

# IMPACT OF SUBSTRATE MATERIALS ON RELIABILITY OF HIGH POWER LED ASSEMBLIES

Ranjit Pandher, Ph.D. and Ravi Bhatkal, Ph.D.  
Alpha Assembly Solutions, a MacDermid Performance Solutions Business  
South Plainfield, NJ, USA  
Ranjit.Pandher@AlphaAssembly.com

Kurt-Jürgen Lang  
Osram Opto Semiconductors, Regensburg, Germany

## ABSTRACT

New high power LED package designs provide high lumen density that can enable significant system cost reductions through fewer LEDs and smaller PCBs. The materials stack determines the CTE mismatch between the high power LED ceramic sub-mount and the substrates (including Metal Core PCB or FR4 substrate types). Choice of the substrate can impact reliability of the solder joints in thermal shock/cycling. One of the key questions is: What role does the substrate type play in the LED package-to-board assembly reliability? This paper presents a study to help answer this question. Assembly of high power ceramic sub-mount LEDs was conducted with both aluminum MCPCB and FR4 substrates with multiple solder alloys. Thermal cycling was conducted under the conditions of -40C to 125C for 1000 cycles. Solder joint strength was measured at multiple intervals during thermal cycling by conducting package shear. The impact of substrate type is quantified for multiple solder alloys and recommendations are presented. Solder alloy characteristics and failure mechanisms that impact reliability for a given substrate are discussed.

Key words: LED, MCPCB, Substrates, Thermo-mechanical reliability

## INTRODUCTION

Development of high power blue LEDs brought the use of LED in general lighting to a reality. For LED lights to compete with other traditional lighting technologies such as incandescent and Compact Fluorescent Lamps (CFL), they had to have good luminous efficacy and long operating life while maintaining competitive cost structures. While LED chip designers were working to improve the quantum efficiency of the LED chip itself, the packaging and assembly industry started exploring backend process materials and processes to improve performance and reduce costs.

While it is well known that LEDs chips are efficient in converting electrical energy to light energy as compared to others (and are expected to be more efficient in the future as scientists are working new chip designs, materials and processes), there remains a large fraction of electrical

energy is lost as heat[1]. Removal of this heat from the chip to ambient has been a challenge for the LED packaging industry[2]. The mechanism of heat dissipation in LEDs is totally different from that observed in incandescent lamps and CFLs. For example, the filament temperature in an incandescent lamp is ~2500C, while the typical LED chip junction temperature is below 125C. In incandescent lamps, a significant amount of unwanted heat generated is dissipated as infra-red (IR) radiation while heat transfer by radiative process in LEDs is negligible. The primary mode of heat dissipation in LED is conduction through the substrate. Therefore, the LED packaging and assembly industry had to find creative ways to find a low resistance heat conduction path from LED to ambient. This led to development of new packaging materials including the sub-mounts/substrates, circuit boards and materials used to join these parts. This study investigates the impact of substrate materials on long-term reliability of high power LEDs.

Traditionally, LED dies are mounted on an Al<sub>2</sub>O<sub>3</sub> or AlN sub-mount using a die attach material. Then this LED package is assembled with solder materials on a circuit board. In a new emerging packaging process, LED die are directly attached on a circuit board through a chip-on-board (COB) process. In both packaging schemes, the circuit board technologies, in addition to its primary role of providing a mechanical fixture and path for electrical connections, also provide a route for heat dissipation from LED die to the heat sink. Therefore, appropriate selection of the circuit board material is of utmost importance as the total thermal resistance of the whole stack should be as low as possible (provide ref). Materials with poor thermal conductivity can result in fast degradation of the LED due to high temperature operation at high power [3]. Operating the LED at lower current to maximize efficiency, limits the total light output from the LED.

**Table I:** Properties of common materials used in substrates and circuit boards.

Material	Thermal Conductivity (W/m.K)	Coefficient of Thermal Expansion (CTE) (ppm/K)
Aluminum (MCPCB)	204	25
Copper (MCPCB)	386	16
FR4 (PCB)	0.3-0.8	17
Al <sub>2</sub> O <sub>3</sub> (Sub-mount)	18	7
AlN (Sub-mount)	140	4

Table I shows two of the most important properties of a few common materials used in high power LED substrates and circuit boards [4]. Al-core and Cu-core MCPCBs have the best thermal conductivity. Even though the thermal conductivity of the substrate material determines its heat dissipation capability, other properties such as CTE and strength and modulus of the material will determine its long-term performance in high stress situations.

