Optimization of a MEMS based Micro Capillary Pumped Loop for Chip-level Temperature Control

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ABSTRACT

Recent results in the microfluidics group at the Berkeley Sensor and Actuator Center and the Air Force Research Laboratory have shown that a micro-capillary pumped loop (micro-CPL) can move extreme amounts of heat (< 200 W/cm^2) to provide integral cooling to electronics or MEMS type devices. However, the current design has not been optimized because of the time and cost of fabrication of prototypes. Furthermore, experimental results are not clear because they cannot separate different heat transfer effects such as convection and radiation. Numerical tools have been used to understand experimental results and are being implemented to improve this design and to shorten the design and fabrication process.

Keywords: micro-capillary pumped loop, temperature control.

1 INTRODUCTION

The conceptual design and fabrication of a micro-CPL was first presented by Kirshberg, et al. (1999). It encompasses the initial design of a completely passive three-port micro-CPL, schematically shown in Figure 1. It is important to realize that micro-devices can support extremely high gradients because of their small size. The evaporator region will be placed in direct contact with the micro-processor, sensor, or other electronic chip for which cooling is required and used to maintain an optimal temperature. It was determined that the micro-CPL resulted in a backside cooling effect of at least 7 degrees when a laser delivering 7.5 W (+/- 0.2 W) with a spot-size diameter of 1.0 mm was focused on the front side of the evaporator region. CFD results have verified the cooling effect of the device by simulating spot laser heating of a simple 2D axisymmetric glass plate on blank silicon wafer with natural convection boundary conditions. Two-dimensional spreading of the heat in this very thin device was observed in the massive temperature gradients depicted in the computational results. An analytical study was used in determining the non-optimized geometry of the device, including the evaporator dimensions (1000 microns x 2000 microns) and the length of the liquid and vapor lines (35 mm). An integrated computational model of thermal and fluidic effects will also be implemented to optimize the micro-CPL geometry. Imposing the limits of the thermal boundary conditions defined by the nature of the evaporator and condenser, and then finding an acceptable pressure drop will obtain the lengths of the vapor and liquid lines. The two-phase nature of the fluid flow in the condenser is another concern in this problem that will be addressed with analysis and computational modeling. The preliminary calculations are presented here.

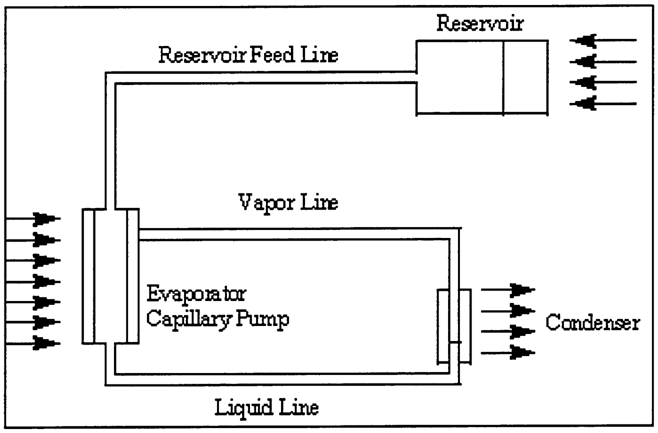

Figure 1. Schematic of a micro-CPL.

2 ANALYSIS

Table 1 provides specifications for a micro-CPL with rectangular liquid/vapor line cross-sectional geometries, in addition to a planar evaporator and condenser with a grooved capillary wicking structure (Kirshberg et al., 2000). An analysis of the micro-CPL Capillary Pumping Limit was conducted following the rationale of Dickey and

Peterson (1994) but including the pressure drop of the vapor line.

Table 1. Micro-CPL specifications.

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

3 EXPERIMENT

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 whatever electronic package requires cooling. 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.

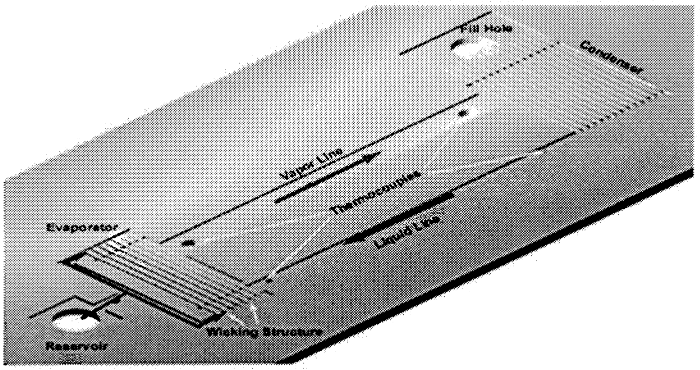

Figure 2. A sketch of the micro-CPL.

