HIGH THERMAL, HIGH OPERATING TEMPERATURE INTERCONNECTS FOR ULTRA HIGH POWER LEDs

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ABSTRACT
Use of super/ultra-high power LEDs is increasing. For high performance applications such as street lighting and ultra-high power density illumination, use of ultra-high power can enable significant systems cost reduction through use of fewer LEDs, smaller PCBs, smaller heat sinks and lighter load bearing structures. In order to be able to drive the LEDs harder and to increase light output in a smaller footprint, one needs efficient thermal performance at the LED die-to-package connection. The ultra-high power density, combined with high thermal metal substrates, (which have high CTE mismatch with ceramic sub-mount LEDs) necessitates use of ultra-high reliability interconnects for elevated temperature operation at the package-to-board connection. This paper presents two technology platforms: 1. Sintered silver, which enables significant increase in light output at package level, and 2. High temperature creep resistant solder alloys that provide high thermal cycling reliability under high temperature and high CTE mismatch conditions.

Key words: LED, Ultra High Power, High Reliability, LED Lifetime, Sintered Silver, Creep Resistant Solders

INTRODUCTION
The LED lighting revolution is on. The global acceptance of LED based light sources has entered many different markets including, high power lighting segments which are largely driven by their end-application. Several applications are adopting high and ultra-high power LEDs [1,2]. Examples include roadway/street, industrial, architectural lighting, projection and entertainment lighting. All these applications demand long term reliability of the light source. New high and ultra-high power LED package designs provide high lumen density that can enable significant system cost reductions through fewer LEDs, smaller PCBs, and smaller heat sink size requirements. However, the high lumen density and smaller heat sink also means long term operation of LED at elevated temperatures. That means all the components and materials have to survive in those operating conditions.

The role of interconnects in LED assembly is fundamental to:

- Convey power and information efficiently and reliably over the rated life.
- Get the heat out faster and more reliably over the rated life.
- Enable more light output, consistently, for longer periods of time from the same package and system footprint.

KEY ISSUES IN ULTRA-HIGH POWER LED ASSEMBLY AND POTENTIAL SOLUTIONS
Key issues in ultra-high power, high operating temperature applications include:

- Lifetime improvement through higher reliability and lumen maintenance over long periods of use.
- High rate of thermal dissipation through the stack, enabling lower junction temperatures while pumping increased current through the system.

Ultra-high power LEDs (> 5W) have significant current flowing through them [2], which generates large amounts of heat. In a typical LED package architecture, LED dies are bonded on a ceramic substrate (also called submount) which has circuit designed for electrical and thermal interconnects. This LED mounted on submount with electrical connects and possibly with a lens at the top is usually called a LED package. To improve heat dissipation, these ultra-high power LED packages are assembled on Metal Core PCBs (either Al or Cu based-metal), MCPCB. There is a significant CTE mismatch between the ceramic submount in the LED package and the MCPCB. For example, the ΔCTE between AlN submount and the Al MCPCB is 20 ppm/C, and the ΔCTE between the AlN sub-mount and the Cu MCPCB is 12 ppm/C, as shown in Figure 1.

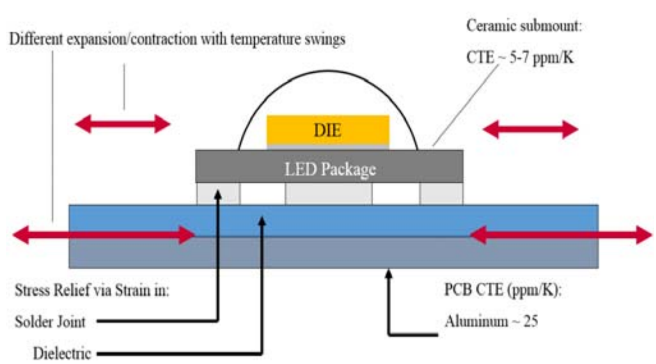

Figure 1. Drawing of an Assembled High-Power Ceramic LED on a Metal-Core PCB Showing CTE Differentials.

