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Thermal Analysis of LED Packaging with Single-Walled Carbon Nanotube Heat Sink

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ABSTRACT

The thermal issue is still the bottleneck of a light emitting diode (LED) system to sustain its operational performance. In this paper, we design, simulated, and analysed an LED packaging with single walled carbon nanotubes as a heat sink. The 5W LED packaging is simulated with different types of LED chips materials which comprise gallium nitride, indium nitride, zinc oxide, zinc selenide and titanium dioxide. Using LED chips materials as the heat source, the heat flow is conducted through the bottom layer to the heat sink and dissipates by convection or radiation heat transfer to the surrounding. The addition of thin film on top of the phosphorus layer functions to enhance the recombination rate and guided the flow of heat to the bottom. The 5W titanium dioxide light emitted diode packaging (LED packaging C) has been successfully demonstrated to have overall temperature reduced to around ~10°C by using single walled carbon nanotube heat sink as compared to copper heat sink and aluminium heat sink. Meanwhile, carbon material as thermal interface material and substrate also plays a major role as a thermal cooling solution in LED packaging. For 5W titanium dioxide light emitted diode packaging, under self-heating conditions, the maximum average temperature generated is 81.05 °C. Despite that, under convection conditions, the maximum average temperature generated is 41.53°C.

Keywords: Light emitting diode packaging, heat sink, single-walled carbon nanotube, temperature

1. INTRODUCTION

The light emitting diode (LED) offers the most promising advantages vis-à-vis traditional lightings such as wide color range, low voltage supply, flexibility, durability and environment-friendly. Nowadays, many light sources from the old generation such as cold cathode fluorescence lamps in display, automotive headlights and home lighting are slowly being replaced by high power LEDs [1-3]. As the next generation of the illumination source, several studies have been investigated and proposed to further enhanced the optical performance and thermal cooling profile [4]. The LED lifetime can be shorter if the system has poor design on thermal management. Therefore, an effective thermal design and reliable thermal characterization, combined with a suitable material are critical for LED packaging. Some articles reported that the highest junction temperatures of the LED introduce the activation of non-radiative recombination [5]. Although the lattice defect is responsible for the non-radiative recombination. However, improper applying of the current and power source raises the operating temperature.

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More studies found that the drop of the internal quantum efficiency is the major contribution to the causes of deterioration in luminous efficacy in LED [6-7]. Moreover, long-term exposure to the higher temperature of the LED may also cause degradation of metal contacts and the phosphor resin materials which ultimately results in the gradual decay in luminous efficacy and device catastrophic failures [8]. Furthermore, most of the studies done by external research teams reports declare that as junction temperature increases, the forward biasing is dropping due to the decreasing bandgap energy of the LED active region resulting in a decrease in series resistance [9]. The decrease in series resistance is due to higher acceptor activation occurring at rising temperatures, which causes higher conductivity in p-type layer and active layers. In fact, as quantum efficiency dropped, the emission wavelength of the LED deteriorated with increased temperature. In those particular levels, the blue LED with gallium nitrate (GaN), and yellow phosphors are the most visible case because when LED temperature increases, the luminous output degradation along with shifts of peak wavelength due to the change in peak energy of the phosphors [10].

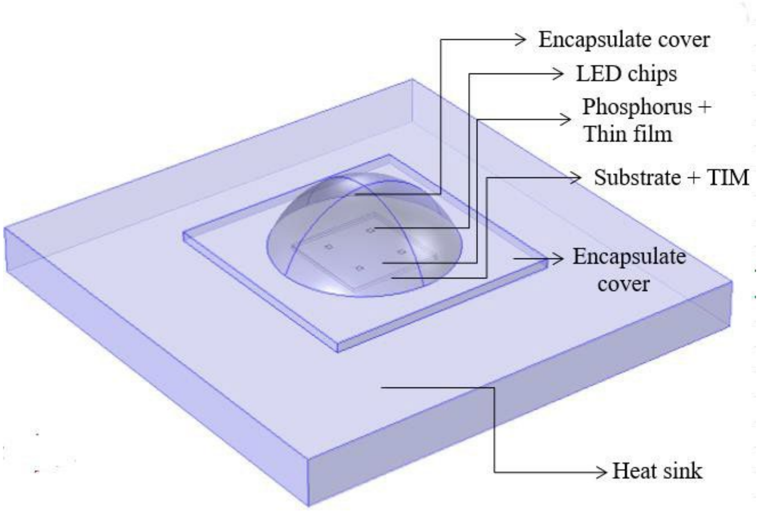
The LED generates a visible light when an electrical current across the p-n junction of the semiconductor material. However, when an electron is paired with a hole and drops off to lower energy level, the radiation emitted due to this process however is not always as light. In practical, LEDs are not operating at 100% efficiency [11], partially the input power is converted into luminescent but only 15-18% is converted to input energy and remained inputting energy is trapped inside the chip and conversion of energy into heat and light takes place at the junction results in heating effect inside the chip. The ideal performance of a white LED is measured at a junction temperature of 25°C. However, when coming up with a practical situation, most of the time LED operates at much higher junction temperatures between 60°C and 80°C [12]. This means under normal conditions of use, the light output of a LED is always lower than its rated value. Indium gallium nitrate (InGaN) based LED RGB is only suffering 5-20% degradation in the light output. Whereas red and amber LEDs are generating 25% and 45% less light respectively [12].

There are several methods for solving the thermal issues in LED, applying the heat sink is the most common method and still a reliable solution for future applications. The solid state heat sink has some disadvantages such as difficulties in production along with the LED system, the weight, flexibility and cost increases as the size of the LED array [13]. Furthermore, carbon family materials such as graphene have been discovered as a possible replacement for the existing LED material or as heat sink material due to their unique properties of flexibility, electrical and thermal conductivity [14]. Nevertheless, many researchers have begun their research on other applications by applying carbon related materials [15].

