

An Overview -Advanced Packaging for Solid State Light Emitting Diode(SSLED) Lighting

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Abstract

Implementation of advanced packaging concepts in SSLED lighting has the potential to make a significant impact on worldwide energy and environmental concerns. In US Department of Energy studies (ref 1), it has been estimated that, on average, 2.1 quads of energy (the equivalent to 55 million tons of oil) could be saved annually by the implementation of Solid-State Lighting (SSL) nationwide. SSL uses solid-state Light Emitting Diodes (SSLEDs) for general illumination instead of traditional incandescent or fluorescent lighting sources. This paper will present an overview of the issues for current SSLED lighting technologies, and how advanced packaging and integration concepts can address these concerns.

In traditional lighting sources, the majority of electrical power is converted to radiant energy-visible light, IR and UV radiation and only a small fraction is converted to heat (~ 8 to 42%). However in SSLEDs, the electrical power is converted to visible light (~20%) and heat (~80%). Heat generated in Light Emitting Diodes (LEDs) has to be conducted away from the source or else the device junction temperature will rise. Without adequate thermal management, both the device performance and lifetime will be adversely affected by higher junction temperature.

High cost of SSLED-based lamps is another major factor preventing the widespread use of SSLED lighting. Currently LED lamps cost 50 to 100 times more than traditional lights. Despite the considerably longer lifetime of an LED light, the average consumer is not willing to pay the higher upfront cost.

The key to addressing these concerns is having a packaging solution that will provide adequate thermal management at a lower price. In this paper, the current and advanced packaging solutions are presented.

Key words: packaging, solid-state lighting, LED, thermal management, packaging cost

1. Introduction

Modern civilization depends on lighting for all aspects of life – daily routine, leisure, transportation, communication, and manufacturing. Quality of life has continuously improved with each new advance in lighting from fat-burning lamps to candles to gas lamps to incandescent lights. Now we are at the cross-road of another lighting evolution, referred to as solid-state lighting (SSL). Compared to the current lighting technologies like incandescent and fluorescent lamps, SSL can provide light with less energy and it is more environment-friendly. SSL is more efficient than traditional light because it has high light efficacy (lumens/watt of energy consumed) and the output light is more directional. In developing SSL that is more reliable and less costly, electronic packaging concepts have a very critical role to play.

1.1 Traditional and Solid-State Lighting Technologies

Traditional lights use electrical filaments, plasma or gas discharge as a light source. Incandescent light, invented by Thomas Edison in the nineteenth century, uses electricity to heat a coiled tungsten wire that is encapsulated in vacuum glass bulb. In most incandescent bulbs, the coil heats up to 3000-4000°K to give white light. In fluorescent light, commercialized in the mid-twentieth century, ultra-violet light is generated by striking an electrical discharge in a glass tube containing a low pressure gas such as mercury and argon.

Solid-state lighting refers to a type of lighting that utilizes light emitting diodes, inorganic or organic, as sources of illumination. Inorganic LEDs are made of Compound Semiconductor materials, which have direct band-gaps that facilitate efficient production of photons. The most efficient visible light-emitting

materials today are drawn from three and four component systems such as aluminum, indium, gallium, phosphide or nitride. Single-color inorganic LEDs are already in use and they have proved to have been bright, robust and long-lasting. Two key advantages of using inorganic LEDs are size and brightness [2]. Typically, they are 1 mm square in size and give luminescence of 2×10^8 cd/m², which is equivalent to 70W incandescent bulb. This brightness can potentially go significantly higher by further improving the efficiency of LEDs. The main challenge for inorganic LEDs is to achieve an affordable white-light LED that functions with high efficiency, high color rendering and long-life.

Organic LEDs (OLEDs) are made of carbon-based solids with discrete molecules, whose molecular weight typically exceeds 400 [3]. Low voltage organic devices have been demonstrated with amorphous materials made into extremely thin films, a few tens of nanometers thick. The molecular structure of one efficient LED that has been demonstrated consists of three phenylpyridine moieties, chelated to an iridium ion [4]. Compared to inorganic LEDs, OLEDs are larger in size and give moderate brightness. The brightness of 10^4 cd/m², which is needed for white light, has been demonstrated with OLED with relatively smaller lifetime in the order of thousands of hours. Also with these brightness value ranges, 1000 sq. cm or so will be needed to produce same amount of light as 70W incandescent light bulb. There is a large interest in OLEDs because of the low fabrication costs. Since there is no requirement to match lattice parameters of the device films to an expensive single crystal substrate, amorphous organic films can be deposited inexpensively on low cost and large area substrate materials like glass, plastic or metal foils. For example, printing techniques can be used to deposit OLED materials on Kapton sheets using reel to reel manufacturing process.