During thermal cycling experienced by the ultra-high power LED assembly in applications such as projection, or outdoor lighting or automotive, the high ΔCTE causes significant strain energy build-up in the solder joint between the LED submount and the MCPCB, during the thermal cycling experienced in use. This is shown schematically in Figure 2 demonstrated by Peter Hall at AT&T Bell Laboratories [3,4]. This strain energy buildup causes micro-cracking, and eventually, failure of the joint.

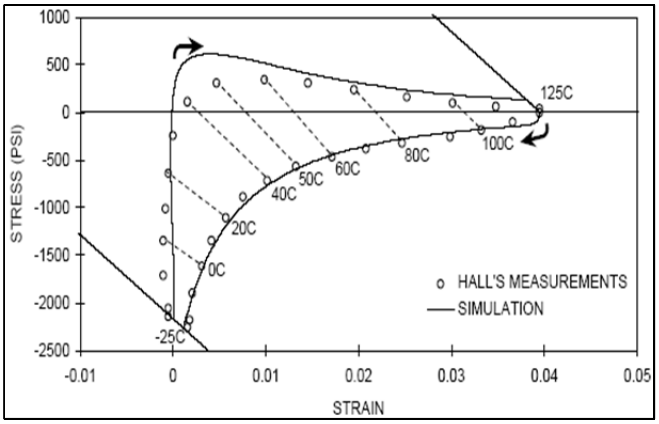

Figure 2. Solder Joint Hysteresis Loop During Thermal Cycling Between -25°C and 125°C.

One strategy to combat this issue and improve the reliability of ultra-high power LED assemblies is to use high temperature creep resistant solder alloys. High temperature creep resistant alloys help improve microstructural stability under high operating temperature and thermal cycling conditions [5].

EXPERIMENTAL DEATAILS

To understand the LED lifetime dependence on the second level interconnect (LED package to circuit board) we used commercially available Luxeon Rebel white LED packages from Lumileds. These LED packages were assembled on Aluminum core MCPCB's using two types of solder pastes. One of the pastes was made with SAC305 powder while the other one was made with another SAC alloy designed for high reliability (called HR Pb-Free alloy in this paper). Following two reflow profiles were used:

1. **260LV:** 150-200C soak for 120min, 260C peak and 90-96s TAL.
2. **RecoLV**: 150-200C for soak 110s, 240c peak and 90-70s TAL.

All the reflows were in N2 atmosphere. A total of 72 LEDs were assembled for each paste and each reflow. Of the 72 LEDs, 36 were used for LED light up test and other 36 were used for die shear test. For die shear test, 12 packages were sheared right after soldering, another 12 each after 500 temperature cycles and 1000 cycles respectively. All the assembled LED were x-rayed to measure voids in the reflowed joints. Both the pastes showed similar voids (8-14%) under both the reflow conditions.

All the LED's were forward biased using a low voltage DC power supply running in constant voltage mode and current was recorded for each LED. These LEDs were then subjected to temperature cycling in an air to air chamber with -40 to +125C and 30min dwell at both the extremes. LEDs were taken out at regular intervals, biased again under identical conditions and forward current recorded each time. An LED was considered a failure if the electrical power through the LED dropped below 70% of the original. The test was run up to 1000 cycles.

To understand the effect of thermal conductivity of the interconnect materials, commercially available 1mm X 1mm UV LED dies from SemiLeds were attached to ceramic substrates using two types of die-attach pastes. One of the die attach pastes was a sintered silver paste with bulk thermal conductivity ~130W/mK while other material was a conductive epoxy paste with bulk thermal conductivity ~20 W/mK. Both of these pastes were sintered/cured at 200C. After die bonding the bonded LEDs were singulated and tested individually. Each LED was mounted on a thermoelectrically cooled heat sink set at 25C. LEDs were powered by a DC power supply capable of switching current within <30 μS and current through LED was measured using a fast sampling (10 Ks/S micro-amp capable multi-meter. LEDs were operated up to maximum specified power. Junction temperature at each operating current was measured following the technique described in EIA/JESD 51-1 standard [6].

