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Heat Dissipation of Printed Circuit Board by the High Thermal Conductivity of Photo-Imageable Solder Resist

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Thermal management issues with IC packages have been growing as electronic systems have become smaller with a higher functionality. Since the high junction temperature of IC packages induces the low performance and malfunction of electronic systems, the thermal dissipation capability of electronics is important for stable electrical performance and electro-mechanical reliability. However, the conventional cooling methods that depend on air flow path and heat sink structure is not sufficient to meet the growing thermal requirements of IC packages. Since there is limit on conventional design, such as optimization air flow path and heat sink structure, to dissipate more heat through an exhaust fan system. The main purpose of the present research is to reduce the junction temperature of the IC package by using a Printed Circuit Board (PCB) coated with new Photo-imageable Solder Resist (PSR) that has high thermal conductivity. The thermal conductivity of the newly developed PSR is about five times as high as that of the conventional PSR for PCB(0.23~0.25W/m·K). The PCB was prepared by the EIA/JEDEC standard, JESD51-7. Experimental and finite element analyses were performed to investigate the effect of SR on thermal dissipation capability. The experimental and FE results show that the high thermal conductivity of PSR can reduce the steady-status regulator surface temperature by about 3~8K as an air flow conditions around PCB. Also, the high thermal conductivity of SR is more effective under a low air heat transfer coefficient condition. Therefore, it is believed that an improved heat transfer with a PSR of high thermal conductivity should provide stable electrical performance for the IC package.

Keywords: PSR, thermal conductivity, heat dissipation, PCB

1. INTRODUCTION

One of the challenges for an electrical system is how to lower the junction temperature of an IC package for high electrical-mechanical reliability. Since set size becomes slim and small and high transfer speed of information data is required simultaneously. If the junction temperature is lowered, then the IC packages can achieve good electrical-thermal reliability.

Conventional methods, which force heat dissipation through the exhaust fan by a heat sink, have made unnecessary noise and they need room for cooling system components.[1-4] This heat dissipation solution may be limited by additional costs and difficulties in meeting the trends of a slim set due to the junction temperature of the IC package. Due to this, having the surface temperature reduced by a PCB enhanced heat dissipation is an attractive solution since a PCB is similar to a nonconductor of heat due to its low thermal conductivity. Xuejun Fan found that insulated metal PCB is superior to FR-4 based PCB,[5-6] while Cho showed that Al plate embedded PCB is very effective for the heat dissipation of PCB.[7]

PSR (Photo-imageable Solder Resist) protects the circuit layer in PCB from some particles or corrosion and insulates the electrically circuit layer. Also, the PSR helps make the soldering process easier by eliminating the PSR around the solder balls. PSR is made of pigments, functional additives, inorganic solvents, and functional fillers based on the thermoset being hardened by heating or light. It has been strongly urged that PSR must have a high reliability level under thermal stress and high electric insulation characteristics in order to meet the trends of a thinner and smaller size.[8]

Since the thermal conductivity of thermoset, the main component of PSR, is as low as 0.2 W/m·K to 0.25 W/m·K, the filler that has a high thermal conductivity should be contained in PSR in order to increase the thermal dissipation of PCB. Many studies have been performed to improve the thermal dissipation capability of the polymer matrix by

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increasing the high conductivity filler contain volume.[9-11] The heat dissipation characteristics of Al_2O_3 have been studied by measuring the loading volume and shapes of the Al_2O_3 in acrylic resin.[12] The thermal conductivity of Polybenzoxazine was increased to 32.5 W/m·K by loading boron nitride(BN) up to 88 wt. %.[13] (wt. % means ratio filler weight to total weight.) C. P. Wong also found that Silica Coated Aluminum Nitride (SCAN) is the most effective in increasing the thermal conductivity among ceramic fillers, such as silica, BN, Alumina, and SCAN in liquid encapsulants.[14]

This paper discusses the experimental and FE analysis that shows that the heat dissipation of PCB can be improved by high thermal conductivity PSR. During the experiment, a wind tunnel, commonly known as suction or an indraft style, was manufactured with the EIA/JEDEC standard, JESD51-6. This wind tunnel was used to measure the heat dissipation effect of the PSR under variable air convection conditions. Also, the heat dissipation effect of the PSR was calculated under variable copper area ratios in the circuit layer and air convection conditions by the FEA.

