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A novel flat polymer heat pipe with thermal via for cooling electronic devices

Kai-Shing Yang [a], Tsung-Yi Yang [b], Cheng-Wei Tu [a], Chih-Ting Yeh [b], Ming-Tsang Lee [b,*]

[a] *Green Energy & Environment Research Laboratories, Industrial Technology Research Institute, Hsinchu 310, Taiwan, ROC*
[b] *Department of Mechanical Engineering, National Chung Hsing University, Taichung 402, Taiwan, ROC*

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ABSTRACT

The efficiency and heat transfer characteristics of a newly designed flat polymer heat pipe that uses copper micro thermal via was investigated using a fabricated laboratory model to measure the amount of heat that could be removed from a given heat source (a heater or a light emitting diode (LED) module) under a range of different operating conditions. The heat pipe consists of a copper frame 1 mm thick which is sandwiched between top and bottom sheets of FR4 polymer to form a vapor chamber. Copper meshes were used for the wick structure in the vapor chamber. The design also includes an array of thermal via, formed by 0.5 mm holes drilled through the polymer, which are copper plated and filled with resin similar to the FR4 polymer. This novel design enhances heat conduction through the wall of the polymer heat pipe. A transient dual interface method (TDIM) was used to measure the thermal resistance of the LED module mounted on the flat heat pipe. Experimental results showed that use of the thermal via design reduced the lateral thermal resistance by 20–25%. The thermal resistance of the flat heat pipe was also affected by the filling ratio of working fluid and the tilt angle. When the flat heat pipe with thermal via was used as a mounting substrate with the LED module located in the center of the top surface, experimental results showed the thermal resistance of the substrate was reduced by 57%.

1. Introduction

Efficient lighting devices are of great importance to energy saving and sustainability. The luminous efficiency of light emitting diodes (LEDs) has increased rapidly over the last decade and they are now available for many different kinds of lighting application. The LED has many advantages: it is DC driven, has a quick response, a long life, a simple structure, a compact size, is vibration-resistant, is non-polluting, suitable for mass production and is available in many colors. This gives the LED the potential to replace most existing traditional lighting sources. However, at the present time between 70% and 85% of the input power to an LED is wasted as heat. As the luminous requirement and thus the input power to the LED increases, the power density and chip temperature of the LED is greatly increased, and this leads to a reduction in luminous efficiency [1,2]. For an LED in a flat compact package, the surface area available for convective heat transfer is limited. This makes heat dissipation from the substrate critically important to the thermal management of an LED [3].

In practice, substrates with a large area compared to the lateral size of the LED are commonly used to increase the convective heat transfer. However, the big differences in size between the LED chip and the substrate results in considerable thermal spreading resistance effect and this makes effective heat dissipation through the substrate for LEDs [4,5] difficult to achieve, especially in the lateral directions. As a consequence, there are large temperature differences between the LED chip and the edges of the substrate, and the result is high chip temperature. Flat plate heat pipes are considered as potential alternatives to the common solid substrates due to the ability of transferring heat laterally with small temperature differences between the concentrated heat source (at the evaporator section) and the cold edges (at the condenser section) of the flat plate heat pipes [5]. Furthermore, the heat sinks used in current LED lighting units account for 70% of the total weight of the assembly [6]. This is not an ideal situation for advanced lighting designs where compact size is important. A heat pipe can transfer heat while keeping a relatively uniform temperature distribution owing to the inherent phase change heat transfer mechanism [7–11]. There are no moving parts in an ordinary heat pipe and simple fluids, such as water, can be used as the working fluid. Heat pipes are widely applied especially for cooling electronic devices where a high heat transfer rate with small

* Corresponding author.
E-mail address: mtlee@nchu.edu.tw (M.-T. Lee).

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temperature differences is required [10,12,13]. Flat heat pipes are ideal for electronic packages in many common devices that also need to be flat and thin. A sophisticated design provides an equivalent thermal conductivity of 6500–7000 W m^{-1} K^{-1} and a heat flux of 10–20 W cm^{-2} [12,14,15]. A polymer heat pipe has the added benefit of being light in weight and compatible with most electronics fabrication. A polymer can also be flexible, and good electrical insulation properties make it very suitable for simple incorporation in electronics packaging. Oshman et al. designed and fabricated a flat flexible heat pipe which utilized a multilayer polymer/aluminum material for the structure and triple layer sintered copper woven as the wick [16]. With the sophisticated design and materials, a low thermal resistance of approximately 1–3 K W^{-1} was obtained. The low thermal conductivity of most polymers presents serious heart transfer problems, which needs to be carefully addressed to make polymer heat pipes applicable for electronics cooling [17,18]. Metal structures such as copper-filled thermal via arrays embedded in the polymer could effectively reduce the thermal resistances through the polymer substrates for heat pipes and thus improve the performance of the polymer heat pipes [19–21]. In this study we investigated the performance of a flat polymer heat pipe used as both the substrate and the heat sink for high power density electronics components. A novel flat heat pipe made of FR4 polymer with copper thermal via array was designed, fabricated and tested. It is emphasized that in the current study we investigated the heat transfer performance of the flat heat pipe with thermal via array that were made of cost-effective materials and simple manufacturing process. Pure water was used as the working fluid in our experiments and the lateral heat transfer resistance of the flat heat pipe with different working fluid filling ratios and tilt angles was measured to evaluate its ability of spreading heat. To check the performance of the fabricated flat polymer heat pipe for cooling electronics with high power density, an LED module was used as the heat source and a transient dual interface method (TDIM) was used to measure the thermal resistance of the LED module mounted on the flat heat pipe.

