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ABSTRACT
InGaN-based High Power blue LEDs exhibit a maximum light conversion efficiency of 40%, which decreases further at high drive currents. Thus, more than 60% of the electrical input power is dissipated as heat in an LED chip, leading to a rise in the junction temperature of the LED. Junction temperature has a significant impact on the light conversion efficiency of the LEDs. Also, it reduces LED lifetime by excessive heating and results in subsequent failure of the LED chip. Thus, heat flow from junction to heat sink is important for maintaining the junction temperature as well as the light conversion efficiency and light output in a high power LED package. Heat flow can be facilitated by using high thermal conductivity die attach materials for packaging LED die on the MCPCB. Therefore, commercially available LEDs have been characterized for evaluating the affect of different die-attach materials on LED junction temperature and light conversion efficiency at different drive currents. Also, the variation of peak emission wavelength and light conversion efficiency with heat sink temperature has been determined for the packaged LEDs. The results and observations have been presented here along with recommendations for future work.

INTRODUCTION
The junction temperature in the LED increases with increasing drive current since, more than 60% of electrical input power is dissipated as heat due to efficiency droop at high drive currents in InGaN LEDs. This rise in the junction temperature reduces the light output by increasing the probability of non-radiative recombination. Thus, the dissipated heat needs to be removed from the junction in order to maintain the light conversion efficiency and light output from the High Power LED package. The various components in the heat flow path in a High Power LED package as shown in Figure-1 are LED junction, substrate (Sapphire, SiC, Si), die attach material, MCPCB, thermal interface material and heat sink. The thermal conductivity of the die attach being lower than some of the other components in the heat flow path can play a significant role in determining the thermal resistance from junction to heat sink which further affects the heat flow rate and junction temperature in the LED package.

EXPERIMENTAL
LED packaging
For junction temperature and light output characterization, 1W blue SemiLED chips with peak emission wavelength of 455 nm were used. These were packaged on a 1 cm × 1 cm Aluminum Metal Core PCB with two different die attach materials (SAC-305 and SnBiAg) used as models. The thermal conductivities and packaging processes used for these two die attach materials are summarized in Table-1.

| Table 1: Thermal Conductivity and Process Specifications for Die Attach Materials |
|------------------------|-----------------|-----------------|
| Die Attach Material    | Thermal Conductivity (W/m-K) | Process Conditions |
| SAC-305                | 60              | 245 °C peak, 60 sec TAL |
| SnBiAg                 | 20              | 182 °C peak, 60 sec TAL |

Junction temperature measurement by Forward Voltage Method
Equation-1 describes the variation of the LED forward voltage with junction temperature. In order to assess the junction temperature of the LED using forward voltage, two sets of measurements need to be done- a calibration...
measurement and the actual junction temperature measurement. The calibration measurement is done in a temperature-controlled oven wherein the forward voltage is measured at different ambient temperatures when the LED is driven at a very low drive current (<30 mA) to avoid self-heating so as to keep the junction temperature as close to the ambient temperature as possible. The calibration measurement gives the temperature coefficient of the diode forward voltage (dVf/dT).

\[
\frac{dV_f}{dT} = \frac{eV_f - E_g}{eT} + \frac{1}{e} \frac{dE_g}{dT} - \frac{3k}{e}
\]  

(1)

In the second set of measurements, the forward voltage drop from high drive currents (0.3 A, 0.5 A, 0.7 A) to 0.01 A is recorded while maintaining the heat sink temperature at 20 °C. This forward voltage drop and the temperature coefficient of diode forward voltage derived earlier are used to calculate the junction temperature of the LED at different drive currents.

Optical measurements using Labsphere Integrating Sphere

Labsphere electrical, optical and thermal characterization system (TOCS) was used for the light output measurements of LEDs packaged with different die attach materials. Two sets of measurements were done: light conversion efficiency and peak emission wavelength versus drive current and sink temperature. For these measurements, the LEDs were placed on the heat sink with indium foil as the thermal interface material between the MCPCB and heat sink. The sink temperature was varied using Arroyo Instruments TECSource temperature controller and LEDs were driven using Agilent Power Supply. For the first set of measurements with varying drive current, heat sink temperature was maintained constant at 20 °C with the TECSource temperature controller and for the second set of measurements with varying heat sink temperature, the drive current was maintained constant at 30 mA to avoid self-heating of the LED die.

RESULTS AND DISCUSSION

Effect of Different Die Attach Materials on LED Junction Temperature

Figure 2 shows the junction temperature as a function of the LED drive current for the two die attach materials measured using the forward voltage method described in Sec-2.2. It is seen that the LEDs packaged with die attach materials whose thermal conductivities are 60 W/m-K and 20 W/m-K, resp. exhibit a small difference in the junction temperature (2.2 °C) at the maximum rated drive current for SemiLED (0.7 A). In order to confirm these results, the junction temperature at a drive current of 0.7 A was calculated for LEDs packaged with these two die attach materials using Equation-2.

\[
T_j = T_{\text{board}} + R_{\text{junc-board}} \Delta W
\]

(2)

\[
T_{\text{board}} = T_{\text{sink}} + R_{\text{TIM}} \Delta W
\]

(3)

The heat sink temperature was maintained at 20 °C for junction temperature measurement using forward voltage method and this value was used for the calculation of board temperature. The calculated board temperature at 2.2 W power dissipation is 20.02 °C. The value of thermal conductivities, cross-sectional area and thickness for heat flow for the various components in the heat flow path are presented in Table-2. Thermal resistance and calculated junction temperature values are presented in Table-3. It is seen from Table-3 that the calculated value of difference in the junction temperature (1.9 °C) of LEDs packaged with the two die attach materials is in good agreement with the value determined experimentally (2.2 °C).

<table>
<thead>
<tr>
<th>Component</th>
<th>Thermal Conductivity (W/m-K)</th>
<th>Layer Thickness (µm)</th>
<th>Cross-Sectional Area (m²)</th>
<th>Thermal Resistance (K/W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LED Substrate</td>
<td>40</td>
<td>155</td>
<td>10⁻⁴</td>
<td>0.25</td>
</tr>
<tr>
<td>SAC-305 (Die Attach)</td>
<td>60</td>
<td>25</td>
<td>10⁻⁴</td>
<td>0.417</td>
</tr>
<tr>
<td>SnBiAg (Die Attach)</td>
<td>20</td>
<td>25</td>
<td>10⁻⁴</td>
<td>1.25</td>
</tr>
<tr>
<td>Dielectric</td>
<td>2</td>
<td>20</td>
<td>10⁻⁴</td>
<td>10.09</td>
</tr>
<tr>
<td>MCPCB</td>
<td>240</td>
<td>1600</td>
<td>10⁻⁴</td>
<td>0.007</td>
</tr>
<tr>
<td>TIM</td>
<td>82</td>
<td>100</td>
<td>10⁻⁴</td>
<td>0.012</td>
</tr>
</tbody>
</table>
The assembly process for the LED package may yield less than 100% pad coverage and voiding in the die attach layer. For the junction temperature calculation using package thermal resistance, it has been assumed that the pad coverage is 100% and no voiding occurs in the die attach layer and thus, the thermal resistance of the die attach layer for these calculations is lower than the thermal resistance in the actual package. This explains lower junction temperatures from package thermal resistance calculations as compared to the values measured by the forward voltage method.

**Effect of different die Attach materials on LED light output and quality**

Junction temperature has a significant impact on the light conversion efficiency of the LEDs. High thermal conductivity die attach materials can improve the light conversion efficiency by reducing the junction temperature at high drive currents. Thus, the light conversion efficiency and light output of LEDs packaged with two die attach materials (SAC-305 and SnBiAg) was recorded at different drive currents. Figure-3 (a-b) show the light conversion efficiency and light output versus drive current data measured at a constant sink temperature of 20°C for the two LED packages with different die attach materials. It is seen from Figure-3 (a) that the LED packaged with SAC-305 shows lower drop in light conversion efficiency at high drive currents as compared to the LED packaged with SnBiAg due to better thermal management in the former resulting from higher thermal conductivity of SAC-305. At 1 A drive current, the LED packaged with SAC-305 shows 2.4% higher efficiency than the LED packaged with SnBiAg. The high light conversion efficiency is translated into higher light output (Figure-3 (b)) which is almost greater than 1.1 times for the LED packaged with SAC-305 as compared to the LED packaged with SnBiAg at 1 A drive current.

<table>
<thead>
<tr>
<th>Die Attach Material</th>
<th>Thermal Resistance of LED Package (K/W)</th>
<th>Junction Temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SAC-305</td>
<td>10.86</td>
<td>45.10</td>
</tr>
<tr>
<td>SnBiAg</td>
<td>11.69</td>
<td>47.03</td>
</tr>
</tbody>
</table>

The table above shows the calculated thermal resistance and junction temperature for LED packages with different die attach materials.

**Figure 3.** (a) Light Conversion Efficiency, (b) Light Output as a function of the LED drive current for LEDs packaged with SAC-305 and SnBiAg die attach materials.

Figure-4 (a-b) show the variation of the peak emission wavelength with LED drive currents for LEDs packages with SAC-305 and SnBiAg die attach materials, respectively. The peak emission wavelength for both LEDs follows a similar trend i.e. the peak emission wavelength first decreases with increasing drive current and then increases at high drive currents. For these measurements, the sink temperature was maintained at 20°C. This trend is explained by two competing effects with increasing drive current i.e. rise in junction temperature and QCSE (Quantum Confined Stark Effect). While QCSE causes the energy levels in the quantum wells to move farther apart due to increasing electric field, the junction temperature rise with increasing drive current causes the effective band-gap to decrease. This leads to decrease in the peak emission wavelength as QCSE dominates at lower drive currents and increase in peak emission wavelength as effect of junction temperature dominates at higher drive currents. Since, a noticeable variation in peak emission wavelength due to junction temperature requires at least a 20°C difference in the junction temperature (Figure-6), no difference in peak emission wavelengths for the two LEDs was recorded in this case as the junction temperature difference for these is only 2-3°C.

**Figure 4.** Peak Emission Wavelength as a function of the LED drive current for LED packaged with (a) SAC-305 and (b) SnBiAg die attach material.

**Effect of heat sink temperature on light output and quality**

For a 1 W LED on FR4 PCB with a TIM of thermal conductivity 3 W/m-K, there is almost a 50°C difference between the sink and junction temperature. For such an LED on Si substrate with a die attach material of thermal conductivity 57 W/m-K under 1 W operation, the junction temperature is 104°C while the sink temperature is 53°C. Thus, in order to emulate the real operating conditions of a 1 W LED, the light conversion efficiency of SemiLEDs LEDs with different die attach materials was characterized at different sink temperatures. The sink temperature was regulated using the Arroyo Instruments TECSource Temperature Controller. Figure-5 (a-b) show the variation in the light conversion efficiency as a function of the sink temperature at drive currents of 1 A and 1.1 A, resp. for LEDs packaged with SAC-305 and SnBiAg die attach materials.
The junction temperature of the LEDs increases with the sink temperature and thus, light conversion efficiency decreases with increasing sink temperature. Heat flow from the junction is affected by the thermal conductivity of the die attach material and thus, the drop in LED efficiency with sink temperature is an indication of effectiveness of the die attach material in heat flow from the LED junction to the heat sink. It can be seen from Figure-5 (a-b) that the efficiency drop from 20 °C to 70 °C sink temperature is higher for LEDs packaged with SnBiAg as compared to SAC-305 due to higher thermal conductivity of SAC-305 die attach material. As seen from Figure-5 (a-b), the light conversion efficiency at a sink temperature of 70 °C is 0.2 % and 0.8 % higher for LEDs packaged SAC-305 as compared to those with SnBiAg at 1 A and 1.1 A drive currents, respectively. Also, the typical sink temperature for a 60 W LED lamp in the open base down configuration is 75 °C. As seen from Figure-6, the LED peak emission wavelength changes at the rate of 1 nm per 20 °C. Therefore, a typical LED lamp in this configuration would show a 2-3 nm variation in peak wavelength under operation.

