 1 shows the aluminum wire bonding structure, which is currently the mainstream structure for power modules, and the newly developed package structure.

In the conventional structure, the main current paths are formed from aluminum bonding wires and the direct copper bonding (DCB) substrate. On the other hand, in the newly developed structure, circuit

paths are formed from a DCB substrate, a power board and Cu pins instead of bonding wires. Additionally, this new structure uses epoxy resins as the encapsulating material instead of silicone gel. The features and technologies of new structure that uses these new materials will be discussed below.

2.1 Downsizing

Power modules are being made smaller and smaller with the rise in power density of power chips and the reduction of thermal resistance resulting from improved packaging technology. In the conventional structure, aluminum wire requires a certain amount of area for bonding. Large current capacity power

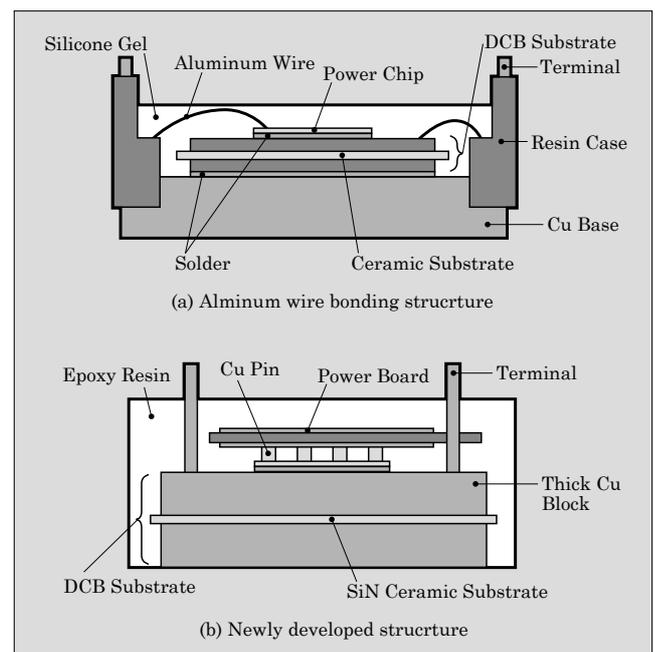


Fig.1 Comparison of power module structure

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modules require larger number of wires and result in many aluminum wires on the DCB substrate. This is a barrier to realize the high-density packaging i.e. the downsizing of power modules.

In the newly developed structure, Cu pins are used to connect power board to power chips, instead of using aluminum wires. The power board has a printed circuit board structure and current flows through its Cu pattern and Cu pins.

Because this structure allows current to flow in a vertical direction with respect to a power chip, power chips can be located close to each other. Furthermore, two layers of current paths, on both the DCB substrate and the power board, contribute to downsizing of the power module.

2.2 Low thermal resistance

In order to downsize power modules having high power density and to prevent temperature rise of the power chips, the thermal resistance of the power module package must be reduced. An alumina ceramic substrate is generally used in conventional structure shown in Fig. 1. This alumina ceramic acts as a large thermal barrier in the conventional structure due to its low thermal conductivity of about $20 \text{ W}/(\text{m}\cdot\text{K})$. In order to reduce this large thermal resistance of the alumina ceramic, various developments have been undertaken.^{(1),(2)}

In the development of this new structure, a much thicker Cu block is bonded to the silicon nitride (SiN) ceramic substrate in order to realize a further reduction of thermal resistance. The reason why a SiN ceramic substrate is used is because SiN has a larger thermal conductivity than alumina ceramic as well as large strength to endure the stress that occurs with

