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Characteristics of heat transfer and fluid flow in a fractal multilayer silicon microchannel☆

Shanglong Xu *, Yue Li, Xinglong Hu, Lili Yang

Department of Mechatronics Engineering, University of Electronic Science and Technology of China, Chengdu, China

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ABSTRACT

An experimental and numerical investigation of a fractal-like multilayer silicon microchannel heat sink is conducted for high heat flux applications. The design and fabrication of the heat sink and experimental facility are described. The unit thermal resistance, pressure drop and Nusselt number of the multilayer microchannel are determined by layer number for a range of flow conditions. The results indicate that the fractal-like multilayer microchannel architecture has a significant effect on the performance of heat transfer and fluid flow. The heat sink is shown to provide favorable cooling performance with low volume thermal resistance (2.5Kcm^3/W for 5 layers) and pumping power (0.07 W at 400 ml/min) for different power density electronics applications.

1. Introduction

Three-dimensional integrated circuits (3-D ICs) stack multiple device layers through direct vertical paths between layers in a small volume, which achieves considerable reduction in global wire delay compared to traditional 2-D chips [1,2]. As these devices become smaller, their heat flux levels increase rapidly [3,4]. Therefore, an effective cooling strategy for micro-devices is required, especially when they are made from silicon substrates. The microchannel heat sink is one of the most promising devices to cool the miniature systems [5], which can be made by microfabrication processes [6]. The multilayered microchannel heat sinks are usually attached on the heat generating devices. Cooling fluid is supplied to the 3-D stack using fluidic channels on the substrate. The presence of a cooling path at each layer enables direct heat dissipation from individual device layers.

Single layer microchannels etched directly into the backs of silicon wafers were first shown to be an effective cooling solution by Tuckerman and Pease [7] in which a maximum of 790 W/cm^2 was rejected. Although the cost of fabricating the micro heat sinks currently prohibits application in production level electronics, the study showed that microchannel structures are well suited to cooling electronic devices. Following this pioneering work, much work has focused on single layer and multi-layer microchannel heat sinks fabricated from a highly thermally conductive solid, such as copper or silicon, with rows of small channels fabricated into the surfaces by precision machining or chemical etching [8,9]. Y.J. Cheng [10] used the Computational Fluid Dynamics (CFD) to simulate the flow and heat transfer in stacked, two-layer microchannels with multiple MEMS easily-produced microstructures. Experimental and numerical characterization of 1 and 2 layer silicon microchannel heat sinks in parallel flow and counter flow configurations were investigated by Patterson et al. [11]. They concluded that the combined flow configuration resulted in a more uniform surface temperature while the parallel flow configuration showed a lower maximum surface temperature. Ortega et al. [12,13]performed modeling and experimental work on heat transfer and pressure drop characteristics of single and multilayered silicon carbide(SiC) heat sinks. They used an Extrusion Free form Fabrication (EFF) technique to manufacture a novel class of multilayered microchannel heat sinks from SiC, then studied their heat transfer.

Also several studies have been done by Hung et al. [14] and Wong et al. [15], the multilayer microchannel heat sink has a remarkable efficiency in lower thermal resistance and less pressure drop than the traditional microchannel heat sink.

Bejan [16] proposed a fractal-like bifurcating flow network and studied its flow performance. Chen and Cheng [17] studied both heat transfer and pressure drop in the tree network. A comparison of it with the parallel channel structure showed a stronger heat transfer capacity and a lower pumping power. Alharbi [18] investigated a three-dimensional fractal-like branching network. They found that the local pressure recovery at each bifurcation results in a lower total pressure drop than that with conventional, parallel, straight-channel networks. Senn and Poulikakos [19] conducted a three-dimensional simulation for a tree-like net. They found that the tree-like net required only half the pressure drop and had higher heat transfer efficiency of a serpentine flow pattern. Calame [20] presented a silicon microchannel ooler and fabricated it by deep reactive ion etching with a goal of providing effective cooling of low-temperature cofired ceramic microwave chip packages and emerging GaN-on-SiC semiconductors for high power

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* Corresponding author.
E-mail address: xusl1607@gmail.com (S. Xu).

