Material Selection for Microchannel Heatsink: Conjugate Heat Transfer Simulation

A. Uday Kumar¹, Arshad Javed², Satish K. Dubey³

¹, ², ³ Department of Mechanical Engineering, BITS Pilani -Hyderabad Campus, Telangana, India 500078.
Corresponding Author E-mail: p2015412@hyderabad.bits-pilani.ac.in

Abstract: Heat dissipation during the operation of electronic devices causes rise in temperature, which demands an effective thermal management for their performance, life and reliability. Single phase liquid cooling in microchannels is an effective and proven technology for electronics cooling. However, due to the ongoing trends of miniaturization and developments in the microelectronics technology, the future needs of heat flux dissipation rate are expected to rise to 1 kW/cm². Air cooled systems are unable to meet this demand. Hence, liquid cooled heatsinks are preferred. This paper presents conjugate heat transfer simulation of single phase flow in microchannels with application to electronic cooling. The numerical model is simulated for different materials: copper, aluminium and silicon as solid and water as liquid coolant. The performances of microchannel heatsink are analysed for mass flow rate range of 20-40 ml/min. The investigation has been carried out on same size of electronic chip and heat flux in order to have comparative study of different materials. This paper is divided into two sections: fabrication techniques and numerical simulation for different material microchannel heatsink. The presented study and findings are useful for selection of materials for microchannel heatsink.

Keywords: Microchannel heatsink, Conjugate heat transfer, Performance simulation.

1. Introduction

Recent trend of miniaturization and advances in the computational capabilities of electronic devices has increased the generation of the heat flux in the electronic-chips significantly. Future electronic devices are expected to have heat flux dissipation rates up to 1 kW/cm² [1] [2]. Therefore, thermal management of electronic systems is very important to ensure its optimum performance and reliability. Current air-cooled heatsinks are unable to meet this demand. Hence, liquid cooled microchannel heatsinks are preferred. To further enhance the performance of liquid cooled microchannel heatsink, different materials and shapes can be investigated. Microchannels are defined based on their hydraulic diameter, i.e. if hydraulic diameter of channel is in between 10μm and 200μm then the channel is defined as microchannel [3]. Tuckerman and Pease (1981) studied...
microchannel heatsink, they concluded that convective heat transfer coefficient in the channel varies inversely with the channel width [4].

The performance of microchannel heatsink depends on the channel shape, coolant, volume flow rate and the heatsink material. Various fabrication techniques are available to fabricate microchannels, based on the materials used and the required topology. Fabrication techniques can be broadly classified into two categories; conventional technologies and modern technologies. Conventional technologies refer to micro deforming, micro sawing, micro milling and dicing. Whereas modern technologies refer to MEMS techniques, Laser micro machining, electro-discharge machining, and micro are moulding [5].

This paper is presented in two sections; the first section deals with discussion on fabrication techniques; afterwards a conjugate heat transfer simulation is presented to evaluate the performance of microchannel heatsink.

2. Fabrication Techniques
The conventional and modern techniques for fabrication of microchannel are discussed here.

Conventional techniques
Conventional techniques also known as micro-mechanical techniques. Micro-deformation, Micro-sawing, Micro-milling and Dicing, are included in Conventional techniques. Micro deformation is a technique used to fabricate a rectangular array of microchannels by using a patented tool [5]. Using a prescribed angle of interference, the ductile materials plastically deforms to obtain the required shape. In some cases micro deformed materials may require post treatment, depending on the strain hardening rate of the material. This technique can be used for metal and non-metals. The advantage of Micro deformation techniques are fast and cost effective [6]. Micro sawing technique is used to fabricate rectangular channels in silicon and metals. Using Micro sawing technology, channel width of 0.1 mm to 10 mm range can be achieved with high and low aspect ratios [7]. Fret saw blade is used for fabricating rectangular microchannel. This technique is cost effective and consumes less time for fabrication. Micro milling is the one of the most versatile fabrication techniques, in which a milling tool having a diameter of hundreds of micrometre is used. Using micro-machining rectangular channels for metal and silicon can be fabricated in the range of 0.1 to 10 mm [5].

