

Transient Thermal Analysis as a Test Method for the Reliability Investigation of High Power LEDs during Temperature Cycle Tests

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Abstract

Light emitting diodes (LEDs) are today standard and mature light sources. They have several key advantages, like small size, low energy consumption and long lifetime. However, high reliability of the LED system is required to achieve long lifetime of the light source. Thermo-mechanical stress due to temperature cycle causes failure of electronic systems. The electronic component itself or the interconnect device, e.g. printed circuit board (PCB) might fail. In many cases, the weakest link is found to be the solder interconnect between package and the board. Cracking of the interconnect causes an open contact and the system fails.

In this paper we compare the existing methods to investigate LED interconnect failures during temperature cycle tests like the simple “light-on-test”, electric resistance measurement and the shear test. We describe and introduce the transient thermal analysis as a measurement method. We present the first reliability data analysis with transient thermal analysis of ceramic high power LED packages on Al-IMS during air to air thermal shock test (-40°C to +125°C) and correlate it with cross sections. We demonstrate the sensitivity of the thermal analysis to detect solder joint failures of the assembly. We compare the results with electric resistance measurements and light on tests and show that the resolution is significantly higher compared to the methods applied today. The sensitivity of the method enables us to detect the crack in a solder joint much earlier than the final failure of the joint, i.e. the open contact.

Key words: LED thermal measurements, Life-time analysis, Non-destructive reliability tests, Reliability of LED solder joint, Transient thermal analysis, Temperature cycle tests.

I. Introduction

LED modules are today a standard and a mature method to produce light [1],[2],[3]. Within the last few years, the efficiency of LEDs has been continuously increased above the level of compact fluorescence lamps. The main hurdles for continuous growth on many markets are mainly the high costs of the LED systems. Reliability and long lifetime of LED systems are the counter-arguments to equalize the present cost disadvantage of LEDs. Therefore, the reliability of LED lamps has a fundamental importance for a sustainable success of the LED technology. The high cost pressure on light sources increases the risk that unreliable LED system designs are introduced. The automotive market is one paradigmatic example where the LEDs promise life time to that of a car and are therefore attractive for car makers and end customers. The customer does not need to exchange light bulbs anymore and the car maker saves build-in-space because the light sources don't

need to be accessible anymore. In addition, LEDs enable fancy designs which allow differentiating looks. Higher costs of the LED systems are justified as long as the LED systems don't fail. Failing LEDs in front or rear lights of design driven premium cars can create significant cost impact due to the required exchange of expensive LED modules resulting in a loss of reputation of the car manufacturer.

Due to the costs of high power LEDs, they are driven in the system at their limits with respect to temperature and current to get maximum light flux with a minimum number of LEDs. Both parameters are essential for reliability and long lifetime. Adequate reliability testing of LED assemblies is therefore essential to ensure the required performance and lifetime of LED modules.

One well known failure mode of electronic systems is the solder contact between components, i.e. the LED package and the printed circuit board. Especially for ceramic LED

packages with a large CTE (Coefficient of Thermal Expansion) mismatch between standard boards like Fr4 or Al-IMS and the component, the solder joints are often the weakest link which leads to failure. Hence the LED industry has to develop appropriate test methods to detect the cracking of the solder joint. The first and simplest test is the so called “light-on-test” of the LED [4]. As long as the LED “lights on”, the solder contact is defined as consistent. However, this test is rather rough and not adequate to detect solder cracks. The LEDs have quite large solder contacts for thermal management. The solder contacts start to crack from the corner of a package and the crack grows in direction to the center because the stress is highest in the corner where the effective length for the thermo-mechanical mismatch is highest. In the center of the package the solder often holds the package on the board. As long as the package is mechanically hold in place an electrical contact can be formed by pressure even if there is significant solder- crack. This implies that a LED can pass the light-on-test even with severe cracks in the solder contact.

Another possibility to measure the quality of the solder joint is the destructive shear test [5]. The shear force of the device is reduced when a crack grows through the solder joint. However, besides the fact that the shear test is a destructive method, the shear strength of the solder material itself degrades with temperature driven intermetallic phase growth.