Figure 5 (a-b). Light Conversion Efficiency as a function of the Sink Temperature for LEDs packaged with SAC-305 and SnBiAg die attach materials at different drive currents

Figure 6. Peak Emission Wavelength as a function of Sink Temperature for blue 1W SemiLEDs at 30mA drive current

CONCLUSIONS

Commercially available blue LEDs have been characterized for evaluating the affect of different die-attach materials on LED junction temperature, light output and quality at different drive currents. It was found that by replacing a die attach materials with thermal conductivity of 20 with a material having thermal conductivity of 60 W/m-K, the light conversion efficiency could be increased by 2.4% at 1 A drive current. Also, this translates into a light output improvement of 10-11%. Further, the affect of sink temperature on light output and quality was determined for the LEDs packaged with these two die attach materials. It was found that high sink temperatures led to loss of LED light conversion efficiency which further increased the junction temperature of the LED. Thus, the LEDs packaged with SAC-305 exhibited 0.2 % and 0.8 % higher light conversion efficiency as compared to LEDs packaged with SnBiAg as SAC-305 facilitated efficient heat flow from the LED junction to the heat sink. Also, it was determined that the peak emission wavelength of the 1 W blue LED changed at a rate of 1 nm per 20 °C change in sink temperature which could cause significant shift in the chromaticity of LED lamps where the typical sink temperatures are in the range of 75-100 °C.
INTRODUCTION
LED technology is seeing widespread adoption in a range of end markets including lighting, automotive and display applications. LEDs offer several advantages such as energy efficiency, long life, instant turn on and off, high luminance, high brightness, color control (e.g. pure red, orange, and white light), shock and vibration resistance, and styling and design freedom.

LED lighting systems such as exterior lighting, can be described in terms of a hierarchy shown in Figure 1 below.

For high power LED applications such as projection, street lighting and automotive headlamps, materials used in the packaging and assembly of LEDs need to be able to handle high thermal loads and high thermal cycle and vibration reliability requirements. In this paper, we discuss the mitigation of thermal and reliability issues in high power LED lighting systems with two of Alpha®’s advanced materials platforms.

KEY ISSUES IN LED LIGHTING
Key issues in high power LED lighting include:

- Heat dissipation at all levels of the lighting system
  - Heat buildup can lead to device failure
  - Voiding under thermal pads leads to heat buildup, loss of efficiency and potential failures
- Directionality of light output
- Applications such as spotlights or headlights need good control of LED die/package tilt and optical axis
- Reliability and Longevity
  - Long term thermal cycling requirements and vibration resistance during operation are critical for reliable operation of the LEDs for the design life.
- Efficiency and brightness improvement
  - Efficiency is critical for reduction of energy consumption, while brightness improvement (increased light output) is needed to reduce cost per lumen.
- Rework
  - It is difficult to rework LEDs assembled, so first pass yield is critical

Materials and components were chosen based on commercially available LED packages, solder pastes and flexible substrates.

THE ROLE OF HIGH THERMAL AND HIGH RELIABILITY MATERIALS IN LED LIGHTING
- High thermal and high reliability die attach and assembly materials enable rapid heat extraction, thus enabling performance improvement, reliably, over the expected lifetime.
- Key requirements for advanced die attach and assembly materials used in LED die attach and package-on-board assembly are:
  - Die Attach
    - Very high thermal conductivity
    - Thin, uniform bond line for die tilt control and thermal performance
    - No bleed-out or die top contamination
    - High thermal cycle reliability with high CTE mismatch
    - High creep resistance
  - Package-on-Board Assembly
    - Low/acceptable void level assembly
    - Package tilt control
    - High creep-fatigue resistant solder alloys leading to better thermal cycling performance
    - High vibration resistance
    - Excellent printability and first time right assembly
TWO KEY ALPHA® TECHNOLOGY PLATFORMS FOR HIGH THERMAL, HIGH RELIABILITY

- Alpha®’s novel high thermal, high reliability materials for LED die and package attach can help improve the design window and performance.
- High creep fatigue resistant solders
  - Maxrel™ alloy based preforms and paste for die/package attach
- Silver sintering die attach materials
  - Argomax® Ag film for die attach
  - Fortibond™ pressureless sintering

Maxrel™ Creep Resistant Alloy
Maxrel™ alloy is a creep resistant solder material that increases reliability of the solder joints subjected to thermal cycling in high CTE mismatch material stacks. Figure 2 shows Maxrel alloy performance vs SAC305 alloy in thermal cycling of ceramic submount LEDs assembled on Metal Core PCBs. High creep resistance of Maxrel™ alloy provides better thermal cycling performance.

Figure 2. Thermal Cycling Performance of Maxrel™ Alloy vs SAC305 Alloy
Maxrel™ alloy has unique reflow properties that minimize die / package tilt and die float. This leads to more uniform bond lines and control of die tilt as shown in Figure 3.

Further, the higher creep resistance of Maxrel™ alloy provides increased reliability while reducing bond line, which in turn means that Maxrel™ alloy can provide lower thermal resistance in the joint.

Further improvements in reliability can be obtained by tailoring the ratio of modulus of the solder to the modulus of the dielectric.

Argomax® Ag Sintering Technology
Argomax® Ag sintering materials can be processed at 190C to 300C under pressure, to form a pure Ag interface. After bonding, Argomax® joint has a melting point of 962 C, same as bulk silver. The material and process yields joints with thermal conductivities in the ~250W/mK range, with thin, uniform bond lines. The resulting bond is a pure diffusion bond with no intermetallics.

Argomax® Ag sintering technology, offered in a film form factor, can provide automotive Led assemblies with:

- 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 dies closer together without movement or "die float" which yields higher lumen density in smaller area.
- 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.
- Very high die shear strength and thermal cycling/thermal shock reliability as shown in Figure 4.
Argomax® Provides High Thermal Cycle and Thermal Shock Reliability

The process is high volume manufacturing capable, with sintering process UPH capability in excess of 20,000 die bonded per hour. This is shown in Figure 5.

Processing Options
- Die-level film lamination (DTF Process)
- Wafer back-side lamination
- Large area bonding

Fortibond™ Pressureless Ag Sintering Technology
Fortibond™ pressureless Ag sintering technology, currently in paste form, is new Ag sintering technology platforms developed by Alpha that can be used for die attach using existing equipment sets for printing/dispensing, placement and sintering.

- Pressure-less Silver Sintering Paste compatible with existing dispense / printing, die bonding and curing equipment
- Sintered silver joint enables high temperature stability during secondary reflow
- High bulk thermal conductivity (135+ W/mK) enables lower junction temperature / higher light output
- Available in print & dispense versions with pin transfer versions in development.
- Regular refrigerator storage and shipping without dry ice for easy economical handling

Fortibond pastes demonstrate high performance. For example, the Fortibond AL12P printable paste shows shear strength in the 25 MPa range, passes typical LED package thermal cycling, thermal shock and thermal aging requirements, as well as withstanding multiple refloows in MSL Level 1 testing for the die attach material.

- Die-Shear Strength: >25MPa
- Thermal Cycling: Passed 1000 cycles with -40 to 125C
- Passed 1000 hrs aging at 175C with no change in die-shear strength
- Thermal Shock : Passed 1000 cycles from -55 to +125C
- Passed Moisture Sensitivity Level (MSL) Level 1

Fortibond™ is a Pressure-less silver sintering technology platform designed to address applications that require assembly at zero / low pressure by processes compatible with existing equipment. (on both semiconductor packaging as well as SMT assembly lines) shown in Figure 6.

Summary and Conclusions
High reliability, high thermal technologies such as Maxrel™ alloy, Argomax® Ag sintering film and Fortibond™ pressureless sintering technology can be used to provide high reliability, high thermal joints for LED assembly in high power lighting applications.

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LED Die Attach Technologies - Considerations

Gyan Dutt & Ravi Bhatkal

Abstract

Die attach material plays a key role in performance and reliability of mid, high and super-high power LEDs. The selection of the suitable die-attach material for a particular chip structure and application depends on several considerations. These include packaging process (throughput and yield), performance (thermal dissipation and light output), reliability (lumen maintenance) and cost. Eutectic gold-tin, silver-filled epoxies, solder, silicones and sintered materials have all been used for LED die-attach. Often, use of a particular technology platform results in trade-off between different attributes.

This white paper reviews process, performance and reliability attributes of the die attach technologies. Then it addresses the fit between these die-attach materials, different chip structures (like lateral, vertical and flip-chip) and their operating power levels. Finally it describes the positioning of different technologies for applications in general lighting segment. This review clearly shows that given the diversity in chip structures, package designs and applications, all material platforms have a place in LED die attach. A diverse portfolio that provides die attach options to LED device makers and packagers is required to meet the process and performance demands in this rapidly changing market.

Keywords: LED, Packaging, Die Attach, Silver Sintering, Conductive Adhesive, Solder, AuSn

LED Performance, Reliability & Die-Attach

Mid power to super-high power LEDs are being operated at increasing current and power levels (for applications such as lighting and mobile flash among others). This trend has again brought the need for robust thermal dissipation to the forefront. If the heat dissipation is not managed properly, the LED performance can degrade significantly – resulting in loss of radiant flux, change in forward voltage, wavelength shift and eventually reduced lifetime.

Die-attach is the first layer that comes into contact with the LED die and its thermal performance and stability has a direct impact on LED light output, light extraction and lumen maintenance over time. The die-attach material and (more importantly) the process together have a significant effect on the cost of ownership of the light engine.

LED Chip Structures, Power Levels and their Performance Factors

There are three main LED chip structures as shown in Figure 1. The Lateral structure consists of laterally spaced electrodes (with one wirebond for each electrode) and is used in low power applications. The Vertical structure, used for most of the high and super-high power applications, consists of a conductive substrate at the bottom which forms the bottom electrode with the current flowing vertically. The flip-chip structure has both electrodes on one side and is put face down on the substrate. It provides the highest lumen density at cost lower than vertical structure. These three structures can also be mounted directly on a board, next to each other, to form modules called Chip-on-Board.
Die-Attach Technology Platforms – Gold-tin eutectic, Solder, Conductive Adhesive, Sintered Materials

Eutectic gold-tin (80/20 Au/Sn by weight) has been the “gold standard” die-attach material for high reliability applications for several decades. For LED die attach it is used either as a pre-coated layer on LED backside, or a preform or in form of solder paste. All these forms involve different processes and performance. Although the cost of ownership of AuSn die attach is much higher than other materials, it is still the material of choice for high power applications due to its proven thermal (57W/mK) and reliability (high creep & fatigue resistance with second reflow compatibility).

Conductive Adhesives (mostly silver filled epoxies) constitute the largest class of thermal die-attach materials (by unit number), not just for LEDs, but for all semiconductor packages. They are compatible with the existing back-end packaging equipment and provide an attractive cost and performance balance (50W/mK thermal with second reflow compatibility). Since they stick to bare silicon, they are the preferred material of choice for dies without back-side metallization (like GaN on silicon).

Sintered silver materials consist of micro/ nano scale silver particles which undergo atomic diffusion to fuse together at 180-300°C to form nano-porous yet predominantly metallic silver joint (961°C melting point). They can applied in either paste or film format and sintering can happen either in a press (requires new equipment) or a regular oven. These materials, with cost in-between conductive adhesive and eutectic-AuSn, have been shown to provide superior mechanical reliability and higher thermal performance (than AuSn). For LEDs, sintered materials have been shown to improve the lumens output by 30+% for red & green LEDs as well as UV LEDs.

Solder (mostly SAC based), provides exceptional value with low cost, fast assembly process with reasonable thermal performance (50-60W/mK). Lately there has been a trend to make flip-chip structure compatible with solder on SMT lines. However, since SAC solder melts in 217-221°C range, its use is limited to applications where either high temperature stability is not required in operating
conditions or during further processing (like secondary reflow). SnSb based solder with melting point range 245-251°C can survive second reflow below 240°C peak temperatures.

**LED Die-Attach Materials Comparison**

There are three key considerations for selecting material for die attach in a LED application.