Colored LEDs are cost-effectively used in many applications like traffic signals, automobile indicators, and instrument panel lighting. However, the largest impact on energy use will come from the replacement of building and street lighting with Solid-State lighting. Building and street lighting require high quality white light. With the LED technology available today, white light cannot be produced using single material LED. There is a strong motivation to develop white light LEDs because of the huge potential for energy saving. In the US, 8% of energy and 22% of electricity is used for lighting. A significant energy savings from the use of SSL will result in huge impact on overall reduced energy use.

Human eyes perceive light of wavelength 400 to 700 nm ranging in color blue at 400 nm, yellow at 550 nm and Red at 700 nm. Any light output outside this range is beyond human perception and thus will be wasted. The white light is a combination of two or three colors, red, blue and yellow light (sometime green is also added in the mix as a fourth color). LEDs are not inherently white light sources. LED white light is produced using one of the two approaches as shown in Figure 1. The first option (see Figure 1a) is called the Phosphor Conversion approach. A blue or UV LED is coated with yellow phosphor material, to generate a combination of the blue and yellow light to yield white light. The second option (See Figure 1b) is called RGB color mixing approach. Two, three or four color LEDs are assembled side by side integrated with color mixing optics to render white light. The main advantages of the Phosphor Conversion approach are technology maturity, lower cost, and high luminous flux. The disadvantages are the light has bluish appearance and the light beam may have color variability. The advantage of using the RGB approach is that we can get higher flexibility in color rendering to get different shades of white. The main disadvantage of using the RGB approach is that the individual LED responds differently to drive current, operating temperature, dimming and operating time. Thus, better controls are needed on individual LEDs.

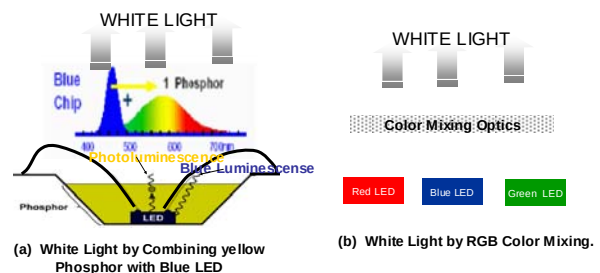


Figure 1: Approaches to make White Light LEDs.

1.2 Advantages of using Solid-State Lighting

Comparison to traditional lighting technologies, Solid State Lighting provides several advantages for use in building and street lighting. **Lower Energy Consumption:** As shown in Figure 2a [1], LED lighting consumes less power and lasts longer without sacrificing light output per watt. Luminous efficacy values shown in this table are from 2008. As illustrated in Figure 2b, the trend is to improve the efficacy of solid-state lighting to 200 lm/Watt by 2020. By achieving this benchmark, SSL offers a huge savings in energy consumption. **Higher lifetime:** As shown in Figure 2a, the lifetime of LED device is 50K hours, which is a many-fold higher than traditional

light sources. **Less Wasted Light:** LED light produces more uniform and directional lighting, which reduces wasted light. **Lower Maintenance Cost:** Significantly higher lifetime results in less replacement of the lamps and cost savings. **Higher Mechanical Integrity:** LED lamps are not affected by vibration and shock unlike traditional lights. In addition, LED lamps are in solid casing that does not fail easily like glass that is used for traditional lights. **Slower Device Failure:** LEDs do not fail catastrophically like traditional lights; instead they dim slowly over time.

1.3 Main Disadvantages with SSL

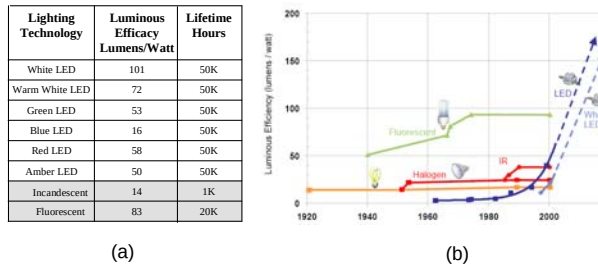


Figure 2: (a) Table showing the traditional and the Solid-State LED Efficacy and Lifetime (in 2008). (b) Trend line for efficacy of traditional and Solid-State Lighting [1].

