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Study of Evaporation Phenomena in Micro Channels

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Abstract — **Two-phase convective flow in micro channels has numerous promising applications such as electronic cooling. This study investigates evaporation phenomena and capillary-driven heat in a rectangular micro channels structure with hydraulic diameters of 100~250μm and length of 75mm. The micro channels made of (110)-orientated silicon is fabricated by bulk micromachining. The temperature distributions in micro channels chip structure, as well as the induced evaporation mass flow rate of water, were measured under different heat flux and inclination angle. Thermal resistances were calculated to evaluate the chip cooling performance. The experimental results show that with an increase of the imposed heat flux, the evaporation mass flow rate increases and thermal resistance decreases. The effect of channel sizes and inclination angle on the heat transfer characteristics are also examined.**

Keywords- evaporation; micro channels; inclination angle; thermal resistance

I. INTRODUCTION

Capillary force and capillary pressure difference are main driving force for working fluid transfer in micro channels, and are also important factors for electronic cooling systems designing. Studies of micro-channels on heat transfer since Tuckerman and Pease [1] in 1981, analyzed compact water-cooled integral rectangular micro channels heat sink for silicon integrated with Pyrex glass. The heat sink may greatly enhance the feasibility of ultrahigh-speed VLSI circuits applications. In 1996, Peng and Peterson [2] found that turbulent heat transfer was to be a further function of a new dimensionless variable Z in rectangular micro channels. Such that Z=0.5, will be the optimum configuration for turbulent heat transfer regardless of the groove aspect ratio. Liao and Zhao [3] in 1999 showed experimental results with an increase of the imposed heat flux. The heat transfer coefficient increases to a maximum value and then decrease afterward. It also found that the liquid-vapor interface moved toward the downward-facing heated surface as the imposed heat flux was increased. In 2004, by measured the marching velocity and position of a capillary meniscus, L. J. Yang et al. [4] describe an experimental method and an analytical model for characterizing the surface energy inside a micro channel of micrometer size. Nilson et al. [5] in the same year derived from evaporating flow in open rectangular micro channels. With a uniform depth and a width that decreases along the channel axis, results demonstrate that tapered channels provide substantially better cooling capacity than straight channels of rectangular or triangular cross section. In this study, we discuss the results for silicon-based micro channels by testing repeatedly. Finally, we try to build up experimental data base of micro channels capillary force for electronic cooling application.

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II. THEORY

In this study by using theory of surface energy and calculate thermal resistances, we can find out what the different of micro channels chip structures design. Also compare to the experimental results which in different situation when imposed heat flux or inclination angle changed. Young's law [6] shows a liquid droplet on a solid surface at steady state, and there are three surface forces, including γ_{la}, γ_{sa}, and γ_{sl}, acting at the liquid/solid/air interface as Fig.1.

$$\gamma_{sa} - \gamma_{sl} = \gamma_{la}\cos\theta \qquad (1)$$

where θ is the contact angle.

The effective surface tension force can be deduced from the derivative of the surface energy of the whole fluidic system with respect to the spatial coordinate [7]. The total surface energy (E_s) of the capillary channel is composed of contact surface areas multiplied by surface tension and surface energy (E_0) it means the part stored in the filling reservoir. E_0 is hardly changes due to the infinitesimal amount of liquid filling into the capillary.

$$E_s = E_0 + A_{sl}\gamma_{sl} + A_{la}\gamma_{la} + A_{sa}\gamma_{sa} \qquad (2)$$

Fig.2 is the configuration of a capillary micro channel, and the wetting area is follow with working fluid transfer direction.

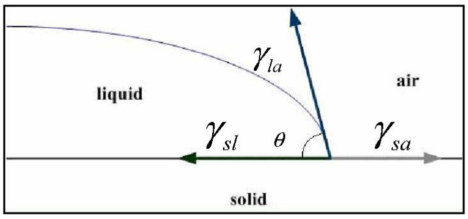

Fig.1 Liquid/solid/air interface of a droplet.

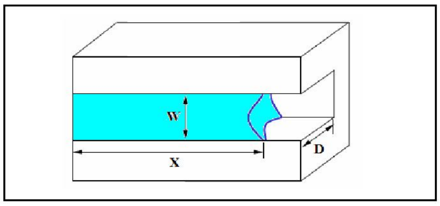

Fig.2 Liquid surface of capillary micro channel.

