High Heat Flux Heat Pipes Embedded in Metal Core Printed Circuit Boards for LED Thermal Management

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Abstract

As LED applications continue to expand beyond lighting and sensors, the power levels and heat dissipation requirements will also continue to increase. Thermal management is becoming a major design issue for high-power LED systems. The size and weight of conventional bulk metal heat sinks cannot satisfy shrinking packaging constraints. Active cooling methods, such as forced air cooling or even pumped liquid, can provide acceptable performance but at the expense of increased energy consumption, reliability and most notably noise. Passive phase change (liquid to vapor) cooling devices, such as heat pipes, 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 in general solid-state lighting (SSL) and other higher intensity lighting products will require adapting these heat pipe technologies to the form-factor, material and cost requirements unique to SSL products. This paper describes a recent development effort that integrates heat pipes with novel wick structures into metal core printed circuit boards (MCPCB) for high power LED devices. The novelty of the advanced wick structure lies in a low evaporative thermal resistance, which was engineered to address the high heat fluxes associated with LED devices. The embedded heat pipes use water as the working fluid, allowing the MCPCB to significantly improve heat spreading capability over conventional PCBs and MCPCBs. Experimental results show an average of 35 - 45% reduction in thermal resistance from typical MCPCB sizes and materials, which agrees with numerical modeling. The advanced wick structure was engineered to maximize the evaporative heat transfer coefficient near the heat input area (>8 W/cm^2-K) while maintaining high heat transport limits (>30 Watts per heat pipe). In this paper, the continuing study on heat transfer enhancement in a single-diode LED assembly is reported. Future development efforts will integrate the design in practical applications including arrays, address manufacturing issues and improving cost efficiency.

Keywords

Two-phase passive cooling, Metal Core Printed Circuit Board, high power LEDs, heat pipes, high heat flux

1.0 Introduction

According to the U.S. Department of Energy (DOE), solid-state lighting (SSL) technology has the potential to cut U.S. lighting energy consumption by 25% and contribute significantly to our nation's climate change initiatives. 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, resistances to breakage and vibration, sustained performance in cold ambient environments, reduced infrared or ultraviolet emissions, and instant-on performance. Table 1 shows the potential advantages, as well as challenges facing LED lighting technologies. Although the electrical power to visible light energy conversion efficiency shows significant improvement over incandescent lighting, the 70 – 80% non-radiant heat dissipation poses a significant challenge on the thermal management side of the device [1].

Cost competitiveness and quality have been identified by the 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 to become comparable to CFLs by 2015. Since a large portion of the energy in LED devices becomes waste heat and the LED junction temperature affects the device's long-term reliability, developing cost effective high performance thermal management technologies places a pivotal role in improving the LED's quality and cost competitiveness [1].

Table 1. Power Conversions for White Light Sources [1].

	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 Energy	19%	42%	37%	70 – 80%
Total Energy	100%	100%	100%	100%

High brightness LEDs (HBLEDs) are finding increasing usage in applications like high bay lighting, theatrical stage lighting, and UV curing among others. A typical HBLED chip has a 1mm^2 mounting surface area and a total power consumption of 1 Watt. According to the power to heat conversion rate of 70 – 80%, the heat flux can be as high as 80 W/cm^2. In the next few years, that heat flux is expected to

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increase to over 300W/cm^2 in some applications, which is 6 - 7 times higher than that of convectional CPU chips [2]. The high junction level heat fluxes, coupled with dense packaging, 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. The state-of-the-art thermal solutions for LED applications most often relies on conduction through low thermal conductivity thermal interface materials to solid Aluminum heat sinks, which are becoming inadequate at dissipating the increasing heat fluxes.

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, which involves thermal material research, package design optimization, and LED array optimization, are important to determine the package thermal resistance [3, 4, 5, 6]. The board-level thermal management research is mainly focused on solder material, bonding method improvement, and printed circuit board design optimization [7, 8, 9, 10, 11]. On the system level, fin-heat sinks with external active cooling is still the mainstream method in industry due to its high reliability and lowest cost [5].