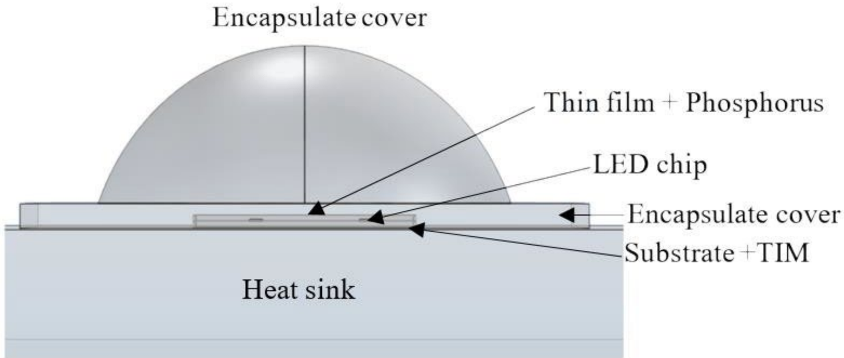
In this paper, thermal issues of 5W LED packaging are studied with different types of LED chips materials which comprise gallium nitride (GaN), indium nitride (InN), zinc oxide (ZnO), zinc selenide (ZnSe) and titanium dioxide (TiO2). The 5W titanium dioxide LED packaging (LED packaging C) utilizing single walled carbon nanotube (SWCNT) as the heat sink produces the highest average package temperature of 81.05°C and 41.53°C, under self-heating and convection conditions, respectively. In contrast, as compared to 5W titanium dioxide LED packaging with copper (Cu) heat sink and aluminium (Al) heat sink, the single-walled carbon nanotube (SWCNT) heat sink has the ability to reduce the LED package temperature around ~10°C.

2. LED PACKAGING DESIGN AND METHODOLOGY

Figures 1(a) and 1(b) are shown the LED packaging design that is constructed in software. These figures are presented in 3D and 2D designs, respectively. The LED packaging is designed according to Chatterjee's work., the geometry itself consists of seven different types of the material layer. From the bottom, in between the heat sink and substrate is filled with thermal interference material (TIM). The four LED chips are placed on the substrate surface and arranged in array form. Apart from that, the metal contact and wire bonding consider negligible in this simulation where a layer of phosphorus and a thin film passive layer is covered on the top of the LED chip surface. Lastly, 40 mm diameter dome shape of the encapsulate cover is used for the LED packaging. The details dimensions are listed in Table 1.



(a)



(b)

Figure 1. LED packaging model (a) 3-D design and (b) 2-D design.

Table 1 Dimension for LED packaging layer

Dimension	Heat sink	Substrate	TIM	LED chip	Phosphorus	Thin film
Width (mm)	100	20	20	1.15	20	20
Length (mm)	100	20	20	1.15	20	20
Height (mm)	10	0.525	0.005	0.15	0.5	0.01

Table 2 Non-adjustable materials in packaging layers

Material	Heat capacity, Cp(J/kg.K)	Density,ρ (kg/m^3)	Thermal conductive, k (W/m.K)	Ratio of specific heat, γ	Surface emission, Ɛ
Phosphorus	590	4560	14	-	-
Sapphire (Al_2O_3)	730	3965	35	0.21	-
Silicon oxide (SiO_2)	730	2200	1.4	-	0.72

Table 3 Adjustable materials in packaging layers

Layer	Material	Heat capacity, Cp(J/kg.K)	Density, ρ (kg/m^3)	Thermal conductive, k (W/m.K)	Surface emission, Ɛ
LED chip	GaN	130	6150	490	-
	InN	308.93	6810	38.4	-
	ZnO	507.871	5676	44	-
	ZnSe	339	5270	18	-
	TiO_2	697	4050	11.8	-
Substrate	Si	700	2329	130	-
TIM	Al_2O_3	730	3965	38	-
	AlN	3230	250	3300	-
	B.Q TIC 4000	-	-	4	-
	Ag	-	-	9.1	-
	Graphene	-	-	10	-
Heat sink	Al	904	2700	236	0.8
	Cu	384	8960	401	0.74
	SWCNT	710	1500	683	0.98

Materials studies are divided into two parts namely as non-adjustable and adjustable. The properties of non-adjustable materials are shown in Table 2, which consist of phosphorus, thin film and encapsulate cover. The materials used in thin film and encapsulate cover are sapphire (Al_2O_3) and silicon oxide (SiO_2), respectively. These materials are used till the end of the simulation. Meanwhile, the adjustable materials are performed on four layers. These four consist of a LED chip, substrate, thermal interface material (TIM) and heat sink as shown in Table 3.

This study intends to use carbon material as a thermal cooling solution in LED system. To be more specific and observe the effect of changes in material, three LED packaging namely as A, B, and C with different combination materials are designed and simulated. Table 4 summarizes the material swap in LED packaging for A, B and C. LED packaging A used copper (Cu), bergquist TIC (B.Q TIC) 4000 and silicon (Si) as a heat sink, TIM, and substrate, respectively. Meanwhile, LED packaging B used aluminium (Al), silver (Ag) and Al_2O_3 as a heat sink, TIM, and substrate, respectively. Lastly, LED packaging C used carbon material as a heat sink, TIM, and substrate. These carbon materials consist of a single walled carbon nanotube (SWCNT), graphene and ceramic (AlN). As reported in [16], carbon nanotube (CNT) has the possibility to control the heat flow direction and if the CNT synthesis with specific polymer material it could form a nanoporous structure in the heat sink which is more helpful in natural heat convection to dissipating heat energy from the device. The CNT has great potential for the next generation of heat sink material. This potential can be considered for future application trend, which is more towards on wearable application, lightweight heat conductor, durable, low-cost in production, bendable and eco-friendly. Whereas a dramatic degradation SWCNT is performed at temperatures above 450 °C. This indicates that it is not a factor for conventional lighting applications, but caused the issue in extreme conditions such as exploration and automotive [17].