The main disadvantages associated with LED lights are their thermal sensitivity and cost. The heat generated by the LEDs must be managed more precisely to maintain the performance and lifetime of the device, and they are relatively more expensive than conventional lighting. Since LED packages affect both these factors, these two issues are discussed in more detail.

1.3.1. Thermal Management

Traditional technologies convert 8 to 27% to visible light, 36 to 73% of electrical power to IR and UV radiant energy, and a relatively lower percentage, 19% to 37%, is converted to heat. On the other hand, in a typical LED 15 to 25% of electrical power is converted to visible light and 75-85% to heat[5]. There is negligible power converted to radiant energy. If the heat is not removed away from the LED die where the heat is generated, its junction temperature will rise, which higher will degrade the LED performance and lower its lifetime.

In a LED, higher junction temperature degrades performance in two ways. At a higher junction temperature, the light output will decrease as shown in Figure 3 [5]. The light output is inversely proportional to junction temperature. In addition to

the effect on light output, the wavelength of the output light will also increase at higher junction temperatures as shown in Figure 4 [6]. This shift will make orange

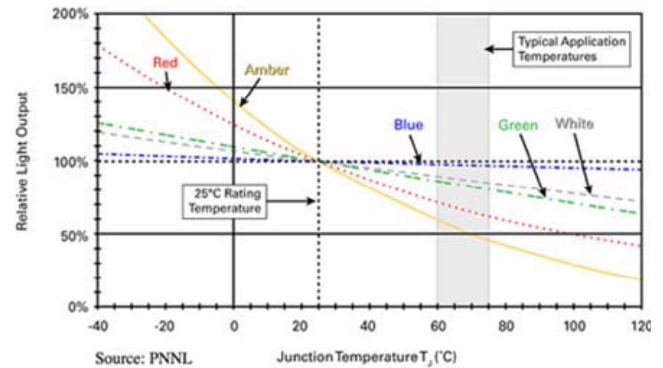


Figure 3: Light output as a function of junction temperature for different color LEDs.

light to appear red or white light to appear blue.

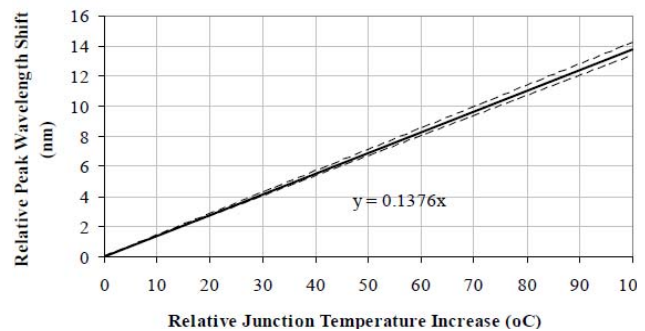


Figure 4 –The relative peak wavelength shift as a function of junction temperature. The solid line is the mean value, and the dotted lines show the standard deviation. [6].

A higher junction temperature will also adversely affect the lifetime or long term reliability of a LED device. Unlike traditional light sources, LED light sources do not fail catastrophically. Instead the light output degrades gradually over time. The useful operating lifetime of a power LED is extremely long; however, the gradual fading of the light over time may reduce the light output below a specified minimum. At that time, re-lamping will be required. The dependence of lifetime on junction temperature is shown in Figure 5 [7].

The LED light designers need to minimize this light degradation and lifetime by reducing the junction temperature using better thermal management. Ideally, the junction temperature should be as close to ambient temperature as possible. However, in the current state-of-the art technologies, the junction temperature is typically in the range of 60°C to 75°C (see Figure 3).

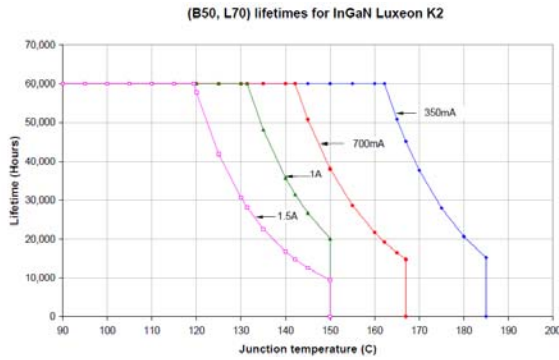


Figure 5: Lifetime data for 70% luminance maintenance as a function of junction temperature at different current levels for LUXEON K2 LEDs from Philips Lumiled [7].

