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Numerical Simulation and Experimental Researches on the LED Reliability under Temperature Loading

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Abstract: The reliability problem must be solved for achieving large-scale application about LEDs, and the temperature is a key factor to affect LED reliability. In order to find the temperature effects on the module of high-power light emitting diodes (LEDs), a finite element approach was used to study the reliability problems of LEDs under high temperature and low temperature. A thermal shock experiment of LEDs was conducted by thermal shock chamber. The numerical simulations were used to obtain the thermal stress distribution of the LED modules. The simulated results showed that the stress generated at interfaces of all kinds of materials is relatively large comparing to the other parts in LED. After the thermal shock test, the rate of LED failure is 4%. The reasons of failure are high junction temperature of chip, materials degradation, thermal mismatch of materials, delamination and so on. Base on the above simulations and experiments, failure mechanisms were analyzed. These conclusions provide a basis for further study of the reliability of the LED under temperature loading. At the same time it provides a foundation for designing the package reliability about LED modules.

Keywords: LED, thermal stress, numerical simulation, thermal shock, reliability.

1. Introduction

High power Light Emitting Diodes is a solid-state semiconductor device that can convert electrical energy into visible light. Owing to their low energy consumption and long lifetime, etc, LEDs are considered to be the fourth generation light source. But the large-scale application of LEDs needs to solve reliability issues. If only the reliability of LED is improved, the LEDs can really perform the excellent features: long lifetime, high luminous efficiency, energy saving and so on. The temperature is a major factor affecting LED reliability. If LEDs are used in the high temperature, the low temperature and the alternating high and low temperature environment, there will be many unexpected problems, such as luminous efficiency reducing and color temperature changing.

There are many people studying the LED reliability under temperature loading. Narendran N et al. [1] have confirmed by experiments: the lifetime of LED is exponential declined with the junction temperature of chip increasing. DeMilo C et al. [2] used finite element analysis to find that the thermal stress of LED have a great relationship with the thermal expansion coefficient difference between the chip and substrate in LED, and the lifetime and brightness of the LED also associated with the junction stress of chip. S. Yamakosh et al. [3] reported that the output power and time of the LED can use the exponential function, which satisfied the relationship of the Arrhenius Equation about the degradation coefficient and junction temperature of the LED devices. This relation has been widely used to describe a variety of long-term degradation of the LED law. For the high power LED, based on current semiconductor manufacturing technology, the input power of LED have only about 5% to 10% of the energy to convert into light energy, and the other energy is converted into heat [4]. How to manage the thermal energy of the high-power LED, is the crucial problem of LED device packaging and device applied designing. Sheng Liu et al. [5] installed a micro-pump system on the radiator to solve the LED heat problem, and found that its thermal performance is superior to the heat pipe and heat sink. In recent years, there are a lot of related reports about pack-

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aging thermal problem of High-power LED. M. Arik et al. discussed the thermal problems in high-power LED devices and system-level packaging process, and compared the different chip materials and the different bonding technology how to affect the heat dissipation of LED in 2001 [6]. In 2003, they had established and analyzed the thermal model of the white-LED phosphor particles [7]. In 2004, they found out some key thermal problems on the LED chip-scale packaging process by he finite element analysis and experiments [8]. B.B. Kerezsi et al. used S-N curves to analyze cracking due to repeated thermal shock. The thermal shocks may eventually lead to crack initiation and crack growth. In some cases these cracks lead component to failure [9]. Many people conducted the reliability test on various electronic products by thermal shock. Y. Wang et al.[10] investigated the stress field and failure mode of plasma sprayed Al2O3-13%TiO2 coating under thermal shock. The effects of interface morphology and coating defects on thermal stresses were discussed. N. M. Poon et al. [11] studied the residual shear force strength of Sn-Ag and Sn-Bi lead-free SMT joints after thermal shock. All joints were subjected to various cycles of thermal shock with temperature ranging from 25°C to 125°C. Voids and cracks were also observed in the joint of Sn-Bi solder alloy after 1000 thermal shock cycles. Quan Chen et al. [12] studied junction temperature during degradation process of high power light-emitting diodes. They thought that the thermal mismatch between the epilayer of chip and the substrate of package raised junction temperature in the later aging time.

