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An experimental study on hydrothermal performance of microchannel heat sinks with 4-ports and offset zigzag channels

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ABSTRACT

For cooling specific chip of 2 mm∗10 mm, the 4-ports and offset zigzag microchannels are designed. The fluid flow and heat transfer characteristics of 4-ports silicon heat sinks with rectangle and zigzag microchannels have been investigated experimentally. Deionized water is employed as the cooling fluid with flow rates of 28–72 ml/min. Results show the 4-ports heat sink can effectively reduce pressure drops and reduce temperature rising along the flow directions for the fixed flow rates. For 4-ports with rectangle microchannel, the pressure drops is decreased about 70% and average temperature also is reduced by 2.8 °C. It can be interpreted that 4-ports structures reduce the length of channel and increase channel number, which leads to the flow velocity decreased by 0.5 times and the fluid distribution more uniform. Compared with 4-ports with rectangle microchannels, for 4-ports with zigzag microchannels heat sink, the pressure drop is reduced under the lower flow rates but increased slightly under larger flow rates. And temperatures of all flow rates are reduced, which is reduced by 3.8 °C and pressure drop only increased 2.6 kPa at flow rates of 72 ml/min. It can be interpreted that zigzag cavities redevelop thermal boundary layer and enhance the fluid disturbance to make the fluid mixing better. Additional, zigzag cavities also enlarge heat transfer areas and reduce the fluid velocity by increasing flow cross-section areas. Under fixed pumping power, 4-ports with *Z* can meet the larger heat dissipation and smaller flow rates requirement.

1. Introduction

With the fast sophistication of nano-technologies and the high heat dissipation requirement in a small area of electronic devices such as chips and processers, thermal management is considered as the key technology to ensure its operation performance and reliability. Application of microchannel heat sinks that have great potential of achieving smaller, lighter-weight, higher-performance and lower-cost dissipates the heat from power source to cold fluid. Since the classical work of Tuckerman and Pease [1], microchannel cooling has drawn more attention from researchers of liquid and boiling cooling. Compared with air, liquid cooling is more attractive for the higher specific heat and thermal conductivity. Boiling heat transfer could remove larger quantities of heat than single phase liquid cooling, but instabilities, high pressure drops and low critical heat fluxes might constitute major roadblocks for application [2].

The methods of enhancement heat transfer for given heat dissipation question can be divided into two aspects: improving transport properties of coolants and optimizing microchannel geometer. The dielectric fluids are preferred for electrical properties, but limited with lower specific heat and thermal conductivity [3]. The liquid metal with low melting point and high thermal conductivity was proposed as working fluid for chip cooling equipment [4]. But lower specific heat, higher density and viscosity of that could bring fluid temperature rising for fixed heat flux, which would lead to deteriorate heat transfer. Additional, the higher thermal conductivity nanoparticles are added in fluids to form a suspension nanafluids, such as different properties Al_2O_3 [5] and nano liquid metal [6]. However, the instabilities of nanofluids, such as agglomeration and sedimentation of nanoparticles, are the main constraints in application [7]. Increased particle concentration might cause viscosity increased, but generates a high flow resistance in turn. For coolants, the water has the best thermal properties and been used extensively to show the feasibility of liquid cooling [8]. Using deionized water, maintaining a low ionic concentration and a high electrical resistivity, is another possible option [3]. Therefore, the deionized water is used as working fluid in present paper. In order to reduce thermal contact resistance, the heat sink can be directly embedded on the back of heat source, which is usually made of silicon [9].

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Nomenclature

A_{heater}	area of heater surface m^2
A_b	area of channel borrow m^2
A_s	area of channel sidewalls m^2
c_p	special heat capacity kJ/(kg·K)
D_h	hydrodynamic diameter m
f	friction factor
h	heat transfer coefficient W/(m^2·K)
h_c	depth of channel m
L	length of channel m
Nu	Nusselt number
Q	heat rate W
Δp	pressure drop Pa
P_p	pumping power W
Q_v	flow rate ml/min
R	electrical resistance K/W
Re	Reynolds number
R_{th}	thermal resistance K/W
T	temperature °C
u	fluid velocity m/s
W_c	channel width m
W_w	fin width m
P_p	pumping power W

Greek symbols

ρ	density kg/m^3
λ	thermal conductivity W/(m·K)
μ	dynamic viscosity kg/(m·s^2)
η	fin efficiency
δ	Thickness of heat sink base m

Subscript

av	average
f	fluid
in	inlet
max	maximum
out	outlet
s	solid
w	channel wall

Thus, the silicon is used as material of heat sink in this paper.

