Maleimide Resin Blends with Enhanced Toughness for High-Temperature Semiconductor Packaging

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Abstract

Highly heat-resistant molding materials are required for manufacturing power modules. We investigated a sheet molding material where a blend of rigid and flexible maleimide resins (MA and MB, respectively) offer high heat resistance and toughness enhancement for wide-bandgap semiconductor packaging applications. We found that the MB formulation with 30% by weight of the maleimide resin enhanced toughness of the maleimide resin blend. This formulation passed −55/200°C package-level temperature cycle tests without compromising the heat resistance. We also found that the maleimide resin blend exhibited a strong adhesion strength to Cu foil (7.3 N·cm⁻¹). This performance maintained even after thermal storage at 200°C for 1,000 h. We think that the developed sheet molding material can be used for high-temperature-operating power modules manufactured with fan-out panel-level packaging.

Keywords: Maleimide, Molding Sheets, Power Modules, Wide Bandgap, Panel Level Packaging, Embedded Die, Reliability, Adhesion, Heat Resistance, Flexural Toughness

1. Introduction

Increasing the efficiency of power modules in electric vehicles is vital for greenhouse gas reduction. For the sake of reducing power loss in the power modules, compound semiconductors (SiC or GaN) that operate with lower loss than Si semiconductors have been increasingly adopted as switching elements for power modules.[1, 2] These wide-bandgap (WBG) semiconductors can operate at temperatures exceeding 200°C, while the operable temperature limit for Si semiconductors is approximately 150°C. As a result, materials with higher heat resistance than epoxy resin, which is conventional semiconductor molding material, are emerging for WBG power devices.

Recently, maleimide, benzoxazine, and cyanate ester resin have been studied as heat-resistant molding material. [3–7] In these literatures, maleimide resin, which is highly heat-resistant and does not produce desorbed components during thermosetting because of its rigid succinimide structure, has been recognized as a promising candidate of alternative material to epoxy resin. However, cured maleimide resin is too brittle so that it hinders its applications in semiconductor packaging. Studies have been conducted to reduce its brittleness by modifying maleimide resin with an allyl compound.[8–12] The maleimide and allyl groups undergo the ene reaction, as shown in Fig. 1(a), and the Diels–Alder reaction, as shown in Fig. 1(b), to form the cross-linked product. According to Rozenberg

![Fig. 1 Reactions between maleimide and allyl groups: (a) Ene reaction, (b) Diels-Alder reaction.](image_url)
et al., 2,2’-Diallylbisphenol A (DABPA) has a unique reactivity in allyl compounds. The Diels–Alder reaction does not proceed because of the steric hindrance of the isopyridine group. Instead, as shown in Fig. 2(a), the homopolymerization of the intermediate produced in the ene reaction or, as shown in Fig. 2(b), the copolymerization of the intermediate and the maleimide group proceeds sequentially.[13, 14]

Meanwhile, studies have been conducted to apply fan-out packages (FOPs) as the packaging of standard logic ICs.[15–18] Because FOPs form a re-distribution layer (RDL) on the complex that molds the chip, they can provide both small and thin packaging. Furthermore, their short wiring length provides superior electrical properties. In addition, their manufacturing costs are low because FOPs do not require a packaging substrate. The main manufacturing method for FOPs is fan-out wafer-level packaging (FOWLP), which is performed on a wafer-sized carrier. However, the productivity of this method is low because a rectangular package is formed on a circular carrier. Therefore, researchers have developed fan-out panel-level packaging (FOPLP), which forms an RDL on a rectangular panel with a larger area than that of the wafer.[19–21] The leading resin molding method for FOWLP is compression molding, which uses a granulated or liquid molding material. Moreover, both of these materials, along with sheet molding materials, can be selected for FOPLP. Sheet molding materials encapsulate chips using a laminator, a type of PCB manufacturing equipment, eliminating the need for large molding equipment and expensive metallic molds. In recent years, researchers have developed power modules that use FOPLP or the technology that applied it, i.e., embedded die technology.[22–27] Glass-fiber-reinforced composites have also been used as a sheet molding material for power modules.[28, 29] However, although these composites facilitate the control of panel warpage, they do not allow for effective impregnation with resin and make it challenging to produce thin packaging. Furthermore, a maximum of 175°C was employed in these studies.

