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MITIGATING HOT SPOTS IN PLANAR AND THREE-DIMENSIONAL (3D) HETEROGENEOUS MICROSYSTEMS USING LIQUID COOLING

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ABSTRACT

We discuss techniques for hot spot mitigation using single phase liquid and two phase cooling, for both planar and 3D chips. In single phase flow through a finned microgap, the approach of fin clustering near hot spots is described. Heat transfer and pressure drop characteristics of various configurations are presented. For 3D stacked architectures, both fin clustering and tierwise flow variations for thermal control are discussed. Flow boiling in finned microgaps offers the potential of reduced mass flow rates, and temperature gradients compared to single phase forced convection, for handling non-uniform power maps. Three-dimensional, transient computations using the Volume of Fluids (VOF) approach for flow boiling are presented to explore selected strategies for hot spot mitigation. Comparisons of VOF predictions with experimental data gathered using microfabricated test structures are presented.

INTRODUCTION

As the traditional transistor scaling dictated by the Moore's Law slows, the emerging trend is towards heterogeneous integration, or combination of multiple functionalites in a single chip, interposer enabled package (2.5D package), or three-dimensional (3D) chip stack. Such compact heterogeneous integration of logic, memory and other functionalities creates highly non-uniform heat flux distributions, or power maps, as well as large volumetric heat generation rates. On a single chip with an average typical background heat flux of 100 W/cm^2, localized "hot spot" regions could have heat fluxes that are an order of magnitude higher, and can change rapidly with time. Handling these large spatial and temporal variations in an energy efficient fashion presents a challenge, even for planar chip architectures. The challenges in handling hot spots become even more pronounced in 2.5D packages, and 3D stacked chips. For continuing advances in heterogeneous microsystems, addressing the mitigation of hot spots remains a key challenge.

Increasing chip heat fluxes in bi-polar Si chips prompted the development of microchannel cooling by Tuckerman and Pease (1984), who demonsrated heat fluxes of 790 W/cm^2 in single phase cooling using de-ionized (DI) water. A key issue associated with single phase cooling is that as the mean fluid temperature increases downstream, the wall surface temperature is offset in a similar fashion for fully developed conditions, leading to the undesirable high temperature gradients along the coolant flow path. Also, an array of uniformly sized microchannels cannot provide spatially and temporally variable cooling capability needed for localized hot spots.

Green et al. (2009) investigatd a hybrid F2/S2 (fluid-to-fluid, spot-to-spreader) heat sink that uses two separate flow loops per tier, with one fluid (e.g., water) dedicated to hotspot regions only, and the second fluid (e.g., air) used for removing the background heat fluxes. Successful removal of up to 365 W/cm^2 in hotspot regions, and background heat fluxes of 20 W/cm^2 was experimentally demonstrated, with pressure drops lower than 100 kPa. An alternative approach is to combine solid state and fluidic cooling techniques to handle hot spots and background heat fluxes, respectively. Sahu et al (2015) combined localized solid-state cooling, with global liquid cooling. Their solution consisted of a single phase liquid microchannel heat sink designed to remove background heat flux. An array of active solid-state SiGe superlattice coolers were fabricated at the back of the heat sink to dissipate heat from localized hotspots. Localized hot spot removal capability of over 300 W/cm^2 was demonstrated.

HOT SPOT COOLING WITH FIN CLUSTERING: SINGLE PHASE CONVECTION

The use of conventional microchannel array, or a microgap populated with uniform pin fin arrays for microfluidic cooling designed for average background heat flux removal may not provide adequate surface area for heat transfer in the vicinity of hotspots, and therefore significant temperature gradients might arise in such zones. In recent years, variable density of pins has been proposed as a solution to homogenize the device temperature by increasing the available area for heat transfer in the flow direction (Rubio-Jimenez et al (2012), Lorenzini-Gutierrez and Kandlikar (2014)). Sharma et al. (2014) presented a numerical study to assess the concept of hotspot-targeted manifold microchannel heat sinks with multiple inlets and outlets using water as coolant. Narrow channels were defined in the hotspot areas, while wider channels were used to cool background zones. Model predictions suggested the capability of this design to remove hotspot heat fluxes up to 300 W/cm^2, in combination with a background heat flux of 20 W/cm^2 with a pressure drop below 35 kPa.

