Development of a Flat-Plate Cooling Device for Electronic Packaging

Seok-Hwan Moon, Gunn Hwang, and Hyun-Taeck Lim

In this study, a microcapillary pumped loop (MCPL) that can be used as a cooling device for small electronic and telecommunications equipment has been developed. For thin devices such as an MCPL, securing a vapor flow space is a critical issue for enhancing the thermal performance. In this letter, such enhancement in thermal performance was accomplished by eliminating condensed droplets from the vapor line. By fabricating the grooves in the vapor line to eliminate droplets, a decrease in thermal resistance of about 63.7% was achieved.

Keywords: Electronic cooling, thermal packaging, thermal resistance, phase change, condensed droplet.

I. Introduction

The size and thickness of a variety of portable electronic devices are decreasing. Due to the limited space available in such devices, this trend is making it difficult for engineers to find proper solutions for thermal management. Recently, along with pressed heat pipe modules [1], materials with high thermal conductivity, such as aluminum, copper, and graphite, have frequently been used for thermal management. In particular, flat-plate-type heat pipes have been considered to overcome the limits in application that circular-type and pressed-type heat pipes have been undergoing. Although heat pipes have the critical advantage of a high thermal conductivity, thin versions developed for application in small package structures demonstrate low thermal performance. This is due to an increase in flow resistance by a counterflow created between the vapor and liquid, as well as to a difficulty in securing proper vapor flow space. To solve this problem, a thin flat-plate microcapillary pumped loop (MCPL) was suggested by Kirshberg and others [2]. Due to the flow separation characteristic between the vapor and liquid, the MCPL has the advantage of high thermal performance compared with other phase change heat pipes having the same size and thickness. Since the first suggestion of a flat-plate-type MCPL by Kirshberg, mainly analytical and fabrication studies [3] have been conducted. Moon and others [1] provided experimental results for an MCPL in 2007. In the authors' results, the MCPL showed normal operating characteristics for separating the vapor and liquid flow. However, the MCPL showed a problem in that condensed droplets are created on the wall of the vapor line. The condensed droplets increase the flow resistance of the vapor and result in a decrease of thermal performance. In this letter, the design, fabrication process, and experimental results to solve this problem are discussed.

II. Fabrication

1. Operating Characteristics and Design

Unlike a heat pipe, an MCPL uses separated vapor and liquid flow lines. Therefore, there is no friction resistance on the interface between the vapor and liquid phases except shear stress on the wall, which results in an increase in thermal performance. Figure 1 shows the early designed MCPL used in the present study. In the MCPL, the evaporator, vapor line, condenser, liquid line, and reservoir are combined in one flat plate. The liquid, which is saturated in the grooves of the evaporator, is vaporized using an input power, and the vapor is then transported to the condenser through the vapor line, which has a wide cross section area. After the vapor releases latent

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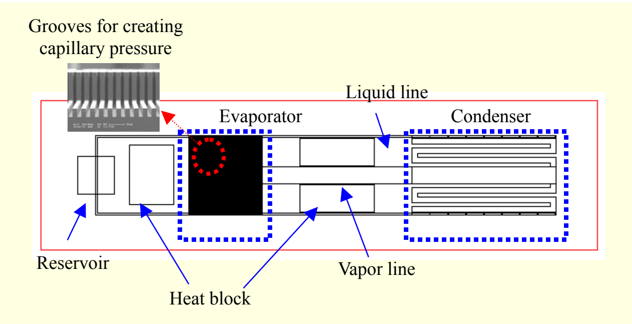

Fig. 1. MCPL structure.

heat at the condenser, the vapor is then condensed by 20ºC water cooling. The condensed liquid then flows back to the evaporator through two different liquid lines, thus creating a circulating mechanism. The MCPL designed in this letter has a total length of 70 mm, a width of 20 mm, and a thickness of 1.5 mm. The vapor line, 0.5 mm (height) × 2 mm (width) × 40 mm (length), is connected to the 9 mm × 10 mm evaporator and 10 mm × 20 mm condenser. The early design of the MCPL, shown in Fig. 1, showed normal operating characteristics through an experimental test [4]. However, a visual investigation through a glass top plate revealed the phenomenon shown in Fig. 4(a), in which droplets were created due to the condensing of the vapor and clung to the wall of the vapor line and part of the condenser. The formation of these droplets in the vapor line increases the flow resistance of vapor with large specific volumes and results in a decrease in the thermal performance of the MCPL. Therefore, longitudinal grooves were designed and fabricated on the top and bottom walls of the vapor line to eliminate droplets.