At Philips, an electrical resistance test method was introduced for solder joint analysis of LED packages comparable to the electrical resistance measurements used for CSP and BGA packages in the semiconductor industry [6]. For the electrical resistance test method, dummy packages have to be generated. The specification of an LED allows the forward voltage to shift within a range of 10% after which the LED is defined as failed. For white LEDs (using phosphor conversion pumped by a blue light emitting junction) the forward voltage is 3 V resulting is an error of 300 mV created by the drift of the forward voltage. Above this 300 mV drift, the LED itself is considered as failed. To avoid this large effect of the junction on the electrical resistance measurement for solder joint reliability testing, dummy LED packages without die are used for solder joint reliability testing. A dummy LED package is created by shorting anode and cathode in the package. By testing in-situ a significant improvement of detectability of cracks in the solder joint was achieved. In this paper we evaluate the next step of test method improvement by using transient thermal analysis to detect solder joint failure of LED packages. The transient thermal method is a well established method for thermal

characterization, i.e. the measurement of the junction temperature and the thermal resistance of an LED package [7], [8]. For high power devices where a significant amount of heat has to be conducted through the solder joints to the printed circuit board, changes in the thermal path can be detected by the change of the thermal resistance. The calculation of the thermal resistance for a transient thermal measurement requires measuring the real thermal power step $P_{thermal}$. In addition, a linear factor k (called k -factor) between forward voltage and temperature has to be measured for each LED [1]. Until now the approach to measure the thermal resistance to detect crack formation in the solder joint is not applied in reliability tests of SMD packages because the measurements and data evaluation are considered as time consuming and expert know how is required. However, the measuring effort can be significantly reduced because we are targeting to evaluate only the changes in the transient temperature curves that occur during reliability testing but not the absolute thermal resistance. Due to cracks in the solder joint, the thermal resistance of the joint degrades and by measuring the change of thermal resistance compared to the initial situation, we can identify a cracked joint. In the first part of the paper we describe the transient thermal analysis and the applied data evaluation algorithm to obtain information on the solder joint integrity without measuring k -factor and real thermal power step. In the later part, we investigate the thermal transient measurement method for solder joint integrity analysis by using Ceramic LED packages on Aluminium Insulated Metal Substrates (Al-IMS). We compare the results of this transient thermal testing with the solder joint reliability tests that was performed earlier like the light-on-test and electrical resistance measurements and show that the resolution is significantly higher.

II Transient Thermal Analysis

A common method to measure the thermal resistance of microelectronic packages which contain active semiconductor devices is the transient thermal analysis [7], [8]. The thermal response of a system like an LED package on a printed circuit board is measured time resolved after switching a heat load as shown in **Fig. 1**. For example, initially a constant heat flux (I_{drive}) is applied until the thermal equilibrium in the package is reached. The thermal equilibrium is then changed by switching off the heat flux. The forward voltage V_f is measured applying a small sensing current. The temperature $T(t)$ is measured at a significant location time resolved while the system transfers into its new thermal equilibrium.

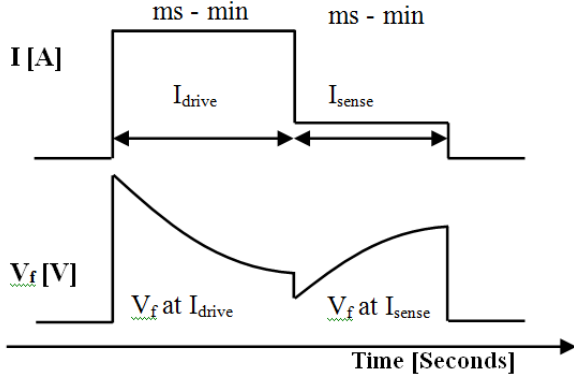


Fig. 1 Transient thermal measurement

The forward voltage V_f of the junction of a semiconductor is temperature dependent. The non-linear dependence can be derived from semiconductor theory by the Shockley equation [9]. Nevertheless, in the temperature range of the measurement the nonlinearities are small and can be neglected. A linear factor k , called the k -factor, is used to describe the relation between V_f and the temperature T .

$$V_f = -k \cdot T + const \quad (1)$$

The k -factor of a semiconductor is in the range of 2mV/K [1],[2],[4]. The theory of the time response of a thermal network like a LED package is well described in the JEDEC51-14 standard [10].

