A review of passive thermal management of LED module

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Abstract: Recently, the high-brightness LEDs have begun to be designed for illumination application. The increased electrical currents used to drive LEDs lead to thermal issues. Thermal management for LED module is a key design parameter as high operation temperature directly affects their maximum light output, quality, reliability and life time. In this review, only passive thermal solutions used on LED module will be studied. Moreover, new thermal interface materials and passive thermal solutions applied on electronic equipments are discussed which have high potential to enhance the thermal performance of LED Module.

Key words: HB LEDs; LED module; thermal management; passive thermal solution; thermal interface material
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1. Introduction

The light output of high-brightness (HB) LEDs have reached a level that is comparable with incandescent and halogen bulbs with much lower energy consumption. Hence, the replacement of conventional light sources with LEDs is straightforward for illumination application with novel lighting concepts. With the development of HB LED technology, the luminous output is doubled every 18 to 24 months[1]. The power dissipation is also increased, and this results in serious consequences for the thermal management in an LED module.

The maximum light output, quality, reliability and the life time of LEDs are all closely related to the junction temperature. Thus, thermal management has become a key reliability issue for LED module and various solutions have been proposed. Moreover, it has a high probability for improving the thermal performance of LED module with new thermal materials and solutions which have been employed or tested on semiconductors.

2. Heat generation and transfer

LEDs generate light and heat by using different mechanisms as compared to the incandescent bulb. With the injection of electrical energy, the electron energy will be partly converted into light and partly into heat. Obviously the research into LED technology is focused on optimizing the light emitting efficiency. Currently, the LEDs in the market have an efficiency of about 10%–20%. Consequently 80%–90% of the energy is converted into heat[2]. Hence, the challenge of thermal management is to conduct heat from the LED package to the environment with a sufficient heat transfer rate.

Figure 1 shows a schematic diagram of typical architecture of LED module which includes an LED package, a thermal solution and a board for electrical and thermal connection. Although each module has a unique structure, generally the LED package consists of a LED chip enclosed in a package of a polymer lens and a plastic carrier holder.

Heat is generated by the LED chip inside the package. Although some heat can be dissipated with radiation and natural convection along the package surfaces, most of the heat will be conducted to the heat sink. The major part of the heat will be transferred to the environment by convection from an optimized designed heat sink. On the other hand, radiation on the surface of the heat sink occurs naturally and it cannot be ignored as the average critical temperature of the LED module is high[3].

The heat sink could also be replaced by other thermal solutions which include forced air cooling, heat pipe, thermoelectric, synthetic jet flow cooling, liquid system, etc. Compared to active thermal management, passive solutions have the advantages of a simple structure, easy fabrication, application flexibility and low cost. Therefore, only passive cooling solutions will be discussed in this review.

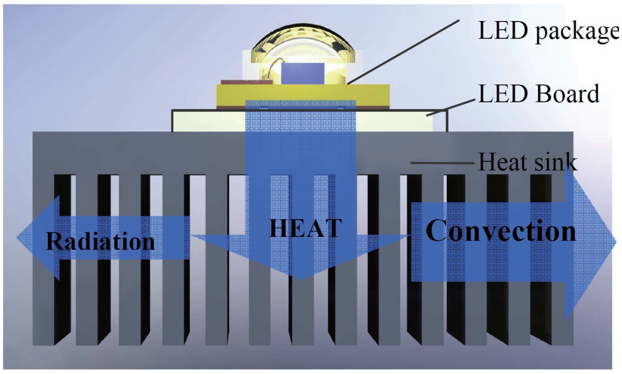

Fig. 1. Schematic diagram of thermal path of LEDs.

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Table 1. Passive thermal solution for microelectronics devices[5].

