Development of the Micro Capillary Pumped Loop for Electronic Cooling

S.-H. Moon, G. Hwang

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Seok-Hwan Moon, Gunn Hwang
Microsystem Team,
Electronic and Telecommunications Research Institute,
161 Kajeong-Dong, Yusong-Gu, Daejeon 305-350, KOREA
Email: {shmoon, hwangun}@etri.re.kr

***Abstract*-Electronic devices have been minimized but the performance of those is becoming better and better. Therefore it is needed to develop new cooling methods suitable for a thin packaging structure with high thermal density. The thin flat plate type micro CPL(capillary pumped loop) with the thickness less than 2mm was developed in this study. The proposed micro CPL has two staged grooves in evaporator instead of poles for preventing backflows of the vapor bubble and the simpler structure than that of a micro CPL with the poles. Also a large vapor space from the evaporator to the condenser was constructed in the middle plate therefore flow resistance of the vapor could be reduced. The micro CPL was fabricated using MEMS technology. The micro CPL was composed of lower, middle and upper substrates. The lower substrate was made of silicon and the middle and upper substrates are made of Pyrex glass for visualization. Through a preliminary test it was checked that there was no leakage at the adhesion interface between lower and middle or upper substrates and at the bonding interface between lower substrate and fill tube. Although the experimental studies for the micro CPL have been poor till now, we have obtained the reasonable experimental results in this study. The performance test result has showed 8.5W of the heat transfer rate for the micro CPL and we could observe the operating characteristics of circulating or evaporating and condensing by visualization. Pure distilled water was used as the working fluid.**

I. INTRODUCTION

Since the electronic communication devices, especially mobile devices, have been toward the trend in miniaturization and slimness, the structural packaging density in the devices is increased. Therefore it has been predicted that a thermal dissipation problem will be issued. The requested thickness of a flat type heat pipe module for packaging in a notebook PC about 8 years ago is 2mm. Recently, a sub-notebook PC or UMPC(Ultra Mobile PC) which emphasizes mobility, smallness and slimness are being offered. While the multi-functions as much as the functions in the notebook PC is requested for the devices, a thinner thickness than 2mm is requested in thermal design using a cooling module. Therefore, it has become extremely difficult to offer an optimal cooling solution for the small mobile devices. The metal spreaders with high thermal conductivity which mainly used in the electronic packaging till now run the risk of capability limitation for increasing heat flux. Therefore development of the cooling methods with lager cooling capacity is needed. The heat pipe with two-phase change mechanism has been used as an alternative of the metal spreader in a decade. The micro heat pipe with polygonal cross section and the flat plate heat pipe developed in ETRI[1] have proper structures and sizes as cooling solutions for the mobile devices. However a cooling method with thinner thickness than 2mm is requested. It is not easy to develop such a thin cooling solution with two-phase change mechanism. Moreover, although the thin cooling solution with two-phase change mechanism is developed, the heat transport capacity of that could not exceed small wattage. The micro CPL(Capillary Pumped Loop) developed in this study has a possibility of large heat transport capacity relatively. The CPL with macro size has been studied from long time ago and has been improved in a view of thermal capacity. However, the first study for the flat type micro CPL which fabricated using MEMS technologies was performed by J.Kirshberg et al. (Univ. of California at Berkeley) in 1999[2]. The micro LHP(Loop Heat Pipe) with a similar concept to the micro CPL was developed by A. Hoelke in 1999[3]. Since then, the micro CPL with two through holes for filling working fluid was developed by Laura Meyer et al.(GE) in 2003[4]. All these days, a study for the micro CPL has not been performed. Moreover, the previous studies for the micro CPL were limited to the area of analytical and fabrication process and the reasonable experimental data for the thermal performance have not been offered. This is due that the design and the fabrication of the micro CPL is not easy. Especially, the more precise technology in the fabrication processes of the filling and controlling of working fluid under vacuum circumstance is requested.

