Thermal and Optical Characterization of High-power LEDs

Nicholas Herrick, Ranjit Pandher
Alpha Assembly Solutions

***Abstract*—High-power LEDs generate significant heat that, if not efficiently removed from the assembly, leads to lower luminous flux and lower operating efficiency. High thermal conductivity die attach materials significantly decrease the thermal resistance of an LED stack. Because the majority of heat is transported through the die attach layer, the thermal conductivity of the materials in the heat path is significantly impact overall device performance. The effect of high performance die attach materials are easy to observe and affect end user performance (e.g. by increasing total luminous flux and limiting color shift in the LEDS emission spectrum). However, determining the precise thermal conductivity of high thermal conductivity die attach materials is challenging. We present an adaptation of JESD51-1 to the challenge of measuring sintered silver die attach material's thermal conductivity in-situ as compared to SAC305 solder when used to package AlGaInP/Si vertical LEDs. By removing the dielectric and using a suitably fast source measurement unit we measured Alpha sintered silver's thermal conductivity as 206.8 W/m-K.**

***Keywords*—LED characterization, die attach, sintered silver, SAC305, junction temperature.**

I. Introduction

Die attach materials used in the assembly of Light Emitting Diodes (LED) directly influence their operating temperatures. Higher thermally conducting materials, such as sintered nano-silver, allow an LED to operate at lower temperatures. This leads to higher luminous flux, efficiency, color stability, and reliability. Materials manufacturers like Alpha increasingly structure their research and development activities around the thermal conductivity of their die attach products.

Evaluating the thermal conductivity of die attach materials typically requires either thick layers or low thermal conductivity. Measuring the thermal conductivity of sintered nano-silver products is challenging because of their high thermal conductivity. Also, it is almost impossible to prepare a thick sample using standard techniques via in use sintering conditions. Measurements done on a sample prepared under dramatically different sintering conditions are not representative of real life performance. Sintered silver must therefore be measured in-situ, i.e. by attaching an LED die to a substrate. The goal in this experiment was to confirm that

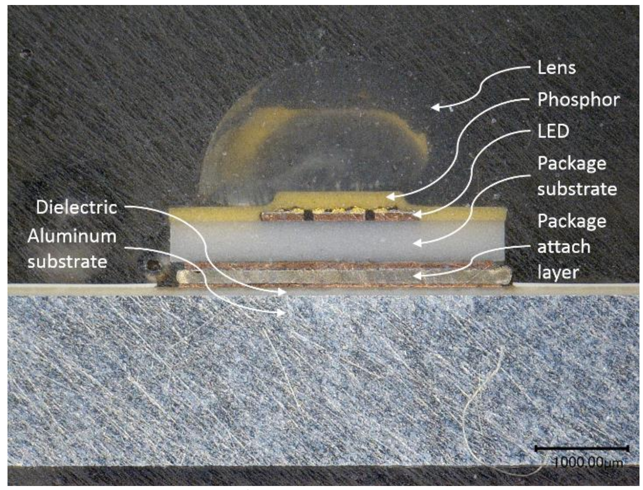


Figure 1 Cross section of a Lumileds Luxeon® Rebel LED package assembly. Heat generated at the LED junction conducts through the stack layers to reach the heat sink. These layers include the chip, die attach layer (Level 1), package substrate, package attach layer (Level 2), dielectric, and metal substrate.

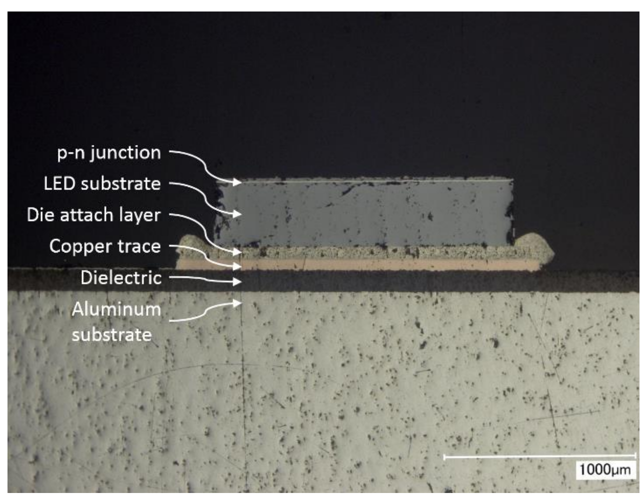


Figure 2 Cross section of an AlGaInP/Si vertical LED attached with sintered silver to an aluminum substrate with a dielectric. The dielectric layer has high thermal resistance and is therefore undesirable in high-power operations. Furthermore, to measure the thermal conductivity of low-resistance die layers the dielectric layer must be omitted.

sintered silver maintains its high thermal conductivity when used as a die attach material in high-power LED assemblies.

Heat generated at the p-n junction of the LED is dissipated via radiation, convection, and conduction. Heat dissipation by radiation at typical LED operating temperatures is negligible. Heat loss through convection is also small and can be eliminated during measurement by restring the air flow around LED. Typically, 10-30% of the electrical power an LED consumes is radiated as visible light, while the rest is released as heat. This heat leaves the LED predominantly via conduction through the die attach layer stack. The die attach layer is one of many layers in the thermal stack up of an LED.

