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Thermochimica Acta 455 (2007) 148–155
thermochimica acta
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Thermal characterization of thermally conductive underfill for a flip-chip package using novel temperature sensing technique

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Available online 9 December 2006

Abstract

The thermal characteristics of thermally conductive underfill in flip-chip package was studied. To enhance the thermal conductivity of underfill, the epoxy was mixed with thermally conductive fillers, such as silica (1.5 W/mK), alumina (36 W/mK) or diamond (2000 W/mK). Coefficient of thermal expansion (CTE) was changed by filler and its content and CTE was 28 ppm for 60 wt% silica, 39 ppm for 60 wt% alumina and 24 ppm for 60 wt% diamond. Thermal conductivity was calculated from the measurement of thermal diffusivity, density and specific heat capacity under the various temperature conditions with the various fillers. To investigate thermal characteristics of different underfill, diode temperature sensor array (DTSA) was fabricated, which consisted of 32×32 array of diodes (1024 diodes) for temperature measurement and eight heaters for heat source on an 8 mm $\times$ 8 mm of silicon surface. The DTSA was packaged by flip-chip packaging method and applied with the same power (0.84 W) for different underfilled packages. Finally, the thermal simulations with ICEPAK matched very well with the measurement.
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Keywords: Flip-chip package; Underfill; Diode temperature sensor array; Diamond

1. Introduction

Microelectronic systems have been required to be the higher integration density, the faster performance and the lower cost. The flip-chip technology has been a promising candidate for microelectronics in the next generation, because of the shortest possible leads, the lowest inductance, the highest frequencies, the best noise control, the highest density, the greatest number of I/Os, the smallest device footprints, and the lowest profile [1]. In addition, the thermal power has also increased with increasing the integration density and the performance. For general logic device devices, the power dissipation is expected to be 109 W in 2012 [2]. As increasing the thermal dissipation, i.e. the operating temperature, the performance and the reliability of a component will be decreased exponentially [3]. In most of the microelectronic components including flip-chip, there were many polymer composite materials of quite low thermal conductivities, such as 0.2 W/mK of epoxy. Where the underfill is the very important part of the flip-chip package and also which is composed of epoxy polymer and the ceramic fillers, mainly silica of very low thermal conductivity, 1.5 W/mK. These polymeric underfill encapsulation materials enhance the flip-chip solder joints reliability and become very attractive for the plastic packaging of direct chip on board applications [4]. In this study, we investigated viscosity, coefficient of the thermal expansion (CTE), density, thermal diffusivity, heat capacity and a thermal conductivity of underfill under the various temperature conditions with the various fillers. Fillers were silica, alumina with thermal conductivity 36 W/mK and diamond with 2000 W/mK. For the measurement of thermal characteristics for the various underfill materials, diode temperature sensor array (DTSA) chip was fabricated, which was packaged by flip-chip packaging method on printed circuit board (PCB). Finally, the thermal models of the DTSA packaging by ICEPAK, showed how the heat is transferred in the DTSA packaging.

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doi:10.1016/j.tca.2006.11.034

2. Experimental

2.1. Underfill

The resin compound in this study was composed of primer and hardner. The primer was composed of bisphenol-A epoxy, ERL-4221 and 1,6-hexandiol diglycidyl ether. Those were mixed and blended with 7:1:2 ratios at 50 °C and 100 rpm for 3 h. The hardner was made from the anhydride and 3-imidazole with 99:1 ratio. And finally the primer and hardner were mixed with 1:1 ratio in the rotation mixer.

Filler materials' characteristic properties were shown in Table 1 [5–7]. Properties of epoxy in Table 1 were measured in this study. Filler shape and mean size were also shown in Table 1 and Fig. 1. Underfill was made from mixing epoxy and fillers. Filler contents were 10 wt%, 30 wt%, 50 wt% and 60 wt%. Subsequently underwent two-step curing; 1 h treatment of 70 °C and another 1 h at 150 °C.

From the measurement of thermal diffusivity, specific heat capacity and bulk density of the samples, thermal conductivity was calculated as following equation:

$$K = \alpha\rho C_p \qquad (1)$$

where K is the thermal conductivity, α the thermal diffusivity, ρ the bulk density and C_p is the specific heat capacity [8]. The thermal diffusivity of a material was measured with the laser flash method and the Cowan analysis [9–11]. The sample size for the laser flash measurement, was 8 mm × 8 mm and 1 mm thick and the surface was polished to mirror-like surface.

Differential scanning calorimetry (DSC) was used to analyze the curing behavior, glass transition temperature (T_g) and specific heat capacity (C_p) with sapphire reference. Thermal stability was measured with thermogravimetry analysis (TGA). The CTE of underfill was determined by the thermomechanical analysis (TMA) in an expansion quartz system (30–200 °C) at a 5 °C/min heating rate. CTE was measured with TMA with samples of 10 mm length, 10 mm width and 1 mm thickness. The cone and plate rheometer was used to analyze the viscosity of the underfill from 30 °C to 80 °C. The morphology was analyzed with the scanning electron microscopy (SEM).

