Reliability test and failure analysis of high power LED packages*

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Abstract: A new type application specific light emitting diode (LED) package (ASLP) with freeform polycarbonate lens for street lighting is developed, whose manufacturing processes are compatible with a typical LED packaging process. The reliability test methods and failure criterions from different vendors are reviewed and compared. It is found that test methods and failure criterions are quite different. The rapid reliability assessment standards are urgently needed for the LED industry. 85 ℃/85 RH with 700 mA is used to test our LED modules with three other vendors for 1000 h, showing no visible degradation in optical performance for our modules, with two other vendors showing significant degradation. Some failure analysis methods such as C-SAM, Nano X-ray CT and optical microscope are used for LED packages. Some failure mechanisms such as delaminations and cracks are detected in the LED packages after the accelerated reliability testing. The finite element simulation method is helpful for the failure analysis and design of the reliability of the LED packaging. One example is used to show one currently used module in industry is vulnerable and may not easily pass the harsh thermal cycle testing.

Key words: LED package; ASLP; accelerated reliability test; failure analysis

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1. Introduction

Solid state lighting in terms of high power LEDs will be the fourth illumination source to substitute the incandescent lamp, fluorescent lamp and high pressure sodium lamp[1]. LEDs have superior characteristics such as high efficiency, low power consumption, high reliability and long life[2]. Currently, high power LEDs have found applications in outdoor and indoor illumination, automotive front lighting, backlighting for large LCD displays and city improvement engineering[3−5]. The theoretical viewpoint is that LEDs can work as long as one hundred thousand hours with perfect conditions. However, the material degradation and structure damage due to the electrical, thermal, chemical and mechanical stress will lead to the lumen degradation, color variation or even early death of the LEDs. The reliability of the high power LEDs is becoming a big issue for the emerging illumination applications which must be considered during LED products development procedure with concept of design for reliability (DfR) which has been practiced in many industries in the past few decades[6].

The failure mechanisms of the high power LEDs are complicated during the practical applications which can be coarsely divided into chip level and packaging level, if we define packaging to be system in packaging (SiP) so that the whole light fixture system is also a SiP. In the chip level, the degradation of LED devices will occur due to the generation of nonradiative defects, modifications of the electrical properties of the ohmic contacts and changes in the local indium concentration in the quantum wells under electrical and thermal stresses[7]. In the packaging level, the degradation of package materials such as the molding compound, polycarbonate lens, silicone and phosphor and structure damages such as voids in die attach and delaminations at the different interfaces will have significant effects on the thermal, optical and reliability performance of LED devices under the electrical, thermal, moisture, chemistry and mechanical stress[8]. However, the knowledge of the physical mechanisms which will limit the reliability performance of the LED devices is far not enough and there is not unified evaluation standard yet for the reliability of the LED devices.

In this paper, a new type of ASLP LED package with a freeform polycarbonate lens for street lighting is developed, whose manufacturing processes are compatible with the typical LED packaging process. The reliability test methods and failure criterions from different vendors are reviewed and compared. Some failure analysis method C-SAM, Nano X-ray CT and optical microscope is used for LED packages. Finite element simulation is conducted for one conventional high power package.

2. LED packaging technology

Packaging provides the electrical connection between the LED chips and external circuit and protection of LED chips from the damages of electrostatic discharge, moisture, high temperature, chemical oxidation, and shock *et al*. In addition, packaging enhances light extraction to provide high luminous

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Table 1. Some reliability test conditions adopted by different vendors.

Test method	Stress condition	
	Vendor1	Vendor 2
RTOL	Ambient temperature: 45 ℃ Forward current: maximum in datasheet Test period: 1008 h	Ambient temperature: 55 ℃ Forward current: maximum in datasheet Test period: 1000 h
HTOL	Ambient temperature: 85 ℃ Forward current: maximum in datasheet Test period: 1008 h	Ambient temperature: 85 ℃ Forward current: maximum in datasheet Test period: 1000 h
LTOL	Ambient temperature: –40 ℃ Forward current: maximum in datasheet Test period: 1008 h	Ambient temperature: –55 ℃ Forward current: maximum in datasheet Test period : 1000 h
WHTOL	Ambient temperature: 85 ℃ Forward current: maximum in datasheet Humidity: 85% relative humidity (RH) Time : 1008 h	Precondition at 60 ℃ and 60% RH prior to reflow soldering, 120 h Autoclave: 121 ℃, 100% RH, 15 psig, 96 h
Thermal shock	Temperature range: –40 to 125 ℃ Dwell time: 15 min Transfer time: < 20 s Cycles : 200 cycles	Temperature range: –40 to 110 ℃ Dwell time: 15 min Transfer time: < 20 s Cycles : 1000 cycles
Mechanical shock	Shock: 1500 G Pulse width: 0.5 ms Direction: 5 each, 6 axis	Shock: 1500 G Pulse width: 0.5 ms Direction: 5 each, 6 axis
Salt atmosphere	Ambient temperature: 35 ℃ Salt deposit: 30 g/m^2/day Test period: 48 h	Ambient temperature: 35 ℃ Test period: 48 h