2. Fabrication of Grooves Used for Eliminating Droplets

Figure 2 shows the edited version of an MCPL with grooves in the vapor line of the bottom silicon plate and the top glass plate for eliminating droplets. Seven grooves with a width of 250 µm and depth of 60 µm were fabricated at the bottom silicon plate, and seven grooves with a width of 131 µm and depth of 50 µm were fabricated at the top glass plate. Because these grooves were designed to eliminate droplets, their sizes are larger than those of the transversal grooves used for creating capillary pressure at the evaporator, which have a width of 20 µm and depth of 60 µm. This is because a total pressure drop of the MCPL should be considered for a normal phase change operation, as shown in (1) [4]:

$$\Delta P_c \geq \Delta P_e + \Delta P_v + \Delta P_{cn} + \Delta P_l, \qquad (1)$$

where $\Delta P_c = 2\sigma / r_c$ is the capillary pressure limit, and ΔP_e, ΔP_v, ΔP_{cn}, and ΔP_l are the pressure drops in the evaporator,

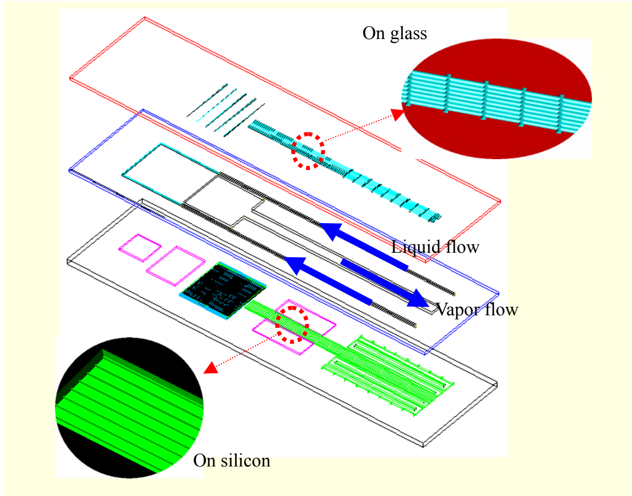

Fig. 2. Grooves used for eliminating droplets.

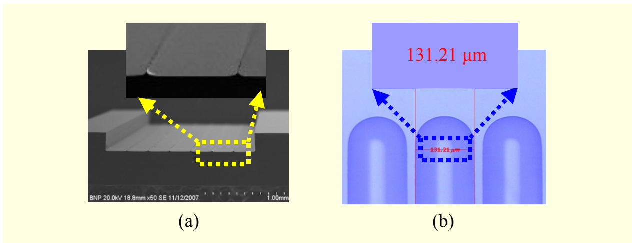

Fig. 3. Fabricated grooves for eliminating droplets on (a) silicon and (b) glass.

vapor line, condenser, and liquid line, respectively. For normal operation of the MCPL, as shown in (1), the total pressure drop through the loop has to be less than the capillary pressure limit created at the evaporator. The maximum pressure in the MCPL was estimated at about 1.01 bar for 100ºC of evaporator temperature. Also, the pressure drop of ΔP_e, ΔP_v, ΔP_{cn}, and ΔP_l were estimated to be 0.18 $\times 10^{-5}$ bar, 49 $\times 10^{-5}$ bar, 1.2×10^{-5} bar, and 15×10^{-5} bar by the numerical analysis, respectively.

Figure 3 shows the fabricated grooves used for eliminating droplets. The grooves in the silicon bottom plate of Fig. 3(a) were fabricated using a deep reactive ion etch (DRIE) process. The grooves in the glass top plate of Fig. 3(b) were fabricated using wet etching and sanding processes. The detailed fabrication processes are as follows. A 3-µm oxide masking layer was deposited onto the silicon bottom wafer using wet thermal oxidation. After photo-resist patterning and dry etching to the oxide layer, 8000 Å of oxide was deposited and patterned as a second masking layer. Next, a first stage of grooves was etched to a depth of 60 µm using the first DRIE process. After removing the remaining PR, a second stage of grooves was etched to a depth of 200 µm using the second DRIE process. Then, the grooves were etched to a depth of 50 µm using wet etching at the vapor line in the top wafer. The bottom silicon wafer was also bonded to a middle glass wafer using an anodic bonding process. The top glass wafer was bonded onto the middle and bottom wafers using a direct bonding process. The envelope for the MCPL was then completed. Pure water was used as the working fluid considering the temperature range within 120ºC, large surface tension for capillary force, large latent heat for the heat transport amount, and compatibility between working fluid and container material of the MCPL. The working fluid was filled until all the grooves and liquid lines in the MCPL were saturated and the amount of working fluid was about 0.0854 g, which was measured by weighing.

