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Warpage Evaluation of High-Temperature Sandwich-Structured Power Module for SiC Power Semiconductor Devices

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***Abstract*—This article presents a sandwich-structured SiC power module that can be operated at 225°C. The proposed power module has two ceramic substrates that are made of different materials (Si_3N_4 and Al_2O_3). The SiC devices are sandwiched between these ceramic substrates. The module also has a baseplate soldered onto the ceramic substrate. Conventional power modules use baseplate materials with a large coefficient of thermal expansion (CTE), for example, Cu (17-18 ppm/°C and Al (23-24 ppm/°C). In the fabrication process, the soldering temperature reaches 450°C because Au-Ge eutectic solder is used. A problem was found in the fabrication process of the module because of the high soldering temperature and CTE mismatches of the components. Furthermore, for high-temperature operation, a thermal cycle of −40°C to 250°C will be needed to ensure reliability and it is important to decrease the warpage of the module during the thermal cycle. By using stainless steel (CTE: 10 ppm/°C) for the baseplate, the warpage measured at room temperature was reduced to one-third that of a module using a Cu baseplate. Further, the warpage displacement from 50°C to 250°C was also reduced.**

***Keywords*—SiC, high temperature, warpage, power module, Si_3N_4 substrate, baseplate**

Introduction

Silicon carbide (SiC) power devices have attracted a great deal of attention as future power devices. They are very attractive because they are high voltage and have low on-resistance and a short switching time. SiC power devices can be operated at high junction temperatures [1, 2]. The authors are developing a high-temperature SiC power module that can be operated at a junction temperature greater than 200°C, at which silicon devices cannot be operated, because of the high-temperature characteristics of SiC [2]. A high-temperature power module requires a smaller heat sink [3]. As a result, devices such as inverters can be made much smaller than conventional devices.

A power module generally has a structure in which power semiconductor devices are bonded on a metallized ceramic substrate. The other side of the ceramic substrate is attached to a heat sink through thermal grease for cooling. Recently, instead of using thermal grease, a structure with a ceramic substrate directly bonded on a heat sink has been developed to reduce the thermal resistance of power modules [4]. The power module proposed in this article also has a structure in which a ceramic substrate is directly bonded to a heat sink to reduce the thermal resistance.

Regarding the electrical performance, SiC devices have a very short switching time, and this generates a large surge voltage. To prevent this surge, a structure in which SiC metal-oxide-semiconductor field-effect transistors (MOSFETs) are sandwiched between two ceramic substrates was chosen. By adopting this structure, the inductance of the module can be reduced [5-7].

On the other hand, for operation at high temperature, Au-Ge eutectic solder [8] is used. In the fabrication process of the proposed module, the soldering temperature is much higher than that of a conventional power module [9]. This high-temperature process could cause bonding defects resulting from deformation of the elements of the module. This deformation is caused by mismatches of the coefficients of thermal expansion (CTEs) of the materials used in the module. Further, the CTE mismatch between the ceramic substrate and heat sink causes excessive warpage of the module, especially if the heat sink is made of Al or Cu, which have very large CTEs compared with ceramic substrates.

Operating the power module at high temperature also causes excessive warpage displacement of the module, which might reduce the long-term reliability. To ensure the long-term reliability of the module, which is designed to be operated above 200°C, a thermal cycle from −40°C to 250°C is needed. Further, it is very important to understand how the warpage behaves during the thermal cycle.

In this study, a sandwich-structured power module that can be operated at 225°C was realized. The structure and fabrication process of the power module are first explained. Then some

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problems with the module are identified. The countermeasures and method of evaluation are also mentioned. Next, the measurement and simulation results are discussed. Operation at 225°C is also confirmed. Finally, the conclusion is presented.

Structure and Fabrication Process

A. Structure of the Module

Fig. 1 shows the structure of the proposed module. The module includes two arm circuits that correspond to one leg of the inverter. To reduce the inductance of the module, a structure in which SiC MOSFETs are sandwiched between two metallized ceramic substrates was chosen instead of conventional Al wire bonding. The drain pads of the SiC devices are soldered to ceramic substrate 1. The other side of ceramic substrate 1 is soldered directly to the heat sink. However, for simplicity, the module shown in Fig. 1 has a baseplate instead of heat sink. The module discussed in the following sections also has a baseplate. The source and gate pads are joined to ceramic substrate 2 by Al bumps [10] to connect electrically. On the other side of ceramic substrate 2, passive elements can be mounted. For example, a capacitor and resistor can be mounted to constitute a snubber circuit. Metal blocks are used to connect the two substrates electrically, and all the solder used in the module is Au-Ge eutectic solder, which has a melting temperature of 356°C. The metal blocks are made of Cu-W, considering the CTE mismatch in the vertical direction against the SiC devices and Al bumps. Ceramic substrate 2 has vias to connect the upper and lower Cu wiring patterns electrically. To form complex structure such as vias, alumina is used for ceramic substrate 2. On the other hand, Si_3N_4 is used for ceramic substrate 1 because it has greater toughness and a higher thermal conductivity than alumina.

The SiC devices used in the module are CPMF-1200-S080B (CREE) [11]. Fig. 2 shows a sample of the proposed module.