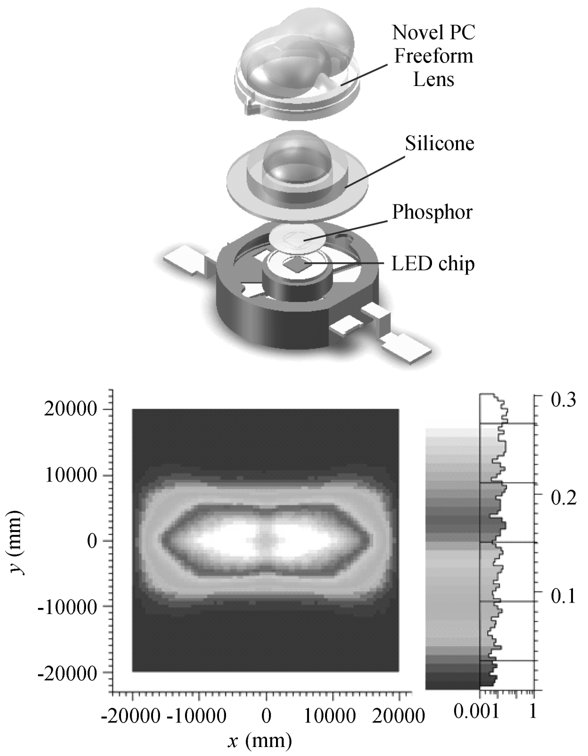


Fig. 1. Novel application specific LED package with freeform lens and its light pattern.

flux, dissipates generated heat from the chip to increase reliability and life and controls the color for specific requirements. Many packaging types of LED have been invented by different companies for high power LEDs. As shown in Fig. 1, a novel application specific LED package (ASLP) with freeform polycarbonate lens for street lighting has been developed by our group with an effective freeform design method[9], whose manufacturing processes are compatible with the typical LED packaging process. The rectangular light pattern can be achieved directly through the ASLP. The application specific LED package provides an effective solution to high performance and low cost LED fixtures and will probably become the trend of LED packaging. Wafer level packaging and direct white light packaging of LED devices are also in rapid development.

3. Reliability issues for LED packaging

As mentioned before, the reliability is a key issue for the application of LED devices. Parametric failure and catastrophic failure are two failure modes for LED devices. The parametric failure is defined as that the key parameters of LED devices like lumens degraded from initial value to a certain amount and the catastrophic failure is defined as the LED devices will not illuminate due to the electric or structural damage. The service life of LED device can be defined by mean time to failure (MTTF). As to the lighting purpose, it generally refers to the operation time during which the output luminous flux of LED devices attenuates to 70% of the initial value for the high power LED package. In order to evaluate the life of the LED device, some accelerated life test methods have been adopted according to the MIL, STD, GB, IEC and JEDEC standards. By the accelerated reliability test the life evaluation of LEDs devices can be finished within several weeks or months. Usually, after testing life characteristics under high accelerated stress such as current, thermal, humidity and mechanical stress, the life under normal stress can be derived using the accelerated models such as Arrhenius model, Peck's model, Eying model and Coffin-Manson model[6]. The environment reliability tests are also used to simulate the operation environment

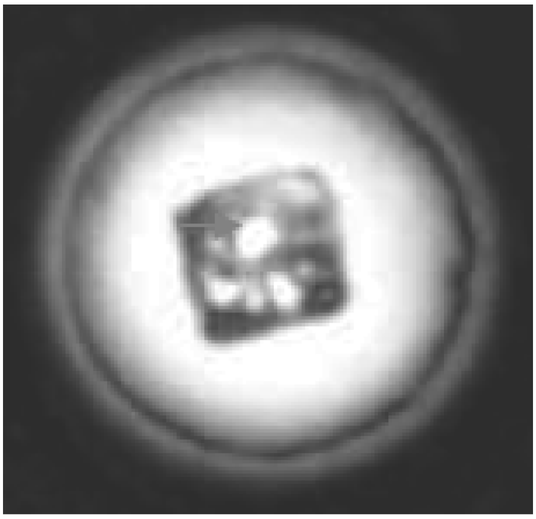


Fig. 2. C-SAM image of the voids within die attach layer of LED package.