Lorenzini et al (2016) investigated a single phase microfluidic loop for the combined cooling of hotspot and moderate background power, using a pin fin enhancd microgap. Two different test vehicles were considered, in which the heat transfer surface area was locally increased by clustering a dense array of pin fins in the hotspot region for one configuration, while for the other the clustering was uniform in the spanwise direction. DI water was used as the coolant through a Si microgap with 200 um spacing. The hotspot heat flux ranged from 250 to 750 W/cm^2, while the background heat flux was fixed at 250 W/cm^2. The maximum temperature of the combined device was below 65 °C for an inlet water temperature of 21.3 °C, with moderate temperature gradients and pressure drop. In addition to the experiments, a computational fluid dynamics/heat transfer model capable of predicting spatially resolved temperature fields arising from heterogeneous heating was successfully compared with experimental data.

Here we present computational simulations of single phase convection and flow boiling in pin fin enhanced microgaps. The pin fins allow for routing of electrical interconnections needed for 3D stacking, as well as enhance the heat transfer surface area. The focus is on a single fluid delivery and exit pathways, as the simplest configuration for handling hot spots and background heat fluxes simultaneously. Fig. 1 shows top views of four designs of pin fin clustering examined experimentally and computationally. Both circular cross-section, and hydrofoil cross-section pins are examined.