In this study, a micro CPL was fabricated using silicon and glass materials. The lower substrate with silicon was fabricated using MEMS process and the middle and upper substrates with glass were fabricated using sanding and wet etching process respectively. And then the three fabricated substrates were integrated by anodic and direct bonding. The developed micro CPL has structural characteristics. The evaporator has two-staged structure of grooves, which could prevent back-flow of bubbles which may create at the evaporator and reserve large space for vapor flow. Also, the middle substrate placed between the upper and lower substrates helps to reserve large space for vapor flow. The reservation of the space for vapor flow is important in the devices like heat pipe and micro CPL etc. with two-phase change mechanism since the thermal performance of the devices are dependent on the inner hydraulic diameter. As the space of the vapor flow is decreased as the thermal performance of the devices is exponentially decreased.

Through this study, the flat plate type micro CPL was designed and the fabrication processes for the substrates with silicon and glass were developed. Especially, the filling process of the working fluid under vacuum circumstance was developed. From the previous study[5], the thermodynamic characteristics of the micro CPL was investigated. The experimental data for thermal performance were offered and the visualization was carried out to investigate the two-phase change mechanism.

II. Design of the micro CPL

The micro CPL is composed of evaporator, condenser, vapor and liquid lines like a conventional heat pipe. Fig.1 shows the structure of the micro CPL. Contrary to the conventional heat pipe, the micro CPL has the separated vapor and liquid lines, which could eliminate a viscous resistance between vapor and liquid flow. Also the micro CPL has a reservoir. The micro CPL has three plates of upper, middle and lower substrates. The lower substrate has an evaporator with two-stage grooves and a condenser with meandering structure. The middle substrate has vapor and liquid lines. The upper substrate roles as a sealing cover and has grooves on the glass corresponding to the evaporator of the lower substrate to prevent creating water-drops. The material of lower substrate is silicon and the middle and upper substrates are glass. The two-staged grooves with 20㎛(width)*60㎛(depth) are constructed in parallel on the lower substrates to create a capillary force. With the two-staged structure of grooves, the back-flow of the bubbles which may create at the evaporator could be prevented and a large space of vapor flow could be reserve. The bottom stage out of the two-staged grooves has 80㎛ of depth and the top stage has 200㎛ of depth. A reservoir with a through hole for filling working fluid is placed near the evaporator. The through hole is integrated with fill tube for filling working fluid. Based on the preliminary study[IMAPS], the vapor line was designed as 2mm(width)*500㎛(depth) considering large specific volume of vapor. The two liquid lines with 250㎛(width)*500㎛(depth) is placed at the side of the micro CPL. The table 1 shows the micro CPL's specifications. The heat transfer mechanism of the micro CPL is similar to that of conventional heat pipe. The heat supplied to the evaporator vaporizes liquid in the grooves to vapor. The vapor moves to the condenser carrying latent heat by pressure difference along the vapor line. The vapor is condensed at the condenser with meandering structure after releasing latent heat to the environment. And then, the condensed liquid is back-flowed to the top stage of the evaporator grooves through the two liquid lines. So the circulation is working continuously until operating limitation.

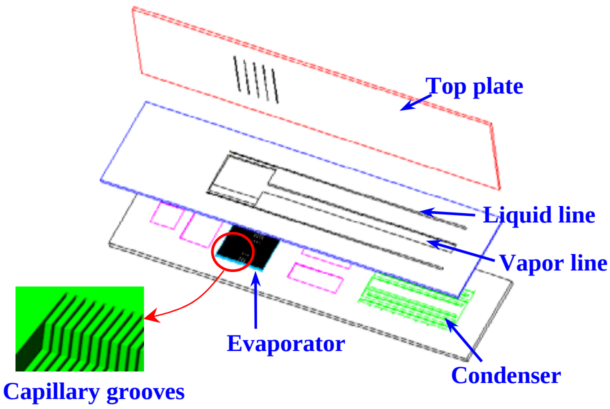

Fig.1 The structure of the micro CPL

Table 1. Specifications of the micro CPL

Section	Dimension
Evaporator Area	9*10㎜
Groove Width/Height	20*60㎛
Groove Number	167
Vapor Line Height/Width	500*2000㎛
Vapor Line Length	20㎜
Liquid Line Height/Width	500*250㎛
Liquid Line Length	35㎜
Condenser Area	10*20㎜
Bend at Condenser	3

III. Fabrication process

The micro CPL is completed by the integration of the upper and lower substrates which are fabricated by the particular process respectively. The vacuum and sealing process is applied to that in the end. A double polished silicon wafer and a Pyrex® 7740 glass wafer were used as the lower and upper/middle substrate of the micro CPL respectively. Fig.2 shows the fabrication process of the silicon wafer. The key point of the process is fabricating the two stages using deep etching process.