**EXPERIMENTAL DETAILS**

A comprehensive study was undertaken with multiple variables. Details of the Test Vehicle, LED Package and solder paste used are summarized in this section.

**Table II:** Substrate Materials

Substrate Materials Details:	
FR-4	Epoxy / Fiber Glass
AL MCPCBs	TC LM
AL MCPCBs	TC MP

**Package - Osolon LED**

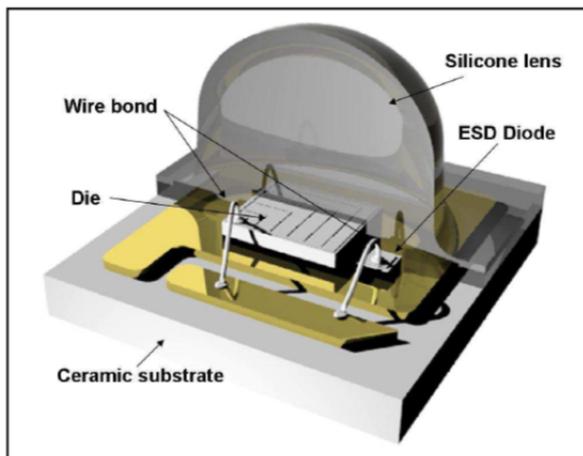
A commercially available LED package (Osolon LX) was used in this study[4]. OSOLON LEDs are used in applications that need maximum luminous flux with little consumption of space, and with a very stringent lifetime requirements [4]It is a square LED with a ceramic base and integrated contacts (bottom terminated) and a hard silicone cast as lens. Figures 1 –and 2show the schematics of Osolon LED package[5]. This LED is compatible for Pb-free soldering (what does this statement mean?) and can be surface mounted. Their performance and design, make them suitable for various forms of lighting and illumination technology, ranging from general lighting, industry, backlighting, projection and automotive applications. Due to their very compact design, the LEDs are also particularly suitable for being operated in clusters.

The ceramic base has the decisive advantage that it is stable with regard to light, regardless of the wavelength. In addition, it has sufficiently good thermal conductivity and enables thermal connection to the PC board.

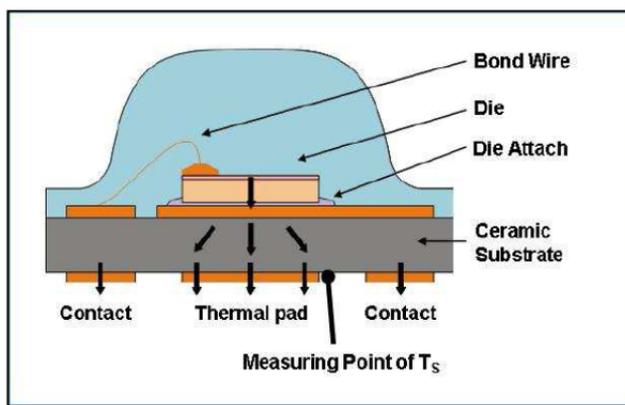
Details of the package used are as follows:

- Thin GaN Technology

- Part Number: LXW CNAP
- Type: LMW CNAP-6J7K-37-DF-LH



**Figure 1:** Osolon LED structure.



**Figure 2:** Primary heat flow in the Osolon

**Solder Pastes**

Two different solder pastes with Pb-free alloys were selected for this study.

**Table III:** Solder Paste details

Solder Paste	Solder Alloy
NC Paste#1	SAC305 Type 4
NC Paste#2	HR Pb-Free Alloy Type 4

**Table IV: Test Matrix**

Test Factors/Variables:	
PCB Substrates	FR-4 (Epoxy / Fiber Glass)
	AL MCPCBs (TC MP)
	AL MCPCBs (TC LM)
Solder Paste	NC Paste # 1 (with SAC305 Alloy)
	NC Paste# 2 (with HR Pb-Free Alloy)
Reflow Profile	260C LV
Constant Factors:	
Reflow Environment	N2
Package	Osram Oslon

**Table V: Evaluation Matrix:**

	Test	Initial (0 Cycles)	500 Cycles	1000 Cycles
1	Voiding – X-Ray Analysis	All Parts		
2	Thermal Cycling			
3	Package Shear	10%	10%	10%
4	Cross-section (IMC Measurement)	10%	10%	10%
5	Failure Analysis	10%	10%	10%

**ASSEMBLY**

Table VI List the SMT equipment that was used for the LED assembly.