The most common industry evaluation of LED thermal behavior is of the junction-to-ambient thermal resistance. In this test the whole LED stack is measured at once, with no differentiation between various component layers. This method is sensitive to variations in thermal interface material, substrate, and dielectric thickness. In this paper we outline how we combined existing LED test standards and methods to simultaneously measure thermal and optical properties of some high-power LEDs. Furthermore, because standard thermal conductivity tests have a limit to their upper range, we outline methods we used to measure the high thermal conductivity of sintered silver.

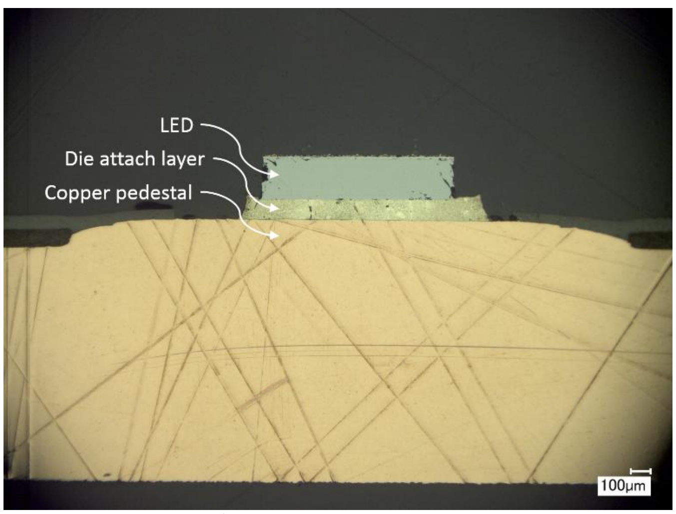


Figure 3 Cross section of an AlGaInP/Si vertical LED attached with sintered silver to copper pedestal extruded from a substrate. This geometry is referred to as an active substrate because of the lack of dielectric layer and allows for high-sensitivity measurements of the LED stack.

II. LED Assembly

A. LED Dies and Packages

LED chips use a die attach material to adhere to a substrate. The die attach material forms an important link in the thermal path of the LED to ambient. In many cases the die attach material also forms the electrical connections. An LED chip affixed directly to a metal substrate is an example of chip-on-board architecture and is common in high-power LED designs. Lower-power LEDs are commonly packaged for ease of assembly (see Figure 1).

The layered-structure of a single chip-on-board LED stack can be considered one-dimensional from the P-N junction through the die attach layer (see Figures 2 and 3). After heat enters the metal substrate it can spread in-plane before it is conducted to the heat sink and then to ambient. Therefore, because of the small cross-sectional area of the 1-dimensional stack each layer needs to be highly thermally conductive (or, equivalently, have low thermal resistance), see Table II.

The benefit of lower thermal resistance of an LED stack can be higher luminous flux for the same operating temperature and current, higher efficiency and longer lifetime for the same electrical power, or higher efficiency and longer lifetime for the same luminous flux.

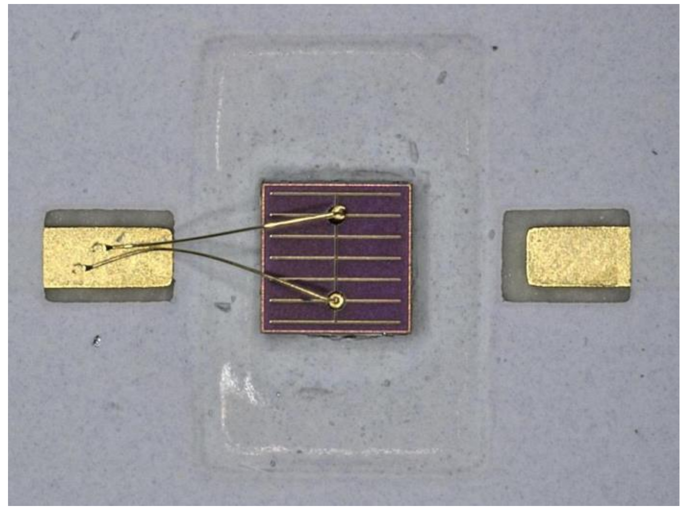


Figure 4 A red 1 x 1 mm high-power vertical AlGaInP/Si LED with wirebonds connecting the cathode to the substrate trace. The anode is the bottom surface of the LED and is connected to the grounded copper pedestal of the substrate via a die attach material.

The LEDs used for this experiment were AlGaInP on Si substrates (Figure 4). They were 1 x 1 mm, 225 µm thick with a typical operating current of 350 mA, peak wavelength of 624 nm, and forward voltage of 2.4 V (at 350 mA).

B. Die Attach Materials

In this study we sought to understand the influence of the die attach layer on the thermal and optical performance of high-power LEDs. Die attach materials vary widely in their thermal performance, price, and intended applications (see Table I). We compared two die attach materials: a mid-performance industry standard solder alloy (SAC305) and a high-performance alternative (sintered nano-silver paste).

SAC305 is an electronics industry standard lead-free solder alloy composed of 96.5% tin, 3.0% silver, and 0.5% copper. SAC305 has a well-characterized bulk thermal conductivity of 64 $W/m \cdot K$. However, the effective thermal conductivity of SAC305, when used as a die attach material, will be slightly different because of voids and the formation of interfacial intermetallic compounds. The purpose of SAC305 in this experiment was to function as the control as we investigated the unknown in-situ thermal conductivity of sintered nano-silver.

The sintered nano-silver paste used here is designed for pressure-less die attach and other SMD assembly of electronics, including high power LEDs. The material uses typical SMD 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 5.

