ABSTRACT
High-power and LED devices generate significant heat that, if not efficiently removed from the assembly, leads to lower operating efficiency and/or lower luminous flux and shorter lifetime. Because the majority of heat is transported through the device interconnect layer, the thermal resistance of the heat path significantly impacts overall device performance. Higher thermal conductivity interconnect materials significantly decrease the thermal resistance of the stack. The effects of high performance interconnect materials are easy to observe and affect end user performance and reliability (e.g. by increasing total luminous flux, efficiency, and color stability). These effects become more pronounced as these devices are over driven and are particularly important in power electronics and UV LED applications.

In this study, a series of interconnect materials, including sintered nano-silver, SAC305 and a hybrid silver sintering epoxy, were used to assemble high-power AlGaInP/Si LEDs for laboratory testing. Junction temperature, thermal resistance, thermal conductivity, total luminous flux, peak wavelength, and efficiency were measured according to JESD51-1 and LM-79-08.

In this paper we discuss the technical and design challenges associated with making accurate thermal resistance measurements across a multi-layered stack. The results of this laboratory study show the comparative performance of identical devices assembled with a variety of interconnect materials. A field example showing enhanced UV LED device performance with high thermal interconnect material is presented.

Key words: UV LED, die attach, sintered silver, thermal resistance, interconnects

INTRODUCTION
Proper cooling of LEDs during operation requires high performance interconnects to conduct heat away from the p-n junction (the light generating region). Doing so lowers the junction temperature of the LED and increases the efficiency. While 20-60% of the electrical power is converted to photons, the remainder is converted to heat. In laboratory settings and in luminaires convection across the die is negligible or non-existent. Instead, nearly all the heat moves down through the die, die attach layer, substrate trace, dielectric, and then the substrate base material (typically FR4, aluminum, or copper, see Figure 1) [1] [2]. It then moves through the thermal interface material and into the heat sink where it is exhausted to ambient. Any of these layers can serve as a bottleneck for the heat transfer, but especially layers towards the top of the materials stack where the cross sectional area is still small. Therefore, these layers must have high thermal conductivity to effectively cool the LED [3]. The thermal performance of the whole LED stack is measured as thermal resistance (Rth) in units of degrees Kelvin/Watt (or, equivalently, degrees Celsius/Watt).

SINTERED SILVER AS DIE ATTACH MATERIAL
The sintered nano-silver paste used here is designed for pressure-less die attach and assembly of electronics components, including high power LEDs. The material uses typical SMT manufacturing processes such as printing and dispensing. It must, however, be sintered at high temperature in an oven. During high temperature sintering the silver paste bakes off its solvents while adjacent nanoparticles diffuse together to form a porous structure as shown in Figure 2.

Once the silver paste is printed, dispensed, or stamped, the LED is placed on the deposit via a standard SMT pick-and-place machine or a die bonder. This is possible because this sintered silver paste is so-called pressure-less – meaning many kilograms of pressure aren’t needed during the sintering process in order to make the silver bond.

The thermal conductivity of bulk silver is $429 \, W/m \cdot K$, but because of nano-pores the expected thermal conductivity of...
sintered silver is lower. Nano-flash thermal conductivity measurement of bulk sintered silver is approximately 230 W/m·K. A sintered silver die attach layer’s thermal conductivity will be based on the size of the nano-silver particles, the solvents and resins used in the paste, assembly pressure, and sintering temperature and duration.

**HYBRID SILVER SINTERING MATERIALS**

Another high-performance die attach technology is known as hybrid silver sintering [4]. These are epoxy-based materials that combine the high thermal conductivity of nano-silver sintered materials and the adhesion properties of silver-filled epoxies. They are composed of micron-sized silver flakes and organic and polymer components. During curing they pull adjacent flakes together promoting increased contact and sintering. They have high thermal conductivities (up to 150 W/m·K) but are assembled pressure-less and adhere to bare substrates (whereas solder and nano-silver sintering pastes require metallized surfaces). Curing hybrid silver sintering materials is done in two steps in a box oven, with typical peak temperatures of 200-250 C for 1-2 hours.

**SUBSTRATE DESIGN FOR HIGH PERFORMANCE MEASUREMENTS**

Compared to all other LED thermal stack materials, dielectrics have high thermal resistance. This limits the junction temperature measurement precision and completely precludes measurement of high performance die attach materials. Using a metal substrate with an active pedestal eliminates the dielectric layer and permits a direct heat path from the LED to the heat sink (see Figure 3).

In our high performance interconnect studies we use dielectricless substrates. High-power vertical LEDs are attached directly to the metal substrate via a die attach material. Heat conduction from the die then moves in approximately a one-dimensional fashion into the substrate. By varying the thickness of the die attach layer we can isolate its contribution to the material stack.

