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Enhanced heat transfer in a micro-scale heat exchanger using nano-particle laden electro-osmotic flow☆

Marwan F. Al-Rjoub [a], Ajit K. Roy [b], Sabyasachi Ganguli [b], Rupak K. Banerjee [a,*]

[a] Mechanical and Materials Engineering Department, University of Cincinnati, Cincinnati, OH, USA
[b] Nanoelectronic Materials Branch, Materials and Manufacturing Directorate, Air Force Research Laboratory, WPAFB, OH, USA

A R T I C L E I N F O

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A B S T R A C T

This research presents a multi-channel micro-scale heat exchanger for thermal management of microelectronics hot spots. Electro-osmotic flow (EOF) was implemented to drive the cooling liquid through the micro-channels of the heat exchanger. Various cooling liquids including, deionized water, distilled water, borax buffer, and Al_2O_3 nano-particle solution, were tested and compared based on their flow rates and increase in cooling liquid temperature. The micro-scale heat exchanger was fabricated using a combination of polydimethylsiloxane (PDMS) and silicon dioxide-coated substrate. A constant heat flux heater was used to simulate the heat generated by microelectronic devices. The flow rate of the cooling liquid and its temperatures at the inlet and the outlet reservoirs were measured. Deionized water produced a flow rate of 30.1 μL/min and 2 °C increase between the inlet and the outlet reservoir temperatures at 1 W heating power and 400 V of EOF. The flow rate and the increase in temperature of distilled water at the same conditions were 22.7 μL/min and 3 °C, respectively. For the borax buffer the flow rate was 33.1 μL/min and the increase in temperature was 2.7 °C. Most notably, there was an increase in temperature of 2.4 °C with a lower flow rate of 20.4 μL/min when the Al_2O_3 nano-particle solution was used. Among all cooling liquids, the Al_2O_3 nano-particle solution showed the highest scaled specific heat energy removal with a maximum of ~69% increase compared to deionized water. Further, the current micro-scale heat exchanger device was able to produce higher electro-osmotic flow rates due to the use of PDMS on three sides of the micro-channel; thus providing smoother walls and higher zeta-potential while the silicon surface allowed heat transfer to the cooling liquid. The increased flow rate allowed enhanced heat removal from higher heat flux areas (hot spots) of microelectronic devices without the need for high-pressure pumping systems.

1. Introduction

Modern microelectronic devices have higher computational power while their sizes are smaller than their predecessors. This leads to higher heat generation rates per unit area of the microchip (i.e., heat flux). A major concern that is associated with the increase in heat generation is the formation of hot spots that can lead to heat fluxes in the order of 2 kW/cm^2 [1]. These hot spots are usually linked to the logic blocks of the microchip that generate higher heat flux compared to memory blocks. In order to dissipate these high heat fluxes, new heat removal techniques are required instead of conventional low-capacity heat sinks. Different approaches have been implemented to increase the heat removal rates from microchips including: using improved fluid pumping techniques, introducing new designs of heat exchangers that are made of micro-channels, and implementing cooling liquids with higher thermal conductivity.

One of the new techniques to handle high heat flux hot spots is to use electro-osmotic flow (EOF) in micro-channels. In this case, the flow is maintained by applying an electric field across the liquid, thus eliminating the need for high pressure mechanical pumping systems. EOF is a phenomenon that occurs when an electrolyte solution is brought in contact with a surface, such as the walls of a micro-channel. The contact between the liquid and the surface leads to the formation of an electrical charge on the surface of the micro-channel. The electrical charge on the surface attracts counter ions from the bulk solution leading to the generation of the electric double layer (EDL). When an electric field is applied between two points across the liquid, charged ions in the EDL start to move in the direction of the electric field. The motion of these ions drags adjacent liquid volume and diffuses to the center of the micro-channel due to viscous forces. Further details of the theory and applications of EOF can be found in Probstein [2].