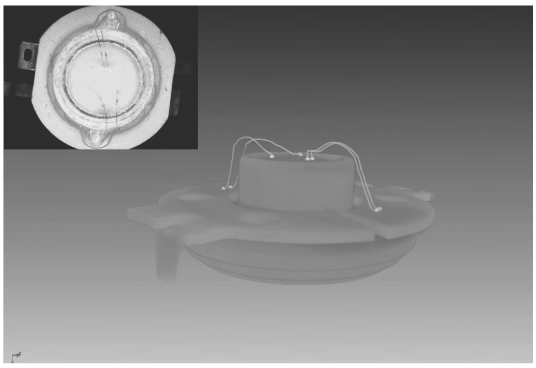
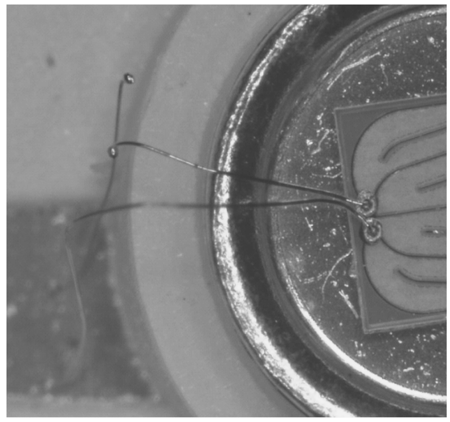
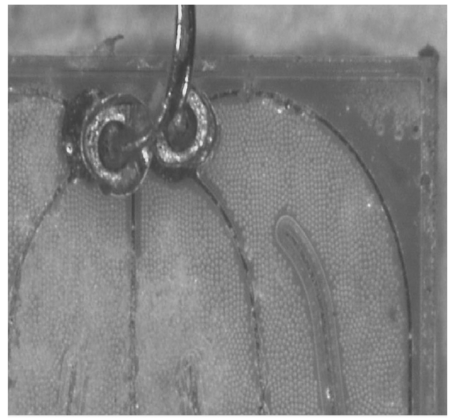


Fig. 3. Nano X-ray CT image of LED package.

of LED devices in order to detect the potential defects within the LED devices in the early stage of the product design and manufacture. Typically environment reliability testing methods used for LED packages by some vendors are listed in Table 1. The test methods RTOL, HTOL, LTOL and WHTOL are referred to room temperature operating life test, high temperature operating life test, low temperature operating life test and wet high temperature operating life test respectively. It can be found that the test conditions are quite different. In the current LED industry, there has not been uniform accelerated life testing methods and standards for LED devices yet. In addition, the accuracy of life perdition is low due to many reasons such as inappropriate field loading and lack of understanding of the failure modes and failure criteria. It is necessary to determine the failure mechanisms of LED devices through performing a detail failure analysis and multi-physics simulation. The voids are detected by the C mode scanning acoustic microscope (C-SAM) in the die attach layer as shown in Fig. 2 which will affect the thermal dissipation performance and mechanical reliability of LED package which has been demonstrated by the FEM simulation[7]. The structure of LED package is examined by the Nano X-ray CT in order to find the manufacture defects which are shown in Fig. 3. The fused failure of gold wire due to high energy electrical currents and bond wire liftoff failure due to mechanical loading has been found by the optical microscopic analysis as shown in Fig. 4. The defects in terms of



(a)



(b)

Fig. 4. Failure modes of LED package. (a) Fused failure of gold wire. (b) Bond wire liftoff failure.

delaminations and cracks due to the thermally and moisture induced stresses and strains are also discovered at the interface between silicone and PC lens and in silicone respectively as shown in Fig. 5

Wet high temperature operating life test has been used to evaluate the reliability performance of the LED modules. The test at 85 ℃/85 RH conducted with 700 mA and is applied to our LED modules, as compared to other three internationally well known vendors. The data points are averaged for five modules. It is shown that the significant degradation has been observed for two vendors, while our modules are consistent with one module, which is shown in Fig. 6. It is noted that the same size heat sinks are used for all our modules and another three vendors.