Substrates are clamped to a thermoelectric heat sink held at a constant 25 C. A thin ribbon of highly-conformable indium (thermal conductivity K = 81.8 W/m·K) is used as the thermal interface material.

![Figure 2. Electron microscope image of sintered silver microstructure showing characteristic micro-pores.](image)

![Figure 3. An active pedestal with no dielectric layer. The die here is directly attached to the copper substrate via a sintered silver die attach material. This improves experimental precision and allows for measurement of high performance die attach materials.](image)

**MEASUREMENT TECHNIQUES**

**Overview**

The thermal resistance of an LED stack can be measured directly via electrical and optical tests. Both have established industry standards. Depending on the sophistication of the test equipment greater precision and accuracy can be achieved. Higher precision methods measure the thermal conductivity of a layer, such as the die attach material.

**Junction Temperature**

The junction temperature of the LED is the temperature of the p-n junction. This shouldn’t be confused with the solder point temperature, which is the temperature of the solder pad. We measure the junction temperature of LEDs via the dynamic voltage method outlined in JESD 51-1 [5]. To calculate the junction temperature it is necessary to first measure the temperature sensitivity parameter of the LED, which is also known as the k-factor.

The k-factor is determined by measuring the voltage across an LED at a series of known temperatures when operated at low power. To avoid self-heating, the current through the LED should be below the self-heating threshold of the diode. JESD 51-1 specifies this value as below the knee of the diode’s IV curve.

For best results, and in all but the most simplified circumstances, LEDs should be placed in an oven to ensure a known temperature at the junction. The exception to this situation is if the LED die attach stack is sufficiently
thermally conductive to allow for k-factor calibration on a heat plate. In general, LED packages have too much thermal resistance for heat plate calibration. Bare LED chips from the same bin have very similar k-factors, therefore measuring a few gives a reasonable approximation for the remainder.

Once the k-factor is known, current is passed through the LED and it is allowed to come to thermal equilibrium with a heat sink held at a constant temperature. Once thermal equilibrium has been reached, the voltage is measured to determine the electrical power. The LED heating current is then switched off and a sensing current is applied. As the LED cools to the temperature of the heat sink, the voltage rises to a reference voltage that corresponds to the heat sink temperature. Depending on the total thermal resistance of the LED assembly, the duration of this cooling behavior can be from hundreds of microseconds to many seconds. The voltage of the LED immediately after the current switches is called the sensing voltage. The following equation is then used to calculate the junction temperature:

\[ T_J = \frac{V_R - V_S}{k} + T_{HS}. \]

- \( V_R \): is the reference voltage of the LED.
- \( V_S \): is the sensing voltage of the LED after switching from heating to sensing current.
- \( k \): is the temperature sensitive parameter in units of volts/degree Celsius.
- \( T_{HS} \): is the temperature of the heat sink, in Celsius.

We measured the junction temperature of the LED at several operating currents and also measured the optical efficiency of the LED in an integrating sphere. The thermal power of the LED is the difference between the electrical power and the optical power. This is the amount of electrical energy per unit time that is converted to heat. Knowing this quantity and the junction temperature at several operating currents, we can calculate the thermal resistance of the LED assembly and test system:

\[ T_J = R_{th} \cdot P_h + T_{HS}. \]

- \( T_J \): is the junction temperature, in Celsius.
- \( P_h \): is the thermal power of the LED, in Watts.
- \( R_{th} \): is the thermal resistance of the LED assembly, in C/W (equivalent to K/W).
- \( T_{HS} \): is the temperature of the heat sink, in Celsius.

**Die Attach Influence on Junction Temperature**

Figure 4 shows a comparison of die attach materials used in the assembly of high-power vertical red LEDs on dielectricless substrates. These samples were constructed identically with only the die attach material differing. The bond line thicknesses of the samples were chosen to represent the ideal process conditions for that particular material so as to form a better picture of in-use performance (see Table I).

Nano-silver particle size, paste rheology, and processing parameters all determine the ultimate thermal performance of the sintered silver die attach materials. In Figure 4, two sintered silver materials show an 8% difference in junction temperature at 3.0 Watts. These are compared to hybrid silver sintering epoxy which is 5% higher at the same electrical power input and SAC305 which is extrapolated to be 10% higher. Differences between die attach materials become more pronounced the higher the electrical power.

![Die Attach Material Comparison](image)

**Figure 4.** Junction temperature measurements of LEDs assembled with different die attach materials. For each material the ideal bond line thickness was used (see Table I).