1.3.2. Cost

The relatively higher cost of LED lighting is the main roadblock to switching from traditional lighting to LED lighting source. In 2008, integrated LED lamp costs were \$170/Klm, whereas traditional lighting technologies' costs were \$0.30 to \$4/Klm [1]. One of the main costs in LED lamps is the

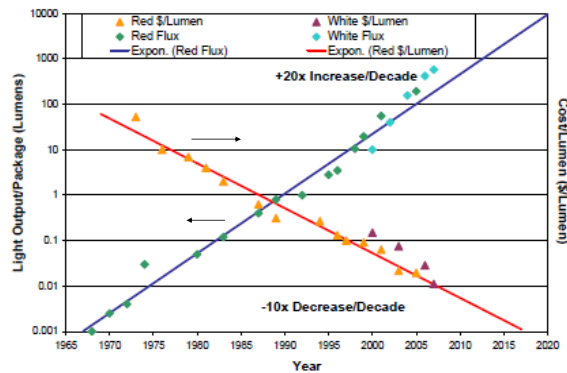


Figure 6 – LED cost and flux trend with time [1].

cost of packaging, which includes the thermal management solution.

Figure 6 [1] shows that the Department of Energy forecast to make LEDs with higher light output at lower cost. Both the industry and the government are funding R&D activities to keep the cost trend line going down well into the future.

The true cost of lighting depends on multiple factors, including the cost of the lamp, the labor cost to replace a lamp, the useful operating life, the power

consumption of the lamp, and the cost of electricity. One cost model [8] that has been presented is as follows.

$$\text{CostOfLight} = \{10/\text{LampLumens}\} * \{[(\text{LampCost} + \text{LaborCost})/\text{Lifetime}] + (\text{EnergyUse} * \text{EnergyCost})\}$$

Where:

CostOfLight = the true cost of lighting.

LampLumens = the light output of the lamp in lumens

LampCost = Initial cost (first cost) of the lamp in dollars.

LaborCost = the labor cost necessary to replace a lamp in dollars.

Lifetime = the useful operating life of the lamp, expressed in 1000 hours.

EnergyUse = the power consumption of the lamp, expressed in watts.

EnergyCost = the cost of electricity necessary to operate lamp \$/kWh

LED packaging directly affects the initial cost of lamp, light output and its lifetime. Figure 7 shows the trend in the cost breakdown of different components of a solid-state lamp, namely the LED, power supply circuits, thermal management and assembly costs. Packaging plays a major role in the last three components. Currently, these three components account for two-thirds of the overall cost. There are on-going efforts by the industry and the government to significantly reduce the cost of lamps. By 2015, the lamp cost is expected to be less than 30% of the current cost. During this period, the fabrication cost of LED devices is expected to be reduced at a faster rate, making the contribution of packaging-related costs to be a higher percentage of the total cost.

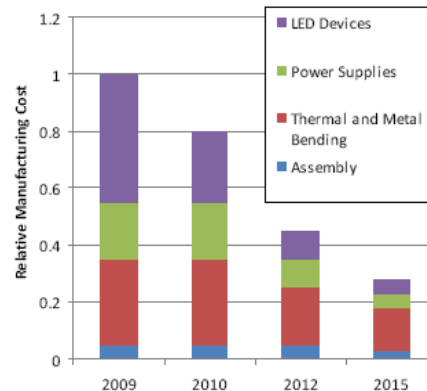


Figure 7: Manufacturing cost trend for Solid-state LEDs[9].

2. Role of Packaging

Advanced packaging technologies have a very critical role in the success of Solid State Lighting and the future of energy consumption. Typically, there are three different stages in SSL as illustrate by an example of a street light in Figure 8. First, the LED

dies are fabricated by growing compound semiconductors (e.g. GaN) on a growth substrate material, which is either SiC or sapphire[1,10]. Next, LED dies have to be packaged and then made into a solid-state lamp referred to as luminaire. Solid-state lamps (Luminaires) are made so that they could directly replace the traditional lighting sources.

