LIGHT EMITTING DIODE PERFORMANCE & OPTIMIZATION

Trevor Howard, Seth Kennedy, Derek Tenner, Kasemsak Kijkanjanapaiboon, and Xuejun Fan
Department of Mechanical Engineering
Lamar University
arethoward@gmail.com, seth.t.kennedy@gmail.com, dbtenner@gmail.com,
samkasemsak@yahoo.com, xuejun.fan@lamar.edu

With technology paving the road for economic solutions that will reduce the amount of energy consumed, Light Emitting Diodes (LEDs) are quickly becoming a popular and the desired form of illumination. LEDs are up to ten times more efficient than incandescent lights and are double the efficiency of compact fluorescent lights (CFLs). While CFLs are comparable in efficiency, they contain mercury and produce ten times the amount of heat as an LED. Another advantage of LEDs is that they can withstand a wider range of environments. The LEDs used for household lighting produce blue light. To provide the desired white light, they are manufactured with a yellow silicone phosphor encapsulant. While the encapsulant allows for the emitting of white light, it has a few disadvantages. One in particular is that some of the light output is reduced which leads to a decrease in efficiency, and perhaps the biggest downside is the change in light output color over the lifespan of the LED. Due to the heat generated inside the LED and other environmental factors, the silicone phosphor encapsulant hardens and degrades over time. While the change in color is common among other types of light bulbs, it is more often noticed in LEDs due to their longer lifespan. The efficiency and lifespan of LEDs has been well documented. Of all of the factors that contribute to the long life and high efficiency of LEDs, the junction temperature is one of the most crucial. The junction temperature of the LiteOn 5630 LED was estimated using thermal modeling from data collected from a LabSphere Illumia® Light Measurement System. This system allows a myriad of performance data to be gathered and analyzed from nearly any light source. The results have shown that purity, efficacy, and efficiency are all related to the LED's junction temperature. By having a clearer understanding of how external temperature and LED module design affects junction temperature, the industry will have a more accurate estimation of LED lifespan and efficacy at real world operating conditions. This research is funded by a Lamar University Office for Undergraduate Research Grant.

Introduction

With technology paving the road for economic solutions that will reduce energy consumption, LEDs are quickly becoming a popular way to light up the world. LEDs are up to ten times more efficient than incandescent lights and operate with twice the efficiency of compact fluorescent lights (CFLs). While CFLs are comparable in efficiency, they contain mercury and produce considerably more heat than LEDs. Apart from their excellent performance, LEDs can also handle harsh environments and have an unbeatable lifespan.

Current technology allows for the manufacturing of three different types of LEDs. These are characterized by their light output color: red, blue, or green. The LEDs used in household lighting, such as the LiteOn 5630 which was analyzed in this paper, produce blue light. To provide the desirable white light, the LEDs are manufactured with a yellow or orange silicon phosphor encapsulant.

Since light has additive properties, LED lights are capable of producing a desired color light wave by directing various color lights at the same intensity, producing a color. When blue, red, and green lights are focused together at the same intensity, the resulting color is white. This coloration correlation scheme is presented in (Fig. 1). LED lighting design focuses on the addition of various colors at various temperatures in order to produce the desired white light illumination.

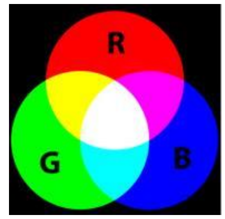

Fig. 1: Tri-Color Chart

While the encapsulant allows for the emittance of white light, it also has a few disadvantages. One in particular is that some of the light output is reduced which results in a decrease in efficiency. Perhaps the biggest downside is the subtle change in light output color over the lifespan of the LED. This color change is caused by the hardening and degradation of the silicon phosphor encapsulant over time. While a change in color is common among other types of light bulbs, it is more often noticed in LEDs due to their longer lifespan.

To reduce the degradation in light output quality of the LED module, further studies should be directed at heat dissipation to enhance performance. Analyzing LED performance for a range of power inputs and a range of chip board temperatures will provide a better understanding of how to design specialized heat sinks to improve LED performance. This experimental stage will be conducted with the use of a LabSphere Illumia® Light Measurement System.