Die Attach Material	*Thermal Conductivity* $(W/m \cdot K)$	*Application*
SnBi Solder	20	Low temperature assembly
80Au/20Sn	57	High reliability
SAC305 Solder	64	Inexpensive
Silver Filled Epoxy	149	Electrical insulator, High thermal conduct.
Sintered Silver	100-250	Electrical conductor, High thermal conduct.

Table I A few of the common die attach materials and their thermal conductivities used in LED assembly. This experiment used SAC305 and sintered silver.

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 $W/m \cdot K$. However, the question considered here is whether sintered silver maintains high thermal conductivity when used as a die attach material in high-power LED applications.

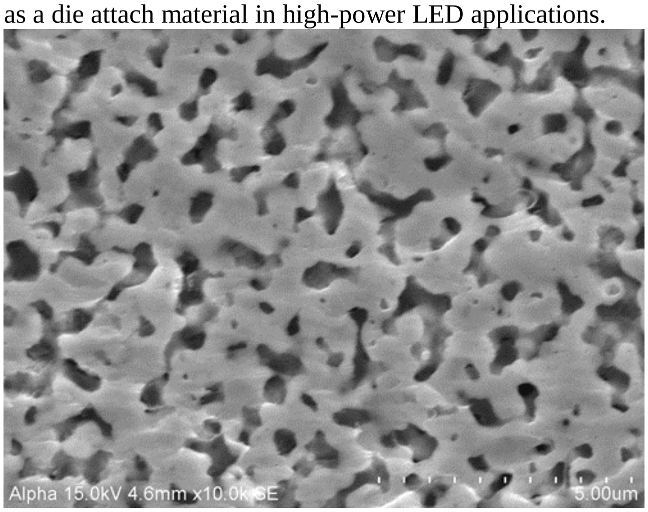


Figure 5 Electron microscope image of sintered silver microsctructure of showing characteristic micro-pores. The thermal conductivity is lower than bulk silver because of indirect heat paths through the micro-pores.

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. Because bond lines are typically only 10-50 µm thick, and exist only between a substrate and die, their thermal conductivity must be measured in-situ. Fortunately, by using the high-power LED as both a heat source and a temperature sensor we can perform precise measurements of the thermal conductivity in-situ.

C. Bond Line Measurement

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:

- 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. Figures 1-3 are examples of LED assembly cross sections.

- Vertical measuring microscope - An Olympus STM6 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.

For the purposes of this experiment we required LEDs with a range of BLTs. We assembled our LEDs using stencils from 1 to 7 mils (25-177 µm) thick with resulting BLTs ranging from 10 to 160 µm.

D. Substrate and Dielectric

LED substrates are typically made of copper or aluminum. These high-conductivity metals allow heat to spread before it enters the thermal interface material (TIM) and the heat sink. However, most LED substrates have a dielectric layer between the die attach pad and the metal core. This layer has comparatively high thermal resistance, so much that the total thermal resistance of the LED stack is overwhelmingly dominated by the thermal resistance of the dielectric layer (see Table II).

Layer	*Thermal Conductivity* $(W/m \cdot K)$	*Layer Thickness (µm)*	*Cross-sectional Area* (m^2)	*Thermal Resistance* $R_{th}(K/W)$
LED (Si)	149	175	10^{-6}	1.17
Die Attach Layer (see Table I)	10 - 250	50	10^{-6}	5 - 0.2
Dielectric (optional)	2.4	25 – 75	10^{-6}	10.4 – 31.3
MCPCB (Cu)	390	1200	10^{-4}	0.03
TIM (Indium)	82	200	10^{-4}	0.02

Table II Calculated thermal resistances (R_{th}) for each layer of the LED assembly used in this experiment. The dielectric layer contributes the most to the total R_{th}, after which is the die attach layer.

In our experiment we needed to measure the very small thermal resistance of sintered silver. At first, because of the high thermal resistance of the dielectric layer we were unable to measure the sintered silver resistance with sufficient precision. With the dielectric layer present the thermal resistance of a sintered silver layer was only 0.8% of the total thermal resistance, which is within the noise of the measurement. Solder die attach materials comprise only 2.7% of the total thermal resistance when a dielectric is present, making these measurements challenging, but possible.

LED substrates with active pedestals present a work-around for this problem. An active pedestal (see Figure 3) allows for dies to be placed directly on an extruded co-planar extension of the metal substrate with no dielectric present. This gives a direct heat path to the metal substrate and vastly decreases junction-to-ambient thermal resistance. While this approach isn't necessarily practical for manufacturing (it isn't always desirable to have the LED's anode electrically grounded to the heat sink) it works well for the experimental goal of measuring low resistance layers.

Removing the dielectric layer increased the sintered silver die attach layer's contribution to 8.4% of the total stack resistance and solder's contribution to 21.3%. This ten-fold increase makes the measurement possible with commercial off-the-shelf hardware.

III. Thermal Measurements

This test is based on JEDEC Standard EIA/JESD51-1 [1]. Because the forward voltage of a diode varies with the temperature of the P-N junction it can be used as a temperature sensor. Also, diodes generate significant heat when they are operated at high power, so they can also be used as heaters. To use an LED as a temperature sensor, it should be operated at very low current so that there is no internal heating. For use as a heat source it should be operated at high current to generate enough heat to raise its temperature significantly. By rapidly switching between high current and low current (sensing) modes, we can utilize diodes as test devices to measure the thermal resistance of all the layers in the die attach stack. 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.

