Performance of a MEMS based Micro Capillary Pumped Loop for Chip- Level Temperature Control

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ABSTRACT

To provide direct cooling to electronics and Micro Electro Mechanical Systems, a three port micro-capillary pumped loop (CPL) was designed, fabricated and tested using current MEMS technology. The two wafer design consists of a silicon and a borofloat glass wafer. An evaporator, condenser, reservoir, and liquid and vapor lines were etched into the silicon wafer, while the glass wafer serves as a cover plate into which grooves were etched for capillary pumping. The geometry of the components of the device were determined via an analytical study. A finished device was run near steady state using laser spot heating and water as the working fluid. It was determined that a 1mm x 2 mm evaporator operates at a constant 100 C until wick dry-out at a laser power of 7.5 W (+/- 2 W). Furthermore, with the same laser power the micro-CPL resulted in a backside cooling of at least 7 degrees C.

INTRODUCTION

As electronics and devices become smaller and more complex, new technologies are needed to provide adequate cooling while meeting the size limitations of the system. The properties of a micro-CPL are ideal for such applications. CPL's are capable of carrying a much greater heat load due to their single directional flow. It is for this reason that CPL's also offer a wider degree of freedom in their geometry than conventional heat pipes. The evaporator, condenser, liquid and vapor lines can be designed and placed to optimize heat ejection while conforming to system constraints.

A micro cooler can be designed for single phase or phase change heat transfer to reject heat from electronic packages in the same manner as heat pipes (Peterson, et al. 1993) Due to their small size micro-devices can support extremely high temperature gradients and can be placed in direct contact with electronic component for which cooling is required.

The development for such a device is challenging due to the phase change and thermodynamics on the micro scale. Other difficulties include evaluating the effect of various CPL geometries, formulating a new process for the fabrication of the devices and it's working fluid and developing appropriate calibration and testing diagnostics to verify the coolers performance are also .

The conceptual design and fabrication of a micro CPL was first presented by Kirshberg, et al. (1999) This design consisted of a completely passive three port micro-CPL. A schematic of which is shown in Figure 1. This paper is continuation of this work in the micro-CPL's development.

ANALYSIS AND FABRICATION

The design geometry and potential heat transfer of the CPL was determined by conducting an analysis on the capillary pumping limit of the system using the rationale of Dickey and Peterson (1994) in addition to incorporating the pressure drops in the liquid and vapor lines. In this analysis it was assumed the liquid/vapor lines possessed a rectangular cross section while the evaporator and condenser were planar with a grooved capillary wicking structure.

The determined geometries are summarized in Table 1. Figure 2 illustrates the maximum heat transfer versus vapor/liquid line length with water as the working fluid, the evaporator operating at a constant 100C with 3 degrees of sub-cooling and a condenser heat transfer coefficient of 10 W/m^2-C.

Figure 3 illustrates the design of the micro-CPL. The evaporator, condenser and liquid/vapor lines are fabricated from a single crystal silicon wafer. The wicking structure consists of axial grooves wet etched into a standard borofloat glass wafer, which serves as a cover plate. Glass was chosen because of its transparent nature, however this wicking structure will eventually be etched directly into the backside of the electronic package requiring cooling.

The fabrication of the fluidic channels in the silicon wafer requires two separate deep reactive ion etches. Initially, 3μm of oxide were thermally deposited onto the wafer. A photoresist mask was then created on top of the oxide. The oxide was plasma etched in a Lam etcher in order to create an oxide mask for the wafer. 10μm of thick photoresist were then spun on top of the oxide mask, which once exposed, developed and baked, served as a mask for the

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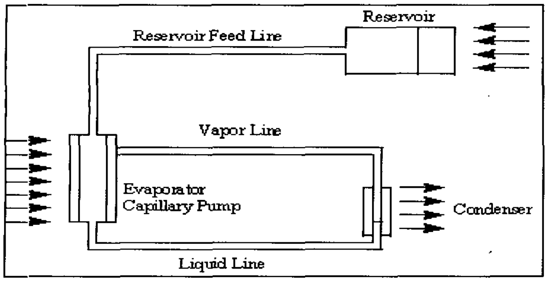

Figure 1 – Schematic of a micro-CPL

Evaporator Length	2000 µm
Evaporator Width	1000 µm
Condenser Area	2.0e+06 sq. µm
Groove Height	50 µm
Groove Width/ Number	50 µm / 8
Vapor Line Width	150 x 450 µm
Liquid Line Width	150 x 150 µm
Vapor/Liquid Line Length	35 mm
Liquid Line Re Number	42
Vapor Line Re Number	488
Projected Heat Removal	4 Watts