Table 1
Material properties of fillers used [5–7]

	Filler			
	Epoxy	Silica	Alumina	Diamond
Density (g/cm^3)	1.19	2.2	3.98	3.5
Thermal conductivity (W/mK)	0.23	1.5	36	2000
CTE (ppm)	75.18	0.5	6.6	0.8
Modulus (GPa)	3	74	385	1050
Poisson's ratio	0.4	0.19	0.21	0.068
Filler shape	–	Spherical	Polygon	Polygon
Filler mean size (μm)	–	3	0.3	1

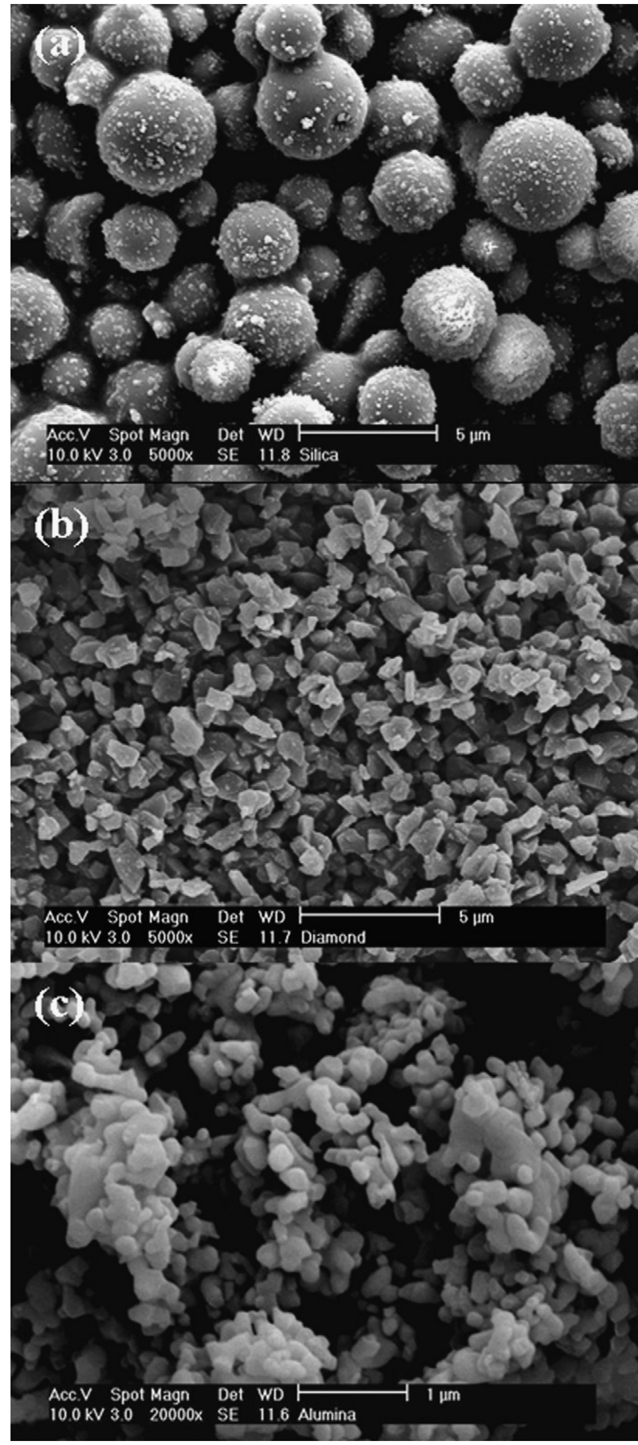

Fig. 1. SEM micrographs of fillers: (a) silica, (b) diamond all 5000× and (c) alumina 20,000×.

2.2. DTSA

2.2.1. Working principle of DTSA

Constant current causes a forward voltage drop across a silicon diode. And the forward voltage drop decreases as the temperature of a silicon diode increases. Usually, silicon diodes have a forward voltage drop of 0.7 V that decreases by 2 mV for every 1 °C increase in near the room temperature. It could be derived by the diode I–V characteristics from followed equation [12]:

$$i_D = I_0 \exp\left(\frac{qV}{kT}\right) \quad (2)$$

where i_D is the diode current, I_0 the reference current, $q = 1.6 \times 10^{-19}$ C, $k = 1.38 \times 10^{-23}$ J/K and V is the voltage.

2.2.2. Layout design and fabrication

The manufacturing processes of a DTSA are as follow; first, a series of n-wells were created on a wafer, second, n+ and p+ doping were diffused for creating p+ and n+ regions. Third, metal1 and metal2 were deposited on a wafer for interconnecting rows and columns diodes, respectively. Fourth, polysilicon heaters were deposited for heating and controlling the temperature of a DTSA.

DTSA has 1024 diodes in 12 mm × 12 mm area. And eight polysilicon heaters of 1 kΩ are embedded onto a silicon wafer for heating the DTSA. And the positions of eight heaters are concentrically loacated in a DTSA. The resistance of heaters was designed to be 1 kΩ. As shown in Fig. 2, the pad size of the DTSA is designed 600 μm × 600 μm for flip-chip packaging. Therefore, the effective sensing area of a DTSA is 8 mm × 8 mm.

2.2.3. Packaging

The general flip-chip packaging technique was used to interconnect the DTSA pads to the PCB board for external signals. PbSn solder balls of 300 μm diameter were reflowed and joined for 240 °C and underfill was despensed at 80 °C. Underfill was loaded with various fillers such as silica, alumina, and diamond, with 30 wt% and 50 wt% content. And after cured in furnace at 150 °C for 1 h. Scanning acoustic tomography (SAT) was used to detect the defect in underfill.

