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Thermal Transient Characteristics of Die Attach in High Power LED Package

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Abstract: The rapid advances in high power light sources and arrays as encountered in incandescent lamps have induced dramatic increases in die heat flux and power consumption at all levels of high power LED packaging. The lifetime of such devices and device arrays is determined by their temperature and thermal transients controlled by the powering and cooling, because they are usually operated under rough environmental conditions. The reliability of packaged electronics strongly depends on the die attach quality, because any void or a small delamination may cause instant temperature increase in the die, leading sooner or later to failure in the operation. Die attach materials have a key role in the thermal management of high power LED packages by providing the low thermal resistance between the heat generating LED chips and the heat dissipating heat slug. In this paper, thermal transient characteristics of die attach in high power LED package have been studied based on the thermal transient analysis using the evaluation of the structure function of the heat flow path. With high power LED packages fabricated by die attach materials such as Ag paste, solder paste and Au/Sn eutectic bonding, we have demonstrated characteristics such as cross-section analysis, shear test and visual inspection after shear test of die attach and how to detect die attach failures and to measure thermal resistance values of die attach in high power LED package. From the structure function of the thermal transient characteristics, we could know the result that die attach quality of Au/Sn eutectic bonding presented the thermal resistance of about 3.5K/W. It was much better than those of Ag paste and solder paste presented the thermal resistance of about 11.5~14.2K/W and 4.4~4.6K/W, respectively.

Keywords: Die attach quality, Thermal transient analysis, High power LED Package, Au/Sn eutectic bonding

1. Introduction

Recently with the beginning of high power LED package, the requirement of drive current increasing power consumption has increased and the amount of the heat flux generated in these devices has gained. Therefore, effective removal of heat in order to maintain a safe junction temperature is the key to meet the heat flux per high power LED package. Effective thermal management of high power LED package is complex because of the dependence of conduction, convection and radiation. In particular, die attach quality in high power LED package is the crucial factor of thermal resistance between the chip and the heat slug because die attach is very important packaging processes. We can look for the good die attach with the thermal transient analysis that has been used to evaluate the thermal behavior of all of packages for a long time.[1)]

This is the method that the time dependence of temperature is characteristic to the geometrical and material structure of the surroundings of chip such as the heat flow path of the structure and the evaluation of this curve may lead to various models of this heat flow path. Because thermal issues of die attach in high power LED package are not dealing with find-

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ing ways to qualify the behavior of die attach and die attach problems usually can't be detected by the electronic test, obviously die attach quality has to be checked by analyzing thermal transient characteristics of die attach.[2,3]

Structure functions measured and simulated from the evaluation of thermal transient response functions have advantages in the thermal transient testing of electronics structures. Several methods for checking die attach quality have been developed to measure thermal transient characteristics on the basis of the structure function evaluation. With the help of the structure functions, die attach quality of high power LED package can be determined and they can be used to determine partial thermal resistances in a heat flow path. The structure functions can be obtained by direct mathematical transformations from the measured or simulated thermal transient response functions of the system.[4]

In these measurements we can know that the values of the structure functions and their slopes depend on parameters of die attach materials. If we know the geometric and materials parameters, we can determine thermal resistances of die attach materials by evaluating structure functions from fast and simple thermal transient measurements.

In this paper, by measuring and simulating thermal transient characteristics of die attach, we present die attach materials and processes that can be used to reduce the thermal resistance in high power LED package. These evaluations are always known through cumulative and differential structure functions based on thermal transient measurement methods.

2. Experimental

2.1 Physical specification

In order to check the quality of die attach, it is necessary to design high power LED packages with the uniform and constant structure for the heat generating LED chip and the heat dissipating heat slug. In this experiment, we used the LED chip with a geometrically enhance Epi-down design to maximize high extraction efficiency and require only a single wire bond connection. Also, we used the heat slug with Si conductor fabricated by the semiconductor process. This constant heat slug is a key factor to check the quality of die attach because the thermal resistance of heat slug is constant.

