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Analysis of solder joint reliability of high power LEDs by transient thermal testing and transient finite element simulations

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ABSTRACT

An innovative sensitive test method is developed to detect solder joint cracking for high power LED packages. The method is based on transient thermal analysis and can fully replace the still dominating light-on test. For experimental application of the model, test groups of LED packages were soldered with two different lead free solders (SnAgCu305 and Innolot FL-640) on Aluminum Insulated Metal Substrate (Al-IMS) and exposed to temperature cycles. Transient thermal measurements were performed directly after assembly and after specific cycle numbers. After data processing the increase of the relative thermal resistance between the initial signal at "0" cycles and "*n*" cycles is obtained and correlated with cracks in the solder joint by cross sections. Based on the CAD and material data of the LED package a finite element (FE) model is set up. The time-resolved temperature curves are properly reproduced by transient thermal simulation. The measured "0" cycle curves are fitted using the FE model by adjusting a few material parameters within their allowed tolerance range. A parameter sensitivity analysis is performed. The impact of a crack in the solder joint between package and printed circuit board (PCB) on the time resolved temperature curve is simulated. The simulated crack propagates from the corner of the package to its center. The experimental measured curves are reproduced. Based on the simulation a failure criteria is defined, representing a crack length between 20% and 30% of the solder joint area, and Weibull curves are calculated. A higher creep resistance for the test group soldered with Innolot FL-640 compared to the test group soldered with SAC305 is observed.

1. Introduction

High temperature operating conditions are often a key requirement for electronic systems. Aditionally, in automotive applications the difference between ambient and operating temperature can be very large. One of the most critical consequences is the thermo-mechanical stress in the electronic system. Due to mismatch of Coefficients of Thermal Expansion (CTE) of electronic package and Printed Circuit Board (PCB), like FR4 or Al-IMS (Aluminum Insulated Metal Substrates), the thermo-mechanical stress and the temperature cycles need a special consideration. Often the solder joints between package and PCB are the weakest link and fail. High sensitive and reliable test methods to check failures in solder joints are required to reduce duration and costs for reliability and lifetime testing. In the paper, the case of application focuses on ceramic LED packages and the reliability of the solder joint during temperature cycling.

At present there are different approaches used in the industry for reliability analysis of the solder joint of LED packages on PCB during temperature cycling. The still dominating approach is the familiar light-on test [1]. As long as the LED "lights on", the LED package is defined as functional. It is well-known that the cracks in a solder joint start from the outer corner and grow towards the center because the thermomechanical mismatch is highest in the corners. As a result, the LED package is often connected solely at the center of the package to the board. Thus, an electrical contact might still be formed and the LEDs can pass the light-on test even if the contacts are almost fully cracked. Obviously, the light-on test is not sensitive to detect crack formation.

Destructive shear testing is a second test method for solder joint analysis [2]. It is based on the approach that a crack in the solder joint reduces the shear strength. The reduction of shear force is taken as indication for crack formation. However, it has to be noted that, due to aging of the solder joint, the microstructure

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changes and the shear strength of the bulk solder degrades even without crack formation.

Another approach for solder joint analysis of LED packages is the electrical resistance test based on methods in IPC-785 and IPC-9701 [3]. The disadvantage of this test method is the shift of the forward voltage V_f during reliability testing. Even severe automotive applications allow the V_f to shift 10% before the LED is considered as failed. Manufacturing of test packages without LED die is required for high sensitivity as long as the V_f of the LED packages is not extremely stable during reliability testing, i.e. within approximately 1%.

Acoustic microscopy is another common method to observe delamination and cracks in electronic packages. However for LED packages on Al-IMS the resolution is very limited [3]. Also with X-ray computational tomography cracks in solder joints can be detected. However the technique is still to cost intensive and presently restricted to dedicated failure analysis and not applied on large scale reliability investigation or testing in production.

In this paper a novel test method is applied based on transient thermal analysis which is a well-known approach for thermal characterization and thermal resistance measurement of electronic packages [4–7] and in especially for LEDs [8–11]. However, the measurements are considered complicate and time consuming because the thermal load and the k-factor (a linear factor between forward voltage and temperature, see Eq. (1)) have to be measured. Therefore, in earlier publications, it was introduced an algorithm to eliminate the influence of both the k-factor and the thermal load [12,13] by measuring a relative thermal resistance which is sufficient for reliability analysis which focus on changes in the thermal path.

