Die Attach Materials and LED Functional Performance

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ABSTRACT

Die attach materials play a key role in functional performance and reliability of light-emitting diodes (LEDs). Selection of a suitable die-attach material for a particular chip structure and application depends on several considerations. These include performance (light output and thermal dissipation at operating temperature), reliability (lumen maintenance and mitigation of thermo-mechanical stresses over lifetime), packaging process (equipment, throughput and yield) and cost factors. Eutectic gold-tin, silver-filled epoxies, solder, silicones and sintered materials have all been used for LED die attach. Often, use of a particular material technology results in trade-offs between different performance attributes.

In this study we used different die-attach materials (solder, silver epoxy and silicone-based) to package lateral, vertical and flip-chip LEDs. For vertical and flip-chip structures (which require electrically conductive die attach), solder, silver epoxy and silver-filled silicone materials were used. Lateral dies (on non-metallized sapphire substrates) were bonded with silicones (both conductive and insulated) as well as silver epoxy. The optical and electrical performance of the assembled packages was then characterized by junction temperature, luminous flux and efficacy measurements in an integrating sphere (according to IES LM-79-08).

The paper describes these results and discusses the effect of die-attach material properties and chip structure on LED functional outputs. The results clearly indicate that while optical characteristics of the die-attach material dominate the light output of lateral LEDs, junction temperature management (via die-attach thermal conductivity) is important for achieving optimal functional performance for higher power vertical and flip-chip LEDs.

Key words: LED, Die Attach, Flip-Chip, High Performance, LED Package

INTRODUCTION

LED die packaging still accounts for ~1/3 the cost of the packaged LED. The last few years have seen several trends in LED packaging, namely: 1) flip-chip and chip-scale packaging (CSP) adoption; 2) growth of a packaged mid-power segment (0.2-0.5W) with lateral dies and chip-on-board (COB) modules; and 3) increased focus on infrared (IR) and ultraviolet (UV) LEDs for new applications (with higher power vertical structures). All these trends, with different chip structures, are driven by underlying need for higher efficacy (lm/W), lower cost (lm/$) and longer lifetime in a smaller form factor.

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 package (and the light engine).

With several material technologies available for die attach (like eutectic gold-tin/Au80Sn20, silver based conductive adhesives, solder and silicone-based adhesive), selecting a suitable material for a particular chip structure (lateral, vertical and flip chip) is essentially about making trade-off decisions between different process or performance attributes.

In this study we attached different structure LEDs (lateral, flip chip, and vertical) with different die-attach materials (silver epoxy, solder and silicone). These packages were then subjected to industry standard optical and electrical performance tests.

Die-attach Materials Overview

The descriptions below provide an overview of die-attach materials.

Eutectic gold-tin or AuSn. Euctectic gold-tin (80/20 Au/Sn by wt.) has been the "gold standard" die-attach material for high-reliability applications. For LED die attach it is used either as a pre-coated layer on the LED backside, a preform, or in the form of solder paste. The typical process is flux-less with an automated bonder with scrubbing capability. Lately, AuSn solder paste as well as flux-assisted processes (with pre-coated dies or preforms) have been used for higher throughput. 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 high thermal conductivity (57W/mK) and proven reliability (high creep and fatigue resistance with secondary reflow compatibility).

Conductive adhesives. Conductive adhesives (mostly silver-filled epoxies) constitute the largest class of thermal die-attach materials (by unit number) for semiconductor power packages. They are compatible with the existing back-end packaging equipment and provide an attractive cost/performance balance (typically up to 50W/mK thermal with secondary reflow compatibility). Because they stick to bare silicon, they are the preferred material of choice for dies without back-side metallization (like GaN on silicon).

Solder. Solder (mostly SAC-based) provides exceptional value with low cost and fast assembly process with reasonable thermal performance (50-60W/mK). Lately, there has been a trend to make the flip-chip structure compatible with solder on surface mount technology (SMT) lines. However, because SAC solder melts in the 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 a melting point range between 245-251°C can survive second reflow below 240°C.

