Considerations and Challenges for Large Area Embedded Micro-channels with 3D Manifold in High Heat Flux Power Electronics Applications

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Abstract—Embedded microchannel with 3D manifold heat sinks (EMMCs) offer two primary advantages over conventional microchannel heat sinks: increased thermal performance and decreased pressure loss. The unique 3D fluid routing mechanism of the manifold reduces pressure losses and, resultantly, reduces required pumping power. Previous simulations and experimental studies have been limited to cooling of small footprint electronics, typically on the order of 5x5mm². This work explores the effects of scaling up the footprint of the cooling area using single phase water. A constant heat flux is applied at the top of the microchannel cold plate and the manifold routes fluid in and out of this cold plate. Achieving similar thermal performance with a larger footprint necessitates scaling flow rate approximately proportional to area. Therefore, significantly higher pressure losses are expected as the heater area is scaled up from 5x5mm² to 20x20mm². For example, in order to achieve a target performance of 0.078 cm²-K/W, pressure drops from the inlet to outlet are 2 and 35 kPa for the 5x5mm² and 20x20mm², respectively. In addition, increasing the flow rate of liquid results in the location of the hottest spot on the device shifting away from the center of the device. Finally, this paper discusses ongoing and future experimental work and methods of improving thermal and pressure performance in large-scale EMMCs.

Keywords—Embedded microchannels, active cooling, large-footprint electronics cooling, simulations

I. INTRODUCTION

Increasing power density of electronics drives demand for improved thermal management. Active liquid cooling is one effective strategy for removing high heat fluxes, particularly when microchannels are employed. In contrast with larger channels, microchannels offer more surface area for liquid to contact the cooled substrate, leading to significant improvements in cooling performance, albeit with increases in pressure loss. Tuckerman and Pease pioneered the use of microchannels for electronics cooling. They demonstrated a heat flux dissipation of 790 W/cm² with thermal resistance of 0.090 °C/W and 31 psi (214 kPa) pressure drop with 50μm wide channels over a 10x10mm² with water as the working fluid [1]. Since this seminal work, other groups have carried forward the use of microchannels for active fluid electronics cooling. 3D manifold liquid routing allows for substantial decreases in pressure loss while maintaining impressive thermal performance. In 3D manifold routing, liquid is often fed from two directions and distributed along the length of the microchannels, making a u-turn before exiting through the manifold (Fig. 1). Researchers have expanded this field considerably, characterizing the performance and working principle of EMMC devices and attempting to model and optimize them [2-7].

As the cooling footprint increases, higher flow rates are required to maintain favorable thermal performance. This results in higher pressure losses, necessitating the use of increased pumping power, which can be challenging due to the limits of commercially available pumps, increasing pump size in systems with space and weight constraints, and energy consumption. Additionally, larger devices tend to be more fragile and higher pressures increase the risk of failure. To date, most EMMCs have been limited to the footprint of single chips and hotspot cooling, approximately less than or equal to 10x10 mm². Demand for cooling solutions of power modules has raised interest in the potential and effects of increasing the size of this technology.

This work seeks to understand the effects on pressure drop and thermal performance of scaling the cooling footprint of EMMCs. Design D7 from a parametric study by K.W. Jung, et. al. from Stanford on 5x5mm² cooling footprint EMMCs was used to inform design choices. This design used cold plate microchannels with 50μm width and demonstrated thermal resistance of 0.065 with a pressure drop of 8 kPa at a heat flux of 800 W/cm² and a flow rate of 0.2 lpm single-phase water [8].

This paper presents single-phase water simulation results for EMMCs similar to design D7 in Jung’s parametric study for cooling footprints of 5x5mm², 10x10mm², and 20x20mm². Effects on pressure drop, thermal performance, and hotspot location for large-scale EMMCs are discussed. Ideally, large (>20x20 mm²) devices would be able to achieve similar thermal performance and pressure drops to smaller devices. We discuss physical limitations to this goal, as well as methods of approaching it.