B. Fabrication Process

Fig. 3 shows the three-step module fabrication process. In the first step, SiC devices are flip-chip bonded to ceramic substrate 2 at room temperature by Al bumps that were built on the SiC devices. In the second step, the metal blocks are soldered with Au-Ge eutectic solders having melting temperature of 356°C in vacuum chamber. The temperature of the vacuum chamber was set to 450°C to ensure the solder wetting is well. Further, 20 g weight was set on the sample to assist the solder wetting. Finally, ceramic substrate 1, ceramic substrate 2, the baseplate, and the passive elements, which constitute a snubber circuit, are soldered all at once in vacuum chamber. The snubber circuit was placed at the desired position by positioning tool made of carbon. The solder used in this process was also Au-Ge eutectic solder. The temperature of the vacuum chamber was set to 450°C and 20 g weight was also set on the sample via the positioning tool.

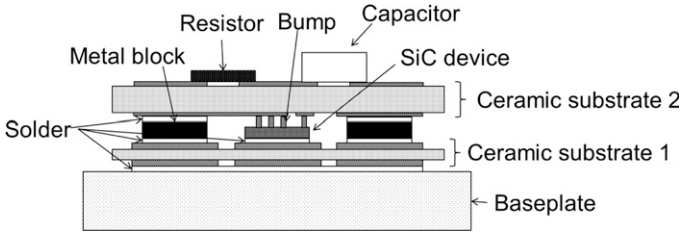

Fig. 1. Structure of the proposed module.

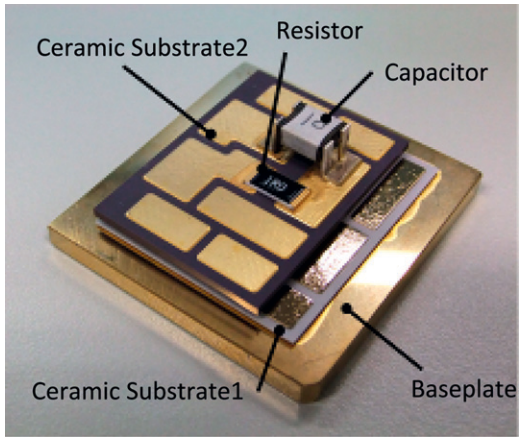

Fig. 2. Sample of the module.

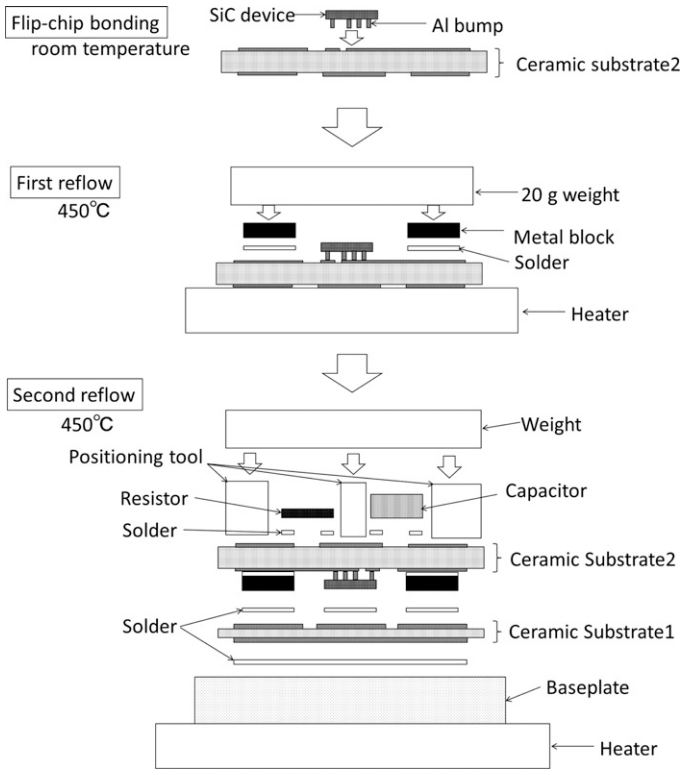

Fig. 3. Module fabrication process.

Evaluation Methods

A. Warpage of Ceramic Substrate 1

As mentioned previously, the proposed power module is fabricated at 450°C, which is an extremely high temperature

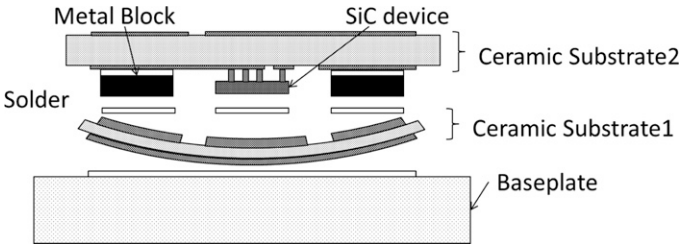

Fig. 4. Warpage of ceramic substrate 1 under second reflow temperature.

compared with that used for a conventional power module using silicon devices. Because of the high-temperature fabrication process, the difference in the thermal expansion increases dramatically; this results in warpage of ceramic substrate 1, which may cause bonding defects [12, 13]. The ceramic substrates used in typical power modules have Cu wiring patterns on one side, to which semiconductor devices are bonded. On the other side of the ceramic substrate, a Cu solid pattern is formed. If the ceramic substrate having the solid pattern is used for ceramic substrate 1 in the proposed module, the imbalance of the CTEs between the wiring-patterned side and the solid-patterned side will warp ceramic substrate 1. Fig. 4 shows a schematic view of the warpage occurring during fabrication.