Several status quo about temperature reliability researches of LED can be found from the existing literature: 1) At present, the domestic and foreign researches mainly concentrated in the package and system-level thermal management techniques, and rarely considered the effects of temperature on the LED reliability, especially in the accelerated test of LED. The temperature loading will causes large thermal stress. In fact, packaging, preservation, use and the heat dissipation problem of LED will have to place in some temperature environment, so the temperature is an important factor affecting the LED reliability. 2) The literature on the reliability of the LED about temperature is relatively small, and especially the article of temperature cycling and thermal shock is less. There are different perspectives: some people think that the thermal stress caused by temperature can be ignored, but the other people point out that temperature is a main reason leading LED to failure. 3) The LED reliability test about temperature is relatively rare. This may be due to the limitations of equipment and experimental conditions, the large costs of accelerated test, and the unobvious results of accelerated test. Meanwhile, finite element method and virtual analysis that were used to study the reliability of LED about temperature are also relatively rare.

Based on the above current situation, a LED module was dissected to observe its internal structure. Some parameters were obtained to establish the model for simulation. The LED modules are simulated subjecting to high temperature and low temperature. The thermal stress distribution was obtained by the simulation. Then some thermal shock experiments were conducted. During the thermal shock, the varied temperature parameters of the LED were monitored. The failure mechanisms of LED module are analyzed.

2. Numerical simulations

In order to conduct our researches, a LED module was selected to do the anatomy. The module was cut and polished to become 1/2 module of LED. Then a microscope was used to conduct geometric analysis of LED, and the parameters of various parts in LED were defined for establishing the numerical model. In order to reduce modeling and computational complexity in the modeling process, the real model do some reasonable simplification: 1) taking into account the symmetry factor, 1/4 model of the LED module is OK; 2) the LED module is roughly circular structure, so it can be further simplified as a two-dimensional structure. These simplifications greatly reduce computer hardware requirements for the simulation, and at the same time, greatly speed up the calculation speed. 1/4 LED model was established in Fig.1. Its structure includes lens, phosphor, solder layer, heat sink, molding compound, substrate and chip.

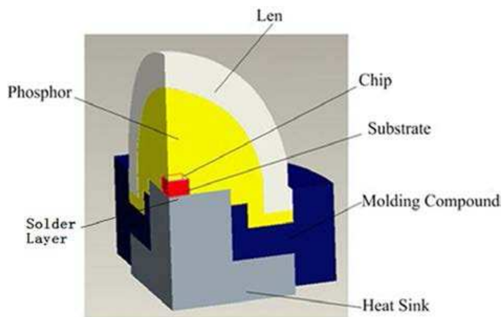

Figure 1 1/4 LED model and its internal structure.

The chip size was $1\ mm \times 1\ mm$. The simplified two-dimensional model was given out to conduct simulation. The number of the grid is 1880. It is shown in the Fig.2.

The material properties were shown in Table 1. After selecting the material properties, we could simulate the thermal matching and thermal stress distribution in the various components of LEDs under thermal loads. In the simulated process, according to the microscopic structure of the LED, some data of seven materials were used in the following table 1.

When conducting the high temperature modeling, the LED modules were supposedly placed in the high temperature chamber. The temperature in the chamber increased

Table 1 Materials property of LED components in the simulation

Number	Pats	Materials	Thermal conductivity/ $(w \cdot m^{-1} \cdot K^{-1})$	CTE $/K^{-1}$	Young's modulus /Gpa	Poisson's ratio
1	chip	GaN	170	7.75×10^{-6}	210	0.17
2	substrate	SiC	490	3×10^{-6}	400	0.16
3	Phosphor layer	Phosphor /Silicone	0.00768	4.5×10^{-5}	5.2	0.35
4	Lens	Silicone	0.12	3.8×10^{-5}	5	0.40
5	Heat sink	copper	401	1.8×10^{-5}	110	0.34
6	Solder layer	Sn63Pb37	50	2.5×10^{-5}	12.23	0.43
7	Molding compound	plastic	7.68×10^{-2}	5×10^{-5}	3.75	0.35

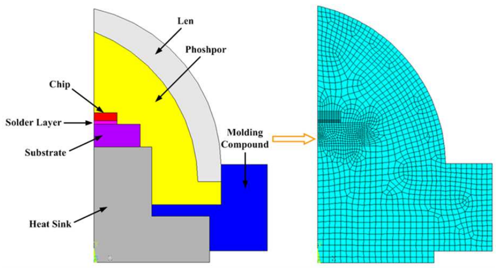

Figure 2 Grid used in the LED model.