The thermal network is described by a Cauer RC-network. However, the Cauer network can be transformed into a Foster network for which the transfer function can be analytically calculated [10]. For n -discrete RC nodes of a Foster network one obtains:

$$T(t) = -\frac{V_f(t)}{k} = \frac{P_{th}}{k} \sum_{i=1}^N R_{th_i} (1 - e^{-\frac{t}{R_i C_i}}) \quad (2)$$

The real thermal resistances and capacities are then calculated by the C_i and R_i of the Foster representation [10]. The usual way to calculate the thermal resistance from the transient measurement is by the structure function. **Fig. 2** represents the structure function of an LED during temperature cycling. In the structure function, the thermal path from the junction to heat sink of an LED is plotted as a function of thermal capacity (C_{th}) and thermal resistance (after numerical transformation from Foster to Cauer network) [7]. The changes of the R_{th} of the example LED package with increasing the number of temperature cycles are visible. The thermal resistance (R_{th}) from junction to case of the temperature controlled heat sink is approximately obtained by the value at which the C_{th} goes to infinite. The time response of the temperature is linear with the power step $P_{thermal}$ and with $1/k$. Therefore we merge the k -factor and the power step in one linear constant: $f_{lin} = P_{thermal}/k$.

For the analysis of solder joint integrity, we are not

interested in the absolute R_{th} value but only in relative changes in the thermal path at the solder joint region. During reliability analysis, the efficiency of the LED, i.e. the $P_{thermal}$ and the k -factor can change. This will affect the relative changes in the thermal path at the solder joint interface. Therefore, we need to apply a normalization method to eliminate these linear factors. The normalization method is based on [11].

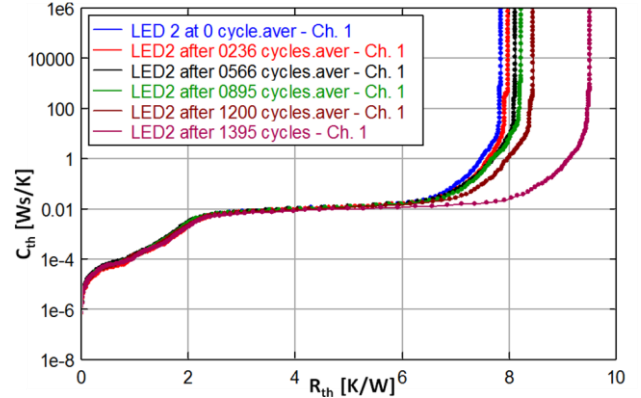


Fig. 2 Structure function of LED 2 at different temperature cycles.

III Algorithm for Data Evaluation

Fig. 3 shows transient V_f signals of an LED after different temperature cycles. In **Fig. 3 (a)** the measured time depended $V_f(t)$ signals are shown. In **Fig. 3 (b)** the derivatives $a_{V_f}(z)$ are depicted, with z defined as the logarithmic time $z = \ln(t)$:

$$a_{V_f}(z) = \frac{P_{thermal}}{k} \frac{d}{dz} V_f(z) \quad (3)$$

In **Fig. 3 (b)** the differences due to thermal cycling in the curves are observed between 10 ms and 100 ms. The peak at 50 ms is growing with increasing cycle number. This is the time interval where the heat flows out of the ceramic package through the solder joint. The peak at 50 ms in the derivative curves indicates a maximum in the slope of the temperature curve. When the solder joint cracks, the temperature gradient will be larger and the slope is steeper because the heat flow is hindered. Due to the fact that the thermal capacities in a semiconductor are well ordered from very small thermal capacity (junction) to medium thermal capacities (heat spreader) to large thermal capacity (board) the location of a change in the time derived curve can be localized along the thermal path and in the time domain. Failures in the LED die itself would appear much earlier in the time region below 1 ms. As mentioned the linear factor f_{lin} can change during temperature cycling. Therefore we change from the linear to logarithmic representation:

$$A_{V_f}(z) = \ln\left(\frac{P_{thermal}}{k} \frac{d}{dz} V_f(z)\right) = \ln\left(\frac{P_{thermal}}{k}\right) + \ln\left(\frac{d}{dz} V_f(z)\right) \quad (4)$$

The first part $\ln(P_{thermal}/k)$ is an axis offset which might change during cycling when the light output and the k-factor are not stable during cycling. This potential axis offset can be eliminated. The curve $A_{V_f}(z)$ after n-cycle is moved onto the curve at 0-cycles for a selected time window. This is done by a simple one-dimensional fit:

$$\text{Min}_b \left[\int_{z_{start}}^{z_{stop}} (b + A_{V_f_0-Cycles}(z) - A_{V_f_n-Cycles}(z))^2 dz \right] \quad (5)$$

