An Innovative Passive Cooling Method for High Performance Light-emitting Diodes

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Abstract

Thermal management challenges are becoming a major roadblock to the wide use of high-power LED lighting systems. Incremental improvements in conventional bulk metal heat sinks and thermal interface materials are projected to be insufficient to meet these challenges. Active cooling methods, such as forced air and pumped liquid cooling, may provide better performance but at the expense of higher cost and energy consumption. Passive phase change (liquid to vapor) cooling devices, such as heat pipes and thermosyphons, are well established in the electronics industry as a very effective and reliable way of removing excess waste heat at low thermal resistance. Successful application of heat pipes and thermosyphons in solid-state lighting (SSL) products will require adapting the technologies to the form-factor, material and cost requirements unique to SSL products. This paper describes a recent development effort that integrates a planar thermosyphon into a printed circuit board (PCB) for LED devices. The planar thermosyphon/PCB uses a dielectric fluid as the heat pipe working fluid, achieving significantly improved heat spreading performances over conventional PCBs. Analytical modeling showed a more than 50% thermal resistance reduction from typical metal core PCBs. A low temperature electroplating technique was also investigated to fabricate wick structures onto PCB surfaces to enhance the boiling heat transfer performance of the dielectric fluids. Test results showed that a boiling heat transfer coefficient of 20,000W/m^2-K can be achieved with the 3M Novec fluid. In this paper, the preliminary study on heat transfer enhancement by using the PCB planar thermosyphon in single LED assembly was reported. Future development efforts will verify the design in practical applications, address manufacturing issues and improve the cost efficiency.

Keywords

Two-phase passive cooling, PCB-based dielectric planar themosyphon, high power LEDs, boiling heat transfer enhancement, low temperature sintering

1. Introduction

According to the U.S. Department of Energy (DOE), solid-state lighting (SSL) technology has the potential to cut U.S. lighting energy usage by one-quarter and contribute significantly to our nation's climate change solutions. Compared with conventional white light sources such as incandescent, fluorescent, and metal halide lamps, light-emitting diodes (LEDs) provide significant benefits including compact size, long life, ease of maintenance, resistance to breakage and vibration, good performance in cold temperatures, reduced infrared or ultraviolet emissions, and instant-on performance. Table 1 shows the potential advantages as well as the challenges facing LED technology. Although the electrical power to visible light conversion efficiency of 20-30% represents significant improvement over the incandescent light sources, the 70-80% non-radiant heat dissipation poses a significant challenge to the thermal management of the device.

Cost competitiveness and quality have been identified by DOE as the two additional roadblocks in the commercialization path of the LED technology. Currently, LEDs cost 10 times more than incandescent lamps and 5 times more than compact fluorescent lamps (CFL). DOE's goal is to reduce the LED cost comparable to CFL's by 2015. Since a large portion of the energy in LED devices becomes waste heat and the LED junction temperature affects device's long-term reliability, developing thermally and cost effective thermal management methods plays a key role in improving LED's quality and cost competitiveness.

Table 1: Power Conversion for White Light Sources

	Incandescent	Fluorescent	Metal Halide	LED
Visible Light	8%	21%	27%	20-30%
IR	73%	37%	17%	0%
UV	0%	0%	19%	0%
Total Radiant Energy	81%	58%	63%	20-30%
Non-Radiant Heat	19%	42%	37%	70-80%
Total Energy	100%	100%	100%	100%

High brightness LEDs (HBLEDs) are finding increasing usage in applications like LED lamps, display backlighting, and camera flash for cell phones. A typical high power LED chip has 1mm^2 surface area with a total power consumption of 1W. According to the 70-80% power to heat conversion rate in LEDs, the heat flux can be as high as 80 W/cm^2. By 2012, the heat flux will reach about 340 W/cm^2, which is 6-7 times higher than that of conventional CPU chips [1]. The high heat fluxes at the junction level, coupled with the dense packaging of many components into a small package, results in two thermal management challenges: temperature uniformity across multiple LED junctions and in-plane heat spreading at the heat sink and PCB package levels.