<table>
<thead>
<tr>
<th>Material</th>
<th>BLT Range</th>
<th># of LEDs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sintered Silver 1</td>
<td>20-32 um</td>
<td>9</td>
</tr>
<tr>
<td>Sintered Silver 2</td>
<td>20-32 um</td>
<td>8</td>
</tr>
<tr>
<td>Hybrid Sintered Silver</td>
<td>13-35 um</td>
<td>6</td>
</tr>
<tr>
<td>Solder (SAC305)</td>
<td>53-68 um</td>
<td>10</td>
</tr>
</tbody>
</table>

**Table I.** Die attach material BLTs and sample quantities used in Figure 4.

**Bond Line Thickness**

The thickness of the die attach layer, alternately referred to as the bond line thickness (BLT), is a key property of an LED assembly. Thicker BLTs relieve thermal stresses, but contribute to higher overall thermal resistance. We measured the BLT of our LEDs in two ways, via cross section and a vertical measuring microscope.

Cross sectioning - The LED is cross sectioned to allow direct optical inspection of the bond line. This is the most accurate way to measure bond line thickness, but does not allow for die tilt measurements because it is a single slice through the die. Figure 3 is an example of an LED assembly cross section.
Vertical measuring microscope – A measuring microscope was used to optically measure the bond line thickness of an intact LED assembly. This type of microscope has a very narrow depth of field and a calibrated focus axis. By focusing the microscope on a surface, zeroing the z-axis, and then refocusing on a new surface, the user can measure the vertical distance between the two.

This procedure requires knowing some information about the LED package, specifically the thickness of the LED die and the planar location of the bottom of the die attach layer. If these are known, then by measuring the vertical distance between the two and subtracting the die thickness we can calculate the BLT. Performing these measurements for all four corners gives an indication of the die tilt. In practice, this method is accurate to within +/-5 µm.

Thermal Resistance Results
We measured the junction temperature of 80 high-power vertical red LEDs assembled on dielectric-less substrates. As in Figure 4 (a subset of these samples), dies were assembled identically except for the die attach material.

![Figure 4](image)

Figure 4 showed a clear difference between die attach materials at high electrical powers. Generally, though, thinner bond lines have better thermal performance and smaller differences between die attach materials.

Optical Measurements
In addition to measuring the junction temperature and thermal resistance, there are a few optical measurements that are useful in the LED industry. These measurements were performed in an integrating sphere according to LM-79-08 [6].

![Figure 6](image)

Figure 6. Integrating sphere used to measure optical emissions. A heat plate mounted on the outside of the sphere holds the LED sample at a constant temperature during tests. This integrating sphere is set up to perform 2π measurements.

A 0.5 m diameter integrating sphere was used in 2π mode, meaning that the LED was placed on the edge of the interior of the sphere as shown in Figure 6. For calibration, two radiometrically calibrated halogen lamps were used to serially calibrate the integrating sphere and then thermoelectric heat sink’s test surface and mounted LED (Figure 7).

![Figure 5](image)

Figure 5. Comparison of die attach materials used to assemble red vertical LEDs. Thermal resistance (Rth) values refer to the total Rth of the LED assembly and heat sink.

Plotting these LEDs’ thermal resistances versus their BLTs shows comparative performance of the thermal stacks, shown in Figure 5. The slope of the fitted lines are proportional to the thermal conductivity of the die attach materials. Sintered silver shows the lowest thermal resistance values – especially at high BLTs where the effect is exaggerated. The measurements overlap at low BLTs. This is likely due to low measurement accuracy because
A linear CCD-spectroradiometer gathered light via a small satellite sphere and optical fiber. The spectroradiometer had a spectral range of 360 - 1000 nm. After the LED was illuminated it was required to stabilize to within 0.02°C for 15 seconds.

Measured Optical Parameters
The following optical parameters were acquired for each current level:

- Emission Spectrum - was measured from 360-1000 nm. Peak, center, and dominant wavelengths can be extracted from the emission spectrum.
- Optical Power - is the total amount of light emitted by the LED and measured in Watts.
- Luminous Flux - measures the total optical power of the LED as seen by the human eye. It is expressed in Lumens and is calculated by multiplying the photopic response of the human eye by the radiometrically calibrated emission spectrum.
- Efficiency - communicates the conversion rate of electrical power (in Watts) to optical power (also in Watts) of the LED. It is expressed as a percentage. When this parameter includes the efficiency of the power driver and electronics it is referred to as wall plug efficiency.
- Efficacy - is measured in Lumens/Watt and is an indicator of how efficiently the LED converts electrical power into visible radiation.
- Color Coordinates – CIE 1931 (XYZ) and CIE 1976 (u’, v’) color coordinates as well as color-correlated temperature, and duv.