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Nomenclature

d	hydraulic diameter(mm
L	length of a channel segment(mm)
k	level of each branch
β	diameter ratio
γ	length ratio
H	depth of channel (mm)
$W_{k'}$ k'th	level segment width (mm)
$P_{k'}$	wet perimeter of the k'th-level segment (mm)
$A_{k'}$	wet area of the k'th -level segment (mm^2)
L_{tot}	total length of the flow channel (mm)
L_{kt}	length of the end of the pipe (mm)
K_t	level of the end of the pipe
h_a	averaged heat transfer coefficient(W/Kcm^2)
c_p	specific heat (J/kg K)
A_w	total area of the walls of the microchannels(cm^2)
q	heating power (W)
T_{wa}	average wall temperature(K)
T_{in}	inlet bulk temperatures of the working fluid(K)
T_{out}	outlet temperatures of the working fluid(K)
Nu	Nusselt number
λ	thermal conductivity of water (W/mK)
$\triangle P$	pressure drop across heat sink manifold (kPa)
q_v	volume heat flow (W/cm^3)
Q	volumetric flow rate (ml/min)
R_A	thermal resistance(Kcm^2/W)
A	heated surface area of heat sink(cm^2)
R_V	volume thermal resistance(Kcm^3/W)
q_w	heat flux of heat sink (W/cm^2)
p	pumping power (W)
h	height of the heat sink (mm)
T_{max}	maximum temperature of wall (K)
k	turbulent kinetic energy (W)
k_{tc}	thermal conductivity (W/mK)
E	energy (J)
δNu	the ratio of the averaged heat transfer coefficient
Nu_1	single heat transfer coefficient
Nu_m	multilayer heat transfer coefficient
E_{ij}	mean deformation rate (m/m s)
S_E	external energy inputs (W)
$\vec{u}$	three-dimensional velocity vector (m/s)
$\vec{f_b}$	three-dimensional body force (N)

Greek symbols

ε	rate of viscous dissipation (W)
φ	energy dissipation function due to viscous stresses (W)
μ	dynamic viscosity (kg/m s)
μ_t	turbulent dynamic viscosity (kg/m s)

microwave amplifiers. Luo [21] established a compact thermal model to model thermal characterization of a fractal microchannel cold plate for high temperature uniformity in multiple heat sources. Then the experiments were also conducted to validate the model. The experimental and simulated studies of the heat transfer performance of fractal and branching microchannel networks were also conducted [22–26], although the microchannel structures were different. They found that the fractal microchannel heat sink was effective to increase the heat transfer coefficient.

These studies are aimed to investigate the effect of fractal-like or stacked microchannel on the hydraulic and thermal performance of heat sink. They have not given a great attention to the heat sink that combines both two types of structures and there is almost no study on them. This study investigates the fluid flow and heat transfer characteristics of fractal-like silicon microchannel heat sink fabricated with single and multiple layers.

2. Design of the microchannel heat sink

The structural parameters of multilayered fractal-like mainly include branching angle, number of branches, channel diameter and length of each level and number of layers. Beginning with Murray's study of blood vessels [27], Pence [28] developed a fractal-like branching channel network in a disk-shaped heat sink. There is an optimal size step (change in hydraulic diameter) at each paring node of the fractal-like network such that the global flow resistance is minimized. It is given by

$$d_{i+1}/d_l = n^{-1/3} \tag{1}$$

Where d is the hydraulic diameter, and n is the number of branches into which each channel splits. For the present analysis, $n = 2{,}3$. The index i denotes a low-order branching level and i + 1 denotes a higher-order branching level at a bifurcation(i = 0 are the tubes that touch the center). A typical physical model as well as the structure parameters are shown in Fig. 1. The fractal-like microchannel nets are characterized by the following scaling laws:

$$\beta = \frac{d_{k'+1}}{d_{k'}} = n^{-1/3} \tag{2}$$

$$\gamma = \frac{L_{k'+1}}{L_{k'}} = n^{-1/2} \tag{3}$$

Where L is the length of a channel segment, and n is the number of branches into which each channel splits. The index k' indicates the level of each branch, indexed from 0 to 3. For the bifurcating channel configuration n = 2 and according to Eq. (2) and (3), the diameter ratio β and the length ratio γ are 0.7937 and 0.7071, respectively. The equation of the hydraulic diameter is as follows:

$$d_k = \frac{4A_{k'}}{P_{k'}} = \frac{2Hw_{k'}}{H + w_{k'}} \tag{4}$$

The channel network has a constant channel depth H in this study. $A_k$is the wet area of the k'_{th}-level segment, $P_{k'}$ is the wetted perimeter of the k'_{th}-level segment, $w_{k'}$ is the k'_{th}-level segment width. According to Darcy's law, the equation of $w_{k'}$ is:

$$w_{k'} = \frac{w_{k'+1}H}{\beta\left(w_{k'+1} + H\right) - w_{k'+1}} \tag{5}$$

According to Eq.(3), the equation of the total length of the whole flow channel is as follows:

$$L_{k_t} = \frac{L_{tot}}{\sum_{i=0}^{k_t}\left(1/\gamma^i\right)} \tag{6}$$

WhereL_{k_t} is the length of the end of the pipe, k_t is the level of the end of the pipe, L_{tot} is the total length of the flow channel.

Based on the conditions given above, the channel dimensions for the single layer fractal-like network are calculated, shown in Table 1. Only the $H_{k'}$ is different between the multi-layered and the single layer structures. The total height are 0.75 mm, 1.25 mm, 1.75 mm, 2.25 mm and 2.75 mm, respectively, when the number of layers is from 1 to 5. The diameter of heat sink is 40 mm.