To date, many heat dissipation solutions have been investigated for the thermal management of high-power LEDs, from the chip package level to the printed circuit board (PCB) level to the system level. The package-level thermal management research [1- 5, 11], which involves thermal material research, package design optimization such as 3D packaging design and LED array optimization, and theoretical simulations, is important to determine the packaging thermal resistance of LEDs as well as reduce the footprint. The board-level thermal management research [6-10] is mainly focused on solder material, bonding method improvement, and printed circuit board design optimization. On the system level [4, 12-20], fin-heat sinks with external active cooling is still the mainstream method in industry due to its high reliability and lowest cost. Aside from conventional fans, piezoelectric fans [3, 23] have gained increasing interest from industry. Two-phase passive cooling methods like heat pipes and vapor chambers [15] are becoming good options for emerging HBLEDs. Due to the very high flux heat dissipation requirements, active liquid cooling is widely studied [13-14, 18-19]. Other than active liquid cooling, some novel and advanced methods have also emerged, such as micro-channel coolers [24], electrohydrodynamic approaches [22], and thermoelectric cooling [17]. However, these strategies often involve complex design processes, reliability issues, cost issues, high power consumption, which are the main obstacles for their commercialization and utilization.

In this paper, an advanced high-power LED cooling technology targeted at reducing the thermal resistance on the board level is presented. This technology integrates a passive two-phase thermosyphon into a printed circuit board, which effectively converts the PCB into a high performance heat spreader. Although vapor chamber printed circuit boards and vapor chamber heat sinks have been investigated by other groups [9, 15], the novelty of the current concept is the direct bond between the PCB/heat spreader and LED devices that eliminates extra thermal interfaces as well as the need for electrical insulation between heat sink and PCB. Thus the new design can significantly enhance cooling that allows the LED to run at higher fluxes without degradation in performance, and improve heat spreading that is particularly effective in cooling arrays of high density chips.

2. Passive Heat Spreader (PHS) Printed Circuit Board (PCB)

The thermosyphon is a proven cooling technology with exceptional heat transfer performance. A traditional thermosyphon is a tubular metal structure that consists of an evaporator and a condenser section. A planar thermosyphon can be viewed as a highly efficient heat spreader. When subjected to heating by an electronic device attached to the evaporator, the working fluid inside the thermosyphon vaporizes and thereby limits temperature rise. The vapor condenses back to liquid at the condenser, which is cooled by an external heat sink. In the gravity field, the condensed liquid falls back to the evaporator in the form of a liquid film on the sides of the thermosyphon.

Figure 1(b) illustrates the design concept where the copper lid (at top), PCB and the copper thermal pad (at bottom) form the envelope of the thermosyphon. Compared with the typical surface mount LED in Figure 1(a), the thermosyphon design replaces the low thermally conductive dielectric layer by an enclosed vapor space filled with dielectric fluid. The copper thermal pad of the chip package can be directly soldered to the thermosyphon for minimal interface thermal resistance. It should be pointed out that one PCB thermosyphon heat spreader can have multiple, discrete copper thermal pads to accommodate arrays of LED devices. The dielectric working fluid for the thermosyphon provides the necessary electrical isolation to prevent short circuiting. This feature eliminates the need for a ceramic substrate separating the thermal pad from the electrical circuitry and eliminates the associated thermal resistance. In summary, the technology presented in this paper has the potential of improving thermal performance and simplifying the LED packaging, which will in turn result in cost savings.