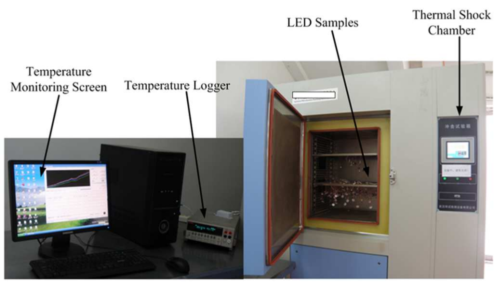

Figure 3 Thermal shock chamber and temperature monitoring system.

from the room temperature to 150°C. Due to the different coefficient of thermal expansion in these materials, all parts of LED will induce thermal stress. Similarly, when conducting the low temperature modeling, the LED modules were supposedly placed in the low temperature chamber. The temperature declined from the room temperature to -50°C. This will also generate temperature stress.

3. Experiments

The products of LED are easily damaged in our daily life. This is because there are some problems about their reliability. Thermal shock is that the rapid heating or cooling cause the temperature of objects to change in a short time. The purpose of thermal shock test is to observe the failure of LED in the condition of thermal shock. This will induce thermal stress and accelerate the failure of the samples. The changes of LED characteristics will be confirmed in a short period of time, and we will find the problem of LED failure caused by the different coefficient of thermal expansion in dissimilar materials. The method can be used to observe the defects of LED. Some practices have proved that, if the method of thermal shock test combined with the online monitoring and other means, this can not only find quality failure existed in products, but also find a number of potential defects by the trend analysis of relevant data, and this will help to improve production process, product design, material selection, lifetime prediction and failure mode analysis.

In order to determine the effect of temperature on the silicone/phosphor composites, the composites were subjected to thermal shock, and 100 LED samples were impact at 150°C and -50°C for 1000 cycles. In the experiments, a thermal shock chamber is used. The thermal shock chamber has three zones: high temperature box, low temperature box and testing box. The temperature uniformity is ± 2°C in the testing box. In the testing process, a temperature logger was used for online monitoring the temperature of LED. The temperature monitoring system is used to real-time monitor the temperature on the surfaces of LED, and it can measure the temperature uniformity of thermal shock chamber. Doing so is to make the results of experiment more authentic. In the testing zone, the LED samples were hung in the air at the test box for more uniform heating lest they were affected from the tray. The thermal shock chamber and the monitoring system were shown in Fig. 3.

During the process of temperature shock, there are 20 minutes of temperature keeping time, so the whole LED will be considered to put in the uniform temperature field of high or low temperature. 100 LED samples are put in the thermal shock to conduct thermal shock test. The tem-

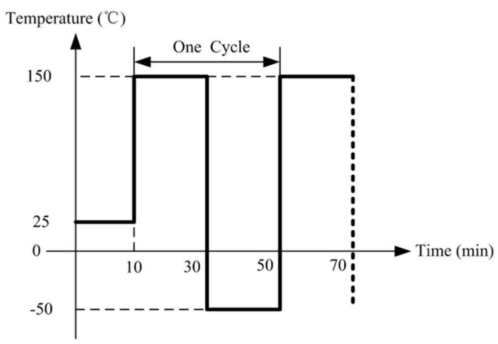

Figure 4 The curve of thermal shock.

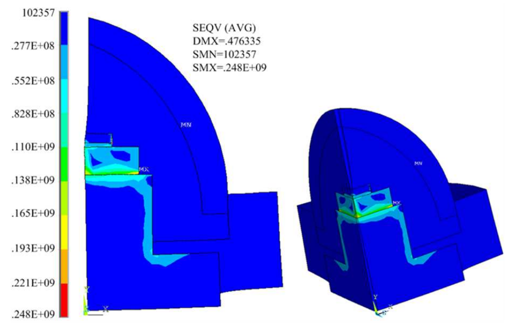

Figure 5 Thermal stress and deformation in LED under the low temperature.