Many researchers used EOF to remove the heat generated by microelectronic devices and tested different cooling liquids that were mostly water-based. One of the earlier designs of EOF micro-channel heat exchangers was presented by Laser et al. [3]. In their design, multiple deep micro-channels that were arranged parallely transported the cooling liquid between the inlet and the outlet reservoirs to reduce

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* Corresponding author at: 593 Rhodes Hall, Mechanical and Materials Engineering Department, University of Cincinnati, Cincinnati, OH 45221, USA.
E-mail address: rupak.banerjee@uc.edu (R.K. Banerjee).

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the temperature of the high power density hot spots. Jiang et al. [4] tested a two-phase closed-loop micro-channel cooling system. In that system an external EOF pump was used to circulate the cooling liquid between the heat exchanger and the heat rejection unit, maintaining the microchip temperature at less than 120 °C. Jung et al. [5] studied the differences between nanofluids and pure water using a single micro-channel and compared the convection heat transfer coefficient as well as the friction factor for both cases. Eng et al. [6] designed a silicon-based heat spreader using EOF to pump the cooling liquid; a reduction of 4 °C in the device temperature was achieved. A recent study by our group (Al-Rjoub et al. [7]) reported that EOF-driven flow in micro-channels can achieve higher heat transfer compared to pressure-driven flow. In this study, it was shown that there was an increase of 10% in the value of Nusselt number (Nu) when EOF was used compared to other pressure-driven flows.

Most recent studies with regard to the thermal management of micro-chip devices using EOF were mainly either analytical or numerical. To the best of the authors' knowledge there were no experimental studies to test EOF driven microchip cooling systems in the recent past. Pramod et al. [8] presented a numerical and theoretical analysis of cascade EOF micro-pumps for the cooling of microchips. They reported an increase of 13% in the value of Nu number when EOF was used compared to pressure driven flow. A numerical study by Vocale et al. [9] presented EOF in micro-channels having an elliptical cross section with a constant wall heat flux. Their study showed that the increase in the electro-kinetic diameter of the elliptical micro-channels increased Nu number. Another numerical study involving thermally fully-developed EOF flow through rectangular micro-channels was presented by Su et al. [10]. The study investigated the effects of the microchannel aspect ratio, the ratio of Joule heating to heat flux, and the ratio of the characteristic length of the micro-channel to Debye length on the temperature distribution inside the micro-channel. They found that the temperature profiles were significantly dependent on the ratio of Joule heating to heat flux when the ratio of the characteristic length to Debye length is small. An experimental study of heat transfer and pressure drop in micron-sized tubes was presented by Wang et al. [11]. In their study a comparison between micro-scale and macro-scale Nu number showed that there was 1.89–5.82 increase in the value of Nu number in micron-sized tubes. The above mentioned study didn't implement EOF; however they investigated developing and fully-developed pressure driven flow.

The current study introduces a new concept of micro-scale heat exchanger design based on new and combinations of different materials while testing different types of cooling liquids. A schematic of the heat exchanger is presented in Fig. 1 showing its major components. The micro-scale heat exchanger was made using a combination of polydimethylsiloxane (PDMS) and silicon dioxide surfaces. The PDMS surfaces enclosed three sides of the micro-channel and the silicon dioxide surface was the fourth surface that sealed the micro-channels and conducted heat to the cooling liquid inside them. Choosing PDMS on the three surfaces increased the zeta-potential of the micro-channels and produced better quality surfaces (less roughness) compared to silicon etching [12,13]. Increasing the value of zeta potential increased the EOF velocity leading to an increase in the flow rate of the cooling liquid. This increase in the flow rate can enhance the heat transfer from the silicon substrate to the cooling liquid leading to improved micro-heat exchangers with higher heat-removal capacity.

