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Thermal simulation of joints with high thermal conductivities for power electronic devices

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ABSTRACT

The thermal properties of new power modules joined by materials with high thermal conductivities, such as Ag or Cu nanoparticle joints, can differ from those of current modules joined by ordinary solders with low thermal conductivities. However, these properties have not been thoroughly investigated thus far. The overall thermal resistance of a simple simulation module was calculated by the 3-dimensional finite element method to study the correlation between the thermal conductivity of the joint layer and the thermal properties. The calculation results identified an optimal thickness to achieve the minimum thermal resistance when the thermal conductivity of the joint layer is much higher than that of the heatsink. This is presumed to occur because the thermal resistance decreases in the heatsink much more than it increases in the joint layer, owing to the increased uniformity of thermal spreading as the joint-layer thickness increases to the optimal value. This effect of thermal resistance reduction with thickening of the joint layer is seen when the thermal conductivity of the joint layer is sufficiently higher than that of the heatsink and the area of the joint layer is sufficiently smaller than that of the heatsink. The same effect is also expected in an actual module with a joint between a silicon carbide chip and a direct bonded copper substrate. This study reveals that the design concept for power modules should change to preliminarily estimate the optimal thickness to achieve the minimum thermal resistance when the thermal conductivity of the joint layer is much higher than that of the heatsink.

1. Introduction

New power electronic devices with compound semiconductors, such as silicon carbide (SiC) and gallium nitride (GaN), have been developed actively because they have the potential to achieve a higher output density than ordinary silicon (Si) devices. An advantage of this is that the chip size can be reduced and the operating temperature is high so that the devices are more reliable for harsh environments and their thermal cooling is more manageable. On the other hand, there is a critical problem that the operation temperature will be higher than for ordinary Si devices, which is severely detrimental for Sn-based solders [1,2]. Therefore, an important issue is to develop a new joint material that endures high temperatures and releases thermal accumulation readily to achieve long-term reliability of devices. Although many new joint materials, such as Au, Zn, and Bi-based alloys, have been studied, they do not have sufficient melting points or thermal conductivities [3–6].

In contrast, a new joint technique that involves sintering of metallic nanoparticles is attracting attention as an alternative to soldering because the particles can be sintered at temperatures much lower than the melting point owing to their high surface energy [7]. To date, Ag nanoparticles have been widely investigated because they are easily synthesized and Ag has a high melting point (962 °C) as well as the highest thermal conductivity (420 W/m K) among metals [8–12]. Although the thermal conductivity for sintered joint hardly shows the same value as the theoretical thermal conductivity because of porosities and remained protection layers, it has potential to achieve the theoretical thermal conductivity if sufficiently packed structure is obtained after sintering.

However, Ag is undesirable because of its high cost and low resistibility against ion migration [13]. In contrast, Cu is inexpensive even though it also has a high melting point (1085 °C) like Ag and nearly the same thermal conductivity (400 W/m K) [14–19]. Therefore, Cu nanoparticles are highly promising for the new joint technique. In a previous study, we examined the thermal conductivities of joints involving the sintering of Cu nanoparticles capped by fatty acid and amine by the steady-heat conduction

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method [20]. The thermal conductivities were estimated from the thermal resistances of the simple module in which the Al_2O_3 heater chip joined to the Cu–65Mo heatsink by Cu nanoparticles was attached to the Al-alloy cooling plate by thermal grease as shown in Fig. 1. The previous study revealed that the thermal conductivity for sintered Cu joint was very small (20 W/m K) after sintering at low temperature (250 °C), but became high enough after sintering at high temperature (350 °C) because of complete decomposition of capping layers. The thermal resistance was small enough at 350 °C that the thermal conductivity could not be estimated precisely. Therefore, it was determined to be higher than 125 W/m K. It indicates that the thermal conductivity for sintered Cu has potential to be the theoretical value (400 W/m K) if completely sintered structures can be obtained.

The nanoparticle joint shows good potential for high temperature operation. However, another problem is that such a joint that consists of a high melting point metal cannot mitigate thermal stress readily because it is harder than ordinary solders. The mismatch of coefficients of thermal expansion between semiconductor chip and heatsink should be low to avoid accumulation of thermal stress in the joint layer. Therefore, heatsinks of pure Cu or Al, despite having high thermal conductivities, are unsuitable because their coefficients of thermal expansion are much higher (Cu: 17 ppm/K, Al: 23 ppm/K) than those of semiconductor chips (Si: 3 ppm/K, SiC: 3.1 ppm/K, GaN 3.2–5.6 ppm/K). To deal with this problem, a heatsink with a low coefficient of thermal expansion appropriate to that of the semiconductor chip should be used (e.g., alloys of Cu and high melting point metals). Cu–65Mo, used for the simple module in Fig. 1, is a typical heatsink with a low coefficient of thermal expansion (8.2 ppm/K), although such alloys with high melting point metals normally have lower thermal conductivities than pure Cu or Al. Therefore, for the new power module with the nanoparticle joint, the thermal conductivity of the joint layer could be higher than that of the heatsink, unlike an ordinary module with solders.