Silicone-based adhesives. Silicone-based adhesives (filled with ceramic-based fillers for heat dissipation) have been the die-attach technology of choice for low-mid power sapphire based lateral LEDs. These materials are transparent, have excellent adhesion and high-temperature stability (resistant to color degradation). The stamping (pin transfer) process has been adopted to achieve very thin bond lines at relatively high throughput for LED die attach.

LED die structures overview

This section discusses the experimental elements of our study.

LEDs. For lateral die structure, green LEDs on a sapphire substrate from III-V semiconductor (TCE13-525, 330x330µm) were bonded on a star-shaped extruded copper pedestal. This design did not include a dielectric layer between the die and the die-attach layer and allowed for high-sensitivity thermal measurements of the stack. Because a sapphire die bottom does not have any metallization, it requires an adhesive die attach (like silver epoxy and silicones) and solder was not used to bond the lateral dies.

For vertical dies, red LEDs on silicon (TCO40-624) from III-V semiconductor were bonded on the same star-shaped copper pedestal. Because vertical dies have the metallized p-electrode at the bottom, only conductive die-attach materials (like solder, silver epoxy and silicone filled epoxy) were used.

To evaluate a flip-chip LED, a Luxeon Flip-chip UV (LxF2-U400 from Lumileds) was bonded onto an aluminum core substrate with electroless nickel immersion gold (ENIG) pads. Conductive die-attach materials (solder, silver-filled epoxy and silicone) were used.

Die-attach materials. To evaluate non-conductive materials, two silicone-based materials (Silicone A and Silicone B) were used for lateral die bonding. Both these materials are commercially available and mainly differed in their transparency (with transparency of Silicone B being higher than Silicone A).

Among silver-based conductive materials, one material was a high thermal silver-filled epoxy (Silver Epoxy) and the other one was silver-filled silicone (Silver Silicone) with the thermal conductivity of the silver epoxy being much higher than that of the silver-filled silicone (**Table 1**). Finally, fine T6 powder (15-25 µm particle size) SAC305-based solder paste (T6 Solder Paste) was used for flip-chip and vertical LED die attach (**Table 2**).

Die Structure	Die Attach Materials
Lateral	Silicone A, Silicone B, Silver Epoxy, Silver Silicone
Vertical	T6 Solder Paste, Silver Epoxy, Silver Silicone
Flip-Chip	T6 Solder Paste, Silver Epoxy, Silver Silicone

Table 1: Die attach materials and the type of dies that were bonded

Die Attach	Optical Transparency @ 450nm	Bulk Thermal Conductivity (W/mK)
Silicone A	~80% (5um thick)	0.5
Silicone B	>83% (1mm thick)	0.2
Silicone Epoxy	0	>25
Silver Epoxy	0	60
T6 Solder Paste	0	60

Table 2: Die attach materials properties

Die-attach set-up. Pin transfer (also called stamping) was used to transfer the die-attach material (from a reservoir) onto the substrate. The die was then aligned, placed on the substrate and then reflowed. An ASM pin transfer die bonder (ASMD838L) was used for the pin transfer and die placement. The height of the paste in the reservoir was optimized for full die pad coverage and the desired bond line thickness (BLT). A batch oven was used for curing of silicones (150°C for 1hour) and silver epoxy (175°C for 1 hour). The T6 Solder Paste assembly was reflowed in a 7-stage Heller oven (under N_2 environment).

Optical and electrical characterization. The transient voltage method was used to measure the junction temperature of the LED assemblies. These measurements were based on JEDEC Standard EIA/JESD51-1 and have been described in detail [1-2]. Essentially the method is based on rapidly switching the LED between high and low currents, so as to utilize them as test devices to measure the junction temperature. If the switch between heating and sensing currents happens fast enough, then the sensing current can be used to measure the temperature of the previous heating phase. The thermal resistance of all the layers in the die-attach stack can then be calculated. The relationship between the forward voltage and the junction temperature (also known as the k-factor) was established to calibrate the use of the LED as a temperature sensor.

Measurement of the optical properties of the LED assemblies was done according to IES LM-79-08 [3]. The set-up consisted of placing the LED assemblies in a light integrating sphere with a radiometrically calibrated spectrometer.