Table 4 Material swap in LED packaging model

Packaging	Heat sink	TIM	Substrate
A	Cu	Bergquist TIC 4000	Si
B	Al	Ag	Al_2O_3
C	SWCNT	Graphene	AlN

Next, we design and simulate the physics boundary condition defining for the LED packaging. The LED packaging is definite as general modulus structure and heat transfer in solid physics are applied during the simulation. Since the study is more cornered on the reliability of solid states material. Thus the study is focusing on heating generated from the device itself as the heat dissipating either by convection or radiation method. Beyond the basic default setting, a few additional features have been redefined on the designed model. For example, the heat source as the heat energy is generated based on LED power. A thin layer, a layer of TIM is responsible to fill the air gap between the heat sink and substrate surface with a thickness between 2-20µm. Meanwhile, thin film, a passive layer is responsible to enhance the recombination rate for LED luminescence. Lastly, the diffuse surface and heat flux is used for the heat dissipate study.

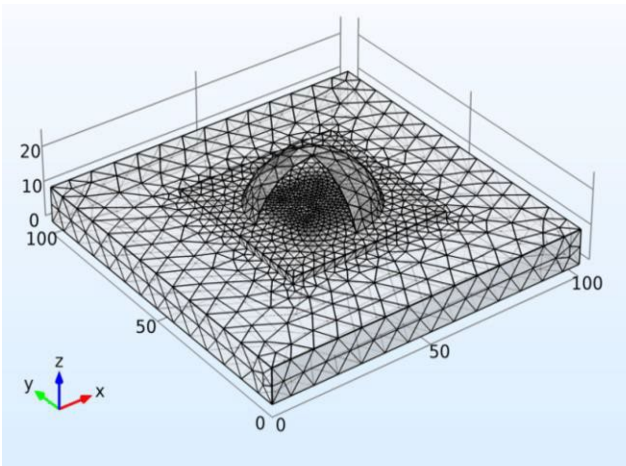


Figure 2. Geometry meshes with domain element model.