2. EXPERIMENTAL CONDITIONS AND SIMULATION MODELS

2.1. Experimental conditions

All thermal properties are very difficult to measure precisely and they can be highly affected by thequality of the specimen. The themal conductivity of the newly developed PSR was determined by using a Laser Flash Apparatus (LFA, Netzsch LFA447). The specific heat and density were measured by a Differential Scanning Calorimetry (DSC, TA instruments Q1000) and Electron Analytical Balance (Mettler Toledo, XS205 DualRange), respectively.

Figure 1 shows the temperature testing equipment. As shown in the figure, the wind tunnel, commonly known as a suction or indraft style, was manufactured with the EIA/JEDEC standard, JESD51-6. The flow management components included a honeycomb, which reduces lateral velocity differences, and screens, which, owing to their higher pressure drop in the flow direction, promote a more uniform axial velocity. The combined effect of these elements is the reduction of intensity in turbulence and the production of a flat velocity profile.[15] The uniformity of the flow, swirl, turbulence, as well as the uniformity of the temperature in the chamber of the wind tunnel, satisfied the EIA/JEDEC standard, JESD51-6.

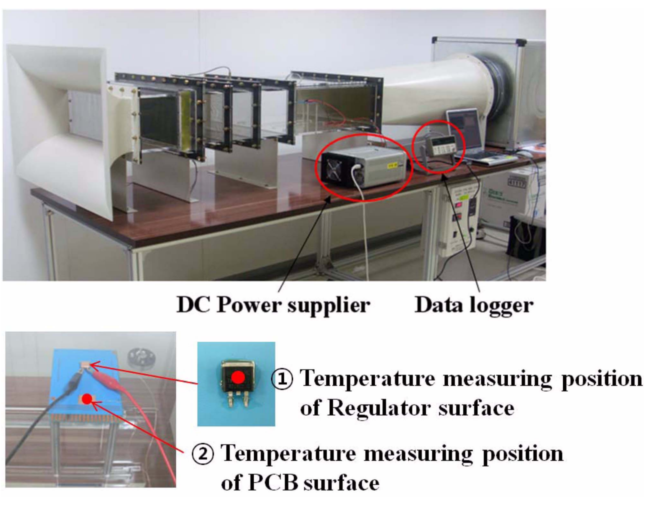

Fig. 1. Measurement equipments.

A regulator, D^2PAK-3, was attached to a PCB by an Sn-Pb solder that was strongly connected to the reflow machine. The PCB was prepared by the EIA/JEDEC standard, JESD51-7. The JESD51-7 is a highly effective thermal conductivity test board for leaded surface mount packages.[16] The PCB had double side circuit layers. The PCB's size was 76 × 114 mm^2. The thickness of the PSR, copper layer, and core layer were 30 μm, 25 μm, 1600 μm, respectively.

There were four specimens that were used to measure the thermal dissipation of the four cases of PCB coated for PSR. Four PSRs were manufactured with a different loading volume for the filler, pigment, and monomer in order to make high thermal conductivity. The loading volume of the filler in the four PSRs were 25 wt. %, 28 wt. %, 32 wt. % and 39 wt. %, respectively, and their sizes were 1 um to 3um. Due to this, these four PSRs had different thermal properties, such as density, specific heat, and thermal conductivity. The T-type thermocouple was attached to the regulator's top surface in order to investigate the surface temperature of the regulator. Although measuring the temperature with thermocouples was considered crucial for this study, and the surface temperature of the regulator was not spatially constant, this measuring method can be effective for measuring accuracy limitations. Although the scope of this study did not measure the high accuracy chip junction temperature, we did analyze the relatively effective new thermal dissipation PSR inks.

The measuring of the surface temperature of the regulator by thermocouple was recorded by a data logger through a RS232 cable (Agilent Co. Ltd). The regulator temperature was measured for 1200 s under an input power of 1.3 W and a room temperature of 20°C.