Based on these backgrounds, we established a basic formulation of a heat-resistant sheet molding material using a curing system of maleimide resin and DABPA with metal oxide particles instead of glass fibers and phenoxy resin as a binder. This molding material, which incorporates 50% by weight silicon oxide particles, had highly fluid with a viscosity of $6.8 \times 10^3$ Pa·s at 90°C. The 5% weight loss temperature of the cured product reached 442°C based on thermogravimetric analysis and was expected to be applied in FOPLP power modules owing to its superior heat resistance.[30] Furthermore, a subsequent investigation revealed that adding a heterocyclic compound containing amino groups to the molding material preserved extremely high adhesiveness on Cu foil despite being exposed to 200°C for 1,000 h.[31] However, the formulation needed to be improved because the cured formulation was brittle and prone to fracture under stress loading. Therefore, this study investigated a blend of rigid skeleton maleimide resin and flexible skeleton maleimide resin that offers high heat resistance and reducing brittleness. The target heat resistance was set at 200°C. To enhance dimensional stability, we set the filling rate of silicon oxide particles to 74% by weight. Generally, introducing flexible chains to molecular structures increases toughness but decreases heat resistance. Furthermore, filling the molding material with particles at a high rate lowers properties, such as fluidity, adhesiveness, and toughness. Therefore, we prepared molding materials from two types of maleimide resins with different blending ratios and evaluated their fluidity, as well as heat resistance, mechanical properties, and adhesiveness of cured formulations. The applicability of power modules manufactured by FOPLP is discussed. Finally, based on the results of package-level reliability, the formulation of a high-toughness sheet molding material that endured 200°C is proposed.

Some of this work has been presented in preliminary form.[32]
2. Experimental Procedure

2.1 Materials
The evaluation sheets comprised maleimide resins, a curing agent, a binder resin, coupling agents, and a filler. Two types of maleimide resin were used: a polymaleimide compound with a rigid molecular structure possessing a biphenyl skeleton (equivalent weight of maleimide group: 250 g·eq⁻¹; hereinafter referred to as MA) and a bismaleimide compound with a flexible molecular structure possessing long-chain alkyls (equivalent weight of maleimide group: 850 g·eq⁻¹; hereinafter referred to as MB), as shown in Fig. 3. DABPA was used as the curing agent such that the maleimide and allyl groups had a ratio of 2:1. Considering compatibility and heat resistance, we used phenoxy resin having a weight-average molecular weight of 30,000 and a glass transition temperature \( T_g \) of 150°C as the binder resin, accounting for 5% by weight of the entire formulation. A heterocyclic compound containing amino groups and 3-glycidyloxypropyltrimethoxysilane was used as coupling agents. The filler was formulated with silicon oxide particles with an average particle diameter of 0.5 μm and maximum particle diameter of 2.0 μm, accounting for 74% by weight of the entire formulation. These materials were dissolved in methyl ethyl ketone to prepare a solution with a solid concentration of 60% by weight. The solution was applied to a polyethylene terephthalate substrate with a release layer containing alkyd resin series as the main component, and evaluation formulations were obtained by drying it. As listed in Table 1, four blending ratios were used.

2.2 Characterization of the uncured material

2.2.1 Thermal characterization
The thermal reaction behavior was investigated using differential scanning calorimetry (DSC; TA Instruments, DSC Q2000). The evaluation sheet was sealed in an aluminum hermetic pan, and the heat flux from 50°C to 300°C was measured with a heating rate of 3°C·min⁻¹ and nitrogen flow rate of 50 mL·min⁻¹.