Here, ceramic substrate 1 is made of Si_3N_4, and its thickness is 320 μm. The Cu wiring patterns and solid pattern are each 150 μm thick. On the other hand, ceramic substrate 2 is made of alumina and is 1,000 μm thick; 100-μm-thick wiring patterns are formed on each side. Because of the thick ceramic layer and thin Cu wiring patterns, the warpage of ceramic substrate 2 can be ignored.

In this article, a countermeasure for reducing the warpage of ceramic substrate 1 was applied by designing the Cu wiring patterns on both sides of the ceramic substrate symmetrically to balance the stress. To confirm the effect of the countermeasure, the warpage of ceramic substrate 1 was measured at 50°C and 250°C, and the displacement from 50°C to 250°C was obtained. The digital image correlation (DIC) method [14] was used to measure the warpage of the ceramic substrate. As shown in Fig. 5, the ceramic substrate sample is placed in a chamber with a hot plate inside. The sample is heated to 250°C. The change in the warpage between 50°C and 250°C is determined by observation with a stereo CCD camera.

B. Warpage of the Module at Room Temperature

In the cooling process during fabrication, the module undergoes the warpage shown in Fig. 6. This warpage is caused by the CTE mismatch between the ceramic substrates and the baseplate. It can be reduced by using a baseplate material having a CTE similar to those of the ceramic substrates.

A simulation using the finite element method (FEM) was performed to estimate the approximate warpage of the module. ANSYS Mechanical was used as the simulation tool. In the simulation, 356°C was defined as the stress-free temperature, and room temperature was defined as 22°C. The material characteristics and dimensions of the components used in the simulation are shown in Table I. To confirm the results, other baseplate materials were also simulated. Al, another typical baseplate material, was simulated; it has a larger CTE than

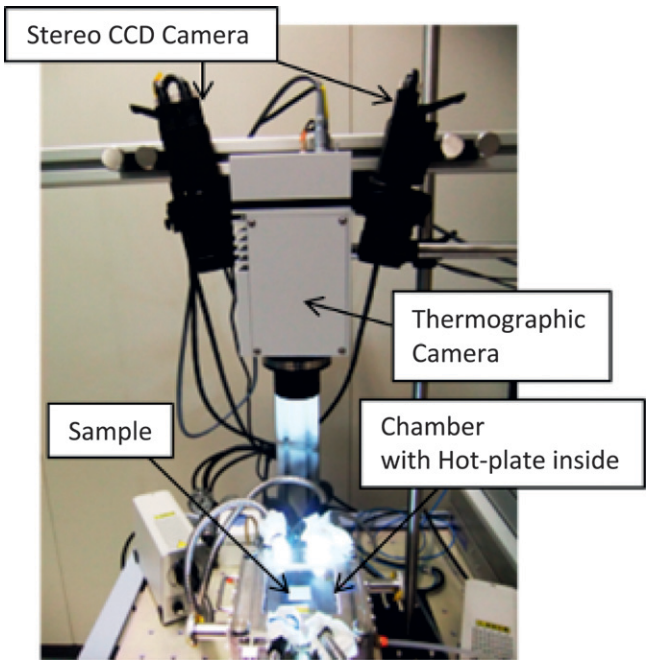

Fig. 5. Digital image correlation (DIC) measurement system.

Cu. The composite materials Cu-W and composite materials 1 and 2 were also simulated. The CTEs of these composite materials can be controlled to some degree to match those of the ceramic substrates.

The warpage was evaluated using different baseplate materials having different CTEs. The module used to evaluate the warpage was structured as follows. A baseplate with a thickness of 3 mm was used. The SiC devices were omitted because they are joined to ceramic substrate 2 by Al bumps that can absorb stress, so the effect on the warpage is negligible. The material of ceramic substrate 1 is Si_3N_4, and that of ceramic substrate 2 is alumina. The apparent CTEs of ceramic substrate 1 and ceramic substrate 2 are calculated as approximately 6 ppm/°C.

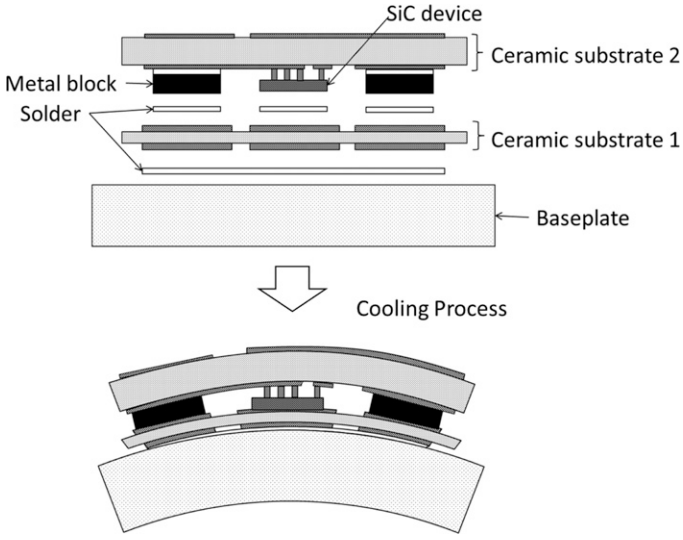

Fig. 6. Warpage of the module at room temperature.