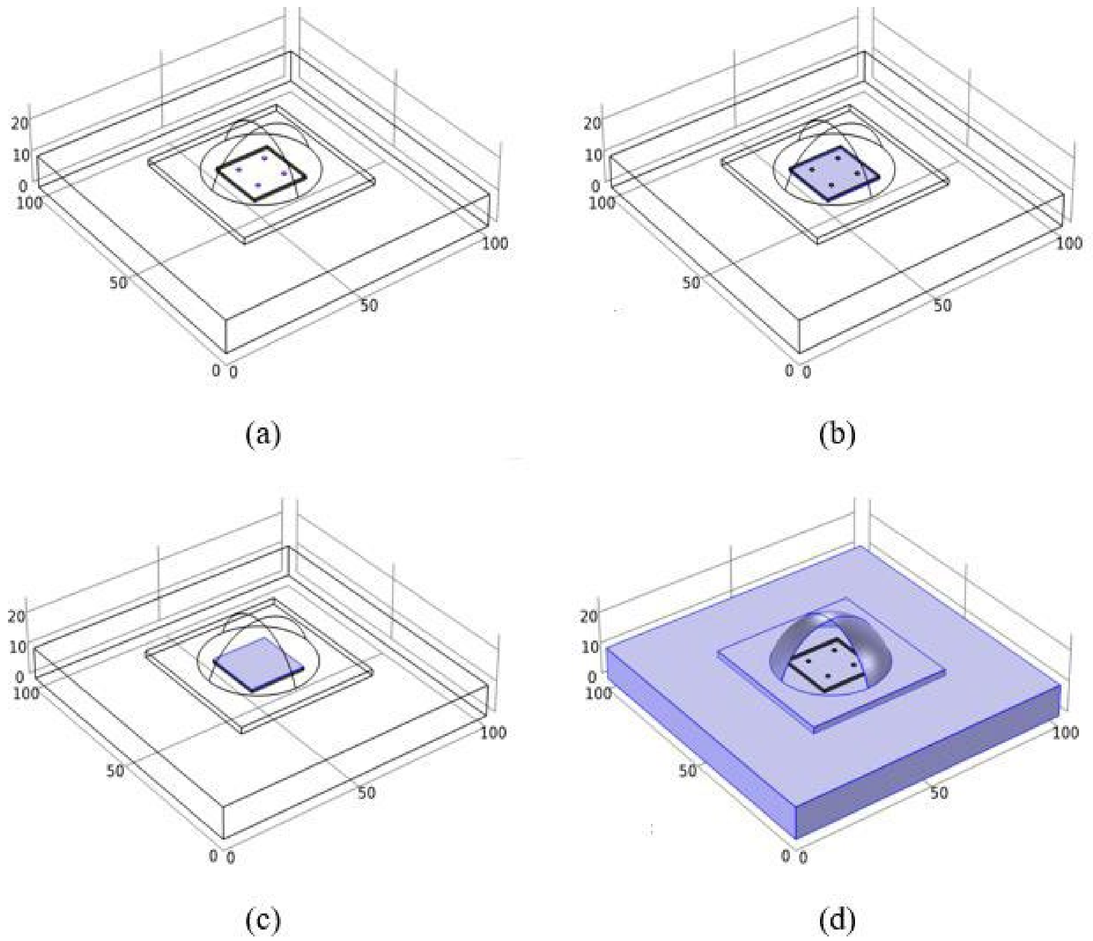


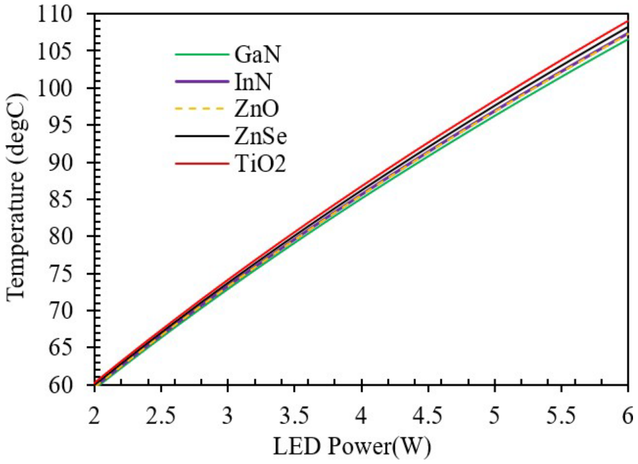
Figure 3. The defined boundary condition, (a) LED chip, (b) TIM, (c) thin film, (d) heat flux and diffuse surface.

The fine grid is selected during the simulation. The simulation used the natural convection method to simulate under normal room temperature with two conditions which is consists of a self-heating and a fixed fluid flow environment with the heat transfer coefficient of 7.5 W/(m^{2}K). Meanwhile, the other parameters input fully depend on the choice of material. Instead of observing the stability and thermal capability of the designed package, the simulation of LED in different power ranges which is from 0-6W with 0.2 per step is carried out. Noted that, each layer is defined with a temperature probe and the data is collected via a probe. Finally, the result is presented in 3D and graph. Figure 2 shows geometry meshes with the domain element model. Meanwhile, Figs. 3(a) - 3(d) below show the boundary condition which is defined during the simulation for LED chips, TIM, thin film, heat flux and diffuse surface.

3. RESULTS AND DISCUSSION

3.1 Material and Temperature Analysis

In this section, the study is focused on the thermal conduction effect between different LED chips materials which comprise GaN, InN, ZnO, ZnSe and TiO_2. The LED chips material is tested in varying the input power under 300K equal to 27 °C ambient environments with two scenarios. The self-heating and thermal transfer to the surrounding are considered during the simulation. A temperature probe is placed on a chip by taking the average temperature on it. A temperature profile for each LED chip material under self-heating conditions is plotted in Figure 4(a). Overall, a temperature gradient is directly proportional to the LED power; the material temperature is not much change if LED power is under 3W. Taking the 5W LED as the study subject, TiO_2 had the highest temperature of 98.29 °C as compared to GaN with lower temperature of 96.25 °C. TiO_2 exhibits poor thermal conductivity and insulating properties. Meanwhile, InN, ZnO and ZnSe recorded temperatures of 96.87 °C, 96.77 °C and 97.64 °C, respectively. Although the temperature difference is a little significant change from long-term perception, it caused thermal issues if involved the environmental factor. In order to demonstrate a magnified view of a temperature profile for each LED chip material under self-heating conditions around 5W LED, the graph in Figure 4(b) is plotted.



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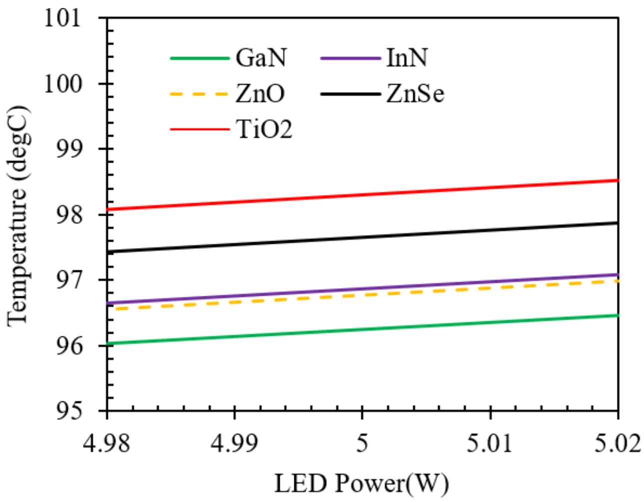


(b)

Figure 4. (a) LED chip temperature as changing in power for each LED chip material under self-heating conditions (b) Magnified view of around 5W LED power.

Similarly, to test the material temperature stability, under similar conditions, the material is simulating up to 12 hours. Figure 5 presents the simulation result of LED chips material temperature dependency with time. In particular, TiO_2 has fast heating properties as takes a shorter time to saturate whereas ZnO is the longest period to reach the saturated temperature. To be more specific, the estimated time for each material is tabulated in Table 5. For GaN, InN, ZnO, ZnSe and TiO_2, the estimated time to saturate temperature is around 6 hours, 6.5 hours, 7 hours, 6.5 hours and 4.5 hours are recorded. Whereas, GaN, InN, ZnO, ZnSe and TiO_2 achieved saturate temperatures around 96.25 °C, 96.86 °C, 96.77 °C, 97.64 °C and 98.28 °C, respectively.