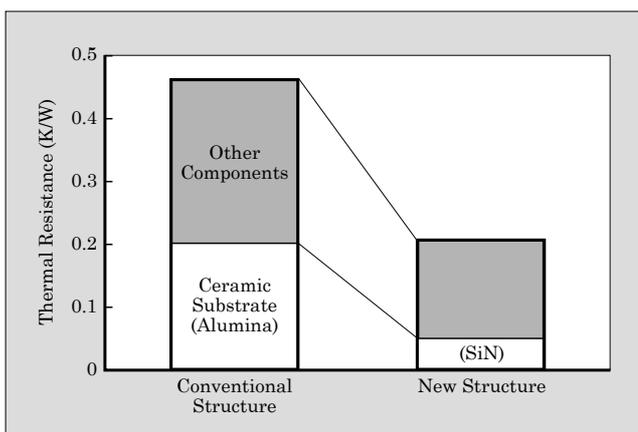


Fig.2 Comparison of power module thermal resistance

*1: The solidus line temperature is the temperature at which alloyed metal starts to melt, and the liquidus line temperature is the temperature at which alloyed metal melts completely. For pure metal, these temperatures are the same, and are called the melting point.

thick Cu block during the thermal cycle. Figure 2 compares the power module thermal resistance of the conventional alumina ceramic structure with that of the newly developed SiN ceramic structure, when implemented with the same size power chips. The thermal resistance of the ceramic substrate in the new structure is one-fourth that of the conventional structure. The new structure enables a 50% reduction in the thermal resistance of the overall structure.

2.3 High temperature operation

One of the advantages of SiC devices is the capability to operate at high temperature. When a power chip can operate at high temperature, the cooling cost can be reduced and the overall system size can be reduced as a result of a downsized cooling system. In order to realize high temperature operation, it is necessary to improve the high temperature withstanding capability of the packaging components, especially the bonding material and the encapsulating material.

Currently, a tin (Sn)-silver (Ag) compound of lead (Pb)-free solder is generally used in power modules. The solidus line temperature*1 of that solder is below 250°C . Because higher temperatures generally cause solder to deteriorate more quickly, a higher solidus temperature and melting point are preferred. However, a high temperature process would cause large stress and strain in the components. In order to reconcile these contradicting issues, Ag-sinter material is now being developed to apply as a bonding material. Figure 3 shows a cross-sectional view of the bonding area with Ag-sinter material.

Ag-sinter material exhibits superior characteristics and is capable of bonding under relatively low temperatures (ca. 300°C) and has a high melting point of ca. 962°C that is the same as Ag bulk material after sintering. Also, its thermal conductivity is larger by one digit than that of Sn-Ag compound solder.

Regarding encapsulating material, conventional silicone gel can withstand the duration of the lifetime (generally 10 years) of a power module at temperatures below 150°C , but has difficulty in enduring if the operating temperature increases. Therefore, the newly developed structure uses a new epoxy resin that has glass transition temperature of over 200°C .

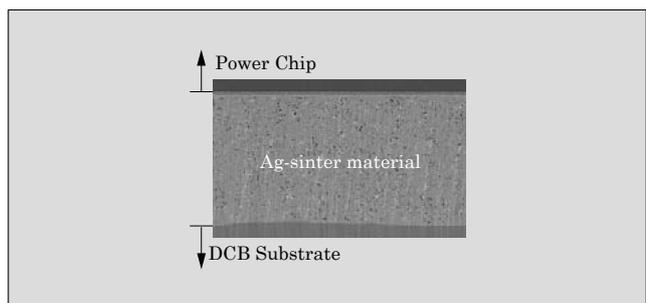


Fig.3 Cross-sectional view of Ag-sinter bonding area

2.4 High reliability

Improved reliability at high temperature is needed in order to realize high temperature operation of the power modules using SiC devices. The primary factors affecting the reliability of a power module having a conventional structure are the lifetime of the bonding area between aluminum wire and power chip electrodes, and the lifetime of the solder layer.⁽³⁾ With the new structure, because aluminum wires are replaced by Cu pins, the factors affecting reliability are different from those of the conventional structure. A power cycling test, an important reliability test for power modules, was carried out with Si devices to compare reliability with that of the conventional structure. Figure 4 compares the power cycling capability of the new structure and the conventional structure.