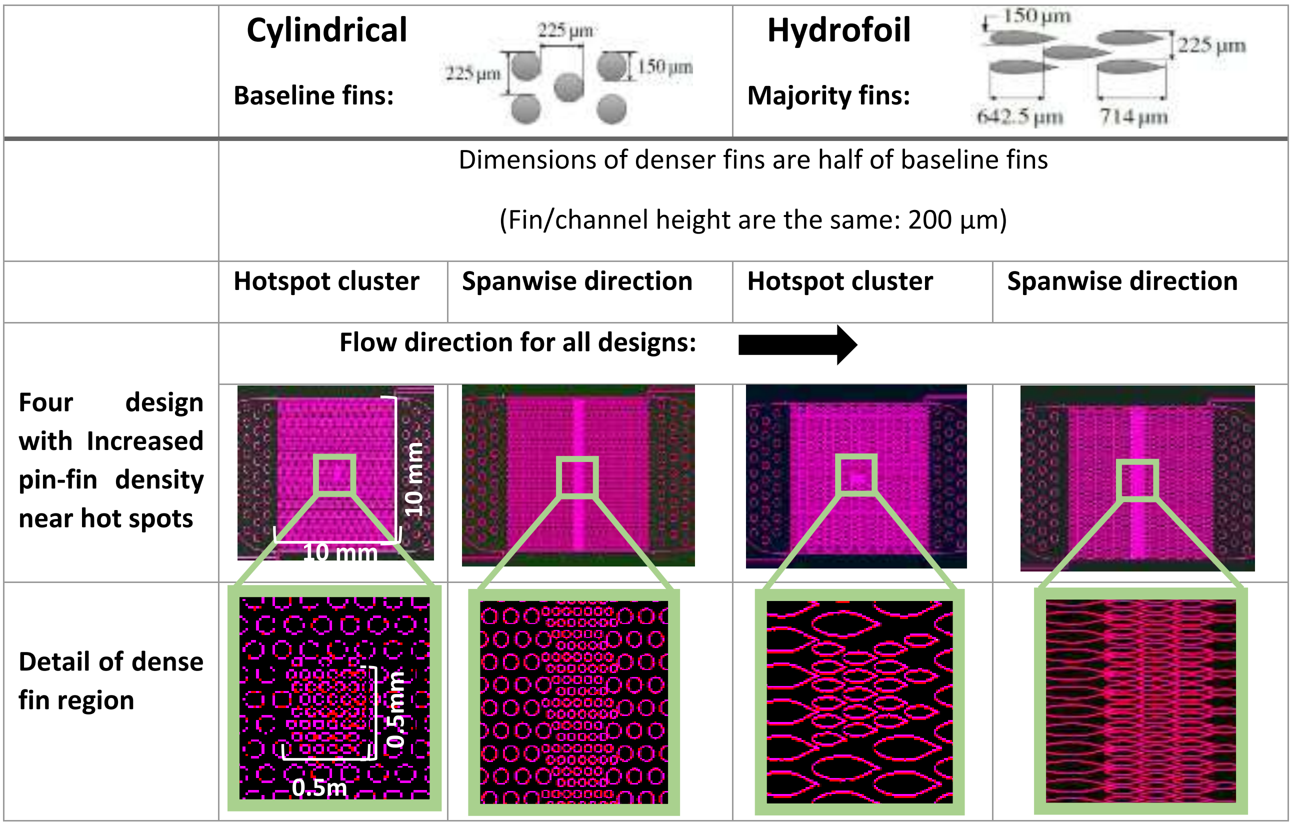

Figure 1. Locally and spanwise clustered pin fin arrays to handle simultaneous background cooling and hot spot removal. Cylindrical and hydrofoil fins are examined.

Fig. 2 shows the measured surface temperature rise in the flow direction for a fixed flow rate, corresponding to Re=1,355, for a background heat flux q''_b = 250 W/cm^2, and hot spot heat flux q''_{hs} = 500 W/cm^2. In general, the chip surface temperature increases from the inlet to the outlet, in response to the increasing bulk fluid temperature. The spanwise clustering seems to result in the lowest temperature rise at the four heater locations. The hotspot temperature rise is the lowest for the hydrofoil spanwise clustering.

Fig. 3 shows the pressure drop for each of the four fin configurations for several flow rates, or Re. The superior thermal performance for the spanwise hydrofoil fin clustering comes at the exense of a larger pressure drop. Localized clustering configurations result in a lower overall pressure drop. Fig. 1-3 show that it is possible to mitigate the impact of hot spots by incorporating localized denser pin fin designs. By incorporating flow boiling, it may be possible to reduce the flow rates, and surface temperature rise in the flow direction.

HOT SPOT COOLING WITH FLOW BOILING

Alam et al. (2013) compared the ability of minimizing temperature gradient and mitigating hotspot in microgap and microchannels. Tested microgap height was from 200 µm to 400 µm. For uniform heating, at the mass flux of 690 kg/m^{2}s and heat flux range from 0 – 60 W/cm^2, microgap device demonstrated a smaller temperature gradient and smaller amplitude of pressure and temperature oscillation than microchannel. Reducing gap heights suppressed flow oscillation as well. When a hotspot was activated, the microgap also showed better temperature uniformity than microchannel, and smaller gap height lowered wall temperature compared to higher gap height. Microgap gave better heat transfer performance at high heat flux since confined slug/annular flow was dominant, and microchannel performed better at low heat flux due to early occurrence of slug/annular flow. At lower mass flux, microgap outperformed microchannel as well.