A thermal analysis was utilized to provide a correlation study on how heat flows through the LED module. This correlation study compared the data collected by the LabSphere and the thermal model to determine the most desirable performance points and discover the mechanisms which

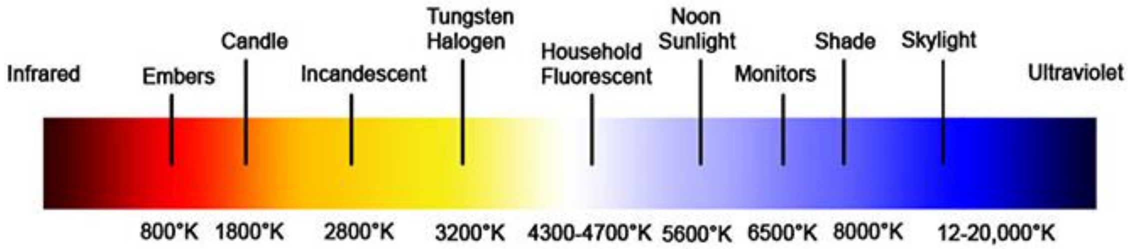

Fig. 2: CCT Scale

lead to component degradation. This may also include the design and analysis of various heat sinks that will help increase the efficiency of the LED and lengthen the lifespan.

A correlated color temperature (CCT) scale relates the output temperature to the resulting thermal color. The color emitted by the light source can be identified using a Kelvin Color Temperature Scale as provided in (Fig. 2). All LED light sources are measured in their ability to accurately render all colors of the spectrum. As a result, a CCT is capable of producing a rough estimation for the temperature. Colors are denoted by either warm or cool. Warm colors are associated by temperatures of 800k to roughly 4700k whereas cool colors range from 4700k to 20000k. The hybrid chart shown in (Fig. 2) gives a representation of the CCT of common light sources encountered as a reference.

For these studies the LiteOn 5630 LED module was utilized. LiteOn recommends running the LED module at 150mA which will provide about 0.5W of power, thus this condition is used as the control. The dimensions of this module are located in the Appendix along with a few characteristics which are useful for comparing the results of the analyses performed in this paper. Some of the materials used in the construction of LED module are InGaN, sapphire, aluminum, copper, and silicon phosphor.

LabSphere Illumia

A LabSphere Illumia® Light Measurement System was utilized to collect the spectral data used in the correlation study. The LabSphere Illumia® Light Measurement System consists of three main pieces. The first is a sphere that encloses a light source. This sphere is coated in a special white lining that reflects nearly all light. The sphere has the ability to measure spectral data from a two or three dimensional light source. The second part is a hardware rack which contains the units used to control power output and light source mounting plate temperature. The third piece to the system is the LabSphere software. The software takes the data gathered from sensors inside of the sphere and outputs various data. This data can be exported for further analysis. This feature was used to export data to Microsoft® Excel where the data was further processed. This facilitated the calculation of the LED's efficiency through the measured power input and spectral analysis data.

The spectral analysis data was collected from the LabSphere Illumia® Light Measurement System. The LabSphere Illumia® software was able to directly output several key parameters and other data directly to Microsoft® Excel. Some of the other key parameters found by the LabSphere Illumia® include color correlation temperature, luminous efficacy, efficiency, color purity, and light power output. Luminous efficacy is the ability to produce visible light. All light sources produce non-visible light in the infrared and ultra-violet wavelengths. These are not desired because they contribute to heat output without being useful to the human eye. The light purity is based off of the color space diagram. Light purity is a measurement of how pure the light output is with respect to pure white light.

The thermal power output of the LED was calculated from the data exported into Excel. The thermal power output was obtained through the equation shown in Eq. (a). The thermal power output was later used in the correlation study. It is important to note that the total light power output calculated by LabSphere is for light visible to the human eye and excludes non-visible light.

Eq. (a)

$$hermal\ Power_{output} = Total\ Power_{\ input} - Light\ Power_{\ output}$$

Thermal Modeling

For the thermal modeling, advanced heat transfer techniques were applied to the LiteOn 5630 LED module. The modeling was performed primarily in one dimension and then modified to provide a two-dimensional approach to the heat flow characteristics of the module. Modeling was performed for three separate cases; each adding components to understand the breakdown of thermal flow. Several assumptions were used such as the convective heat transfer coefficient was 5 W/m^2, ambient temperature was set to 21°C, component structures were rectangular, and the thermal coefficients were estimated. Since component structures were assumed rectangular for ease of the thermal modeling, the geometries and thus the equivalent thermal resistances are not exact.

Case 1:

The first modeling case consists of heat transfer vertically in one dimension through a standalone LED module. This model removed the aluminum printed circuit board, or PCB, which results in convection on the top and bottom of the module (Fig. 3). Conduction also occurs between each of the LED module components. The model includes only the chip itself along with the silicon phosphor and the lead frame. The copper lead tabs were excluded in this case. The equivalent thermal resistance circuit is shown in (Fig. 4).

