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Research paper

An improved design of double-layered microchannel heat sink with truncated top channels

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HIGHLIGHTS

- A novel double-layered microchannel heat sink with truncated top channel is proposed.
- The new design has more uniform bottom wall temperature and lower thermal resistance.
- The performance improvement is due to the weakened heating effect of top channels.
- The performances of the new design are studied at various heat sink geometries.

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ABSTRACT

An improved design of double-layered microchannel heat sink (DL-MCHS) with truncated top channels was proposed. The advantages of the design were studied numerically by a three-dimensional solid–fluid conjugate heat transfer model. The better performance of the design was well demonstrated by comparison with the original DL-MCHS. The results indicate that there exists an optimal truncation position for the top channel to achieve the best DL-MCHS performance, where the coolant temperature in the top channel is approximately equal to that in the bottom channel. The optimal truncation position is determined by the trade-off between the cooling effect and heating effect of the top coolant. Then the effects of individual parameters including bottom channel length (L_x), channel number (N), channel-to-pitch width ratio (β), and total pumping power (Ω) on the performance of the proposed design were investigated. It is found that for the original DL-MCHS with larger L_x, the cooling effect and heating effect of the top coolant are both enhanced compared to the design with smaller L_x. In this circumstance, an appropriate truncated design for the top channel can reduce the top coolant heating effect significantly without the loss of cooling effect. As a result, the advantages of the truncated concept become more obvious when applied in a DL-MCHS with larger L_x. As the same reason, for a specific design with larger N, smaller β or smaller Ω, the truncated design is strongly recommended to enhance the DL-MCHS performance.

1. Introduction

Recently, microelectronic devices are developing towards high integration and high-speed applications. As the feature sizes of the microelectronic devices become smaller and smaller, the generated heat per unit volume has increased more and more substantially. High heat flux has been becoming a major obstacle for the development of the microelectronic devices because the high heat flux significantly deteriorates their performance and shortens their lifetime. It has been reported that, when the operation temperature of the microelectronic devices are between 70 and 80 °C, their reliability will decrease by 5% for a temperature rise of 1 °C [1]. The single-layered microchannel heat sink (SL-MCHS) proposed by Tuckerman and Pease [2] has the advantages of compact size, high heat dissipation per heat load, low coolant requirement, and low

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operation cost. Thus, it has become one of the most important cooling methods for the microelectronic devices, which attracts many researchers to investigate their performance through experimental [3–10] and numerical [11–22] methods. The above studies have shown that the cooling performance of microchannel heat sink can be influenced by coolant fluid [3,9,22], solid material [4–8], geometry structure [10–17,19–22], and chip arrangement [18].

In SL-MCHS, the coolant flows through the channel in one direction to dissipate the heat on the bottom wall. The coolant temperature gradually increases along the flow direction in the channel, resulting in worse and worse heat transfer capacity of the coolant along the flow direction. Thus, the uniformity of temperature distribution is deteriorated due to the large temperature rise. The undesirable non-uniformity of temperature distribution will do enormous harm to the microelectronic devices, which may result in the failure of the devices because of the local overheating or may lead to degraded reliability and short lifetime of the devices due to the internal thermal stresses.

To improve the uniformity of temperature distribution, Vafai and Zhu [23] proposed a design concept of double-layered microchannel heat sink (DL-MCHS) based on stacking two layers of microchannel heat sink structure, one atop the other, with the coolant flow in the opposite direction in each of the microchannel layers. Its advantage consists in that the downstream coolant in the bottom channel was cooled by the upstream coolant in the top channel, thus the coolant temperature in both layers could be compensated through the conduction of the substrate between the two layers, resulting in a considerable decrease of temperature gradient. Compared to the SL-MCHS, this flow configuration increases the temperature difference between the coolant and the channel wall in the bottom channel downstream, and thus enhances the cooling capability of the coolant. Vafai and Zhu [23] also pointed out that the proposed DL-MCHS requires lower pressure drop and smaller total pumping power compared to the SL-MCHS.