In this paper, an advanced high-power LED cooling technology targeted at reducing the thermal resistance on the PCB level is presented. This technology integrates passive two-phase heat pipe technology into a metal core printed circuit board, which effectively converts the PCB into a higher performance heat spreader. Although other two-phase heat pipe technologies have been investigated by other groups [10, 12], the novelty of the current concept involves an exceptionally low thermal resistance heat pipe wick structure that is capable of achieving very low thermal resistances while maintaining high heat transport capabilities. Thus the new design can significantly enhance cooling, which allows the LED to run at higher fluxes without degradation in performance, as well as improve heat spreading that is particularly effective in cooling arrays of high density chips.

2.0 The Heat Pipe Embedded Metal Core Printed Circuit Board

The heat pipe is a highly efficient, proven heat transfer technology. It relies only on the latent heat of vaporization and completely passive transport of a working fluid, sealed within a tubular metal envelope. Traditional heat pipes consist of a copper envelope, an internal liquid circulation wick structure, and water as the working fluid. When the envelope is in contact with a heat source it causes the working fluid to vaporize and as a result, the local saturation temperature and pressure increases. As a result of the pressure differential, vapor flows to the colder end and condenses, releasing the latent heat. The wick structure is a porous medium used to passively pump the condensate back to the heat source, as a result of the working fluid's surface tension. The aforementioned evaporative heat transfer resistance is typically a dominate resistance in the thermal pathway network, especially when subject to relatively high

heat fluxes. Subsequently, this is the focus of the research presented here.

Wick structures are commonly constructed from wire mesh or metal powder, fused to the internal wall of the envelope. For the heat pipes embedded in the MCPCB, a copper and water material system is selected for its high performance, low cost, and ease of manufacturing. Aluminum is commonly selected as the base material for MCPCBs, or Copper when higher thermal performance is required. By soldering copper heat pipes into Aluminum MCPCB substrates, the heat spreading capability of the substrate can be substantially increased. Due to the small diode footprint and close proximately of the heat pipe to the source, the evaporative resistance must be low compared to conventional heat pipes.

2.1 Low Resistance Wick Structure

One design challenge lies in minimizing the evaporator heat transfer resistance, denoted h_{evap}. Design control over this resistance primarily lies within the wick structure construction. It has been shown that sintered metal powder wick structures can exhibit exceptionally high thermal performance [13], especially when properly designed for high heat flux capability. A common limitation to evaporative heat transfer occurs when rapid vapor generation shears liquid away from the hot surface faster than it can be replenished, thereby causing device thermal failure. This effect can becomes more pronounced at higher heat fluxes when the liquid/vapor interface recedes into the thickness of the wick as a result of the increasing local vapor pressure overcoming the capillary pressure of the wick, keeping liquid from recirculating. This limitation is commonly known as the critical heat flux.

It has been shown that relatively fine pore sizes tend to increase the efficiency of thin film evaporation [13], known to exhibit the highest of evaporative heat transfer efficiencies. One additional heat pipe thermal resistance is the conduction through the wick structure to the evaporation interface, due to the low thermal conductivity of the working fluid that typically accounts for 40 – 60% of the wick, by volume. Therefore it is advantageous for the wick structure to be thin, however a thinner wick structure will have a higher liquid flow resistance. Thus, there are competing thermal goals:

- From a liquid delivery standpoint, a thicker wick is desirable for low liquid pressure drop
- From a wick conduction standpoint, a thinner wick is desirable for low conduction resistance
- From an evaporation efficiency standpoint a thinner, finer pore wick structure is desirable for thinner liquid film and higher capillary pressure

It can be concluded that there exists an optimum thickness for any given application, in order to balance thermal resistance with heat transport capacity. If carefully designed, improvements can be made to both sides of the balance without sacrificing the other. A wick structure designed with a liquid feeder section with high permeability and a thinner section with finer pores situated just underneath the heat

input area. This concept has been used in prior art with vapor chamber technologies [13]. In the context of high power LEDs, this concept is necessary in order to be capable of efficiently dissipating the increasingly high heat fluxes at the PCB level.
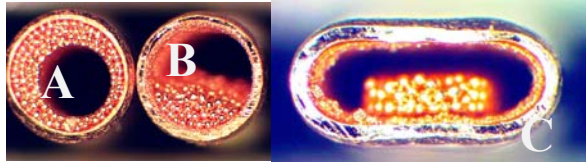

Figure 1. A cross section of three conceptual wick designs that were tested for thermal performance and manufacturability. Each had a similar conceptual design; a thick axial feeder wick with a thin, fine pore monolayer wick situated near the heat input region.