As shown in Fig.2(1), the TEOS film of 2.5㎛ was deposited on the silicon wafer in order to use as a masking layer for the DRIE(Deep Reactive Ion Etch) process. Next, a photolithographic process applied on that and the TEOS was etched as shown in (b). After removing the PR by ashing, a TEOS film of 8000Å was deposited on that again. If the photolithographic process, etching the TEOS and the PR ashing process are conducted again in sequence, the masking layer of TEOS is obtained for the DRIE process of two times as shown in (d). A depth of 80㎛ was etched by the 1st DRIE, then the TEOS film of about 2000Å was remained on the silicon surface. In order to remove the remained TEOS film, a etching was applied all over the surface. If a depth of 200㎛ is etched additionally by the 2nd DRIE, the two stages on the lower silicon substrate is completed as shown in (g). Finally, if the remained TEOS film is removed by HF solution, the structure of (h) is obtained. Fig.2(2) shows the fabrication process of the middle glass wafer. The etching on the glass wafer was conducted by sand blast. As shown in Fig.2(2)(a), the DFR(BF 410 type) film of 500㎛ was attached on the glass wafer in order to use as a masking layer for the sanding process. Next, if the photolithographic process, developing process by the Sodium Carbonate(Na2Co3) and sanding process(b) are conducted in sequence, the final structure on the middle glass wafer as shown in (c) is obtained. The penetrated parts in the middle glass substrate of the integrated plate are still remained. Fig.2(3) shows the fabrication process of the upper glass wafer. As shown in Fig.2(3)(a), the poly-si film was deposited on the glass wafer in order to use as a masking layer for the wet etching process. A patterning was conducted and the poly-si film was etched as shown in (b). After removing the PR by ashing, the wet etching process applied on that(c). The lower silicon substrate of Fig.1(h) and the middle substrate of Fig.2(1)(c) is integrated by anodic bonding. And then that and the upper glass substrate of Fig.2(2)(c) is integrated by direct bonding.

Fig.3 shows the SEM and close-up photographs of the fabricated envelope of a micro CPL. The fill tube is integrated with the envelope of Fig.3. Working fluid is filled into the envelope under vacuum circumstance and then the micro CPL is completed.