Using water as a working fluid, assuming an operating temperature of 100 C and 3 degrees of sub-cooling with a condenser heat transfer coefficient of 10 W/m^2-C, the maximum transport length is shown in Figure 2. The results shown in Fig. 2 predict heat transport potential of 1.4e-01 W-m for the 35mm vapor/liquid lines.

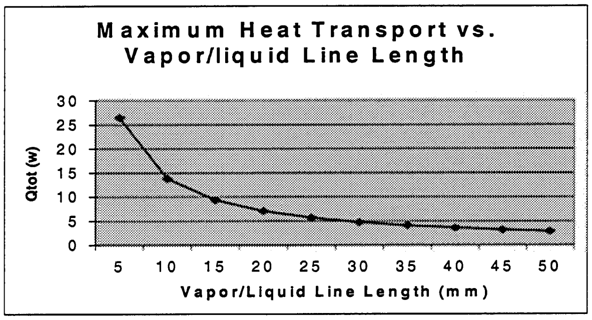

Figure 3. Maximum transport distance for 150x150 micron liquid and 450 x 150 micron vapor lines.

In order to gain quantitative insight into the operation of the micro-CPL, the following experiment was set-up and performed. A CO_2 laser with a spot size diameter of 1.0mm 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 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 illustrates these experiments, while Figure 9 shows the resulting temperature profiles.

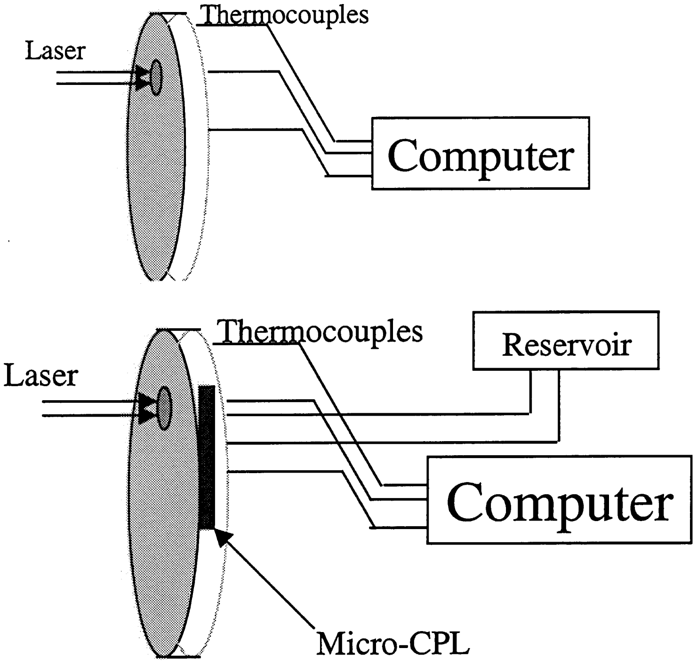

Figure 4. (a) A schematic of the blank wafer (b) and the micro-CPL experiment.

4 RESULTS

Utilizing the CFD-ACE+ suite of software tools, a two-dimensional axi-symmetric model of the blank wafer experiment was constructed. The only difference from the experiment is that the laser spot was simulated as being placed in the center of the wafers (rather than 30mm from the center). After imposing natural convection boundary conditions, the simulation was run until steady-state was reached. These results are shown below in figure 10.

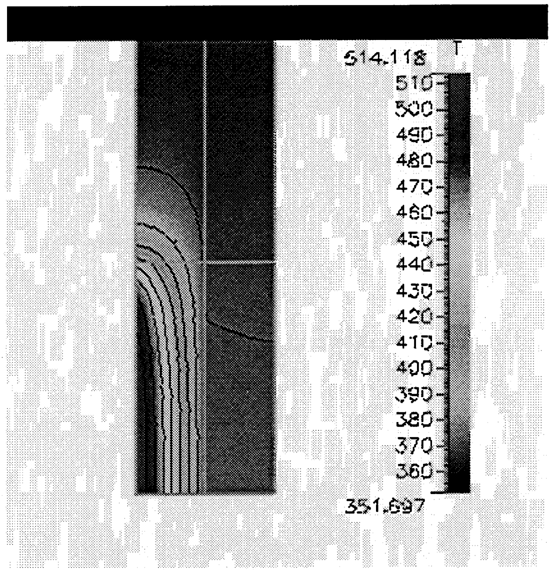

Figure 5. Temperature (K) profile of a cross-section of the blank glass (left) and silicon (right) wafers. The bottom is the center of the wafer (where the heat source is placed on the glass side).