A. Temperature Sensitive Parameter

Using an LED as a temperature sensor requires calibration, i.e. we need to determine its temperature sensitive parameter. The temperature sensitive parameter of an LED, also known as the k-factor, is a linear relationship between the forward voltage across the LED junction and the junction temperature. Figure 6 shows a plot of forward voltage as a function of the temperature for a typical diode used in our experiment. The slope of the line is the k-factor, measured in volts/degree Celsius.

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 our tests we used 0.01 A.

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. The LEDs in this study were all from the same lot and had measured k-factors of 0.00171 V/C.

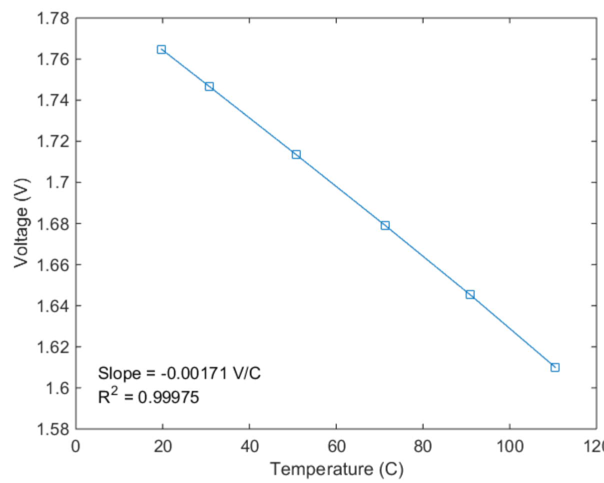


Figure 6 Forward voltage versus temperature plot of an LED. The slope of the line, measured in V/C, is the K-factor temperature sensitive parameter. For best results LEDs should be calibrated in an oven, however simplified LED assemblies (such as vertical LEDs on active pedestals) can be calibrated on thermoelectric heat sinks.

B. LED Heating Transient

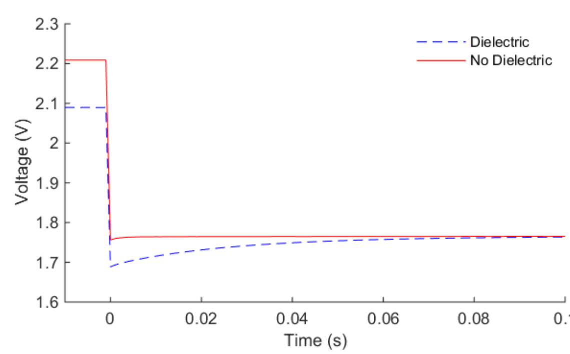


Figure 7 shows the voltage of an LED when it rapidly switches from high to low current. In this case, the LED was operating at 0.7 A for long enough to thermally stabilize, then switched to 0.01 A. At the moment of switching, t = 0, there is a transient event in which the voltage rises quickly because the LED begins cooling down once the current switches. As the LED temperature approaches the sink temperature the voltage stabilizes at the sensing voltage. Using the temperature sensitive parameter we can calculate the junction temperature of the LED during this time (Figure 8). If the power supply switches sufficiently fast, then the voltage immediately after the switch will correspond to the temperature of the LED when it was operating at the heating current.

The duration of the transient voltage response is proportional to the total thermal resistance of the LED assembly, while the amplitude is proportional to the highest temperature the LED sees during its heating phase. Therefore, a substrate with a dielectric will have a longer duration and higher amplitude transient than a dielectric-less substrate. A shorter duration transient is the downside of removing the dielectric and necessitates a fast switching and high resolution power supply. The transient duration for an LED assembled on a dielectric substrate will be around 50 ms, while an LED assembled on a dielectric-less substrate will be around 10 ms.

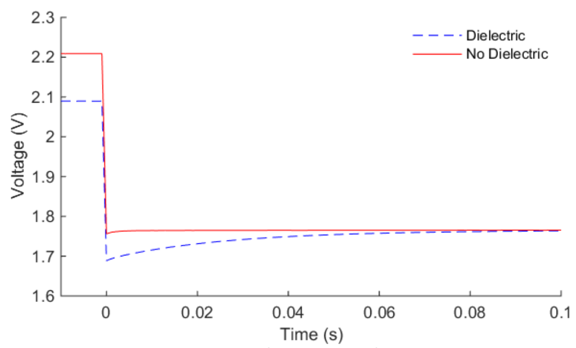


Figure 7 The voltage response of two LEDs following current switching from 0.7 A to 0.01 A. One LED was assembled on a substrate with a dielectric, the other on an active pedestal. $t = 0$ corresponds to when the current was switched from the heating current to the sensing current. The transient voltage feature is the logarithmic change observed in the voltage waveform as it settles into the sensing voltage. The difference between the two substrates shows that the dielectric layer contributes significantly to the total thermal resistance of the system, thereby slowing down the temperature change (see Figure 8). This highlights the challenge of measuring LED junction temperatures on dielectric-less substrates. The two LEDs measured here had different heating and sensing voltages. Sensing voltages were normalized for the aid of the reader.