In order to satisfy the competing design goals, designs were sought after that would place thick liquid feeder wick along the axis of the heat pipe and a fine pore monolayer wick situated under the heat input region. Multiple conceptual designs were derived and each were tested for thermal performance and manufacturability. Each structure has a similar conceptual design, which are shown in Figure 1. Designs A – C were evaluated. Each design was embedded with solder into an Aluminum PCB substrate, thermally evaluated, and performance was compared against solid Aluminum and Copper substrates. Figure 2 shows the finished product, with etched circuitry on the top side and embedded heat pipes on the backside.
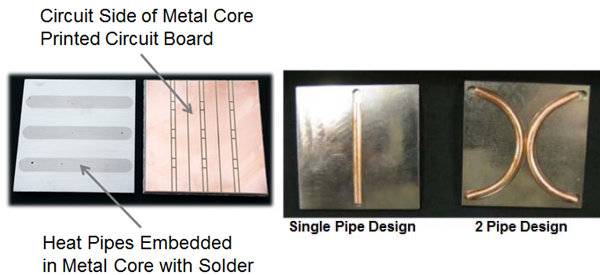

Figure 2. An Aluminum metal core printed circuit board embedded with high heat flux heat pipes (Left). Multiple heat pipe layouts were tested; single and two pipe layouts.

Additionally, two layouts were evaluated with a single heat input source, similar to what is also shown in Figure 2. The layout is highly dependent on the LED array layout and size, which can vary between applications.

3.0 Results & Discussion
The prototype design was developed based on commercially available HBLEDs. First, a numerical CFD model was developed to predict the reduction in PCB thermal resistance that could be attained with the addition of low evaporative resistance heat pipes. Secondly, an experimental investigation was carried out to validate modeling, and examine the various designs for ease of manufacturability.

3.1 CFD Modeling Predictions
The modeling results are shown in Figure 3. The temperature difference, ΔT, is defined as the peak temperature on the heat input side of the PCB minus the average temperature on the heat sink side. The heat load Q_{in} was applied to a pad similar to the size of the footprint of the selected LED, and pin finned heat sink with forced air cooling is applied to the back side.

For the CFD model setup, an effective heat sink resistance of 0.3°C/W was applied to the entire backside of the MCPCB, which is consistent with a reasonably sized pin fin heat sink with forced air convection. The overall size of the MCPCB measured 27cm², which is consistent with common MCPCB sizes associated with high power LED applications. A heat source positioned on center, measuring 0.27cm² was specified at 30 Watts, which resulted in a input heat flux of ~110 W/cm². All other surfaces were assumed to be adiabatic. Base material was 6061 Aluminum and heat pipe modeling parameters were consistent with the researcher's standard heat pipe modeling practice.

The CFD analysis shows that the evaporative heat transfer efficiency of the heat pipe plays a critical role in overall thermal performance of the heat pipe embedded MCPCB. Results suggest that the evaporative heat transfer coefficients typical of standard wire mesh heat pipe wick structures may be inadequate due to the small heat input area of the LED, and consequently a high heat flux. This theory is consistent with experimental data presented in the subsequent section on Experimental Heat Pipe Embedded MCPCBs.

The substrate thermal resistance was calculated by the following relation

$$R_{th} = \frac{T_{peak} - T_{avg}}{Q_{in}} = \frac{\Delta T}{Q_{in}} \tag{1}$$

The thermal resistances of the plain and heat pipe embedded MCPCB were calculated from the CFD results using the relation in Equation (1), and are tabulated in Table 2. The thermal resistance of the heat pipe embedded MCPCB is less than 28% of that of the standard Aluminum MCPCB.