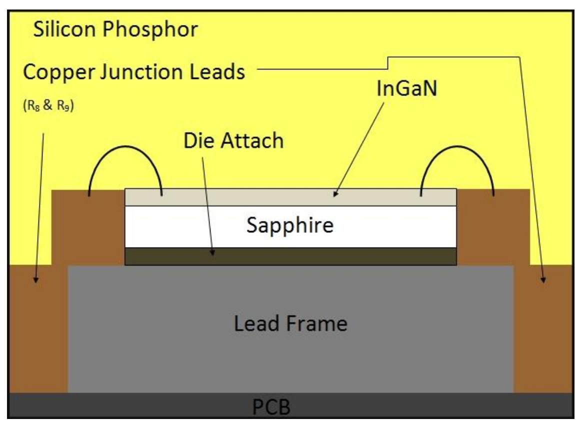

Fig. 3: LiteOn 5630 Simple Layout

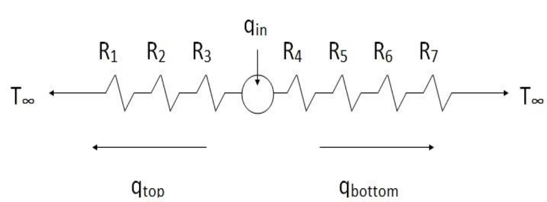

Fig. 4: Case 1 Equivalent Thermal Resistance Circuit

In this circuit, T_∞ is the air temperature around the LED module and for the modeling purposes it was assumed to be 21° C. The thermal resistances R_1 and R_7 are the convective resistances which are calculated using Eq. (b) and Eq. (c).

$$_1 = \frac{1}{h_t \cdot A_m} \qquad \text{Eq. (b)}$$

$$_7 = \quad 1 \qquad \text{Eq. (c)}$$

Descriptions of each of the symbols in the equations are located in the Nomenclature. The remaining thermal resistances are for the conductive heat transfer of the chip component. These are for the following materials: R_2 = silicon phosphor, R_3 = Indium Gallium Nitride, R_4 = sapphire, R_5 = die attach, and R_6 = lead frame. The equations are as follows:

$$_2 = \frac{L_{sp}}{k_{sp} \cdot A_m} \qquad \text{Eq. (d)}$$

$$_3 = \frac{L_{InGaN}}{k_{InGaN} \cdot A_{ch}} \qquad \text{Eq. (e)}$$

$$_4 = \frac{L_s}{k_s \cdot A_{ch}} \qquad \text{Eq. (f)}$$

$$_5 = \frac{L_{da}}{k_{da} \cdot A_{ch}} \qquad \text{Eq. (g)}$$

$$_6 = \frac{L_{lf}}{k_{lf} \cdot A_m} \qquad \text{Eq. (h)}$$

The energy input, q_{in}, is the thermal energy into the LED junction. Likewise, the thermal energy flowing out of the junction is defined as: q_{top} for energy flowing through the top of the module, and q_{bottom} for the energy flowing through the bottom of the module.

Case 2:

The second case is similar to Case 1 with the addition of the copper lead tabs. The addition of these tabs will add two pathways that will be parallel to the flow through the top and through the bottom of the module as seen in (Fig. 5).

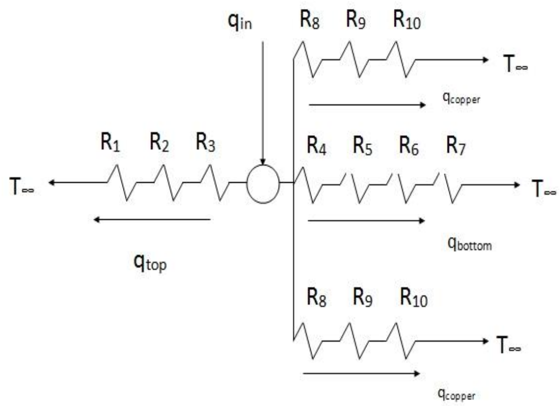

Fig. 5: Case 2 Equivalent Thermal Resistance Circuit

This stage of the thermal modeling is where advanced heat transfer techniques become useful as one-dimensional techniques are applied to create a two-dimensional model. The resistance R_{10} is defined as convective thermal resistance using Eq. (i).

$$_{10} = \frac{1}{h \cdot A_c} \qquad \text{Eq. (i)}$$

Thermal resistances R_8 and R_9 are the conductive thermal resistances through the length of the copper. R_8 is for the length of copper leaving the junction and traveling down to the copper tab located on the PCB. R_9 is the conductive resistance through the thickness of the copper tab. These tabs can be seen in the LED thermal model design in (Fig. 3) and the equations for these equivalent resistances are defined below.

$$_8 = \frac{L_{c\,out}}{k_c \cdot A_c} \qquad \text{Eq. (j)}$$

$$_9 = \frac{L_{c\,down}}{k_c \cdot A_c} \qquad \text{Eq. (k)}$$

The additional thermal flow q_{copper} is simply defined as the thermal energy flowing through the copper lead tabs.