Modern Techniques
MEMS based techniques, Micro molding, Laser micro-machining and Electro discharge machining are classified as modern techniques [5]. MEMS based fabrication techniques are widely used for their flexibility to fabricate complex shape. DIRE (Deep Reactive Ion Etching), Wet etching, LIGA (Lithographie, Galvanoformung, Abformung) and Wafer bonding are classified in MEMS based techniques [8]. Etching is widely used as an alternative to micro-mechanical fabrication techniques. It is a material removal process from the substrate itself or from a layer on the wafer. There are two kinds of etching, wet and dry etching. In wet etching, a liquid etchant is used to remove material from the wafer in a predefined configuration using a photoresist mask. Using deep reactive ion etching, rectangular, trapezoidal, triangular geometries can be fabricated on metals, silicon and glass. This process has low manufacturing uncertainty and it’s a slow process [9]. LIGA is a German acronym for Lithographie, Galvanoformung, Abformung, which refers to (Lithography, Electroplating, and Molding). Using LIGA high aspect ratio as well as complex microchannels can be manufactured [8]. Recently, 3D printing and laser micro-machining technology has gained popularity for microchannel fabrication. Using this technology any material with complex topologies can be fabricated with utmost precision. Further, the process is too expensive [5] [9] [10]. A brief comparison among the techniques are shown in the table 1.
Table 1. Comparison of various fabrication techniques for microchannel

| Fabrication technique | Materials                | Advantages & Limitations                                                                 | References |
|-----------------------|--------------------------|------------------------------------------------------------------------------------------|------------|
| Micro-deformation     | Metals and non-metals    | Quick, low cost and in some cases post treatment is required                            | [6] [8]    |
| Micro-machining       | Metals and silicon       | Quick, low cost, good accuracy and simple geometries can be fabricated                  | [8] [11]   |
| Lithography           | Polymers and silicon     | Complex geometries can be fabricated, and it is a slow process                          | [8] [11]   |
| MEMS(DIRE)            | Metals, silicon and glass| Low manufacturing uncertainty, high aspect ratio channels and slow process              | [8] [9]    |
| Laser micro-machining | Metals and glass         | High precision, complex topologies can be fabricated and too expensive                  | [8]        |

3. Numerical simulation

Model description
The computational domain of microchannel heatsink has a length of 20mm and width of 4mm with 10 channels. Each channel has a depth of 0.25mm and width of 0.2mm. Silicon, copper and aluminum are chosen for different simulation and water is used as liquid medium.

Governing equations and boundary conditions
A three dimensional solid-fluid conjugate heat transfer model is used to simulate the performance of microchannel heatsink. The governing equations are given in equation (1) to (4) [12].

Continuity equation:
\[ \nabla \cdot \mathbf{u} = 0 \]  

(1)

Momentum equation:
\[ \rho_f (u \cdot \nabla u) = -\nabla p + \nabla \cdot (\mu \nabla \mathbf{u}) \]  

(2)

Energy equation:
\[ \rho_f c_p u \nabla T_f = \nabla \cdot (k_f \nabla T_f) \]  

(3)

\[ \nabla \cdot (\kappa \nabla T_s) = 0 \]  

(4)

Where, \( u \), \( \rho \), \( k \), \( c_p \), \( p \) and \( \mu \) represents velocity vector, density, thermal conductivity, specific heat capacity, hydrodynamic pressure and dynamic viscosity. The subscript \( f \) and \( s \) are used for fluid and solid respectively.