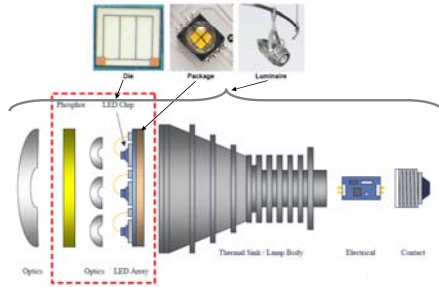
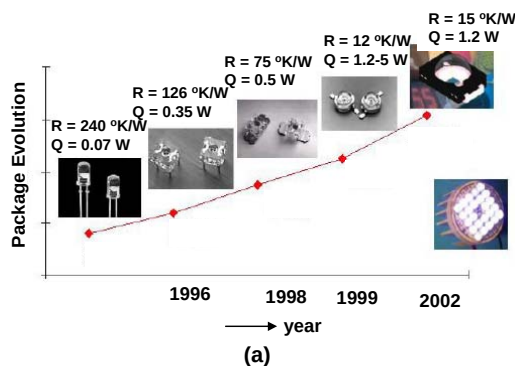


Figure 8: Typical packaging of solid-state light.

Many leading companies spanning the US, Europe, and Asia are pursuing the research, development and manufacturing of solid-state lights. As shown in Figure 6, total lumens per packaged LED is expected to rise to 1000 lumens by 2015 and to 10000 lumens by 2020. This will be achieved by both increasing the efficacy of LED devices and increasing the power per device. Packaging technology has already demonstrated better heat dissipation in the last few years. Figure 9a shows the thermal resistance of the package dropping from 240°C/W in 1996 to 12°C/W in 2002[11]. Power, flux and thermal resistance of some of the current commercial products are listed in Figure 9b[12]. Thermal resistance of current LED packages varies from 8°C/W to 24°C/W. There is continuing R & D efforts in industry to further improve the thermal resistance to below 3°C/W. These new technologies have not all been fully disclosed, and thus it is hard to assess the true state-of-the-art.



2.1 Die Attachment (wire-bond or Flip Chip)

Different vendors make LED dies either in wire-bond or in flip-chip format [13-14]. The light, heat and electrical paths in these formats are illustrated in two examples as shown in Figure 10. With the wire-bond format (Figure 10a), the whole backside area of the die is available for heat dissipation. However, the presence of the growth substrate material in the heat path will increase its thermal resistance. For wire-bond format, growth substrate made of SiC with a high thermal conductivity (120 W/m²°K) are preferred more than sapphire, which has a lower thermal conductivity (30 W/m²°K). It should be noted that SiC wafers cost twice that of sapphire. However, the wafer material cost in a die is a very small fraction of its overall fabrication cost.

In some of the more recent devices, a laser lift-off technique to remove the growth substrate has been developed to further improve the light output efficiency from a LED. Removal of growth substrate has made flip-chip LED attachment possible. With the growth substrate removed, the light can be transmitted through the back of the flip-chipped die as shown in Figure 10b. However, thickness of GaN device layer is only 5 micrometers after the growth substrate is removed. Handling of thin GaN layer will require special techniques. For flip-chip formatted die (Figure 10b), the heat path is through the bump bonds, which is fraction of the total die area. From the cost point of view, flip-chip version will probably be more expensive because there are added expenses associated with growth substrate removal, handling of thin GaN layer and possibly underfilling the gap between the die and the interconnect substrate with an encapsulant.

Thus from the analysis based on packaging options, the wire-bond format may be a better option; however, light output efficiency of the flip-chip version may

Power LEDs-Power vs flux vs thermal resistance			
LED type/Manufacturer	Power Watts	Flux Lumens	Thermal resistance Rth _{ja}
Top LED™/Osram	0.12	2.9	130°C/W
SuperFlux™/Lumileds	0.23	5	130°C/W
Golden Dragon™/Osram	1	21	24°C/W
NSC190D/Nichia	1	23	8°C/W
Luxeon™ I/Lumileds (350mA)	1	30	15°C/W
Luxeon™ III/Lumileds (1000mA)	3	72	15°C/W
Luxeon™ V/Lumileds (700mA)	5	120	8°C/W
Lumileds R&D LED	20+	500+	<3°C/W

(b)

Figure 9: (a) Package evolution as a function of time [11]. (b) Power, Flux and Thermal Resistance of current Commercial LED packages [12].

override these advantages.