2.2. Finite element models

The 3D finite element model for the thermal dissipation enhanced PCB in this study is shown in Fig. 2. The model consisted of a chip and the PCB had two circuit layers. The chip was 10 × 10 mm^2 and 0.6 mm thick. The PCB model sizewas 114 × 76 mm^2. The solder resist, circuit layer and dielectric thickness were 30 μm, 25 μm and 1.6 mm respectively. Thus, the total thickness was 1.71 mm. The PCB and a chip were modeled using 24,672 hexagonal ele-

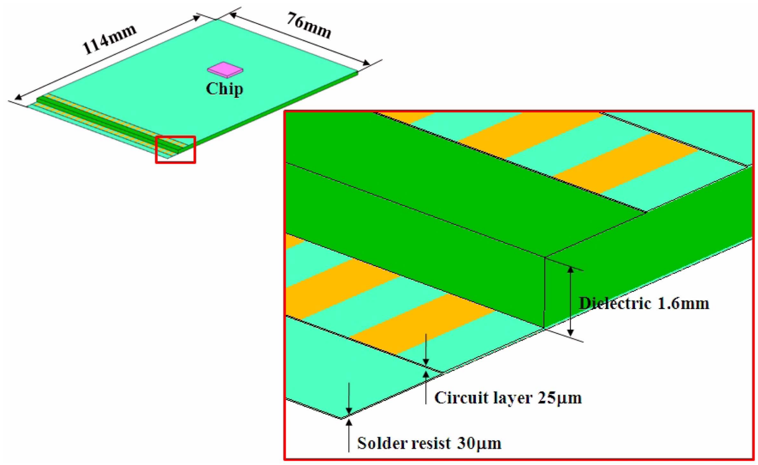

Fig. 2. Schematic diagram of PCB structure.

ments and 27,970 nodes. The FEA calculation was carried out by the use of commercial software MSC/MARC.

Figure 3 shows the copper pattern shapes and the area ratio of the circuit layer of FEA. Three pattern shapes (50%, 75%, 100%) were considered for the copper area ratio in this FEA. The straight line and cross line were 50% and 75% of the copper area ratio, respectively. The finite element modeling consisted of the following assumptions:

(1) The PCB/chip interface was assumed to be glued together and there was no thermal resistance.

(2) The initial temperature was constant at 20°C and it was applied simultaneously to the entire package's surface. Also, the initial temperature was independent of the simulation time.

(3) All layers in the PCB were assumed to have adhered perfectly.

(4) Air cooling occurred by convection but radiation was ignored.

(5) The material properties used in the model are listed in Table 1.

The convection for the FEA boundary condition was considered with the same environmental conditions as the experimental equipment in Fig. 1. The convection environment is shown in Fig. 4. The heat transfer coefficient by con-

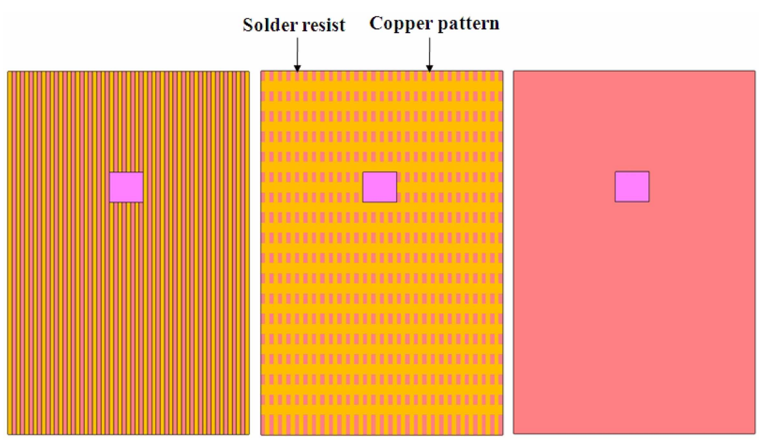

Fig. 3. Copper pattern shape and area ratio in circuit layer for finite element analysis.