The simulations are performed using a constant heat flux of 200 W/m² at the bottom of microchannel array. The water inlet temperature considered for the simulation is 293k with different flow rates in the range of 20-40 ml/min and outflow condition is considered at outlet. The simulations were performed on COMSOL Multiphysics software [13]. Based on the grid independence test, a mesh of 3.7 million elements is chosen for this study.
Validation
To validate the numerical procedure, a standard case available in Kandlikar et.al is considered [3], and the numerical results were compared with the available analytical results. In this validation study, parameters and conditions chosen are shown in table 2. The total pressure drop between inlet and outlet of 43.67 kPa is observed, which is in agreement with the analytical results (43.6kPa). Figure 1. Shows the pressure contours, where the microchannel array is aligned with the x-axis and Figure 2 shows the temperature contours along the x-axis. The average temperature rise in the coolant along the length of channel is 10.3 ºC which is in agreement with the analytical results (10ºC).

| Parameter                  | Values                        |
|----------------------------|-------------------------------|
| Dimensions of the chip     | 10 mm × 10 mm                 |
| Dimension of the channel   | Width-50 μm, depth- 350 μm    |
| Material of microchannel   | Silicon                       |
| Coolant                    | Water                         |
| Coolant mass flow rate     | 0.00239 kg/s                  |
| Heat flux                  | 1×10⁵ W/m²                    |

4. Results and discussion

Thermal performance of microchannel heatsink
In this section, the performance of microchannel heat sink is compared with different materials (silicon, aluminum and copper). In this study the parameters and conditions used in simulation are shown in table 3. Thermo-physical properties of coolant and the microchannel material for the simulation are temperature dependent [14].

| Parameter                  | Values                        |
|----------------------------|-------------------------------|
| Dimension of the chip      | 20 mm × 4 mm                  |
| Dimension of channel       | Width-0.2 mm, depth- 0.25 mm  |
| Materials considered       | Silicon, Aluminum and Copper  |
| Coolant                    | Water                         |
| Coolant mass flow rate     | 20-40 ml/min                  |
| Heat flux                  | 2×10⁶ W/m²                    |
The simulations are performed on aforementioned model considering silicon, aluminum and copper as channel material one by one. The results are presented in Figures 3-5. Figure 3-5 shows the surface temperature of microchannel array made of silicon, aluminum and copper respectively. These results are corresponding to constant flow rate of 20 ml/min. From this result, it is observed that the maximum temperature rise in the microchannel is for silicon and least temperature rise is observed for copper.

Similar to temperature plot, the pressure contours for all three materials are observed. In this study, the trend of pressure along the length of the microchannel array is almost similar in all cases for a fixed mass flow rate. These results are shown in Figures 6-8.

Further simulations are performed to study the effect of mass flow rate on the performance of microchannel, all three materials are considered for this simulation. The performance of microchannel is directly related to average temperature or the rise in temperature attained by the coolant flowing through the microchannel.

Figure 9 shows the average values of temperature for different mass flow rates and different materials. It is observed that the Tavg value is higher in case of silicon when compared with the other materials. Figure 10 shows the difference in temperature of coolant between outlet and inlet of the microchannel for different materials. Similar observations were made for coolant temperature difference.

Figure 3: Surface temperature plot of Silicon: 20ml/min
Figure 4: Surface temperature plot of Aluminum: 20ml/min
Figure 5: Surface temperature plot on Copper: 20ml/min
Figure 6: Pressure contours on Silicon: 20ml/min
5. Conclusion
In the present work, a numerical simulation for an array of microchannel heatsink with specific application to electronic cooling has been performed. The conjugate heat transfer model was implemented in COMSOL and the numerical results were validated with the analytical results. The simulations were performed for silicon, aluminum and copper with different mass flow rates. Results were obtained for temperature rise and pressure drop. The study shows that maximum temperature rise for coolant is in silicon microchannel. The parametric study presented in this paper shows that with the increase in mass flow rate, $T_{\text{avg}}$ and $\Delta T$ change significantly. The numerical model and simulations presented in this paper is useful for selection of materials for microchannel heatsink.

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