The current micro-scale heat exchanger design was based on a multi-channel Si-PDMS micro-pump that was recently designed by our group [14]. The micro-pump has inlet and outlet reservoirs that were connected by twenty micro-channels arranged in parallel. The micro-channels have a rectangular cross section of 150 μm × 100 μm and a length of 20 mm. The micro-pump was able to produce flow rates that were orders of magnitudes higher than other EOF micro-pumps of similar size. It was anticipated that the micro-pump will enhance the performance of heat removal from localized hot spots. In order to test and quantify the performance of the micro-pump in thermal management applications, a heater was attached to the silicon surface to simulate the heat flux generated by hot spots in the microchip surface. The heat was carried by the cooling liquid as its temperature increased between the inlet and the outlet reservoirs. To quantify the heat removed by the cooling liquid, measurements of the cooling-liquid flow rate and the difference between inlet and outlet reservoir temperatures were acquired using a data acquisition system. Further analysis of the micro-scale heat exchanger heat transfer and a comparison between different cooling liquids were performed.

The performance of different cooling liquids, including nano-particle laden liquids, was tested using the micro-scale heat exchanger. Aluminum oxide nano-particle solution, deionized (DI) water, distilled (DS) water, and borax buffer were used as cooling liquids. The amount of heat carried by these liquids was quantified and compared at the same heating power. A comparison of the scaled specific heat energy carried by the cooling liquids is presented in the results section.

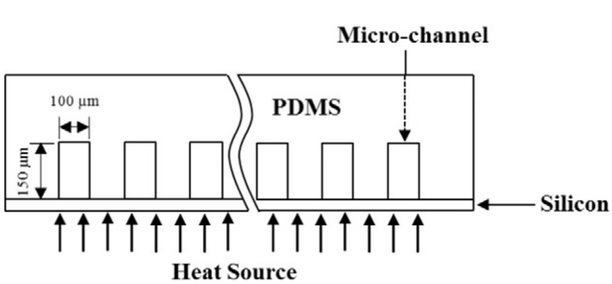

Fig. 1. Schematics of the micro-scale heat exchanger showing its major components; the PDMS micro-channels and the Si substrate.

2. Methods

The micro-pump design presented in our recent publication [14] was modified for testing as a micro-scale heat exchanger. The micro-pump consisted of a PDMS block with micro-channels cast on it along with an oxidized silicon substrate on one surface. The first step for the manufacturing of the micro-pump was to fabricate an SU-8 master for PDMS casting. For that reason, a 3″ silicon substrate was cleaned and SU-8 2075 (MicroChem Corp., Newton, MA) was spun-coated to achieve a 150 μm thickness. The substrate was then soft baked at 60 °C for 10 min. After that, the substrate was aligned with a mask that has a pattern identical to the desired micro-channels and was exposed to UV light. After exposure, the substrate was hard baked over a hot plate at 90 °C for 20 min. Since SU-8 is a negative photoresist, UV-exposed areas of the substrate remained while unexposed areas were washed away in the SU-8 developer (MicroChem Corp., Newton, MA).

The SU-8 master was used to cast the micro-channels in a petri-dish. For that, PDMS (sylgard 184, Dow Corning Corp., Midland, MI) was mixed and degassed in a vacuum desiccator. PDMS was poured over the SU-8 master in a petri-dish and then degassed until all air bubbles were extracted. The petri-dish was then placed over a hot plate at 80 °C for 2 h for PDMS to cure. After curing, PDMS was cut to the desired shape and the reservoirs at the inlet and the outlet were created. The PDMS block, with twenty micro-channels cast into it, and an oxidized silicon substrate were bonded together. Fig. 2 presents the various processes used to fabricate the device having rectangular micro-channels with three PDMS and one silicon surfaces. By the end of these processes a silicon-PDMS (Si-PDMS) test section was obtained and used as an EOF-driven micro-scale heat exchanger.

The micro-channels served as EOF driving conduits having a heat exchange interface between the cooling liquid and the silicon surface. The cooling liquid was in contact with the silicon substrate surface where heat flux was applied. The transport of the cooling liquid between the