1) **Thermal Resistance** – Among the materials discussed above, sintered silver has the highest bulk thermal conductivity (>100W/mK) and has been shown to have the lowest thermal resistance in head-to-head comparison with AuSn and silver epoxies. Eutectic gold-tin thermal conductivity has been measured around 57W/mK, which at thin bond lines (~5um) results in lower overall thermal resistance than silver epoxies (mostly <50W/mK at ~25um bond lines).

2) **Second Reflow Compatibility** – LED packages assembled on submount undergo an additional solder reflow step to attach to the board. AuSn, conductive adhesive as well as sintered silver materials can easily withstand the secondary reflow. Obviously SAC based solders cannot be used reliably in these packages, unless low temperature solders such as Sn-Bi based solders are used for second reflow. However, for applications in which the COB module is screwed to the heat sink, second reflow is not needed and solder is the die-attach material of choice.

3) **Cost of Ownership** – The die-attach step, due to the cost of the die-bonders, is usually the most capital intensive step in LED packaging. So it is important that die-attach material and process is compatible with the existing high throughput dispense/pin transfer bonders. No capital investment and low cost of ownership makes solder, silver epoxies and pressure-less sintered silver materials particularly attractive (over AuSn and pressure-assisted sintering materials).

These three attributes of the die-attach platforms discussed here are compared in Figure 2.

![Figure 2: Attributes of LED Die Attach Platforms](image)

**Chip and Package Structures Fit with Common Die-Attach Materials**

The starting point for die attach selection is usually the end application and design. End application determines the operating environment, while design determines the number and power levels of the
dies. For example, an outdoor lamp will have higher power dies designed to operate in a harsher environment, compared to mid power dies in some bulb or tube designs for use in relatively benign conditions indoor. Within the bulb/luminaire application, different designers may choose between smaller numbers of high-power dies in packages or larger number of low power dies directly on board (COB).

Once these design and end-use decisions have been made, the three attributes described in the previous section are sufficient to make the selection. The power level of the die determines the heat dissipation requirements - higher power dies require high thermal conductivity die attach to keep the thermal resistance low (while low thermal die attach is okay for low power dies). So for high-power and super high power vertical LEDs sintered materials (both pressure-assisted and pressure-less) and eutectic gold-tin are most suitable to lower the thermal resistance and keep the junction temperature manageable for optimal performance of the LED. The mid-power dies (either vertical or flip-chip in package) can use solder and high thermal epoxy. Finally for the low-power lateral LEDs, lower end epoxies (or silicone) may be good enough thermally.

For assemblies that do not go through second reflow (like COB), solder is the preferred die-attach material. For in-package attach silver epoxy, AuSn or sintered materials are essentially the only options. The final major consideration is the cost of ownership (process equipment and throughput). While eutectic AuSn and pressure-assisted sintered materials provide exceptional thermal performance and mechanical reliability they are not compatible with traditional die bonding equipment. Conductive epoxies and pressure-less sintered silver materials can be adopted easily on the existing lines. Solder, on the other hand, is unique in its compatibility with semiconductor packaging as well as SMT lines.
The relative positioning of the materials in Alpha LED die-attach portfolio for different applications on different substrates is shown in Figure 4. Argomax® with the highest thermal and reliability is the highest performance option for super-high power applications like projection and entertainment lighting. Pressure-less sintering Fortibond™, which is compatible with existing equipment yet provides higher thermal and reliability than silver epoxy, is suitable for most high power applications – like vertical UV, flip-chip on ceramic and lead frames (for general lighting and mobile flash) and laser diodes. Conductive adhesive Atrox™ can meet the requirements for most of the mid power vertical dies in general lighting applications (like retrofit bulbs), especially with dies without metallization. Finally solder is the material of choice for any low-mid power application that requires die attach directly on the board (no secondary reflow).

Among the products in Alpha’s LED die attach portfolio, pressure-assisted silver sintering Argomax® has been used for super high power applications like projection lighting. Pressure-less sintering Fortibond™ has been used for high power vertical UV and VCSEL applications. Atrox™ conductive adhesive has been used in vertical bare silicon dies without back-side metallization. Rapid solder compatible flip-chip adoption has opened new opportunities for Lumet™ series fine-pitch T7 paste for bumping on wafer as well as T5/T6 by printing / pin transfer. Maxrel™, SAC305 and SnSb based pastes have also been used by several customers for COB assemblies with flip-chip, lateral and vertical structures.

Figure 4: Alpha® LED Die Attach Portfolio and Applications

**Conclusion**

This review clearly shows that the diversity of LED structures, power levels, applications and process equipment considerations require different die attach solutions. Every die attach material technology is
being used in mass production for packaging LEDs and assembling modules – from silicones and solder to AuSn and sintered silver materials. It is also very important to note that apart from this diversity, the LED market and applications are much more price sensitive and are growing at much faster rate than traditional semiconductor and electronics markets. This has resulted in shorter qualification cycles with renewed emphasis on lower packaging cost with each design cycle. Having a broad portfolio that provides different price and performance options to the customer has created multiple opportunities for Alpha. Most of our customers do prototype builds with several material technologies on different product platforms and end up making the final decision on cost/performance ratio that is unique to their application and business model.
HIGH RELIABILITY INTERCONNECTIONS FOR HIGH POWER LED ASSEMBLY

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ABSTRACT
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. Use of high and ultra-high power packages necessitates use of Metal Core PCBs for thermal management. However, such a materials stack, combined with high operating temperature inherent in such systems, results in significant CTE mismatch between the high power LED ceramic submount and the Metal Core PCB, which places significant performance demands on the solder joints. One of the key questions is: What role does the solder alloy play in the LED package-on-board assembly reliability? This paper presents a study to help answer this question.

Keywords: LED, High Power, High Reliability, LED Lifetime

INTRODUCTION
The lighting revolution is on. The global acceptance of LED based light sources have entered many different markets including, high power lighting segments which are largely driven by their end-application. As local and state governments push for energy efficiency, cities are adopting high power LEDs for many outdoor applications. Examples include roadway/street, industrial and architectural lighting. As a result, customer expectations of reliability for LED based commercial and outdoor lighting are very high. For such applications, a B50, L70 lifetime of 35,000 hours is needed. For these high reliability and lifetime requirements, it is critical to have excellent assembly interconnect reliability to address the above needs. The role of interconnects in LED assembly is fundamentally to:

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

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.

One of the key questions is: What role does the solder alloy play in the LED package-on-board assembly reliability? A systematic evaluation was undertaken to understand the effect of multiple variables on a Metal Core PCBs as seen in Table 1 on assembly and reliability. Details of the test are summarized in the next section:

<table>
<thead>
<tr>
<th>Factors</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alloy</td>
<td>SAC Based Low Silver SAC Based High Creep Resistant</td>
</tr>
<tr>
<td>Profile</td>
<td>Profile – High (260°C Peak) Profile – Recommended (240°C Peak)</td>
</tr>
</tbody>
</table>

Table 1. Defined Variables

ASSEMBLY MATERIALS & COMPONENTS
Test Vehicle
The test vehicle details are summarized in Table 2 below.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Metal Core PCB</th>
</tr>
</thead>
<tbody>
<tr>
<td>Metal Core</td>
<td>Aluminum</td>
</tr>
<tr>
<td>Surface Finish</td>
<td>Immersion-Tin</td>
</tr>
</tbody>
</table>

Table 2. Test Vehicle Details

LED Component
For this study a commercially available ceramic LED with 2.7mm x 2.7mm Solder Footprint was selected to emulate a common high power assembly seen in the market.

Solders Pastes
Solder pastes with three Pb-free alloys were selected for this study. The solder paste flux, alloy, metal percent details are shown in Table 3 below. All solder pastes had zero halogens and had Type 3 grade solder powder.

<table>
<thead>
<tr>
<th>Solder Paste</th>
<th>Alloy Detail</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lumet</td>
<td>Maxrel1</td>
</tr>
<tr>
<td>Lumet</td>
<td>SACX0807</td>
</tr>
<tr>
<td>Lumet</td>
<td>SAC305</td>
</tr>
</tbody>
</table>

Table 3. Solder Paste Descriptions

PROCESS AND TEST METHOD
Equipment Processing Details
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 below.

<table>
<thead>
<tr>
<th>SMT Parameters</th>
<th>Process Conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Print Speed</td>
<td>1 inch/sec.</td>
</tr>
<tr>
<td>Print Pressure</td>
<td>1.25 lbs/inch of blade</td>
</tr>
<tr>
<td>Stencil Release</td>
<td>0.02 inches/sec.</td>
</tr>
<tr>
<td>Print Pressure</td>
<td>1 inch/sec.</td>
</tr>
</tbody>
</table>

Table 4. SMT Process Details

Reflow Soldering
A reflow oven with seven heating and two cooling zones was used for the reflow assembly. All boards were assembled with the following temperature/humidity conditions: 20°C / 46% RH. For this evaluation, two different peak reflow temperatures were evaluated both under a high soak profile for all solder pastes. Table 5 summarizes both reflow profiles used.

<table>
<thead>
<tr>
<th>Reflow Term</th>
<th>Profile</th>
<th>Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reco-LV</td>
<td>High</td>
<td>150-200C/111s Soak 240C</td>
</tr>
<tr>
<td>Standard Peak</td>
<td>Soak</td>
<td>Peak 70s TAL-CE HS</td>
</tr>
<tr>
<td>260LV</td>
<td>High</td>
<td>150-200C/120s Soak 260C</td>
</tr>
<tr>
<td>Elevated Peak</td>
<td>Soak</td>
<td>Peak 94-97s TAL-OS HS</td>
</tr>
</tbody>
</table>

Table 5. Reflow Process Conditions

Test Method
To measure the reliability of the differentiating alloys, an air to air thermal cycling evaluation was performed on the assembled boards. The completed boards assembled with their respective solder paste alloys were placed in an air-to-air thermal cycling chamber at -40°C to 125°C, with 15 minute dwell time. Cycle time was 40 minutes. Thermal Cycling Profile is shown in Figure 1 below:

RESULTS, DISCUSSION and CONCLUSION
Results
Figures 2 to 4 below express the shear value results at initial, five-hundred and one-thousand thermal cycles. Table 6 summarizes the percent change in the initial and final shear values for each alloy.

Figure 2. Thermal Cycles vs Shear Strength for Maxrel

Figure 3. Thermal Cycles vs Shear Strength for SAC305

Figure 4. Thermal Cycles vs Shear Strength for SACX0807

Table 6. Percent Change in Shear Values for Each Alloy

<table>
<thead>
<tr>
<th>Reflow Term</th>
<th>Profile</th>
<th>Condition</th>
</tr>
</thead>
<tbody>
<tr>
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<tr>
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<td>260LV</td>
<td>High</td>
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</tr>
<tr>
<td>Elevated Peak</td>
<td>Soak</td>
<td>Peak 94-97s TAL-OS HS</td>
</tr>
</tbody>
</table>

Figure 1. Temperature Cycle Profile
<table>
<thead>
<tr>
<th>Alloy</th>
<th>Percent Change: 0 to 1000 cycles at -40°C to 125°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maxrel</td>
<td>-25%</td>
</tr>
<tr>
<td>SAC305</td>
<td>-60%</td>
</tr>
<tr>
<td>SACX0807</td>
<td>-61%</td>
</tr>
</tbody>
</table>

Table 6. Percent Change of Shear Values Initial to Final

**Discussion**

Use of high and ultra-high power packages necessitates use of Metal Core PCBs for thermal management. However, such a materials stack, combined with high operating temperature inherent in such systems, results in significant mismatch of the Coefficient of Thermal Expansion (CTE) between the high power LED ceramic submount and the Metal Core PCB, which places significant performance demands on the solder joints. In the case of a super-high or ultra-high power LED assembly on aluminum MCPCB, the $\Delta$CTE between the LED and the MCPCB is 18-20, which is quite high, as shown schematically in Figure 5.

![Schematic of High-Power Ceramic LED on Metal-Core PCB](image1)

Figure 5. Drawing of an Assembled High-Power Ceramic LED on a Metal-Core PCB Showing CTE Differentials.

During thermal cycling experienced by the LED assembly in applications such as outdoor lighting or automotive, the high $\Delta$CTE 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 6 demonstrated by Peter Hall at AT&T Bell Laboratories (Hall, 1984 and 1991). This strain energy buildup causes micro-cracking, and eventually, failure of the joint.