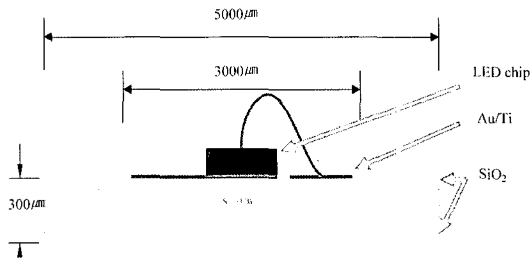


Fig. 1. The schematic of the measured high power LED package

Fig. 1 shows the schematic of the measured high power LED package. As shown in the Fig. 1, high power LED packages largely consist of LED chip, die attach material and Si heat slug. This package was designed to be used in checking die attach quality. The width of top electrode was 300 μm and the whole package was 500 μm. High power LED packages have a sandwich-like heat removal path of different materials ending in the cooling slug. We characterized such devices of the different color, mounted on the cold-plate. We recorded thermal transients at different power levels.

Material specification used in the fabricated high power LED package is presented in Table 1. Here thermal conductivity is a property of materials that expresses the heat which will flow through the material if a certain temperature gradient exists over the material. The thermal conductivity is usually

Table 1. Material specification of LED package

Structure	Thickness (mm)	Thermal conductivity (W/mK)
Au/Ti	0.94	300
SiO_2	1.01	1.7
Si	303.5	130
SiO_2	1.01	1.7

expressed in W/m·K. It is very difficult to measure thermal conductivity because it usually requires a carefully planned laboratory experiment and a lot of time to get to equilibrium. In this Table, the thermal conductivity of structures is the crucial value in the thermal transient measurement and simulation considering one dimensional conduction.

Die attach materials are limited because of the electrical problem such as the short between LED chip and heat slug depending on the location of the chip epi-layer. In this experiment, high power LED packages are fabricated with die attach materials such as Ag paste, solder paste and Au-Sn eutectic bonding. Fig. 2 shows general schematics of die attach process for die attach materials such as solder paste and Ag paste. Die attach processes of this materials have sequences of screen printing of die attach materials with metal mask of the square hole(300 μm × 300 μm), loading of LED chip on the patterned die attach material, heat treatment process to cure die attach materials and wire bonding process to supply the power.

Schematics of Au/Sn eutectic bonding process are presented in Fig. 3. It is not necessary to attach with die attach materials because die attach materials between LED chip and heat slug are formed by being forced with a constant temperature and pressure. From this processes we can form the good and thin Au/Sn die attach materials for dissipating the heat. Die attach processes for Au/Sn eutectic bonding have sequences of the pre-heating treatment at temperature of 200°C, loading of LED chip, heating treatment at temperature of 310°C for 20sec to melt Au/Sn, and wire bonding process.[5)]

Fig. 4 shows the fabricated high power LED package for measuring thermal resistance using the

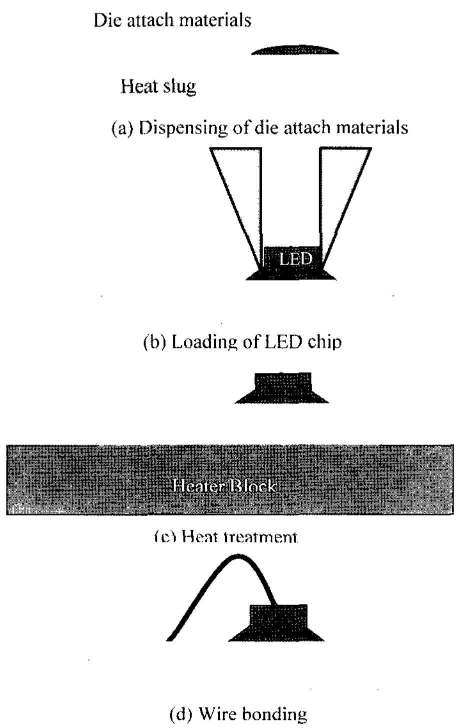


Fig. 2. Schematics of die attach process for die attach materials such as solder paste and Ag paste.

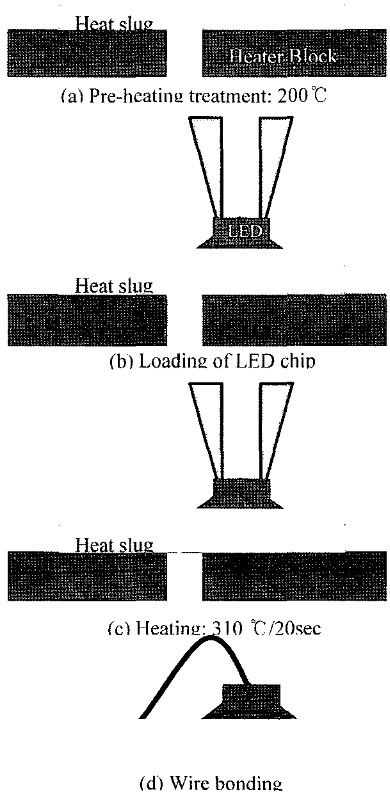


Fig. 3. Schematics of die attach process for Au/Sn eutectic bonding.