Table 1 -Micro-CPL specifications

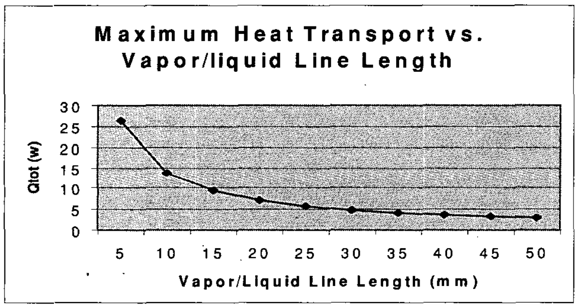

Figure 2- Maximum transport distance for a 150x150 micron liquid and 450x150 micron vapor lines

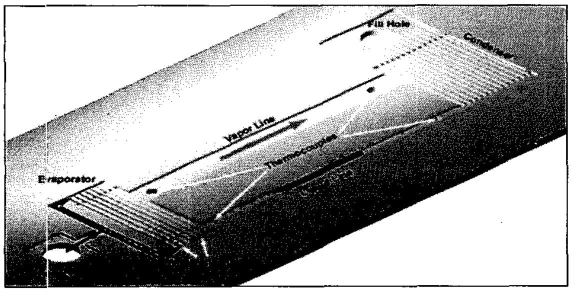

Figure 3 –A sketch of the micro-CPL. The fluidic channels are fabricated from silicon, while the wicking structure is etched into a borofloat glass cover

through holes. A Surface Technology Systems deep reactive ion etcher was used to create the through holes. Once completed, the remaining photoresist was stripped thus revealing the oxide mask beneath it. The wafer was then deep trench etched 150µm, thus creating the fluidic channels. This process is outlined in Figure 4.

The wicking structure is fabricated in the borofloat glass cover plate. 1 µm of undoped polysilicon was deposited on the glass wafer. A photoresist mask was then used when placing the wafer in CF4 plasma. Once the silicon mask was complete, and the photoresist stripped, the wafer was placed in concentrated HF for 6 minutes. This isotropic etch created the parabolic channels, with radius of 50 µm, which function as the wicking structure in the micro-CPL. This process is outlined in Figure 5.

The two wafers are then cleaned, aligned and anodically bonded. The reservoir feed line is then attached to the through hole, which connects the micro-CPL to a pressurized reservoir. A tube is connected to the backside of the silicon wafer via a through hole in order to function as the reservoir feed line. The reservoir is off-chip and pressurized, therefore controlling the operating temperature of the device. Figure 6 shows SEMs of the now completed micro-CPL.

EXPERIMENT

Initial preparation of the micro-CPL is quite similar to that of traditional CPL's. It must be pumped-down prior to filling in order to remove any air that might cause vapor-lock during operation. A turbo-pump was used in conjunction with the extra through-hole in the condenser region towards this end. The device was then flooded, and the reservoir pressurized to 15 psi above ambient. After filling the device successfully, the vapor line was cleared with a hand-held micro-torch. Heat is then applied to the evaporator region. Pictures of micro-CPL's operating continuously are shown in Figure 7.

In order to gain quantitative insight into the operation of the micro-CPL, the following experiment was set-up and performed. A CO2 laser with a spot size diameter of 1.0 mm was used to heat three different wafer configurations. First, a standard 100 mm diameter borofloat glass wafer with 500 µm thickness was anodically bonded to a double-polished p-type silicon wafer with similar dimensions. The laser spot was focused on the glass wafer at a point 20 mm away from the edge of the wafer, and 30mm away from the center of the wafer. Three thermocouples were then placed on the backside of the silicon wafer. The first thermocouple, referred to as "Center" was placed directly underneath the laser spot (30 mm away from the center of the wafer). The remaining thermocouples were placed at distances of 19 mm and 45 mm away from the center of the wafers along the same line as the first thermocouple, and are referred to as "Inboard" and "Outboard" respectively. It was determined that a laser power of 7.5 W (+/- 0.2 W) resulted in a "Center" temperature of just above 100C.

