International Communications in Heat and Mass Transfer 79 (2016) 98–104

Contents lists available at ScienceDirect

International Communications in Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ichmt

A novel flow arrangement of staggered flow in double-layered microchannel heat sinks for microelectronic cooling☆

Yuling Zhai [a,*], Guodong Xia [b,*], Zhouhang Li [a], Hua Wang [a]

[a] State Key Laboratory of Complex Nonferrous Metal Resources Clean Utilization, Faculty of Metallurgical and Energy Engineering, Kunming University of Science and Technology, Yunnan 650093, China

[b] Key Laboratory of Enhanced Heat Transfer and Energy Conservation, Ministry of Education, College of Environmental and Energy Engineering, Beijing University of Technology, Beijing 100124, China

ARTICLE INFO

Available online 25 October 2016

Keywords:
Staggered flow
Double-layered microchannel
Temperature distribution
Thermal resistance
Pumping power

ABSTRACT

A novel flow arrangement of staggered flow (the fluid staggers flow along each layer) is presented to remove higher heat flux and obtain more uniform bottom temperature in double-layered microchannel heat sinks. Compared to the counter flow, the heat transfer performance of two types of staggered flow is studied numerically. The distribution of the total temperature, average bottom temperature, maximum temperature difference and thermal resistance is presented for different flow arrangements under similar pumping power. The results show that the flow arrangement with staggered flow 2 (the fluid flows along the *x* direction at the second layer, while fluid staggers along the *y* direction at the first layer) provides the lowest maximum and most uniform temperature under similar working condition. Moreover, the thermal resistance of staggered flow 2 is much lower than that of counter flow and staggered flow 1 under the similar pumping power, which indicates that it has better cooling capacity for microelectronic cooling.

1. Introduction

With an ever-increasing heat flux in microelectronic devices, the objective of efficient cooling techniques becomes challenge [1]. The new concept of single-layered microchannel heat sinks for great potential in the cooling area of microelectronic devices was firstly proposed by Tuckerman et al. [2]. Since then, a large number of similar studies have been done to enhance heat transfer rate of microchannel heat sinks [3,4]. Based on the previous research works, double-layered microchannel heat sinks with one atop the other were presented [5], which are effective by improving the convective heat transfer rate as well as the heat exchange area per unit volume.

Double-layered microchannel heat sinks with counter flow and parallel flow are proposed as a substantial improvement of heat transfer. Wei et al. [6] conducted experimental and numerical work of the effect of double-layered microchannel heat sink with counter flow on heat transfer performance. It was found that the pressure drop reduced and temperature was more uniform under a heat flux when compared with single-layered microchannel heat sinks. Levac et al. [7] also found that the counter flow arrangement was more superior than parallel flow at all ranges of Reynolds number in terms of the uniformity of temperature. Uniform temperature on the bottom of microelectronic devices is helpful to eliminate the harm of hot spot [8]. Extensive numerical and experimental works have been presented on those kinds of flow arrangement [9–13].

Based on the basic flow arrangement, a novel arrangement of staggered flow for efficient cooling is proposed. This flow structure aims to enable essential improvement of heat transfer performance in microelectronic devices, due to the elimination of hot spot at the bottom surface. To our best knowledge, numerical simulations of staggered flow in double-layered microchannel heat sinks have not been conducted.

The objective of this paper is to investigate the heat transfer performance of staggered flow in double-layered microchannel heat sinks. According to the rectangular heating film, two types of staggered flow are designed and compared to the counter flow firstly. After then, the total temperature, average bottom temperature, maximum temperature difference and thermal resistance are discussed under the fixed pumping power. The corresponding design in the present work is expected to provide a guide to obtain more uniform temperature distribution and higher cooling capacity of double-layered microchannel heat sinks.

2. Design and model of double-layered microchannel heat sinks

Assuming the dimension of the rectangular heating film in double microchannel heat sinks is $W \times L$, where $W = 3$ mm and $L = 5$ mm

☆ Communicated by W.J. Minkowycz.

* Corresponding authors.
E-mail addresses: zhaiyuling00@126.com (Y. Zhai), xgd@bjut.edu.cn (G. Xia).

http://dx.doi.org/10.1016/j.icheatmasstransfer.2016.10.008

Nomenclature

c_p	Specific heat, J/(kg·K)
D_h	Hydraulic diameter, m
f	Fanning friction factor
H_{ch}	Height of channel, m
L	Length of the heating film, m
L_{ch}	Length of the channel, m
L_h	Entrance length, m
Δp	Pressure drop, kPa
Po	Poiseuille number
PP	Pumping power, W
Re	Reynolds number
R_{th}	Thermal resistance, K/W
T_b	Average bottom temperature, K
$T_{b,max}$	The maximum bottom temperature, K
$T_{b,min}$	The minimum bottom temperature, K
T_{in}	Inlet temperature, K
T_{out}	Outlet temperature, K
u	Inlet velocity, m/s
V	Volumetric flow rate, m^3/s
W	Width of the heating film, m
W_b	Rib width, m
W_{ch}	Width of the channel, m