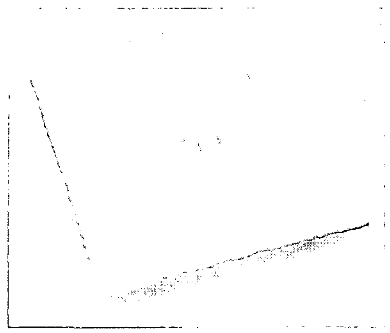


Fig. 4. High power LED package fabricated for measuring thermal resistance using the thermal transient analysis.

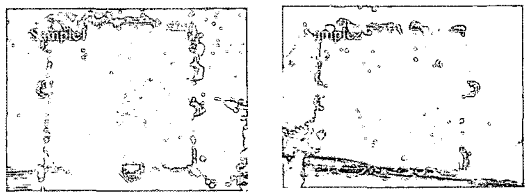
thermal transient analysis. Three different high power LED packages with other die attach materials and processes were fabricated and measured. The bottom of heat slug is glued with the thermal grease on the cold plate in order to have one- dimensional heat flow paths and dissipate the heat occurring in LED chip. Thermal transient characteristics of die attach in high power LED package are measured by the T3ster. The T3ster is the equipment for Thermal transient analysis of LED.

2.2 Die attach quality

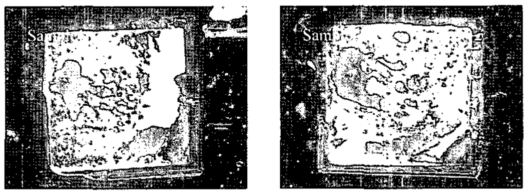
The shear test and visual inspection are the most used technique in order to evaluate the die attach quality. Results of the measured shear test for Au/Sn eutectic bonding, solder and Ag-paste are shown in Table 2. Among die attach materials, the strength of solder paste with the average value of 4.2 kgf is higher than Au/Sn eutectic bonding and Ag paste with the average value of 2.5 kgf and 1.5kgf, respectively. Fig. 5 shows pictures of visual inspection of fracture surfaces after the shear test for Au/Sn

Table 2. Results of the measured shear test for Au/Sn eutectic bonding, solder paste and Ag paste

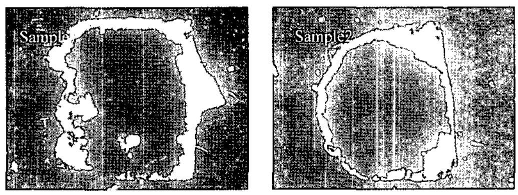
	Sample1	Sample2	Average
Au/Sn eutectic bonding	2.4kgf	2.6kgf	2.5kgf
Soldr paste	4.2kgf	4.3kgf	4.2kgf
Ag paste	1.5kgf	1.5kgf	1.5kgf



(a) Au/Sn eutectic bonding



(b) Solder paste



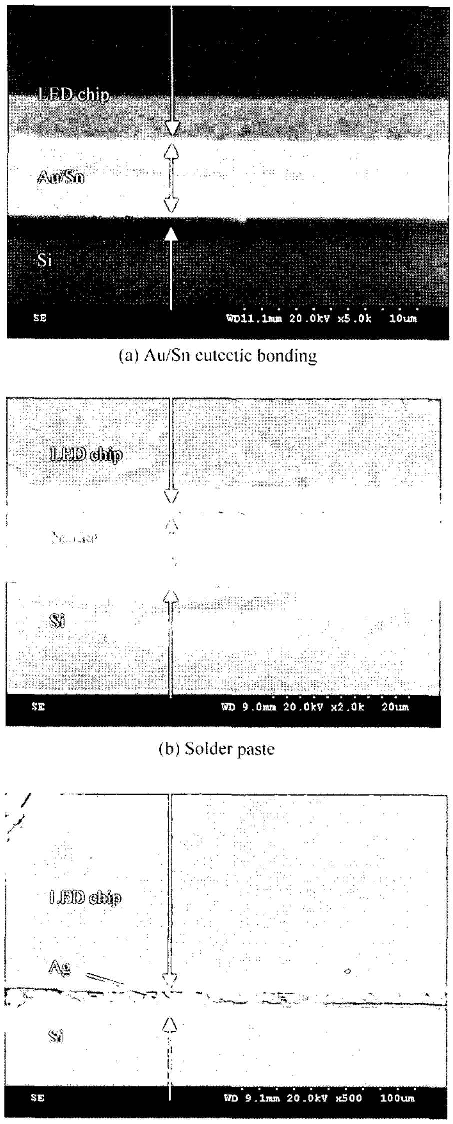
(c) Ag paste

Fig. 5. Visual inspection after shear test of die attach.