Table 2. PCB thermal resistance calculation based on CFD predictions. Thermal load used in all simulations was 30 W.

	h_{evap} [W/cm²-°C]	Total ΔT [°C]	R_{th} [°C-cm²/W]
Aluminum Blank	--	19.7	0.17
Heat Pipe	2	16.5	0.14
	5	15.5	0.13
	10	14.2	0.12

3.2 Experimental Prototypes & Test Setup
In order to evaluate the thermal performance, a thin film resistance heater was used to simulate the LED heat load and flux. The source had a footprint area of 0.26 cm², a maximum heat input of 50 Watts, resulting in a maximum heat flux of 190 W/cm². The heat extraction side of the 2" by 2" x .093" thick MCPCB was cooled by a water circulated

cold plate, with a constant inlet temperature of 45°C. Heat input was calculated from the measured input voltage, a shunt resistor voltage, and the shunt's known electrical resistance. Temperature and voltage measurements were collected using a high speed data acquisition (DAQ) system. The experimental results were averaged from a data set of 15 heat pipe embedded Aluminum prototypes. The uncertainty of the experimental test setup was +/- 0.5°C for temperature measurements and +/- 0.1W on heat input measurements.

The range of heat loads that were tested covered 5 – 35 Watts, or until dryout, whichever occurs first. Dryout is determined by monitoring PCB thermal resistance, and is defined by the slope inflection point (decreasing then increasing) of thermal resistance vs. heat flux. The upper side of the PCB was insulated to minimize losses to ambient. Prior to PCB testing, the thermal resistance was quantified for the cold plate and thermal interface material used to attached the PCB to the cold plate, which was then subtracted out of the of total thermal resistance determined by Eqn. (1).
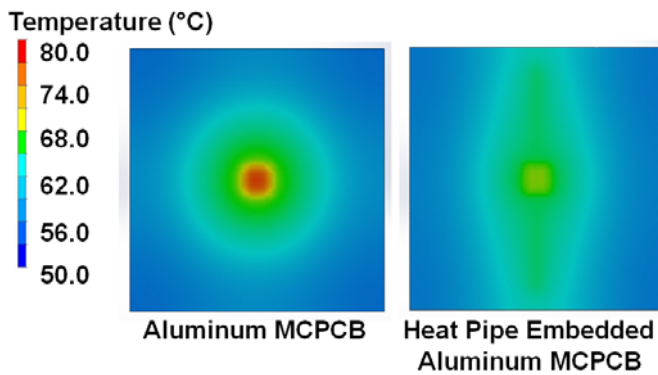

Figure 3. CFD Results showing temperature profiles of the heat input side for plain Aluminum MCPCB (left) and the heat pipe embedded MCPCB (right).

Table 3. Experimental results showing the improvements in thermal performance of the heat pipe embedded MCPCB over a conventional Aluminum and Copper MCPCB.

	Spreading Form Factor (Sink / Heat Input)	Avg. Thermal Resistance [°C-cm²/W]	% Decrease over Aluminum Baseline
Aluminum		0.21	--
Copper		0.19	12%
Heat Pipe - Mesh Wick	100x	0.27	-27%
Heat Pipe - Design A		0.12	45%
Heat Pipe - Design B		0.14	33%

3.3 Experimental Results

Heat pipes were first fabricated with a commonly used wick structure, copper wire mesh. It was shown that the evaporative heat transfer resistance was too high to dissipate the heat fluxes tested. This served as a baseline for the heat pipe embedded MCPCB. The conceptual design C, presented

above, was not thermally tested due to complexity in manufacturing. Designs A and B were thermally tested, and results are shown in Table 3. Both designs show large thermal improvements compared to the plain Aluminum MCPCB, with a maximum of a 45% improvement in thermal resistance.

In this study an MCPCB thickness of .094" was primarily investigated, which is common in many MCPCB applications. The author is aware of applications using .063" thick substrates and therefore efforts to fabricate heat pipes this thin was also explored, though these thicknesses can be very challenging to produce in higher volumes. From a theoretical thermal standpoint, the transport limits and heat flux dissipation ability should not be degraded for thinner heat pipes, however in practice transport limits may be lower due to difficulties in maintaining adequate vapor space for the axial vapor flow within the heat pipe. Significant efforts to develop sub-millimeter heat pipe thicknesses are currently being explored for LED applications and beyond.