2.2.2 Rheological characterization
We used a rheometer (Anton Paar, MCR301) to investigate the complex viscosity and loss factor of the formulation laminated to 1 mm from 30°C to 150°C with a heating rate of 5°C·min⁻¹ and frequency of 1 Hz, respectively.

2.3 Characterization of the thermally cured material

2.3.1 Thermal stability
The thermal decomposition behavior of the cured formulation was investigated using a differential thermal/thermogravimetric analyzer (Shimadzu, DTG-60) to determine the thermal weight loss rate of the formulation cured with a thermal history of 200°C for 4 h, from 50°C to 600°C. The heating rate and airflow rates were 10°C·min⁻¹ and 100 mL·min⁻¹, respectively. The specimen was the bulk formulation of 25–35 mg and 200 μm-thick.

2.3.2 Mechanical property
The mechanical properties of cured formulations such as storage modulus, thermal expansion, and flexural properties were investigated. We used a dynamic mechanical analyzer (NETZSCH, DMA242E) to measure storage modulus from 0°C to 300°C under the following conditions: a heating rate of 5°C·min⁻¹, frequency of 1 Hz, amplitude of 2.5 μm, and specimen size of 20 mm (length) × 5 mm (width) × 200 μm (thickness), respectively. We used a thermomechanical analyzer (NETZSCH, TMA4000SE) to measure thermal expansion from 0°C to 300°C under the following conditions: a heating rate of 5°C·min⁻¹, frequency of 1 Hz, amplitude of 2.5 μm, and specimen size of 20 mm (length) × 5 mm (width) × 200 μm (thickness), respectively, and load of 2 g. We used a tensile/compression tester (Shimadzu, Autograph AGS-X) to measure flexural properties by three-point bending testing under a fulcrum distance, pushing speed, and specimen size of 6 mm, 0.5 mm/min, and 5 mm (width) × 200 μm (thickness), respectively. The formulations cured with a
A thermal history of 200°C for 4 h were used for these measurements.

2.3.3 Adhesion properties

We studied successive changes in the adhesiveness of the formulations on Cu and Si upon high-temperature storage. Figure 4 presents the test configuration for evaluating adhesiveness. Cu adhesiveness was investigated by 90° peel testing. First, a composite was made using a vacuum press laminator (Nikko-Materials, V-130) at 130°C and comprised a Cu foil (150 μm)/evaluation sheet (25 μm)/Si wafer (350 μm). After thermal curing at 200°C for 4 h, the composite was stored in an air atmosphere at 200°C for up to 1,000 h. Then, the Cu foil was peeled off using a tensile/compression tester (Shimadzu, Autograph AGS-X) at a peeling speed of 50 mm·min⁻¹ and a peeling angle of 90° to determine the peel strength. Si adhesiveness was investigated by die shear testing. First, the formulation sheet was laminated onto the mirror surface of a bare Si wafer using a vacuum laminator (ROHM and HAAS, 7024HP5) at 130°C. The laminate body was separated into 2 mm × 2 mm pieces using a dicer (DISCO, DAD3350). Furthermore, the pieces were mounted on the mirror surface of a new bare Si wafer using a flip-chip bonder (Panasonic, FCB-3) whose stage was heated at 100°C. After thermal curing at 200°C for 4 h, the composite underwent die shear testing conducted at a shear speed of 0.2 mm·s⁻¹ using a bond tester (Nordson, Dage 4000). Incidentally, the Si wafer and Cu foil were treated by toluene before use.