![Solder Joint Hysteresis Loop](image2)

Figure 6. Solder Joint Hysteresis Loop During Thermal Cycling Between -25°C and 125°C.

**Conclusions**

1. The shear results for a high power ceramic LED on a metal core PCB subjected to 1000 cycles at -40°C to 125°C indicated that the Maxrel alloy showed highest shear strength and the least degradation / drop upon thermal cycling with a ~25% drop in shear strength from its initial value. In contrast, we see that the SAC based alloys showed a drop of ~60-61% from its initial value.
2. Peak reflow temperatures do not have a significant impact on the shear strength behaviour of all the alloys tested.
3. Stack-ups with high CTE mismatch between the LED submount and the board can increase creep in the solder joints during thermal cycling.
4. 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 Hall's publications (Hall, 1984, 1987, 1991)
LOW VOIDING RELIABLE SOLDER INTERCONNECTS FOR LED PACKAGES ON METAL CORE PCBs

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ABSTRACT
SSL Assemblies need to meet high reliability requirements such as Energy Star Category A which dictates a B50/L70 lifetime of 35,000 hours for commercial and outdoor residential lighting. Solder joints with low void content are critical for long term performance and reliability. Two types of MCPCB substrates, 4 different solder pastes and one type of LED ceramic package were evaluated in this study to develop a low voiding assembly process. Results of the study and recommendations for achieving low voiding are presented.

Key words: LED package, MCPCB; solder joint % voids

INTRODUCTION
Applications for light emitting diodes (LEDs) are increasing dramatically in the lighting sector. The benefits of LEDs over competing technologies include versatility and long-term reliability. Package and luminaire design are critical considerations in ensuring that performance and reliability targets are met for commercial applications.

Customer expectations for LED based luminaires (Solid State Lighting) are very high due to the relatively high cost of such luminaires. For commercial and outdoor residential lighting, 70% lumen maintenance after 35,000 hours and a (3) year warranty is required for LED packages, modules and arrays to meet Energy Star Category A criteria. For high reliability, long lifetime and color maintenance of LED lights, it is critical to have excellent assembly interconnect reliability; i.e., package to insulated metal-core substrate solder joints with low voiding for low thermal resistance and hence good heat dissipation.

ASSEMBLY MATERIALS & COMPONENTS:
Materials and components were chosen based on commercially available LED packages, solder pastes and MCPCB substrates.

High power LED package:
A high power InGaN-based LED package (Ref.1) was used in this study. It is a compact package that can be surface mounted and can provide high lumen output and superior thermal performance. An image and cross-section of the LED package are shown in Figures 1 and 2, respectively (Ref 1).

Figure 1. Image of InGaN LED package

Figure 2. Cross section of LED package

MCPCBs and Dielectric:
The LED package is a surface mount component and can be assembled on a typical FR4 board or on an MCPCB (Metal
Core Printed Circuit Board). MCPCBs are also referred as Metal Clad PCBs. An MCPCB has a thin, thermally conductive dielectric layer bonded to an aluminum or copper substrate for good heat dissipation.

Each of the board materials has its own benefits and limitations. For example, a FR4 board with open or filled and capped vias is a low cost solution for a regular LED assembly. MCPCBs offer more rigidity than typical FR4 boards along with improved thermal performance, enabling heat conduction from LED packages into the metal core board material. A partial image of the MCPCB used in this study is shown in Figure 3; a 6x6 array of 36 parts per substrate was used here. A cross-section of a MCPCB is shown in Figure 4 (Ref 2).

![Figure 3. Image of MCPCB Test Board](image)

For this study MCPCB boards with two dielectric materials were used, as described below:

**MCPCB with Dielectric A:** An MCPCB with dielectric A minimizes thermal impedance and conducts heat more effectively and efficiently than standard printed wiring boards (PWBs), an important attribute for LED packages.

**MCPCB with Dielectric B:** Dielectric B is a low modulus dielectric designed to reduce the strain on solder joints in applications where there is a large CTE mismatch between the surface mount component and the MCPCB substrate. This dielectric is also preferred when the application requires reliable operation over a large temperature range and number of thermal cycles, while still providing very good thermal performance.

The relationship between the modulus of the MCPCB dielectric and the solder over the range of application temperatures to which the assembly will be subjected is a major factor in determining where the strain resulting from CTE mismatch between the surface mount component and substrate will be distributed. The modulus of dielectric A is of the same order of magnitude as that of most common MCPCB dielectrics available on the market, and as such can be referred to as a “standard” MCPCB material in terms of solder joint reliability.

Table 1 summarizes the materials and dimensional details of the MCPCB substrates used in this study, which have ENIG surface finish.

<table>
<thead>
<tr>
<th>Layer ID</th>
<th>Material and Thickness</th>
</tr>
</thead>
<tbody>
<tr>
<td>Metal Core</td>
<td>Aluminum: 1.57 mm</td>
</tr>
<tr>
<td>Dielectric A</td>
<td>76 µm; B: 102 µm</td>
</tr>
<tr>
<td>Circuit Layer</td>
<td>Copper: 35 µm</td>
</tr>
</tbody>
</table>

**Solder paste materials:**
Four different solder pastes (with four different metal alloys) were selected for this study. These pastes used Type 3 solder powder and have 88-90 wt% metal contents. Details of these solder pastes are as follows:

**Solder Paste A:** This is a no-clean, zero halogen, and lead-free SAC305 alloy solder paste designed for a broad range of applications. This solder paste has a broad processing window thereby providing excellent print capability performance and high production yields.

**Solder Paste B:** This is a no-clean, zero halogen, and lead-free Maxrel™ alloy solder paste that is suitable for fine feature printing applications. The Maxrel™ alloy is known for its superior thermal cycling/shock performance relative to other high temperature solder alloys.

**Solder Paste C:** This is a no-clean, zero halogen, and lead-free SACX Plus™0807 alloy solder paste that is suitable for fine feature printing applications and has reduced Ag level for lower cost.

**Solder Paste D:** This is a no-clean, zero halogen, and lead-free solder paste that enables low temperature surface mount assembly due to the low melting point (<140°C) of the SnBiAg alloy.

**LED ASSEMBLY PROCESS**
Table 2 summarizes the SMT equipment that was used for the LED assembly.
Table 2. Assembly Process Equipment

<table>
<thead>
<tr>
<th>SMT Equipment</th>
<th>SMT Equipment Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stencil Printer</td>
<td>Speedline MPM UP3000 Ultraflex</td>
</tr>
<tr>
<td>Pick and Place</td>
<td>Universal Advantis with FlexJet Head</td>
</tr>
<tr>
<td>Reflow Oven</td>
<td>Electrovert OmniFlo 7</td>
</tr>
</tbody>
</table>

Solder Paste Printing:
Solder paste printing was done using the MPM UP3000 stencil printer with a 5 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 3.

Table 3. Stencil printing parameters

<table>
<thead>
<tr>
<th>Print Parameters</th>
<th>Print Parameter Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Print Speed</td>
<td>2.54 cm/sec</td>
</tr>
<tr>
<td>Print Pressure</td>
<td>268 grams/cm of blade</td>
</tr>
<tr>
<td>Stencil Release</td>
<td>0.051 cm/sec</td>
</tr>
<tr>
<td>Snap off</td>
<td>0 cm (on contact printing)</td>
</tr>
</tbody>
</table>

Component Placement:
Universal Instrument’s Advantis pick and place machine with FlexJet head was used for the LED assembly. An off-center pick-up was programmed for the LED package pick-up and placement. Care was taken to avoid any contact of the nozzle exterior with the LED domed silicone lens.

Reflow Soldering:
An Electrovert OmniFlo 7 reflow oven, with seven heating and two cooling zones was used for the reflow assembly. All boards were assembled in an air atmosphere.

Voids Measurement:
A Nikon Model XTV160 Xray machine was used to measure the voids percentages (by area) of the reflowed solder joints. For each solder paste and board dielectric type, (5) boards were assembled and at least 50% of the solder joints on each board were measured for %voids.

Reflow Profile Pre-Screening Test:
A pre-screening test was performed using two types of reflow profiles (high soak and straight ramp), the SAC305 solder paste and MCPCB board with type B dielectric, to determine the best type of profile for the LED assembly based on percent voids in the reflowed joints. The pre-screening test results (shown in Figure 5) show that a high soak profile results in slightly fewer voids and also a narrower % voids distribution. Therefore, high soak profiles were used for this study. The high soak profiles used for the high temperature alloy solder pastes (SAC305, MaxrelTM and SACX Plus™0807 pastes) and the low temperature SnBiAg paste are shown in Figures 6 and 7, respectively.

Voiding Test Results
The % voids data for the test boards was analyzed using Minitab and Microsoft Excel.

A main effects plot for the (2) variables in this study (MCPCB board dielectric and solder paste) is shown in Figure 8. This plot shows that the board dielectric has a relatively minor effect on the overall % voids for the LED package assembled with the various solder pastes on the MCPCB boards. However, the solder paste has a significant effect on % voids. The MaxrelTM alloy paste results in average void percentages of ~15%, while the SAC305 paste results in <9% voids overall.

In Figure 9 is shown a box plot for % voids verses the MCPCB board dielectric type. It shows that overall, the board dielectric had very little effect on the % voids with almost the same medians (10.5, 10.9 % voids) and ranges for both types.
Figure 7. High Soak Profile for SnBiAg Alloy Paste; 100-110°C/75 sec Soak/ 175°C Peak/ 60sec TAL

Figure 8. Main Effects Plot for Board Dielectric and Solder Paste

In Figure 10 is shown a box plot for % voids by MCPCB board dielectric type and solder paste alloy. Apparent here is a slight effect of board dielectric type for the different solder pastes, but the trend varies depending on paste alloy. For the Maxrel™ and SAC305 alloy pastes, the type B dielectric results in lower voids percentages, while for the SACX Plus™0807 and SnBiAg alloy pastes the type A board dielectric results in lower voids percentages. The SAC305 solder paste results in the lowest void percentage of the four pastes; this particular solder paste is known for its’ low voiding attribute. Note that all of the solder pastes resulted in <20% voids, meeting the IPC Class 2 voids specification.

Figure 9. Box Plot of %Voids Verses MCPCB Board Dielectric

Figure 10. Box Plot of % Voids versus Board Dielectric Type and Paste Alloy

Figure 11 is a bar chart of void size verses the % of solder joints. Overall, >90% of the solder joints have void sizes that are 0-4% of the solder joint area. The “Zero” value on the x-axis refers to void sizes that are <0.005%.

Figure 11. LED Assembly Void Sizes
Figures 12 and 13 are bar charts of the average and maximum void sizes, respectively, as a function of solder paste alloy and MCPCB dielectric type. For all (4) solder pastes, the type A MCPCB dielectric results in smaller average and maximum void sizes than does the type B dielectric. The low melting point SnBiAg paste results in the smallest average void size, probably because it is reflowed at a lower temperature than the SAC and Maxrel™ alloy pastes. In terms of maximum void size, the SAC305 and SnBiAg alloy pastes are comparable, with maximum void sizes of 10~13% of the joint area.

Table 4 shows typical X-ray voids images and corresponding voids percentages for each solder paste and board dielectric combination.

**SUMMARY AND CONCLUSIONS**

Commercially available solder pastes with (4) different metal alloys were evaluated for % voids in the reflowed joints when used to attach a commercially available LED package on MCPCB substrates having (2) different dielectric types. The SAC305 alloy paste results in the lowest void percentages in the reflowed joints for both MCPCB dielectrics. This particular paste is known for its good voiding performance. Not discussed herein, but key, is the effect of paste flux on voiding.

The effect of board dielectric type on voiding performance is solder paste specific with (2) of the pastes resulting in lower % voids when reflowed on boards with the type A dielectric (SACX Plus™0807 and SnBiAg pastes) and (2) pastes showing better voids performance on boards with the type B dielectric (SAC305, Maxrel™). In terms of average and maximum void sizes, the reflowed joints for the type A dielectric boards are superior for all pastes, and the SnBiAg paste results in the smallest void sizes.