**Table VI: Assembly Process Equipment**

SMT Equipment	SMT Equipment Details
Stencil Printer	DEK Horizon 03iX
Stencil	4 mil Laser Cut Stainless Steel
Pick and Place	Universal Advantis with FlexJet Head
Placement Nozzle	234J-FJ
Reflow Oven	Electrovert OmniFlo 7

**Solder Paste Printing:**

Solder paste printing was done using DEK Horizon 03iX printer with a 4 mil thick laser cut stainless steel stencil with a 1 to 1 ratio of aperture size to pad size. Stencil printing parameters used for all solder pastes are shown in Table VII below.

**Table VII: Stencil printing parameters**

SMT Equipment	SMT Equipment Details
Print Speed	1 inch/sec.
Print Pressure	1.25 lbs/inch of blade
Stencil Release	0.02 inches/sec.
Snap off	0 inches (on contact printing)

**Component Placement:**

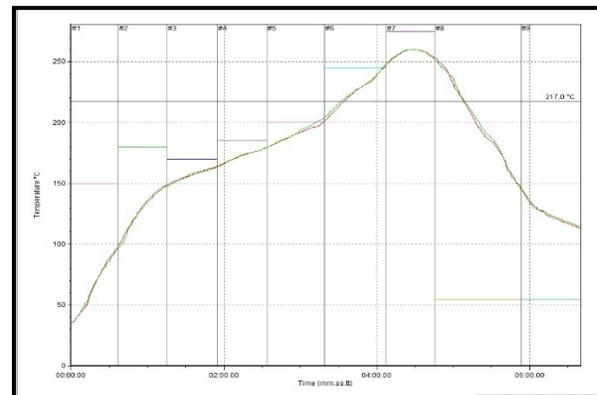
Universal Instrument’s Advantis pick and place machine with FlexJet head was used for the LED assembly. Placement nozzle 234J-FJ was used for the LED package pick-up and placement.

**Reflow Soldering:**

An Electrovert OmniFlo 7 reflow oven, with seven heating and two cooling zones was used for the reflow assembly. The reflow profile used is shown in Figure 3.

**Table VIII: Test Conditions**

Test Conditions:	
Temperature	20°C
Relative Humidity	46% RH
Reflow Atmosphere	Nitrogen (<500 ppm O2 throughout the assembly process)

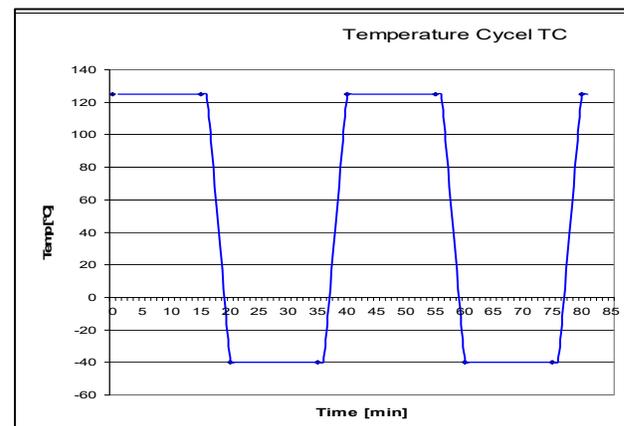


**Figure 3: Reflow profile**

**Thermal Cycling Test**

**Test description:** Air to air thermal cycling was performed on the assembled boards.

**Test details:** Assembled boards were placed in an air-to-air dual chamber thermal cycling chamber with a temperature profile ranging from -40°C to 125°C, with 15 minute dwell time at extreme temperatures. Cycle time was 40 minutes. The Thermal Cycling Profile is shown in Figure 4 below.



**Figure 4: Temperature Cycling profile.**

## Solder Joint Shear Test

To assess the mechanical integrity of the solder joints, joints were sheared and peak shear force was recorded for each of the sheared components. A Dage 4000 shear tester was used for Osion Package Shear. Eight components were sheared for each set. After temperature cycling, parts were taken out after 500 and 1000 cycles and sheared to record any drop in solder joint strength.

## RESULTS AND DISCUSSION PACKAGE SHEAR TEST DATA

**Test description:** For the reliability study, shear tests were performed on the assembled boards. These included initial shear, after 500 TCs and 1000 TCs.