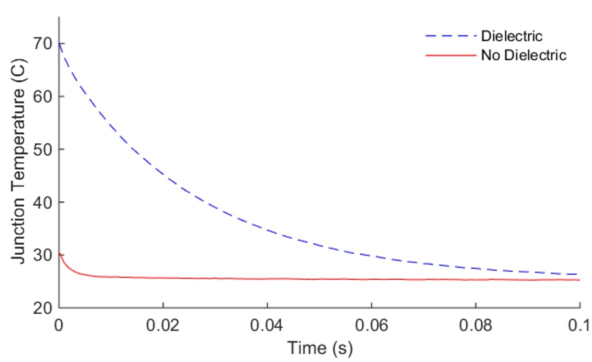


Figure 8 Calculated junction temperatures of two LEDs following current switching from 0.7 A to 0.01 A. The current change occurred at $t = 0$. Because the temperature calculation requires the LED voltage to be measured when the current is below the self-heating threshold, temperature calculations before $t = 0$ are meaningless. The asymptotic destination of the transient was the temperature of the thermoelectric heat sink, which was 25.00 C.

In our experiment we used a source measurement unit is capable of switching from high to low current in under 30 µs. The current and voltage were monitored at 10 kS/s during switching. By acquiring the electrical data at high speed we avoided the need to extrapolate voltage data to t = 0.

We programmatically determined both t = 0 and the peak junction temperature using a LabVIEW program. t = 0 was found by monitoring the second derivative of the voltage for a large peak, which corresponded to the current switch. The program then skipped approximately 30 µs of measurements (during which the current was stabilizing at the new sensing level) and then averaged the next approximately 70 µs. Results were then averaged to determine the transient voltage.

The LEDs used in this experiment have a nominal operating current of 0.35 A. However, because in this experiment the LEDs are cooled using an active heat sink the LEDs were powered up to 0.7 A. Heating currents were 0.1, 0.3, 0.5, or 0.7 A etc.

C. Junction Temperature

The junction temperature (T_j) of an LED is the temperature at the p-n junction where light is generated. It is the chief contributor to the total lifetime of the LED and influences the LED's color, total luminous flux, and efficiency.

The following equation, referred to as the forward voltage shift method, can be used to measure T_j during LED operation:

$$T_j = \frac{V_S - V_T}{k} + T_{HS}. \quad (1)$$

Where:

- V_S: is the sensing voltage of the LED when the current is below the self-heating threshold (measuring current) and the LED is at T_{HS} temperature.
- V_T: is the transient voltage of the LED immediately after switching from heating to measuring current.
- k: is the temperature sensitive parameter in units of volts/degree Celsius.
- T_{HS}: is the temperature of the heat sink in Celsius.

D. Thermal Resistance Calculation

The thermal resistance of the LED package can be calculated by knowing the junction temperature of the LED at several operating currents:

$$T_j = R_{th} \cdot P_h + T_{HS}. \quad (2)$$

Where:

- T_j : is the junction temperature, which is a function of heating power, P_h.
- P_h: is the heating power of the LED.
- R_{th}: is the thermal resistance of the LED assembly, in C/W (or equivalently K/W).
- T_{HS}: is the temperature of the heat sink, in Celsius.

We are focused on the heating power of the LED versus the electrical power, because some of the electrical power is converted into light. Heating power, therefore, is defined as:

$$P_h = P_E - P_O. \quad (3)$$

Where:

- P_h: is the heating power of the LED, in Watts.
- P_E: is the electrical power of the LED (heating current times voltage), in Watts
- P_O: is the optical power of the LED measured in an integrating sphere in Watts.

Figure 9 shows a plot of junction temperature vs heating power. The slope of the line is the total thermal resistance of the LED package, in units of °C/W as shown in Equation 2.

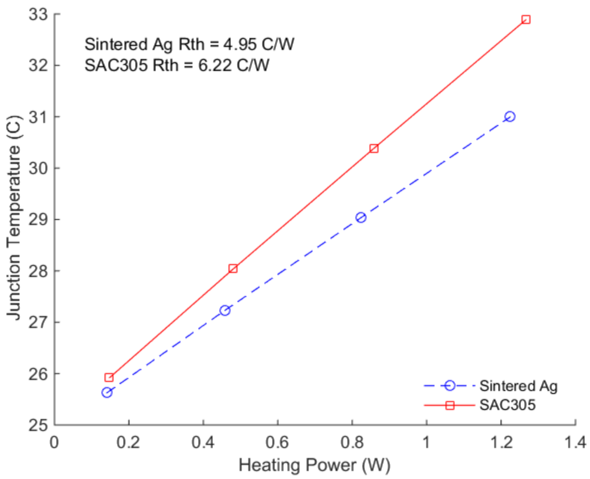


Figure 9 Average junction temperature vs heating power for LEDs with bond line thicknesses of from 25-75 µm. The slope of the line is the total thermal resistance of the LED.

E. Thermal Conductivity

By assembling LEDs identically except for the bond line thickness (BLT), we formed an experiment in which BLT was the independent variable and thermal resistance the dependent variable. Using this method we measured the thermal conductivity of the die attach material:

$$R_{th} = R_S \cdot T_h + R_{Rem}. \quad (4)$$

Where:

- R_{th}: is the total thermal resistance of the LED package, which is a function of T_h.
- T_h: is the thickness of the die attach layer (BLT).
- R_S: is the scaled thermal resistance of the die attach layer, measured in $(K/W \cdot m)$.
- R_{Rem} : is the thermal resistance remnant. It corresponds to the y-intercept of this linear equation, meaning it is the theoretical thermal resistance of the package if the BLT = 0. In other words, it is the thermal resistance of all the non-die attach layers.

