Flip Chip LED Assembly by Solder Stamping/ Pin-Transfer

Impact of Substrate Materials On Reliability of High Power LED Assemblies
Flip chip and Chip Scale Package (CSP) Light Emitting Diodes (LEDs) are being increasingly adopted for applications in TV backlight and mobile flash. Lately they are also being used for automotive interior, street lighting and even and general lighting applications. The advantages of very small form factor, easier optics, improved thermal dissipation and no wire-bond result in unrivaled high lumen density at lower cost.

Eutectic gold tin (AuSn 80/20) is the die attach material of choice for Flip chip LEDs. Lately, there has been a significant effort to make these devices compatible with SMT. However, SMT assembly of these small packages is challenging. Package float and tilt can result in sub-par assembly yields. Flip chip LEDs are tricky because of their rectangular interconnect pads with small gaps (which are getting even smaller). Finally, performance issues like luminous flux degradation due to flux residue and current leakage during reverse bias remain.

In this study, pin transfer (also called stamping) process was adapted to assemble Flip chip CSP LEDs with fine pitch solder paste. Solder reservoir height and die attach conditions were varied to optimize solder spread, voiding and die shear for commercial Flip chip CSPs. Also preliminary results on the effect of cleaning of LEDs (after assembly) on light output and color are also presented.

This study is relevant for LED packaging and LED module assembly makers who use Flip chip for automotive, backlight and general lighting applications.

LED chip structures

There are three main LED chip structures (Figure 1). The Lateral structure consists of laterally spaced electrodes (with one wire-bond 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 Chip-on-Board (CoB) modules.

Flip chip and chip scale package LED

The high lumen density (and low lumen/$) advantage of the Flip chip LED structure (as mentioned above) essentially stems from replacement of the wire-bonds by relatively large area contacts that serve as both electrical and thermal pads. The improvement in heat dissipation allows the chip to be driven at high currents without the need for expensive highly conductive substrate (like CuW) – which, along with reduced defects from absence of the wire-bonds, extends the lifetime. The small form factor (and flat wire-bond free surface) also makes optical design much easier –

- **Figure 1: Common LED structures.**
thereby reducing the cost even further.

Lately there has been a concerted effort by most LED makers to use the Flip chip structure to make a chip-scale package (CSP) with the footprint very close to the flip-chip pads compatible with solder (and SMT reflow process) – especially for COB applications. The idea is to put the solder compatible pads (and sometimes even interconnects) at the wafer-level. The chips can then be picked and placed by either a high precision die bonder (with solder printed or stamped on substrate pads), or preferably, by a regular pick-place machine (also sometimes called a chip shooter) on the SMT line.

The SMT option is very attractive for several reasons. While it adds one step at the back-end (solder pads), it skips the traditional packaging (die attach on a submount substrate and wire-bonding) step completely. As a result the module makers can buy the CSPs and assemble them directly on SMT lines (cheaper equipment with higher throughput).

Experimental

In this study, pin transfer process was adapted to assemble commercially available Flip chip LEDs with solder.

Pin transfer (also called stamping) consists of using a pin (or a set of pins configured to match the footprint of the die) to stamp the solder off a reservoir on to the substrate. The die is then aligned and placed on the substrate (with the solder stamp) and then reflowed. Pin transfer is a very popular for both lateral (mesa) and vertical LED die attach since it is a very high throughput process (up to 10K units per hour), and is SMT compatible. The thin bond line (5-15um typical) ensures lower thermal resistance compared to conventional printing.

ASM pin transfer die bonder ASMD838L was used for the pin transfer with a no-clean solder paste. Commercially available UV Flip chip dies (from Lumileds) were assembled on custom designed silver finish lead frames. Heller 7-stage reflow oven was used to reflow the assemblies. The Flip chip die pads, and the substrate pad are shown in Figure 2, while the reflow profile used is shown in Figures 3.

First the pin transfer stability of solder paste was studied over typical 8-hour work shift with 1x1mm dummy silicon dies (Cr/Ni/Au finish) on FR4 substrate. Paste volume transfer (which translates into bond line thickness control), die shear and die shear failure mode were recorded over 8-hours.

Next the Flip chip dies were assembled on the substrate. Pin transfer reservoir height was varied and fillet size, voiding and die shear were recorded.