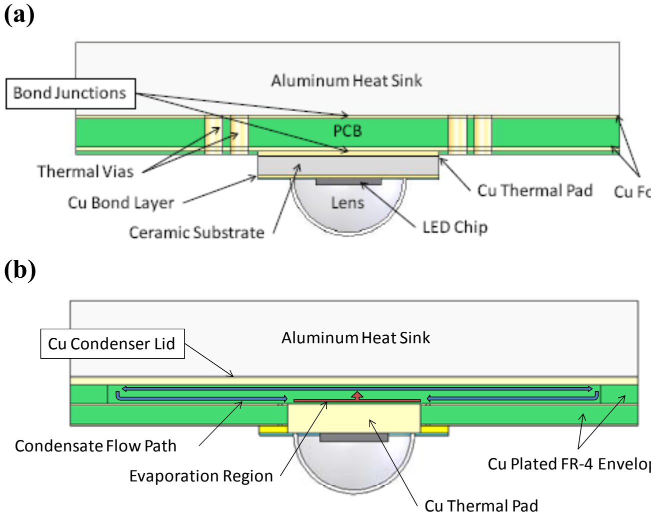

Figure 1: (a) Cross-sectional depiction of a typical surface mount LED mounted to an FR-4 PCB with open thermal vias (anode and cathode not shown). (b) Cross-sectional depiction of the PHS PCB for a single LED package. The LED thermal pad is integrated directly into the FR-4 envelope such that the thermal pad's top surface acts as the evaporator. A copper plated FR-4 frame is used to bond the FR-4 PCB and the copper lid (the condenser). Vapor and condensate flow paths are also shown within the vapor space formed by the FR-4 frame.

Thermosyphons are particularly suited for LED cooling since many artificial lighting applications are in the form of downlighting where the gravity aids in the condensate return inside the thermosyphon. For other orientations, a wick may be used to provide the capillary action needed to drive the liquid against the gravity. The use of a thin layer of wick over the evaporator area will also enhance the boiling heat transfer by providing extra nucleation sites and enhancing liquid supply to local high heat flux areas. Because the design involves a copper clad PCB board, fabricating and bonding the wick to the thermosyphon inner surfaces needs to occur at relatively low temperatures to avoid any damage to the PCB. A novel low temperature electroplating scheme was investigated, and the result is presented in this paper.

3. Results and Discussions

The prototype design was developed based on one of the high brightness LEDs - Cree XLamp® LEDs [21]. In this LED package, the typical dissipated heat fluxes range between 18 and 64W/cm^2 over an area of 4.25mm^2. MCPCBs and FR-4 PCBs with thermal vias as shown in Figure 2 are suggested by Cree to be used with this high power chip package. The PHS PCB was targeted to dramatically reduce the thermal resistances in the PCB and the associated TIM layers. Figure 3 shows the cross-sectional view of the prototype design. Table 2 ~ Table 4 listed the configurations for all three PCBs. The thermal performances of the prototype design as well as the other two PCBs were analyzed using commercial CFD software.

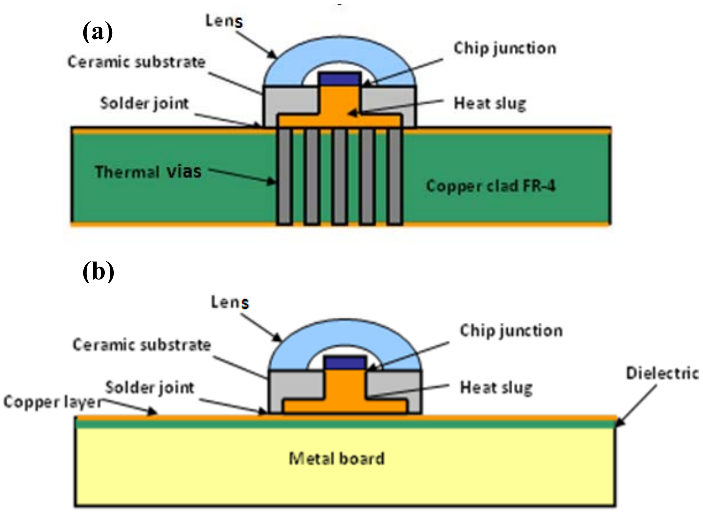

Figure 2: Diagrams of LED chip package mounted on (a) FR-4 PCB with thermal vias, and (b) metal core PCB

Table 2: FR-4 PCB with thermal vias configuration (PCB surface area 270mm^2)

Component	Thickness (µm)	Thermal conductivity (W/m-K)
Top layer copper	70	398
FR-4	1588	0.2
Filled vias (SnAgCu)	1588	59
Bottom layer copper	70	398
Total	1728	--

Table 3: Metal core PCB configuration (PCB surface area 270mm^2)

Component	Thickness (µm)	Thermal conductivity (W/m-K)
Top Layer Copper	70	398
PCB dielectric	100	2.2
Al plate	1588	150
Total	1758	--