Once the scaled thermal resistance, R_S, is known then the thermal conductivity of the material can be calculated:

$$k = \frac{1}{A \cdot R_S}. \quad (5)$$

Where:

- k: is the thermal conductivity of the die attach material, in W/m-K.
- A: is the surface area of the die attach layer.

The thermal resistance remnant R_{Rem} merits additional discussion: it is the sum total resistance of all the in-common elements of the LEDs tested, including the resistance of the die, dielectric (if present), substrate, thermal interface material, heat sink, and boundary layers of the die attach material. These boundary layers have different resistance properties than the bulk die attach material because, in the case of sintered silver, the material makes imperfect physical contact with the adjacent surfaces or, in the case of solder, there exists an alloy gradient at the interface. However, by varying only the BLT of a die attach material we can discount all the other resistance layers, thereby measuring the bulk conductivity of the material in-situ.

F. Thermal Results

Twenty-seven LEDs were assembled with sintered silver covering a BLT range of 10 to 160 µm. These were sintered for 1.5 hours at 225 C. Twenty LEDs were assembled with SAC305 preforms to achieve a BLT range of 18 to 133 µm. These were reflowed in vacuum to minimize voiding. Two wirebonds were used on each LED. Voids were measured and only samples with percentages less than 10% were used in the study. For testing, each LED was mounted to a thermoelectric cooler set to 25.00 C with a layer of indium to act as a thermal interface material. For every measurement the LED was required to thermally stabilize to within 0.02 C of the set temperature for at least 10 seconds. Each LED was powered via constant current at 0.1, 0.3, 0.5, and 0.7 A. Optical and junction temperature measurements were performed at each current level.

Junction temperature measurements using the forward voltage shift method gave a scaled R_{th} of 4,834 $K/W \cdot m$ for sintered silver samples (

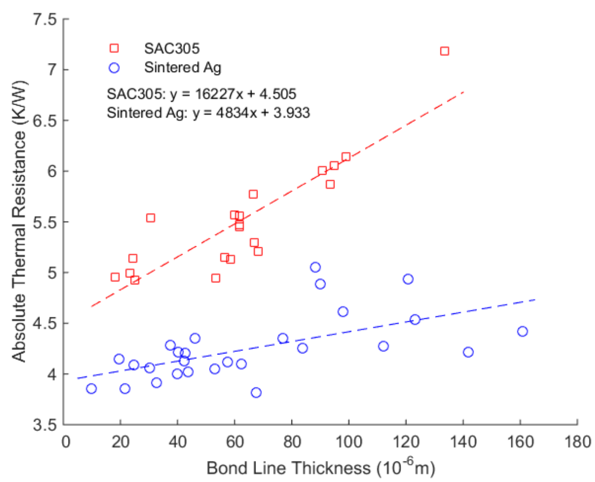
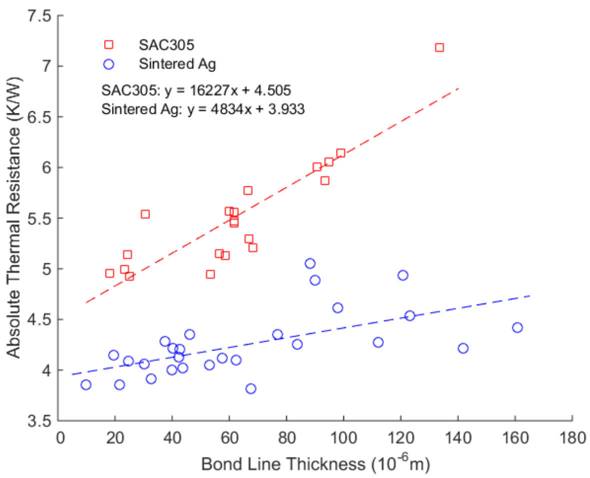


Figure 10). This corresponds to a thermal conductivity of 206.8 $W/m \cdot K$.

LEDs assembled with SAC305 showed a scaled R_{th} of 16,227 $K/W \cdot m$ and corresponding 61.6 $W/m \cdot K$ thermal conductivity.

The y-intercepts of the fitted lines in Figure 10 indicate that sintered silver has slightly lower interfacial resistance than SAC305. This is likely due to interfacial inter-metallic compounds and voids in SAC305 (despite significant efforts to minimize them). The unavoidable existence of voids in solder assemblies (even when using preforms and reflowing in vacuum), versus near void-less sintered silver performance, is a significant drawback.



The purpose of this experiment was to measure the thermal conductivity of sintered silver in-situ. In order to verify the accuracy of the method, we also measured SAC305. Therefore, if our measurement results for SAC305 were accurate, then we have some assurance that our measurements of sintered silver are also accurate. These results are encouraging because they accurately measure the thermal conductivity of SAC305 at 61.6 $W/m \cdot K$, which is known to be 64 $W/m \cdot K$. Our results are within 10% of the published value. We can therefore state with confidence that the bulk, in-situ thermal conductivity of Alpha sintered silver paste is within 10% of 206.8 $W/m \cdot K$.