II. EMMC WORKING PRINCIPLE

The EMMC is composed of two parts, the cold plate and the manifold (Fig. 1a). The cold plate is the cooling surface with etched microchannels. Thermal resistance can be reduced by etching microchannels directly into the backside of the electronic to be cooled (embedded). For controlled heat flux experiments, a metal serpentine resistance heater deposited on the top side of the cold plate acts as the heat source.

This work was supported by Ford Motor Company and the National Science Foundation Center for Power Optimization of Electro-Thermal Systems. Corresponding author: Alisha Piazza, piazzas@stanford.edu

978-1-7281-9764-7/$31.00 ©2020 IEEE

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The manifold serves as a fluid routing structure to decrease the pressure drop in the device. Fluid is fed into two sides of the manifold and is distributed through inlet channels to microchannels in the cold plate. Fluid then exits the cold plate microchannels through outlet channels in the manifold (Fig. 1b).

Fig. 1. (a) EMMC components, area of applied heat flux, and fluid path through manifold, (b) Expanded view of EMMC and fluid routing through manifold and cold plate, (c) Cross section of fluid flow

### III. EMMC DESIGN

All channel dimensions except length were held constant for each simulation to best compare the effects of scaling up the EMMC. Design D7 from work by K.W. Jung, et. al. with a 5x5mm² cooling footprint was used to inform design choices [8]. One major difference from Jung’s work and these simulations is that the inlet was rectangular rather than semi-circular and the plenum and inlet shortened to limit the expansion of the total footprint of the EMMC as channel length increased. These changes were observed to have limited effects on pressure loss and flow distribution. Heat flux was applied at the top surface of a gold heater to include losses associate with the heater and the silicon oxide layer between the heater and the silicon cold plate in the fabricated devices. A thicker gold layer was used in place of thin oxide and gold layers due to meshing constraints. Design dimensions used in this study are defined in Fig. 2 and given in Table I.

Fig. 2. (a) Isometric view of EMMC and length defining cooling footprint, (b) Cold plate dimensions, (c) Manifold dimensions

<table>
<thead>
<tr>
<th>TABLE I. SIMULATED EMMC DESIGN DIMENSIONS</th>
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<td>length</td>
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<td>h_CP</td>
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CP = cold plate, MF = manifold, dimensions are defined in Fig. 2.
IV. SIMULATION CONDITIONS

The EMMC is symmetric along two axes (Fig. 3). Therefore, simulations were conducted for a quarter-cut of the full EMMC device to limit computational efforts. Quarter-device simulations have previously been verified to match full-device simulations and experimental results within the limit of experimental uncertainty [9]. This is particularly useful as device size, and therefore mesh elements, increase.

Simulations were conducted with ANSYS Fluent v16.0 software using a standard k-epsilon model with enhanced wall treatment. In experiments, the EMMC is pressurized, increasing the boiling point of water, so temperatures below 120°C were assumed to be single-phase.

The simulated EMMC consists of two solid silicon bodies and a solid gold heater covering the effective cooling area of the device. Heat flux was applied at the top surface of the gold heater. Water at an inlet temperature of 300°C was used as the working fluid. Flow rates were chosen to attempt to achieve similar thermal performance between different size models, with the assumption and observation that flow must scale approximately proportional to area to achieve this result. Thermal resistance varies approximately linearly with heat flux. Results from an applied heat flux of 800 W/cm², to best compare to Jung’s previous parametric study [8] are presented here. Additional simulations were run at 200, 400, and 600 W/cm². Thermal resistance was observed to vary approximately linearly with heat flux, as expected.

V. SIMULATION RESULTS

Simulation results for a uniform heat flux of 800 W/cm² are presented in Fig. 4. To an approximation, flow rate must scale proportional to area to achieve similar thermal performance. Increasing the cooling footprint from 5x5mm² to 20x20mm² increases the pressure drop by approximately an order of magnitude when considering the same thermal resistance.