Light emitted by LEDs was collected using an integrating sphere. Output of integrating sphere was monitored using a spectrometer. Integrating sphere and spectrometer setup was calibrated using a standard light source.

RESULTS AND DISCUSSION

Figure 3 shows the failure rate as a function of the number of thermal cycles of ceramic submount high power LEDs assembled on Al MCPCB with SAC305 alloy and a creep resistant test alloy called HR Pb-Free alloy. MCPCB dielectrics and solders have much different CTE as compared to the ceramic submount on which LED die is attached. Because of this CTE mismatch, the interconnect goes through cyclic stress during temperature cycling test. At some stage one or the other interface starts cracking resulting in an increase in electrical resistance of the interconnect. This results in decrease in LED power. In this test a drop in 30% of the initial power is considered a failure. The test alloy HR Pb-Free is designed to resist the creep. It is clear that solder joints with creep resistant HR Pb-Free alloy show much lower failure rates than those with SAC305 alloy. There was absolutely no difference in the light-up test of the LEDs assembled under two reflow profile. Figure shows combined results of both the reflow profiles.

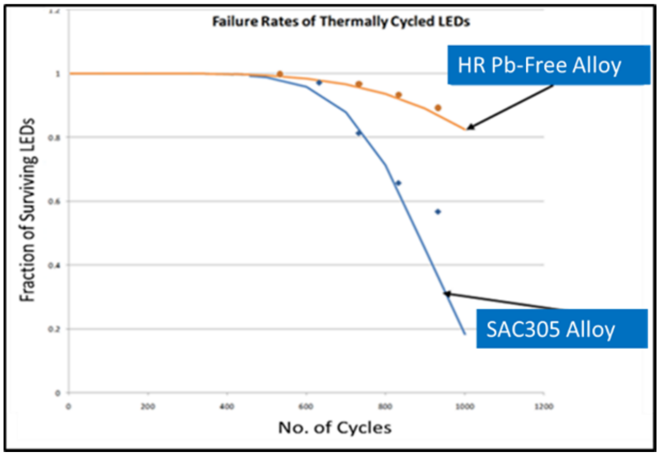

Figure 3. Failure rate vs. number of thermal cycles of ceramic submount high power LEDs on MCPCB.

Figure 4 shows the shear results for a high power ceramic LED on a metal core PCB subjected to 0, 500 and 1000 cycles at -40°C to 125°C. The results indicate that the HR Pb-Free alloy has higher shear strength and the lower degradation / drop upon thermal cycling as compared to SAC305 alloy. After 1000 cycles, HR Pb-Free alloy shows a ~25% drop in shear strength from its initial value. In contrast, we see that the SAC305 alloy showed a drop of ~60-61% from its initial value. There is no significant difference effect of the reflow profile on the shear strength.

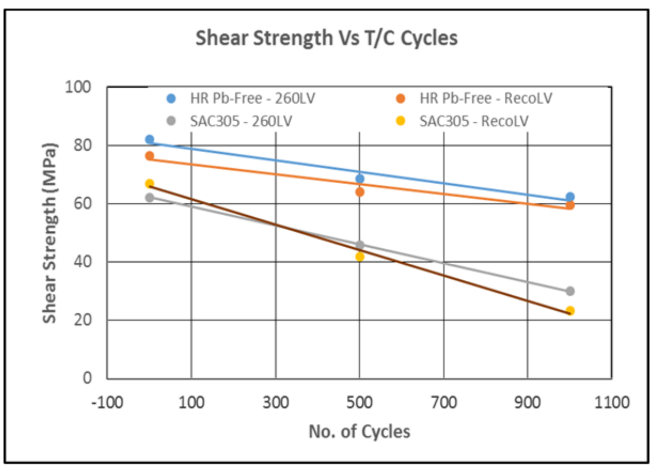

Figure 4. Thermal Cycles vs Shear Strength for HR Pb-Free and SAC305 alloys.