eutectic bonding, solder and Ag-paste, respectively. Bonding area is not bad compared to this of paste materials with visual inspection of Au/Sn eutectic bonding.

The cross-section SEM pictures of the fabricated high power LED package formed by die attach materials of Au/Sn, solder and Ag-paste are presented in Fig. 6. The thickness of layers formed by Au/Sn eutectic bonding, solder and Ag-paste is 5 μm, 10 μm and 10 μm, respectively. In case of solder and Ag-paste, the thickness of the layer could be constantly controlled by screen-printed pastes using the metal mask. As shown in Fig. 6, die attach layers of Fig. 6 (a) and (b) are formed by melting die attach materials at high temperature, and we can see that the particles are not presented in the cross-section die attach layers of Au/Sn eutectic bonding and solder paste compared to Ag paste with different particles by the condition of curing.

But the relationship between the void area and the increase in the thermal resistance is not reasonable



(a) Au/Sn eutectic bonding

(b) Solder paste

(c) Ag paste

Fig. 6. Cross-section SEM pictures for die attach materials of Au/Sn eutectic bonding, solder paste and Ag paste.

and depends on thermal transient characteristics of the actual material.

The effect of voids on the thermal resistances of die attach materials depends on the adhesion between LED chip and the surface of heat slug. If voids are mostly distributed around the heat flow path, they bring about the increase of thermal resistance influencing the thermal behaviors. Very good method to check die attach quality is achieved in the evaluation of the die attach quality by using the thermal transient characteristics and the structure function evaluation.

3. Result and Discussion

Structure functions provide a map of the cumulative thermal capacitances of the heat flow path with respect to the thermal resistances from the junction to the ambient. From the derivative of this function, the differential structure is represented as a function of the cumulative thermal resistance. In both of these functions, the local peaks and valleys indicate reaching new materials or changed surface areas in the heat flow path. More precisely, the peak point usually means the middle of any new region.

The structure functions are appropriate to evaluate die attach quality in high power LED package. The structure functions are defined for structures that one dimensional heat flow path is assured by the applied thermal boundary conditions. Practically this can be obtained with the help of cold plates.

The evaluation of thermal transient simulation can be used for generating the thermal transient modeling purposes. Simulation tools support fast and easy evaluation of the thermal transient behavior. From this fact, thermal transient simulation of die attach characteristics is a useful method to represent the thermal behavior of high power LED package. The thermal transient characteristics of die attach quality can be simulated. Die attach quality in high power LED package is determined from the comparison of the measured and simulated curves.[6,7]

Fig. 7 shows the simulated results of high power LED packages with three different die attach materials. As shown in this figure, the thermal resistance Rj-d from LED chip to die attach materials with Au/Sn eutectic bonding, solder paste and Ag paste is 3.54K/W, 4.49K/W and 11.9K/W, respectively. From this result, we can know the fact that the die-attach quality by Au/Sn eutectic bonding is better than it by

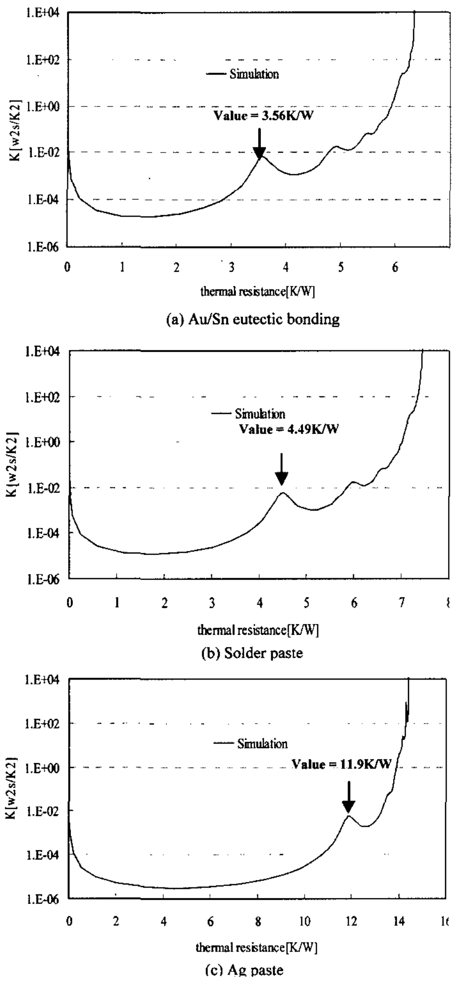


Fig. 7. Simulated results of high power LED packages with three different die attach materials.