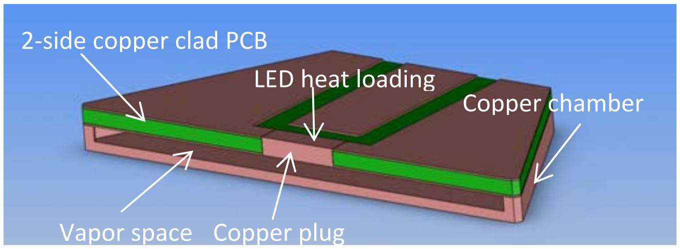

Figure 3: Cross-sectional view of the prototype design of the PCB planar thermosyphon for single LED. A copper plug is implemented in the middle of a two-side copper clad FR-4 PCB via a through hole to simulate the LED thermal pad and the FR-4 PCB is bonded to a copper chamber to form the vapor space which contains the dielectric working fluid.

Table 4: PHS PCB Configurations (PCB surface area 270mm^2)

Component	Thickness (µm)	Thermal conductivity (W/m-K)	Heat transfer coefficient (W/m^2-K)
Copper plug (area 3.3mm x 1.65mm)	728	398	--
Top layer copper	70	398	--
FR-4 dielectric	588	0.2	--
Bottom layer copper	70	398	--
Evaporator surface	--	--	20,000
Vapor space	600	100,000	--
Condenser surface	--	--	10,000
Copper chamber	1000	398	--
Total	1728	--	--

The modeling results are displayed in Figure 4. The total heat load Q_{in} is 1W, and finned heat sink with forced air cooling is assumed on the back side. The total temperature gradient ΔT in the FR-4 PCB, the MCPCB, and the PHS PCB were calculated to be 26.6°C, 7.2°C and 3.7°C, respectively. Thermal resistance R is defined as

$$R = \frac{\Delta T}{Q_{in}}$$

The thermal resistances of the FR-4 PCB, the MCPCB, and the PHS PCB were 26.6°C/W, 7.2°C/W, and 3.7°C/W. The thermal resistance of the PHS PCB is less than one-sixth of that of the FR-4 PCB and half of that of the MCPCB. The reduction in thermal resistance will be even more significant if the elimination of the solder joint between the LED package and the PCB is included in the calculation.

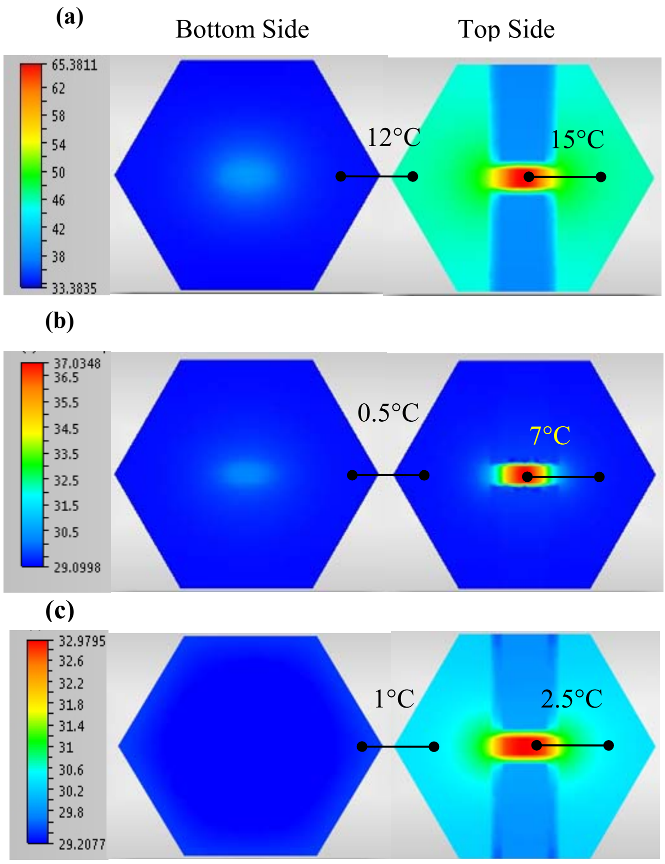

Figure 4: CFD results of the temperature distribution over (a) FR-4 PCB, (b) MCPCB and (c) PHS PCB. Under the heat load of 1W, the temperature difference between the heat loading surface (top) and the bottom of the PCBs were 26.6°C, 7.2°C and 3.7°C, respectively. FR-4 PCB has poor thermal resistance in both heat spreading directions. MCPCB has good axial heat conduction but poor in-plane heat spreading. PHS PCB has low thermal resistance in both directions.