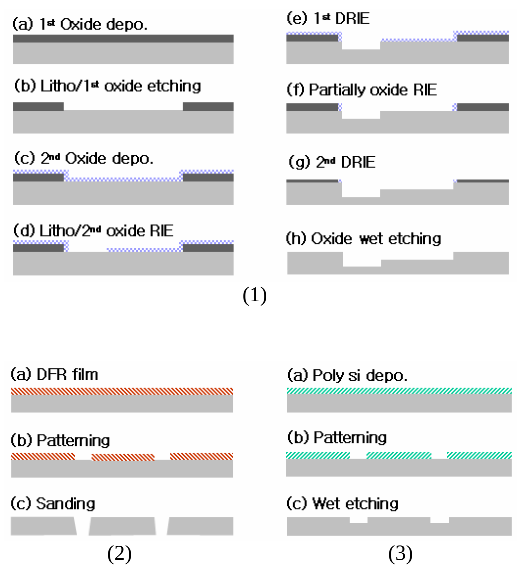

Fig.2 The fabrication process of the micro CPL

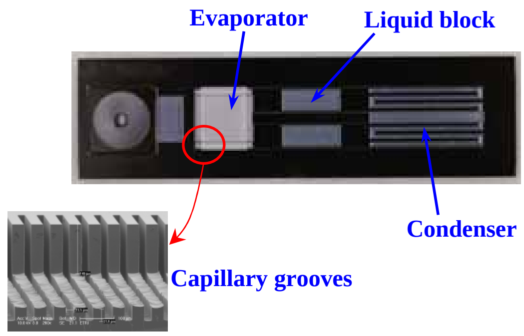

Fig.3 The fabricated micro CPL

IV. Performance test

A. *Experimental apparatus and procedure*

Fig.4 shows the experimental apparatus to investigate thermodynamic characteristics and thermal performance of the micro CPL which operated by two phase change mechanism. A chamber for performance test in which the micro CPL was placed was made of acrylic for visualization. The chamber was maintained in vacuum circumstance. A flat heater with 7*7mm^2 was attached on the back-side of the silicon substrate corresponding to the evaporator for power input. A water-jacket was attached on the back-side of the silicon substrate corresponding to the condenser for dissipating heat. The K-type thermocouples were attached via epoxy bonding to 1 location on the evaporator, 1 location on the vapor line and 1 location on the condenser. Water with high surface tension, high latent heat relatively and suitable for temperature range of 30~160^{o}C was used for working fluid. The working fluid was filled as amount of fully saturating inner grooves of the micro CPL. The thermal load was supplied to the evaporator using a power supply, in steps of 1 or 0.5W, starting with an initial power level of 1W. The amount and temperature of the cooling liquid via the water-jacket was controlled by a thermostat. The wall temperatures of the micro CPL in each power level were recorded when the temperatures of the wall reached steady state. The experimental results of the present study might include the error rate in the measurement, i.e., the error rate in the heat supply(±0.05V for voltage, ±0.01A for current), the temperature measurement(±0.1^{o}C) and the heat loss(±10%)

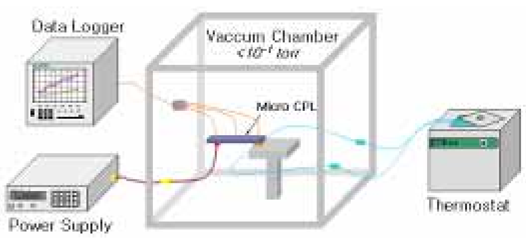

Fig.4 Experimental apparatus

B. Experimental results

After the previous study[5] for investigating thermodynamic characteristics and fabrication technology, the filling technology of working fluid under vacuum circumstance and the reasonable experimental data were obtained through the present study. From the previous study[5], it was understood that the operating limitation of the micro CPL was mainly dominated to capillary pressure limitation. For a normal operating of the micro CPL, as shown in Eq.(1), the total pressure drop through the loop has to be less than the capillary pressure limit created at the evaporator.

$$\Delta P_c \geq \Delta P_e + \Delta P_v + \Delta P_{cn} + \Delta P_l \tag{1}$$

Where, $\Delta P_c = 2\sigma / r_c$, ΔP_e , ΔP_v , ΔP_{cn} , ΔP_l are pressure drops at the evaporator, vapor line, condenser and liquid line respectively. Fig.5 shows the comparison for thermal resistance over from evaporator to condenser between the micro CPL with working fluid and that without working fluid.

In Fig.5, the thermal resistance of the micro CPL with working fluid was lower 2 times than that of the micro CPL without working fluid. This mean that the micro CPL with working fluid was being operated by two-phase change mechanism of vaporization and condensing and the total pressure drop through the loop of the micro CPL did not exceed the capillary pressure like Eq.1. It is not easy for small two-phase change devices like the micro CPL to accomplish a normal operating. This is due that the fabrication of the small size two-phase devices is somewhat difficult compare to the macro size devices. Especially, a little of the non-condensable gas could stop the operating of vaporization and condensing.

Fig.6 shows a variation of the thermal resistance for the micro CPL according to the power input under the constant cooling conditions at the condenser. In Fig.6, the thermal resistance between the evaporator and the condenser was decreased as the input power was increased. The heat transfer rate was 8.5W within 120^{o}C of the wall temperature at the evaporator.

Fig.7 shows the operating characteristics in the turning structure of the condenser near 5W of the input power. In photo.1, the flow pattern was plug flow. As the input power was increased, the flow pattern was changed from the plug flow to the annular flow.