solder paste and Ag paste. This simulation result is assumed about the identical structures for LED chip and heat slug and the variables in this simulation are the thermal conductivity and the heat transfer coefficient. The values of considered variables are presented in Table 3.

The thermal transient tester measures the cooling curve with the time dependence of the temperature. This curve is applied as the step function power is switched on or off. A typical cooling transient curve is measured by powering 350 mA forward current and capturing the forward voltage after switching a

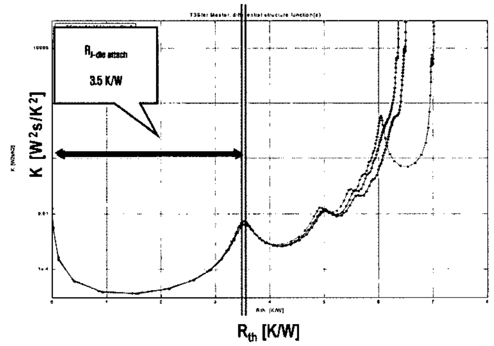
Table 3. Considered variables in the simulation for checking the die attach quality

	Thermal conductivity (W/mK)	Heat transfer coefficient
Au/Sn eutectic bonding	28	1
Solder paste	4.2	0.15
Ag paste	0.616	0.022

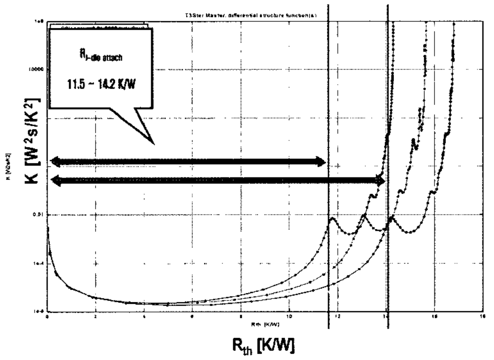
sensor current of 10 mA. A sensitivity factor with the ratio of the forward voltage dependence of the temperature is measured in a previous calibration step. The thermal transient response for high power LED packages is measured from this measurement process and is transformed into the structure functions through the thermal transient analysis. In order to convert the thermal transient response to cumulative and differential structure functions, it is necessary to remove the initial electric transients.

It is easier to identify the comparison of die attach quality between die attach materials using the differential structure function that can be explained as the derivative of the cumulative structure function. Fig. 8 shows measured differential structure functions of high power LED packages with three different die attach materials. As shown in figure, peaks correspond to regions of high thermal conductivity and valleys show regions of low thermal conductivity. The thermal resistance of Au/Sn eutectic bonding, solder paste and Ag paste is presented the value of 3.5K/W, 4.4~4.6K/W and 11.5~14.2K/W, respectively. In case of Au/Sn eutectic bonding and solder paste, the values of the thermal resistance from the chip to die attach are uniformly distributed. But the case of Ag paste is largely distributed because of the curing process of Ag paste.

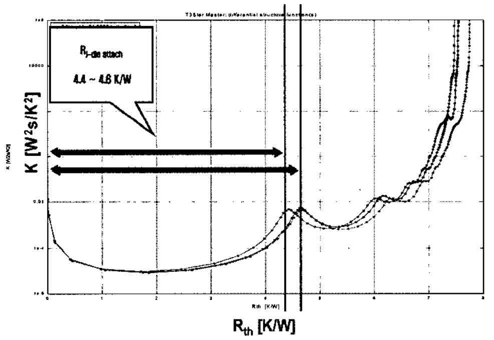
These results enable us to identify Rj-d, junction-to-die attach thermal resistance, because the repeatability of the measurement is good. We can know that the differential structure functions remain always the same in the thermal resistance range belonging to the heat slug. In the differential structure functions shown in Fig. 8(a), we can see variations caused by different fixing force and thermal



(a) Au/Sn eutectic bonding



(b) Solder paste



(c) Ag paste

Fig. 8. Measured differential structure functions of high power LED packages with three different die attach materials.