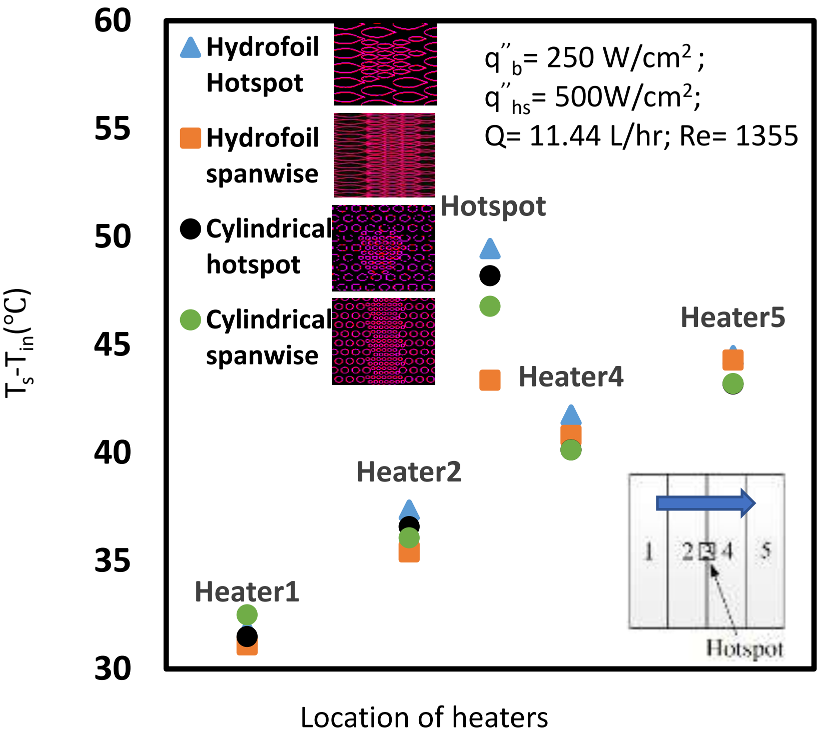

Figure 2 Measured surface temperatre rise along the flow direction for the four fin designs for combined background and hotspot heating, at a fixed flow rate.

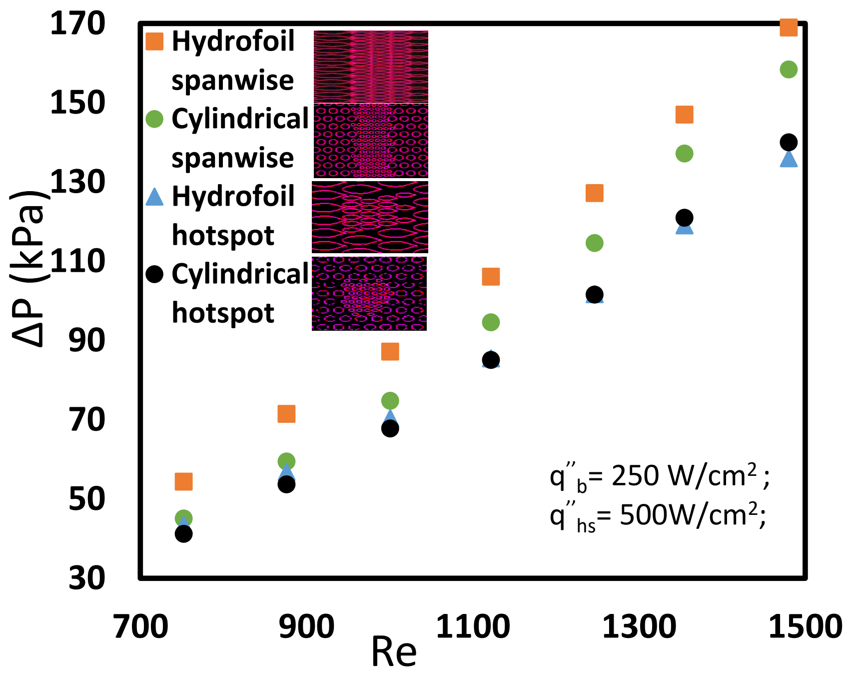

Figure 3 Measured surface temperatre rise along the flow direction for the four fin designs for combined background and hotspot heating, at a fixed flow rate.