RESULTS AND DISCUSSION

The results of the study fall under three main categories, discussed below: 1) Lateral LED; 2) Vertical LED; and 3) Flip-chip LED.

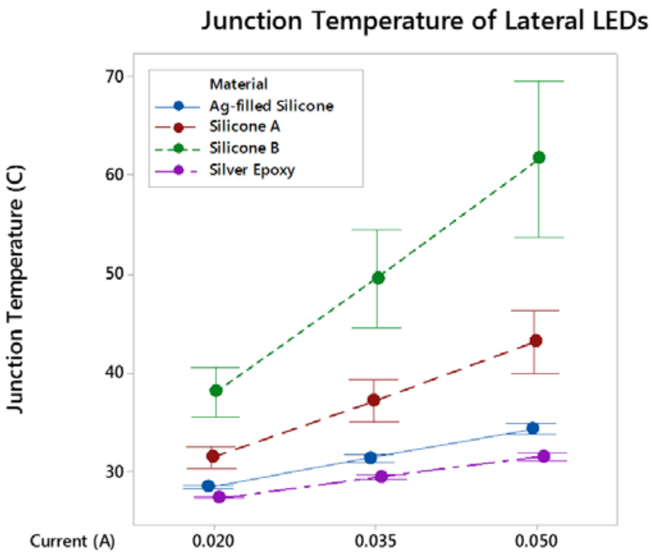

Figure 1: Junction temperature of lateral LEDs assembled with four different die attach materials vs. the operating current.

Lateral LED results. Figure 1 shows the behavior of the junction temperature of the lateral LEDs with increasing current. Lateral LEDs used here do not have any backside metallization. So the choice of die-attach materials eliminated any material that does not stick to non-metallized surfaces, such as solders. Four materials were tested: a silver-filled conductive epoxy, a silver-filled silicone-based adhesive, and two types of non-conducting silicones. Nonconductive silicones were essentially optically transparent, while silver-filled materials are opaque. Among the materials used, silver- filled epoxy has the highest thermal conductivity followed by silver-filled silicone. Unfilled silicones have the lowest thermal conductivity. At any given current, LEDs with silver-filled epoxy show the lowest junction temperature followed by those assembled with silver-filled silicone. Unfilled silicones have much lower thermal conductivity and result in a much higher junction temperature of LEDs assembled with those. Between the two silicones tested, Silicone B has a higher junction temperature.

Figure 2 shows a luminous flux of the same lateral LEDs at three different operating currents. At any given current, silver-filled epoxy shows the lowest luminous flux followed by silver-filled

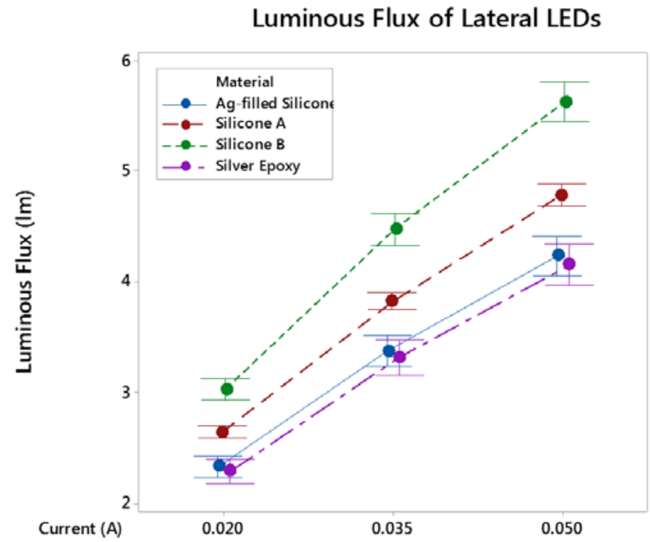

Figure 2: Luminous flux of lateral LEDs assembled with four different die attach materials vs. the operating current.