Table I
Material Characteristics and Dimensions of the Components Used in the Simulation

Components	Materials	CTE (ppm/°C)	Young's modulus (GPa)	Dimensions (mm)
Ceramic substrate 1	Si_3N_4	3	300	28 × 24 × 0.32
Ceramic substrate 2	Alumina	7	300	28 × 20 × 1
Wiring patterns	Cu	17	110	0.15 mm thick (ceramic substrate 1) 0.1 mm thick (ceramic substrate 2)
Metal block	Cu-W (89W-11Cu)	6.5	330	2 × 5 × 0.44
Solder	Au-Ge	13	72.7	thickness 0.03 mm for metal block thickness 0.05 mm for baseplate
Baseplate	A1	23	71	32 × 34 × 3
	Cu	17	110	32 × 34 × 3
	SUS410	10	200	32 × 34 × 3
	Cu-W (85W-15Cu)	7.2	310	32 × 34 × 3
	Composite material 1	6.5	200	32 × 34 × 3
	Composite material 2	7.5	220	32 × 34 × 3

For the baseplate, Cu (17 ppm/°C) or SUS410 (10 ppm/°C) was used. Cu is generally used as a baseplate material, and SUS410 has a CTE that is closer to that of the ceramic substrate than the CTE of Cu. A laser microscope was used to measure the warpage of the samples. The results will be discussed in the "Results" section.

C. Warpage Displacement from 50°C to 250°C

To operate the module at 225°C, a thermal cycle from −40°C to 250°C is needed to ensure long-term reliability. Therefore, understanding how the warpage behaves in this wide temperature range is very important for the long-term reliability. Therefore, the warpage displacement between 50°C and 250°C was evaluated. Fig. 7 illustrates the warpage behavior at 50°C and 250°C schematically. The warpage displacement was estimated by subtracting the warpages at 250°C from that at 50°C. The DIC method [14] was used to measure the warpage.

An FEM-based simulation was also performed to estimate the approximate warpage displacement from 50°C to 250°C. The simulation was simplified by defining the room temperature as flat (stress-free), increasing the temperature to 250°C, and obtaining the displacement between the two temperatures.

D. Double-Pulse Test

To confirm that the proposed sandwich-structured SiC power module can operate at temperatures above the limit for silicon devices, a double-pulse test [15, 16] was performed on a hot plate heated to 225°C. Fig. 8 shows the power module used in the test. The module was encapsulated with silicone gel and stored in a resin case. To connect it electrically to the power source and gate driver, the Cu terminals are bonded with Au–Ge eutectic solder.

Results

A. Warpage Evaluation of Ceramic Substrate 1

The measured warpage displacement of ceramic substrate 1 between 50°C and 250°C is shown in Fig. 9, which also shows the warpage at 50°C and 250°C. The surface on which the SiC devices are soldered is measured using DIC. The measurement results for ceramic substrate 1 with a solid Cu pattern are shown in Figs. 9a-c, and those for ceramic substrate 1 with a symmetric wiring pattern on both sides are shown in Fig. 9d-f.

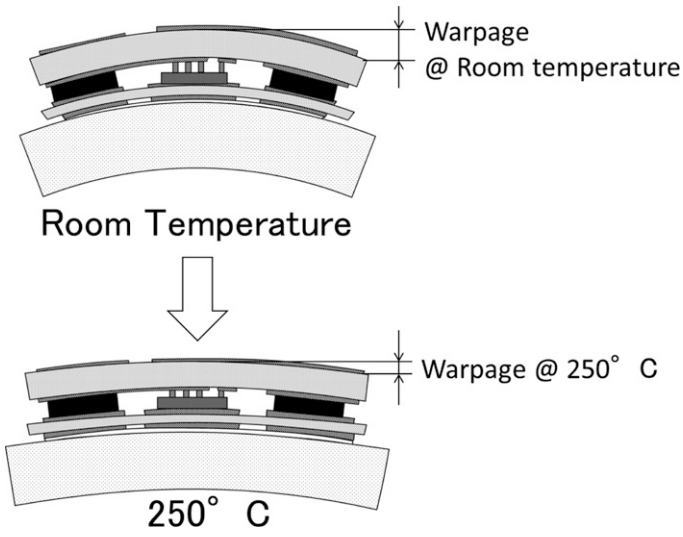

Fig. 7. Warpage of the module at room temperature and 250°C.

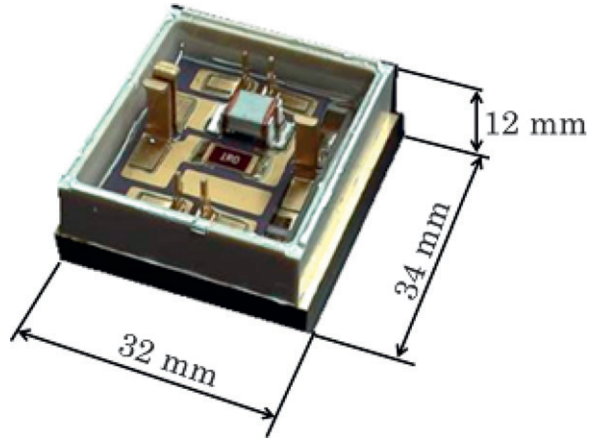

Fig. 8. Module sample for double-pulse test.