Case 3:

Following the trend of Case 1 and Case 2, Case 3 adds another factor to the LED thermal model. The aluminum PCB is added and the convection is removed from this stage because the PCB temperature is measured and controlled during the experiment by the LabSphere software and equipment. The resulting equivalent thermal circuit is shown in (Fig. 6).

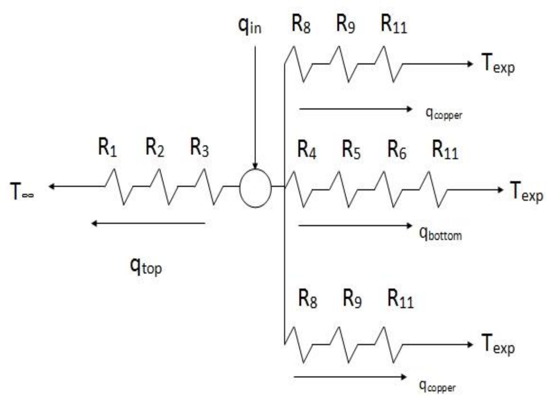

Fig. 6: Case 3 Equivalent Thermal Resistance Circuit

The resistance R_{11} is defined as the conductive resistance through the aluminum PCB. It should also be noted that due to the size and thermal conductivity of the PCB, it doubles as a heat sink.

$$_{11} = \frac{L_{PCB}}{k_{PCB} \cdot A_{PCB}} \qquad \text{Eq. (l)}$$

Other than the addition of the PCB, Case 3 is very similar to Case 2 although the results can be expected to be different.

Results

The results of both the thermal modeling and the experimental sessions will be discussed in this section.

LabSphere Illumia®

Using the LabSphere Illumia® Light Measurement System several variations of an experiment were initiated to examine the LiteOn 5630's performance under various conditions. One session of these experiments dealt with varying power inputs with the PCB at room temperature and the other consisted of controlled PCB temperatures using a constant power input. The averaged results for the experiments can be seen in Table 1 below.

After carefully reviewing the LabSphere

Table 1: LabSphere Illumia ® Results

LiteOn 5630-V23 Variable Power						
Amps (mA)	Input(W)	Light Power (W)	CCT (K)	Efficiency	Efficacy	Purity
75	0.23	0.09	2835	37.5	114.6	61.8
150	0.50	0.16	2843	32.3	98.0	61.3
300	1.10	0.27	2842	24.9	76.3	60.2
LiteOn 5630-V23 Variable Temperature						
Temp (°C)	Input (W)	Light Power (W)	CCT (K)	Efficiency	Efficacy	Purity
25	0.50	0.16	2841	32.5	98.2	61.3
50	0.49	0.15	2835	30.9	95.1	60.5
100	0.48	0.14	2846	29.2	87.9	58.4

experimental data, it is worth noting that the results correlated very well with the manufacturer's published data (see Appendix) for LiteOn 5630. The manufacturer recommended amperage input for the LiteOn 5630 is 150mA and the experimental data was compared to this controlled input.

Experimental results for the variable power inputs were measured at 75mA, 150mA (control), and 300mA. The amperage input of 150mA is used as the control because this is the manufacturer's recommended operating input. As expected, the higher the power input, the lower the efficiency, efficacy and purity. This is due to the increased thermal output of the LED module which caused an increase in junction temperature, thus decreasing performance and life span.

Similar results can be seen for the controlled PCB temperatures. Due to the design of the LED module, the PCB acts as a heat sink and a majority of the thermal energy flows through the PCB. Thus, by controlling the PCB temperature, the LED junction temperature can be controlled. Since an increase in power input raises the junction temperature and in turn decreases the performance, it can be expected that manually raising the junction temperature will also decrease the performance. This assumption is verified by the LabSphere experimental data where the efficiency, efficacy, and purity all decrease with an increase in PCB temperature.