Greek symbols

α_c	Aspect ratio
λ	Thermal conductivity, W/(m·K)
μ	Dynamic viscosity, Pa·s
ρ	density, kg/m^3
Ω	Heat input, W

are the width and length of it, respectively, as shown in Fig. 1 (a). All flow microchannels are placed on the heating film in order to remove high heat flux. The schematic of a cross-sectional single microchannel is depicted in Fig. 1 (b). The width W_{ch} and height H_{ch} of single microchannel in each layer are 0.1 mm and 0.2 mm, respectively. The rib width W_b between each microchannel is 0.1 mm.

From the above mentioned, counter flow (C for short) is selected as reference flow arrangement. According to it, two flow types of staggered flow are proposed. Staggered flow 1 (S1 for short) indicates that fluid flows along the x direction (the length of heating film) at the first layer, while fluid staggers along the y direction at the second layer. Staggered flow 2 labeled as S2 corresponds to the opposite flow direction from S1. The three-dimensional schematic of C, S1 and S2 are shown in Fig. 2. The information of three flow arrangements is summarized in Table 1. In Table 1 of flow arrangement, black and blue arrow lines indicate the flow direction at the first and second layers, which correspond to Fig. 2.

3. Numerical method and data reduction

3.1. Numerical method

For single phase in the microchannel heat sinks, the numerical model can be simplified as: 1) Steady state. 2) Laminar and Newtonian flow. 3) Negligible radiation effect and no slip boundary condition at wall. Therefore, three dimensional and laminar convective heat transfer, the continuity, momentum and energy equations can be written as,

$$\nabla \vec{U} = 0 \tag{1}$$

$$\rho\left(\vec{U} \cdot \nabla \vec{U}\right) = -\nabla p + \nabla \cdot \left(\mu \cdot \nabla \vec{U}\right) \tag{2}$$

$$\rho c_p \vec{U} \cdot \nabla T = \nabla(\lambda \cdot \nabla T) \tag{3}$$

where ρ, μ, λ are density, dynamic viscosity and thermal conductivity of fluid, respectively.

For corresponding boundary conditions are considered as follows. The material of solid zone is considered as silicon with the density, specific heat and thermal conductivity 2329 kg/m^3, 712 J/(kg·K), and 148 W/(m·K), respectively. The working fluid is deionized water with temperature-dependent thermophysical parameter. Uniform heat flux of 10^6 W/m^2 is applied to the heating film of heat sinks, which is simulating the heat input form microelectronic devices. A uniform inlet velocity with a uniform temperature of 298 K is set at all channels' inlet, while the pressure outlet is set at the channels' outlet.

The whole heat sink as shown in Fig. 2 is considered as the computational model in order to obtain the distribution of the whole temperature field. Before accurate analysis of results in the following section, the mesh independence must be evaluated. Three types of uniform meshes with gird number of 200 million (fine), 150 million (medium) and 100 million (coarse) are tested. The counter flow arrangement is used in these tests. The difference of maximum average pressure drop is 2% between 200 million and 150 million, while the maximum deviation between 150 million and 100 million is 7%. Finally, 150 million is selected as the best trade-off between both accuracy and computational time [14].

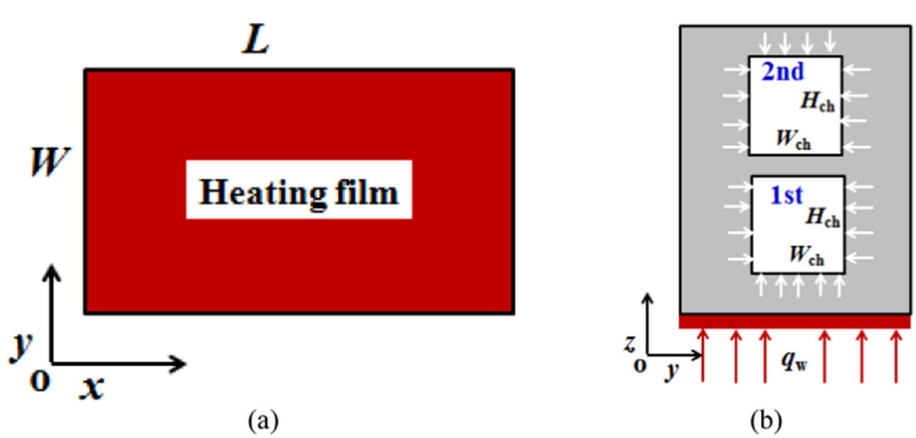

Fig. 1. Schematic of the heating film (a) and single microchannel (b).