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New Trends in Thermal Interface Materials for High-Power LED Packaging Systems

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Abstract – For a successful thermal performance, the right choice and design of the thermal management materials used in LED die-moulding, cooler and soldered parts is a critical engineering problem. Because they are affected by heat emitted from the p-n junction in the LED array and have a great effect on the removal of this heat. Junction temperature is affected by many factors. These are the cooling system, ambient and thermal interface material. Nowadays, low cost and highly successful thermal management solutions are urgently needed. Many solutions have been proposed to provide this kind of heat management. In this study, new approaches to improve the thermal performance of high-power LED packaging systems were investigated and reviewed. Commercial and conventional thermal interface materials were compared with ceramic materials according to their suitability, production conditions, and thermal properties.

Keywords – LED, Thermal interface material, Nitride ceramics, Heat Sink.

I. INTRODUCTION

In recent years, LED lighting systems have played a major role in the lighting market due to their lower power consumption and the potential for creating interesting lighting environments compared to other energy-saving lighting options. Nevertheless, when looking at energy consumption, LED lighting has not yet achieved the desired efficiency, since a significant amount of input energy is released into the environment as heat. Also, the emitted heat shortens the lifetime of the device if it causes the LED chip to overheat. In order to reach the desired working life of the device, it is necessary to operate the chip temperature below the threshold values determined by the manufacturer. To achieve this, the heat sink associated with the LED lamp must provide the required cooling. In addition, the low weight of the material used in the production of the heat sink is another parameter that can be easily installed in the application areas of the device. In addition, the power-saving LED that is available in advanced LED systems enters the circuit when the power to the lamp is cut. Sudden power fluctuations that may occur during this time can cause high temperatures of the LEDs to overheat, causing the LED to lose its brightness and even cause the color to change.

It is obvious that the design of the heat sink for cooling purposes is of great importance to ensure the long life of the LED lamps. The design of the heat-absorbing part should be carried out not only by the thermal performance of the product, but also considering the respective production processes and the production costs per part. Today, there are heat sinks made of metal and ceramics on the market. The heat sinks based on metal (copper, aluminum, etc.) are generally produced in one piece in the form of long bars by extrusion method, then cut into desired lengths. On the other hand, ceramic (AlN, Al_2O_3 and composites) heat absorbers are produced by sintering under high pressure and temperature conditions after being shaped by powder metallurgical methods. For this reason, the selling price per part of a metal-based heat sink is about $20, while for a ceramic heat sink this value starts at about $200. It is also very difficult to find the ceramic heat sink in market as well as with the cost. There are very few manufacturers worldwide (eg CeramCool®, Fischer Electronics) as well as no company that can produce and sell ceramic-based heat sinks in Turkey. Figure 1 contains photographs of metal and ceramic based heat sinks.

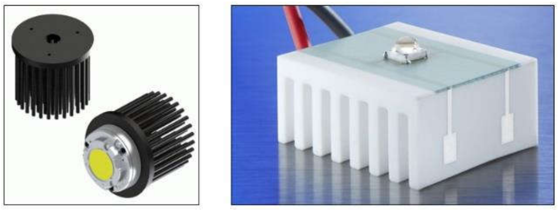

Fig. 1. Sample illustrations of metal (a) and ceramic (b) heat sink pieces [1].

The heat sink for LED lamps can operate with natural or forced heat transfer. Natural heat transfer is preferred because it does not require additional fans and extra electricity consumption. In addition, the noise generated by the electric motor and fans can be prevented by this system. On the other hand, the performance of natural heat transfer heat sinks is lower. For this reason, they require a heavier and more compact design to achieve the required thermal performance.

II. LED PACKAGING OPTIONS AND THERMAL MANAGEMENT

By directly converting the light current into the light in the semiconductor (optical radiation), the LEDs are more efficient than most conventional light sources. However, even in the case of LEDs, almost all electrical energy is converted to heat instead of light. Simply put, as the flow increases, the component creates more heat. Since the semiconductor material used is subject to the maximum temperature limit and the characteristic characteristics such as high voltage, wavelength and service life may vary depending on the temperature, this heat that is turned on must be removed from the LEDs. In particular, thermal management in innovative, miniaturized high performance LEDs is considered to be of great importance and a major engineering problem in reducing current temperatures. Only adequate thermal management at all system levels can allow full use of LED performance and efficiency during operation.