Thermal Modeling

The main purpose for performing the thermal modeling was to perform a correlation study between the performance witnessed during the LabSphere experimental sessions and the changes in junction temperature calculated using advanced heat transfer techniques. These techniques were described in detail previously. The temperature for each layer of the LED module was calculated for each case and experimental analysis, but for simplicity, only the junction temperature, atmospheric, and PCB temperatures are shown. The results for Case 1 are presented in Table 2.

Table 2: Case 1

Thermal Modeling: Case 1				
Experiment	q_{in} (W)	$T_{ambient}$ (°C)	T_{PCB} (°C)	$T_{junction}$ (°C)
75mA	0.14	21	23.56	1812
150mA	0.34	21	23.83	4216
300mA	0.83	21	25.19	10375
25°C	0.33	21	25	4193
50°C	0.34	21	50	4232
100°C	0.34	21	100	4222

As expected, the standalone LED module experiences a very high junction temperature due to the size of the module and convection on each side of the chip.

Table 3: Case 2

Thermal Modeling: Case 2				
Experiment	q_{in} (W)	$T_{ambient}$ (°C)	T_{PCB} (°C)	$T_{junction}$ (°C)
75mA	0.14	21	23.56	1679
150mA	0.34	21	23.83	3906
300mA	0.83	21	25.19	9609
25°C	0.33	21	25	3885
50°C	0.34	21	50	3920
100°C	0.34	21	100	3911

The junction temperature results for Case 2 are shown above in Table 3. The addition of the copper wiring and tabs adds another pathway for the thermal energy to exit the LED module which in return results in slightly cooler junction temperatures than those seen in Case 1. For Case 3 the PCB is added and there is assumed to be no convection on the PCB because the temperature of the PCB is read and controlled directly using the LabSphere. Due to the immense size of the aluminum PCB compared to the small size of the LED module, the PCB acts as a heat sink for the LED. The results can be observed in Table 4.

Table 4: Case 3

Thermal Modeling: Case 3				
Experiment	q_{in} (W)	$T_{ambient}$ (°C)	T_{PCB} (°C)	$T_{junction}$ (°C)
75mA	0.14	21	23.56	23.9
150mA	0.34	21	23.83	24.6
300mA	0.83	21	25.19	27.0
25°C	0.33	21	25	25.7
50°C	0.34	21	50	50.8
100°C	0.34	21	100	100.7

With the final stage in the thermal modeling, the junction temperatures calculated began to fall within the manufacturer's published operating range and the LabSphere experimental results. While Case 1 and Case 2 produced junction temperatures which would instantly render the module inoperable, Case 3 produced results which will provide high efficiency and a long life span from the LiteOn 5630 LED.

The thermal modeling for this research is not exact as several assumptions were made for the thermal conductivity as well as the size and shape of several LED module components. However, the experimental and analytical results correlate well with the manufacturer's recommended operating temperatures.

Conclusion

Performing the variety of different cases for the experimental session provided a thorough understanding of which factors most influence the junction temperature, should they be PCB temperature or input power. The first two thermal modeling cases determined that a heat sink is necessary for the LED module to successfully operate; otherwise it will undergo catastrophic failure. The results from Case 3 in the thermal analysis combined with the LabSphere Illumia® provide an accurate estimation to the thermal energy flow through the LiteOn 5630 LED. While the LiteOn 5630 LED module does not have a specially engineered heat sink, Cases 1 and 2 prove that a heat sink is necessary for the operation of the LED. Without a heat sink, the LED would instantly reach unsustainable temperatures and fail. Further measures can be taken to improve the LiteOn 5630 by engineering a compact PCB which functions better as a heat sink than the existing PCB. A new well-designed heat sink can lead to a desirable compact size with improved performance. This is achieved by incorporating pins or fins onto the heat sink which increases the convective heat transfer. This increase can lower the junction temperature of the LED contributing to a higher performance. Traditional white LEDs utilize a light-emitting semiconductor coupled with a phosphor. Most of the light protons that are produced in this arrangement are absorbed and lost within the semiconductor die. This ultimately leads to a decrease in efficacy and light output. To counteract the decrease, additional research into optic configurations on the phosphor component with appropriate distance away from the die is required. Specially designed optics can release the light photons through the sides of the optics which can produce an astonishing 30 to 60 percent more light output and efficacy. The placement of the phosphor from the semiconductor die also adds an advantage by improving the LED's life.