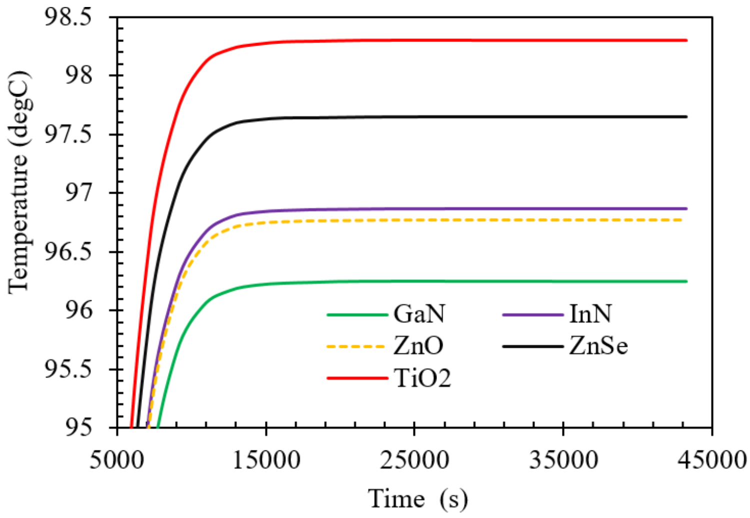


Figure 5. LED material temperature dependency with time.

Table 5 Estimate time to reach saturate temperature for each LED chips material

LED Material	Estimate Time (Hours)	Saturate Temperature (°C)
GaN	6	96.25
InN	6.5	96.86
ZnO	7	96.77
ZnSe	6.5	97.64
TiO_2	4.5	98.28

Indeed, the material thermal conductive could affect the thermal conduction in the material layer, however, the surface emission is much more necessary for a heat sink because the heat energy is conducted through the inner surface from the heat source and dissipated via the external surface by convection and radiation heat transfer. As a thermal bridge to the surrounding, the material must be excellent in thermal conductive and natural surface emission to increase the heat dissipating rate in the application. A heat sink temperature proportional to the LED power with different heat sink materials is plotted in Figure 6. The heat sink materials consist of Cu, Al and SWCNT. To be more specific, under similar simulation design, a heat source of 5W TiO_2 LED is applied to the heat sink materials. As expected, Cu is the best thermal conductor among the selected material but easier to trap the thermal energy within the heat sink and surface emission which is relatively lower than carbon material. Meanwhile, SWCNT is excellent in both thermal conductivity and surface emission rates. Furthermore, the performance of Al is somehow in between Cu and SWCNT.

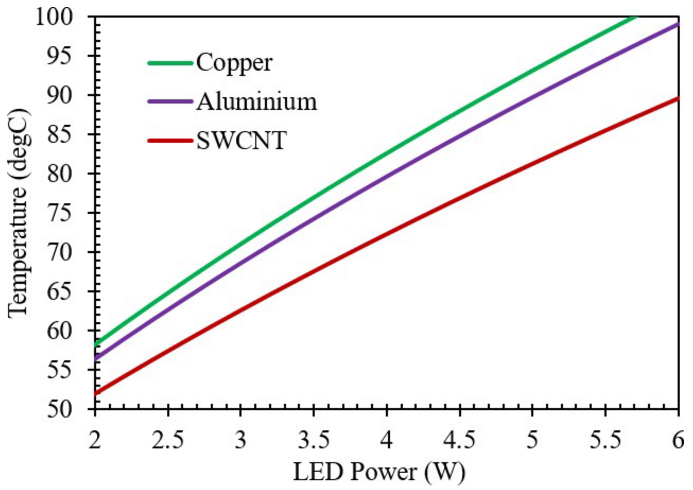


Figure 6. Heat sink temperature dependency on LED power.

In overview, the blue ice 425 is the older generation TIM that only has a thermal conductive of 1.2 W/mK, while the second generation of thermal greases which is TIC 4000 and TIC 7500 has a thermal conductive of 4 W/mK and 7.5 W/mK, respectively. These TIM materials are targeted for low-cost manufacturing. The silver thermal greases are the current commercial commonly used in high power LED as TIM material. The latest TIM material is graphene thermal greases that have a thermal conductive of 10W/mK which is closer to gold thermal greases. Figure 7 shows the plotted graph of temperature versus TIM thickness corresponding to different thermal conductive TIM materials. Three types of TIM have involved in this analysis are silver, graphene and TIC 4000. Figure 7 indicates that the minimum thickness of TIM could lead the better performance in conduction heat transfer. The ideal TIM thickness is 2μm however, due to the limitation of technology, the commonly applied thickness is around 5μm. As TIM thickness is highest than 10μm, the heat transfer process becomes slower and more heat energy started to accumulate in the layer which reduces the efficiency of heat transfer between substrate and heat sink.

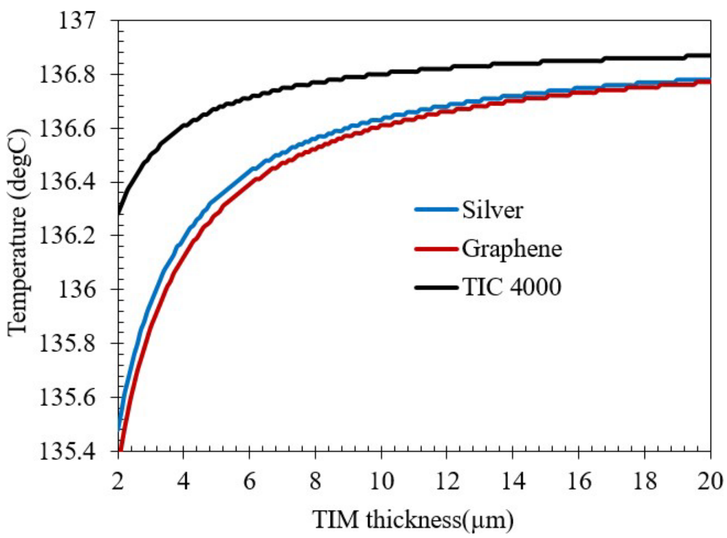


Figure 7. Temperature versus TIM thickness.

