Thermal Management Materials for Advanced Heat Sinks used in Modern Microelectronics

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Abstract. Heat sinks are used for dispensing the heat from a system in many modern microelectronic components. It helps in systematically absorbing the heat from the system and dissipating it to the atmosphere, thereby ensuring system performance, extended life and reliability. The material used for the heat transfer device is one of the utmost significant parameter, which decides the size of the heat transfer device and its heat transfer efficiency. Lower values of density, overall cost, and coefficient of thermal expansion along with higher thermal conductivity, are considered as the essential properties required for any heat sink material. Though, the Copper and Aluminium materials are generally observed to be the best materials for a heat sink applications, some of their alloys are also found to be suitable. The manufacturing difficulty, the higher cost involved, comparatively poor thermo-physical properties and insufficient investigation are some of the factors that have limited the use of advanced composites in heat sink applications. A comparative numerical analysis for different thermal management materials like Copper, Aluminium, Al₂O₃, AlN, and Si₃N₄, is presented in this paper. COMSOL MULTIPHYSICS software is used for the present analysis to check the suitability of these materials for construction of heat sink. Moreover, the study of the cost-effectiveness of the material selected is important before the actual application of that material for heat sinks.

1. Introduction
Extensive research has been initiated in the area of microchannel heat transfer due to the requirement of the high-performance cooling technologies in modern microelectronics. Recently, the microchannels have been recommended by many researchers as an effective technique for the modern micro cooling systems. The larger heat transfer area per unit volume of microchannels and corresponding greater heat removal capacity makes it suitable to be used in heat sink applications. Therefore, it is essential to understand the fluid flow and heat transfer performance characteristics of the microchannels for the proper design of any microchannel cooling systems. The heat exchanger transfers the heat from a higher temperature surface of the electronic component to the lower temperature surrounding medium, preferably air. A heat transfer device (heat sink) is connected to the heat-generating equipment for enhancing the heat dissipation from the hot surface to the coolant medium. The heat sinks can be directly mounted on the enclosure or in the base of microelectronic devices to provide the required heat transfer area. In microelectronics, the surface area available for
heat transfer is very less, and the amount of heat needed to be dissipated is very high. Therefore, the liquid-cooled microchannel heat sinks were introduced to cope up the requirement of higher surface area and higher heat transfer coefficient simultaneously.

2. Literature review
Tuckerman et al. [1] proposed the heat sinks, with microchannels, for the micro-electronic cooling applications. Theoretical and experimental study related to heat transfer (single-phase) in the micro-channels were done in 2015 by Hetsroni et al. [2] to understand the influence of the channel geometry on microchannel performance. Wang et al. [3] in 2008 analysed the performance of microchannel heat sink integrated with a high efficient copper heat spreaders. Theoretical and experimental investigation of the water-cooled straight microchannel heat sink was carried out by Gawali et al. [4] in 2014 to understand the effect of different parameters like pressure drop, heat transfer coefficient, thermal resistance, etc. Pietrak et al. [5] in 2015 reviewed the empirical, analytical and numerical expressions for predicting the thermal conductivity of composite materials. After investigating the copper microchannels for thermal applications, Jarosinski et al. [6] in 2017 examined the possibility of enhancing the thermal conductivity of epoxy resin systems by using composites filled with graphene nano-particles for electrical insulation application. Numerical analysis of microchannels with pin fins were done by Jadhav et al. [7] in 2018 and reported that pin fin size, shape, length and coolant flow velocities should be considered for the proper selection of pin fins for the enhancement of heat dissipation in microchannels. The theoretical, computational and the experimental investigation was done for the enhancement of thermal conductivity of marble powder-filled epoxy composites by Ray et al. [8] in 2018. Numerical analysis of the microchannel heat sinks was done by Jadhav et al. [9] in 2019 to analyse the influence of the various pin-fin configurations (layouts) on the microchannel performance and concluded that the arrangement of the pin fins in the microchannel has a considerable impact on the heat sink performance. Various studies have reported about the use of microchannel for mixing of multi-fluids and related mixing performance [10-13]. Manufacturing of a microchannel heat sink is also a crucial task. The fabrication aspect of microchannels and suitable processes have been reported by Wangikar et al. [14] in 2017.