Nomenclature

A	Area
h	Convective heat transfer coefficient
k	Thermal conductivity coefficient
L	Thickness
q	Energy
R	Equivalent thermal resistance
T	Temperature

Subscripts

c	*Copper*
ch	*Chip*
InGaN	*Indium gallium nitride*
lf	*Lead frame*
m	*Module*
PCB	*Aluminum chip board*
t	*Top*
da	*Die attach*
s	*sapphire*
sp	*Silicon phosphor*
∞	*Ambient*

Labsphere Screenshot

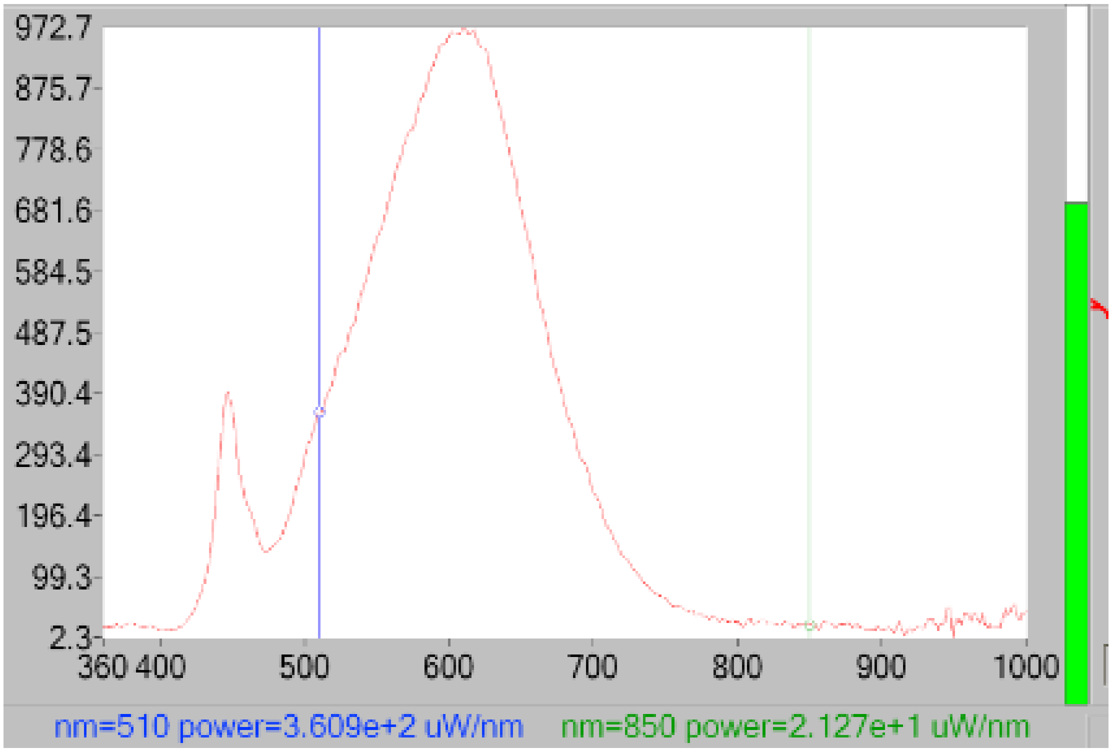

Fig. 7: Intensity vs Spectrum

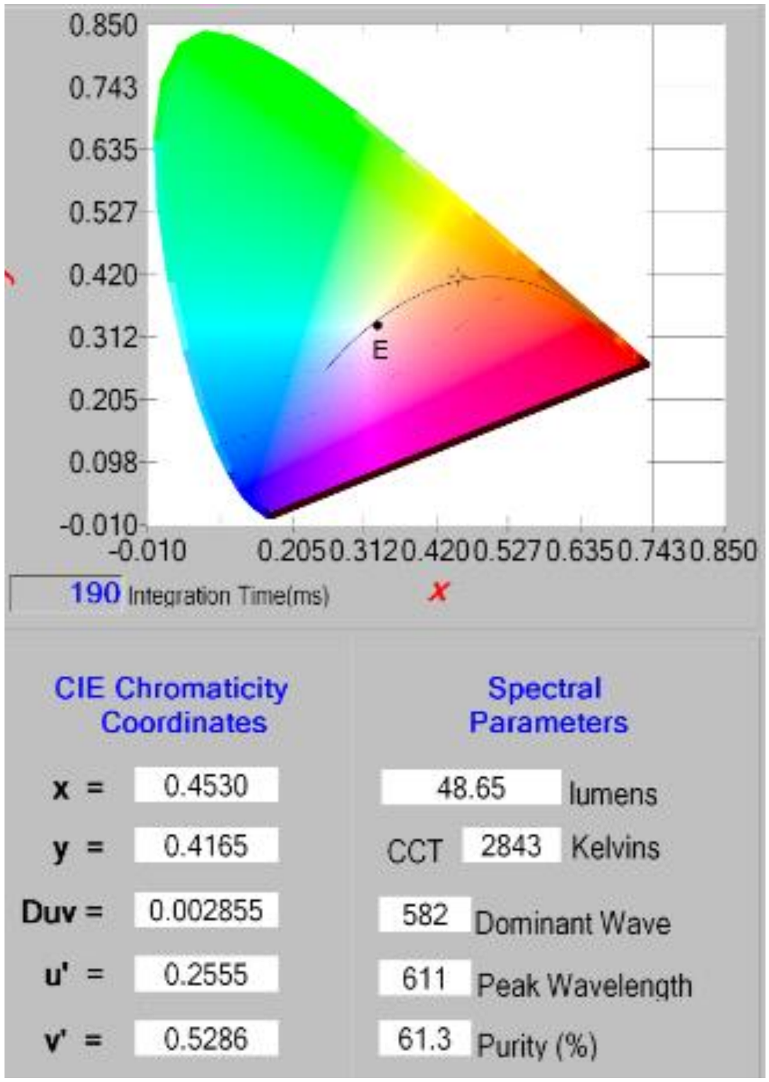

Fig. 8: Chromaticity Chart and Spectral Parameters

LiteOn 5630 Published Data

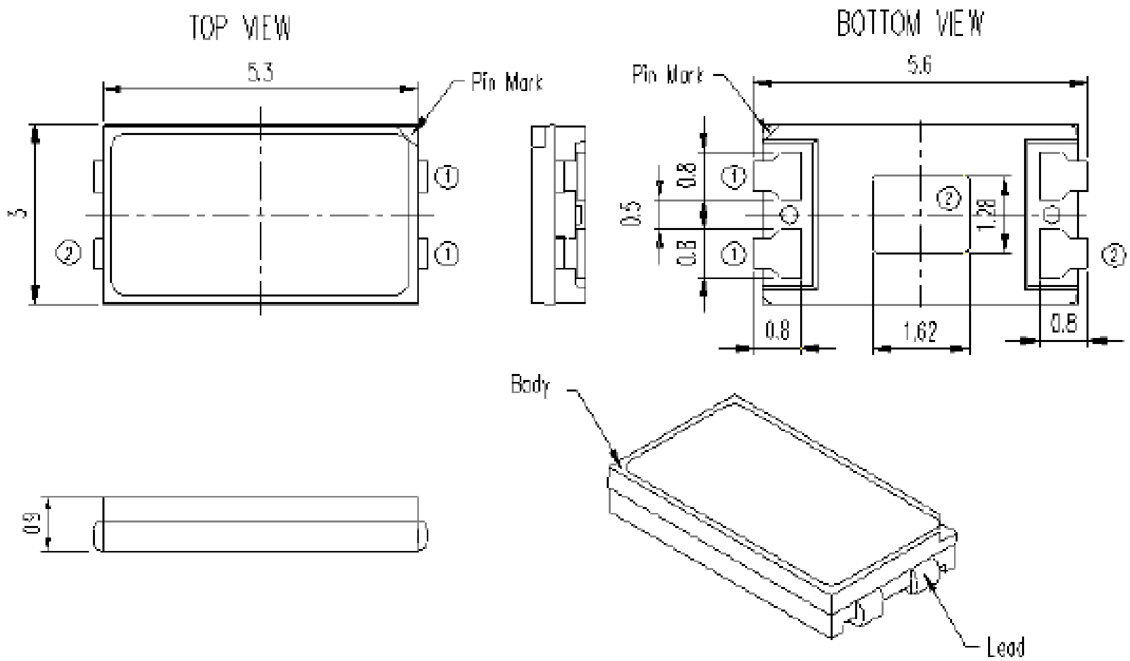

Fig 9: LED Package Dimensions

Parameter	Symbol	Values								Unit	Test Condition
Correlated Color Temp.	CCT	Typ.	2700	3000	3500	4000	5000	5700	6500	‘K	
Chromaticity Coordinates	x	Typ.	0.458	0.434	0.408	0.382	0.345	0.329	0.312	-	I_F = 120mA
	y	Typ.	0.410	0.403	0.392	0.380	0.355	0.342	0.328		
Luminous Flux [1]	Φ_v	Min	41.0	42.5	44.0	44.0	45.5	44.0	42.5	lm	
		Typ.	50	53	54	55	54	55	53		
		Max.	59.0	60.5	63.0	62.0	63.5	62.0	60.5		
Optical Efficiency	η_{opt}	Typ.	133	141	144	146	144	146	141	lm/W	
Color Rendering Index	CRI	Min.	80							-	
Viewing Angle	$2\theta_{1/2}$	Typ.	120							deg	
Forward Voltage	V_F	Min	2.9							V	
		Typ.	3.13								
		Max.	3.3								
Thermal Resistance	Rjt	Typ.	15							℃/W	
ESD-Withstand Voltage	ESD	Min	5K							HBM	V