3.2 Packaging Analysis

Next, we simulate LED packaging using 5W TiO2 LED as the heat source. Three LED packaging namely A, B, and C with different combination materials are defined and listed in Table 4. Meanwhile, Figure 8 and Figure 9 shows the stability of LED packaging temperature under self-heating scenarios and convection heat transfer with specific thermal transfer confidence of 7.5 W/(m2K), respectively. LED Packaging C only takes ~0.6 hours to reach the temperature saturation where LED packaging A is taken ~2.5 hours as longer than LED Packaging C. Under self-heating conditions, the maximum average temperature for LED packaging A, B, and C is 92.62°C, 89.26 °C, and 81.05 °C, respectively. Despite that, under the convection condition, the maximum average temperature for LED packaging A, B, and C is 43.14 °C, 42.7 °C, and 41.53 °C, respectively. For instead, the majority of substrate materials provide a significant change in heat transfer since the material is slightly heat dissipated via radiative heat transfer to the surroundings whereas the heat sink and TIM material contribute significantly to temperature change. LED packaging C using carbon material as the conductor shows that is much more efficient in thermal dissipation as compared to LED packaging A. LED Packaging A used Cu heat sink which has the ability to reduce the convection heat transfer rate to the surrounding. Thus, using the passive thermal cooling profile, applying the SWCNT as the agent of conductor medium the overall LED packaging temperature should be able to reduce ~10 °C as compared to Cu heat sink.

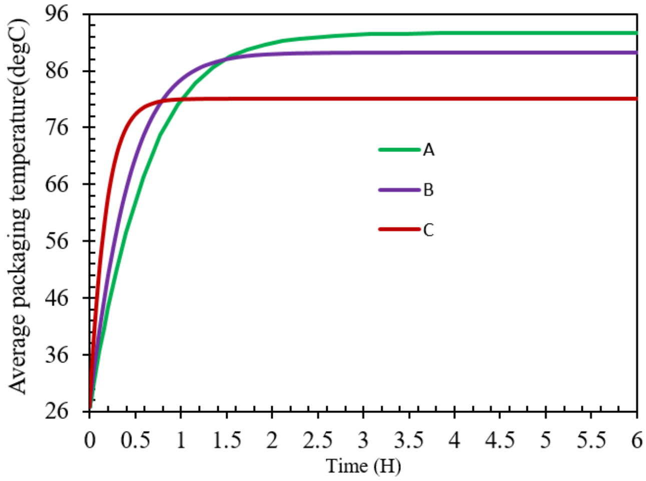


Figure 8. The stability of LED packaging temperature under self-heating conditions.

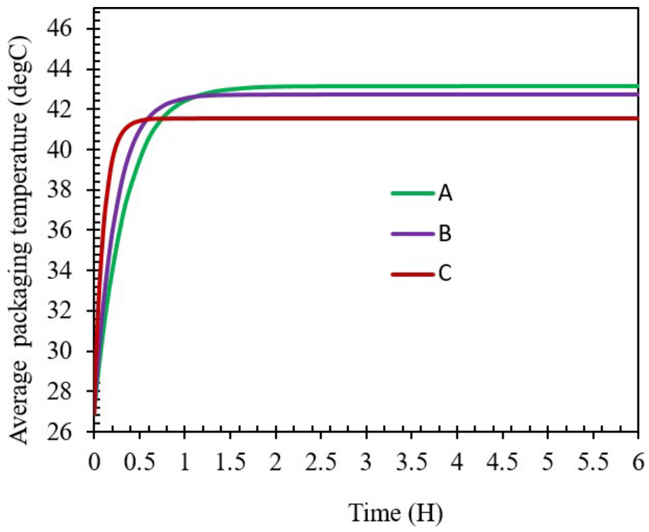
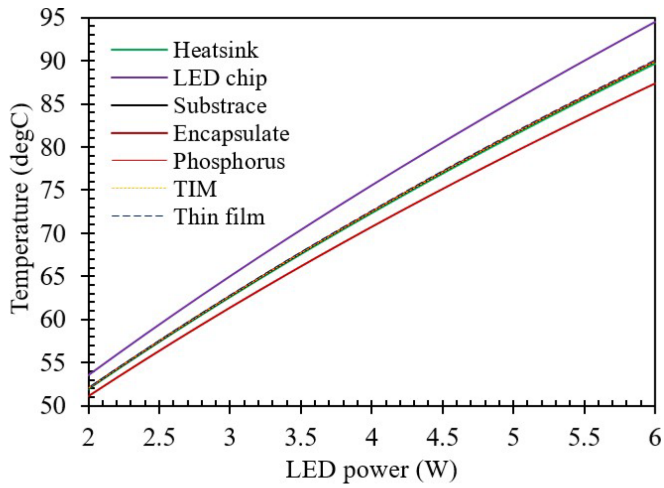


Figure 9. The stability of LED packaging temperature under specific thermal transfer.



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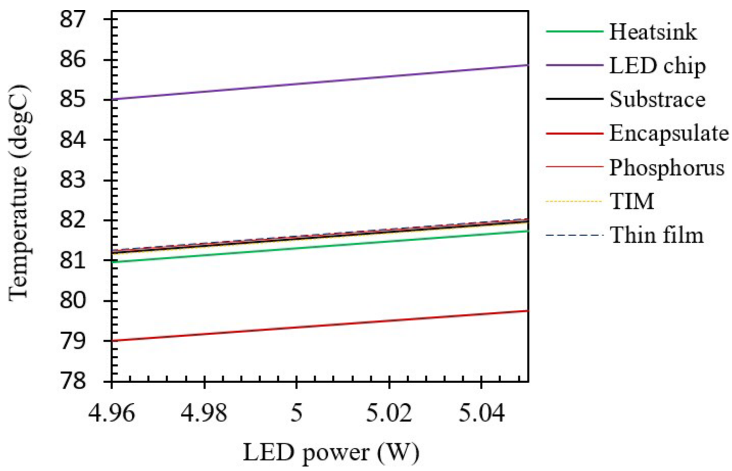

(b)

Figure 10. (a) Junction temperature of LED packaging C under self-heating condition and (b) Magnified view of the junction temperature of LED packaging C under self-heating condition around 5W LED power.