2.4 Package-level reliability

We created a package molded with the evaluation sheet to test package-level reliability. The package had an embedded die structure. The Cu foil on both sides of the starting material, a PCB Core (Hitachi Chemical, MCL-E705G, 200 μm), was etched to leave alignment markers for the mounting process, and the cavity for Si chip mounting was formed through drill routing. Next, the heat-resistant adhesive tape was laminated on one side of the processed PCB core, and the Si mirror chips were mounted on the tape adhesive side exposed from the cavity. Then, the entire PCB core was molded with a 60 μm-thick evaluation sheet using a thermal vacuum laminator, and the adhesive tape was peeled off after curing with a thermal history of 200°C for 4 h to obtain a single-sided molded product. Furthermore, a 30 μm-thick evaluation sheet was laminated on the peeling surface and thermally cured. Finally, the evaluation package was obtained by separating the molded PCB core with a blade dicing machine. The fabrication of packages for reliability testing and the package structure are shown in Figs. 5 and 6, respectively.
After baking the package at 125°C for 24 h, the package underwent three types of reliability testing. The moisture/reflow sensitivity level (MSL) test was performed according to Level 1 of IPC/JEDEC J-STD-020E. The package underwent at 85°C and 85% RH for 168 h, and three rounds of reflow processing with a temperature profile of up to 260°C. Additionally, we conducted up to 1,000 cycles of the temperature cycling (TC) test by subjecting the package to unique conditions (−55/175°C, −55/200°C). The TC conditions were harsher than those outlined in JESD-22-A104, considering potential applications in next-generation power modules.

3. Results and Discussion

3.1 Thermal reactivity and thermal curing condition

The reaction heat was analyzed to determine the appropriate thermal curing condition for the evaluation formulations. Figure 7 presents a DSC chart of the formulations before and after thermal curing. The exothermic peak temperatures \( T_{\text{peak}} \) were 185, 188, 184, and 196°C for MMC1, MMC2, MMC3, and MMC4, respectively. The \( T_{\text{peak}} \) of MMC4 was higher than those of the other formulations because the ratio of the maleimide to allyl groups was fixed at 2:1, and MMC4 had a lower reactivity than other formulations due to the higher number of functional groups. Additionally, peaks were observed at approximately 270°C for MMC3 and MMC4. Figure 8 presents a DSC chart of a single maleimide resin that has not undergone thermosetting. The \( T_{\text{peak}} \) values of MA and MB were 270 and 214°C, respectively, at which the maleimide group homopolymerized. These results support MB being more reactive than MA. The peaks at 270°C were caused by the fact that the allyl group of DABPA was prioritized for consumption by the highly reactive maleimide group of MB, and the remaining maleimide group of MA showed a single polymerization reaction. Therefore, if the amount of MB is equal to or greater than that of MA, a certain amount of the maleimide group in MA is cured on its own, independent of the cross-linked structure formed between MB and MB before thermal curing.
DABPA.

Meanwhile, studies have shown that maleimide resin–DABPA systems form intermediates by the ene reaction at approximately 140°C, and the intermediates copolymerize below 200°C.[33] The temperature range of the reaction between the maleimide and hydroxyl groups of the phe-noxy resin was approximately 180–200°C, depending on their structure.[34] Therefore, the combined action of these reactions led to the peak in the DSC chart of the formulations with a broader temperature range than that of maleimide homopolymerization before thermal curing. Additionally, the formulations exhibited a \( T_{\text{peak}} \) at approximately 190°C.

The aforementioned results confirmed that the primary curing reaction of the formulations occurs at or below 200°C. Extreme temperature conditions should be avoided because setting a high curing temperature for a molding material increases shrinkage stress during cooling and thus causes warpage and reduces package reliability. Therefore, we set the curing conditions to 200°C for 4 h. No exothermic peak was observed on the DSC chart after thermal curing, as depicted in Fig. 7, and all formulations exhibited similar curves. Based on these results, we determined that curing was complete using this thermal schedule.

### 3.2 Thermal flowability

Molding materials for semiconductor packages require high fluidity because the resin needs to fill fine spaces as packages get smaller and thinner. Since heat-resistant organic materials are difficult to soften owing to their rigid framework and strong intermolecular interactions. Reduction in fluidity due to highly filled silicon oxide particles into formulation was concerned. Therefore, we verified the fluidity of the formulations.