Materials selection for the prototypes was based on considerations of performance, compatibility, reliability, and cost. FR-4 PCB was selected as part of the thermosyphon envelope for its low cost and availability in LED systems. Oxygen free copper, a proven heat pipe envelope material, forms the other part of the thermosyphon envelope. Novec 7200 and 72DE were selected as the working fluids for their latent heat, vapor pressures, surface tension properties and their compatibility with other materials in the system. A permeation test was performed on two samples to examine the leakage rate and materials compatibility. In the first sample, a piece of copper clad FR-4 PCB was soldered onto a copper chamber to form a vacuum tight envelop. The second sample had the same setting as the first one except the copper clad layer was partially removed so that the working fluid met the FR-4 directly. Both samples were half filled with the Novec 7200. In 4 months, continuous weight loss was observed on the 2nd sample, but none on the 1st sample. The FR-4 is permeable, but hermetic sealing can be obtained by applying copper coating on the FR-4.

The CFD analysis shows that the evaporation heat transfer in the evaporator of the thermosyphon plays a critical role in the overall thermal performance. As discussed earlier, the use of a thin layer of wick over the evaporator area will enhance the evaporation heat transfer. In particular, sintered powder wicks have been demonstrated in many previous studies to provide high boiling/evaporation heat transfer coefficients at high heat flux conditions. Two approaches to wick fabrication were investigated: intense pulsed light (IPL) sintering and microfabrication electroplating. The IPL sintering technique yielded wicks with inconsistent quality. The electroplating technique, on the other hand, yielded successful results. Figure 5 shows the images of the top and angled views of a sample wick structure with porous posts under a scanning electron microscope (SEM).

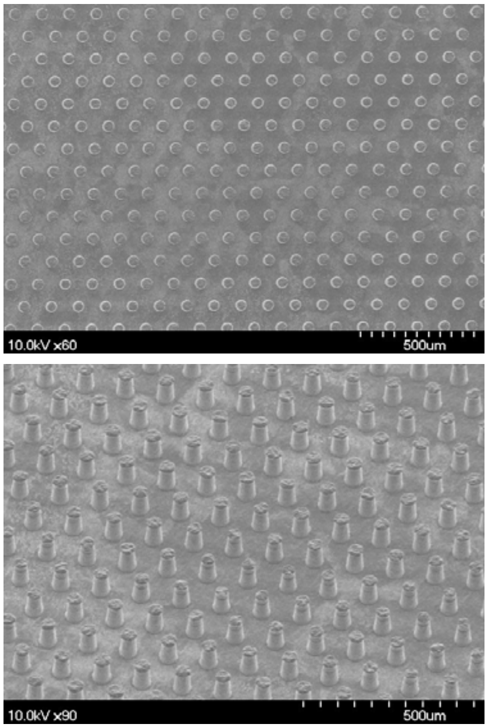

Figure 5: SEM images of electroplated Cu posts on a PCB board. Left: top view. Right: angle view.

Two wick samples of different porosities were tested for their boiling heat transfer performance: a low-solid-fraction (.227) sample (LSF) and a high-solid-fraction (.463) sample (HSF). In both samples, the copper powder posts, 50 μm in diameter and 100 μm in height, were electrodeposited on a 500 μm-thick Si wafer. The pitch distance in LSF and HSF were 100 μm and 65 μm, respectively. The overall wick area was 2.2cm by 2.2cm. A 5 mm x 5 mm thin-film heater was used as the heat source. The samples were held vertically with the lower end dipped in the working fluid to allow the fluid to wick the evaporator region by capillary force. The experiments were performed in a vacuum-tight chamber with the saturation temperature at approximately 33°C for 72DE and 65°C for 7200.