Optical Results
Optical tests show a clear and significant impact of die attach material on LED emission. Figure 8 shows that LEDs assembled with sintered silver have 30% higher luminous flux at 0.7 A (approx. 1.6 W) than LEDs assembled with SAC305. Figure 9 shows a trend among all LEDs towards lower efficiencies as electrical power increases. This is typical among LEDs. However, LEDs assembled with sintered silver had 22% higher power efficiency than those assembled with SAC305 when operated at 0.7 A (~1.6 W). The spectra plotted in Figure 10 show significantly higher radiant emission from an LED assembled with sintered silver versus an LED assembled with SAC305. Furthermore, SAC305 samples showed a shift in peak wavelength at higher operating currents than sintered silver LEDs.
These results are significant and point to clear benefits to end-users regarding overall LED efficiency and brightness. Considered over the lifetime of typical LEDs, the use of sintered silver in commercial die attach applications presents significant cost- and energy-savings to consumers.

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FIELD EXAMPLE – UV DIE ATTACH SINTERED SILVER APPLICATION

For this field example we assembled four vertical InGaAlN on metal alloy UV LEDs onto 3535 packages using a sintered silver die attach material and a silver-filled epoxy. The dies were manufactured by SemiLEDs, model EV-D45A, and had dimensions of 1.2 x 1.2 mm with a maximum forward current of 0.7 A. The LEDs were placed via die bonder and then sintered in a box oven. The packages were then soldered to a substrate. The LEDs in this study came from two different lots. The sintered silver dies had a k-factor of -1.19 mV/C and silver-filled epoxy dies had a k-factor of -1.51 mV/C.

VOIDS

Voids were measured using an x-ray inspection system. In each case voiding was minimal, but we observed voiding on both interconnect layers (see Figure 11 and Figure 12):

- **L1** – The die attach layer composed of sintered silver. Two LEDs were assembled with sintered silver paste, and two LEDs were assembled with silver-filled epoxy.
- **L2** – The package attach layer composed of solder paste.

X-ray void analysis of these samples showed both L1 and L2 voids (see Figure 13). L2 voids are classic solder voids and appear with rounded edges and high contrast. They are located throughout the L2 interconnect pads. L1 voids are only on the periphery of the die attach layer. They are smaller and don’t have the nice rounded edges of classic solder voids. It is especially easy to spot the difference between these two features because L2 voids will extend across the edge of the die (because they are on the layer below the die), while L1 voids only appear under the die.
Optical Results
The UV LED packages were placed in an integrating sphere as described above and illuminated with 0.1, 0.35, 0.5, and 0.7 Amperes until they reached thermal equilibrium with a thermoelectric heat sink held at 25 C. Radiant power, rather than luminous flux, is communicated here because these are UV LEDs and emit outside the visible spectrum.

LEDs assembled with sintered silver show 18% higher radiant power at 0.7 A than LEDs assembled with silver-filled epoxy while also consuming 8% less power (Figure 14). This is because the LEDs are operating at higher efficiencies, as shown in Figure 15. Sintered silver samples run with 24% higher efficiency than silver-filled epoxy samples at 0.7 A.

Figure 12. Packages (left) and UV dies (right) assembled with silver-filled epoxy.

Figure 13. Voiding on the L1 and L2 layers of a UV LED assembled with silver-filled epoxy on a soldered package. The L1 layer is silver-filled epoxy, the L2 layer is solder.

Figure 14. Radiant power of UV LEDs assembled with sintered silver and silver-filled epoxy die attach materials.

Lastly, Figure 16 shows a smaller shift in color coordinates for sintered silver samples. Note that these LEDs appear to be from different production lots because they have different color coordinates. However, the relative shift in their coordinates still communicates relative performance.

Figure 15. Optical efficiency of UV LEDs assembled with sintered silver and silver-filled epoxy die attach materials.
CONCLUSIONS
The choice of die attach material significantly affects the
thermal performance of LEDs, and therefore the optical
performance. High thermal conductivity materials, such as
sintered silver, reduce junction temperatures, increase
radiant power and optical efficiency, and stabilize
thermally-induced color shifts. Measuring the precise
performance of these materials can be challenging and
requires the use of dielectricless substrates. However,
observing the influence of high performance interconnects
on end-use applications (such as UV LEDs) is easier
because the influence on final device performance is large.
LEDs operating at high electrical powers especially benefit
from high performance interconnects.

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Figure 16. CIE Color coordinates of UV LEDs assembled
with sintered silver and silver-filled epoxy die attach
materials. Sintered silver samples showed a shorter color
shift, which implies a higher thermal conductivity die attach
material.

Color Coordinate Shift of UV LEDs

\[ u' \]

\[ v' \]

0.16 0.18 0.2 0.22

\( \bullet \) Sintered Silver, LED 1
\( \bullet \) Silver Epoxy, LED 1
\( \triangledown \) Sintered Silver, LED 2
\( \triangledown \) Silver Epoxy, LED 2

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