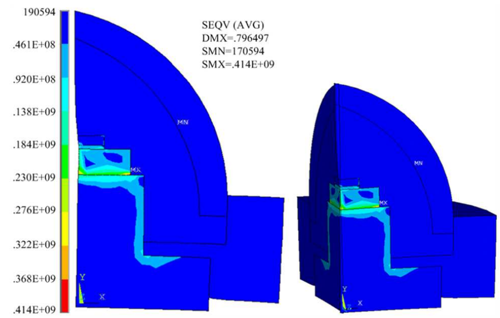

Figure 6 Thermal stress and deformation in LED under the high temperature.

perature range is $-50°C \sim 150°C$. The size of the testing zone is $40\ cm \times 50\ cm \times 60\ cm$. The 100 LED samples were divided into 10 groups, and one group had 10 LED samples. The experiment conducted 1000 cycles of thermal shock. Every 200 cycles all the LED samples were taken out for testing to observe their failure situation. The failure criterion of the thermal shock is that the tested LED samples are no longer able to light up. The curve of thermal shock is shown in Fig. 4. In every cycle, the highest temperature is 150°C, the lowest temperature is $-50°C$, and the hold time is 20 minutes. The time converted from high temperature to low temperature is 30 seconds, and it spent 40 minutes in every cycles.

When LED is working, the primary failure modes are failure caused by fatigue. If the working environment is alternately heating and cooling, such as the thermal shock test, and the material of device and substrate exist the difference of the coefficient of thermal expansion, the connection of one material and the other materials will induce thermal stress. The magnitude and the direction of thermal stress will change with temperature altering. So the thermal shock test is very necessary.

4. Results and analyses

Thermal stress distribution is one of the most important parameters in the electronic packaging structure. The stresses resulting in phosphor layer decay might be induced by temperature. The finite element method is used in our researches to obtain the field of temperature, thermal stress, and deformation. The danger points of LED were found out. The simulated results were shown in Fig. 5 and Fig. 6.

In Fig. 5, the maximum stress occurred in the interface of heat sink and the substrate. The heat sink, the solder and substrate also generated a larger stress. LED components had shriveled and squeezed into the centre of LED sample. It can be seen form Fig. 5, the centre position of LED is left protruding, and the LED had been deformed.

In Fig. 6, LED was put on a high temperature loading in the simulation. The maximum thermal stress also existed in the interfaces of the heat sink and substrate. The difference is that the centre position of LED is left contraction, and the outer layer of LED is expansive state. The LED samples also have some deformation.

Table 2 Experimental results of LED in the thermal shock test

Cycles \ Group	1	2	3	4	5	6	7	8	9	10
0	10	10	10	10	10	10	10	10	10	10
200	10	10	10	9	10	10	9	10	10	10
400	10	10	10	9	10	10	9	10	10	10
600	10	9	10	9	10	10	9	10	10	10
800	10	9	10	9	10	10	9	10	9	10
1000	10	9	10	9	10	10	9	10	9	10

Some experimental data was obtained by the thermal shock test. The experimental results were shown in the table 2. When the thermal shock experiments were conducted 200 cycles, the group 4 and group 7 separately had one LED failed. Then at 600 cycles and at 800 cycles, the group 2 and group 9 accordingly had one LED to be bad. Four LEDs are failure in the100 LEDs, so the rate of failure is 4%.

Recently, there is a growing recognition which the reliability problems of LED were caused by the package. In general, the aging of LED will bring about the decline of the luminous flux and the optical power, color temperature drift and the lower slope of IV curve. Visual inspection and microscopic morphology can check the appearance of LED, and check for burned black, yellowing, deformation, cracks, and so on. There are some reasons for temperature leading LED modules to failure: 1) High temperature causes the packaging material rapidly degradation, and the performance of LED becomes bad. 2) The junction temperature had a large effect with the performance of LED. Excessive junction temperature causes the phosphor layer burning black and carbonizing, and this will make light efficiency of LED drastically decline, sometime, it will occur to catastrophic failure. 3) Due to the mismatch of the coefficient of thermal expansion between the various materials, the internal structure of LED exist the temperature gradient and uneven temperature distribution. Its constituent materials may crack and their interfaces may produce delamination. Delaminating between the silicone and the substrate may lead to the failure of gold wire, resulting in catastrophic failure.

5. Conclusions

In this paper, the thermal shock experiments were conducted and LED was simulation at high and low temperatures. The thermal stress distribution of the LED components was obtained. It was found that the maximum stress occurred in the interface of heat sink and the substrate. The heat sink, the solder and substrate also generated a larger stress. The rate of LED failure is 4% in the thermal shock test. The reasons of failure are high junction temperature of chip, materials degradation, thermal mismatch of materials and delamination between the silicone and the substrate.

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