The assembled parts were cleaned in an in-line and ultrasonic batch cleaning stations at 60C by Zestron Inc. with different cleaning chemistries. The cleaned and un-cleaned parts were characterized for radiant flux before and after aging (at 150C for 1000 hours). Preliminary, pre-aging results are discussed in this paper.

Results

The pin transfer volume stability for solder paste shown in Figure 5. As can be the seen the variation in the volume over 8 hours is maximum 15% (difference between maximum and minimum volumes deposited at 1 hour intervals over 8 hours). This translates into ~2 micron variation in bond-line-thickness.

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Figure 6: Bond Line Thickness variation over 8 hours.

Figure 7: Solder weight variation over time during 8-hour pin transfer over 8-hours.

Figure 5: Bond Line Thickness variation over 8 hours.

Table 1: Process outputs variation with paste reservoir height.

<table>
<thead>
<tr>
<th>Attribute</th>
<th>200 um Reservoir</th>
<th>300um Reservoir</th>
<th>400um Reservoir</th>
</tr>
</thead>
<tbody>
<tr>
<td>Paste Transfer</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Die Placement Wet</td>
<td>No squeeze out</td>
<td>Little / inconsistent squeeze out</td>
<td>Minor squeeze out</td>
</tr>
<tr>
<td>Cured Paste without Die</td>
<td>No proper</td>
<td>Good coalescence</td>
<td>Good coalescence, Optimal paste volume</td>
</tr>
<tr>
<td>MCSB</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Coverage</td>
<td>90%</td>
<td>100%</td>
<td>100%</td>
</tr>
<tr>
<td>Cured Die</td>
<td>No fillets</td>
<td>Inconsistent Fillet</td>
<td>Uniform Fillet</td>
</tr>
<tr>
<td>Void</td>
<td>Very High</td>
<td>~ 20%</td>
<td>10-20%</td>
</tr>
<tr>
<td>Die Shear</td>
<td>1.5 kg</td>
<td>2.5 kg</td>
<td>4 kg</td>
</tr>
</tbody>
</table>

Table 2: Process outputs variation with paste reservoir height.

<table>
<thead>
<tr>
<th>Attribute</th>
<th>500 um Reservoir</th>
<th>600um Reservoir</th>
<th>700um Reservoir</th>
</tr>
</thead>
<tbody>
<tr>
<td>Paste Transfer</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Die Placement Wet</td>
<td>60 um squeeze out</td>
<td>80-120 um squeeze out</td>
<td>80-120 um squeeze out</td>
</tr>
<tr>
<td>Cured Paste without Die</td>
<td>Good coalescence</td>
<td>Good coalescence</td>
<td>Good coalescence, Excess paste volume</td>
</tr>
<tr>
<td>MCSB</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Coverage</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
</tr>
<tr>
<td>Cured Die</td>
<td>Fillets ~ 60 um</td>
<td>Fillets ~ 80-120 um</td>
<td>Fillets ~ 80-120um</td>
</tr>
<tr>
<td>Void</td>
<td>8 to 15%</td>
<td>5 to 12%</td>
<td>5 to 12%</td>
</tr>
<tr>
<td>Die Shear</td>
<td>&gt; 4 kg</td>
<td>&gt; 4 kg</td>
<td>&gt; 4 kg</td>
</tr>
</tbody>
</table>

Flip Chip LED Assembly by Solder Stamping / Pin-Transfer

The reservoir thickness optimization results are discussed next. The bond force had to be kept at the lower end of the bonder range (30-50 grams) to prevent excess squeeze out while the bonding time was kept as low as possible to ensure high throughput. Hence the reservoir thickness optimization becomes a key to ensure that there is no bridging between the p & n pads while at the same time there is enough solder volume for adequate die shear strength for reliability. Flip chip LEDs active light emitting areas are close to the bottom of the die and it is important to ensure that the interconnect material (solder in this case) does not block the light from these active regions.

Figures 7 shows the transferred solder paste, squeeze out after die placement and x-ray of the die-substrate assemblies at different reservoir heights before solder reflow. The assemblies after reflow are shown in Figure 8. It is important to note that at all reservoir heights, the solder squeeze out in-between the die pads was contained and there was absolutely no bridging (as clearly seen in x-ray shots).