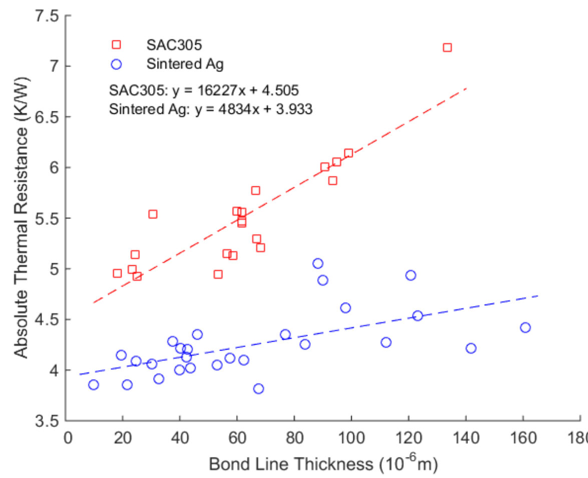


Figure 10 Thermal resistance of LEDs assembled with SAC305 and sintered silver. Each point on the graph represents the R_{th} of an LED plotted against its bond line thickness. The slope of each fitted line is the scaled thermal resistance of that die attach material. The y-intercept of each line corresponds to the remnant thermal resistance for that die attach material. LEDs assembled with sintered silver show lower thermal resistance than LEDs assembled with SAC305. Furthermore, the sintered silver line slope indicates a higher thermal conductivity and the y-intercept implies a lower interfacial resistance than SAC305.

IV. Optical Measurements

In addition to measuring the junction temperature, thermal resistance, and thermal conductivity, there are a few optical measurements that are useful in the LED industry that were also acquired. These measurements were performed in an integrating sphere according to LM-79-08 [2].

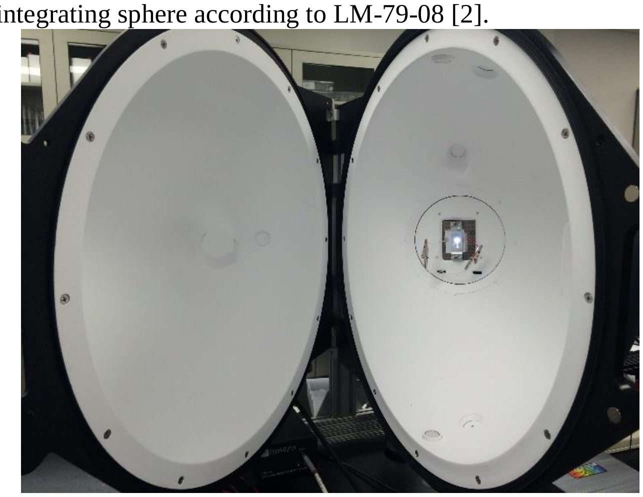


Figure 11 Integrating sphere used to measure optical emissions. A heat plate mounted on the outside of the sphere holds the LED sample at a constant temperature during tests. This integrating sphere is set up to perform 2π measurements.

A 0.5 m diameter Labsphere® integrating sphere was operated in 2π mode, meaning that the LED was placed on the edge of the interior of the sphere as shown in Figure 11. For calibration, two radiometrically calibrated halogen lamps were used to serially calibrate the integrating sphere and thermoelectric heat sink's test surface and mounted LED (Figure 12).

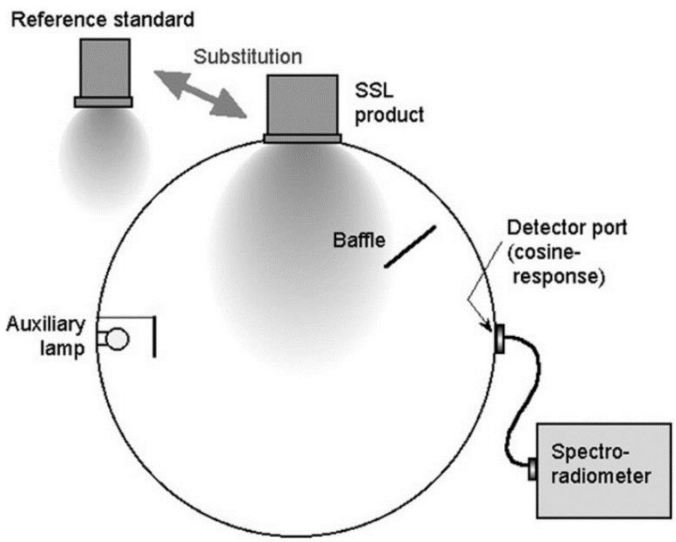


Figure 12 2π sphere geometry for performing spectroradiometric measurements on LEDs [2]. In our case we utilized a secondary sphere as the fiber input instead of a cosine-collector. Two radiometrically calibrated lights were used to calibrate first the sphere and then the LED and socket

A linear CCD-spectroradiometer gathered light via a small satellite sphere and optical fiber. The spectroradiometer had a spectral range of 360 - 1000 nm. LEDs were operated at constant currents of 0.1, 0.3, 0.5, and 0.7 A and the heat sink was set to 25.00 C. After the LED was illuminated it was required to stabilize to within 0.02 C for 10 seconds.

A. Measured Optical Parameters

The following optical parameters were acquired for each current level:

- Emission Spectrum - was measured from 360-1000 nm.
- 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.
- Efficacy - is measured in Lumens/Watt and is an indicator of how efficiently the LED converts electrical power into visible radiation.
- 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.

B. Optical Results

Optical tests show a clear and significant impact of die attach material on LED emission. Figure 13 shows that LEDs assembled with sintered silver have 30% higher luminous flux at 0.7 A than LEDs assembled with SAC305. Figure 14 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. The spectra plotted in Figure 15 show significantly higher luminous emission from an LED assembled with sintered silver versus an LED assembled with SAC305.