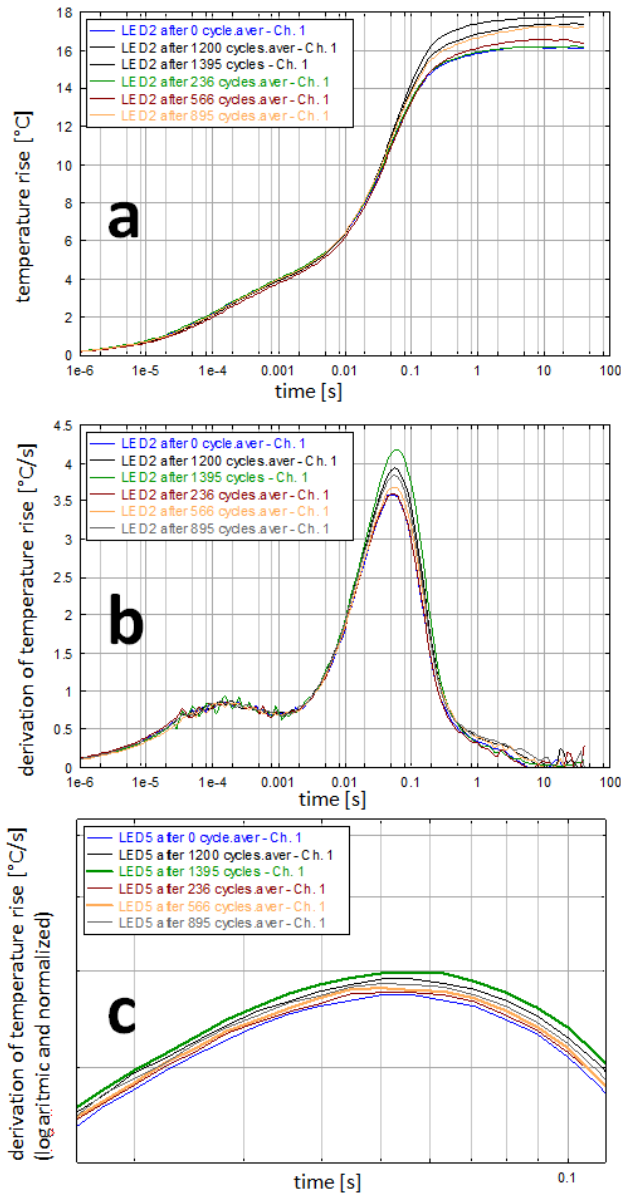


Fig. 3 Measured time dependent $V_f(t)$ [a], time derived data, i.e. $a_{V_f}(z) = a_{V_f}(\ln(t))$ [b], time derived logarithmic data $A_{V_f}(\ln(t))$ normalized [c].

The fit represents the shift of the curves parallel to the (y-axis, i.e. t-axis) on top of each other for a selected time interval. The logarithmic curves after normalization are depicted with high magnification in **Fig. 3 (c)**. We select the time interval between 0.1 ms and 1 ms. During this time the heat flows from the junction to the ceramic, i.e. the temperature gradient between junction and ceramic decays. As long as the heat flows in the LED die itself doesn't change by failure in the die (e.g. delamination or cracks), the result of the fit is pure residual free noise and the normalization is fine. As soon as a significant residual is obtained a potential die failure occurred and the normalization can't be done automatically. Closer inspection is required to verify the potential LED die failure.

VI. Test Sample Description

The device under test is a high power ceramic LED package from Philips Lumileds. It produces lumen output in the range 200-250 lm at 0.7 A at 85°C (hot binning) with wall plug efficiency (WPE) at specified condition of roughly 30%. **Fig. 4** shows the foot-print and the bottom contacts of the ceramic LED. The LED die is located at the top of the ceramic. Heat dissipation occurs through the thermal and electrical pads. On Al-IMS, in dependence of the thermal boundary condition between 35%-50% of the heat flows through the electrical pads [12].