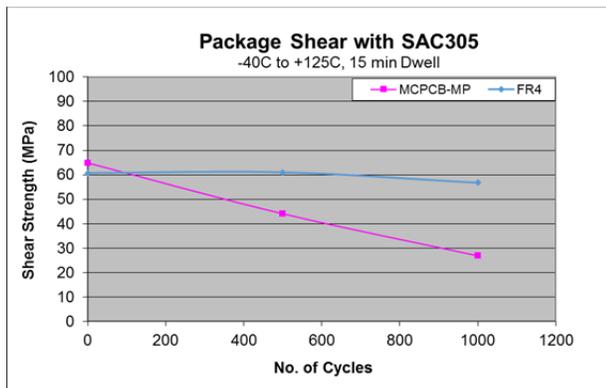


Figure 5: Package Shear Results - SAC305 solder.

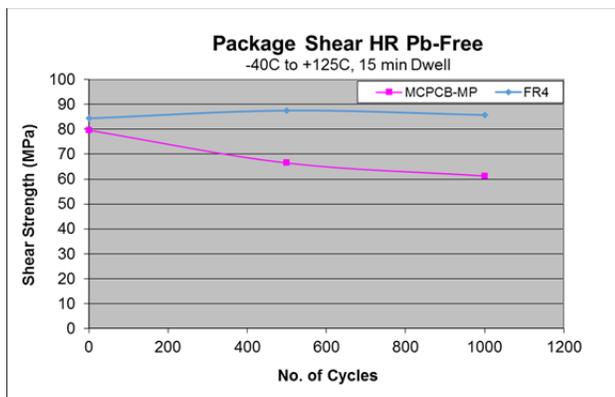


Figure 6: Package Shear Results – HR Pb-Free solder.

Figures 5 and 6 show the shear test results on LEDs assembled with NC Paste # 1-SAC305 and NC Paste # 2 with HR Pb-Free alloy respectively. Shear data is shown for the LEDs assembled on FR4 and MCPCB-MP test boards. No shear data was generated on LEDs on MCPCB-LM boards because the dielectric used in LM boards is so soft that dielectric itself is torn during the shear test. Therefore, shear test results on LM boards were not representative of the solder joint strength.

As seen in Figures 5 and 6, Shear strength of LEDs on FR4 substrates sees almost no change after 1000 cycles while that on MCPCB-MP show a drop by 60% for LEDs assembled with P33-SAC305. The drop in shear strength of

LEDs on MCPCB-MP for LEDs assembled with NC Paste # 2 with HR Pb-Free alloy is about 20%.

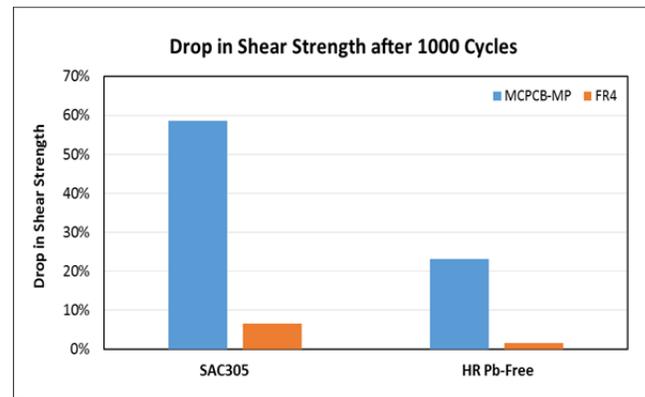


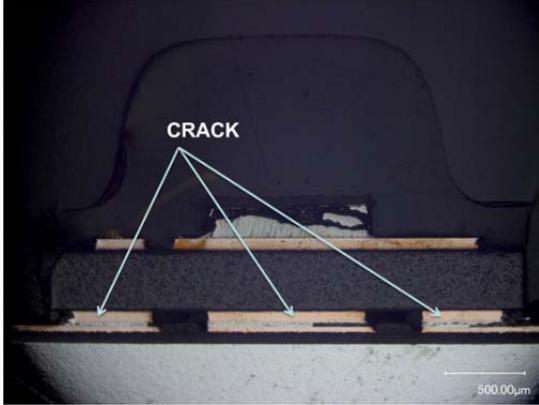
Figure 7: Percentage drop in package shear strength after 1000 cycles.