Taking the derivative of equation (2) with respect to x, we obtain the equivalent capillary force F_{cap} applied on the fluid column along the x-direction. And put the cross-section of channel size design, we can transfer the equation to:

$$F_{cap} = -\frac{dE_s}{dx} \tag{3}$$

$$F_{cap} = \sigma[2\cos\theta(D+W)] \tag{4}$$

where σ is also surface tension and equal to γ_{la}.

The pressure drop ΔP_{cap} across the liquid/air interface is:

$$\Delta P_{cap} = \sigma[2\cos\theta(D+W)]/DW \tag{5}$$

Then, after experimental process finished, we can calculate thermal resistances R to evaluate the chip cooling performance:

$$R = (T_S - T_A)/Power \tag{6}$$

where T_S is the temperature of heat source.

T_A is the temperature of environment.

III. EXPERIMENT

In this experiment, the micro channels are made of (110)-orientated silicon is fabricated by bulk micromachining. Measurements of structures are length of 84mm and width of 12mm, channels inside are length of 75mm in Fig.3. There are total 16 kinds of cross-section size for micro-channels, by four widths (W) of 100μm, 150μm, 200μm, 250μm, four depths (D) of 100μm, 150μm, 200μm, 250μm, and the interval between channels (Wc) is equal to width setting.

After bulk micromachining finished, we make the structure bonding with 7740 pyrex glass in Fig.4. And parameter control of etching surface to cause the differential fluid transfer is very important. (Clearing process, temperature and relative humidity (RH) control…)

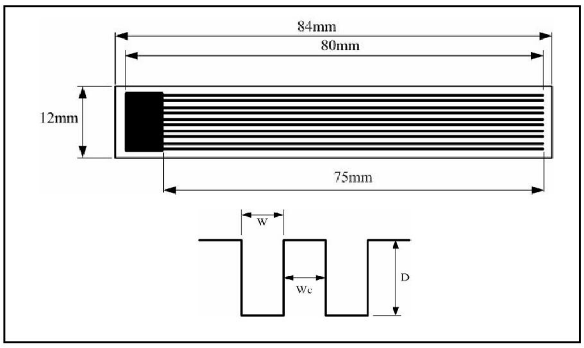

Fig.3 Channel size design.

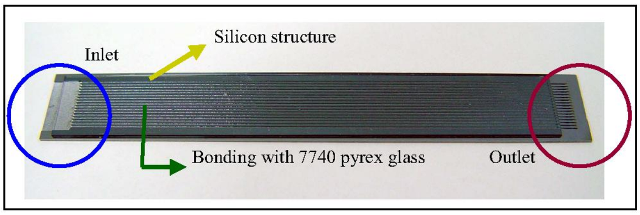

Fig.4 Micro channels structure.

In Fig.4 there is a thin depth water pool at inlet, in order to make sure that working fluid can be transferred into the micro channel as smooth as possible.

This study investigates evaporation phenomena and capillary-driven heat in a rectangular micro channels structure in two parts of capillary test and thermo test shown in Fig.5 and Fig.6.

- Capillary test:

Clean process must be executed twice before capillary testing. When the proceeding started, it should be in the environment with constant temperature and humidity. Without heat source, we try to make the working fluid of pure water be transferred into the micro channels only by capillary force with no other work. By this way, we can find out that in different situation, working fluid may be transferred from inlet through full of channel to the outlet or not. It's also means that in thermo testing, the heating section will fill working fluid enough for evaporate or dry out. Then, each channel structure in every inclination angles position, we measured ten times to catch the experimental data for average.

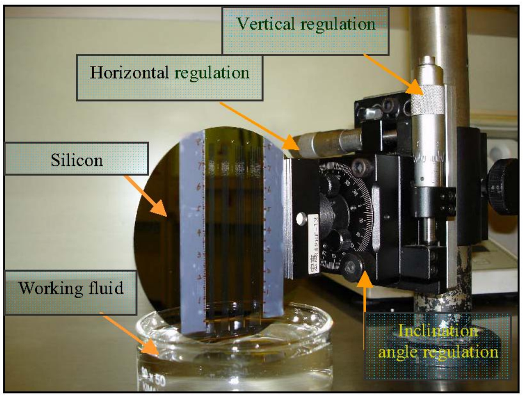

Fig.5 Capillary test device.