III. Experimental Results

Figure 4(a) shows condensed droplets in the vapor line and part of the condenser during a phase change. The droplets were grown through coalescence as the input power was increased. This is due to the droplets inducing a flow resistance of the vapor, resulting in a decrease in the thermal performance of the MCPL, the experimental results of which can be seen in Fig. 5. Figure 4(b) shows photographs taken while the MCPL with grooves for eliminating droplets was in operation. In contrast to Fig. 4(a), 4(b) shows that the condensed droplets in the vapor line can be eliminated completely. The eliminated droplets are transported to the condenser. Figure 5 shows the experimental results for the grooves used to eliminate droplets. An MCPL without working fluid, as well as MCPLs with and without grooves for droplet elimination, were investigated and compared for their thermal performance. As we can see from the results, the effect of the grooves was quite good. The thermal resistance of the MCPL with grooves was decreased about 63.7% compared with that without grooves. The grooved MCPL offered a heat transfer rate of 6.8 W within the steady state evaporator temperature of 120ºC. 6.8 W of input power in which heat loss was already considered for calculation was absorbed entirely by the MCPL. The heat transfer rate of the heat pipe was decreased as its diameter was increased. In particular, if the diameter was decreased below 2 mm, the heat transfer rate was largely decreased [1]. Therefore, in the case of

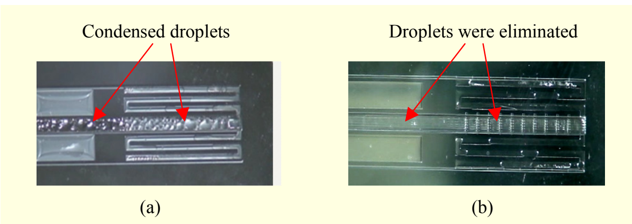

Fig. 4. Photographs taken during operation: (a) condensed and (b) eliminated droplets.

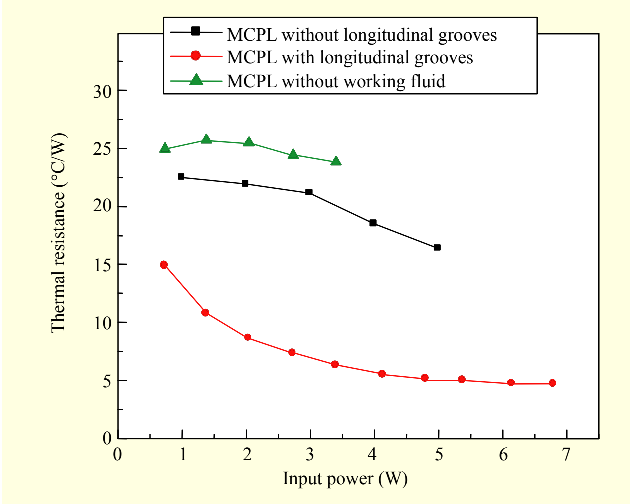

Fig. 5. Thermal enhancement of the MCPL by eliminating droplets in vapor line.

the thin MCPL used in this letter, securing a maximum vapor flow space is very important for thermal performance.

IV. Conclusion

Using separated vapor and liquid lines, an MCPL design for enhanced thermal performance was described in this letter. The proposed MCPL has a wide range of applications due to its thinness and flat-plate-type design. The MCPL was designed and fabricated with grooves for eliminating droplets created on the wall of the vapor line. Through a visual investigation, we found that the droplets were eliminated completely. To enhance the thermal performance, it is very important that a thin MCPL be able to secure maximum vapor flow in a cross sectional area, and based on our experimental tests, we were able to obtain a decrease in thermal resistance of about 63.7% compared with an MCPL without grooves.

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