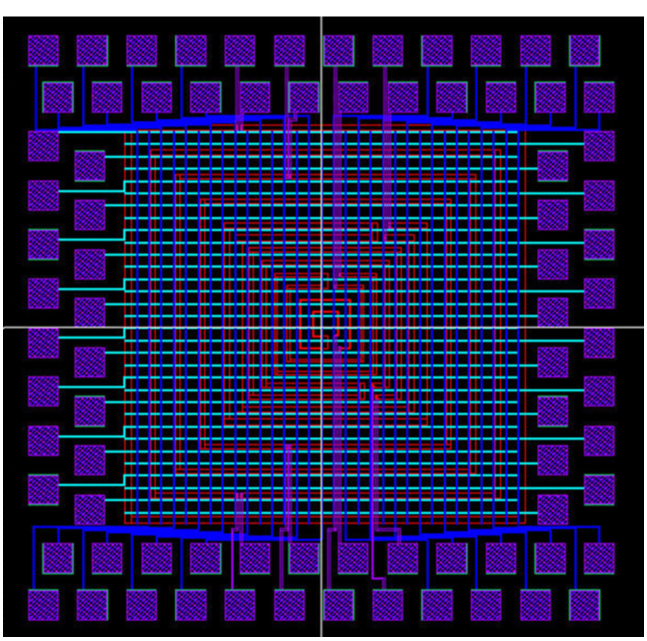

Fig. 2. 32 × 32 DTSA layout.

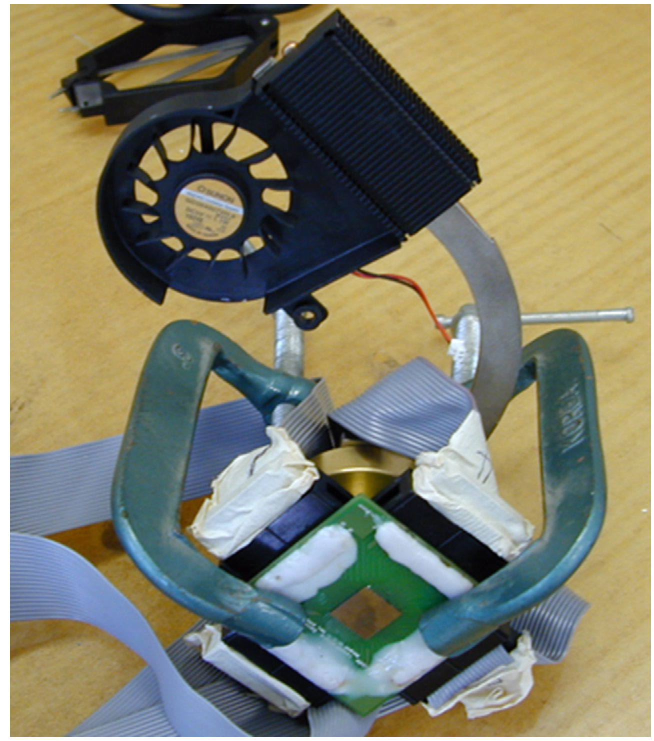

Fig. 3. Flip-chip package with heatsink and cooler.

2.2.4. Calibration

A thermo-hygrostat was used for the temperature calibration of DTSA. The calibrated temperature detection range of DTSA is from 0 °C to 150 °C.

2.2.5. Measurement setup

A heatsink and a cooler were used for effective cooling of a DTSA to measure the thermal effects of underfill in flip-chip package. Fig. 3 showed the experimental apparatus which consists of the heatsink, the cooler and the DTSA package. The thermal paste was used at the interface of PCB, heatsink and cooler. Ambient temperature was 27 °C. The center heater among eight heaters in a DTSA was used for heating and the power is 0.84 W for thermal testing of different underfill packaged DTSA.

3. Results and discussion

To investigate the general behavior of underfill, we used DSC and TGA. The curing of underfill without filler started from about 120 °C and the final reaction occurred at about 190 °C from the DSC result. From the TGA results, the weight loss begun at the above 350 °C and this result was sufficient to the condition of the underfill, thermal stability 1% weight loss; >260 °C. Also, T_g of the underfill without filler was over 130 °C. These results showed good underfill resin properties.

3.1. CTE

Fig. 4 showed the CTE of the various underfill. The CTE in Fig. 4 was measured at lower temperature than T_g. The CTE

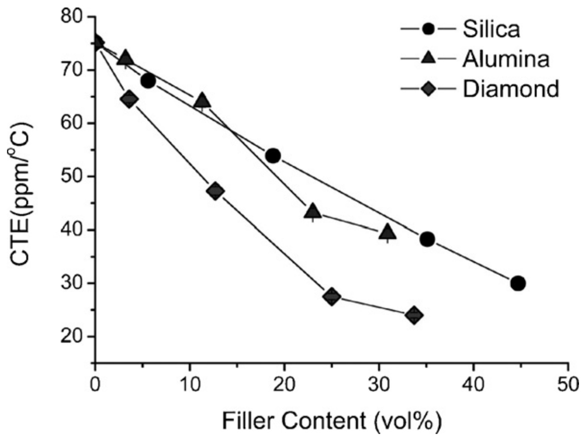

Fig. 4. CTE of various underfill.