Thermal resistance ($R_{thermal}$) is defined as the difference between the average temperature as the heater (representing the average temperature of the device being cooled in applications) minus the temperature of the fluid at the inlet (300°C) divided by the heat flux applied at the top surface of the heater.

$$R_{thermal} = (T_{heater, avg} - T_{fluid, in})/q''$$  (1)

Fig. 4. Thermal performance and pressure drop for varied flow rates in EMMCs with cooling footprints of 5x5mm², 10x10mm², and 20x20mm², with an applied uniform, constant heat flux of 800 W/cm² with single-phase water as the working fluid. The flow rate of water for the whole device and the average temperature of the heater surface is provided for each data point.

Previous work on 5x5mm² devices has found good agreement between experiments and simulations [9]. Additionally, for single phase flow, the hot spot, corresponding to the least effective cooling, is observed at the center of the device in both simulations and experiments for 5x5 mm² heater areas [9,11]. This result is expected because this point is furthest from the unheated silicon regions of the EMMC and furthest from the fluid inlets. At low flow rates, the hot spot is also observed at the center of the device for 10x10 mm² and 20x20 mm² heater areas. As flow rates increase, a shift in the location of the maximum temperature away from the center of the EMMC is observed (Fig. 5). This has not been reported in experiments of smaller devices because flow rates required to achieve desired cooling performance in the single-phase regime are comparatively low. However, flow rates that will result in this effect in larger devices are almost certainly necessary at
high heat fluxes. This hot spot location shift can also be observed by increasing the flow rate in smaller devices and/or by decreasing the manifold channel height in smaller devices (Fig. 6). Observations of this shift in hot spot location in simulations has been reported in at least one previous paper [2].

It is hypothesized that this shift in hot spot location results from the formation of a stagnation pressure point at the symmetrical interface between the two inlets. Flow that can no longer continue along the manifold channel is forced upward into the cold plate, resulting in an impingement effect with high heat transfer coefficient. To confirm that these observations were not a manifestation of simulations not converging due to a large number of mesh elements, we (1) ran simulations with higher than experimentally desired flow rates in the 5x5mm$^2$ devices, (2) ran simulations with the same flow rates as the base 5x5mm$^2$ device simulations in 5x5mm$^2$ devices with shallow channels such that the flow rate through each channel matched that of the 20x20mm$^2$ devices, and (3) ran simulations with single channels instead of quarter devices. Fig. 6 is a representative image of this phenomenon, shown for a 5x5mm$^2$ cooling footprint with reduced channel heights to simulate higher flow rates. This phenomenon is easier to visualize in the smaller device. The shifting location of the hotspot may be relevant to the design of power modules or other devices that large scale EMMCs are expected to cool.

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**Fig. 5.** Temperature profile of heater surface for 20x20mm$^2$ footprint devices. The location of the hottest region shifts as flow rate increases.

**Fig. 6.** Representative image of the shift in location of maximum temperature for high flow rates, show for a 5x5mm$^2$ cooling footprint EMMC with reduced channel heights and an applied heat flux of 800 W/cm$^2$. (1) As flow rate increases, the location of the maximum temperature shifts away from the center of the device. The maximum temperature corresponds with the poorest cooling performance. (2) An increase in pressure is observed at the center of the device in the manifold side, indicating the formation of a stagnation pressure point. (3) Flow path visualization shows low fluid velocity in the manifold and high fluid penetration into the microchannels at the symmetry face of the device, consistent with the stagnation pressure hypothesis. (4) Correspondingly, flow path visualization shows high fluid velocity in the manifold and low fluid penetration into the microchannels near the inlets.
VI. CHALLENGES WITH LARGE SCALE EMMCs

As expected and evident from simulation results, increasing the cooling footprint of the EMMCs increases the pressure drop across the device required to maintain similar thermal performance. This primarily increases pumping requirements, necessitating more powerful and potentially larger pumps with higher energy consumption.