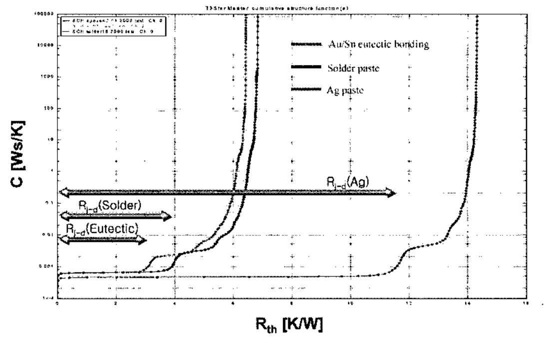


Fig. 9. Measured cumulative structure functions of high power LED packages for the good case of three different die attach materials.

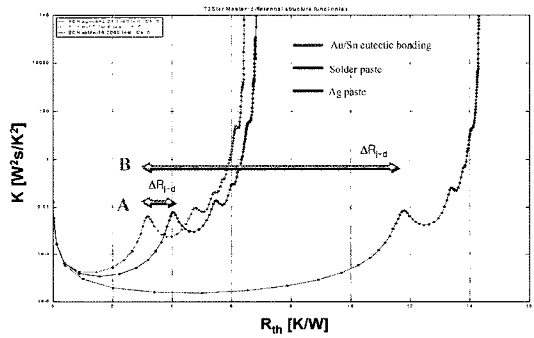


Fig. 10. Measured differential structure functions of high power LED packages for the good case of three different die attach materials.

grease width formed between the heat slug and the cold plate.

Cumulative structure function presented only for the good case of three different die attach materials are shown in Fig. 9. Cumulative structure functions are simply a graphic representation of the one dimensional equivalent thermal RC network of the measured system, thus thermal resistance and capacitance values belonging to the heat conduction path from junction to die attach can be directly indicated. In this figure, the horizontal axis shows the thermal resistance values and the vertical axis shows the thermal capacitance values with a log scale. As shown in the figure, the first vertical step of this curves indicates the thermal capacities of die attach materials. The regions with low capacitance have low thermal conductivity and cause large change in thermal resistance. We can know the thermal resistance of Au/Sn eutectic bonding (Rj-d(Eutectic)), solder paste(Rj-d(Solder)) and Ag paste (Rj-d(Ag)) from cumulative structure functions of this figure.

Fig. 10 shows measured differential structure functions of high power LED packages for the good case

Table 4. Summary of simulated and measured thermal transient characteristics of die attach

Structure	Simulated Rj-d (K/W)	Measured Rj-d (K/W)	Measured Rj-a(K/W)
Au/Su eutectic bonding	3.6	3.5	6.0-6.2
Soloder paste	4.5	4.4-4.6	7.2-7.3
Ag paste	11.9	11.5-14.2	14-16.5

of three different die attach materials. As shown in this figure, we can know the fact that the measurements of the thermal resistance of die attach materials has grasp of the difference of die attach quality by using the differential structure functions. The measurement principle is based on the shift of peaks in the differential structure function for die attach materials as illustrated by Fig. 10.

In this figure, among die attach materials, we can see the result that die attach quality of Au/Sn eutectic bonding is much better than those of Ag paste and solder paste. There are the differences of thermal resistance with respect to Au/Sn eutectic bonding which are section A of about 1K/W and section B of about 8K/W compared to solder paste and Ag paste, respectively. The summary for simulated and measured thermal transient characteristics of die attach in high power LED packages is presented in Table 4. We can know that all of the die attach quality and reliability can be done with the cumulative and differential structure functions using the thermal transient analysis in high power LED package.

4. Conclusion

In this paper we have studied thermal transient characteristics of die attach in high power LED package. We could measure the cumulative and differential structure functions using thermal transient analysis. From this results, thermal transients characteristics can be used to evaluate the effect of the thermal resistance for die attach materials and choose the suitable die attach condition. In fabricated high power LED packages, the die attach quality of Au/Sn eutectic bonding was much better than those of the solder paste and Ag paste in terms of the total thermal resistance.

Also, we have shown that the structure function approach is a very powerful method for characterizing thermal transients of the heat flow path and calculating junction-to-die attach and junction-to-ambient thermal resistances.

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