Table 1. Thermal properties

	Thermal conductivity, W/m·K	Specific heat, J/kg·K	Density, Kg/m^3
Solder resist	0.23	1140	1570
Copper	385	385	8960
Dielectric	0.27	1200	1790

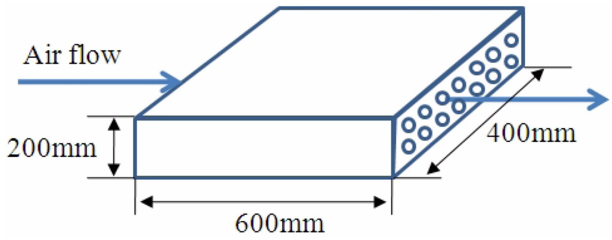

Fig. 4. Chamber structure.

vection was calculated with the chamber surface temperature as constant, while the flow in the chamber was laminar and fully developed. The Nusselt number was calculated by Eqs. 1 and 2:

$$Nu_D = \frac{hD_h}{k} \quad (6)$$

$$D_h = \frac{4A_c}{P} \quad (7)$$

where h represents the heat transfer coefficient, D_h represents the hydraulic diameter, k represents air conductivity, A_c represents the flow cross section area, and P represents the wetted perimeter. In this paper, the three thermal conditions and heat transfer coefficient were 10 $W/m^2 \cdot K$, 50 $W/m^2 \cdot K$, and 200 $W/m^2 \cdot K$. The natural air convection coefficient without enforced flow was assumed to be 10 $W/m^2 \cdot K$.

3. RESULTS AND DISCUSSIONS

3.1. Experimental analysis

Table 2 presents the thermal conductivity of conventional PSR and the newly developed PSR obtained from measurements, as mentioned in Section 2.1. The average thermal conductivity of the newly developed PSR specimens was 0.48, 0.83, and 1.11, respectively. These average values were obtained from the five samples.

Figure 5 shows the regulator surface temperature as a function of air flow velocity with different PSR samples. Ten sample sizes were prepared for this test. In most electronic applications, the wind tunnels are normally used at velocities less than 10 m/s.[16] Thus, the air flow velocity of the ten sample sizes that went through the wind tunnel in order to investigate the heat dissipation effect of the new PSR under an air environment condition was 0 m/s, 2.3 m/s, 4.5 m/s, and 6.3 m/s. The last surface temperature was obtained after the temperature reached a steady-status.

The average surface temperature of the regulator on the PCB coated with a new PSR of 1.11 W/m·K was lowered by approximately 8 K, 6 K, 4 K and 3 K than that of the regulator on the PCB coated conventional PSR of 0.23 W/m·K under an air flow velocity ranging from 0 m/s to 6.3 m/s, respectively.

These experimental results indicate that the capacity of cooling systems, such as the power and size of an exhaust fan or heat sink, in set equipment can be lowered by using a PCB coated with a high thermal conductivity PSR. For example, as shown in Fig. 8, the airflow velocity of 6.3 m/s should be maintained in order to keep the surface temperature at 23 with the conventional PSR coated PCB. However, the air flow velocity could be lowed from 6.3 m/s to 4.6 m/s in order to keep the surface temperature the same with a high thermal conductivity PSR coated PCB. In other words, an air flow velocity of 27% could be saved by the new PSR. Therefore, a cooling fan size or power in set equipment can be reduced with newly enhanced heat dissipation PCB coated PSR. These results are very attractive and useful for manufacturers or the electronics industry since a small fan size or power can reduce noise and promote design flexibility in order to meet the compact shape of set equipment.

Figure 6 presents the PCB surface temperature as a function of air flow velocity. It was measured at position "A", as shown in Fig. 6. The surface temperature measuring condi-

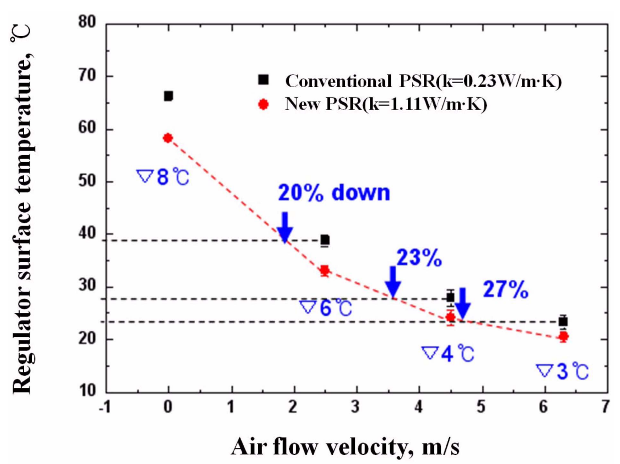

Fig. 5. Regulator surface temperature with PSR as a function of air flow velocity.