4. Finite element modeling for LED: one case study

The finite element method has been used significantly in the modeling and simulation of manufacturing processes and reliability evaluation[6, 10]. A nonlinear finite element analysis has been used for a conventional LED high power package, as shown in Fig. 7. The thermal cycling loading is from –40 to 125 ℃ with 1800 s per cycle. It is found from Fig. 8 that the von Mises stress in the gold wire can reach as high as 191 MPa at –40 ℃ and 140 MPa at 125 ℃, proposing a significant risk for the design of the packaging structure and materials.

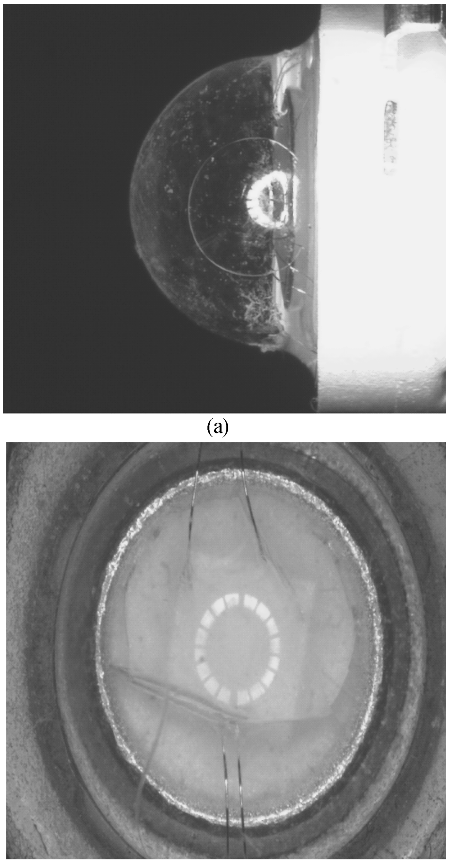


Fig. 5. Defects of LED package after accelerated reliability test. (a) Delamination between the silicone and PC lens. (b) Cracks in the silicone.

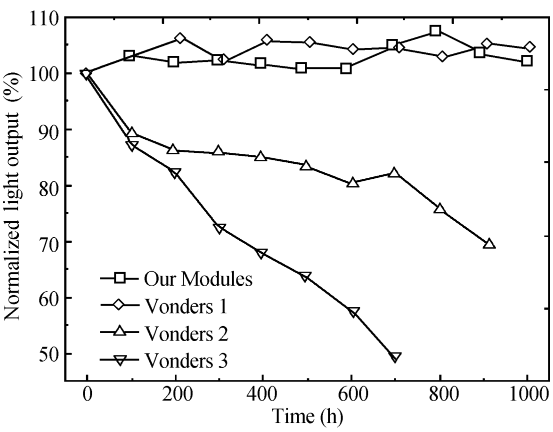


Fig. 6. Degradation of light output of LEDs modules after 85 ℃/85 RH 700 mA test.

5. Conclusion

In this paper, the function of the LED package is introduced and the new type ASLP LED package with freeform polycarbonate lens for street lighting has been developed with an effective freeform design method. The reliability is a key issue for the large scale applications of LED devices. The reliability test methods and failure criterions have been reviewed and compared. It is found that reliability test methods and failure criterions are quite different from different vendors. The uniform test and evaluation standard is urgently needed for the LED industry. Some failure analysis methods such as C-SAM, Nano X-ray CT and optical microscope are used for LED package. Some failure mechanisms such delamination and cracks are found in the LED packages after the accelerated reliability testing. The finite element simulation method is helpful for the failure analysis and design of the reliability of the LED package. One package has been found to be vulnerable to thermal cycling by our modeling.

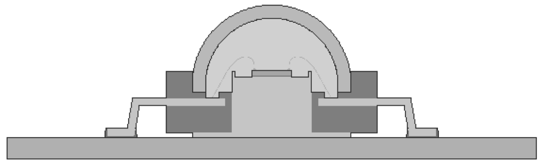


Fig. 7. 2D modelof conventional LED high power package.

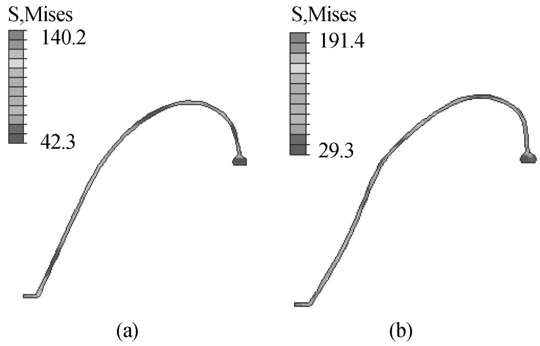


Fig. 8. Von Mises stresses distribution in the gold wire at (a) 125 and (b) –40 ℃.

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