Figure 10(a) indicated the change of junction temperature of LED packaging C as varies LED power under self-heating conditions. Meanwhile, Fig 10(b) shows the magnified view of the junction temperature of LED packaging C under self-heating conditions around 5W LED power. The result of the analysis has achieved the originating purpose. In the ideal case, the thermal design of this study is expected to control the heat distribution from the inner part to the external part of the package, meanwhile as maintained the packaging temperature below that 90 °C to prolong the LED lifetime and enhanced the overall performance. At 5W LED power, components in LED packaging C which consists of a heat sink, LED chip, substrate, encapsulate cover, phosphorus TIM and thin film generated the temperature at 81.32 °C, 85.39 °C, 81.53 °C, 79.33 °C, 81.59 °C and 81.61 °C, respectively. The junction temperature of an LED is given by the equation from $T_j = T_a + (R_{thja}P_d)$ [18]. Where, T_a is the ambient temperature in Celsius. T_j is junction temperature for a given input power in Celsius. R_{thja} is thermal resistance between the LED junction and surroundings (˚C/W). Meanwhile, P_d is the power to be dissipated in Watt.

Originally, the encapsulate cover lens material is epoxy resin which is a thermoplastic material. However, the extended period exposures in higher temperatures, the epoxy resin material slowly change from transparent to yellowish color which is not reliable and caused wavelength shifts. As a replacement, the SiO_2 could provide a similar function as epoxy resin due to its low cost, higher thermal resistance, and transparent crystalline structure. The thin film forms an insulation layer that isolates the inner heat source and prevents the LED chip experience thermal shock due to the environmental factor which means upward LED should remain at lower temperature where the heat energy is guided to the bottom and dissipated through the heat sink. The 3D view of heat distribution from LED chips and the 2D view of heat distribution from LED chips are shown in Figure 11(a) and Figure 11(b), respectively. Meanwhile, Figure 11(c) and Figure 11(d) show the 3D view of heat radiosity from LED chips and the 2D view of heat radiosity from LED chips, respectively. Figure 12(a) and Figure 12(b) are shows the magnified view of heat distribution from LED chips and the magnified top view of heat distribution from LED chips, respectively. Otherwise, Figure 12(c) and Figure 12(d) show the magnified view of heat radiosity from LED chips and the magnified top view of heat radiosity from LED chips, respectively. LED packaging had successfully demonstrated the direction of majority heat flow (black-brown arrow), and heat radiosity (red line) is towards to bottom while only a minority of heat energy is dissipated upward of LED.

Next, further analysed of the average junction temperature and thermal transfer rate within the designed LED packaging C has been demonstrated. Taken the 5W GaN LED, 5W InN LED, 5W ZnO LED and 5W ZnSe LED chips as the heat source, the average junction temperature for different types of the layer is tested at room temperature with the self-heating condition as shown in Table 6. Under the conduction heat transfer theory, the rate of thermal transfer between two domains can be calculated from $= kA\ \Delta T/d$. Where q is the thermal transfer rate unit in J/s or W, k is the material thermal conductivity, A is emitting surface area in m2, ΔT is the difference in temperature and d is the thickness of the object. From the equation, two major variables are the area of the emission surface and the object thickness are influence the change in thermal transfer rate. As the d value increases, the lower thermal transfer rate is produced due to an increment in the thermal resistivity of that material.

Accorded to the heat flow theory, the heat flux always transfers from higher temperature flow to a low-temperature region. Since the upward of the LED packaging form a temperature insulation layer, the direction of heat flow is guided from the center of the LED to the heat sink part. The analysis of junction temperature with different LED chips material as the heat source shows that the LED packaging C design is capable of maintaining the thermal transfer rate by changing the heat source material. In a nutshell, the higher thermal transfer rate caused better heat conduction on that material, However, the thickness of the conduction layer is also the cause of reducing in thermal transfer rate. Table 1 shows the dimensions of the package layer, as compared to the thickness and related to the thermal transfer rate in Table 6. The slower rate of thermal transfer to the heat sink is caused by the thicker layer that increased the thermal resistance of that material. The heat is easily accumulated within the material itself. Therefore a forced external convection heat transfer technique is required to accelerate the heat transfer to the surrounding air and dissipate the heat energy from the device.