For deciding the thermal and geometrical parameters related to a heat sink, it is essential to examine essential different parameters that may affect the performance of a heat sink. The properties of the material used for the manufacturing of the heat sink also decides the performance of a cooling system. While designing a heat sink, the different parameters need to be taken into consideration. Some of them are coolant inflow velocity, pressure drop induced in the microchannel, the size and shape of the microchannel, amount of cooling required in the application, maximum allowable temperature, atmospheric conditions, and the cost involved in the heat sink manufacturing. The thermal performance of microchannel is generally case-specific, resulting in many inconsistencies in the microchannel research and therefore, requires further research in this area.

3. Description of the model
In this paper, numerical analysis of heat sink is carried out using commercial software, COMSOL MULTIPHYSICS. The work is performed for comparing appropriateness of the various materials which can be used for the heat sink construction. Instead of analysing the complete heat sink, a representative elemental volume can be analysed to save the computational time and cost. However, in such a case, selecting a proper elemental size and applying the correct boundary conditions become very important for correctly predicting the behaviour of the complete process. In this work, a heat sink having several microchannels and with water used as a coolant is considered for the study. Since all the channels in the heat sink are identical in shape and size, a three-dimensional microchannel with water in it is considered as a representative elemental volume here. To the bottom surface of the channel, heat flux is applied. The schematic of the microchannel model employed in the analysis is depicted in Figure 1. After passing through the channel base and the
vertical walls, the heat is transferred into the fluid in the channel. Therefore, it can be considered as a conjugate heat transfer problem. Considering this, the conjugate heat transfer module of COMSOL Multiphysics software is employed in this study. The schematic of the microchannel model and the meshed model used in this study are presented in Figure 2.

![Schematic of microchannel model](image1)

**Figure 1.** The base model employed in the analysis.

![Meshed model](image2)

**Figure 2.** Meshed model.

For simplifying the problem, some assumptions are considered. The flow considered is incompressible and steady. The fluid flow considered is laminar with constant velocity at the entrance of the channel. The thermo-physical characteristics of both the solid and fluid-solid interface are assumed to be independent of the temperature. Heat is given (applied) to channel substrate, and there is no radiation heat transfer.

The below mentioned governing equations are employed for describing the heat transfer and flow of the fluid.

**Continuity equation**

\[ \nabla U = 0 \]  

**Conservation of momentum**

\[ \rho(U \cdot \nabla U) + \Delta P - \mu \nabla^2 T = 0 \]  

**Conservation of energy**

\[ U \cdot \nabla T = 0 \quad \text{for solids} \]  
\[ \rho C_p(U \cdot \nabla T) - k_f(\nabla^2 T) = 0 \quad \text{for fluid} \]  

The coolant, in the form of a laminar flow, with uniform velocity enters the microchannel at its front end with a temperature of 293.15K. At the outlet boundary of the microchannel, atmospheric pressure is allocated. Table 1 presents the boundary conditions for control volume considered in the analysis. The governing equations (mentioned above) are solved after applying the boundary conditions using the software to determine the average velocity of the coolant, the pressure drop achieved in microchannel and different temperatures in the fluid domain and heat sink. Further, the values of the average velocity, the pressure drop and the different temperatures are used for calculating different parameters like Reynolds number, friction factor and the heat transfer coefficient for the microchannel. The value of heat transfer coefficient is calculated using inflowing heat flux from the simulation results. The Fanning friction factor is derived from Kakac et al. (1987), where Po is Poiseuille number.
Table 1. Boundary Conditions employed for the model.