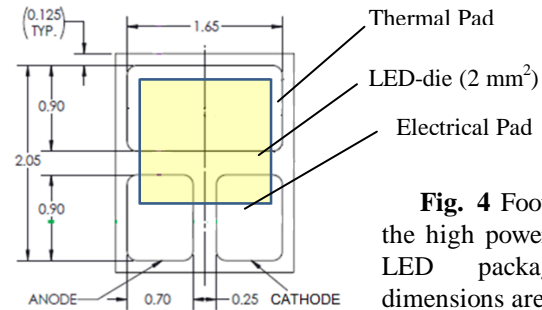


Fig. 4 Foot print of the high power ceramic LED package (all dimensions are in mm).

The LED packages are reflow soldered onto Al-IMS boards with 70 μm thick copper electrical layer and 100 μm dielectric layer with nominal thermal conductivity of 4 W/mK. We chose F640IL Innolot from Heraeus as solder material for the interconnect. For screen printing, a standard stencil printer with a screen thickness of 150 μm is used. LED package (component) assembly of the component to the substrate is done by a Fineplacer from Finetech. We applied a SMT compatible vacuum reflow process to achieve void-free solder joints in an SRO reflow oven from ATV. Quality control of the solder joints of the component is performed by X-ray analysis. The electrical

resistance measurements are performed on dummy devices where the electrical contacts are shorted by wire bonding on top.

V. Experimental Set-up

To compare the simplified relative thermal resistance measurement for solder joint reliability testing with the standard thermal resistance measurement we also determine k-factor and thermal load for the sample batch. The lumen measurements are performed in an Integrating Sphere separated from the transient thermal tester.

The transient thermal measurements (R_{th}) are made by using T3Ster equipment from Mentor Graphics (former MICRED). The device under test (DUT) is mounted to the temperature controlled heat sink of the T3Ster. The heat sink is maintained at a temperature of 25°C. Initially, a junction to case thermal equilibrium is ensured by applying a drive current (I_D) for short duration then the I_D is switched off and a small sense current (I_S) is applied. When the system transfers to its new thermal equilibrium, the cooling down of the junction is measured.

To calculate the real thermal load and real R_{th} the lumen output and k-factor were measured for the LEDs initially and at the end of the test.

Temperature cycling is performed by placing the LEDs in a TST (Temperature Shock Test) chamber with a temperature setting -40°C / +125°C and dwell time in the hot and cold conditions is 30 minutes respectively along with a transfer time of 10 seconds. One cycle takes approximately 1 hour. Investigation points for the transient thermal measurements of the packages were after 100, 250, 500, 750, 1000 and 1500 cycles (**Table 2**). One board with 8 samples was removed for cross section after 895 cycles when severe increase of the transient signals was observed. Cross sections were performed to correlate the transient thermal data with potential cracks in the solder joint.

VI. Results and Discussion

All transient data shown have the k- factor value set to 2 mV/K and assumes P_{el} (electrical power without considering the thermal load). **Table 1** shows the real R_{th} of the depicted LEDs calculated using measured k-factor and thermal load. After 1395 cycles, an average decrease in the lumen output of 2% was observed with a maximum decrease of 3.5 %. Measured k factor values show a variation of 5 % after 1395 cycles.

All LED packages successfully pass the light-on-test after 1395 cycles. However, all LEDs show a significant increase in the peak at 50 ms. Increase of the peak between

10 ms and 50 ms is very pronounced. We evaluated the difference of the peak height, i.e. we subtracted the peak height at zero cycles from the peak height at n-cycles. In **Table 2** the number of samples below the smallest resolvable increase and the number of samples above defined difference values are depicted. For instance, when defining a $\Delta \log=0.2$ as failure criterion the number in the column represents the cumulative failure. Typical cross sections after 1395 TST cycles are depicted in **Fig 5. LED 3** which has a strong increase of the peak has a fully cracked electrical and thermal solder joint. **LED 2** which has a moderate increase of peak height has a significant crack only in the electrical pad. Therefore it is clearly shown that the resolution of transient thermal measurements for solder joint reliability analysis has high resolution. Whereas the electrical resistance measurement [6], performed for the same ceramic dummy LED package on the same Al-IMS reveals that after 1000 TST cycles only a small increase of electrical resistance below 2% is observed which is below the standard deviation. With the thermal measurements it is evident that cracks can be identified before the final failure “open contact” occurs as compared to other classical measurement methods.

Table 1 k-factor, thermal load and thermal resistance of LEDs at 0-cycle.