Figure 9 presents the complex viscosity (\( \eta' \)) and loss factor (\( \tan \delta \)) of the formulations before curing measured with a rheometer. \( \eta' \) and \( \tan \delta \) are expressed as follows:

\[
\eta' = \sqrt{\left(\frac{G'}{\omega}\right)^2 + \left(\frac{G''}{\omega}\right)^2}
\]

\[
\tan \delta = \frac{G''}{G'}
\]

Here, \( G' \), \( G'' \), and \( \omega \) denote the storage shear modulus, loss shear modulus, and angular frequency, respectively; \( \eta' \) represents the resistance of the material to deformation, and \( \tan \delta \) is the percentage of the flow component in material deformation. Thus, a lower \( \eta' \) and higher \( \tan \delta \) indicate that a material is more fluid. The \( \eta' \) value of all formulations dropped as the temperature increased to 150°C. In addition, from past studies regarding epoxy-based molding sheets, we found that the \( \eta' \) value required for molding embedded packages is \( 10^4 \) Pa-s or less.[35, 36] The temperatures at which the \( \eta' \) values of MMC1, MMC2, MMC3, and MMC4 fell below \( 10^4 \) Pa-s were 112, 105, 106, and 103°C, respectively; thus, we expected package molding properties at or above these temperatures. The peak tops of \( \tan \delta \) were observed around 50°C, and no apparent change was detected in the temperature range where \( \eta' \) used for molding was below \( 10^4 \) Pa-s.

Based on the aforementioned results, PCB Core was molded with the chips mounted on the adhesive tape to use a pressurized vacuum laminator (pressing pressure: 0.45 MPa) at 130°C, as detailed in Section 2.4, and we confirmed that all formulations were encapsulated.
presents a cross-sectional image of a package molded with MMC3. The molding material filled the cavity between the chip and PCB core, and the formulation was confirmed to have the required fluidity to mold the package.

### 3.3 Thermal stability

MB has high molecular mobility owing to the presence of long-chain alkyl units and the equivalent weight of the maleimide group of MB is higher than that of MA. Therefore, cured formulations containing MB may have lower heat resistance due to decreased cross-link density. Several methods are employed for evaluating heat resistance, including physical properties such as heat deformation temperature and load deflection temperature, and reliability testing using the target structure. Here, heat resistance was obtained from observing the weight change of the thermoset formulation when heated. Figure 11 presents a TGA chart. The temperature at which the weight of the specimen decreased by 1% ($T_{d1}$) relative to the weight of the specimen before heating was 391, 392, 358, and 361°C for MMC1, MMC2, MMC3, and MMC4, respectively. These results demonstrated that heat resistance decreases when the blend contains more MB than MA. All formulations exhibited a rapid weight loss at approximately 440°C. Because this phenomenon is independent of the MB content, we can infer that at 440°C, vaporization owing to the decomposition of the main chain of the cured material started. All the cured formulations achieved high heat resistance with a $T_{d1}$ of 350°C or higher. Furthermore, MMC1 and MMC2 had exceptionally high heat resistances with $T_{d1}$ values exceeding 390°C remarkably.

### 3.4 Mechanical properties

#### 3.4.1 Storage modulus

Figure 12 presents the temperature dependence of the storage moduli ($E'$) of the formulations after thermal curing. At 25°C, the $E'$ values of MMC1, MMC2, MMC3, and MMC4 were 11.5, 12.3, 11.5, and 9.39 GPa, respectively; For MMC1, MMC2, and MMC3, where the amount of MB is less than or equal to the amount of MA, these values were almost the same. On the other hand, the value decreased in MMC4 in which the ratio of MB to the total maleimide resin was 70% by weight or more. At 200°C, the $E'$ values of MMC1, MMC2, MMC3, and MMC4 were 3.82, 1.21, 0.528, and 0.142 GPa, respectively. These values decreased as the blending ratio of MB increased, likely because of the decrease in cross-linking density owing to the introduction of MB and the high molecular mobility of long-chain alkyls.