1.1. Miniature FR4 flat heat pipe design and fabrication

The flat heat pipes fabricated and tested in this study were made of a composite material (FR4). A schematic of the heat pipe is shown in Fig. 1. FR4 is commonly used in the printed circuit board (PCB) industry as a substrate. Using FR4 heat pipes as the cooling unit for LED module had the advantage of process compatibility, light weight, and good temperature and chemical resistance. A copper frame 1 mm thick (Fig. 1c) was sandwiched between the top and bottom FR4 plates to form the vapor chamber. Two layers of copper meshes: one fine mesh (#200, wire diameter: 50 μm) and one coarser mesh (#100, wire diameter: 115 μm) formed the wick structure in the vapor chamber of the heat pipe. Fig. 1d shows the structure of the vapor chamber. The copper meshes were cut into the size that fit to the vapor chamber and cleaned carefully by rinsing with citric acid solution and deionized water. The cleaned fine and coarse copper meshes were then carefully placed and fixed on the top and bottom interior surfaces of the vapor chamber, respectively, by applying a small amount (3 × 3 small dots) of high temperature solder (PF606-P Lead-free solder paste, Shenmao Technology Inc.). Four small (3 mm × 3 mm × 1 mm) copper rods were used to separate these two meshes as shown in Fig. 1d. The assembled FR4 heat pipes were sealed by applying a low temperature solder (PF602-P Lead-free solder paste, Shenmao Technology Inc.) in a vacuum drying chamber. During the sealing process, the heat pipe was clamped between two thick glass plates to fix the assembly. The sealed heat pipe was then filled with working fluid, i.e. degased distilled water. Before filling the fluid, air in the heat pipe chamber was evacuated to 10^{-3} torr by using a vacuum pump. A precision glass cylinder flange containing measured amount of the degassed distilled water was then connected to the flat heat pipe to charge the working fluid. Finally, the connection tube of the heat pipe was tightly sealed using pliers and solder.

2. Experimental

Two experimental setups were used to measure the heat transfer characteristics. The first is shown in Fig. 2 and was used to investigate the lateral heat transfer ability of the flat heat pipe. A PSM-6003 DC Programmable Power Supply, (GW Instek, accuracy: 0.02% voltage, 0.1% current) with a resistive heater was used to provide heat (6–35 W) to the evaporator of the heat pipe. A water loop served as the condenser which included a YSC Tec. Thermostat (Model: P-20) as a cooling reservoir (at 5 °C) and a YSC Tec, water pump (Model PL103, flow-rate: 10 ml/min). Omega T type thermocouples (reading accuracy ±0.2 °C) and a PC based Yokogawa MX100 multichannel data acquisition system (reading accuracy ±0.05% +0.5 °C) were used to measure and record the temperatures at locations on the heat pipe as shown in the figure. The heater, condenser and thermocouples were in contact to the bottom surface of the heat pipe. An adjustable platform was used to study the performance of the flat heat pipe at different tilt angles. The degassing and filling procedures of working fluid (pure water) follows the description in Tseng et al. [7]. Air in the vapor chamber was evacuated and the working fluid was degassed before filling to minimize the oxidization of metal in the vapor chamber.

The lateral thermal resistance of the flat heat pipe, R, is defined as [10,22,23]:

$$R = \frac{T_e - T_c}{Q_a} \tag{1}$$

where T_e and T_c are the average surface temperatures of the evaporation and condensing sections, respectively. The heat transfer rate of the flat heat pipe, Q_a, is estimated as the mean value of the heating power provided by the power supply at the evaporating section and the heat carried away by the cooling water in the condensing section [10]. Steady state temperature readings were taken when variation of the evaporation section temperatures was less than ±0.2 °C over 600 s. Other information of the heat transfer performance measurement procedure and experimental apparatus can be found in the referenced study [10].

The second measurement system was the T3Ster® which was used for measuring the thermal resistance of the LED module including the flat polymer heat pipe, which served as both the substrate and cooling unit. Fig. 3 shows the T3Ster® experimental setup. The measurement principle of T3Ster® is the electrical test method (ETM) as specified in standard documents JESD51-1 [24] and the transient dual interface method (TDIM) as specified in JEDEC51-14 [25]. A temperature-sensitive parameter (TSP) noted as the K-factor for the LED component under test was calibrated before thermal resistance was measured. The K-factor correlates the variation of forward bias (ΔV_f) of the LED chip and its temperature (ΔT_j) as follows:

$$K_f = \frac{\Delta T_j}{\Delta V_f} \tag{2}$$

After the characteristic K-factor of the LED module is obtained, the chip temperature can be determined from the forward bias measurement results. Details of the T3Ster® measurement principles can be found in our previous publications [3,4,6]. For the thermal resistance measurement on T3Ster® system, the LED (heat source) is attached in the center of the top surface of the flat heat pipe, i.e. the evaporation section as shown in Fig. 3. The bottom