Overall, for all pastes and board dielectric types, >90% of the solder joints had void sizes of 0-4% of the solder joint area and less than 20% voids on average. The SAC305 alloy paste combined with the type B board dielectric results in the lowest % voids (<8.5%).

The boards assembled for this study will be subjected to further tests including electrical measurements, die shear, thermal cycling, thermal shock and solder joint characterization by cross-sectioning (Ref.3).
ACKNOWLEDGEMENTS
The authors gratefully acknowledge the contributions of George Banis (an Intern working with CE) and Esse Leak to this work.

REFERENCES
1. LUXEON® Rebel Board Design and Assembly Application Brief AB32. ©2008 Philips Lumileds Lighting Company.
ABSTRACT
Customer expectations for light emitting diode (LED) based luminaries (Solid State Lighting) are very high due to the relatively high cost of such luminaries. For commercial and outdoor residential applications, a B50, L70 of 35,000 hours and a 3 year warranty is needed to meet EnergyStar Category A requirements. For such high reliability and lifetime requirements, it is critical to have excellent assembly interconnect reliability (i.e. Package to Insulated Metal Substrate attach). This study presents the results of initial work related to understanding the reliability of Solid State Lighting assembly interconnects in a LED Package-Insulated Metal Substrate system.

INTRODUCTION
Applications for light emitting diodes (LEDs) are increasing dramatically in the lighting sector. Their benefits of LEDs over competing technologies include versatility and long-term reliability. Package and luminaire design are critical considerations in ensuring that performance and reliability targets are met for commercial applications.

Customer expectations for LED based luminaries (Solid State Lighting) are very high due to the relatively high cost of such luminaries. For commercial and outdoor residential applications, a B50, L70 of 35,000 hours and a 3 year warranty is needed to meet EnergyStar Category A requirements. For such high reliability and lifetime requirements, it is critical to have excellent assembly interconnect reliability (i.e. Package to Insulated Metal Substrate attach). This study covers the selection of various materials and development of assembly process. The results of initial work related to understanding the reliability of Solid State Lighting assembly interconnect in a LED Package-Insulated Metal Substrate system are discussed along with the process recommendations.
Selection of MCPCBs and Dielectric:
The LUXEON Rebel is a surface mount component and can be assembled on a typical FR4 board or on an MCPCB (Metal Core PCB). MCPCBs are also referred as Metal Clad PCBs. An MCPCB has a thin thermally conductive layer bonded to aluminum or copper substrate for heat dissipation.

Each of the board material has its own benefits and limitations. For example a FR4 board with open or filled and capped vias is a low cost solution for a regular LED assembly. MCPCBs offer more rigidity than a typical FR4 board along with improved thermal performance as all of the SSL packages conduct heat into the board material. An image of the MCPCB is shown in Figure 3. A cross-section of a MCPCB is shown in Figure 4 (Ref 2). Table 1 shows basic details of a typical MCPCB.

In this study we selected an MCPCB with two dielectric materials as described below:

**MCPCB with Dielectric A:** MCPCB with dielectric A minimizes thermal impedance and conducts heat more effectively and efficiently than standard printed wiring boards (PWBs). The low thermal impedance of MCPCB’s outperform other PCB materials and offers a cost effective solution, eliminating additional LEDs for simplified designs and an overall less complicated production process.

**MCPCB with Dielectric B:** Dielectric B is a low modulus dielectric designed to reduce the strain on solder joints in applications where there is a large CTE mismatch between the surface mount component and the substrate of the MCPCB and a significant combination of temperature range and number of cycles in the application as well as high reliability requirements, while still providing very good thermal performance.

Table 1. Basic details of MCPCB

<table>
<thead>
<tr>
<th>Layer</th>
<th>Thickness</th>
<th>Material</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base Layer</td>
<td>0.020”-0.125” /</td>
<td>Aluminum, Copper, Steel, or</td>
</tr>
<tr>
<td></td>
<td>0.5 –3.2 mm</td>
<td>exotic</td>
</tr>
<tr>
<td>Dielectric</td>
<td>0.003”-0.006” /</td>
<td>Usually includes thermally</td>
</tr>
<tr>
<td></td>
<td>75 -150 micron</td>
<td>conductive electrical insulator</td>
</tr>
<tr>
<td>Circuit Layer</td>
<td>1 oz –10 oz /</td>
<td>One or two-layer copper is</td>
</tr>
<tr>
<td></td>
<td>35 –350 micron</td>
<td>common. More layers can be used</td>
</tr>
</tbody>
</table>

The relationship between the modulus of the dielectric in the MCPCB and the solder over the range of application temperatures that the assembly will be subjected to is a major factor in determining where the strain resulting from CTE mismatch between the surface mount component and substrate will be distributed. The modulus of dielectric A is of the same order of magnitude as most common MCPCB dielectrics available on the market, and as such can be referred to as a ‘standard’ MCPCB material in terms of solder joint reliability.
Selection of solder paste materials:
Two different solder pastes were selected for this study. Details of these solder pastes are:

**Solder Paste A:** A no-clean, lead-free SAC305 alloy solder paste with Type 3 grade solder powder, designed for a broad range of applications was selected for this study. This solder paste has a broad processing window thereby providing excellent print capability performance and high production yields.

**Solder Paste B:** A no-clean, lead-free Maxrel™ based alloy solder paste with Type 3 grade solder powder, that is suitable for fine feature printing application was used in this experiment.

ASSEMBLY PROCESS DEVELOPMENT:
After selection of LED package, soldering and dielectric materials, a robust assembly process was developed. Assembly was performed on the same day for all the test boards and pastes. Table 2 summarizes the SMT equipment that was used for this LED assembly.

<table>
<thead>
<tr>
<th>SMT Equipment</th>
<th>SMT Equipment Details</th>
</tr>
</thead>
<tbody>
<tr>
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<tr>
<td>Reflow Oven</td>
<td>Electrovert OmniFlo 7</td>
</tr>
</tbody>
</table>

**Table 2.** Assembly process equipment

Detailed assembly process parameters are discussed in the following three sections:

Solder Paste Printing:
MPM UP3000 stencil printer was used for solder paste printing. A 5mil thick Ni electroform stencil with 1:1 aperture was selected. Though stencil design can be optimized further, a 1:1 aperture stencil data has initially been generated for setting a baseline data. Stencil print parameters used for both solder pastes are shown in Table 3.

<table>
<thead>
<tr>
<th>Print Parameters</th>
<th>Print Parameter Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Print Speed</td>
<td>1 inch / sec</td>
</tr>
<tr>
<td>Print Pressure</td>
<td>1.5 lbs / inch of blade</td>
</tr>
<tr>
<td>Stencil Release</td>
<td>0.02 inches / sec</td>
</tr>
<tr>
<td>Snap off</td>
<td>0 inches (on contact printing)</td>
</tr>
</tbody>
</table>

**Table 3.** Stencil print parameters

Component Placement:
Universal Instrument’s Advantis pick and place machine with FlexJet head was used for the LED assembly. An off-center pick-up was programmed for the LUXEON Rebel package pick-up and placement. Care was taken to avoid any contact / touching of the nozzle exterior to the silicone lens (LED dome).

Reflow Soldering:
An Electrovert OmniFlo 7 reflow oven, with seven heating zones and two cooling zones was used for the reflow assembly. All boards were assembled in an air atmosphere. A straight ramp reflow profile with a peak temperature of 240°C was used for both solder pastes. Please refer to Figure 5 for the reflow profile details.

FUNCTIONAL AND RELIABILITY TESTING
A comprehensive evaluation of the assembled LEDs has been undertaken. This evaluation includes both functional, mechanical and reliability testing of the assembled LED packages. The comprehensive test matrix being investigated is shown in Table 5. This paper presents results from the air to air thermal cycling tests.

1. **Electrical Measurements:**
   **Test description:** Electrical measurements were performed on the as assembled (as soldered) LED packages. Measurements were performed after boards went through air to air thermal cycling test.

   **Test method:** A power supply with the output set at 3V and the current limited over 1 Amp was used to perform the testing. Measurements were done on as soldered boards and on the boards that went through thermal cycling every 100 cycles.
Figure 5. MCPCB Straight Ramp Profile - 1.2C/s 240°C Peak 55s TAL

<table>
<thead>
<tr>
<th>Probes</th>
<th>Positive Rise (°C/min)</th>
<th>Positive Slope (°C/min²)</th>
<th>Raw Time (180°C - 175°C) (min)</th>
<th>Time Above Liquidus (215°C) (min)</th>
<th>Peak Temperature (°C)</th>
<th>Delta T (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>#1: W04LED BPA</td>
<td>2.87</td>
<td>0.47</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>#1: W04LED BPA</td>
<td>2.72</td>
<td>0.45</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
</tbody>
</table>

Table 5. Test matrix for functional, mechanical and reliability testing

<table>
<thead>
<tr>
<th>TEST NAME</th>
<th>TEST DESCRIPTION</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Electrical measurements</td>
<td>'Initial Amperes’ measurement</td>
</tr>
<tr>
<td></td>
<td>Initial LEDs (as assembled)</td>
</tr>
<tr>
<td></td>
<td>After thermal cycling</td>
</tr>
<tr>
<td></td>
<td>After thermal shock</td>
</tr>
<tr>
<td>2 Voiding analysis</td>
<td>Voiding performance for each solder paste on two dielectric materials</td>
</tr>
<tr>
<td>3 Thermal cycling analysis</td>
<td>Thermal cycling air to air analysis</td>
</tr>
<tr>
<td></td>
<td>-40°C to 125°C, 1000 cycles with dwell time of 30 minutes</td>
</tr>
<tr>
<td>4 Thermal shock analysis</td>
<td>Thermal shock liquid to liquid analysis</td>
</tr>
<tr>
<td></td>
<td>-40°C to 105°C, 1000 cycles with dwell time of 30 minutes</td>
</tr>
<tr>
<td>5 Solder joint characterization</td>
<td>Cross sections of LEDs and IMC measurements:</td>
</tr>
<tr>
<td></td>
<td>Initial LEDs (as assembled)</td>
</tr>
<tr>
<td></td>
<td>After thermal cycling</td>
</tr>
<tr>
<td></td>
<td>After thermal shock</td>
</tr>
<tr>
<td>6 Mechanical testing</td>
<td>Package shear:</td>
</tr>
<tr>
<td>(Package shear)</td>
<td>Initial LEDs (as assembled)</td>
</tr>
<tr>
<td></td>
<td>After thermal cycling</td>
</tr>
</tbody>
</table>
**Test results on as assembled boards:**

![Main Effects Plot for Initial Amps](image)

Figure 6. Initial Amperage for different solder pastes and board dielectrics

Figure 6 shows the main effects plot with electrical measurements on as assembled boards. The solder pastes appear to have a greater effect on amperage than the dielectric material.

2. **Thermal Cycling Analysis:**
   **Test description:** For reliability study, air to air thermal cycling was performed on the assembled boards.

   **Test details:** Assembled boards were placed in a Thermotron thermal cycling chamber for reliability studies at -40°C to 125°C, with 30 minute dwell time. Electrical measurements were undertaken with a power supply with a voltage limit of 3.0 volts and a current limit of 2 amps at 0 cycles and then every 100 cycles. Working LEDs were considered as passing, and non-working or dark LEDs were considered failing.

   **Test results and observations:**

   ![Air to Air Thermal Cycle](image)

   Figure 7: Thermal cycles as measured in the Thermotron environmental chamber

   Figure 8 shows the failure rate as a function of the number of thermal cycles of combinations of MCPCB dielectrics and solders. It is clear that with the lower modulus dielectric, joints with both solder paste A and solder paste B show almost no failures over 1000 cycles. With the higher, modulus dielectric, joints with solder paste B with Maxrel™ alloy show much lower failure rates than those with solder paste A with SAC305 alloy.

3. **Solder Joint Characterization:**
   **Test description:** For solder joint characterization, as assembled boards were cross sectioned for microstructure and IMC measurement analysis.

   **Test details:** IMC measurements on the MCPCB A and MCPCB B were performed on as assembled boards for both solder pastes used. SEM images of the cross-sections for both solder pastes were taken and are shown in Figure 9. All IMC measurements are in microns.