Thus, for a given LED package structure and board material used, it is beneficial to use solder joints with improved mechanical and thermal fatigue/creep and vibration resistance. A new class of creep-resistant and vibration resistant alloys has been developed, that can provide this capability, via a micro-structural control approach[3]. These advanced alloys have been developed with special additives for improved thermal stability for high temperature operation and higher thermal fatigue and vibration resistance.

The high heat generated by ultra-high power LEDs also necessitates very rapid heat extraction, to allow the LED to operate at or below the maximum junction temperature specified for the LEDs. For most of LEDs, maximum operating junction temperature is below 125C in continuous operation mode. Further, extremely rapid heat extraction can allow driving the LED harder, while maintaining the junction temperature at an acceptable operation range, especially for the vertical LEDs. This in turn allows for packing higher lumen output in a more compact space.

Sintered silver technology allows for such rapid heat extraction, while providing very high thermal cycle reliability.

Silver sintering materials can be processed at 200C to 300C under pressure or without pressure, to form a sintered Ag interface [7,8] If the joint does not contain any resin, after bonding, the joint has a melting point of 962C, which is the same as that of bulk silver. The materials and processes yield joints with thermal conductivities in the 130-250W/mK range, with thin, uniform bond lines.The resulting bond is a diffusion bond with no intermetallics.

Sintered silver provides ultra-high thermal conductivity, enabling thermal resistance reduction, and therefore lower junction temperatures, or higher drive currents. This can yield brightness improvement and control of wavelength shift and ability to handle very high power densities. An example of this property is shown in Figures 5a and 5b

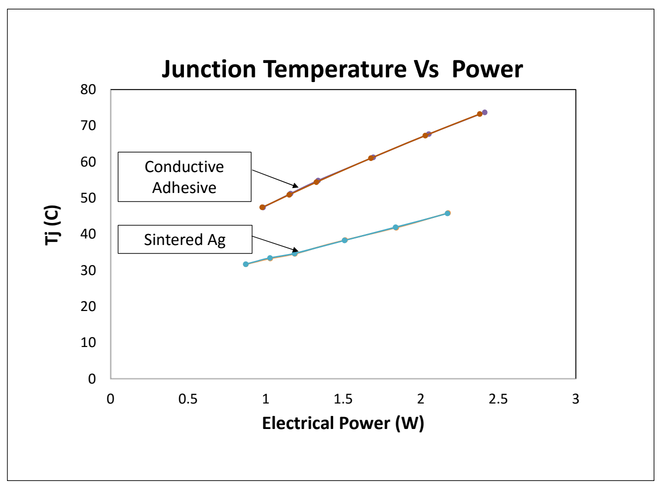

Figure 5a. UV LED: Junction Temperature vs Power for Sintered Ag vs Conductive Adhesive

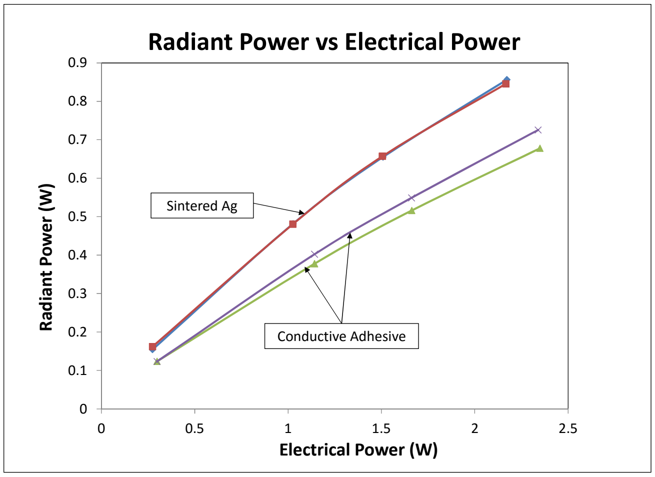

Figure 5b. UV LED: Radiant Power vs Electrical Input Power for Sintered Ag vs Conductive Adhesive