Additionally, the fabrication of larger devices in traditional silicon cleanroom environments is more difficult, time-consuming, and expensive than fabrication of smaller devices. Complications including non-uniformity of etching across the wafers pose particular challenges to large-scale devices. Furthermore, larger devices have thus been more susceptible to breaking during fabrication [10]. High fluid flow rates, resulting in increased pressure, may further contribute to the breaking of samples in experiments.

VII. MODIFICATIONS TO REDUCE PRESSURE LOSS

Increasing the height and/or width of cold plate and/or manifold channels would decrease pressure loss. Increasing the width of the cold plate microchannels would have an adverse effect on thermal performance. Increasing the height of cold plate microchannels has been observed to decrease pressure loss. The height of manifold channels is limited by the uniformity of deep reactive ion etching of silicon and by the available thicknesses of silicon wafers. Etch rates vary with feature size and density, such that the plenum is always etched deepest and the heights of manifold channels decrease from the outermost to the center channels. The plenum may be as much as 100 μm deeper than the center manifold channels for a target plenum depth of 700 μm. Non-uniformity is more apparent as the total etch depth increases. However, additive manufacturing may provide an avenue for achieving more uniform and deeper manifold channels.

VIII. FABRICATION METHODS AND MODIFICATIONS

The challenges of fabricating large scale EMMCs in silicon has led the consideration of alternative fabrication methods. Ideally, the cold plate should be fabricated in silicon or silicon carbide to better represent the devices that would be cooled in an embedded channel configuration. The cold plate is a relatively simple fabrication process, with a single side etched with channels using a Bosch Deep Reactive Ion Etching (DRIE) process.

The manifold silicon fabrication process is more involved and requires significantly deeper etches from two directions. However, the manifold serves primarily as a liquid routing structure and its thermal properties are less critical to device performance. Additive manufacturing in metal or polymer has the potential to aid in EMMC design and testing, particularly during the prototyping stage. The two primary challenges of 3D printing a manifold are (1) resolution of available 3D printers for the large footprints required, and (2) bonding these manifolds to silicon cold plates. Roughness of 3D printed structures and the compatibility of the material of these structures with silicon and common bonding materials poses challenges to this approach.

IX. FUTURE WORK

Future simulation work will include a parametric study on large footprint EMMCs to identify modifications that can improve thermal and pressure drop performance, possible with either existing silicon fabrication techniques or additive manufacturing. Increasing manifold channel width and/or height are primary candidates for improving performance.

Single-channel simulations will be pursued to reduce computational effort. Preliminary results suggest that single-channel simulations are accurate enough compared to full- or quarter-device simulations, especially when comparing relative performance of different designs is concerned.

Additionally, fabrication and experimental efforts to test EMMCs with an effective cooling area of 24x24 mm² is in progress [10]. These devices will be tested independently and paired with a novel power module from the University of Arkansas in a collaboration through the National Science Foundation Center for Power Optimization of Electro-Thermal Systems (NSF POETS).

X. CONCLUSION

Since the pioneering microchannel work of Tuckerman and Pease [1], methods of dissipating high heat flux with low thermal resistance and pressure drop have been pursued. One or both of these metrics are negatively impacted as cooling footprints increase.

Physics dictates that larger pressure losses will always be present in larger footprint devices for a given thermal performance. This work explored the need for high flow rates to achieve good cooling performance in large-scale EMMCs and the associated pressure losses and shift in the location of the hottest point in the devices that result from fluid flow increases.

This work also discussed modifications, including increasing the height and/or width of manifold channels that could improve thermal and pressure performance in large-scale EMMCs. Additive manufacturing may provide a solution to achieving manifolds with uniform and deeper channels than are possible with silicon microfabrication, but challenges with resolution and bonding remain.

ACKNOWLEDGMENT

This work is supported by the Ford Motor Company and the National Science Foundation Center for Power Optimization of Electro Thermal Systems (POETS) with cooperative agreement EEC-1449548.
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