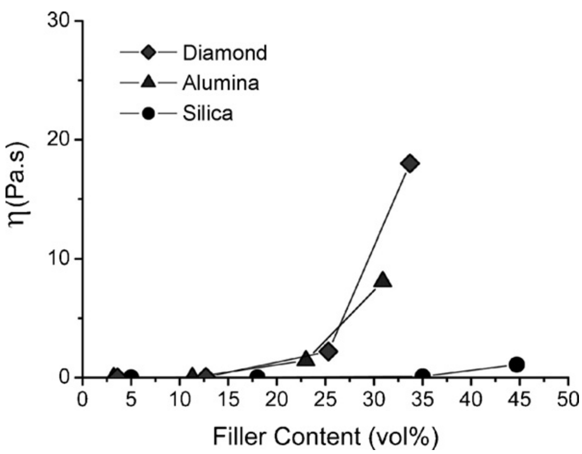

Fig. 5. Comparative plots of viscosity by filler content at 80 °C.

over T_g showed the bigger value. The particle size and materials own CTE property are affected to the CTE results.

3.2. Viscosity

Fig. 5 showed the comparative plot of viscosity by filler content. Underfills with diamond and alumina filler showed higher

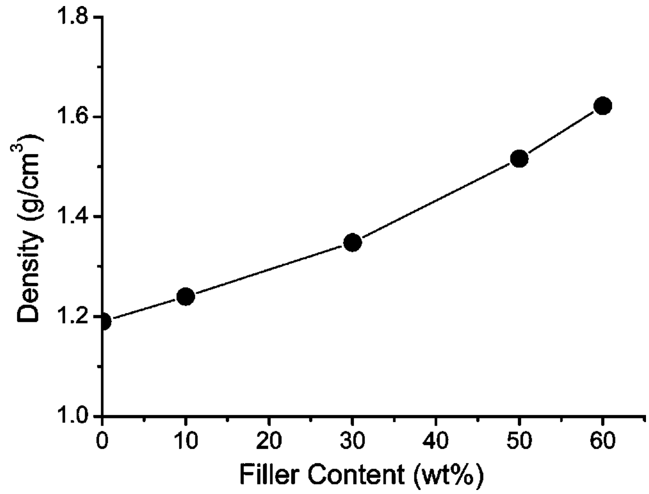

Fig. 7. Density change of underfill with silica filler.

viscosity at both temperature range, since its polygon shape. On the contrary, the shape of silica is very spherical and showed very low viscosity.

3.3. Thermal conductivity

As shown in Fig. 6, the thermal conductivity of underfill without filler was about 0.237 W/mK at 25 °C, and increased to about 0.253 W/mK at 55 °C. The increment depends on the heat capacity increment, 1.30 J/(g °C) at 25 °C and 1.468 J/(g °C) at 55 °C. A density of the underfill without filler was 1.192 g/cm^3.

There was a small density change in this temperature range because of the low value of CTE. In the case of underfill without filler, the thermal conductivity matched quite well with the result measured by the heat flow method, which showed very similar values, 0.234 W/mK at 25 °C.

The density of composite was very similar to the calculated value from epoxy and silica, as shown in Fig. 7. Thermal diffusivity of underfill with silica filler is shown in Fig. 8 and specific heat capacity change is shown in Fig. 9.

As increasing the content of fillers, the thermal diffusivity increased and therefore, the thermal conductivity linearly

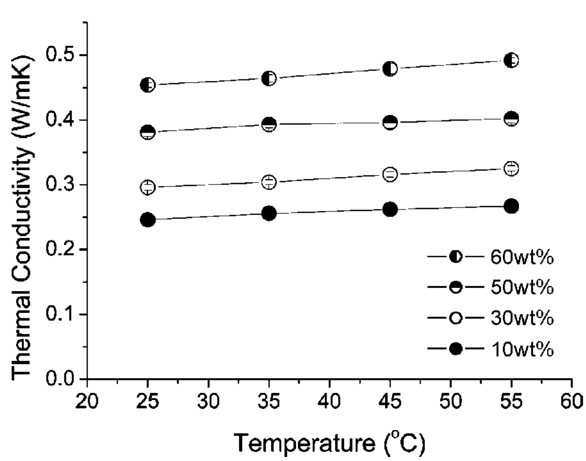

Fig. 6. Thermal conductivity by filler content of silica filler loaded underfills.

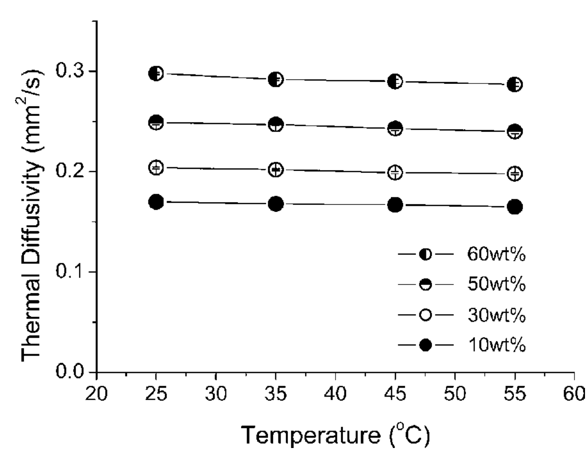

Fig. 8. Thermal diffusivity change of underfill with silica filler.