LED systems can only convert 30-45% of the energy supplied to the light, leaving the remaining energy as heat. Today, a variety of packages and thermal management options are available to enhance LED performance. Heat management is especially difficult for high power LED systems. To reach the top of the heat management challenge, manufacturers should pay attention to LED packaging. However, the protective casing of the LED package usually prevents heat loss. The only solution to remove heat is to carry the conduit behind the package. As a probing solution, thermally conductive layers are used to help facilitate the heat path between the LED and the cooler. It is an ideal solution if this layer is dielectric as thermally conductive. LED manufacturers are constantly working on cost-reducing solutions such as using more reasonable materials or reducing additional manufacturing processes.

There are usually two approaches for high power LEDs. Uniquely, producers can only package one large LED die, or a group of molds can pack like a red, a green blue. The second, known as the chip on board (COB) approach, is to combine many packages on a printed circuit board principle. The prerequisite for packaging LEDs with high power is that both sides of the package surface are interconnected by copper paths on the surface. This requirement is very important because it is necessary to provide power to the LED mold when the package is mounted on the circuit.

Ceramics are a good choice because direct copper plating (DPC) can be applied to the surfaces with very high resolution. DPC is a protective process in which copper parts are sprayed onto the ceramic to form the circuit. A third option has recently become a focus of interest, which is the application of nanoceramics as a coating over melamine or ceramic substrates.

Because manufacturers are constantly increasing their LED power, now 1W packaged LEDs are in the middle power class. The main factor in determining the material to be used is the power density around the chip. Where the package size is large, it is necessary to permanently and rapidly remove the heat-generating energy from the system. Manufacturers collect multiple LEDs in one package to create a powerful device. On this count, a single puck can effortlessly force a 10W power. As a result, it can be said that a solution that meets all sizes is still not available for thermal management of high power LEDs. Every design needs to be audited and material selection should be made according to needs. Therefore, producers should act accordingly and prefer the ideal packaging option for LED lighting. In general, the thermal management of an LED system can be divided into three system levels; LED chip, base and cooling unit. Figure 2 shows a schematic view of an LED package with its thermal management components.

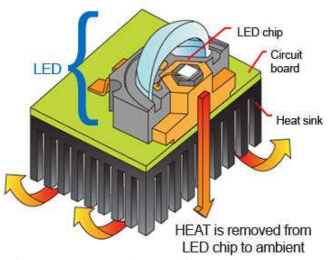

Fig. 2. Schematic representation of heat flow on LED package and thermal management parts [2].

Not only for LED systems, but also for overheating unwanted electronic circuits (eg computer parts), it is necessary to move the heat efficiently to prevent overheating of the components. The heat transfer path of the system is almost the same in all cases. From the heat source (the semiconductor interconnect layer), the PCB flows through the heat sink and through the body and into the ambient air. In LED systems, the heat that is emitted from the chip is carried from the bottom of the chip to the heat absorbent from the bottom and from there to the periphery. The mechanisms of heat transport in the system and the way in which it is removed are very important in terms of designing effective thermal management and selecting the right materials.

It is also important to know which mechanism the heat travels through which regions in LED systems. Generally, the outer package of LED systems is produced from transparent polymeric materials in order to provide both visuality and balance of light. However, since polymeric materials are very weak in terms of heat transfer, almost all of the available heat is removed by the thermal management components located below the system. Figure 3 systematically visualizes current regional thermal conduction mechanisms for an LED system.

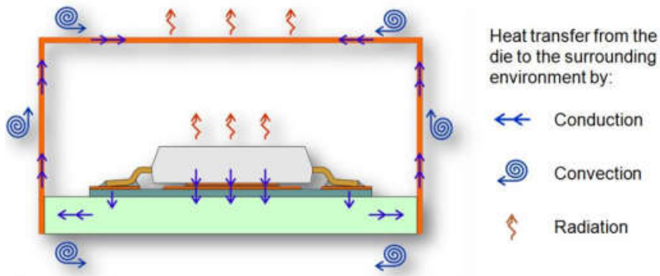

Fig. 3. Heat transfer mechanisms in LED package [3]

III. THERMAL INTERFACE MATERIALS

Heat sinks and LED lamps can be installed together using a layer of thermal interface material (TIM) with high thermal conductivity for high cooling performance. Figure 2 shows a schematic representation of the TIM application for LED package systems.

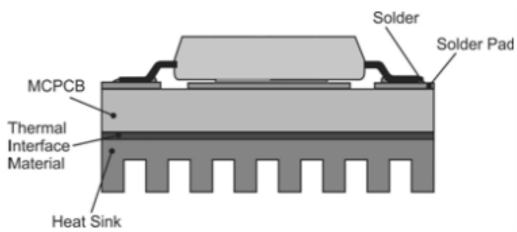

Fig 2. Schematic representation of a LED [4].