Table 2. Thermal conductivity of PSR

	Thermal conductivity, W/m·K	Specific heat, J/kg·K	Density, Kg/m^3
Conventional PSR	0.23	1140	1570
Sample #1	0.35	1236	1402
Sample #2	0.83	785	1509
Sample #3	1.11	817	1602

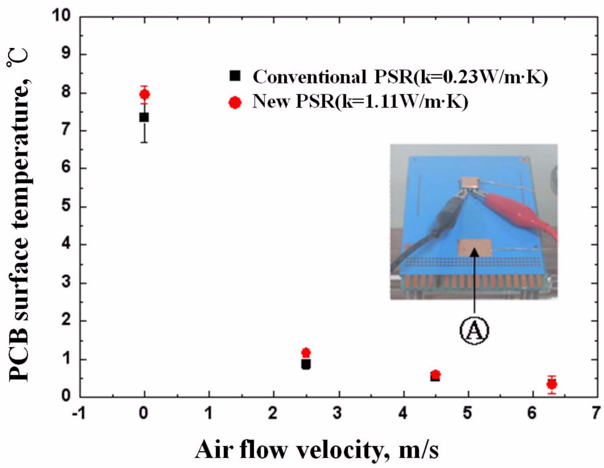

Fig. 6. PCB Surface temperature with PSR as a function of air flow velocity.

tions are the same as Fig. 5. The average temperature of a newly PSR coated PCB at “A” position is about 0.6 K, 0.3 K, 0.07 K, and 0.04 K higher than that of the conventional PSR coated PCB since heat dissipation occurs in PSR through a high thermal conductivity much faster than that of conventional PSR. Also, as the air flow velocity increased and as the difference in PCB surface temperature decreased between high thermal conductivity and conventional PSR, a lot of heat dissipation occurred on the PCB surface by forced air convection than by heat dissipation through PSR in PCB. These results prove that a lot of heat dissipation occurs in PCB with high thermal conductivity PSR.

3.2. Finite element analysis

Figure 7 presents the temperature distribution of the PCB surface after 1200 s at a thermal conductivity of PSR at 0.23 W/m·K and 1.11 W/m·K while the copper area ratio in the circuit layer was 50% and the heat transfer coefficient was 10 W/m^2·K. The maximum chip temperature decreased 2.2 K from 71.1°C to 68.8°C as the PSR thermal conductivity increased from 0.23 W/m·K and 1.11 W/m·K. As the results of Figs. 7(a) and (b) show, a high conductivity of PSR is clearly effective in decreasing the maximum temperature of the chip. Also, PSR thermal conductivity is more effective under a low air heat transfer coefficient. Therefore, a high thermal conductivity of PSR is recommended to electronic products without a cooling fan system.

Figure 8 displays the maximum temperature of a chip after 1200 s as a function of air heat transfer coefficient with the copper area ratio in the circuit layer being 50%. The maximum temperature of the chip decreased in a relatively linear fashion as the heat transfer coefficient increased. Also, the temperature gap of a chip with a PSR thermal conductivity of 0.23 W/m·K, 0.35 W/m·K, 0.8 3W/m·K and 1.11 W/m·K were 2.2 K, 0.6 K, and 0.2 K with a heat transfer coefficient