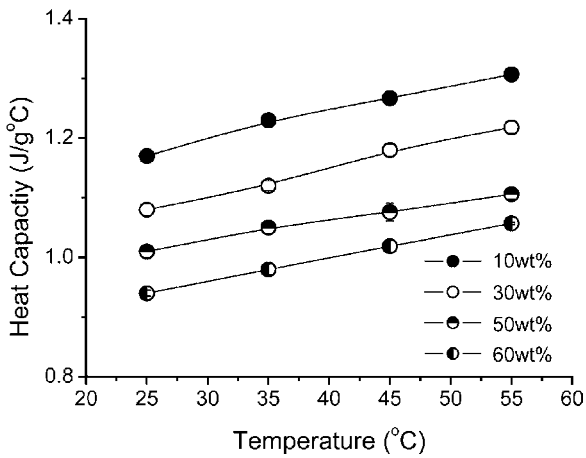

Fig. 9. Specific heat capacity change with silica filler content.

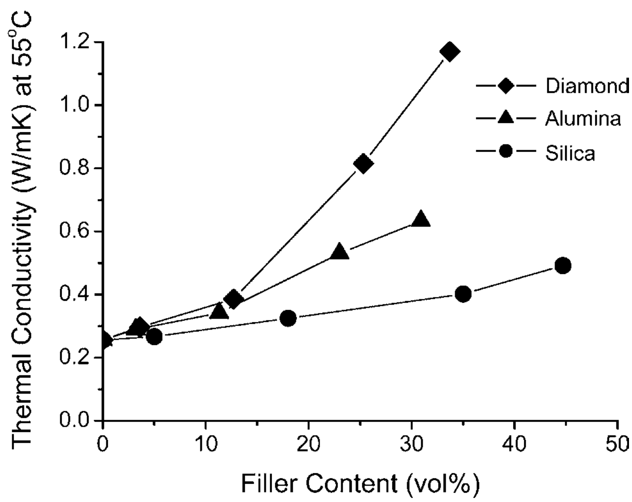

Fig. 10. Comparative plot of the thermal conductivity by filler content at 55 °C.

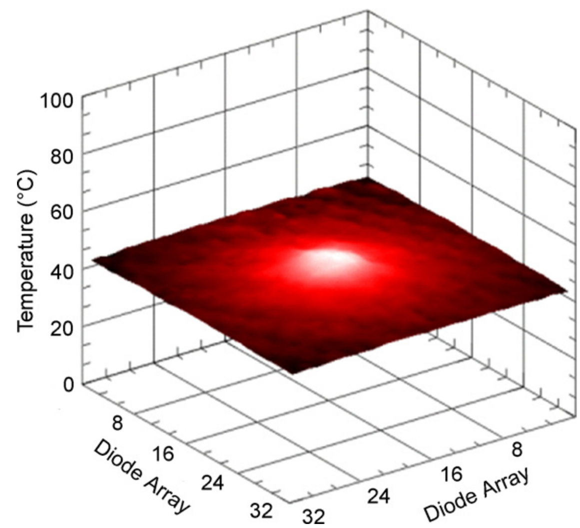

Fig. 12. Temperature measurement of alumina 30 wt% loaded underfill filled package with heatsink and heater power is 0.84 W. (The captured image from the test equipment.)

increased, as shown in Figs. 6 and 8. But with the same content of filler, thermal conductivity increased with increasing temperature because the heat capacity increased.

Using same method, thermal conductivities of underfill with other filler were measured. Underfill with diamond 60 wt% filler showed the highest thermal conductivity value at 55 °C. But in the case of low filler content, 10 wt%, all underfill showed very similar values of the thermal conductivity and thermal diffusivity. In this case, particles of fillers dispersed homogeneously and isolated without contact in the polymer with other particles. But the underfill with higher filler content, showed the improved thermal properties of underfill, because of the forming of the thermally conductive chains of fillers.

