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Document downloaded from:

<http://hdl.handle.net/10459.1/66129>

The final publication is available at:

<https://doi.org/10.1016/j.applthermaleng.2018.08.030>

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Numerical optimization of a hotspot-targeted microfluidic cooling array for microelectronics

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Keywords

- A microfluidic scheme is designed for energy efficient cooling of electronic chips
- The cooling scheme consists in an array of microfluidic cells
- Non-uniform and time dependent heat load scenarios are applied
- The distribution heat extraction capacity self-adapts to the heat load scenarios
- Low chip temperature non-uniformities and pumping power are achieved

Keywords

Hotspot-targeted cooling
Electronics cooling
Self-adaptive cooling
Energy efficient computing
Microfluidic cell array

Abstract

Thermal management in integrated chips is one of the major challenges on micro- and nanoelectronics. The rise of power density raised the need for microchannel liquid cooling solutions. This technology has poor temperature uniformity and requires high pumping powers. In this work, a cooling scheme aiming for high temperature uniformity and low pumping power is numerically studied. The cooling scheme consists in a matrix of microfluidic cells with thermally activated microvalves, which tailor the local coolant flow rates to avoid overcooling and improve the temperature uniformity. This system is assessed with steady state CFD studies combined with temporal integration in a time dependent and non-uniform heat load scenario. The studied cooling scheme improves, with respect to existing devices for similar applications, the chip temperature uniformity while reducing the pumping power by 50%.

Nomenclature

ΔT	Increase of temperature [°C]
T	Temperature [K]
ΔP	Pressure drop [Pa]
Q	Flow rate [mL/min]
P	Power [W]
q''	Heat flux [W/cm ²]
R	Thermal resistance [m ² ·K/W]
K	Valve opening factor
ΔT_q	Normalized temperature difference [°C]

1. Introduction

Cooling of microelectronic components has been extensively studied since the 1980s. Today's advanced information and communication technology (ICT) trends involve further integration, at the die and the package level. Die stacking and heterogeneous integration of temperature sensitive components are the technological paths ahead for a large share of ICT applications. Thermal viability of advanced micro- and nanoelectronic systems is one of the major challenges of the ICT community [1]. Until now, microelectronics thermal

management has been based on continuous air cooling, using passive approach by natural convection or active air cooling with a fan and heat sink depending on the power level. However, Integrated Circuits (ICs) stacking and compact assemblies make conventional air heat dissipation challenging, raising the interest in liquid cooling technologies, preferred for their cooling capacities, compactness and high performance. Single-phase liquid cooling has long been identified as an effective and feasible approach for cooling high heat flux density chips. Starting with the landmark work of Tuckerman and Pease [2], liquid cooling of chips has been analyzed in great detail including investigations on traditional microchannel heat sinks [3], manifold microchannel heat sinks [4,5] and spray and jet cooling [6]. Most of the research on liquid cooling of chips has been focused on maximum temperature reduction under uniform heat flux dissipation conditions. However, it is also necessary for the chip temperature to be as spatially uniform as possible (i.e. approaching the isothermal chip condition). Indeed, large temperature gradients in the package increase thermal stresses in the heat sink interface, reduce electronic reliability in high temperature regions and create circuit imbalances in CMOS devices [7]. Some studies have focused on reducing chip temperature nonuniformity under a uniform heat flux map, including the use of flow boiling of dielectric liquid [8], single phase liquid cooling with variable pin fin density [9], variable microchannel width in the streamwise direction [10–12] and double-layer microchannel structures [13]. Hybrid jet impingement/microchannel cooling schemes have shown their capacity to provide low thermal resistances, good temperature uniformities and lower pressure drops than conventional microchannel devices for specific heat flux distributions [14,15].

In high performance chips, the large difference in heat dissipation between hotspot and background regions makes the goal of isothermal junction temperatures even more challenging. Several approaches have been proposed to achieve an isothermal chip condition by preferential cooling of hotspots (henceforth referred as hotspot-targeted cooling). For effective hotspot-targeted cooling, Dang et al.[16] and Kandlikar et al. [17] reported that thermal resistance can be reduced by circulating the coolant through microchannels, etched into the backside of the chip (also termed as embedded or direct chip backside microchannel cooling). Attempts using single phase liquid cooling have also been reported with different degree of success [18]. Among the major findings in the literature, one can note that power densities larger than 400 W/cm^2 can be extracted with micro-channel single-phase conditions [19,20]. However, they are not able to provide a good temperature uniformity that preserves the reliability and efficiency of the cooled device. Furthermore, microchannel cooling designed for thermal performance tends to sacrifice pumping power, using high flow rates and pressure drop. An optimum thermal management approach should therefore provide higher cooling rates at the hot spot to achieve a uniform temperature while minimizing the overall flow rate and pressure drop of coolant fluid. The pressure losses are the main drawback of conventional microchannels and they must be lowered for pumping power reduction.