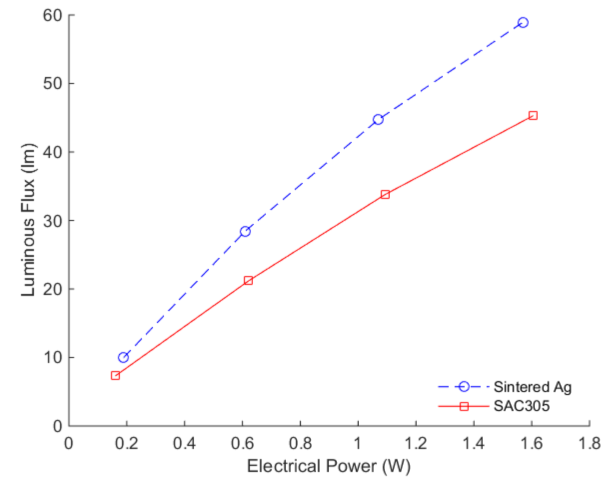


Figure 13 The average luminous flux of LEDs assembled with SAC305 and sintered silver die attach materials. Luminous flux is a measure of the total light output of an LED. These results were obtained using a spectroradiometer.

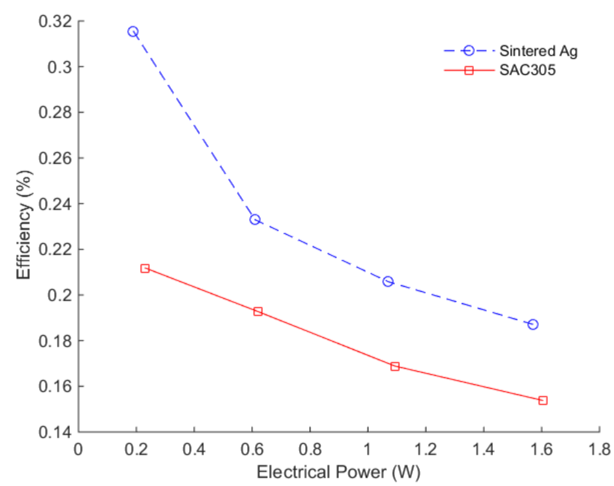


Figure 14 The average efficiency (measured in Watts/Watt) of LEDs assembled with SAC305 and sintered silver die attach materials. As the electrical power increases all LEDs experience lower efficiency. This effect can be somewhat mitigated by using higher thermally conductive die attach layers, such as sintered silver, as shown.

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.

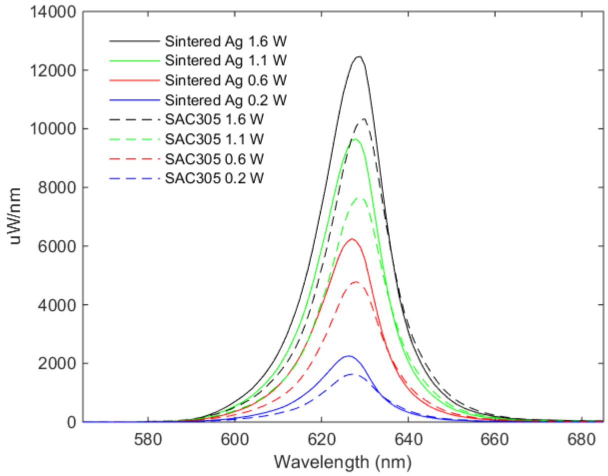


Figure 15 Emission spectra of two LEDs assembled with SAC305 solder and sintered silver die attach materials with equal bond line thickness. The LED assembled with sintered silver showed higher luminous flux and less peak wavelength temperature shift than the LED assembled with SAC305. (The spectra were acquired from 360-1000 nm but only the narrowband emission region is shown here for clarity.)

V. CONCLUSION

The die attach layer is an essential heat conduction path of an LED and its performance strongly depends on thermal conductivity. While JESD51-1 is the standard for determining the total thermal resistance of an LED assembly we needed to adapt it to measure the bulk thermal conductivity of high-performance sintered silver. By assembling test samples without dielectric and using sufficiently fast power switching, we measured the thermal conductivity of our sintered silver material at 206.8 $W/m \cdot K$. In order to assess the accuracy of our method we also measured SAC305 as compared to its bulk conductivity of 64 $W/m \cdot K$, and measured 61.6 $W/m \cdot K$, which is within 10%.

Furthermore, we performed optical measurements of LEDs assembled with the two die attach materials and saw significantly higher luminous flux and efficiency in sintered silver samples.

Sintered silver die attach materials, such as Alpha pressureless sintered silver paste, offer excellent optical and thermal performance improvements versus SAC305 solder.

VI. FUTURE WORK

Building on this work, in the future we intend to measure the temperature dependence of LED optical outputs using a high resolution spectrometer. Also, this paper focused on high-power vertical LEDs on metal substrates, so in the future we plan to examine mid-power packages on flexible LEDs as well as flipchip architectures. Lastly, we anticipate increasing performance of sintered silver at longer sintering times and will study that further.

VII. REFERENCES

[1] Electronics Industries Association, "EIA/JESD51-1 Integrated Circuits Thermal Measurement Method Electrical Test Method (Single Semiconductor Device)," 1995.

[2] Illuminating Engineering Society, "IES LM-79-08, Electrical and Photometric Measurements of Solid-State Lighting Products," 2008.