#### 3.4.2 Thermal expansion

Figure 13 presents the elongation–temperature curve of the evaluation sheet after thermal curing based on the specimen length at 25°C. The elongation relative to temperature change increased as the MB content increased. Similar to the temperature dependence of $E'$ described in Section 3.4.1, these results are related to the decrease in the cross-linking density and the molecular mobility of long-chain alkyls, indicating sufficient correspondence with $E'$. Furthermore, the coefficient of thermal expansion (CTE) of MMC1, MMC2, MMC3, and MMC4 calculated in the temperature range 0–200°C were 23, 38, 45, and 58 ppm·K$^{-1}$, respectively. Because Si and Cu, the substances
to which molding materials adhere, have a lower coefficient of linear expansion than the formulations, the CTE mismatch increases as the amount of MB in the blend increases. Therefore, package reliability may decrease because of the increased thermal stress based on MB.

### 3.4.3 Flexural properties

Figure 14 presents the relationship between the flexural stress ($\sigma_B$) and flexural strain ($\varepsilon_B$) obtained from three-point bending testing after thermal curing, as well as their relationships with the MB replacement rate. The values of $\sigma_B$ and $\varepsilon_B$ increased when the MB content increased. The $\sigma_B$ values of MMC1 and MMC4 were 54 and 103 MPa, respectively. Accordingly, we confirmed that blending with MB reduced brittleness, which is a disadvantage of maleimide resin. Compared to the flexural properties of MMC3, the $\varepsilon_B$ of MMC4 showed a higher increase than $\sigma_B$. The result suggested that the long-chain structure of MB causes nonlinear deformation behavior. Therefore, the flexural properties improved as the amount of MB increased; however, the CTE also increased, as indicated in Section 3.4.2. This trade-off is discussed in detail in Section 3.6.

### 3.5 Adhesion properties

Molding materials for semiconductor packaging must possess strong adhesiveness to prevent delamination owing to the stress produced in environmental testing.[37, 38] In particular, the adhesiveness to Si and Cu, which are commonly used for lead frames and wiring, is an essential property for semiconductor package molding materials. In addition, because organic materials are prone to thermal decomposition, their properties may deteriorate after long-term storage at high temperatures. We aimed to enable the practical use of these materials for a long period at 200°C; thus, the product was stored at this temperature to evaluate adhesiveness. Figure 15 presents the relationship between the Cu foil peel strength and storage time. The peel strength of MMC1 was 0.6 N·cm⁻¹ before storage, and it exhibited the lowest peel strength of all; the peel strength increased upon blending with MB. Notably, MMC3 had the maximum peel strength, and an optimal amount of MB was found. Meanwhile, the peel strength of the copper, which is treated the adhesion enhancement, with build-up or substrate materials was reported as from...
0.5 to 1.2 N·cm⁻¹.[39] The peel strengths of MMC2 and MMC3 were initially 7.3 and 11 N·cm⁻¹, respectively, and these values did not decrease during thermal storage. Accordingly, we found that MMC2 and MMC3 had substantial adhesive properties on Cu without any special treatment and are also excellent molding materials with long-term adhesive stability. Figure 16 presents the relationship between the die shear strength of a Si chip and storage time at 200°C. There was no significant difference in shear strength because of the amount of MB, and no increase or decrease in die shear strength was observed with storage time. Because the failure mode under all conditions was cohesion failure and the maximum shear strength of the epoxy-based molding sheet was 48 MPa, all formulations had excellent adhesiveness to Si. These results indicate that an appropriate amount of MB contributed to improved reliability because the adhesiveness to Cu was remarkably enhanced. Additionally, all formulations had high shear strengths to Si regardless of the amount of MB.

### 3.6 Package reliability

Because semiconductor packages comprise multiple components, thermal stress is generated by a CTE mismatch between the materials when the parts are subjected to temperature changes. The stress can cause delamination of component interfaces, cracking, and device fracture, eventually causing electronic components to malfunction. Meanwhile, semiconductor packages are generally used after soldering them to a substrate. Recent semiconductor packages include devices mounted on a substrate by a melting solder using the reflow method. Because reflow is a high-temperature process that can melt the solder, airborne moisture absorbed by the semiconductor package can rapidly vaporize and expand. The vaporization force cause interface delamination and cracks that can lead to failure. To verify the resistance of molding materials to these phenomena, we created packages using the formulations and conducted MSL and TC tests.