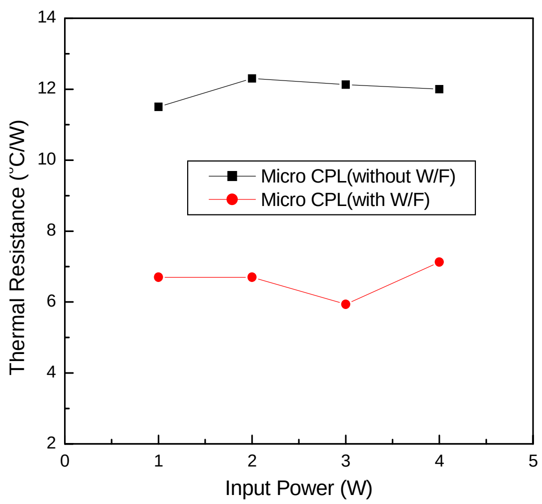

Fig.5 Comparison thermal resistance between the micro CPL with W/F and the one without W/F

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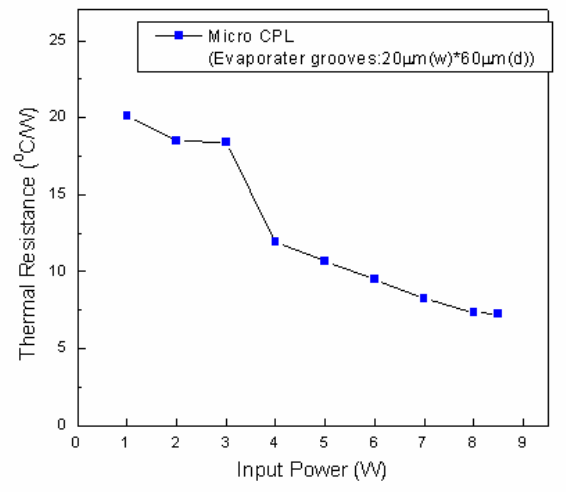

Fig.6 The heat transfer rate according to increasing of input power

Fig.7 Flow pattern at the condenser near 5W of input power

V. Conclusions

In the present study, the filling technology completing under vacuum circumstance was developed and the experimental data for the micro CPL which shows a normal operating characteristics was successfully obtained. From the performance test, the micro CPL with working fluid shows higher thermal performance about 2 time than that without working fluid. This results means that the micro CPL was being operated normally by two-phase change mechanism of vaporization and condensing. The thermal resistance between the evaporator and the condenser was decreased as the input power was increased. The heat transfer rate was 8.5W within 120°C of the wall temperature at the evaporator. Through the visualization, it was understood that the flow pattern at the turning path of the condenser was plug flow and then the flow pattern was changed from plug flow to annular flow as the input power was increased. The heat transfer rate obtained in the present study was not limiting power. Therefore the limiting power for the micro CPL would be estimated through the next performance tests.

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REFERENCES

[1] S. H. Moon, G. Hwang, H. G. Yun, "Improving Thermal Performance of Miniature Heat Pipe for Notebook PC Cooling," Microelectronic Reliability, Vol.42, No.1, 2002

[2] J. Kirshberg, et al., "Cooling Effect of a MEMS Based Micro Capillary Pumped Loop for Chip-Level Temperature Control," ASME 2000, MEMS Vol.2, pp.143-150, 2000.

[3] A. Hoelke, et al., "Analysis of the Heat Transfer Capacity of a Micromachined Loop Heat Pipe," ASME 1999, Vol..3, pp.53-60, 1999.

[4] L. Meyer, "A Silicon-Carbide Micro-Capillary Pumped Loop for Cooling High Power Devices," 19th IEEE Semi-Therm Symp., pp.364-368, 2003.

[5] S. H. Moon, G. Hwang, et al., "Development of the Micro CPL for a Thin Packaging Structure," 8th International Heat Pipe Symposium, A9-3, 2006.

[6] J. S. Suh, et al., "Friction in Micro-Channel Flows of a Liquid and Vapor in Trapezoidal and Sinusoidal Grooves," Int. J. of Heat & Mass Transfer, Vol. 44, pp.3103-3109, 2001.