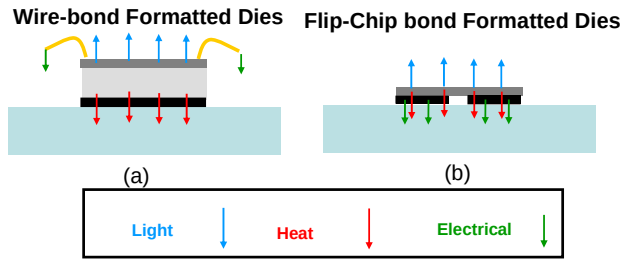


Figure 10: Light, heat and electrical paths in wire-bonded and flip-chip bonded LEDs.

2.2 Package Structure

The packaged LED has to be assembled on a board so that the driving circuitry can be connected to it. Figure 11a shows the structure of a typical commercial package with the interconnect board and heat sink. The thermal resistance of the total package, R_{total} , can be divided into four components, $R_{package}$, $R_{interconnect\ board}$, $R_{PCB\ Core\ and/or\ w\ baseplate}$ and $R_{heat\ sink}$.

$$R_{total} = R_{package} + R_{board} + R_{PCB\ Core\ and/or\ baseplate} + R_{heat\ sink} \quad \text{.....Eq. 3}$$

The thermal resistance of the board is usually very high, ranging from 9.7°C/W for FR4 printed wire board (PWB) with thermal vias on an aluminum baseplate, to 3.4°C/W for a multi-core board with an enhanced dielectric [13]. A better thermal management option for these commercial packages would be to attach the package directly to the heat spreader plate with high thermal conductivity, as shown in Figure 11b. In this case, Eq. 3 changes to:

$$R_{total} = R_{package} + R_{heat\ spreader} \quad \text{Eq. 4}$$

Eliminating the high thermal resistance of the dielectric from the package and directly attaching the

LED die to the heat spreader will significantly lower the junction temperature. Our preliminary thermal analysis, as shown in Figure 11, has confirmed a significantly better thermal solution even without heat sink.

2.3 Choice of Heat Spreader Material

Thermal conductivity of the heat spreader will affect the LED junction temperature and overall thermal resistance of the package. When GaN die is directly attached to the heat spreader in the improved package structure, as shown in Figure 11b, the thermal expansion mismatch between the die and heat spreader material must be considered. Thermal expansion mismatch will induce thermal stresses at the die/heat spreader interface which could cause long term reliability concerns (e.g., possibly causing the package or the die or the attach material to crack or delaminate during temperature cycles). Thermal strains are directly proportional to die size and in many cases where the die sizes are small (~1mm square) and temperature cycle range is not high, they may not pose a serious problem. Table I lists thermal properties of the LED die materials, sapphire, SiC and GaN, and some of the leading candidate heat spreader materials. Copper has high thermal conductivity and is a relatively inexpensive material; however, its thermal expansion coefficient is significantly larger than that of the LED materials. Aluminum is an alternative to copper. The thermal conductivity of aluminum is lower and is even less expensive than copper. The diamond-copper composite has a much higher thermal conductivity, a much better thermal expansion match to the LED materials, but is significantly more expensive. The copper-molybdenum-copper layered composite and the tungsten-copper composite have a better thermal expansion match to the LED materials, and are less expensive than diamond-copper, but their thermal conductivity is lower than that of copper.

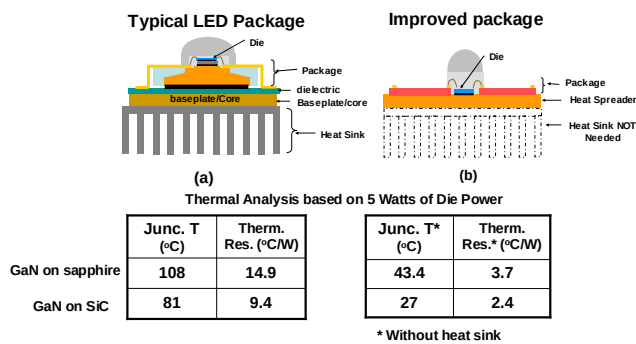


Figure 11: Illustration with preliminary thermal analysis (junction temperature and thermal resistance) of: (a) a typical commercial LED package and. (b) an alternative improved packaging option.

Table 1: Material Properties of SSLED Die and Candidate Substrate/Heat Spreaders.