silicone, Silicone A and Silicone B. These are interesting results showing how the optical transparency affects the overall optical efficiency of the packaged LED. LED quantum efficiency decreases with increasing junction temperature. However, not all of the photons generated by electron-hole pair recombination are extracted as useful light. This is especially true for lateral LEDs. The PN junction of lateral LEDs is grown on a sapphire substrate. Sapphire is partially optically transparent and light generated at the PN junction travels in all directions. To get the maximum efficiency, all of those photons should be collected. Silver-filled epoxy and silver-filled silicone absorb ultraviolet (UV), visible and near infrared (IR) radiation. Therefore, when these materials are used in die attach, the fraction of light traveling towards the substrate is lost. On the other hand, silicones are transparent, therefore all the light traveling in that direction is ultimately reflected back from the metallized substrates. That is why LEDs assembled with transparent silicones show higher luminous flux (and efficacy) even though those LEDs are operating at higher junction temperature as compared to silver-filled opaque die-attach materials. This effect can be seen visually in the pictures of operating LEDs shown in **Figure 3**. Among the nonconductive silicones as well, die-attach assemblies with higher optical transparency Silicone B had higher light flux (compared to Silicone A, even though Silicone A had higher thermal conductivity).

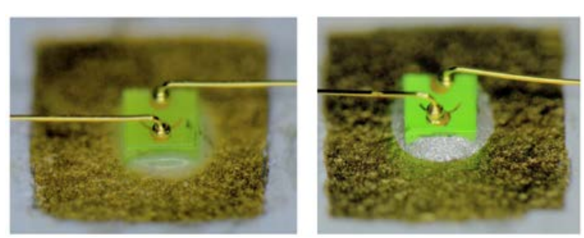

Figure 3: Pictures of operating LEDs assembled with silver-filled epoxy (opaque) and silver-filled silicone (transparent) die attach materials.

Vertical LED Results

Figure 4 shows the vertical LED bonded by silver epoxy. The top side electrode is wire-bonded, while the die bottom serves as the other electrode.

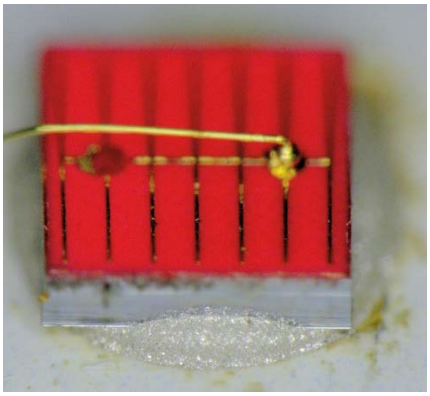

Figure 4: A vertical LED assembled with silver epoxy.

Figure 5 shows the junction temperature of vertical LEDs assembled with three types of die-attach materials: SAC305 solder paste, a silver-filled epoxy and a silver-filled silicone. The plots show junction temperature at three operating currents. In the vertical LED, the current path is through the die-attach layer, therefore, die-attach material has to be electrically conducting. That is why no silicone is used in this part of the experiment. Not surprisingly, the measured junction temperature of LEDs assembled with these materials is in the reverse order of their thermal conductivities. Silver-filled epoxy with thermal conductivity >60W/mk shows the lowest junction temperature at any current, closely followed by solder. Silver-filled silicone shows the highest junction temperature.

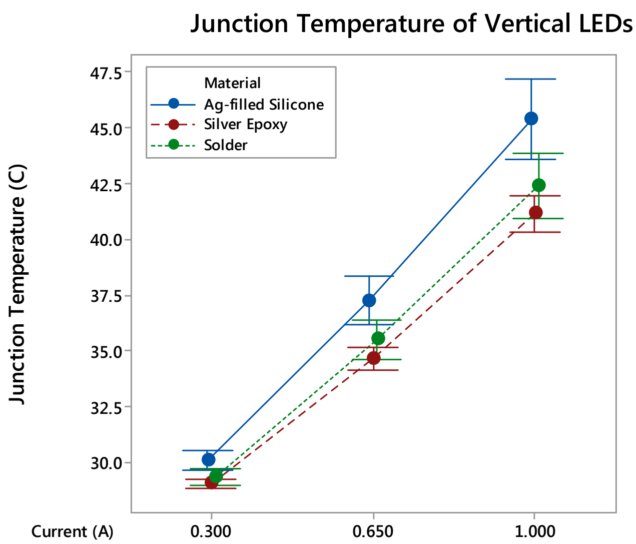

Figure 5: Junction temperature of vertical LEDs assembled with three different die attach materials vs. the operating current.