   **Test results and observations:**

   SEM images and IMC measurements show:
   - Presence of a continuous Ni layer was noted at the interface of the MCPCB and solder pastes.
   - Both Solder paste A and Solder paste B had similar IMC thickness on MCPCB A (around 1.65 micron). For MCPCB B material, Solder paste A had IMC thickness of 1.3 microns while Solder paste B had IMC thickness of 1.08 microns.

4. **Voiding Analysis, Thermal Shock and Component Shear:**
   Voiding analysis, Thermal shock and Component shear tests are currently underway and will be published in Phase II of this work.
CONCLUSIONS AND SUMMARY
From the test results, one can conclude that:
1. The creep resistance of the solder is a significant factor in minimizing failures in solder joints due to strains incurred in thermal cycling.
2. The relationship between the modulus of the dielectric to the modulus of the solder over the temperature range in the thermal cycle can be an effective way to manipulate the strain away from the solder joint in thermal cycling, hence reducing failures due to solder joint fatigue.

Further, it is well understood in the literature that the magnitude of the thermal cycle, the geometry of the assembly under test, the CTE mismatch of the materials, and the duration of the dwell time in the thermal cycle (up to the time it takes for creep in the solder joint to be complete) will also have an impact on the device reliability as a function of solder joint fatigue and cracking in thermal cycling. With that understanding, we would expect that:
1. An MCPCB with a copper substrate would put less strain on the solder joint resulting in less damage to solder joints.
2. A smaller magnitude thermal cycle (such as one for indoor lighting applications) should also cause less strain on the solder joint.
3. A shorter dwell time at the extreme temperatures would allow the solder joint less time to creep, resulting in less damage to the joint per cycle.
4. Using a more creep resistant solder material would increase reliability of the solder joints subjected to such cycling.
5. The combination of solder and dielectric materials can be optimized in order to provide the required reliability for a given application.

ACKNOWLEDGEMENTS
The authors would like to thank Proloy Nandi and Anil Kumar K.

REFERENCES
1. ‘LUXEON® Rebel Board Design and Assembly Application Brief AB32 (10/08)’ by Philips Lumileds Lighting Company.
3. ‘Performance and Reliability of Thermal Management Substrates for LEDs’ by Justin Kolbe and Sanjay Misra.

Figure 9. SEM micrographs of solder joints on MCPCB A for Solder Paste A and Solder Paste B
CHARACTERIZATION AND OPTIMIZATION OF BOARD WARPAGE FOR LINEAR LED LIGHTING ASSEMBLIES

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South Plainfield, NJ, USA
Amit.Patel@alphaassembly.com

ABSTRACT
Board warpage in fiber-glass epoxy laminate boards known as “FR” boards, is a familiar phenomenon seen in traditional electronics manufacturing. The growth of the LED general lighting market has propelled the usage of high-aspect ratio boards where the length is significantly greater than the width FR type boards for a variety of applications. A significant percentage of these boards are adopted for linear lighting applications where warpage of the PCBs is most commonly seen.

Warpage, also known as bow, is defined as the deviation from flatness of a board characterized by a roughly cylindrical or spherical curvature. Board warpage leads to stress and defects in the material stack such as weakening/cracking of solder joints, cracking of solder mask, component misalignment and in some cases, such warpage inhibits subsequent processing stages of the assembly.

This paper presents a structured study to characterize the effect of warpage “bow” driven by different assembly process conditions on FR circuit boards with two dissimilar glass-transition properties designed as high aspect ratio linear lighting strips.

Keywords: LED, Linear Lighting, Tube Lights, Solder, Bow, Warpage, Flex.

INTRODUCTION
Linear “tube” lights are one of the most adopted design forms for illumination. Historically, these tube lights have used florescent technology. The applications for linear lighting range across numerous applications from retail, industrial, commercial, and residential lighting. Today, with the realized benefits of Light Emitting Diodes (LEDs), these designs are being converted to this solid state technology.

LED-based linear lighting lamps may look similar to their traditional counterparts on the outside, but differ vastly upon closer inspection:

(I) Materials Stack: Aside from the difference in light sources, the overall material stack varies. Figure 1 depicts a typical completed stack of a linear light strip with a mid-power LED on an FR based printed circuit board (PCB). Despite many types of PCBs in use, from thick Metal Core PCBs, to thin polymer based flexible substrates, the most widely adopted PCBs for linear lighting is FR. An FR based board provides many advantages for the LED lighting industry, primarily, ease of sourcing, flame-resistance, retention of high mechanical and electrical insulation and lastly, and a diverse choice of fabrication designs and material cost advantages.

Figure 1. Cross section of a commercial mid-power LED on FR PCB.

(II) The Process: One of the major differences between fluorescent and LED technology is how the assembly process takes place. LED based lighting systems require a heavier usage of SMT / Wave soldering processes. In the case of linear light systems the construction uses a panelized design to process multiple strips simultaneously. It is ultimately this very process of thermal excursion combined with the material selection that causes warping/bow.

Today, there are several key ways to reduce or eliminate warpage, each having their own advantages and disadvantages: (I) Optimization of assembly process conditions, (II) Mechanically adhering PCBs i.e. with fasteners and or clips and lastly, (III) Modification of material selection and/or design.

1 (Khandpur, 2005)

2 Alpha® Cross Sectional Analysis
For this evaluation, the motivation to evaluate the effects of item (I): the assembly process and its effect on warpage is crucial as this is conventionally, the first article that is examined in the occurrence of warpage. Table 1 summarizes our approach to characterize different types of FR properties under variable process conditions of a soak and straight ramp profiles.

<table>
<thead>
<tr>
<th>Factors</th>
<th>Factor Levels</th>
</tr>
</thead>
<tbody>
<tr>
<td>FR PCB Property</td>
<td>FR – 180 Glass Transition</td>
</tr>
<tr>
<td></td>
<td>FR – 130 Glass Transition</td>
</tr>
<tr>
<td>Processing Temperature</td>
<td>Profile – High (245°C Peak)</td>
</tr>
<tr>
<td>Condition</td>
<td>Profile – Low (180°C Peak)</td>
</tr>
<tr>
<td>Profile</td>
<td>Straight</td>
</tr>
<tr>
<td></td>
<td>Soak</td>
</tr>
</tbody>
</table>

Table 1. 2 Factorial Level Design of Experiment

**ASSEMBLY MATERIALS & COMPONENTS**

**Test Vehicle**
The test vehicles used for this evaluation are designed in-house at Alpha®. The design considerations are based on general market observations. Furthermore, the boards are functional which allows for operational testing. Table 2 summarizes dimensions and general attributes of the test vehicle.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Board 1</th>
<th>Board 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dimensions</td>
<td>460mm x 65mm</td>
<td>460mm x 65mm</td>
</tr>
<tr>
<td>Thickness</td>
<td>0.75mm</td>
<td>0.75mm</td>
</tr>
<tr>
<td>FR-Grade</td>
<td>FR4</td>
<td>FR4</td>
</tr>
<tr>
<td>Filler</td>
<td>Filler</td>
<td>No Filler</td>
</tr>
<tr>
<td>Laminate (T&lt;sub&gt;g&lt;/sub&gt;)&lt;sup&gt;3&lt;/sup&gt;</td>
<td>180</td>
<td>130</td>
</tr>
<tr>
<td>Copper Layer</td>
<td>35µm Thick</td>
<td>35µm Thick</td>
</tr>
<tr>
<td>Surface Finish</td>
<td>OSP</td>
<td>OSP</td>
</tr>
</tbody>
</table>

Table 2. Test Vehicle Summary

**LED Component**
For this study a mid-power package was selected due to its common utilization in indoor linear lighting applications. It consists of a 3535 lead-frame design (3.5mm x 3.5mm). A small notch on the corner of the package marks the cathode side of the emitter package. The anode and cathode both serve as thermal pads for the emitter, with the majority of the heat being conducted through the larger pad, corresponding to the cathode as seen in Figure 2.

![Figure 2. LED Package Rendering Including Solder Footprint](image)

**Solders**
The processing temperature conditions and its effect on different T<sub>g</sub> laminates are largely dictated by alloy selection. A standard SAC305 alloy with a melting point range of 217-221°C and a novel low-temperature Sn-Bi based alloy (SBX02) with a melting point of 138.5°C are used.

**PROCESS AND TEST METHOD**

**Equipment Processing Details**
Table 3 summarizes the SMT equipment used for assembling mid-power LED packages on the test vehicles.

<table>
<thead>
<tr>
<th>SMT Equipment</th>
<th>Equipment Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stencil Printer</td>
<td>DEK Horizon 03iX</td>
</tr>
<tr>
<td>Pick and Place</td>
<td>Fuji NXT II</td>
</tr>
<tr>
<td>Placement Nozzle</td>
<td>Flex Jet nozzle</td>
</tr>
<tr>
<td>Reflow Oven</td>
<td>Electrovert OmniFlo 7 Zone</td>
</tr>
</tbody>
</table>

Table 3. Equipment Process Details

**Reflow Soldering**
A reflow oven with seven heating and two cooling zones was used for the reflow assembly. All boards were assembled in an air atmosphere with the following Temperature/Humidity conditions: 20.4-25.2°C / 16-47% RH. Table 4 summarizes both reflow profiles under low and high temperature conditions.

<table>
<thead>
<tr>
<th>Alloy</th>
<th>Profile</th>
<th>Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>SAC305</td>
<td>Soak</td>
<td>150-200_83s 245°C Peak 63-66s</td>
</tr>
<tr>
<td>SAC305</td>
<td>Straight</td>
<td>150-200_60s 244°C Peak 62-65s</td>
</tr>
<tr>
<td>SBX02</td>
<td>Soak</td>
<td>150-180_30s_180°C Peak 76s</td>
</tr>
<tr>
<td>SBX02</td>
<td>Straight</td>
<td>150-180_27s_179°C Peak 76-80s</td>
</tr>
</tbody>
</table>

Table 4. Reflow Process Conditions

**Test Method**
A variety of test methods and procedures exist to measure the deviation from flatness. This evaluation uses the IPC 650TM 2.4.22 methodology, Figure 3 describes the procedure of measuring the subject. The linear lighting test vehicles are laid on a flat surface with all four corners making contact, using a filler gauge, the highest point from the surface is

---

<sup>3</sup> Glass Transition Temperature
measured which is approximately at the center. The same procedure is repeated for each board that has undergone reflow. The values are recorded as a difference between pre-assembly and post reflow assembly.

It is evident that low temperature processing using SBX02 alloy produces lower levels of warpage when compared to standard SAC assembly. Now, the effect of processing temperatures with laminates of different $T_g$ properties are investigated in Figure 6.

Interestingly, we observe that linear boards built with laminates using the 130°C $T_g$ property produces lower levels of warpage when compared to 180°C $T_g$. We hypothesize that the influence of CTE interaction plays a more significant role. The combination of low temperature SBX02 alloy and 130°C $T_g$ produces the lowest level of warpage.

**RESULTS AND CONCLUSIONS**

**Results**

The interaction between the factors and their effect on warpage can be seen in Figure 4 below. Processing under lower peak temperature of 180°C driven by the use of the SBX02 alloy produces the lowest levels of warpage. Secondly, the type of profile used - Straight vs. Soak has minimal effect on this particular assembly. Lastly, the laminate system with glass transition temperature ($T_g$) of 130°C generated lower levels of warpage.

Overall, with the exclusion of the $T_g$ property, the use of low temperature SBX02 alloy produces a 38% reduction in warp as seen in Figure 5.

**Conclusions and Summary**

Board warpage leads to stress and defects in the material stack such as weakening/cracking of solder joints, cracking of solder mask, and component misalignment. In some cases, it can inhibit subsequent processing stages of the assembly.