At the lowest reservoir height (200um), the volume of solder transferred was inadequate to cover the entire pad area and did not coalesce to form a uniform interconnect layer between the die and the substrate. The distinct circular deposits of wet solder (BLT) over 8 hours – which meets the spec for almost all applications (see Figure 6 for the measured BLT variation).

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at can be seen both before and after the reflow. For 300um height setting, the paste did coalesce, however, the spread around the pad was non-uniform.

On the other end, higher reservoir heights (600-700um), resulted in excessive volume transfer that excessive spread around the pad and may block the light emitting regions (or block the reflective pad on the substrate thereby indirectly reducing the light extracted).

The volume of transferred solder also results in different levels of die shear and voiding. Excessive solder (from a thick reservoir height), although not desirable for active light emission, does help reduce the voiding and increase the die shear strength. The low volume transfer (off the lower reservoir heights, especially 200-300um) resulted in higher voiding and lowest die shear.

Table 1 summarizes the process outputs like die shear, voiding, fillet, coalescence, mid-chip solder balling etc. as a function of reservoir height.

It is important to note that the intermediate reservoir height settings (at 400-500um) gave the optimal balance between coverage (which impacts die shear and voiding), coalescence and fillet spread.

The effect of cleaning of the assemblies on radiant flux is shown in Figure 10. The measurements clearly indicate that radiant flux output is significantly higher for the cleaned assemblies irrespective of the chemistries used. The radiant flux for the best-cleaned assemblies is of the order of 15% higher than the un-cleaned ones.

It would be interesting to track the change in radiant flux for these assemblies during the high temperature aging at 150°C. Those results would be presented elsewhere.

Summary / conclusion
Pin transfer / stamping process was successfully adapted for high throughput assembly of Flip chip LEDs. The paste volume was optimized to achieve high die-shear, low voiding and minimal spread-out for highest light extraction. Solder paste stability over 8-hours of the stamping / pin transfer process was also demonstrated.

Preliminary functional performance testing of the assembled UV LEDs suggest that cleaning after assembly can have significant positive impact on the radiant flux output.

ACKNOWLEDGMENT
The authors appreciate the help of Ravi Parthasarathy and Christine Anderson of Zestron Inc. (located in Manassas, Virginia, USA) towards cleaning of the flip-chip assemblies with different cleaning chemistries on Zestron cleaning equipment.
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New high power LED package designs provide high lumen density that can enable significant system cost reductions through fewer LEDs and smaller PCBs. The materials stack determines the CTE mismatch between the high power LED ceramic sub-mount and the substrates (including Metal Core PCB or FR4 substrate types). Choice of the substrate can impact reliability of the solder joints in thermal shock/cycling. One of the key questions is: What role does the substrate type play in the LED package-to-board assembly reliability? This paper presents a study to help answer this question. Assembly of high power ceramic sub-mount LEDs was conducted with both aluminum MCPCB and FR4 substrates with multiple solder alloys. Thermal cycling was conducted under the conditions of -40°C to 125°C for 1000 cycles. Solder joint strength was measured at multiple intervals during thermal cycling by conducting package shear. The impact of substrate type is quantified for multiple solder alloys and failure mechanisms that impact reliability for a given substrate are discussed.
ant properties of a few common materials used in high power LED substrates and circuit boards [4]. Al-core and Cu-core MCMPCBs have the best thermal conductivity. Even though the thermal conductivity of the substrate material determines its heat dissipation capability, other properties such as CTE and strength and modulus of the material will determine its long-term performance in high stress situations.