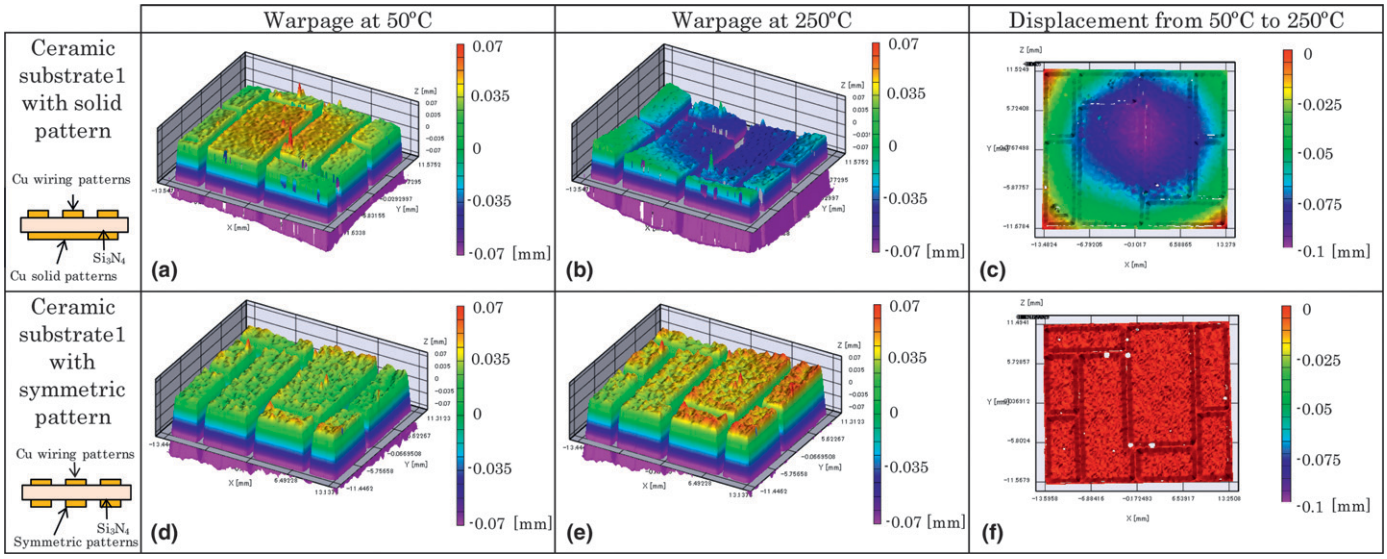

Fig. 9. Warpage of ceramic substrate1 at 250°C measured by DIC. (a), (b), and (c) Ceramic substrate having solid Cu pattern. (d), (e), and (f) Ceramic substrate having symmetric Cu pattern on both sides.

The substrate with a solid pattern exhibits upward warpage at 50°C (Fig. 9a). Downward warpage occurs when the substrate is heated to 250°C (Fig. 9b) owing to the imbalance of the Cu volume on each side of the substrate. The displacement of the substrate with a solid pattern between 50°C and 250°C is approximately 90 μm (Fig. 9c). On the other hand, the substrate having a symmetric wiring pattern on both sides exhibits no warpage at both 50°C and 250°C, and the displacement is less than 10 μm (Figs. 9d-f). By adopting the symmetric wiring pattern on both sides of the ceramic substrate, the warpage displacement from 50°C to 250°C was reduced to one-ninth that of the ceramic substrate having a solid pattern on one side or less. In the fabrication process, ceramic substrate 1 will be soldered at 356°C, which is much higher than 250°C. The warpage of the ceramic substrate without a countermeasure can be estimated as 140 μm at 356°C.

B. Warpage Evaluation of the Module at Room Temperature

Fig. 10 shows the warpage of modules having Cu and SUS410 baseplates measured at room temperature using a laser microscope. The surface of ceramic substrate 2, on which passive elements can be mounted, was measured to evaluate the warpage of the module. Because the dispersion of the Cu wiring pattern thickness is large, which makes the result difficult to understand, the Cu wiring pattern is blanked out and appears white. The ceramic part of ceramic substrate 2 was evaluated. The module using the Cu baseplate showed an upwardly convex warpage of approximately 140 μm (Fig. 10a). This is caused by the difference in CTEs between the ceramic substrate and the baseplate in the cooling process during fabrication. Cu has a larger CTE than the ceramic substrate and thus shrinks much more than the ceramic substrate. Consequently, upwardly convex warpage occurred. On the other hand, the module using the SUS410 baseplate also exhibited upwardly convex warpage, but the measured warpage was only approximately 40 μm (Fig. 10b). By adopting SUS410 for the baseplate, the warpage was reduced to one-third that of the module using the Cu baseplate or less.