This test results shows that the new structure has more than 30 times the power cycling capability as compared to the conventional structure under the conditions of chip junction temperature swings (ΔT_j) of 125 K and 150 K. One of the reasons for the improve-

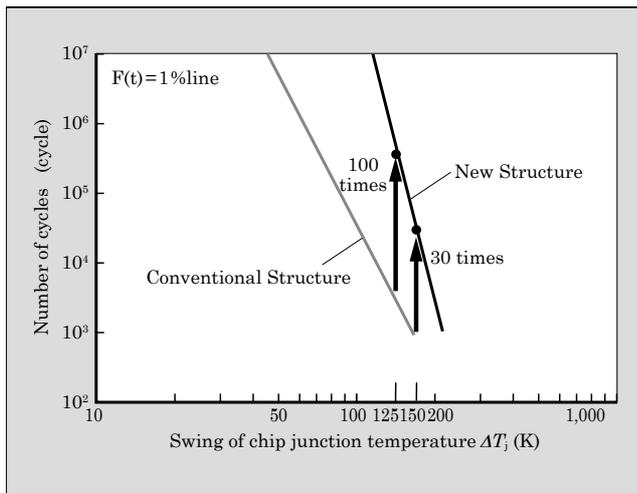


Fig.4 Comparison of power cycling capability

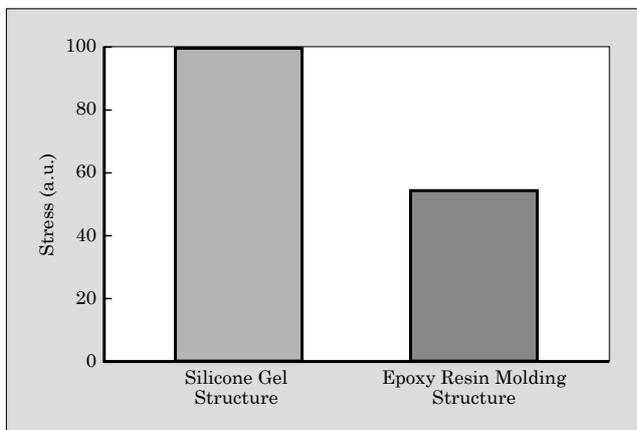


Fig.5 Comparison of stress occurring at bonding material underneath power chips

ment in power cycling capability is the epoxy resin molding structure. Figure 5 compares the stress occurring at the bonding material underneath the power chip in the cases of silicone gel and epoxy resin (result of FEM analysis). The vertical axis in Fig. 5 shows the values of stress occurring at the bonding material underneath power chip with silicone gel structure as 100.

This results shows that the epoxy molding structure reduces the stress at the bonding material by about half. It is speculated that the epoxy resin molding structure suppresses deformation of the power chips and the DCB substrate, for which expansion and constriction are repeated freely in silicone gel structure. A thermal cycling test was also carried out under the temperature range between -40°C and 150°C , and the results show that the new structure has a greater than 3,000 cycle capability.

3. Prototype Modules with New Structure

The following two types of prototype modules were designed with the new structure that realizes downsizing, low thermal resistance, high temperature operation and high reliability.⁽⁴⁾⁻⁽⁶⁾