This simulation clearly illustrates the massive temperature gradients which exist along the thickness of the wafers when a 1.0 mm diameter laser spot with 7.5 W laser power is placed on the glass surface. The temperature profile in the silicon is essentially one dimensional, validating. This validates the design position of the thermocouple on the back of the silicon wafer for measuring temperature at the glass-silicon interface.

Simulations of an integrated fluid flow and heat transfer model have also been performed and compared to analytical results (see Table 2).

Table 2. Pressure drop in vapor and liquid lines, and condenser.

Δp	CFD	Analytical
vapor line	356.8 Pa	435.4 Pa
liquid line	12.5 Pa	24.38 Pa

The analytical pressure drop is obtained using the following equation:

$$\Delta P_v = \rho\left(\frac{64}{\mathrm{Re}_v\left(2/3 + 11/24\left(h_v/w_v\right)\left(2 - h_v/w_v\right)\right)}\right)\left(\frac{L_v}{D_v}\right)\left(\frac{\bar{v}_v^2}{2}\right)$$

In this equation the friction constant of 64 is based on a correlation for macrotubes. Experimental data of flow in microtubes shows data below that by 19% to 27% (Choi et al.).

For this analysis the pertinent dimensions and flow parameters of the micro-CPL are listed in Table 3.

Table 3. Dimensions and parameters of μCPL.

Evaporator Length	2000 μm
Evaporator Width	1000 μm
Condenser Area	700 μm^2
Vapor Line Width	150 x 350 μm^2
Liquid Line Width	150 x 150 μm^2
Vapor/Liquid Line Length	25 mm
Liquid Line Re Number	1.4
Vapor Line Re Number	20

5 CONCLUSION

The micro-CPL provides at least 7 degrees of cooling to the backside of the device when a 7.5 W (+/- 0.2 W) laser spot with 1.0 mm diameter is placed on the front side of the evaporator region. This cooling effect is attributed to the micro-CPL's making use of the latent heat of vaporization and sensible heat of the fluid in the device. Due to the nature of electronic packages in general, this cooling effect might very well be used to optimize a device by allowing it to run at lower temperatures.

With these preliminary numbers in hand, it is the author's task to optimize the micro-CPL and help refine the experiments. Also, the condenser, which is not restricted in size as the evaporator is, can be further improved to deliver better performance to the CPL. In the experiments the condenser was allowed to run passively, yet it will enhance the micro-CPL's performance to spot cool the condenser (thus forcing condensation at an exact location while allowing for further sub-cooling of the liquid upon its return to the evaporator.) A vacuum chamber is being constructed so that the micro-CPL might be tested without convective heat losses to the ambient, in order to more accurately determine the maximum heat flux capacity of the device. Finally, due to the massive temperature gradients that the micro-CPL can support, it is necessary to take temperature measurements inside the device rather than simply on the backside. To this end, a thermal imaging system will also be employed and a more accurate comparison to the heat transfer model can be made.

In this study we have begun to analyze pressure drops and thermal effects in the vapor and liquid lines. We have also begun a simple model for the condenser which is not restricted in size as the evaporator (see sample calculation below). The model will consist of a simple microtube with convection boundary conditions for cooling. The flow is two-phase. The following assumptions are made: (1) no two-phase mixture, (2) condenser tube diameter of 300 μm, (3) vapor is perfectly mixed, i.e., no temperature variation in the bulk of the vapor. Optimization of the micro-CPL will be completed with further modeling of these inetgrated components.

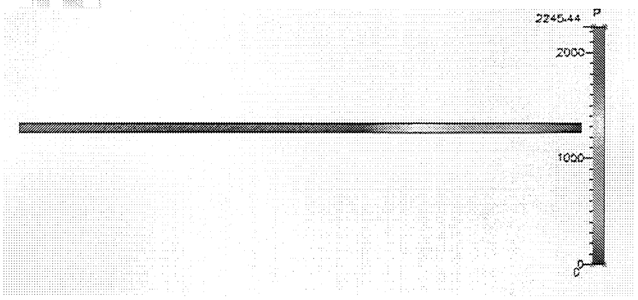

Figure 6. Sample calculation of the pressure drop (Pa) in a simplified condenser model. Flow occurs from the left and the vapor-liquid interface is just right of center.

ACKNOWLEDGMENT

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