4.0 Conclusions

The feasibility of a high heat flux capable heat pipe embedded in a metal core printed circuit board concept for high power LED cooling was demonstrated through numerical modeling and an experimental study. The MCPCB was made of Aluminum with a copper heat pipe embedded in it using solder, and using water as a working fluid. Three conceptual wick designs were developed in order to dissipate high heat fluxes with low evaporative thermal resistance. Two were selected for thermal evaluation based on ease of fabrication. A numerical CFD model was used to predict the PCB thermal resistance, and was experimentally verified. It was experimentally shown that the heat pipe embedded MCPCB had a 35 – 45% lower thermal resistance than a plain Aluminum MCPCB.

It can be concluded that these novel low evaporative resistance wick structures will enable high heat flux dissipation at the circuit board level with the use of embedded heat pipes. These advanced heat spreaders will provide means of PCB level thermal management for next generation of high brightness LEDs. Further investigations will focus on various applications, integration strategies, and high volume manufacturability.

Works Cited

[1] A. Fan, R. Bonner, S. Sharratt and Y. S. Ju, "An Innovative Passive Cooling Method for High Performance Light-emitting Diodes," in *Semi-Therm*, San Jose, CA, 2012.

[2] J. Zhang, P. Niu, D. Gao and L. Sun, "Research Progress on Packaging Thermal Management Techniques of High Power LED," *Advanced Materials Research,* Vols. 347-353, pp. 3989-3994, 2012.

[3] R. H. Horng, J. S. Hong, L. T. Tsai, D. S. Wuu, C. M. Chen and C. J. Chen, "Optimized Thermal Management From a Chip to a Heat Sink for High-Power GaN-Based Light-Emitting Diodes," *IEEE Trans on Electron Devices,* vol. 57, no. 9, 2010.

[4] J. Lau, R. Lee, M. Yuen and P. Chan, "3D LED and IC wafer Level Packaging," *Microelectronics International,* vol. 27, no. 2, pp. 98-105, 2010.

[5] Y. X. Qin and R. Hui, "Comparative Study on the Structural Designs of LED Devices and Systems Based on the General Photo-Electro-Thermal Theory," *IEEE Trans on Power Electronics,* vol. 25, no. 2, 2010.

[6] Hui Yu, Jintang Shang, Chao Xu, Xinhu Luo, Jingdong Liu, Li Zhang and Chiming Lai, "Chip-on-board (COB) Wafer Level Packaging of LEDs Using Silicon Substrates and Chemical Foaming Process(CFP)-made Glass-bubble Caps," in *International Conference on Electronic Packaging Technology & High Density Packaging*, 2011.

[7] N. Wang, A. Hsu, A. Lim, J. Tan, C. Lin, H. Ru, T. Jiang and D. Liao, "High Brightness LED Assembly using DPC substrate and SuperMCPCB," in *IEEE 4th International Microsystem Packaging Assembly and Circuits Technology Conference IMPACT*, 2009.

[8] V. Chen, G. Oliver, K. Roberts and D. Amey, "Benchmark Study of Metal Core Thermal Laminates," in *IEEE 5th International Microsystems Packaging Assembly and Circuits Technology Conference (IMPACT)*, 2010.

[9] L. Moon-Ho, H. J. Lee and Y.-J. Kim, "Design and Fabrication of Metal PCB based on the Patterned Anodizing for Improving Thermal Dissipation of LED Lighting," in *IEEE 5th International Microsystems Packaging Assembly and Circuits Technology Conference (IMPACT)*, 2010.

[10] F. Hou, D. Yang, G. Q. Zhang and D. Liu, "Research on heat dissipation of high heat flux multi-chip GaN-based white LED lamp," in *IEEE 12th International Electronic Packaging Technology and High Density Packaging Conference (ICEPT-HDP)*, 2011.

[11] L. Bo-Hung, C. Chih-Ming, H. Ray-Hua, C. Yi-Chen and W. Dong-Sing, "Improvement of thermal management of high-power GaN-based light-emitting diodes," in *Microelectronics Reliability*, 2011.

[12] X. Luo, R. Hu, T. Guo, X. Zhu, W. Chen, Z. Mao and S. Liu, "Low thermal resistance LED light source with vapor chamber coupled fin heat sink," in *60th IEEE Electronic Components and Technology Conference (ECTC)*, 2010.

[13] P. Dussinger, "High Heat Flux, High Power, Low Resistance, Low CTE Two-Phase Thermal Ground Planes for Direct Die Attach Applications," in *GOMACTech 2012*, Las Vegas, NV, 2012.