Fig. 11 shows the results of a simulation under the following conditions. The initial condition was stress-free at 356°C, which is the melting temperature of Au-Ge eutectic solder. Warpage was simulated by cooling to room temperature. The warpage was evaluated by determining the displacement of the upper surface of ceramic substrate 2. Figs. 11a and 11b show the simulation results for the module using Cu and SUS410 baseplates, respectively. The simulation results were confirmed to exhibit the same tendency as the measurement results. Fig. 12 compares the simulation and measurement results. The horizontal axis is the CTE of the baseplate, and the vertical axis is the warpage of the module. In addition, modules using Al, Cu-W, and composite material baseplates (as shown in Table I) were also simulated. The simulation results agree well with the measurement results. Thus, it is possible to predict the warpage

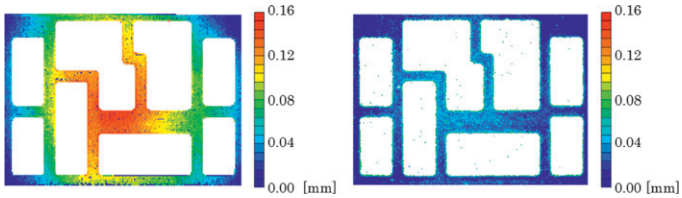

Fig. 10. Warpage of module at room temperature measured by laser microscope. (a) Cu baseplate sample and (b) SUS410 baseplate sample.

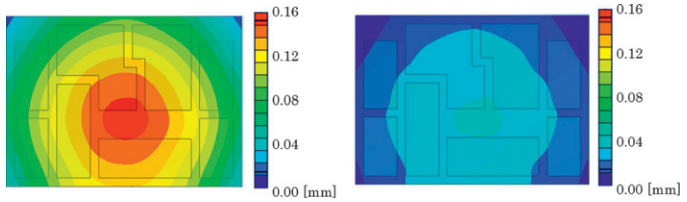

Fig. 11. Simulated warpage of module at room temperature. (a) Cu baseplate sample and (b) SUS410 baseplate sample.

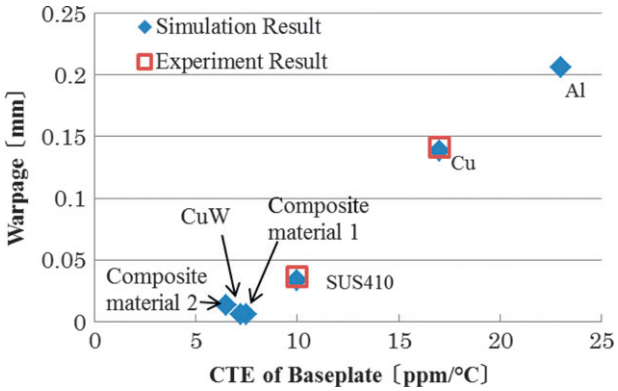

Fig. 12. Warpage vs. CTE of the baseplate at room temperature.

that occurs in the module with different baseplate materials. The warpage of the module using a baseplate with a CTE of 6-7 ppm/°C, such as Cu-W and composite material, is predicted to be the smallest. This agrees well with the apparent CTE of ceramic substrates 1 and 2. On the other hand, the Al baseplate is predicted to have the largest warpage among these materials because of its large CTE.

C. Evaluation of Warpage Displacement from 50°C to 250°C

The displacement from 50°C to 250°C was measured using DIC by referencing the warpage at 50°C. The results are shown in Fig. 13, which also shows the warpage at 50°C and 250°C. The displacement between 50°C and 250°C was obtained by subtracting the warpage at 250°C from that at 50°C.

The warpage of the module using the Cu baseplate at 50°C (Fig. 13a) reflects mainly the Cu wiring pattern of ceramic substrate 2, and the module exhibits upward warpage, which agrees with the laser microscope measurement result at room temperature. The warpage of the module using the SUS410 baseplate at 50°C (Fig. 13d) also agrees with the laser microscope measurement result. Raising the temperature to 250°C

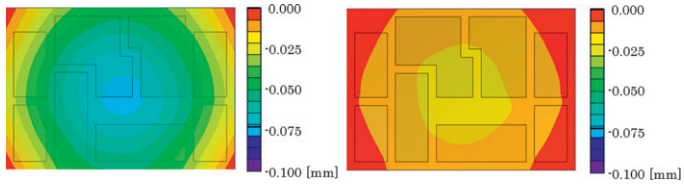

Fig. 14. Simulated warpage displacement from room temperature to 250°C. (a) Cu baseplate sample, (b) SUS410 baseplate sample.

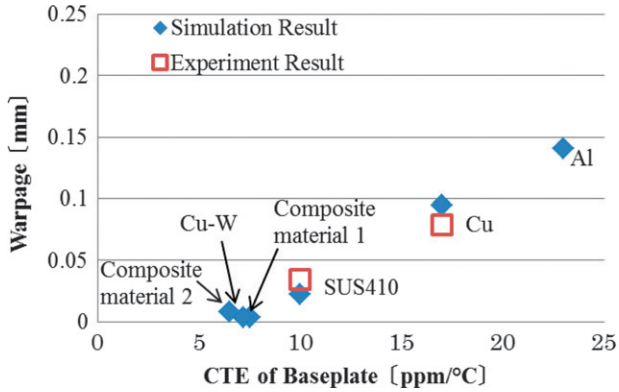

Fig. 15. Warpage displacement vs. CTE of the baseplate from 50°C to 250°C.

significantly alleviated the warpage of the module using the Cu baseplate (Fig. 13b). From these results, the displacement of the module using the Cu baseplate between 50°C and 250°C is obtained as 80 μm (Fig. 13c). On the other hand, the warpage of the module using the SUS410 baseplate at 250°C (Fig. 13e) differs little from that at 50°C (Fig. 13d). As a result, a displacement of 35 μm between 50°C and 250°C was obtained for this module. This confirms that the tendency was the same as that obtained by measuring the warpage at room temperature.