For the optimization microchannel geometers, firstly the parameters of rectangular microchannel have been conducted by minimizing entropy generation or thermal resistance [10–12]. The flow of microchannel heat transfer is generally laminar for the low *Re* number. Then, based on theory of improving flow turbulence and redeveloping thermal boundary layer, the micro fins and complex microchannels were proposed. The different shapes of pin fins were studied such as hexagonal and other five shapes [13], uniform offset strip fin [14] and increasing fin density along the flow direction [15], which would improve temperature uniformity. Besides, porous media was filled in microchannel to enhance heat transfer performance. The heat transfer performance of a microchannel filled with a porous material in the slip-flow regime was higher than the one in the no-slip regime [16], and the thermal model was developed in [17]. Micro pin fins and porous media could provide significant heat transfer enhancement albeit with great pressure drop penalty.

Some complex microchannels are designed to redevelop thermal boundary layer, such as sinusoidal microchannel [18], converging [19] and microchannel with internal vertical Y-shaped bifurcations [20]. The heat transfer enhancement of those were more favorably over the pressure drop penalty, but those channel only change the flow direction with constant microchannel cross-sections. For further enhancing the fluid disturbance and redeveloping thermal boundary layer, the microchannels with periodic changing cross-section were studied [21–23] and optimized parameters. The hydraulic and thermal boundary layers were redeveloping in each separated zone for the interrupted channel, which shorted effective flow length, resulting in the overall heat transfer enhanced by [21,22]. Results of [23] showed the periodic triangular reentrant cavities could enhance thermal performance by interrupting boundary layer, enlarging heat transfer areas and forming vortexes to enhance mixing of cold and hot fluid. Although the pressure drop increased, the performance evaluation criteria were larger than 1. The similarly results also were found [24], which studied experimentally the microchannel heat sink with fan-shaped reentrant cavities of sidewalls. Parameters of that was optimized further by [25], cavity shapes from triangular to trapezoidal and rectangular. And optimum thermal structure was found for microchannel with trapezoidal groove with groove tip length ratio of 0.5, groove depth ratio of 0.4, groove pitch ratio of 3.334, grooves orientation ratio of 0 and $Re = 100$. The Nusselt number of that was improved of 51.59% and friction factor only increased by 2.35%. Additional, the inlet/outlet and channel layouts have great effect on fluid distribution and temperature uniformity. Heat sink configurations were investigated [26] and fluid distribution of I-type configuration was more uniform. Separating heat sink into several compartments could improve fluid distribution uniformity and enhance temperature uniformity [27]. And same time, increasing channel number and reducing channel length could also decrease flow resistance [28].

Based on the results described above, the novel microchannels and fin pins could enhance heat transfer albeit with larger pressure drop penalty. A new phenomenon was discovered in our team, the microchannel with offset zigzag grooves in sidewalls enhanced heat transfer and reduced flow resistance due to increasing porosity [29]. And 4-ports configuration could reduce flow resistance and improve heat transfer by reducing channel length and increasing channel number [30]. Therefore, the heat transfer and flow characteristics of heat sinks with 4-ports configuration and offset zigzag microchannels (4-ports with *Z*) are investigated experimentally, and compared with 2-ports and 4-ports with rectangle microchannels (2-ports with *R* and 4-ports with *R*) in this paper.

2. Experimental procedure

2.1. Micro-fabrication and Preprocessing of heat sink

The micro heat sink, partial enlarged view of microchannels and packaging are showed in Fig. 1, which is consisted with Pyrex 7740 glass of 500 μm and silicon wafer of 400 μm. Inlet and outlet of 1 mm were processed on the glass by sand blasting technology of drilling hole. And 220 μm microchannels and headers were etched, and 0.1 μm heater film was sputtered on another wall of silicon, respectively. In order to simulate the uniform heating, the three parallel serpentine strips were designed by reducing current crowing in the meander bends. And electrical leads were located on the diagonal of heat sink. Then silicon and glass were bonded anodically. The detail machining process is described in [24]. There are no significant undercuts or unexpected deformation, and the error of etching depth is ± 0.3 μm by testing. The same inlet shapes of parallel channels were designed to improve flow distribution uniformity. To reduce heat loss, adiabatic grooves were located on the outsides of channels areas.

Conductive silver pulp and A/B glue were used to connect heaters and printed circuit boards, which were used to connect electrical leads and heaters. The A/B glue ensured to connecting tightly. A thin layer