Figure 7 shows the % drop in shear strength. This can be explained keeping in mind the physical properties of the test board materials and LED package substrate. During temperature cycling the solder joints experience cyclic stress in the lateral direction due to CTE mismatch between the circuit board material and the LED sub-mount material. As shown in table I, the CTE of FR4 is 17 ppm/K and Aluminum is 25 ppm/K while that of  $Al_2O_3$ (LED substrate) is 7ppm/K. Therefore, the CTE mismatch for LEDs assembled on FR4 boards is 10ppm/k while those assembled on MCPCB-MP boards is 17ppm/k. Therefore, the solder joints in LEDs on MCPCB will experience much higher stress during temperature cycling as compared to those assembled on FR4 boards.

In addition to CTE mismatch, modulus of the materials involved also plays a key role. While solder joint is experiencing a cyclic stress during temperature cycling if the circuit board material is soft (have low modulus), it will tend to deform first which will in turn reduce stress at the solder joint. FR4 has relatively lower modulus than Aluminum, therefore, stress on the solder joints of LEDs on FR4 boards will still be lower. That also further explains almost no drop in shear strength of the LEDs on FR4 boards.

As seen in Figure 7, the drop in shear strength of LEDs on MCPCB assembled with SAC305 solder is 60% while for the LEDs assembled on with HR Pb-Free solder drop in shear strength is only 20%. This is due the fact that HR Pb-Free solder is designed to withstand high stress situations.

## CROSS-SECTION ANALYSIS OF SOLDER JOINTS



**Figure 8:** NC Paste # 1 with SAC305 on MCPCB-MP after 1000 cycles. Cracks are observed in solder joints for all three pads.



**Figure 9:** NC Paste # 2 with HR Pb-Free alloy on MCPCB-MP after 1000 cycles. Small cracks observed in solder joints on only one of the pads.

Figures 8 and 9 show pictures of typical cross-sectioned solder joints.

The cross-section analysis shows that:

SAC305 alloy joints on MCPCB-MP show cracking after 1000 cycles for all three pads.

HR Pb-Free alloy joints on MCPCB-MP show only minor cracking (and only on one side of the pad) after 1000 cycles, and crack growth is minimal.

Interestingly, HR Pb-Free alloy joints showed no cracks in assemblies on FR4 and MCPCB-LM even after 1000 cycles.

## OBSERVATIONS AND CONCLUSIONS

Performance of LEDs assembled on three types of the substrates has been compared. Key observations are:

- LEDs on FR4 boards show minimal drop in shear strength irrespective of the solder alloy.
- Due to high mismatch in CTE, the MCPCB-MP substrates show a steep degradation of shear strength upon temperature cycling.

- HR Pb-Free alloy showed highest strength and little drop in shear strength after thermal cycling.
- In thermal cycling test, HR Pb-Free alloy showed stable performance on all types of substrates.

In conclusion, for a given alloy (SAC305 or HR Pb-Free), FR4 shows the least drop in shear strength of the joints. In the case of MCPCB-MP substrates, HR Pb-Free shows the highest reliability.

## ACKNOWLEDGEMENTS

The authors would like to thank Westin Bent and Ramazan Soydan of Alpha for their help in assembly of the LEDs, testing and analysis.

## REFERENCES

- [1] M. H. Crawford, J. J. Wierer, A. J. Fischer, G. T. Wang, D. D. Koleske, G. S. Subramania, M. E. Coltrin, R. F. Karlicek, Jr., and J. Y. Tsao, "Solid-State Lighting: Toward Smart and Ultraefficient Materials, Devices, Lamps, and Systems 1", in D.L. Andrews, Ed., "Photonics Volume 3: Photonics Technology and Instrumentation" (Wiley, 2013).
- [2] Mehmet Arik, Charles Becker, Stanton Weaver and James Petroski, "Thermal Management of LEDs: Package to System", Third International Conference on Solid State Lighting, edited by Ian T. Ferguson, Nadarajah Narendran, Steven P. DenBaars, John C. Carrano, Proc. of SPIE Vol. 5187.
- [3] Steven Keeping, "Understanding the Cause of Fading in High-Brightness LEDs", Electronic Products Feb 2012
- [4] Andreas Stich, Kurt-Jürgen Lang, Rainer Huber "Details of the Assembly and Solder Pad Design of the OSLO, OSLO SSL and OSLO Square Family" an Application Note, Osram Opto Semiconductors.
- [5] Reliability of the OSLO Product Family" an Application Note, Osram Opto Semiconductors.

“