It is clear that using lower processing temperatures can reduce warpage by 38% as shown in this evaluation. This is ultimately driven by the selection of low versus high melting point alloys. End-use environment and application needs to be carefully considered when attempting to convert to different alloys. In the case of indoor linear lighting using mid power LEDs on FR boards: it is feasible to use Sn-Bi based alloys such as SBX02 alloy.
ENABLING THE USE OF PET FLEXIBLE SUBSTRATES FOR LED LIGHTING APPLICATIONS

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Brent Sweitzer, James Toonen, Bob Hanson
Multek
Northfield, MN, USA
Brent.Sweitzer@Multek.com

ABSTRACT
This paper presents a structured study covering the assembly of mid power LED packages on thermally conductive polyethylene terephthalate (PET/Polyester) and polyimide flexible substrates. The study evaluates the feasibility of using PET as a low cost, low temperature alternative with SnBi Alloy to traditional polyimide with SAC based alloy assemblies. Initially, an assembly method was developed for both polyimide and PET based substrates. In order to validate the use of PET as an alternative to polyimide substrates, electrical testing, voiding, and thermal cycling tests were conducted. The results of processability and long term reliability of using low temperature solders (SnBi based SBX02 alloy) on PET versus traditional SAC 305 on polyimide are presented in this paper.

Keywords: SSL, LED, Low Temperature Assembly, Flexible Circuits, Polyimide and PET Substrates, Sn-Bi, SBX02, Solder Paste.

INTRODUCTION
LEDs are now becoming more prevalent and are being widely used in a variety of applications such as Automotive Lighting, Commercial and Indoor Lighting. Further system cost reductions to enable wider adoption can be achieved by:

- LED package cost reduction through innovative package design and high throughput, high volume manufacturing.
- Substrate cost reduction through reductions in material stack / footprint, improvement in process flexibility and process cost reductions.

Polyimide (PI) is the most commonly used flexible substrate in conjunction with SAC-based Solder Pastes (a melting point of around 218°C). Advancements in Polyethylene Terephthalate [commonly known as Polyester (PET)] flexible substrates, coupled with low temperature assembly of LEDs, can enable further system cost reductions while enabling new design form factors.

This study assessed the feasibility of utilizing PET flexible substrates with low temperature solder paste for Solid State Lighting (SSL).

ASSEMBLY MATERIALS & COMPONENTS
Materials and components were chosen based on commercially available LED packages, solder pastes and flexible substrates.

Mid Power LED package
For this study a 3535 package was selected. It consists of a 3.5mm lead-frame design. A small notch on the corner of the package marks the cathode side of the emitter. The anode and cathode both serve as thermal pads for the emitter, with the majority of the heat being conducted through the larger pad, corresponding to the cathode as seen in Figure 2.

Figure 1. Image of Mid Power LED Package (Refer 1)

Figure 2. LED Package Rendering Including Solder Footprint (Refer 1)

Polyimide (PI) and Polyethylene Terephthalate (PET) Substrates
Flexible circuits allow for a reduced board material stack over rigid boards and are able to provide designers with a higher design freedom in the SSL industry. The increased demand for flex circuits is most noticeable in applications for indoor linear lighting, cabin lighting for automobiles,
backlights for mobile displays, digital cameras and flat panel displays.

There are a number of different materials used as base films for flexible circuits including: polyester (PET), polyimide (PI), polyethylene naphthalate (PEN), Polyetherimide (PEI), etc. Each substrate has its unique electrical, mechanical, chemical and thermal properties. For this study the LED packages were assembled on two base materials, Polyimide (PI) and Polyethylene Terephthalate (PET). Both substrates have a similar thickness and construction comprised of a copper-aluminum composite.

The test vehicle with both substrates was designed in a 9x7 LED matrix. A total of sixty-three (63) LED packages were assembled in this configuration as shown in Table 1. The image of the test vehicle used is shown in Figure 3.

Table 1. Details of the Test Vehicle Substrates

<table>
<thead>
<tr>
<th>Test Vehicle Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polyethylene Terephthalate (PET)</td>
</tr>
<tr>
<td>Dimensions: 18”x12”</td>
</tr>
<tr>
<td>Solder Pad Sites: 63 (9x7)</td>
</tr>
<tr>
<td>Polyimide (PI)</td>
</tr>
<tr>
<td>Dimensions: 18”x12”</td>
</tr>
<tr>
<td>Solder Pad Sites: 63 (9x7)</td>
</tr>
</tbody>
</table>

Figure 3. Substrate Design

A cross sectional view of the PI substrate is shown in Figure 4.

Figure 4. Cross Sectional View of the Flexible Substrate (Polyimide) (Refer 2)

Solder Paste

Lead-free Sn-Ag-Cu pastes are typically used in assemblies utilizing polyimide flexible substrates. Solder Pastes using Sn-Ag-Cu alloys have melting ranges between 217°C and 228°C, requiring reflow temperatures in the range of 245°C to 265°C. Although manufacturers who utilize flexible circuits have adapted to these higher reflow temperatures, a set of very strong drivers is pushing forward the use of lower reflow temperatures in application of LEDs assembled on flexible substrates. The major benefits of using low temperature alloys are: (Refer 3, 4, 5)

- Assembly of heat sensitive packages and components.
- Long-term reliability, as low temperature solders reduce exposure to thermal excursion, warpage and other defects caused by excessive heat.
- Reduced material costs by using low temperature alloy and solder paste, low Tg PCBs and low temperature compatible components.
- Reduced energy costs through lowering temperature processing.
- Higher throughputs by reducing reflow / processing cycle time.

In general, assemblies involving LED components are considered to be temperature-sensitive. Heat induced defects such as browning and softening of the silicone lens, and discoloration of the white solder mask typically utilized in LED assemblies, affects the light output. Furthermore, in case of flexible circuits/assemblies, higher temperatures can cause delamination and warpage of substrates. Low-temperature solders are preferred for these applications. In this study a novel low-temperature Sn-Bi based alloy (SBX02) solder paste is used allowing the assembly of the LED packages to be reflowed under 175°C. Further, a solder paste with a SAC305 alloy was also used as the baseline.

PROCESS AND ASSEMBLY DETAILS

Test Matrix

Based on the package, substrate and materials selected the process involved three key assembly combinations, Figure 5 shows these combinations. First combination involved using a polyimide substrate with a SAC305 solder paste representing the current industry practice. The second combination involved again, a polyimide substrate in conjunction with a low-temperature SBX02 alloy based solder paste. This combination represents the traditional substrate with the low-temperature solder paste. The final combination used a Polyester (PET) substrate with the low-temperature solder paste (SBX02 alloy).

Figure 5. Three Tier Combination of LED assemblies on Flexible Substrates.
Process Details

Table 2 summarizes the SMT equipment that was used for assembling the LED packages onto the substrate combinations.

Table 2. SMT Equipment Summary

<table>
<thead>
<tr>
<th>SMT Equipment</th>
<th>Equipment Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stencil Printer</td>
<td>Standard Stencil Printer</td>
</tr>
<tr>
<td>Pick and Place</td>
<td>Standard Pick and Place</td>
</tr>
<tr>
<td>Placement Nozzle</td>
<td>Flex Jet nozzle</td>
</tr>
<tr>
<td>Reflow Oven</td>
<td>Seven Zone Reflow Oven</td>
</tr>
</tbody>
</table>

Solder Paste Printing

Solder paste printing was done using a stencil printer with a 5 mil thick laser cut stainless steel stencil with a 1:1 aperture size to pad size ratio. Stencil printing parameters used for all solder pastes and board combinations are shown in Table 3.

Table 3. Print Parameters

<table>
<thead>
<tr>
<th>SMT Parameters</th>
<th>SMT Process Details (SI Standard)</th>
<th>SMT Process Details (Metric System)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Print Speed</td>
<td>1 inch/sec.</td>
<td>25 mm/s</td>
</tr>
<tr>
<td>Print Pressure</td>
<td>1.25 lbs/inch</td>
<td>0.22 kg/cm</td>
</tr>
<tr>
<td>Stencil Release</td>
<td>0.02 inches/sec</td>
<td>0.508 mm/sec</td>
</tr>
<tr>
<td>Snap off</td>
<td>0 inches (on contact printing)</td>
<td></td>
</tr>
<tr>
<td>Wipe Frequency</td>
<td>Dry wipe after each print</td>
<td></td>
</tr>
</tbody>
</table>

Component Placement

A pick and place machine with flex jet head was used for the picking and placing the LED package. Care was taken to avoid any contact of the nozzle exterior with the LED domed silicone lens.

Reflow Soldering

A reflow oven, with seven heating and two cooling zones was used for the reflow assembly. All boards were assembled in an air atmosphere with the following Temperature/Humidity conditions: 20.4-25.2°C / 16-47% RH. All of the substrates used in the study were pre-baked before going under their respective reflow conditions. The table below and Figure 6 summarizes the reflow conditions for each combination.

Table 4. Reflow Parameters

<table>
<thead>
<tr>
<th>Substrate + Solder Paste</th>
<th>Reflow Conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polyimide + Lumet™ P39 SAC305</td>
<td>High Soak 150-200C/105s 245C Peak 68-75s TAL</td>
</tr>
<tr>
<td>Polyimide + Lumet™ P53 SBX02</td>
<td>Low Soak 100-120C/104s 175C Peak 65s TAL</td>
</tr>
<tr>
<td>PET + Lumet™ P53 SBX02</td>
<td>Low Soak 100-120C/104s 175C Peak 65s TAL</td>
</tr>
</tbody>
</table>

RESULTS AND DISCUSSIONS

After the final assembly, multiple tests were undertaken:

1. Electrical testing of the assembly in the “light on” mode was conducted by measuring the current across each board and paste combination. This verifies proper assembly and functionality of the circuits in the as assembled state.
2. A voiding study was conducted by X-Ray analysis to study the performance of SAC305 and SBX02 on both PET and Polyimide.
3. A cross section analysis was conducted to examine the characteristics of the solder joint in the as assembled state.
4. The study evaluated the reliability of each assembly by exposing all of the paste and substrate combinations to thermal cycling. “Light on” current measurements and cross sectional analysis were recorded for 250 to 1000 cycles. The thermal cycling conditions used were -40°C to +85°C with a 30 minute dwell time.

Light On Current Measurements and Results

A light on current test was conducted to ensure the LED packages both on PET and Polyimide were operational. Using a commercially available power supply with a constant input voltage of 25V, the current across each circuit was recorded as shown in Figure 7. Each substrate was tested visually to ensure the LED lit for a minimum of 3 seconds as seen in Figure 8.
The current measured across each circuit produces a low variation from the mean. A significant decrease in current would indicate an increase in resistance. The light output test confirmed that all combinations of the LED circuits passed the reflow processing conditions. Furthermore, the LED circuit shown in Figure 8 lit up confirming there are no failures within the assembled LED package, solder layer or board circuitry.

Voids Measurement and Results

Voids can reduce the overall rate of heat transfer between the LED package and board. This reduction of heat transfer efficiency can cause the LED to degrade much quicker. This can lead to:

- Reduced solder joint integrity which lowers overall life expectancy / reliability of the LED.
- Inefficient manufacturing process with reduced first pass yields.
- Higher costs due to scrapped materials i.e. boards, LED packages, and solder.

An X-ray machine was used to measure the voids percentages (by area) of the reflowed solder joints. A total of 40 randomly selected solder sites for each solder paste and board combination were evaluated.

A typical example of an individual site on PET with SBX02 under X-Ray inspection can be seen below in Figure 9. Void % by pad and total void % were analyzed.

Figure 9. Void % by Total Area

Figure 10 shows a box plot for percent voids per total pad area for the 3 combinations of paste and substrate type. It shows that overall, the percentage of voids are under 10%. PET in conjunction with the use of SBX02 solder paste produces the least amount of voids as seen in Table 5.

<table>
<thead>
<tr>
<th>Combination</th>
<th>Mean Void %</th>
<th>Standard Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>PET + Lumet™ P53 SBX02</td>
<td>5.82</td>
<td>1.97</td>
</tr>
<tr>
<td>Polymide + Lumet™ P39 SAC305</td>
<td>7.23</td>
<td>3.64</td>
</tr>
<tr>
<td>Polymide + Lumet™ P53 SBX02</td>
<td>8.46</td>
<td>2.43</td>
</tr>
</tbody>
</table>

The average percentage of voiding in all 3 combinations falls below 10%. The maximum size of a single void including their respective sum of standard deviation for any combination falls below 10.89%.