Two similar tests were then performed on an identical set of anodically bonded glass and silicon wafers, with the noted exception that a micro-CPL was now fabricated between the wafers. The micro-CPL was not insulated and the condenser exposed to quiescent room air. The evaporator region of the micro-CPL lies 30 mm from the center of the wafer, at the "Center" point. When the micro-cooler was filled with air (no working fluid), a laser power of 7.5 W (+/- 0.2 W) resulted in a "Center" temperature of 78 C (+/- 1.0 C). Finally, the micro-CPL was filled with water and pressurized. Due to the latent heat of vaporization and sensible heating occurring within the filled micro-CPL, an identical laser power resulted in a lower "Center" temperature of 71 C (+/- 1.0 C). Figure 8 shows the resulting temperature profiles.

NUMERICAL ANALYSIS

Utilizing CFDRC's code, a two-dimensional axi-symmetric finite difference model, similar to that of the blank wafer experiment, was constructed. The model differed from the experiment in two ways. First, in the numerical model, the laser spot was simulated as being placed in the center of the wafers (rather than 30mm from the center). Secondly, the heat flux delivered by the laser spot was significantly less in the numerical model, with a total laser power of only 4.2 W, and a spot size diameter of 3.5 mm. Imposing natural convection boundary conditions, the simulation was run until steady-state was reached. The results for the temperature profile of the center of the wafers are shown below in figure 9.

This simulation solution showed a greater than 150 degree temperature differential along both axes when a 3.5 mm diameter laser spot of 4.2 W was applied at the glass surface. This resulted in a large temperature gradient in the glass due to its poor thermal conductivity. Heat spreading increased in a radial direction with an increase in incident laser power.

CONCLUSION

Using a 1 mm diameter laser with a power of 7.5 W (+/- 0.2 W) the micro CPL provides 7 degrees of cooling to the backside of the wafer using water as the working fluid. It was also found that using this laser power a 1mm x 2 mm evaporator operated isothermally at 100 C until the wick dried out. The cooling effect of the CPL is attributed to the use of the latent heat of the of the working fluid. Due to the nature of electronics packaging the cooling effect of the micro-CPL could be integrated to aid in the cooling and thermal optimization of electronic components.

From these results the author will now try to optimize the micro-CPL and refine the experiments. In these experiments the condenser was allowed to run passively,

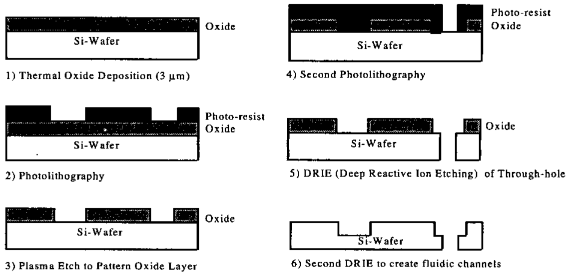

Figure 4 – Fabrication process for the silicon wafer

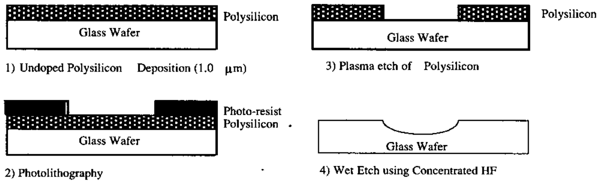

Figure 5-Fabrication process for the glass wafer

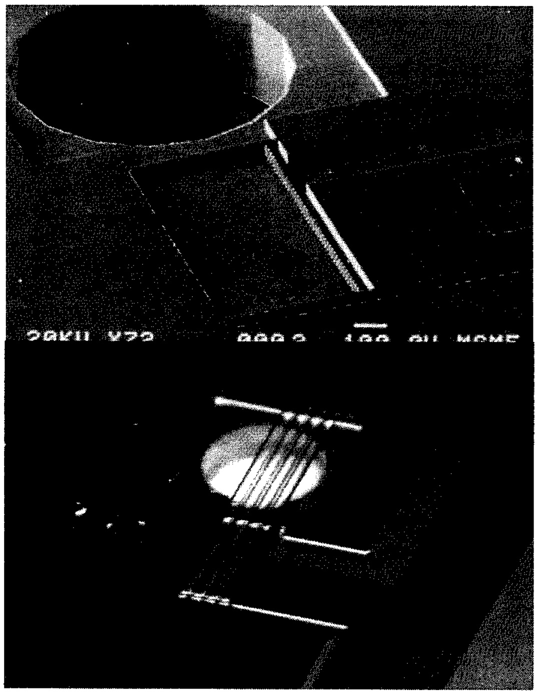

Figure 6-(a)Top view of the condenser, plenum and fill hole regions. (b) Condenser region after anodic bonding to glass cover plate