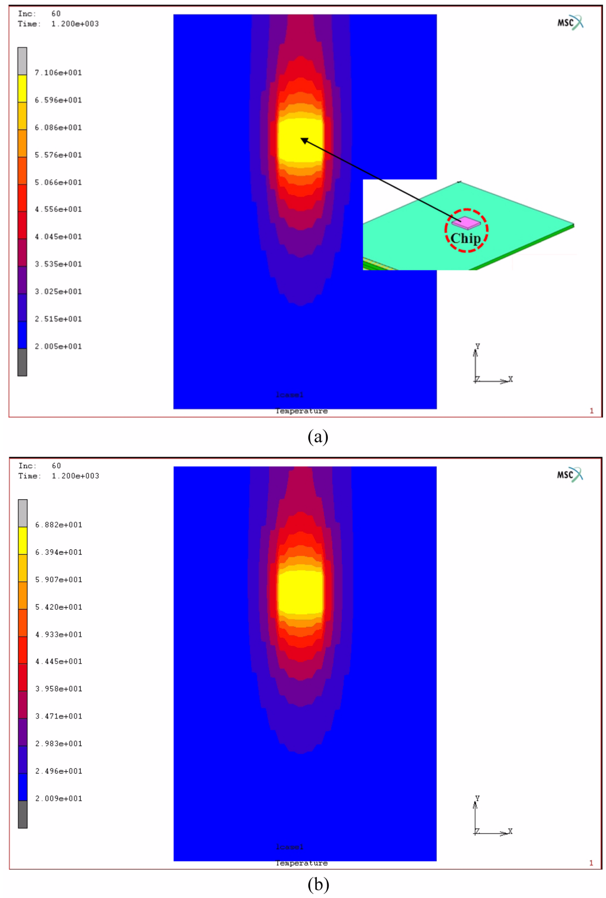

Fig. 7. Temperature distribution of PCB with copper area ratio in circuit layer of 50%: (a) PSR thermal conductivity of 0.23 W/m·K and air heat transfer coefficient of 10 W/m^2·K and (b) thermal PSR thermal conductivity of 1.11 W/m·K and air heat transfer coefficient of 10 W/m^2·K.

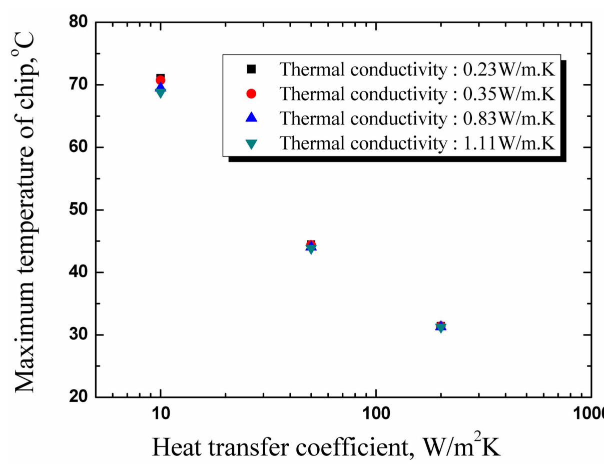

Fig. 8. Maximum temperature of chip as a function of air heat transfer coefficient with copper area ratio in circuit layer of 50%.

of 10 W/m^2·K respectively. This is due to the high thermal conductivity of PSR decreasing as the heat transfer coefficient increases. Therefore, as mentioned above, the benefits of the high thermal conductivity of PSR increase in products with natural convection environments.

4. CONCLUSIONS

Thermal analysis by FEA and experimental analysis were performed to prove the heat dissipation capability of PSR in a PCB. In the experimental analysis, the wind canal oriented electric applications and PCB were performed with the EIA/JEDEC standards JESD51-6 and JESD51-7, respectively, in order to improve the calculation accuracy of the heat dissipation capacity of the PCB. The heat from the circuit layers was hard to dissipate to air by forced convection since the circuit layers were embedded in dielectric and PSR with low thermal conductivity. Thus, high thermal conductivity PSR accelerates heat dissipation from the circuit layer to the air. Also, the junction temperature can be lowered by improving the heat transfer from the chip to the PCB.

Experimental results show that the regulator surface temperature can decrease from 3 to 8K with a high thermal conductivity PSR as air flow velocity. Also, the surface temperature at the surface position, of the PCB with a high thermal conductivity PSR is 0.04 K to 0.6 K higher than that of PCB with conventional PSR.

The FEA results show that the maximum chip temperature decreases 7.8 K as PSR thermal conductivity increases from 0.23 W/m·K and 1.11 W/mK under a heat transfer coefficient of 0.33 $W/m^2 \cdot K$. However, the maximum temperature reduction value of the chip decreases as the heat transfer coefficient increases.

As a result, a high thermal conductivity of PSR is more effective under a low air heat transfer coefficient, such as air conditioning in electronic products without a cooling fan system. However, a high thermal conductivity PSR coated PCB can be used in advanced electronic systems for high electrical performance in terms of electrical-thermal reliability. Also, it can give set design flexibility to electronic system designers with the benefits of reducing cooling fan power or size.

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