Figure 6 shows the luminous flux of the same three type of vertical LEDs at three different currents. Not surprisingly, LEDs with the lowest junction temperature (those assembled with silver-filled epoxy) show the highest luminous flux, and those with the highest junction temperature (silver-filled silicone die attach) show the lowest luminous flux (and efficacy).

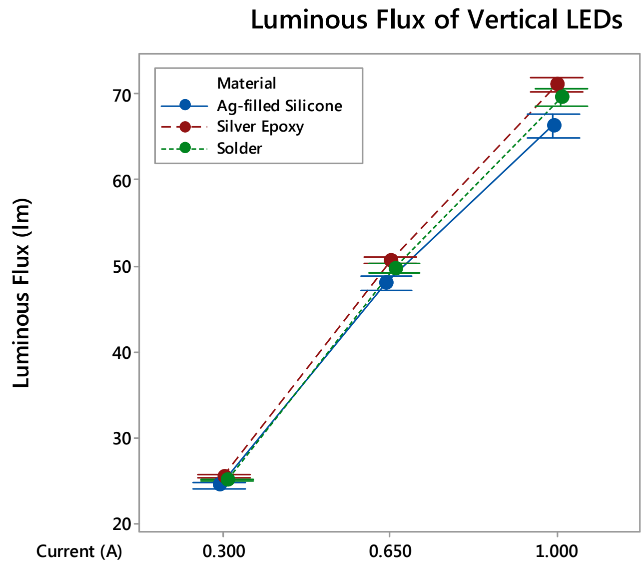

Figure 6: Luminous flux of vertical LEDs assembled with three different die attach materials vs. the operating current.

Unlike lateral LEDs, vertical LEDs have a conducting substrate, and that substrate has a backside metallization. This metallization layer reflects back the light going towards the die attach later. Therefore, unlike lateral LEDs, there is no advantage to using a transparent die attach material. The only properties of the die-attach material that matter are the thermal properties and the electrical conductivity

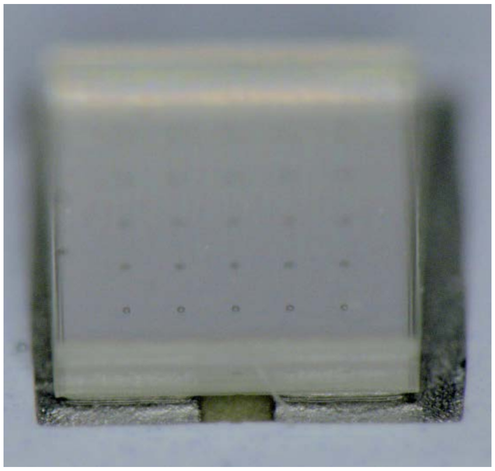

Figure 7. A flip-chip LED assembled using solder.

Flip-chip LED results. Like vertical LEDs, flip-chip LEDs also need an electrical conducting die attach material to bond the anode and cathode pads (see **Figure 7**). Therefore, silver-filled epoxy, silver-filled silicone and SAC305 solder paste were used. Most of the LEDs assembled with silver-filled epoxy and silver-filled silicone either demonstrated a shorted P and N terminal, or demonstrated a small leakage current. This situation arises because of the fact that the PN junctions on the flip-chip LED dies ~~is~~ are exposed on the side. Any of the die material wicking up on the side is likely to short the PN junction. It is impossible to avoid any fillet on the side of the die when using an epoxy- or silicone-based die-attach material. Solder does not have that problem, because during the soldering process, the solder always sticks only to metallized surfaces. Even if there is any solder paste outside the die during die placement, all of it pulls back underneath the die, onto the two pads during solder reflow because of the solder surface tension. Therefore, the only good results we obtained on flip-chip LEDs is when solder was used as the die-attach material. This result is consistent with our previous work on flip-chip die attach by solder stamping [4].