Conventional heat sinks with uniform distribution of microchannels or pin fins present the disadvantage of undercooling hotspot areas due to both the insufficient local heat transfer coefficient and the inadequate heat exchange area. Different approaches have been suggested in recent years to address this issue [21]. Sharma et al. [22] presented a numerical study to assess the concept of hotspot-targeted manifold microchannel heat sinks with multiple inlets and outlets using water as coolant, in which narrow channels are defined in the hotspot areas, while wider channels are used to cool background zones. Model predictions suggested the capability of this design to remove hotspot heat fluxes up to 300 W/cm^2 , the microchannel design is based in the worst operating conditions with maximum heat flux on each hot spot simultaneously, in combination with a background heat flux of 20 W/cm^2 and a pressure drop below 35 kPa. Localized microchannels were shown by Collin et al. [20] to achieve high local heat flux of 1185 W/cm^2 with a pressure drop below 20 kPa. Nevertheless, these cooling devices do not tailor their behavior to the time-dependent heat load scenarios. As a consequence, their constant flow rate distributions are overly conservatives and lead to oversized pumping powers for varying operating conditions.

Azarkish et al. [23] introduced a self-adaptive microfluidic system for thermal management of microelectronic chips with non-uniform thermal maps. The smart and self-adaptive microfluidic system, formed by an array of microfluidic cells with individually variable coolant flow rates, is designed to achieve an adequate cooling with minimum pumping power as well as appropriate surface temperature uniformity. The coolant mass flow rate of each zone is controlled independently based on its temperature by using temperature-regulated microvalves. The local cooling is adapted to the zone heat flux. In the present work, the smart and self-adaptive microfluidic system is numerically simulated to optimize the internal geometry of the cooling cells. The thermo-hydraulic performance of the resulting cooling device is assessed under non-uniform and both steady-state and time dependent heat load scenarios.

2. Description of the cooling device

The proposed approach consists of an array of microfluidic cells, each one responsible for removing the local heat flux (Figure 1). Coolant flow is fed in parallel to the cells to minimize the pressure drop and allow local

throttling of the flow rate according to the local heat flux. The local flow rates are controlled through self-adaptive microvalves [24] that tailor their aperture to the local temperature (Figure 2).

Figure 1: a) Coolant distributor above cells array and b) microfluidic cell.

Figure 2: Microvalve a) placement, b) cold position and c) hot position [24]

The microfluidic cell array has been conceived in order to provide the following advantages compared to the conventional microchannel microfluidic systems:

- Local control: The microvalve opening, which depends on its own temperature, allows tailoring of the mass flow rate of each microfluidic cell to the local cooling needs. As a consequence, the overall cooling can be managed easily with low pumping power cost.
- Low pressure drop: The length of each cell is short. Therefore, if high local coolant flow rate is needed near the hotspot zones, the corresponding pressure drop is not very significant.
- Versatile microfluidic actuation: With microchannels or other cooling schemes, the design is optimized for a given heat load at a given flow rate or is adapted to the worst case scenario. The self-adaptive local coolant flow rate provides versatility in order to adapt to varying spatial and temporal heat load scenarios.

In this paper, three geometries of the microfluidic cells are numerically studied. The first one consists on a cell with an external size of $2 \times 1.2 \text{ mm}^2$ without any fin inside (cell MC0, Figure 3). The coolant, water in this study, enters the cell from the coolant distribution layer through an inlet slot located on the cold side of the cell (opposite face to the heat load) and exits through the outlet slot on the same side, which also connects to the distribution layer. The outlet flow path allows the microvalve, which regulates the coolant flow rate for each microfluidic cell, to be located near to the chip zone where its temperature is maximum (end of the coolant flow path), in order to narrow the relationship between the valve temperature (and so its opening) and the maximum chip surface temperature (safe function).