In the first part of the paper the developed algorithm is described and applied experimentally on ceramic LED packages (see Fig. 1) soldered with two different solders (SAC305 and Innolot: Sn91, 175/Ag3, 5/Cu0, 7/Ni0, 125/Sb1, 5/Bi3) on Al-IMS board. The relative degradation of the solder joints is analyzed. A failure criteria is defined based on the sensitivity of the measurement. The culminated failure distribution is calculated and the Weibull diagram is plotted for the two solders.

In the second part of the paper, a FE model is described based on the CAD and material data of the LED package. Transient thermal cooling down simulations are performed. Data regarding the thermal capacitance of the semiconductor material and the phosphor containing silicone are not available from data sheets and are estimated by data of similar materials reported in the literature. These data are adjusted in the model to fit the simulated curve to the experimental curve. Good matching over the full time domain is achieved. Afterwards the impact of cracks on the transient temperature curves was simulated with the FE model. The model reproduces faithfully the experimental behavior observed in the temperature shock test and from the simulation a crack length for the failure criteria is calculated.

2. Relative thermal resistance

It is well known that when a LED lights-on, the minor part of the input power is converted into light and the major part is dissipated as heat. This thermal load is conducted from the LED-die through the package and the board to the heat sink. Cracks in the solder joint disrupt the thermal path and the temperature of the device increases. Transient thermal analysis is a common method to reconstruct the thermal path and measure the thermal resistance of microelectronic packages, which contain an active semiconductor device [4–8] and in especially an LED [9–11]. The thermal response of a system like an LED package on a printed circuit board is time resolved measured after switching a heat load. In the following discussion we consider a LED initially driven with a large heating current (e.g. 1 A) representing a thermal heat flux P_{th} until the thermal equilibrium in the package is reached. By switching off the heating current the thermal equilibrium is changed. The temperature $T(t)$ of the epitaxial layer is time resolved measured by the temperature dependence of the forward voltage V_f of the junction. The temperature dependence of the V_f of a semiconductor can be linearly approximated in a sufficient small temperature range, e.g. below 50 °C [14]:

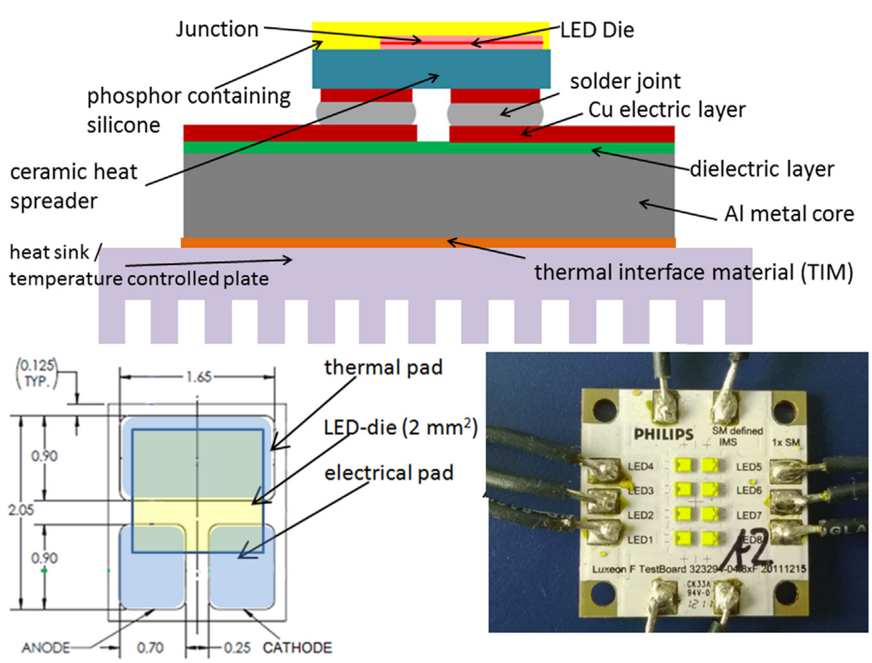

Fig. 1. Schematic drawing of a ceramic LED package soldered on an Al-IMS board (top side) and of the assembly structure of the test module (left side bottom). Footprint of the LED package (right side bottom).