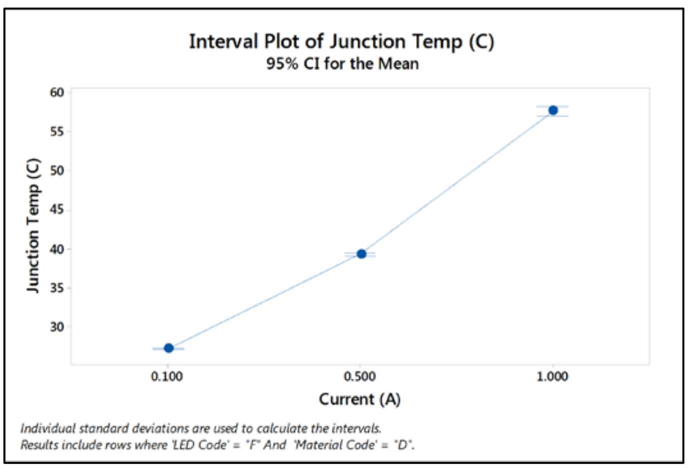

Figure 8. Junction temperature of flip-chip LEDs assembled with SAC305 solder paste die attach material vs. the operating current.

Figure 8 shows a plot of the junction temperature of flip-chip LEDs assembled with SAC305 solder paste vs. operating current. Not surprisingly, higher current results in a higher junction temperature. Luminous flux follows the same trend, as shown in **Figure 9**. Just like the vertical LEDs, both die attach pads on the flip-chip LEDs are metallized. Therefore, any light going towards that side is reflected back before reaching the die attach layer. Therefore, there is no advantage to using a transparent conducting die-attach material, even if you could find one.

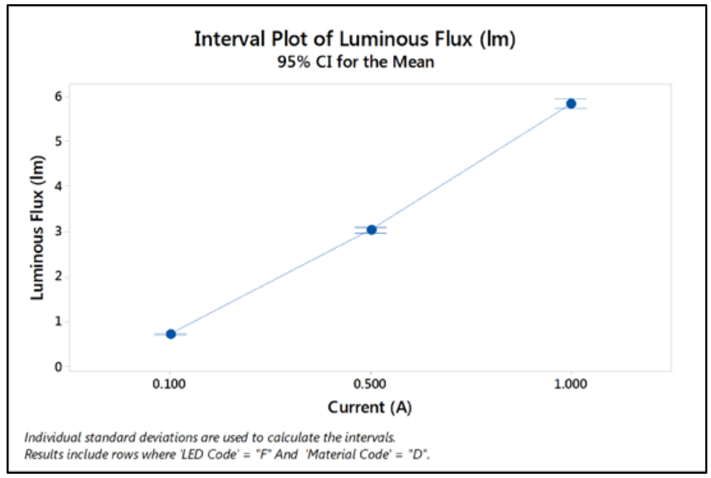

Figure 9. Luminous flux of flip-chip LEDs assembled with SAC305 solder paste die attach material vs. the operating temperature.

SUMMARY

The study systematically evaluated the effect of thermal and optical properties of die- attach materials on functional performance characteristics of lateral, vertical and flip-chip LEDs (junction temperature, light output and efficacy).

For lateral LEDs, the optical transparency of the die-attach material was found to dominate the extracted light output. Even though high bulk thermal conductivity materials (silver-filled epoxy and silver-filled silicone) enabled lower junction temperatures (and hence, higher quantum efficiency), the extracted light output (up to the maximum current limit) was much lower than for optically transparent materials (which had much higher junction temperatures).

For vertical LEDs, high bulk thermal conductivity die attach (as expected), resulted in lower junction temperature (higher quantum efficiency), as well as higher light output. Optical transparency of the die-attach material was irrelevant because the light is reflected off the metallized electrode at the bottom and does not come in contact with the die-attach layer.

Finally, functional performance of flip-chip LEDs was found to be strongly influenced by the fillet around the light-emitting junction. Any conductive material covering the active PN area was found to cause current leakage resulting in dark spots and low light output. Solder (due to its high surface tension) wet-out the metallized substrate pads and did not make the fillets contaminating the PN area. This suggests that solder (other than eutectic AuSn, of course) is a suitable material for flip-chip die-attach for LEDs.

This study clearly suggests that there is no universal die attach for LED packaging and LED die structure must be taken into account to select the optimal suitable die attach material and/or process.

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