Schultz et al. (2015) tested a radial microgap with embedded pin arrays using the same fluid. The test device was 20.25 mm × 20.25 mm, and had 8 core heaters and 16 hotspot heaters. They found that 50% increase in mass flow rate only resulted in 8% increase in two phase heat transfer coefficients. Increase in mass flow rate did not necessarily help to mitigate temperature nonuniformity.

In order to understand the flow boiling characteristics in pin fin enhanced microgaps, a strip of the larger microgap in the central region, Fig. 4, is simulated using the volume of fluids (VOF) method.

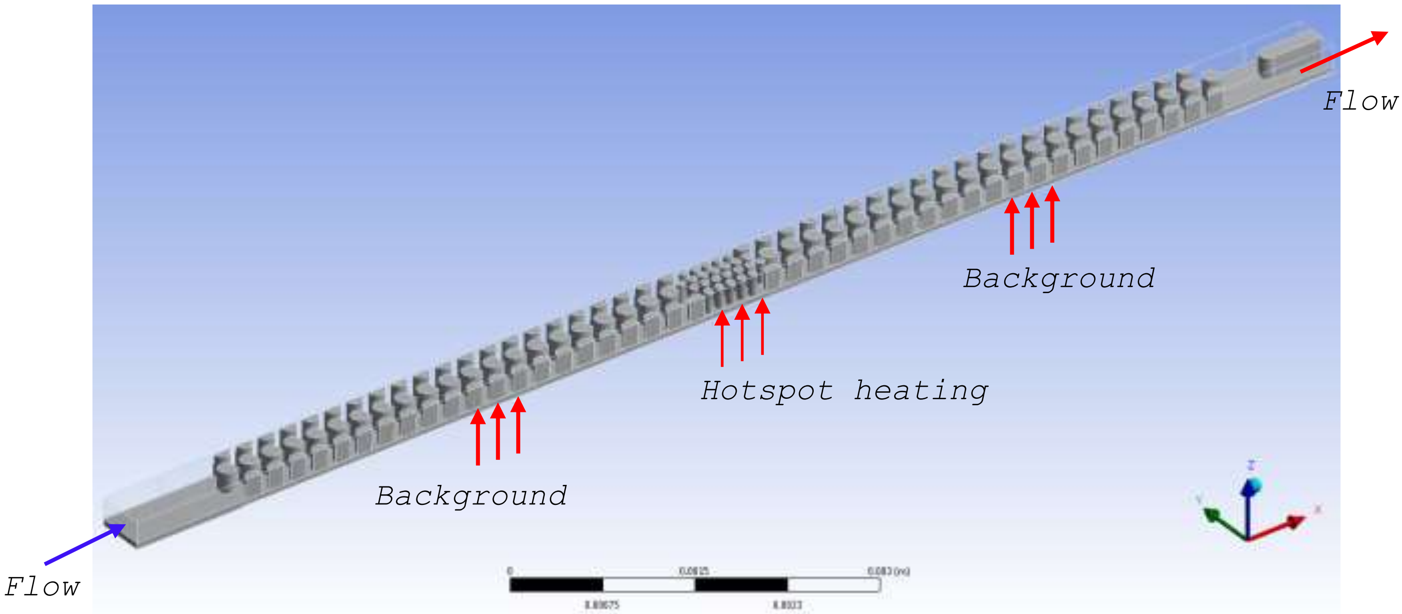

Fig. 4 Flow boiling simulation domain in microgap with variable pin fin density for the assessment of hotspots

The simulations were performed for Refrigerant R245fa, at a mass flux:of 1,000 kg/m^{2}s. The background heat flux, q''_b, was 50 W/cm^2 and the hotspot heat flux, q''_{hs}, was in the range 50-200 W/cm^2. Heat conduction in the Si chip and fins were included, along with temperature dependent thermal conductivity of Silicon. The dimensions of the background and hotspot fins used in the simulations are provided in Fig. 5. Fig. 6 shows the surface temperature and phase distributions when the heat fluxes in the background and hot spot regions are 50 W/cm^2. For this condition, the denser fin aray in the central region of the hot spot causes a cooling effect.