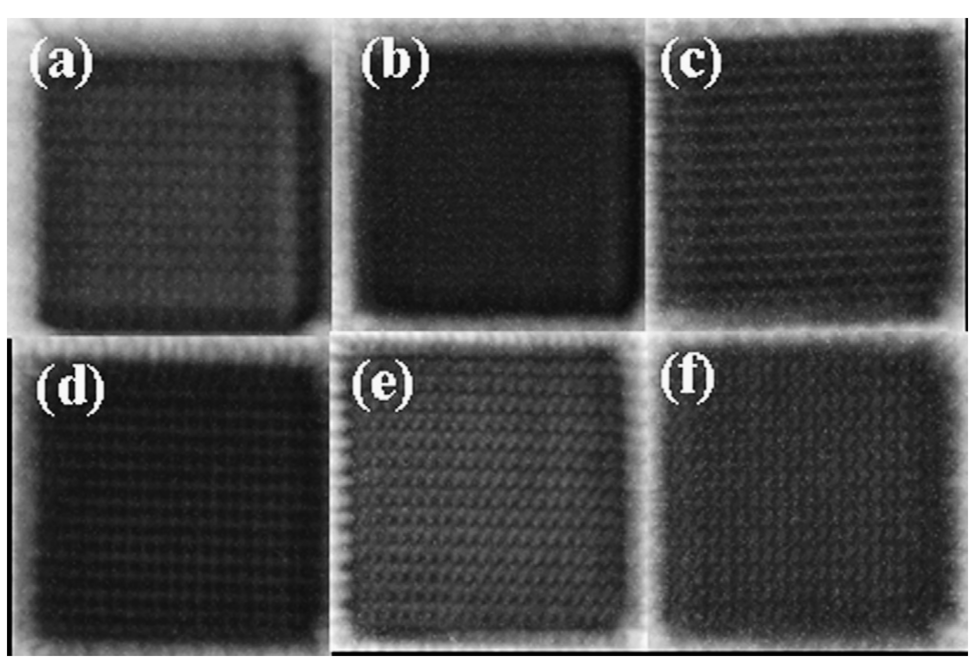

Fig. 11. SAT image of: (a) silica 30 wt%, (b) alumina 30 wt%, (c) diamond 30 wt%, (d) silica 50 wt%, (e) alumina 50 wt% and (f) diamond 50 wt% loaded underfill in package.

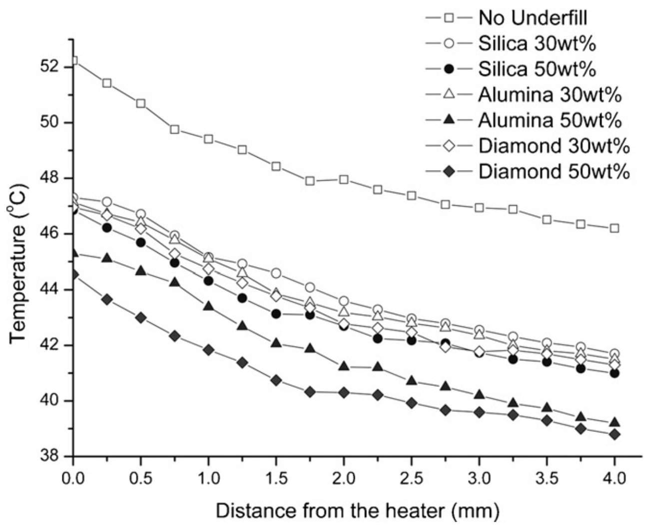

Fig. 13. Temperature distribution of various package with heatsink and heater power is 0.84 W.

Fig. 10 showed the comparative thermal conductivity of various filler types by vol%. It showed that the diamond filler loaded underfill had the best thermal conductivity values. In diamond filler loaded case, the thermal diffusivity and the change of specific heat capacity were much bigger than those of other filler.

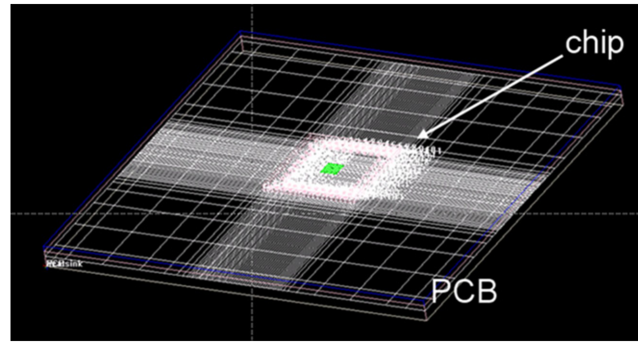

Fig. 14. The structure of package for the computer simulation.

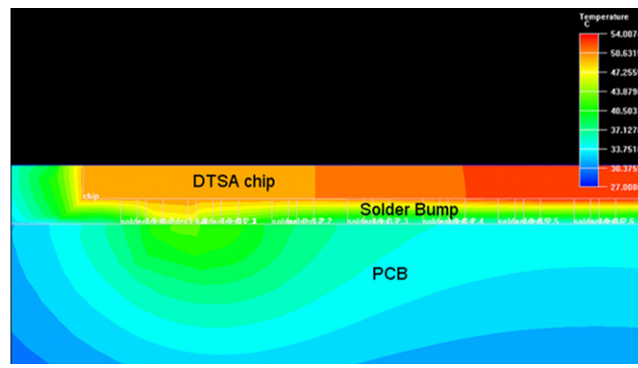

Fig. 15. Computer simulated result of DTSA package without underfill.