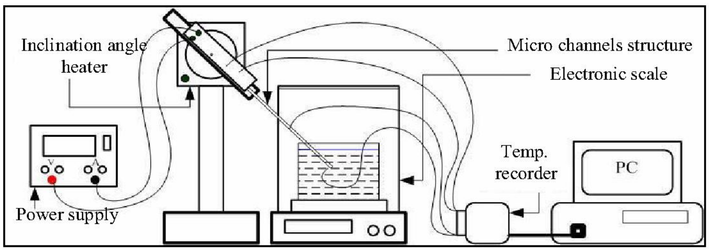

Fig.6 Thermo test.

● Thermo test:

In the thermo testing, micro-channels structure is fixed on the inclination angle heater in Fig.6. Outlet of structure is put on the heat source at the upper position and inlet at lower position when inclination angle increased. Working fluid movement in this study defined to capillary transferred only. In opened environment, we use pure water for working fluid be transferred to heating section and evaporated.

By using T-type thermocouple (range of -100℃~ 400℃), data of temperature distribution can be measured from recorder to computer per unit time. Thermal resistance can be calculated with temperature drop from heat source and environment. In the same time, the vapor loss in evaporating section could be measured at the inlet by using electronic scale. With the loss quality of working fluid at inlet, we can find out the average of mass flow rate.

IV. RESULTS AND DISCUSSION

Capillary test with inclination angle started before the thermo test. By the observation of capillary transfer experiment, there were several sizes of micro-channel structure couldn't bring working fluid through full channel length when inclination angle increased (TABLE.I). The phenomena also stand for in these circumstances, working fluid can't be transferred to the evaporating section and capability was decreased (Fig.7). Then we could measure each contact angle (Fig.8) value, analyzing theory of surface tension and capillary force compare to the experimental data. The phenomena also stand for in these circumstances, working fluid couldn't be transferred to the evaporating section and capability decreasing.

In thermo test, the temperature distributions in micro channels chip structure as well as the induced evaporation mass flow rate of water. They were measured under different heat flux and inclination angle. Thermal resistance was calculated to evaluate the chip cooling performance. Compared to differential inclination angle and channel size, we found the curves of thermal resistance (R_{total}) and evaporation mass flow rate ($\dot{m}$) with heat flux (*Watt*). In Fig.9 and Fig.10 show that with same channel depth of 100μm and 4 widths of 100μm, 150μm, 200μm, 250μm at three kinds of inclination angles (a) 0°, (b) 45°, (c) 90°. Experimental results show that with a decrease of the channel size, the thermal resistance decreases and evaporation mass flow rate increases. The effect of the imposed heat flux increase, trend are the same.

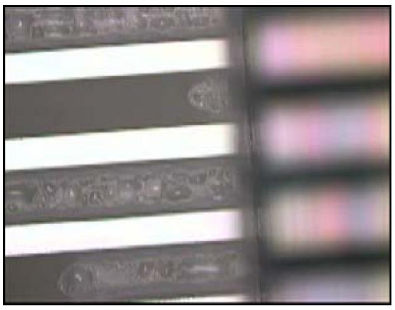

Fig.7 Working fluid transfer non-continuously.

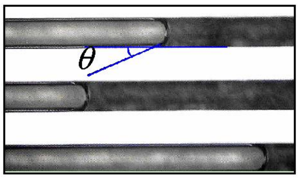

Fig.8 Contact angle in micro channel.

TABLE.I WORKING FLUID TRANSFER CIRCUMSTANCES

Channel Width (W) Unit: μm	Channel Depth (D) Unit: μm	H.D. Unit: μm	I.A. 0°	I.A. 45°	I.A. 90°
100	100	100	O	O	O
	150	120	O	O	O
	200	133	O	O	O
	250	143	O	O	O
150	100	120	O	O	O
	150	150	O	O	O
	200	171	O	O	O
	250	188	O	O	X
200	100	133	O	O	O
	150	171	O	O	O
	200	200	O	O	X
	250	222	O	X	X
250	100	143	O	O	O
	150	188	O	O	X
	200	222	O	X	X
	250	250	O	X	X

O : fluid can be transferred through full channel length
X : fluid can not be transferred through full channel length
H.D.: hydraulic diameter
I.A.: inclination angle

V. CONCLUSION

In this study, we have presented an experimental approach of water evaporation rate in micro channels. The experimental results show that in evaporation phenomena with imposed heat flux increasing, the mass flow rate of evaporation increased and thermal resistance decreased. We also find that with a decrease of the channel size, the thermal resistance decrease and evaporation mass flow rate increase. This is related to the enhancement of the capillary force in micro channels. Finally, we try to build up experimental data base of micro channels capillary force for electronic cooling application.