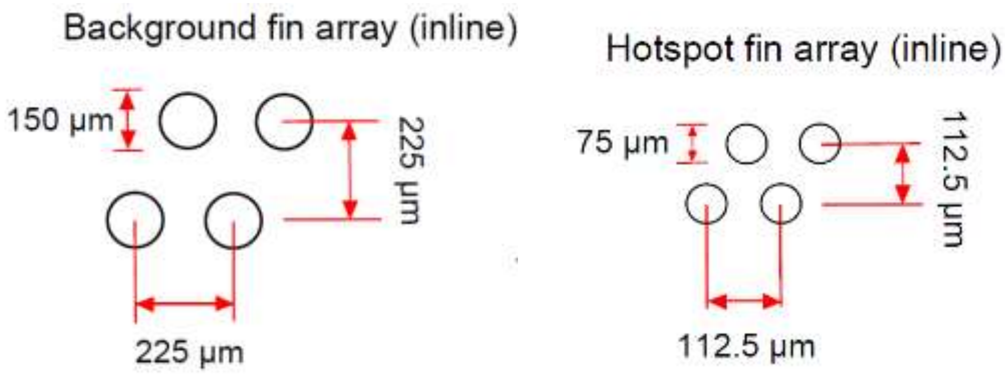

Fig. 5 Relevant dimensions of the pin fin array

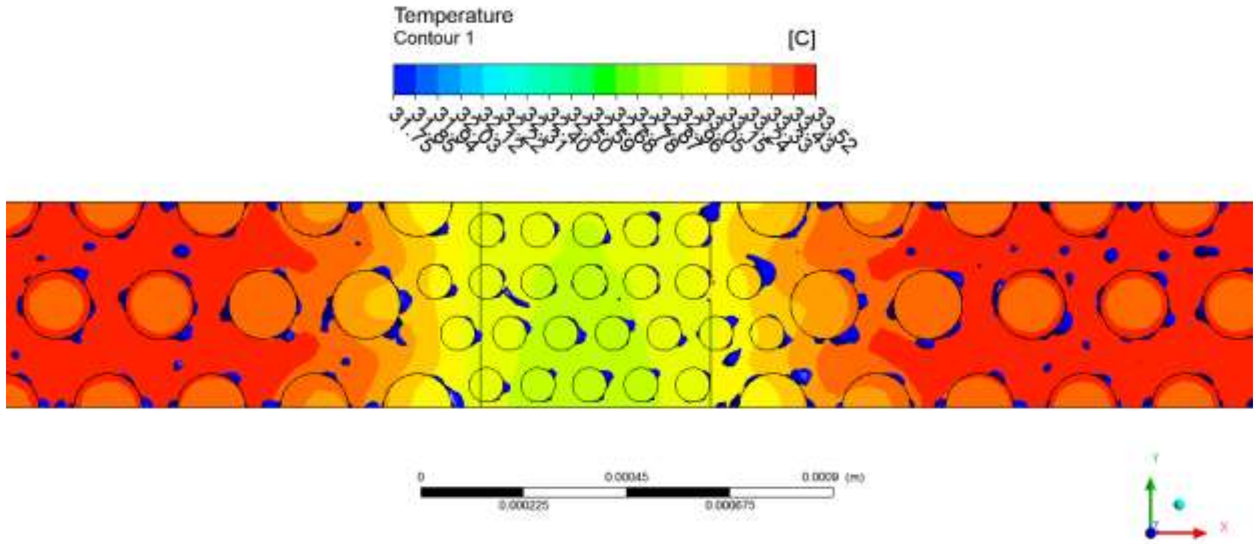

Fig. 6 Temperature and phase distribution for $q''_B = q''_H = 50\ W/cm^2$

CONCLUSIONS

Microgaps with local clustering of pin fins is a viable approach for addressing hot spots in the presence of large background heat fluxes. Computations are presented for single phase flow and flow boiling to illustrate the impact of pin geometrical parameters, solid and fluid thermophysical properties, and hot spot and background heat fluxes on the surface temperatures. Computational predictions can be utilized as a valuable design tool for such heat sinks.