The simulated warpage displacement is shown in Fig. 14. The initial condition was stress-free at room temperature.

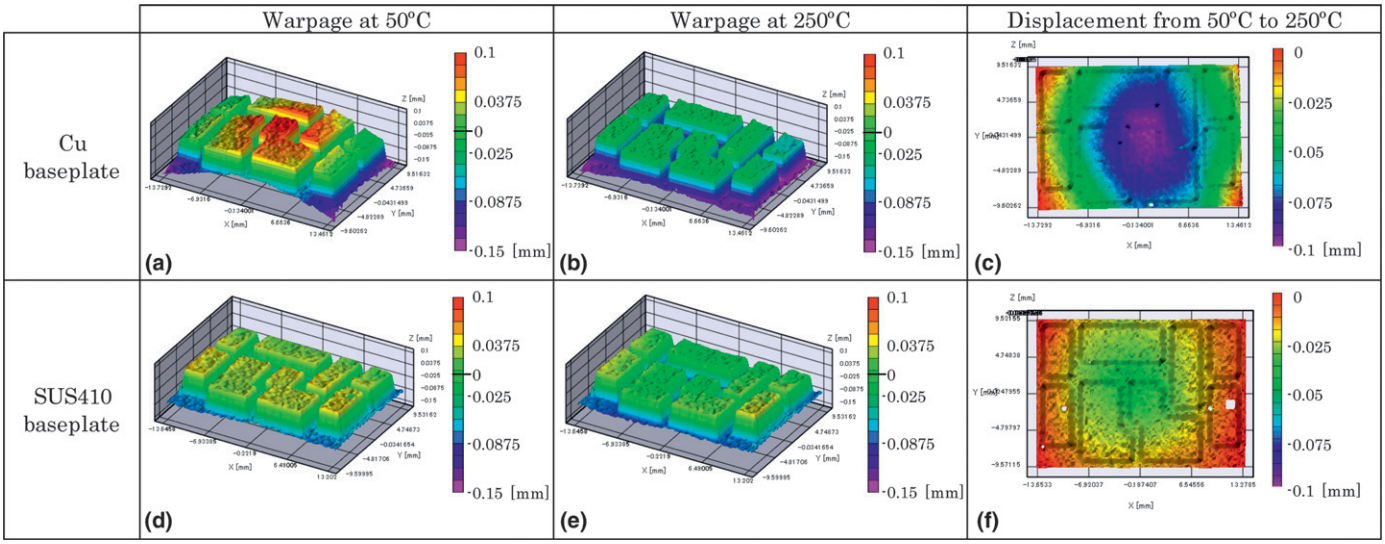

Fig. 13. Warpage displacement of module from 50 to 250°C measured by DIC. Warpage of Cu baseplate sample at (a) 50°C and (b) 250°C, and (c) warpage displacement of Cu baseplate sample from 50°C to 250°C. Warpage of SUS410 baseplate sample at (d) 50°C and (e) 250°C and (f) warpage displacement of SUS410 baseplate sample from 50°C to 250°C.

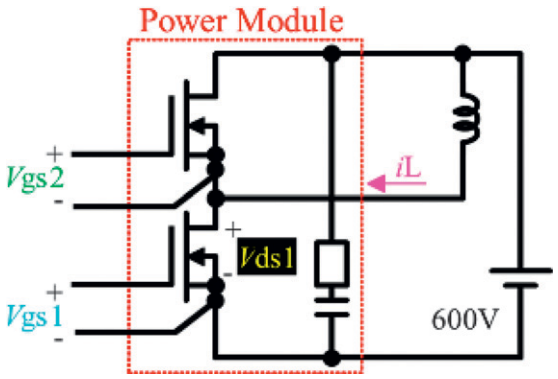

Fig. 16. Equivalent circuit of the module.

Warpage was simulated by raising the temperature to 250°C. These conditions were used to obtain the displacement between the two temperatures but cannot be used to obtain the absolute warpage, as mentioned above. The warpage of the upper surface of ceramic substrate 2 was evaluated. Figs. 14a and 14b show the simulation results for the modules using the Cu and SUS410 baseplates, respectively. The simulation result was confirmed to exhibit the same tendency as the measurement result. In addition, the relationship between the CTE of the baseplate and the warpage displacement from 50°C to 250°C is shown in Fig. 15, which includes the results for modules using Al, Cu–W, and composite materials 1 and 2, as shown in Table I. The modules using baseplates with a comparatively large CTE, such as Cu and Al, exhibit excess warpage and can be predicted to have some problems with long-term reliability [12, 17]. However, if the baseplate has a CTE similar to that of the ceramic substrate, the long-term reliability may be expected to improve. To confirm this, a thermal cycle will be conducted in future work. In addition, warpage during the power cycle must be considered.