Solder Layer Measurements and Results

Cross section analysis of the assembled LEDs is presented below; Examples of PET and polyimide using SBX02 are shown in Figures 11A, B and 12A, B below. Polymide using SAC305 are shown in Figures 13A, B. Figures 11A, 12A and 13A correspond to a general cross section profile of the assembled LED package, while 11B 12B and 13B shows the edge view (fillet) of the solder joint structure.
The solder joints exhibited excellent fillet. No visual cracking was observed across all 3 combinations.

**Thermal Cycling Measurement and Results**
Reliability plays an important role in applications of LED devices, modules and systems. To understand the reliability performance of each combination, assemblies were exposed to thermal cycling. All board and paste combinations were placed in a thermal cycling chamber at -40°C to +85°C, with 30 minute dwell time. Each assembled combination was evaluated in light on state by recording the current across each circuit (Figure 14).
Figure 14. Current across each board and paste across 250 to 1000 cycles at [-40°C + 85°C]

<table>
<thead>
<tr>
<th>Combination</th>
<th>Mean Current at 1000 Cycles</th>
</tr>
</thead>
<tbody>
<tr>
<td>PET + SBX02</td>
<td>31.20 mA</td>
</tr>
<tr>
<td>Polyimide + SAC305</td>
<td>31.40 mA</td>
</tr>
<tr>
<td>Polyimide + SBX02</td>
<td>31.00 mA</td>
</tr>
</tbody>
</table>

A total of 5 circuits of each board and paste combination were analyzed by recording the current at a constant input voltage of 25V for 250 to 1000 cycles. The ANOVA results show that the average current recorded is in statistical range (P value of 0.61) of the current measurement mean calculated in Figure 7 (31mA) which is considered to be initial (T0). The results at 1000 cycles conclude there is no significant change in the current across the assembled combinations.

SUMMARY
1) PET with Lumet™ P53 solder paste with SBX02 alloy can be used as an alternative to Polyimide with SAC305 based solder pastes, for LED assembly in certain solid state lighting applications.
2) All of the assembled packages passed the “light on” current test indicating that there are no failures within the solder joint, LED package itself or board circuitry as assembled.
3) The X-Ray inspection showed minimal voiding percentages that meet or exceed typical SSL industry requirements.
4) All of the assembled paste and substrate combinations using mid-power LED packages were able to withstand 1000 cycles at -40°C to +85°C with a 30 minute dwell time.

In conclusion, PET substrates coupled with low temperature solder enabled LED assembly provide several advantages, such as:
1) Enabling system cost reduction by using a lower cost board and assembly material stack.
2) Enabling lower energy costs through low temperature assembly.
3) Enabling the use of SAC solder based LED die attach.

REFERENCES
[1] Ref 1 - “LUXEON 3535L, Assembly and Handling Information – AB203”
[4] Ref 4 - Ribas Morgana, Chegudi Sujatha, Kumar Anil1, Pandher Ranjit, Mukherjee Sutapa, Sarkar Siuli1, Raut Rahul and Singh Bawa “Low Temperature Alloy Development for Electronics Assembly”
[5] Ref 5 - Morgana Ribas, Ph.D., Sujatha Chegudi, Anil Kumar, Sutapa Mukherjee, Siuli Sarkar, Ph.D. Ranjit Pandher, Ph.D., Rahul Raut, Bawa Singh, PhD, “Low Temperature Alloy Development for Electronics Assembly – Part II SMTAI-2013”
ABSTRACT
The LED lighting industry and indeed, the electronics industry, prefers to have "shiny solder joints", indicated by a qualitative visual examination. No metrics exist to quantify "shininess" of the solder joints. This paper presents the concept of reflectivity as a metric to quantify "shininess" of the joint. A novel approach to quantifying "Reflectivity" of solder alloy joints has been developed and implemented.

Reflective properties of assembled solder alloy joints are seldom analyzed. However, in new market applications such as LED lighting, the ability to quantify the reflectivity of alloys can provide greater value. The techniques developed by Alpha are presented in this study allow designers and manufacturers the ability to quantitatively assess aesthetics of the solder joints, impact of flux residue and select materials that provide a performance and cost of ownership advantage.

In this study, differing solder alloys and flux chemistries are examined for their relative reflectivity. Both alloys are assembled under identical conditions to minimize statistical variation. Using a commercially available spectrometer system the alloys are analyzed and compared to a calibrated mirror.

Investigation of solder alloys of dissimilar flux chemistries and alloys reveals a significant reflectivity difference. The methodology of the experiment and results are discussed in this paper.

Keywords: LED, Reflectivity, Solder, Cored Wire, Brightness, SAC305

INTRODUCTION
Solder joints are seldom quantified for their reflectivity properties. Traditionally, solder joints are characterized visually for their “shininess/glossiness”. With the emergence of new markets such as the LED industry the implications of quantifying attributes such as solder shine and flux residue by means of reflectivity can provide greater value.

Joints soldered with cored wire are consumed in abundance for many different lighting applications. Most commonly, these spools of solder are used to assemble the connection between the control power driver board to an LED engine array fixture, board to board connections for linear lighting and serve as the electrical gateway for Edison socket-based bulbs as shown in Figure 1.
The motivation for running two different evaluations is to ultimately test the sensitivity of Alpha’s technique to quantify reflectivity. The first phase (Evaluation-1) asks the question if the technique of quantifying reflectivity is capable of discerning between two alloys which are fundamentally dissimilar in visual appearance. [1] The second evaluation attempts to quantify the difference between two of the same family of alloys with dissimilar rosin-based flux chemistries, ultimately measuring the influence of flux on the reflectivity of the alloy.

ASSEMBLY MATERIALS & EQUIPMENT

Cored Solder Wire
The alloys evaluated in this study are tin-copper and SAC (tin-silver-copper) based alloys. The alloys are in the form of a cored solder wire with a continuous core of 2% rosin flux.

High Precision Solder Feeder
In order to compare different flux chemistries and different alloys of cored solder wires it is crucial to reduce as much variable noise from the assembly as possible. An automated high precision solder wire feeder is used to reduce the variation. The solder wire feeder allows (I) the precise amount of solder wire weight to be deposited onto the test cap coupon and (II) ensures the rate of solder deposited is consistent throughout the entire assembly removing the need to manually assemble the caps.

Substrate / Coupon Cap
A brass cap component treated with the process of electroplated nickel is used as shown in Figure 3. A key factor in testing the reflectivity of the proposed solder alloys is to have a consistent surface structure. A variety of different coupons / substrates were tested to generate the most consistent and even solder surface morphology. Once assembled, the cap structure used in this study produced, along with other factors explained in the other sections of this paper, the lowest variation in the morphology of the solder structure.

Soldering Station
A digital soldering station with an adjustable solder tip temperature was used to conduct assemblies at various solder iron tip temperatures.

Spectrometer, Light Source and Probe
The human eye perceives specular reflection as a continuum from dull to shiny. This is a subjective, qualitative measurement. However, an optical reflectance meter measures spectral reflectance via the ratio of incident to reflected light from a surface. In this way spectral reflectance can be measured more accurately and quantitatively than by a human.

The experimental apparatus consists of a commercially available tungsten-halogen lamp connected via fiber optic to a reflectance probe and a spectrometer with a wavelength range of 350-1000 nm.[2] The probe is a 6-around-1 bifurcated fiber bundle with six incident fibers and one return fiber. A neutral density filter is used to reduce the light intensity in order to match the dynamic range of the detector.

Calibration
Initial calibration is performed against a NIST-traceable aluminum-on-fused silica mirror. In this way the reflectance measurements of various samples are compared to a common, known standard. The reflectivity of the mirror used in this study was ~87 – 93% in the visual range.

PROCESS AND TEST METHOD

Sample Processing
Reducing the variability of the assembly process is crucial. There are important factors which need to be controlled when attempting to form a consistently even solder surface. This is important because the reflection analyzing system is sensitive to surface morphology. [3] The largest sources of noise when soldering the test cap coupons are: (I) the rate at which the solder is reflowed onto the substrate, (II) the weight of solder and (III) the temperature of the solder iron. These noise factors were controlled in the following manner: (I-II) a high precision automatic solder-wire feeder enabled the precise amount of 0.5grams of solder wire length to be fed onto the end cap at a rate of 10mm/s. A total of 15 caps were soldered for each alloy to produce a good statistical sample size.
The assembly of the samples used a digital soldering station with an adjustable dial to vary the solder iron tip temperature. The solder iron tip was validated during the assembly of each cored wire assembly. The end caps were assembled at three tip temperatures: 650, 750, and 800°C.

**Test Method**

A custom built fixture is designed to ensure (I) repeatability of the assembled coupon caps against the reflection probe and (II) further minimize the ambient light entering the probe during testing. The soldered samples are placed at a fixed distance from the probe to emit a beam of light that covers no more than the solder surface of 10mm in diameter. The halogen light source transmitted through a neutral density filter emits light on to the soldered end cap via a bifurcated fiber optic probe which serves as both a transmitter and receiver. The receiving end of the probe collects the amount of visible light reflected back and is analyzed through the spectrometer’s software which ultimately provides a reflective percentage calibrated against a mirror. Figure 4 depicts the test setup of measuring the reflective percentage of the soldered samples.

**RESULTS AND CONCLUSIONS**

**Results of Evaluation I**

When two different alloys are used the system is able to discern differences in reflectivity between them. The tin-copper alloy produces higher reflectivity at each tip temperature than the SAC305 alloy as shown in Figure 5A and supported by the P-Value in Figure 5B.

<table>
<thead>
<tr>
<th>Solder Iron Tip Temperature</th>
<th>SAC Alloy Identical Flux</th>
<th>Tin-Copper Identical Flux</th>
</tr>
</thead>
<tbody>
<tr>
<td>650°F</td>
<td>7.72</td>
<td>26.33</td>
</tr>
<tr>
<td>750°F</td>
<td>8.37</td>
<td>28.71</td>
</tr>
<tr>
<td>800°F</td>
<td>6.47</td>
<td>31.30</td>
</tr>
</tbody>
</table>

Table 1. Results of Reflection Value Based Off Solder Iron Tip Temperature for Dissimilar Alloys

**Results of Evaluation II**

When analyzing Tin-copper alloys with dissimilar flux chemistries and varying solder iron tip temperatures the results indicate that a significant difference exists in the reflectivity as shown in Figure 6A further confirmed by the P value in Figure 6B.

**Figure 5. Statistical Difference of Reflection Values for Dissimilar Alloys**

![Figure 5. Statistical Difference of Reflection Values for Dissimilar Alloys](image)

**Figure 6. Tin-Copper Alloys with Dissimilar Flux Chemistries Reflective Values**

![Figure 6. Tin-Copper Alloys with Dissimilar Flux Chemistries Reflective Values](image)
<table>
<thead>
<tr>
<th>Solder Iron Tip Temperature</th>
<th>Tin-Copper Dissimilar Flux A</th>
<th>Tin-Copper Dissimilar Flux B</th>
</tr>
</thead>
<tbody>
<tr>
<td>650F</td>
<td>11.22</td>
<td>26.33</td>
</tr>
<tr>
<td>750F</td>
<td>10.04</td>
<td>28.71</td>
</tr>
<tr>
<td>800F</td>
<td>7.63</td>
<td>31.30</td>
</tr>
</tbody>
</table>

Table 2. Results of Reflection Value Based Off Solder Iron Tip Temperature for Dissimilar Flux Chemistries

Conclusions and Summary

Reflective values of assembled solder joints are seldom if at all analyzed in the market place. However, in new applications such as LED lighting, the ability to precisely quantify the reflectivity of alloys can provide important added value and implications.

The technique of using a spectrometer system to scatter visible light onto a soldered sample and measure its reflective value against a standard mirror enables objective comparison between different solder alloys and flux chemistries far better than human perception.

In conclusion, based on the results of measuring both dissimilar alloys and flux chemistries the techniques of measuring solder joint reflectivity developed by Alpha demonstrate that the influence of the assembly processes and choice of materials can affect the reflective values of a final solder joint assembly.

References