Fig 10: Electro-Optical Characteristics

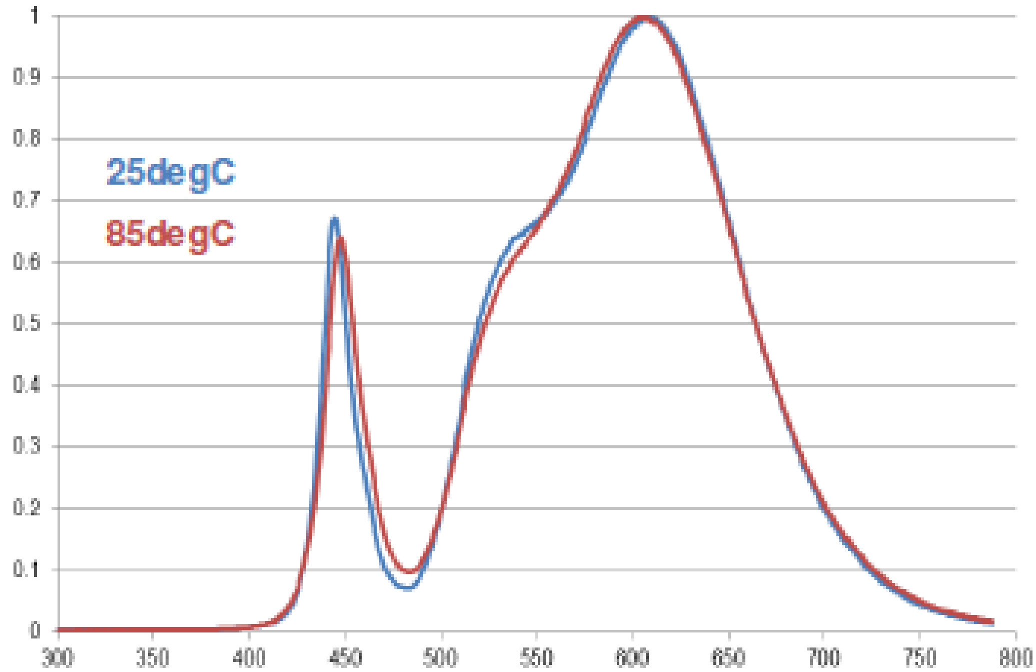

Fig 11: Intensity vs Spectrum

References

[1] J. A. Byrdson, *Plastics Materials*, 7^{th} ed., Butterworth-Heinemann, Oxford, 1999

[2] Anon. "Sapphire Properties," http://www.roditi.com/SingleCrystal/Sapphire/Properties.html, 2013, (accesses January 2014)

[3] C. Mion, "Investigation of the thermal properties of gallium nitride using the three omega technique", http://repository.lib.ncsu.edu/ir/bitstream/1840.16/5418/1/etd.pdf, 2005, (accessed January 2014)

[4] A. D. McConnel, S. Uma, KE. Goodson, "Thermal Conductivity of Doped Polysilicon Layers", *Journal of Microelectromechanical Systems*, vol. 10, no. 3, September 2001.

[5] Anon. "LED Middle POWER: 5630 Product Data Sheet",http://optoelectronics.liteon.com/upload /media/light/Datasheet/LTW-5630AZL%20Series%20Data%20 Sheet_V3_20130913.pdf, (accessed January 2014)

[6] J. Sanderson, "Color Purity of LEDs", http://www.deepsea.com/wp-content/uploads/article-Color-Purity091214.pdf, 2009, (accessed January 2014)

[7] Anon. "LabSphere: Spectral Flux Measurement Systems", http://www.labsphere.com/illumia/, 2014, (accessed January 2014)

[8] A.E. Roggio Sr. "Creating White Light by Adding - Not Subtracting – Color", *Hearst Electronic Products*, http://www.digikey.com/en-US/articles/techzone/2011/may/creating-white-light-by-adding---not-subtracting---color, 2011, (accessed February 2014)

[9] Lighting Research Center. "Improving LED Light Output and Efficacy Through SPE™", http://www.lrc.rpi.edu/programs/solidstate/speLED.asp