**Experimental details**

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

<table>
<thead>
<tr>
<th>Substrate Materials</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>FR-4</td>
<td>Epoxy / Fiber Glass</td>
</tr>
<tr>
<td>AL MCMPCBs</td>
<td>TC LM</td>
</tr>
<tr>
<td>AL MCMPCBs</td>
<td>TC MP</td>
</tr>
</tbody>
</table>

**PACKAGE - OSLON LED**

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

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

Details of the package used are as follows:
- Thin GaN Technology
- Part Number: LXW CNAP
- Type: LMW CNAP-6J7K-37-DF-LH

**SOLDER PASTES**

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

<table>
<thead>
<tr>
<th>Solder Paste</th>
<th>Solder Alloy</th>
</tr>
</thead>
<tbody>
<tr>
<td>NC Paste #1</td>
<td>SAC305 Type 4</td>
</tr>
<tr>
<td>NC Paste #2</td>
<td>HR Pb-Free Alloy Type 4</td>
</tr>
</tbody>
</table>

**Table III: Solder Paste details**

**Test Factors/Variables**

<table>
<thead>
<tr>
<th>PCB Substrates</th>
<th>AL MCMPCBs (TC MP)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solder Paste</td>
<td>NC Paste #1 (with SAC305 Alloy)</td>
</tr>
<tr>
<td></td>
<td>NC Paste #2 (with HR Pb-Free Alloy)</td>
</tr>
<tr>
<td>Reflow Profile</td>
<td>260°C LV</td>
</tr>
</tbody>
</table>

**Constant Factors**

<table>
<thead>
<tr>
<th>Reflow Environment</th>
<th>N2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Package</td>
<td>Osram Oslon</td>
</tr>
</tbody>
</table>

**Figure 1: Oslon LED structure.**

**Figure 2: Primary heat flow in the Oslon Package.**

**SOLDER PASTE PRINTING**

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

<table>
<thead>
<tr>
<th>SMT Equipment</th>
<th>SMT Equipment Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stencil Printer</td>
<td>DEK Horizon 03iX</td>
</tr>
<tr>
<td>Stencil</td>
<td>4 mil Laser Cut Stainless Steel</td>
</tr>
<tr>
<td>Pick and Place</td>
<td>Universal Advantis with FlexJet Head</td>
</tr>
<tr>
<td>Placement Nozzle</td>
<td>234J-FJ</td>
</tr>
<tr>
<td>Reflow Oven</td>
<td>Electrovert OmniFlo 7</td>
</tr>
</tbody>
</table>

**COMPONENT PLACEMENT**

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

**REFLOW SOLDERING**

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

**Figure 3: Reflow profile**
Impact of Substrate Materials On Reliability of High Power LED Assemblies

**THERMAL CYCLING TEST**

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

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

![Figure 4: Temperature Cycling profile.](image)

**Solder Joint Shear Test**

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

**Results and discussion**

**PACKAGE SHEAR TEST DATA**

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

![Figure 5: Package Shear Results - SAC305 solder.](image)

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

As seen in Figures 5 and 6, shear strength of LEDs on FR4 substrates sees almost no change after 1000 cycles while that on MCPCB-MP show a drop by 60% for LEDs assembled with P33-SAC305. The drop in shear strength of LEDs on MCPCB-MP for LEDs assembled with NC Paste # 2 with HR Pb-Free alloy is about 20%.

![Figure 6: Package Shear Results – HR Pb-Free solder.](image)

![Figure 7: Percentage drop in package shear strength after 1000 cycles.](image)

**Cross-section analysis of solder joints**

![Figure 8: NC Paste # 1 with SAC305 on MCPCB-MP after 1000 cycles. Cracks are observed in solder joints for all three pads.](image)

![Figure 9: NC Paste # 2 with HR Pb-Free alloy on MCPCB-MP after 1000 cycles. Small cracks observed in solder joints on only one of the pads.](image)
Figures 8 and 9 show pictures of typical cross-sectioned solder joints.

The cross-section analysis shows that:
- SAC305 alloy joints on MCPCB-MP show cracking after 1000 cycles for all three pads.
- HR Pb-Free alloy joints on MCPCB-MP show only minor cracking (and only on one side of the pad) after 1000 cycles, and crack growth is minimal.

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

Observations and conclusions

Performance of LEDs assembled on three types of the substrates has been compared. Key observations are:
- LEDs on FR4 boards show minimal drop in shear strength irrespective of the solder alloy.
- Due to high mismatch in CTE, the MCPCB-MP substrates show a steep degradation of shear strength upon temperature cycling.
- HR Pb-Free alloy showed highest strength and little drop in shear strength after thermal cycling.
- In thermal cycling test, HR Pb-Free alloy showed stable performance on all types of substrates.

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

ACKNOWLEDGEMENTS

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