D. Double-Pulse Test Result

A double-pulse test [15, 16] was conducted using the power module to which countermeasures were applied (Fig. 8). The test was performed on a hot plate heated to 225°C. The equivalent circuit of the module is shown in Fig. 16. V_{DC} is set to 600 V. The waveform of the double-pulse test is shown in Fig. 17. The first pulse width is 30 μs, and the second is 8 μs. The current is set to 25 A. A 20-ns current fall time and 50 V surge voltage were observed. The stray inductance of the module was estimated as 5 nH by fitting the result. This test result confirms that the module can operate at 225°C, which is above the limit for silicon devices.

Conclusions

- A sandwich-structured power module that can be operated at 225°C was realized, and measurements and simulations of the module's warpage yielded the following information.

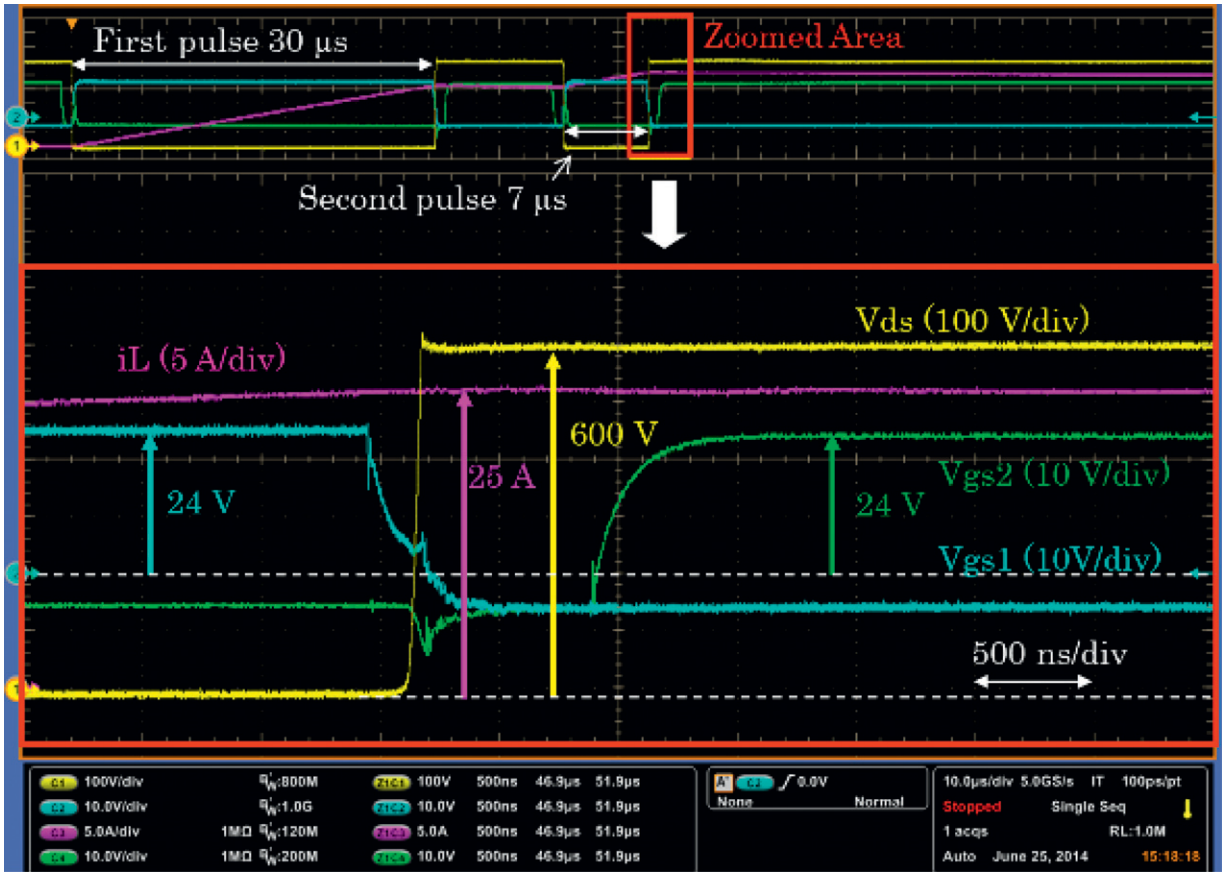

Fig. 17. Wave form of double-pulse test at 225°C.

- In the high-temperature fabrication process using Au-Ge eutectic solder (melting point, 356°C), soldering defects caused by warpage of ceramic substrate 1 occurred. The problem was alleviated by adopting symmetric wiring patterns on both sides of ceramic substrate 1 instead of a conventional solid pattern.
- The warpage of the module could reduce the long-term reliability. The warpage is caused by a CTE mismatch between the ceramic substrates and baseplate. By adopting a SUS410 baseplate, the warpage of the module at room temperature was reduced to one-third that of a conventional Cu baseplate. The warpage displacement from 50°C to 250°C was also reduced by using a SUS410 baseplate.
- A double-pulse test of the proposed module was performed at 225°C; it confirmed that the module can be operated at a temperature above 200°C, at which silicon devices cannot be operated.
- In future works, the correlation between the warpage and reliability will be confirmed by implementing a thermal cycle test. Further, the warpage during a power cycle will be considered. In addition, the cooling performance of the SUS410 air-cooling heat sink will be evaluated.
- Additionally, the warpage depends not only on the CTE mismatches but also on the thickness, Young's modulus, yield stress, thermal conductivities, and other parameters. These parameters will be considered in the next step.

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