	K-Factor (mV/K)	Thermal load (W)	Thermal resistance (R_{th}) (K/W)
LED 2	1.92 ± 0.02	1.53 ± 0.01	11 ± 0.3
LED 3	1.92 ± 0.02	1.52 ± 0.01	11.4 ± 0.3
LED 5	1.94 ± 0.02	1.49 ± 0.01	11.8 ± 0.3

Table 2 No. of samples which are below and above a defined peak height difference (comparing samples at n-cycles with 0-cycle).

TST No. of Cycles	Log derivative - normalized (A.U)				
	≤0,2	>0,2	>0,8	>1	>1,5
100	53/53	0/53	0/53	0/53	0/53
236	52/53	1/53	0/53	0/53	0/53
566	42/53	11/53	3/53	0/53	0/53
895	18/53	35/53	25/53	7/53	1/53
1200	4/45	41/45	25/45	8/45	3/45
1395	0/45	45/45	38/45	22/45	17/45

Total number of samples: 53 Total No. of Samples: 45

Presently we are running a new test batch with dummy LED packages to verify that no material changes in the Al-IMS of the present board batch compared to the former

study occurred. 1000 cycles have been finished but only a small average increase below 2% of the electrical resistance is observed which is below the standard deviation. With the thermal measurements it is evident that cracks can be identified before the final failure “open contact” occurs as compared to other classical measurement methods.

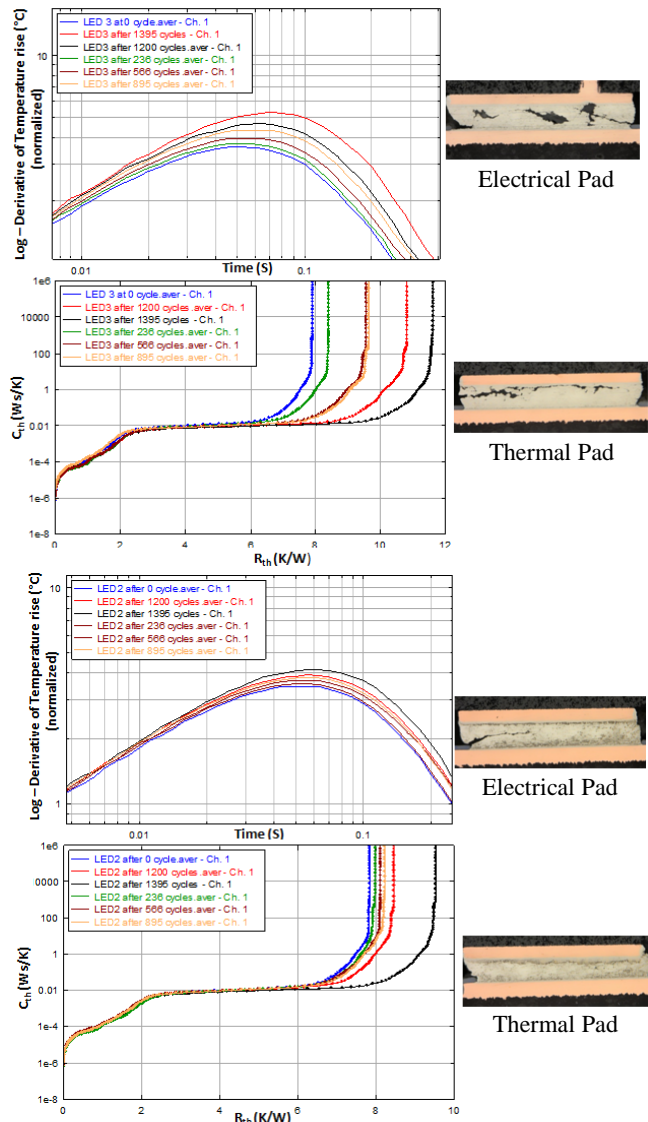


Fig 5 Transient thermal signal, structural function and cracks for selected LEDs. The cross-section is done after 1395 cycles.

VII. Conclusion and Outlook

The superior sensitivity of the transient thermal measurements compared to electrical resistance and light-on measurements is demonstrated for the ceramic test package under evaluation. It is demonstrated that light-on

measurements are not adequate to observe the crack growth of the solder joints. Presently we are running transient FE simulations to define failure criteria which represent a 50% cracked solder joint. Also, we have set-up equipment for in-situ thermal resistance measurement to be able to track the development of the thermal degradation in-situ during cycling. The simplified thermal measurements for package integrity have a high potential to become a standard measurement method for high power package reliability.

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