Figure 5a plots Junction Temperature vs Electrical Input Power for high power LEDs and Figure 5b plots Radiant Power vs Electrical Input Power, for high power UV LEDs, for sintered Ag die attach material compared to conductive adhesive die attach material. It is clear that sintered Ag consistently results in lower junction temperature at a given input power, and provides higher radiant power at a given input power.

Further, Ag sintering technology in a film form factor [7,8], can provide LED assemblies with several additional advantages such as:

- No die tilt, highly controlled and uniform bond line, which provides excellent control of directionality and optical axis.
- No bleed-out of the die attach material, ensuring die-footprint-conformal die attach yielding smaller package and module sizes.
- Placement of an array of die closer together without movement or "die float" which yields higher lumen density in smaller area.
- Very high die shear strength and thermal cycling/thermal shock reliability.

CONCLUSIONS

1. For high and ultra-high power LEDs, for a given LED package structure and board material used, it is beneficial to use solder joints with improved mechanical and thermal fatigue/creep and vibration resistance. A new class of creep-resistant and vibration resistant alloys has been developed, that can provide this capability, via a micro-structural control approach. These advanced alloys have been developed with special additives for improved thermal stability for high temperature operation and higher thermal fatigue and vibration resistance.
2. Sintered silver technology has several benefits for high and ultra-high power LEDs, including enabling higher light output while maintaining junction temperature, enabling excellent control of tilt, directionality and optical axis, and providing very high thermal cycling reliability.
3. These emerging technologies are enabling us to push the envelope in implemeting ultra-high power LEDs in several applications.

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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] Stephanie Pruitt, "Global LED Market Overview", Strategies in Light, Santa Clara, March 11-13, 2016.

[3] Hall, P. M., "Strain measurements during thermal chamber cycling on leadless ceramic chip carriers soldered to printed boards", Proceedings, 34th Electronic Components Conference, New Orleans, LA, May 14-16, 1984, pp. 107-116.

[4] Hall, P.M., "Forces, moments, and displacements during thermal chamber cycling of leadless ceramic chip carriers soldered to printed boards", IEEE Transactions on Components, Hybrids and Manufacturing Technology, 1984, Vol. 7, No. 4, Dec. 1984, pp. 314-327.

[5] Pritha Choudhury, Morgana Ribas, Anil Kumar, Sutapa Mukherjee, Siuli Sarkar, Ranjit Pandher, Rahul Raut, Bawa Singh, and Ravi Bhatkal, "NEW Lead-Free Alloy For High Reliabilty, High Operating Temperature Applications" International Conference on Soldering and Reliability (ICSR), Toronto, Canada May 13-15, 2014.

[6] EIA/JESD 51-1 Integrated Circuits Thermal Measurement Method – Electrical Test Method.

[7] Dmitry Titushkin, Alexey Surma, Michiel de Monchy and Anna Lifton "Aspects of reliability improvement for large area power semiconductor devices through sintering" PCIM Europe Conference, 10–12 May 2016, Nürnberg, Germany.

[8] Francois Le Henaff, Gustavo Greca, Paul Salerno, Olivier Mathieu, Martin Reger, Oscar Khaselev, Monnir Boureghda, Jeffrey, Durham, Anna Lifton, Jean Claude Harel, Satyavrat Laud, Weikun He, Zoltan Sarkany, Joe Proulx, John Parry, "Reliability of Double Side Argomax® Silver Sintered Devices with various Substrate Metallization", PCIM Europe Conference, 10–12 May 2016, Nürnberg, Germany.