| Boundary                  | Fluid Boundary condition | Thermal Boundary Condition |
|---------------------------|--------------------------|---------------------------|
| Front Fluid inlet         | Inlet                    | Adiabatic                 |
| Front Fluid outlet        | Outlet                   | Adiabatic                 |
| Channel Front solid       | Wall                     | Adiabatic                 |
| Channel Back solid        | Wall                     | Adiabatic                 |
| Channel Left surface      | Symmetry                 | Symmetry                  |
| Channel Bottom surface    | Wall                     | Uniform heat flux         |
| Channel Right surface     | Symmetry                 | Symmetry                  |
| Channel Top surface       | Wall                     | Adiabatic                 |

4. Analysis of the baseline model

Table 2. Parameters set microchannel used for analysis.

| Parameter                              | Baseline value |
|----------------------------------------|----------------|
| Channel wall thickness (W)             | 200µm          |
| Channel length (L)                     | 15000µm        |
| Channel fluid flow area                | 1000µm X 1000µm|
| Heat flux                              | 20W/cm²K       |
| Thermal conductivity of water          | 0.608W/m K     |
| Density of water                       | 1000kg/m²      |

The parameters employed for the basic model analysis are presented in table 2. Due to its higher thermal conductivity value, the copper material is chosen for the basic model. Initially, the basic model is checked for grid independence. As depicted in Figure 3, the numerical results for the coolant temperature at the outlet (Figure 3a) and the pressure drop (Figure 3b) from the microchannel are considered for the grid independency. It can be observed from the simulation results that after the third configuration, an increase in the number of elements has an insignificant influence on the results. Therefore, the third configuration can be considered for further analysis.

Figure 3. Mesh Independent Test (a) For outlet temperature (b) For pressure drop.

For the basic model validation, the simulation results are compared with the results from Gawali et al., as shown in Figure 4a and 4b. Figure 4a compares the friction factor and Figure 4b compares the heat transfer coefficient. The present work is found to be in better agreement with the results of Gawali et al. [4].
5. Results and Discussion

This work is performed to analyse the appropriateness of various thermal management materials for the heat sink applications. The various thermal management materials like Copper, Aluminium, Al₂O₃, AlN, and Si₃N₄, are the materials considered for this study. The coolant flow through the microchannel is considered to be fully developed laminar flow. The values of inlet velocity range from 0.2 m/s to 1 m/s. The different performance parameters used for understanding the effect of different heat sink materials are pressure drop, heat transfer coefficient and friction factor.

The pressure drop in the microchannel with different Reynolds number values is portrayed in Figure 5. As the Reynolds number increases, pressure drop increases. Since the flow cross-section area is the same for all microchannels with different materials, the pressure drop values observed also remain similar. The pressure contours for the microchannel, is as shown in figure 6. The Fanning friction factor is a function of loss of pressure because of the wall friction. Since, all microchannels have the same amount of surface contact area with fluid, wall friction in all microchannels remains the same. Thus, the nature of the friction factor curve remains similar for all the microchannels with different materials, as shown in Figure 7. Higher Reynolds number corresponding to higher coolant flow velocities, increases the thermal boundary layer disturbance in the microchannel. Increase in the flow disturbance results in a higher value of heat being carried away from the microchannel walls. Thus, the heat transfer coefficient value generally increases with increase in Reynolds number.
Figure 8 depicts the heat transfer coefficient curves obtained for microchannels with different heat sink materials. The heat transfer coefficient performance of copper microchannel heat sink observed is best among the different materials considered in this study. The higher value of thermal conductivity of the copper material, can be regarded as one of the most important reason for the higher performance of the copper microchannel. The Velocity profile in the microchannel is shown in Figure 9, and the surface temperature of the fluid in the microchannel is portrayed in Figure 10.

6. Conclusion
Three-dimensional square microchannels of different thermal management materials are compared to observe the effect of change in the material on the microchannel heat sink performance. Firstly, a basic microchannel model of copper is validated using the results of Gawali et. al. The basic model is further compared with microchannels of other materials like Aluminium, Al₂O₃, AlN, and Si₃N₄. Among the different material chosen for the study, the copper microchannel is observed to be having the best performance. Copper microchannel with a comparatively higher value of thermal conductivity can be considered as the reason for its best performance, when compared to microchannels made of other materials.
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