The test results, as shown in Figure 6, indicate that the HSF wick exhibits higher heat transfer coefficients than the

LSF wick. For 3M dielectric fluid 72DE, although partial dry-out occurred at heat fluxes around 10W/cm^2, heat transfer coefficients as high as 10,000W/m^2 K was achieved with the HSF sample. In the tests with two different 3M dielectric fluids, heat transfer coefficients as high as 20,000W/m^2 K was obtained for the HSF sample in 72DE below 6W/cm^2.

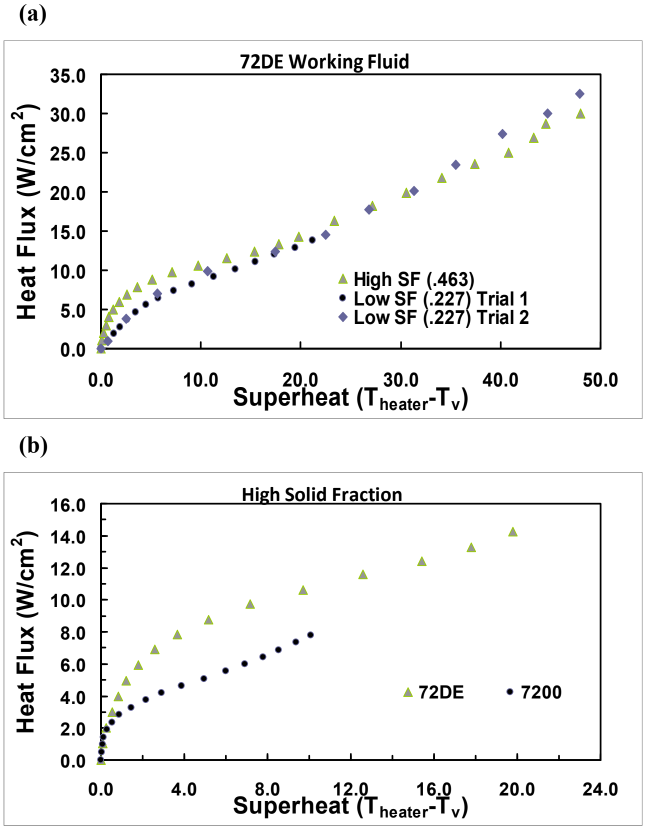

Figure 6: Experimental Results for Boiling Heat Transfer Tests. (a) Low solid fraction sample and high solid fraction sample were both tested with 3M Novec dielectric fluid 72DE. Partial dry-out started at heat fluxes around 10W/cm^2. (b) High sold fraction sample was tested with both 3M Novec dielectric fluids 72DE and 7200. Heat transfer coefficient as high as 20,000 W/m^2 K achieved for 72DE at heat fluxes up to 6W/cm^2.

4. Conclusions

The feasibility of a novel PCB based planar thermosyphon concept for high power LED cooling was demonstrated through numerical simulation and experimental study. This PHS PCB was made of a FR-4 PCB lid and a copper chamber, and used a dielectric working fluid. Although an initial permeation test showed the dielectric fluid permeated through the PCB wall, standard copper cladding solved the PCB permeation issue. Wick structures were applied to the evaporator of the thermosyphon to achieve the desired boiling heat transfer performance. Numerical simulations of a representative CREE LED package incorporating various thermal management methods, including FR-4 PCB with thermal vias, MCPCB and the new PHS PCB, were performed to identify the performance enhancements by the new concept. It was shown that the heat transfer performance of the PHS PCB improved by 50% over the MCPCB and 86% over the FR-4 PCB. An experimental investigation on using various wicks for boiling heat transfer enhancement was conducted, which revealed that a boiling heat transfer coefficient of 20,000W/m^2 K can be achieved with 3M 72DE dielectric fluid and an advanced wick structure at heat fluxes up to 6W/cm^2. Various low-temperature wick fabrication techniques were also investigated Further enhancing the phase change heat transfer will be studied by testing with different working fluids e.g. DI-water, and improving wick structures. Also, additional wick structures will be added to make the PHS independent of gravity.

Acknowledgments

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