REFERENCES

T. Alam, P.S. Lee, C.R. Yap, and L. Jin, 2013, "A comparative study of flow boiling heat transfer and pressure drop characteristics in microgap and microchannel heat sink and an evaluation of microgap heat sink for hotspot mitigation," International Journal of Heat and Mass Transfer, 58(1), pp. 335-347.

C. Green, A.G. Fedorov, Y.K. Joshi, Fluid-to-fluid spot-to-spreader (F2/S2) hybrid heat sink for integrated chip-level and hot spot-level thermal management, ASME J. Electron. Packag. 131 (2009) 025002.

D. Lorenzini-Gutierrez, S.G. Kandlikar, Variable fin density flow channels for effective cooling and mitigation of temperature non-uniformity in three dimensional integrated circuits, ASME J. Electron. Packag. 136 (2), 2014, 021007.

D. Lorenzini, C. Green, T. E. Sarvey, X. Zhang, Y. Hu, A. G. Fedorov, M. S. Bakir, Y. Joshi, Embedded Single Phase Microfluidic Thermal Management for Non-Uniform Heating and Hotspots Using Microgaps With Variable Pin Fin Clustering, Int. J. of Heat and Mass Transfer 103, 2016, 1359–1370.

A. Rubio-Jimenez, S.G. Kandlikar, A. Hernandez-Guerrero, Numerical analysis of novel micro pin fin heat sink with variable fin density, IEEE Trans. Compon. Packag. Manuf. Technol. 2 (5), 2012, 825–833.

V. Sahu, Y. Joshi, A. G. Fedorov, J.–H. Bahk, X. Wang, and A. Shakouri, Experimental Characterization of Hybrid Solid-State and Fluidic Cooling for Thermal Management of Localized Hotspots, IEEE Transactions on Components, Packaging and Manufacturing Technology, Vol. 5, No. 1, 2015, pp. 57-64

M. Schultz, F. Yang, E. Colgan, R. Polastre, B. Dang, C. Tsang, M. Gaynes, P. Parida, J. Knickerbocker, and T. Chainer, "Embedded Two-Phase Cooling of Large 3D Compatible Chips with Radial Channels," Proc. ASME 2015 International Technical Conference and Exhibition on Packaging and Integration of Electronic and Photonic Microsystems collocated with the ASME 2015 13th International Conference on Nanochannels, Microchannels, and Minichannels, American Society of Mechanical Engineers, pp. V003T010A007-V003T010A007.

C.S. Sharma, M.K. Tiwari, S. Zimmermann, T. Brunschwiler, G. Schlottig, B. Michel, D. Poulikakos, Energy efficient hotspot-targeted embedded liquid cooling of electronics, Appl. Energy 138, 2015, 414–422.

D.B. Tuckerman, R. Pease, High-performance heat sinking for VLSI, IEEE Electron. Device Lett. 2 (5), 1981, 126–129.

F. Yang, M. Schultz, P. Parida, E. Colgan, R. Polastre, B. Dang, C. Tsang, M. Gaynes, J. Knickerbocker, and T. Chainer, "Local Measurements of Flow Boiling Heat Transfer on Hot Spots in 3D Compatible Radial Microchannels," Proc. ASME 2015 International Technical Conference and Exhibition on Packaging and Integration of Electronic and Photonic Microsystems collocated with the ASME 2015 13th International Conference on Nanochannels, Microchannels, and Minichannels, American Society of Mechanical Engineers, pp. V003T010A006-V003T010A006.