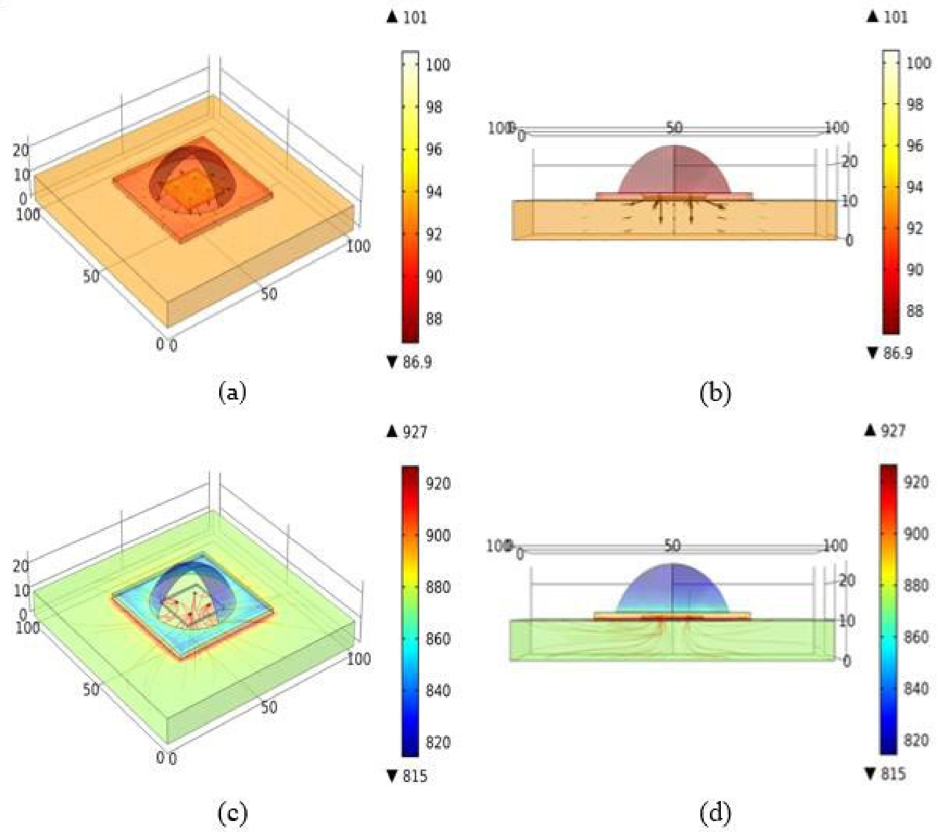

Figure 11. (a) The 3D view of heat distribution from LED chips, (a) The 2D view of heat distribution from LED chips, (c) The 3D view of heat radiosity from LED chips and (d) The 2D view of heat radiosity from LED chips.

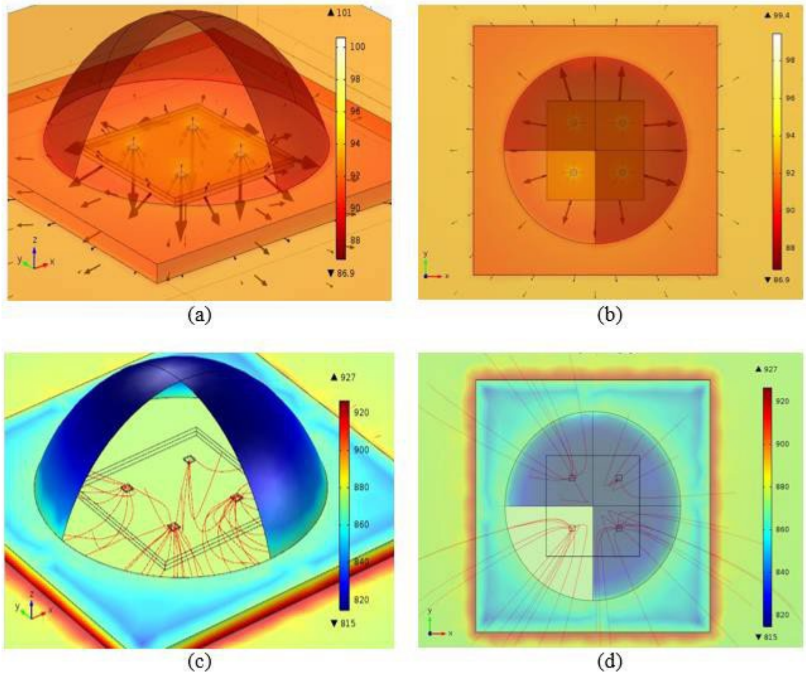

Figure 12. (a) Magnified view of heat distribution from LED chips, (b) Magnified top view of heat distribution from LED chips, (c) Magnified view of heat radiosity from LED chips and (d) Magnified top view of heat radiosity from LED chips

Table 6 Comparison of junction temperature in LED packaging C with different LED chip material

Average junction temperature (°C)						
Layer	**GaN**	**InN**	**ZnO**	**ZnSe**	**TiO_2**	**Thermal transfer rate (W)**
Encapsulate cover	79.32	79.32	79.32	79.33	79.33	3.86×10^2
Thin film	81.56	81.58	81.57	81.59	81.61	3.82×10^5
Phosphorus	81.55	81.56	81.56	81.58	81.59	3.09×10^3
LED chip	83.24	83.87	83.77	84.70	85.39	-
Substrate	81.53	81.53	81.53	81.53	81.53	6.90×10^5
TIM	81.52	81.52	81.52	81.52	81.52	2.18×10^5
Heat sink	81.32	81.32	81.32	81.32	81.32	1.87×10^5

4. CONCLUSION

A thermal study of 5W LED packaging based on different LED chips material which are GaN, InN, ZnO, ZnSe, and TiO_2 has been successfully simulated and analyzed. These materials have been chosen as a selected material study due to the high potential for being used in the next generation LED. 5W TiO_2 LED packaging (LED packaging C) using carbon material as the heat sink, TIM, and substrate, is more efficient in thermal dissipation as compared to LED packaging A and B. By using SWCNT as the heat sink, 5W TiO_2 LED has the ability to generated highest average package temperature around 81.05 °C and 41.53 °C under self-heating condition and convection condition, respectively. In contrast, as compared to LED packaging A and C, 5W TiO_2 LED is able to reduce the packaging temperature around ~10 °C. Furthermore, the analysis of junction temperature with different LED chips material as the heat source shows that the LED packaging C design is capable of maintaining the thermal transfer rate by changing the heat source materials.

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