Material	Thermal Conductivity (W/m ² K)	Thermal Expansion Co-efficient 10 ⁻⁶ /K (m/m)	Density gm/cm ³	Young's Modulus (GPa)
LED Materials				
Sapphire	30	8	3.97	372
SiC	120	4.0	3.1	410
GaN	1.3	3.17	6.2	204
Candidate Substrate/heat spreader materials				
Al	216	23.5	2.7	69
Cu	394	17	8.9	180
Diamond-copper composite	1200	6	5.5	255
Cu-Mo-Cu (13-74-13)	195 (in-pane) 165 (Thru-thickness)	5.9	9.88	195
W-Cu10	185	5.9	16.8	292

2.4 Selection of Die Attach Materials

The selection of the die-attach material is critical for both long-term reliability and thermal management. The die-attach material must be able to withstand the thermal strains induced by thermal expansion mismatch between the die, interconnect substrate and the heat spreader. Typically, these strains for a large LED die (~3mm square) could be as high as 10^{-1} mm/mm. In addition, the die-attach material is in the thermal path; thus, its thermal conductivity will affect the junction temperature. Table 2 lists the options for the die-attach materials, and their thermal resistances in the proposed package structure. Both conductive adhesives and solders are good options to consider. Conductive adhesive provides the lowest thermal resistance because adhesives can be applied with lower thickness relative to typical thickness of solder. As expected, the thermal resistance of the non-conductive adhesive is significantly higher. If non-conductive adhesive is used for a 5 Watt LED, the junction temperature will rise by 20°C. Thus, a non-conductive adhesive should only be considered in circumstances where the die has to be electrically isolated from the substrate.

Table 2: Options for Die-Attach Materials and their Thermal Resistance

Material	Thermal Conductivity (W/m ² K)	Thickness in Package Structure (micrometer)	Thermal Resistance (°C/W)
Solder (63/37)	51	50	0.98
Conductive Adhesive (DieMat DM6030)	30	15	0.5
Non-conductive Adhesive (Bondline 7258)	3	12	4

2.5 Encapsulation

The light output from LED must be optimized and channeled by using lens made of encapsulants. In the case of phosphor-based white light LEDs, encapsulants are used as a vehicle to deposit phosphors on LEDs. Usually, two encapsulants are layered over the die as shown in Figure 11b. The bottom encapsulation is silicone-based, which provides protection for the wire bonds. The top encapsulant, Encapsulant 2, will be an epoxy-based material, which can be the matrix for phosphors.

2.6 Cost Reduction in LED Packaging

For SSL to be successful, aggressive approaches to cost reduction have to be taken. The cost reduction has to come not only from manufacturing, but also from the selection of simpler packaging structure that have higher heat dissipation efficiency. Since keeping the die junction temperature close to ambient temperature is very critical, current packaging approaches use expensive heat sinks. Typically, the heat sinks needed must have a thermal resistance in the range of 1 to 5°C/W, which cost around \$1 to \$10 per unit [15]. Thus by eliminating the heat sink, a significant cost savings could be realized as in the improved package structure shown in Figure 11b. Another cost reduction option could come from the low cost mass-producible techniques like wafer-level packaging processes.

The costs can be significantly reduced by using innovative LED packaging approach that uses simple package structure with less thermal resistance without the use of expensive heat sinks as shown in Figure 11b.

3. Conclusions

Two main issues that must be addressed to enable widespread use of solid-state lighting are thermal efficiency and cost of packaged LEDs. Without adequate thermal solutions to minimize the junction temperature of the LED device, both performance and lifetime will be adversely affected. Currently solid-state lights cost 50 to 100 times more than traditional lights. Despite the considerably longer lifetime of an LED light, the average consumer is not willing to pay the higher upfront cost. The key to addressing these concerns is having a packaging solution that will provide adequate thermal management at a lower price.

The choice of die attachment, flip-chip or wire-bonded, and package structure play a critical role in reducing the junction temperature; however, selected technology should also be low cost. One option for package structure is to use high thermal conducting

heat spreaders. Another option may be to eliminate the interconnect dielectric from the heat path by attaching the LEDs directly to the heat spreader. Also the use of solder or high thermal conductivity adhesives for die attach will help reduce the junction temperature. In our thermal analysis, we have shown that significantly lower junction temperature and potentially lower cost can be achieved by adopting these guidelines to develop a package structure, which may not require the use of an expensive heat sink.

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