Since the study conducted by Vafai and Zhu [23], many researchers began to investigate the performance of the DL-MCHS [24–50]. The earlier studies focused on the effectiveness verification of the DL-MCHS design [24–26], which further confirmed the report of Vafai and Zhu [23]. Follow then, some researchers paid their attentions to parameter optimization and structure design for the DL-MCHS to improve the heat sink performance. The methods include single parameter analysis [27–34] and multi-parameters optimization [35–40]. In the single parameter analysis, the researchers focused on the effect of individual parameter on the performance of the DL-MCHS, and obtained the optimal channel number [27,28], channel aspect ratio [27–29], channel-to-pitch width ratio [27], and coolant flow velocity [28,30,31]. Consider that the performance of the heat sink was influenced by multiple parameters, the optimal structure and operation condition cannot be obtained only by single parameter analysis. Consequently, some researchers introduced the genetic algorithm [36,38,40], conjugate-gradient method [35,39], direct search algorithm [37], and other inverse optimization algorithms for simultaneously optimizing multiple parameters to get the optimal structure and operation condition of the DL-MCHS. The optimized parameter sets include: the channel number, channel-to-pitch width ratio, bottom channel aspect ratio, and top channel aspect ratio [35]; the channel number, channel width, and channel height [36]; the channel number, channel width, channel height, rib thickness, and inlet velocity [37]; the channel width, channel height, and rib width [38]; the channel number, bottom channel height, vertical rib width, horizontal rib thicknesses, and coolant velocity [39]; the rib thickness, channel width, and channel height [40]. In the original DL-MCHS proposed by Vafai and Zhu [23], the parallel rectangular microchannel was employed. For further enhancement of the convective heat transfer capability of the coolant, many improved microchannel structures were proposed such as trapezoidal channel [41], wavy channel [42,43], honeycomb channel [44], channel with rotatable separating plate [45], and channel with interconnects between vertical channels [46]. Besides, coolant is another important factor to influence the performance of the heat sink. It is reported that nanofluid exhibits higher thermal conductivity compared to the base fluid. Several studies [49,50] have discussed the performance of the DL-MCHS with nanofluid as coolant and found that the overall thermal resistance can be significantly reduced.

To avoid the design complexity of the coolant flow loop in the DL-MCHS, the same coolant and inlet temperature were selected in both layers. Consider the counter flow arrangement in the DL-MCHS, the downstream coolant with higher temperature in the top channel will inevitably heat the upstream coolant with lower temperature in the bottom channel, leading to a decreased cool capability of the upstream coolant in the bottom channel. Consequently, though the temperature compensation characteristics of the DL-MCHS could improve its performance, the drawback above mentioned still hinders the DL-MCHS to reach its best performance. Unfortunately, this issue was never been focused on in Refs. [23–50].

Based on the above analysis, an improved design of the DL-MCHS with truncated top channels was proposed in this work, as shown in Fig. 1a. In the new design, the bottom channels were identical to those of the original DL-MCHS. Differently, the top channels were truncated at their downstream region to prevent the downstream coolant with higher temperature in the top channel from heating the upstream coolant with lower temperature in the bottom channel. The new design is expected to further decrease the overall thermal resistance and maximum temperature difference on the bottom wall. The effectiveness of the new design was justified by a three-dimensional solid–fluid conjugate heat transfer model, and the mechanism of the performance improvement was revealed. Finally, the performance of the new design was discussed for the DL-MCHS with various channel lengths, channel numbers, channel-to-pitch width ratios, and total pumping powers. These results could provide theoretical guidance for the actual application of the new design.

2. Improved design of double-layered microchannel heat sink

The schematics of the improved and original DL-MCHS are shown in Fig. 1a and b, respectively. The original DL-MCHS has a dimension of $L_x \times L_y \times L_z$, and both layers have the same structure. Each layer consists of N channels and $N+1$ ribs. Considering the symmetry of the heat sink, a unit structure composed of one channel with two half-ribs was taken as the computational domain. The cross-sectional area of the channel is $W_c \times H_c$ ($W_{c1} = W_{c2} = W_c$ and $H_{c1} = H_{c2} = H_c$). The width of the vertical rib is W_r. The thicknesses of the bottom, middle, and top horizontal ribs are δ_b, δ_m, and δ_t, respectively.

The proposed new design is identical to the original DL-MCHS except that the top channels are truncated downstream. The truncation length is l, thus, the length of the top channel is decreased to $L_{x2} = L_x - l$. Here, a dimensionless truncation length is defined as $\lambda_l = l/L_x$. The middle horizontal rib is split into two parts with the same thickness of $\delta_1 = \delta_2 = \delta_m/2$.

The bottom of the heat sink, generally, is attached to a heating surface such as integrated circuits or electronic chips with a uniform heat flux, q_w. The bottom coolant flows along the x-direction, while the top coolant flows opposite to the x-direction.