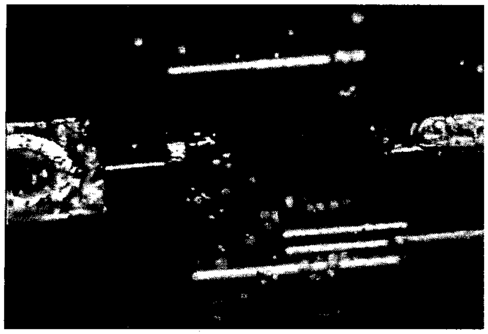

Figure 7-Evaporator of the CPL operating at steady state

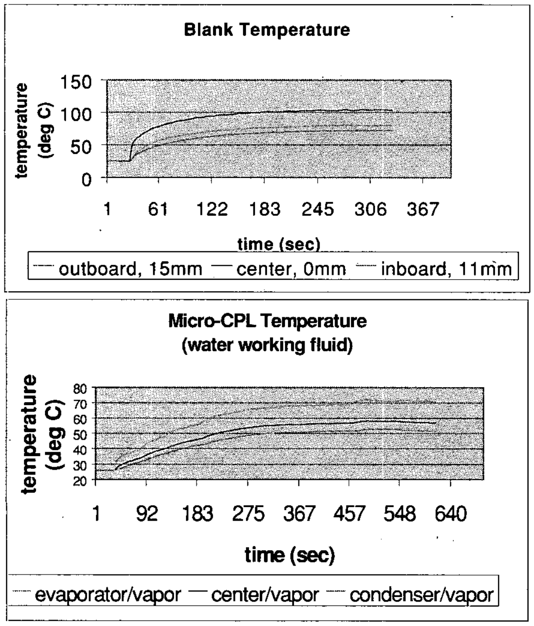

Figure 8-Temperature profiles for the (a) micro-CPL filled with air (no working fluid) and (b) micro-CPL filled with water

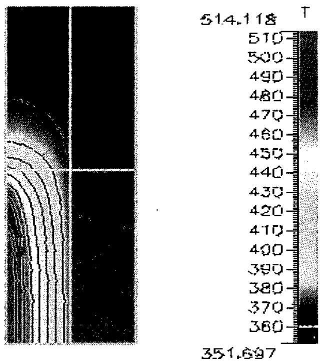

Figure 9-Temperature profile of a cross section of the blank glass (left) and silicon (right) wafers. The bottom is the center line (where the heat source is placed on the glass side). Due to scaling, the outer sections of the wafer are not shown.

however spot cooling of the CPL will force condensation in an exact location thus allowing further sub-cooling for the fluid returning to the evaporator. Also in previous experiments the condenser of the micro-CPL was held at the same size of the evaporator. Increasing the condensers size will allow larger loads of heat to be removed as well as providing better contact with the condenser for possible utilization of the extracted heat from the CPL.

For future experiments a vacuum chamber has been constructed so the micro-CPL can be tested with convective effects to determine the maximum heat flux capacity of the device. Finally, a thermal imaging system will be employed to monitor the high temperature gradients that can occur inside the device as well as on the backside.

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REFERENCES

Blevins, R.D., 1984, Applied Fluid Dynamics Handbook,Van Nostrand Reinhold Company, New York.

Dickey, J.T. , and Peterson G.P. , 1994,"Experimental and Analytical Investigation of a Capillary Pumped Loop," *Journal of Thermophysics and Heat Transfer*, Vol 8, No. 3, pp. 602-607.

Faghri, A., 1995, Heat Pipe Science and Technology, Taylor & Francis, Washinton D.C.

Hoelke, A., Henderson, H.T., Gerner F.M., Kazmierczak, M., 1999 "Analysis of the Heat Transfer Capacity of a Micromachined Loop Heat Pipe," *Proceedings of the ASME Heat Transfer Division,* HTD-Vol. 364-3 pp. 53-60.

Kirshberg, J., Yerkes, K., and Liepmann, D., 1999 "Micro-Cooler for Chip-Level Temperature Control," SAE *Aerospace Power Systems Conference*, P-341.

Peterson, G.P., Duncan, A.B., and Weichold, M.H., 1993, "Experimental Investigation of Micro Heat Pipes Fabricated in Silicon Wafers," *Journal of Heat Transfer*, Vol 115, pp. 751-756.