The thermal properties are crucial to establishing the packaging design of the new power module because they will influence the long-term reliability. In order to achieve the long-term reliability, many unique packaging designs have been invented to reduce the thermal resistance so far. Thermal grease is often used to attach power modules to cooling plates, but it can cause much of the thermal resistance. Therefore, it was reported that directly bonded structures between power modules and cooling plates were applied to reduce the thermal resistance [21,22]. It was also reported that composite materials with carbon fibers or a thick Cu block were used for plates because of high thermal conductivities [23,24]. However, there is no report about an influence of the joint layer on the thermal resistance.

In this study, calculation analyses of the thermal properties were carried out on the assumption that the joint layer has a much higher thermal conductivity than that of the heatsink, which corresponds to the nanoparticle joint. We found the unique feature that an optimal thickness can be determined to achieve the minimum thermal resistance when the thermal conductivity of the joint layer is much higher than that of the heatsink. This optimal thickness cannot be shown in the ordinary packaging design with solders.

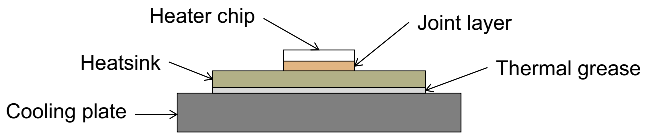

Fig. 1. Schematic view of the simple simulation module.

2. Calculation

The simple simulation module shown in Fig. 1 was used for the calculation model to investigate the thermal properties by varying the parameters. The simple simulation module was limited to basic components which were enough to investigate an effect of each parameter on the thermal property clearly. The dimensions and thermal conductivity of each component are shown in Table 1.

The calculations were carried out by the 3-dimensional finite element method with ANSYS Workbench 14.0 under conditions identical those in a previous paper [20], assuming a heat flux of 100 W/cm^2 applied to the Al_2O_3 heater chip and cooling water of 65 °C flowing in the Al-alloy cooling plate with a thermal transfer coefficient of 9000 W/m^2 K as the boundary conditions. Other boundaries are isothermal, because natural convection is so small that it is negligible. The calculations were carried out using approximately 30k of hexahedron cells. The average computational time is 1 min.

The thermal conductivities of the joint layer and the heatsink, the thickness of the joint layer, and areas of the heatsink and grease were varied to investigate their influences on the thermal properties (Table 1). The default values for the thermal conductivity of the heatsink and areas of the heatsink and grease were defined as 207 W/m K and 800 mm^2, respectively, as in our previous paper [20]. These values correspond to the thermal conductivity of Cu–65Mo and the area of a typical 20 × 40 mm^2 rectangular heatsink. The maximum thermal conductivity of the joint layer and heatsink was defined to be 400 W/m K, which corresponds to that of Cu.

Thermal resistances (R_{th}) are calculated using Eq. (1).

$$R_{th} = (T_1 - T_2)/P \qquad (1)$$

where T_1 is the temperature of center on the surface of the heater chip, T_2 is cooling water temperature, and P is amount of heat of the heater chip. Thermal resistances of individual objects are calculated by temperature differences of each interface of the objects at the center position of the chip.

The actual power module was usually designed as shown in Fig. 2, as described in previous papers [25–27]. The thermal properties of the actual power module were also studied by the same calculation in order to compare them between both the simple and the actual models because it is important to confirm whether the similar thermal property would be also feasible in the actual model for the real packaging design. Fig. 2 shows the calculation model for the actual power module in which a SiC chip joined to a direct bonded copper (DBC) substrate with Al_2O_3 was soldered to a Cu–65Mo heatsink attached to an Al-alloy cooling plate by thermal grease. Table 2 shows the dimensions and thermal conductivity of each component. The thickness and thermal conductivity of the joint layer between the SiC chip and the DBC substrate were varied from 0.1 to 0.5 mm and 70 to 400 W/m K, respectively.

Table 1
Dimensions and thermal conductivities of components of the simple simulation module.

Component	Area (mm^2)	Thickness (mm)	Thermal conductivity (W/m K)
Heater chip (Al_2O_3)	36	0.5	20
Joint layer	36	0–1.5	70–400
Heatsink	36–1600	3	100–400
Grease (Silicone)	36–1600	0.06	4.5
Cooling plate (Al alloy)	16,490	5	140