Category	Typical application	Normal load (W)	Cost at 10, 000 pieces ($)
Heat sink	Plate fin, Pin fin	5–50	0.5–10
Phase change recirculation	Heat pipe, Vapor chamber	100–150	15–100

3. Passive thermal management of LED module

3.1. LED board

As depicted in Fig. 1, an LED package is mounted to a substrate. One of the most direct solutions is to use substrate which has sufficient heat conductivity to conduct the heat generated away from the LED package. In industry, printed circuit boards (PCB) are typically used to mechanically support and electrically connect the LED package. The most commonly used LED board is FR4. A number of thermal vias for FR4 are essential due to its low thermal conductivity (0.23 W/(m·K)) since capped or uncapped vias will dramatically increase the heat transfer rate. Meanwhile, an alternative board with high thermal conductivities could be used for better thermal performance. For example, it is very attractive for using ceramic based boards in LED module with aluminum oxide (Al_2O_3) (25 W/(m·K)), aluminum nitride (AlN) (180 W/(m·K)) and the metal core (MC) PCB (copper with 1–5 W/(m·K) thin dielectric isolation layer)[4]. Currently, the MCPCB has the best optimal performance to cost ratio.

3.2. Passive thermal solutions

A package with a board is the typical current structure of the LED module. This structure has to be mounted to a thermal solution for heat dissipating. With the advantages of a simple structure and low cost, the passive cooling methods are always preferred. Generally, the passive thermal solutions could be categorized by the mechanisms for removing heat to the environment, into, (1) Passive heat sink: It is the basic passive thermal solution which is designed without air flows. The performance of heat sink is relative to various factors under the consideration of natural convection and radiation. (2) Phase change recirculation system: The principle of this system is to conduct heat away from the critical part through phase change at the high temperature region and reverse phase change at the lower temperature region. The liquid-vapor cycle which will be discussed in this study is typically used. Moreover, these phase change systems still need to be connected to heat sinks.

Table 1 shows the typical range of cost and thermal load for passive solutions of microelectronics which is very similar to LEDs. Currently HB LEDs used 5–10 W for small applications and even more than 20 W for lager system designs. Thus, the passive heat sinks should be theoretically sufficient for thermal management of current LED module (with low energy consumption less than 50 W). According to the much lower cost compared to heat pipe, heat sinks are the most widely used type of passive cooling device.

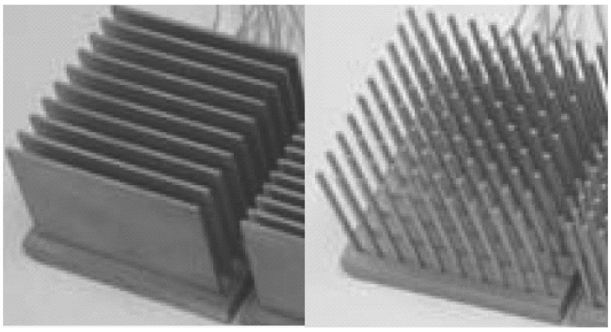

Fig. 2. Plate-fin and Pin-fin heat sinks[6].

Table 2. Thermal performance of heat pipe, aluminum and copper plate for electronics packaging of 10 W[9].

Material	Density (kg/m^3)	Thermal conductivity (W/(m·K))	Thermal resistance (K/W)
Aluminum	2780	240	6
Copper	8330	380	2.3
Heat pipe	4440	25000 (effective value for vapor passage)	1.2

3.2.1. Passive heat sink

In thermal management of the LED module, the heat needs to be transferred to the environment, mostly via heat sink, through natural convection and radiation. Natural convection varies from situation to situation depending on the conditions of fluid flow, the structure of heat sink and the mode of fluid flow. Designing methodology of heat sink has been well outlined in many researches. In the design routine, air flow scheme, chimney effects, surface radiation and boundary layer developments need to be taken into consideration.

Figure 2 shows the two common types of heat sinks which are widely used in the industry. The parameters need to determine the optimum performance within a set of design constraints which typically include: fin length, fin thickness, fin number, base thickness, material, etc. Iyengar *et al.*[7] have investigated the optimum parameters for plate and pin fins and their results show that pin–fin type is a superior thermal solution. The design for heat sink is not only depend on the architectures but also the materials. The materials with low cost, low density, high thermal conductivity and high surface area are very attractive. One example is that Oak Ridge National Laboratory (ORNL) recently managed to fabrication carbon foam heat sink which has excellent thermal properties at a relatively low cost[8].

3.2.2. Phase change recirculation system

Heat pipe is one of phase change recirculation systems, which is normally used as interconnect base between the heat sources and fins in passive thermal solution. The pipe dimension, structure and orientation will directly decide their efficiency. Table 2 shows the thermal performance of horizontal orientation heat pipe and conventional materials. For a 10 W electronics packaging, the heat pipe has advantages of low thermal resistance and intermediate density compared with the same geometry of aluminum and copper plate.