Table 2 demonstrates the reliability evaluation results. 12 packages of each formulation were tested in the MSL test, and all formulations passed Level 1, which has the strictest conditions among those specified in IPC/JEDEC J-STD-020E. TC tests were performed at 300, 500, and 1,000 cycles, and 12 packages were collected and inspected at each cycle. All formulations passed up to 1,000 cycles at −55/175°C, confirming that the evaluation sheets had high environmental reliability. However, under −55/200°C conditions, the MMC4 packages developed surface defects after 500 cycles due to cracking in the molding material. In the MMC3 packages, no cracking was observed in the molding material but around the Si chip corner, which was discolored with white. Figure 17 presents the optical and cross-sectional SEM images of the MMC3 and MMC4 packages after the TC test under 1,000 cycles of −55/200°C conditions. From the cross-sectional image of the white discoloration area of the MMC3 package, the cracking of the molding material starting from the corner of the Si chip was observed.

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**Table 2** Package-level reliability test results on an embedded package molded with formulations.

| Formulation | Number of non-defective packages/Number of inspections |
|-------------|-------------------------------------------------------|
|             | MSL1 | TC (−55/175°C) | TC (−55/200°C) |
| MMC1        | 12/12 | 12/12         | 12/12         |
| MMC2        | 12/12 | 12/12         | 12/12         |
| MMC3        | 12/12 | 12/12         | 12/12         |
| MMC4        | 12/12 | 12/12         | 12/12         |

* White discoloration on the corner of Si chip
chip was confirmed. The cross-sectional image of the MMC4 package indicated larger cracks in the molding material than that of MMC3 and delamination between the Si chip and the molding material. Cracking and delamination occurred in MMC3 and MMC4 despite their excellent breaking properties. As a reason for that the effect of the increase in thermal stress by CTE mismatch was more significant than that of the improvement in the breaking properties due to the increase in the MB amount.

However, in the formulations, we found that MMC2 containing 30% by weight MB maintained a high $T_{d1}$, which is an index of heat resistance, and exhibited high adhesiveness to the Cu foil. Moreover, the formulation had high reliability to withstand the harsh TC test at −55/200°C for 1,000 cycles. Although the molding material with enhanced performance would be possible by further investigating the amount of MB, MMC2 can be applied to power modules operating at temperatures over 200°C.

4. Conclusion
We prepared maleimide-based molding sheets by blending rigid and flexible maleimide resins, followed by evaluating the blending ratio and its relationship with various properties. The heat resistance of the cured material decreased when MB accounted for at least 50% by weight of the maleimide resin. However, the formulation with 30% by weight MB showed heat resistance equivalent to that without MB, and had high heat resistances with $T_{d1}$ values of 391°C based on thermogravimetric analysis. Although the flexural properties of the formulations improved as the blending ratio of MB increased, the CTE also increased. Meanwhile, the formulation without MB had a significantly low adhesiveness with a Cu foil peel strength of 0.6 N·cm$^{-1}$. However, the molding material with an MB ratio of 30% by weight exhibited a peel strength of 7.3 N·cm$^{-1}$, demonstrating that MB significantly improved adhesiveness. In addition, the formulation was characterized by high adhesiveness despite being exposed to 200°C for 1,000 h. Package-level TC tests (−55/200°C) showed that formulations with an MB ratio of 30% by weight or less had no external or internal defects, while those with an MB ratio of 50% by weight or more developed cracks in the
molding material because of the increased CTE mismatch. In conclusion, the formulation with a MB ratio of 30% by weight exhibits excellent properties for WBG semiconductor power modules manufactured with FOPLP. We will conduct structural analysis to reveal the relationship between the physical properties of molding materials and crack development and further material formulation and design for enhanced performance using data science.

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