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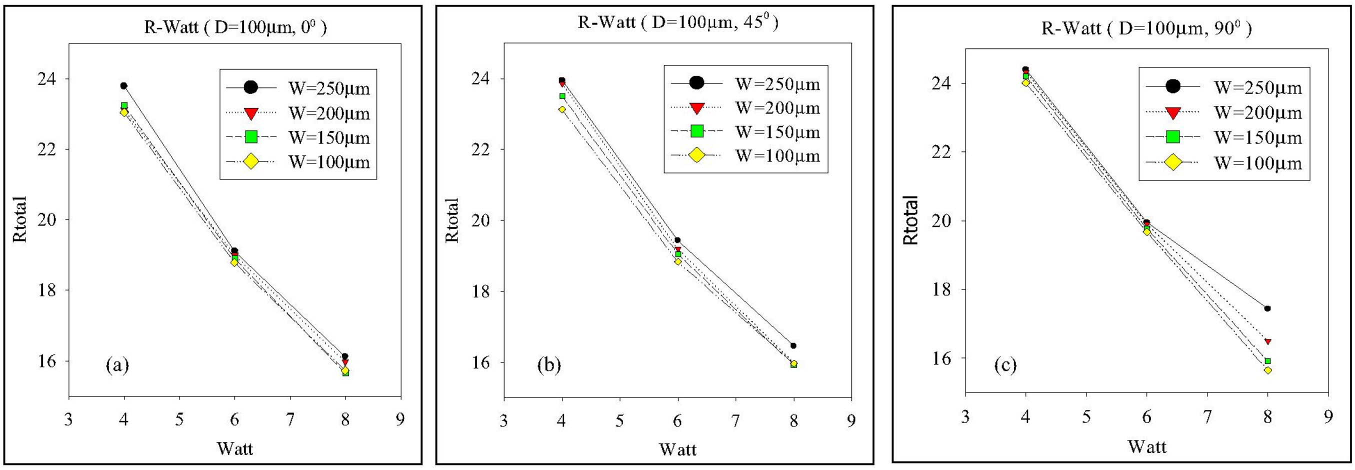

Fig.9 Thermal resistance (R_{total}) with heat flux (*Watt*) at inclination angle (a) 0° (b) 45° (c) 90° and channel depth of 100μm .

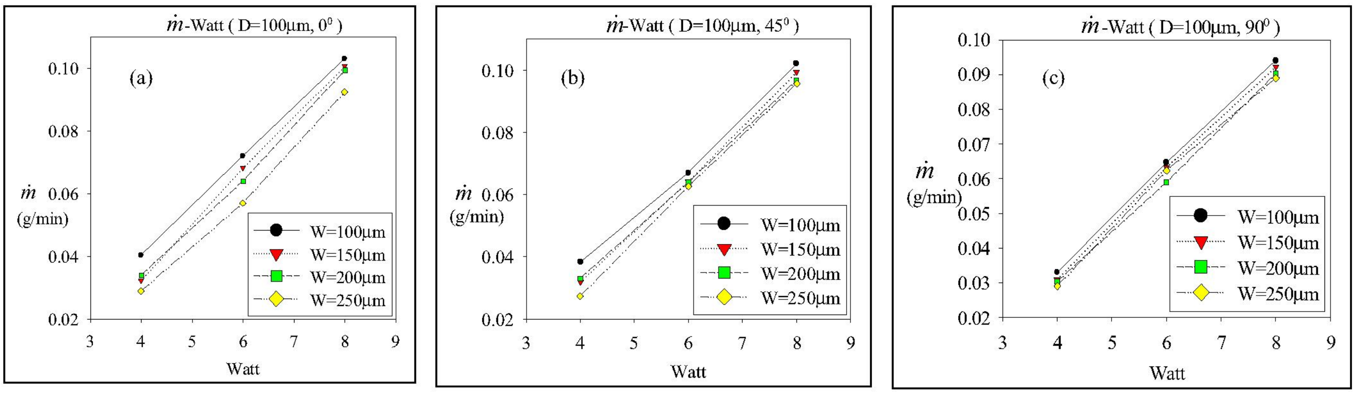

Fig.10 Evaporative mass flow rate ($\dot{m}$) with heat flux (*Watt*) at inclination angle (a) 0° (b) 45° (c) 90° and channel depth of 100μm.