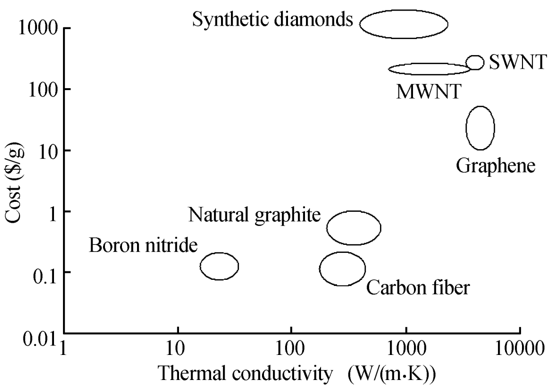

Fig. 3. Cost functions of high thermal conductivity materials[18].

Another major consideration in heat pipe is the selection of working liquid as it is directly responsible for the heat transfer capability. Acetone, methanol, ethanol and water are suitable for electronic application at the temperature range from 0 to 100 ℃[10]. For improving the heat transfer properties, investigations have shown that nanofluids consisting of nanoparticles exhibit a significant improvement of thermal conductivity in heat pipe[11, 12].

With the high thermal conductivity and relatively low density, heat pipe is quite an efficient passive cooling solution for high power LEDs. Lu *et al.*[13] implemented the concept of the heat pipe with natural convection for LED mudule and the results show that the junction temperature can be controlled steadily to less than 100 ℃ for heat load of 100 W. Kim *et al.*[14] report the thermal characterization of high power LED arrays with heat pipe as well.

Micro heat pipe (MHP) and vapor chamber (VC) have the same principle as heat pipe. They have already been tested on the semiconductor materials to enhance the thermal performance of silicon and they are found to be very suitable for HB LEDs. One experiment by Berre *et al.*[15] showed a maximum improvement of up to 300% in effective thermal conductivity by the application of MHP with liquid arteries in silicon. In addition, Wu *et al.*[16] have found that the VC can significantly improve the thermal permance of heat sinks up to 20% to 40% as compared with the solid copper bases.

4. Thermal interface material

In order to minimize the thermal resistance, thermal interface materials (TIMs) are essential to apply to connect different components of the LED module. Studies show 60% of the thermal resistance of a system is in TIMs[17]. For the potential implementation of the LED module, Zweben[18] lists serial low (or the potential to be low) cost high thermal conductivity materials with a low coefficient of thermal expansion.

Figure 3 shows the typical range of cost functions for high thermal conductivity materials which is probable to apply on LEDs. The boron nitride (BN) is widely used as TIMs in electronics. Compared to BN, some of the other materials are very competitive with their high thermal conductivity and acceptable price. Since the thermal management problem is not unique to LEDs and there is a certain similarity between electronic packages and LED packages, materials used in the semiconductor industry have a high potential to improve the thermal performance of the LEDs. One potential material in consideration is the carbon nanotubes which have experimentally determined heat conductivities of about 500–3000 W/(m·K) for a multi-wall carbon nanotube (MWNT) and about 3500 W/(m·K) for a single wall carbon nanotube (SWNT)[19]. In addition, the graphene has the advantages of the ease for silicon integration and extremely high thermal conductivity in the range of 3080–5150 W/(m·K)[20], which has a high possibility for thermal management in future nano-electronic circuit and LED applications.

5. Conclusion

Thermal management is a key issue for current and future HB LEDs. Passive solutions are always preferred in industry for the simple structure and low price. Since the major part of heat generated by the LED chip will be transferred to heat sinks, designs with low thermal resistance of LED boards and heat sinks are essentially considered. Currently, heat sinks and phase change recirculation systems are the most common passive cooling solutions. Considering the commercial LEDs with power consumption less than 50 W, heat sinks are theoretically sufficient for the thermal management, while heat pipes still need to compete with heat sinks for future developments with pros of thermal performance but cons of high cost. In addition, high thermal conductivity TIMs are indispensable which lead to considerable thermal issues in the LED module. Meanwhile, advanced thermal materials and novel thermal solutions which are already successfully applied on microelectronic packages have a high potential to be used on the LED module.

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