Thermal interface material (TIM) applications are one of the key thermal management techniques that facilitate the rapid transport of heat absorbing heat from the LED. TIM is an effective material in terms of heat transfer and compliance, since the air gap between the substrate and the heat sink can be effectively filled [5]. Anithambigai et al. (2011) emphasized the importance of the selection of the thermal interface material (TIM) with the correct thermal conductivity for the LED systems in particular [6]. TIM can be formed from conductive paste, grease, phase change materials (PCMs), thermal pads, and thin films [7]. Among all these options, thin film is a good approach where the bond layer thickness can be controlled. AlN is a semiconductor material that has unique properties such as superior thermal stability [8,9], superior high temperature stability, hardness and abrasion resistance as well as broadband spacing. For this reason, blue light emitting diodes, short wavelength lasers, and ultraviolet light detectors are high-potential candidates for manufacturing [8]. AlN thin films and coatings have been fabricated with various techniques such as microwave plasma chemical vapor deposition, plasma assisted molecular beam epitaxy, metal organic chemical vapor deposition, pulsed laser deposition, and reactive magnetron sputtering. There are also studies that investigate the effects of additives such as Se, Hg and Si on the film properties of AlN coatings [10]. Pantha et al. (2010), the reason for the poor behavior of Si-doped AlN coatings under tensile strain is the formation of numerous edge dislocations in the structure as a result of Si addition. AlN thin film based TIM was reported by the same author group and reported effective results on both the Tj and R values of the high-power LED[11]. In addition, the usability of BN thin films as TIM and the effects on LED performance have been tested by the same group. The results show that the use of AIN and BN thin films as TIM improves the LED performance [12].

There are several studies in the literature on effective cooling of LED lamps. Among these articles, the design of LED module packages, including packaging orientation, as well as the detailed production and performance of package, base and thermal interface materials, are available [13].

Luo et al. (2010) has conducted both experimental and numerical studies on a new generation heat sink design combined with a new generation cooling unit for high power LEDs. The system they designed according to the results obtained has effectively increased the cooling performance by exhibiting 0.654K / W resistivity at 27 ° C [13]. Arika et al. (2004) examined the thermal management of a set of LED lamps and a winged heat sink assembly [14]. El Ying et al. (2011), a heat-absorbing optimization associated with a high-power LED spotlight was numerically investigated. Scheepers and Visser (2009) investigated the thermal management of high-power LEDs using a heat sink using a numerical approach[15,16] and compared the detailed thermal model with simpler resistance models. In a study by Christensen and Graham (2009), a 3D numerical simulation was presented with a cooler for a researched, high-safety LED lamp array of compact LED systems, and the thermal resistance network was analyzed by trying to predict different contributions for heat management[17]. Chi et al. (2008) performed thermal analysis of high power LED lamps and associated heat sinks using a CFD numerical simulation with some heat transfer correlations, including radiation heat transfer[18]. In a study by Weng (2009), it is shown how a detailed 3D CFD analysis can improve the thermal performance of LED lighting systems[19]. Yu et al. (2011) discusses the numerical simulation and optimization of a radial cooler with two alternative configurations with an empty centerpiece for LED cooling purposes, resulting in the impossibility of optimizing heat cooling and coolant mass[20]. Yu et al. (2010) reported their experimental work for a similar heat sink configuration[21]. Huang et al. (2010) reviewed the thermal dynamics of LED systems including LED lamps and heat sinks[22]. Houl et al. (2011) examined the thermal dynamics of an LED array system[23]. Ha (2009) performed a numerical simulation of a high-power LED package and extracted the most realistic thermal resistance values available for the system[24]. Yu et al. (2010, 2011 and 2012), analyzed the effect of radiation heat transfer on the thermal performance of radial heat sinks[20,21,25]. In the literature, studies that consider the search for an effective cooling method for LED systems as a simple combination of thermal resistance.

IV. CONCLUSION

AlN is one of the thermal interface materials commonly used in LED packages in this respect. This is because; high thermal conductivity, effective electrical insulation, high optical transparency, thermal and chemical stability. Previous works have shown that LED performance is improved by using AlN and BN coated substrates. However, the most important drawback here is that the methods used to produce AlN coated substrates are very expensive. In many studies, expensive production methods such as plasma nitriding, magnetron sputtering, PVD and CVD have been used for fabrication of AlN coatings. As a conclusion, nitride ceramics as a thin film or as a filler in polymer composites has a great potential to improve the thermal performance of electronic devices which are needed to be cooled to achieve longer lifetime with sustainable performance such as high-power LEDs.

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