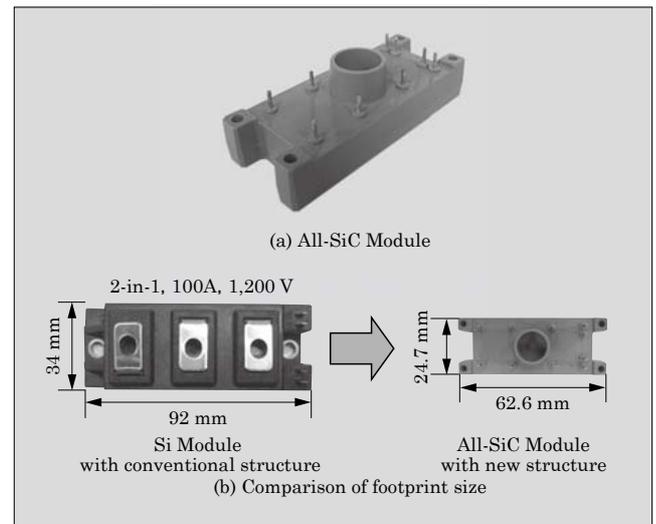


Fig.6 External view of All-SiC module and its footprint size

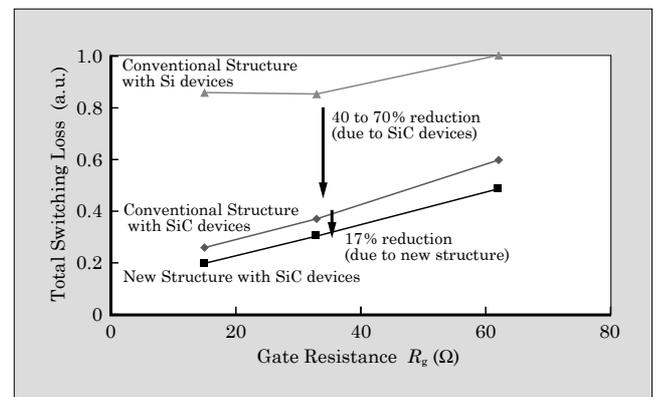


Fig.7 Loss evaluation by switching tests

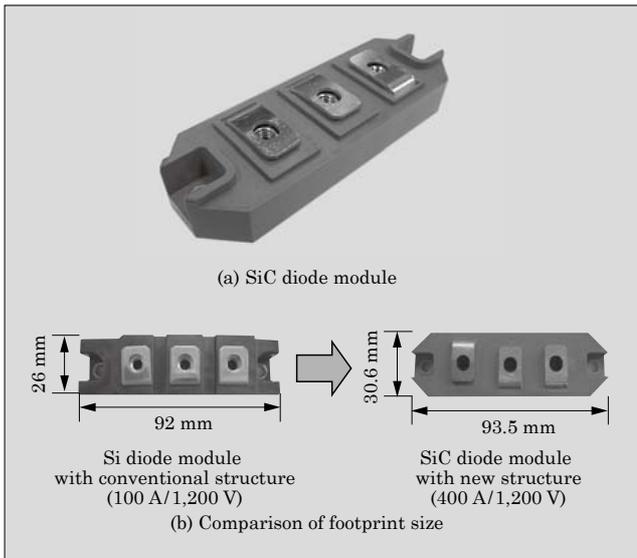


Fig.8 External view of SiC diode module and its footprint size

3.1 All-SiC module

The all-SiC module shown in Fig. 6(a) is 2-in-1 module rated at 100 A and 1200 V and equipped with SiC MOSFETs and SiC SBDs. The module has dimensions of 62.6 mm (length)×24.7 mm (width)×19.0 mm (height). Compared to a Si module having conventional structure and the same rating, the all-SiC module has a footprint of about half the size (see Fig. 6(b)).

The reasons for this small footprint size the all-SiC module are the new structure with Cu pin connection technology for the high-density mounting of power chips, the low thermal resistance structure for high thermal dissipation, and the low loss SiC devices and high temperature withstanding components having high reliability at high temperature operation.

Figure 7 shows the switching test results with different gate resistances of Si and SiC devices and different module structures in order to clarify the improvement in characteristics of the new structure and SiC devices.

The loss reduction with SiC devices is 40 to 70%, and a further 17% loss reduction is attributed to the new structure. The small parasitic inductance of the new structure as a result of the downsized current path is thought to limit the surge voltage and thereby reduce the switching loss.

3.2 SiC diode module

The SiC diode module shown in Fig. 8(a) is configured as a SiC SBD diode module with 2 arms in series and is rated at 400 A and 1200 V. The dimensions are 93.5 mm (length)×30.6 mm (width)×17.0 mm (height). Compared to a 100 A Si diode module with a conventional structure, this SiC diode module has four times the current density with about the same footprint size (see Fig. 8(b)).

4. Postscript

A new power module structure with Cu pin connections, Ag-sinter bonding and epoxy resin molding has been developed. This packaging technologies are able to take full advantage of the superior characteristics of SiC devices. Moreover, a prototype all-SiC module and SiC diode module were designed and their improved characteristics were evaluated.

In the future, Fuji Electric will verify the superior characteristics of this new power module through field tests and will continue to advance technology for the conservation of energy.

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