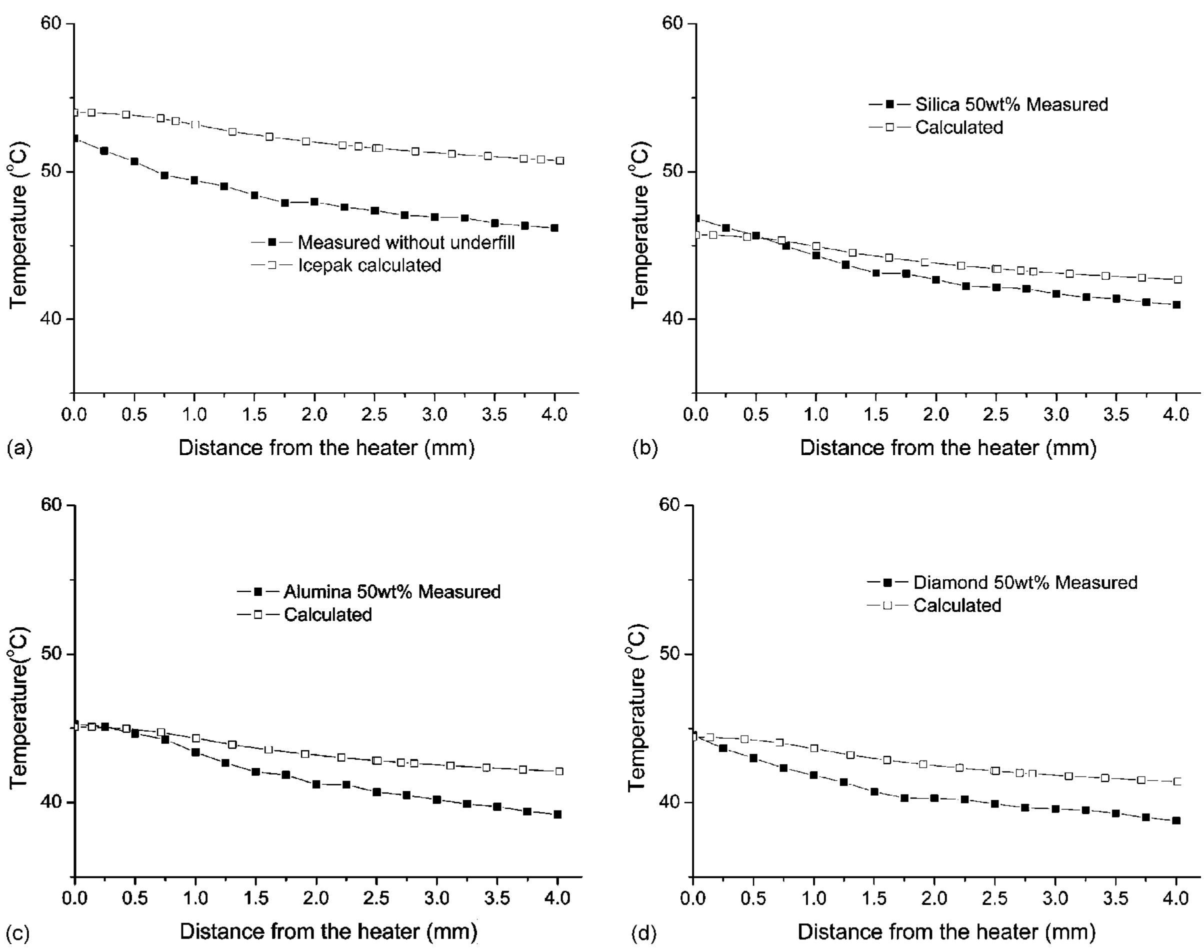

Fig. 16. Temperature distribution; calculated and measured with: (a) without underfill, (b) silica, (c) alumina and (d) diamond 50 wt% loaded underfill filled package.

3.4. Temperature measurement

We chose two kinds of filler content, 30 wt% and 50 wt%, because all thermal conductivities of 10 wt% fillers showed similar values and in the case of 60 wt% filler, the viscosity of underfill was too high to dispense, as shown in Fig. 5.

Before measuring the temperature distribution, the packaged DTSA were examined by SAT, as shown in Fig. 11 and no defects were found.

To investigate the thermal characteristics of underfill, we measured the temperature distributions of a DTSA. First, we applied 0.84 W on the center heater in the DTSA. Then, we scanned the 1024 temperature signals from diodes in the DTSA. The experimental result for 30 wt% alumina with heatsink is shown in Fig. 12.

Fig. 13 showed the comparative temperature plots of various underfill. The heater power is 0.84 W. The package of 50 wt% diamond underfill showed the lowest temperature and the package without underfill showed the highest temperature. From this result, big temperature difference existed between packages with underfill and without underfill, because the underfill can easily help to transfer the heat from heater to PCB or lead frame. Especially in this study, bumps were a peripheral array. The underfill affected more seriously to the heat dissipation in the peripheral array than that in the area of solder balls.

Fig. 13 showed that results of temperature distributions of various filler loaded underfill. Thirty weight percent and 50 wt%'s difference of thermal conductivity as shown in Fig. 10 had the similar tendency of temperature distributions of various underfill in packages.

The heat transfer paths of this package were the convection from the top of chip to the ambiet and the condution from solder and underfill to the heatsink. To know specific heat transfer in a DTSA package, we used the thermal models by using ICEPAK.

3.5. Simulation

Fig. 14 showed the schematic diagram of computer simulation for the package.

The thermal model of a DTSA package is like as follows—system size: 50 mm × 50 mm × 2.7 mm, PCB thickness: 2 mm, underfill thickness: 0.3 mm, chip thckness: 0.4 mm, solder: diameter 0.3 mm (80 solder balls are installed), heater size: 0.2 mm and heatsink: 50 mm × 50 mm.

Measured values at 45 °C were used for the thermal conductivity values of various underfill in the thermal model. Because

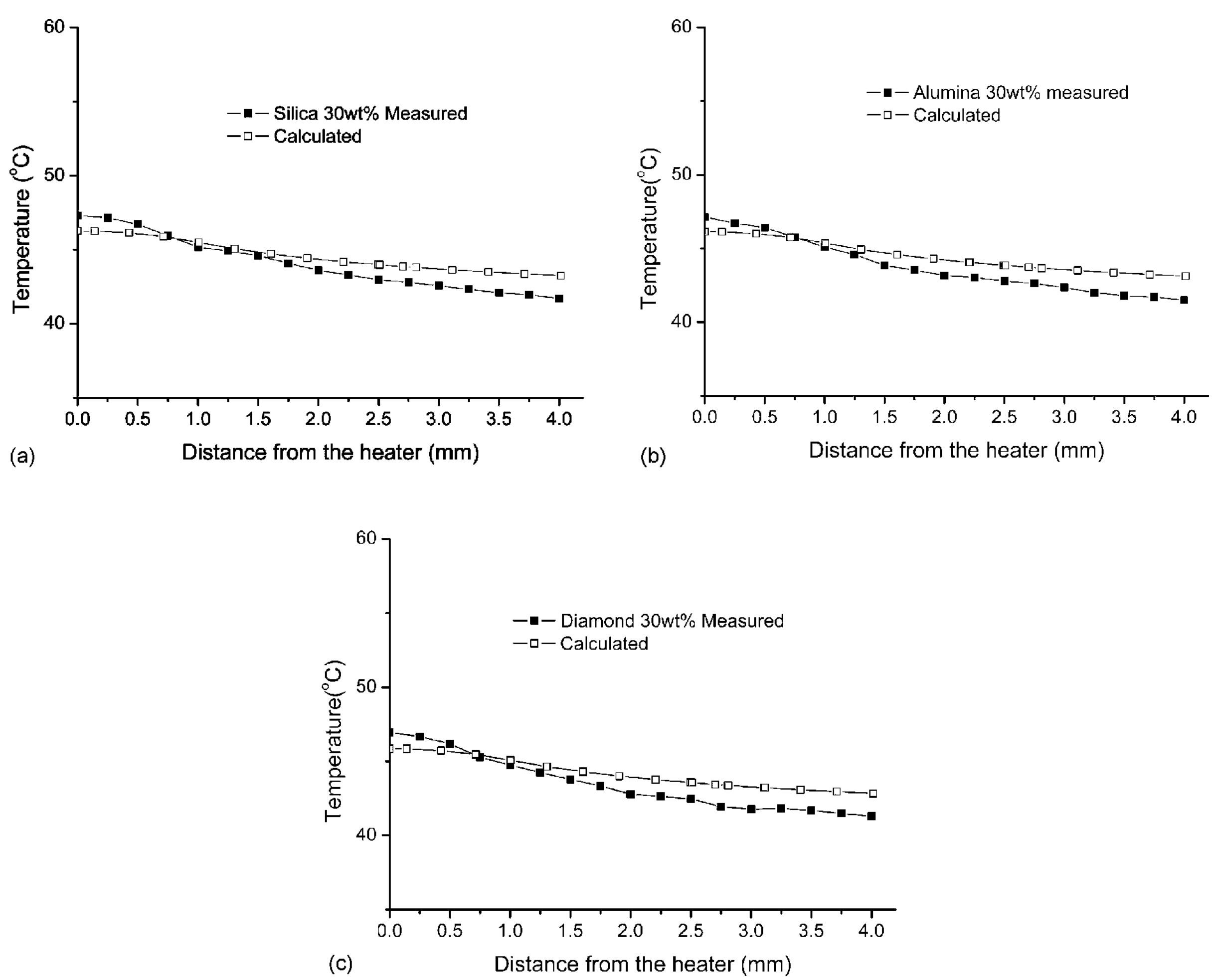

Fig. 17. Temperature distribution; calculated and measured with: (a) silica, (b) alumina and (c) diamond 30 wt% loaded underfill filled package.

the measured maximum temperature range of pacakge was around 45 °C.

The simulation result of a DTSA package without underfill is shown in Fig. 15, the calculated maximum temperatures were similar to the experimentally measured maximum temperature. Silica 50 wt% loaded underfill showed calculated value: 45.71 °C and measured value: 46.85 °C. Alumina 50 wt% underfill filled package showed calculated value: 45.1 °C and measured value: 45.29 °C. Package with diamond 50 wt% underfill showed simulated value: 44.41 °C and measured value: 44.54 °C.

From those results, the thermal model of a DTSA was suitable for investigating the thermal effect of underfill.

Comparative plots of simulated and measured temperature distributions are shown in Figs. 16 and 17. The calculated results showed some deviations from measured values at the edge of the chip. But in center of chip, the simulated and measured values were almost same. This small divergence comes from the difference of convection between real and calculation states.

As shown in Figs. 16 and 17, diamond 50 wt% underfill had the least maximum temperature and temperature distribution among the specimens.

4. Conclusions

We investigated viscosity, coefficient of the thermal expansion, density, thermal diffusivity, heat capacity and a thermal conductivity of underfill under the various temperature conditions with the various fillers. Fillers were made with materials, such as silica, alumina (36 W/mK), and diamond (2000 W/mK). And also we made diode temperature sensor array chip which was packaged by flip-chip packaging method for investigating the thermal characteristics of the various underfill. Finally, we made the thermal models for the DTSA package with ICEPAK from the thermal conductivity data measured at 45 °C. Thermal conductivity results of various filler loaded underfill showed good consistency with DTSA measurement and ICEPAK modeling. These results show how the heat is transferred in the DTSA package.

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