Figure 3: MC0 design (dimensions in mm)

In a second design, fins are included within the microfluidic cell to build a 6 microchannel configuration (cell MC6, Figure 4a). Their length corresponds to the distance between the inlet and the microvalve. They are expected to improve the heat transfer, hence require lower flow rates to keep the chip below the temperature limit, but on the other hand, the narrow flow paths will generate more pressure drop. Based on previous studies [14, 15], a tailored fin design is proposed (cell MC6T, Figure 4b). The aim of this solution is to keep the heat extraction capacity to values relatively close to the ones of the MC6 model, but with lower pressure drops and a higher temperature uniformity of the chip area above the fluidic cell.

Figure 4: a) MC6 and b) MC6T designs (dimensions in mm)

3. Cooling device steady state performance assessment

3.1 Numerical model

A numerical model is used to develop a parametric study to assess the performance of each cell individually as a function of the cell dimensions and the internal geometry of the cells for several heat fluxes with a given coolant inlet temperature. The maximum chip temperatures ($T_{\max, \text{chip}}$), temperature non-uniformities (ΔT_{chip}), pressure drops (ΔP), flow rates (Q) and hydraulic pumping powers (P_{pump}) are analyzed for each of the 3 designs considered and compared to the ones obtained with conventional microchannels. A commercial finite element solver (COMSOL) is used to model the steady-state fluid flow and heat conduction in a single cell, taking in account the water and silicon properties and it's temperature dependence to reach an accurate model.

Due to longitudinal symmetry, only half of the cooling cell is considered in the numerical model with a symmetry boundary condition at the cut plane. The boundary conditions of the numerical models considered in this steady-state study are as indicated in figure 5.

Figure 5: a) Boundary conditions of the numerical model b) Model mesh

In order to fix the maximum flow rate needed to maintain the chip temperature in the adequate range the worst case is considered, with a heat flux of 300 W/cm^2 along the whole cooling cell. The coolant inlet temperature of 50°C and the maximum allowable chip temperature is 100°C .

The flow is considered laminar since the maximum Reynolds number is 420 at the inlet of MC0 cell (highest value of all cases studied). The mesh sensitivity analysis has been carried out showing convergence as a function of mesh refinement with a final account of 603921 elements.

3.2 Thermo-hydraulic Performance

Table 1 shows the thermo-hydraulic performance of the 3 microfluidic cells geometry, when submitted to the worst boundary conditions. The flow rate was varied until the maximum allowable temperature was reached.

Table 1. Thermo-hydraulic performance of the cooling cell in worst conditions.

Model	q'' (W/cm ²)	T_{in} (°C)	Q_{cell} (mL/min)	$T_{chip,average}$ (°C)	$T_{chip,max}$ (°C)	R (cm ² °C/W)	ΔT_{chip} (°C)	ΔP (Pa)	P_{pump} (W)	COP (-)
MC0	300	50.0	7.68	93.7	99.7	0.145	13.2	3791	$4.85 \cdot 10^{-4}$	$1.48 \cdot 10^5$
MC6	300	50.0	3.48	93.8	99.1	0.146	10.1	1331	$7.72 \cdot 10^{-5}$	$9.33 \cdot 10^5$
MC6T	300	50.0	3.72	98.6	100.0	0.167	4.0	1291	$8.00 \cdot 10^{-5}$	$9.0 \cdot 10^5$

To achieve the same thermal resistance across all designs, the pumping power varies significantly. The high pressure drop caused by the low heat extraction capacity at cell MC0, that requires high flow rates (Q_{cell}) to reach the temperature limitation, imply that models MC6 and MC6T need the lowest pumping power of designs studied. However, the tailored microchannel cell (MC6T) reaches a non-uniformity of 4.0 °C that improves largely the 10.1 °C obtained by the uniform microchannel cell (MC6).

The temperature distribution across the chip surface is shown in Figure 6 for the three models. MC6 presents a temperature increase along the longitudinal direction from the inlet to the valve position ($x = 1.7$ mm), typical from straight microchannels. The tailored microchannels MC6T shows a rather constant temperature distribution, this confirms the usefulness of increasing the fins density along the coolant flow path to compensate for the increase in fluid temperature. MC0 temperature profile reaches its maximum before the outlet ($x = 1.2$ mm), due to the relatively low heat exchange capacity within the microfluidic cell and to the fact that most of the heat transfer is occurring near the inlet and outlet.

Figure 6: Thermal map of the chip surface ($z=0$) for a) MC0, b) MC6, c) MC6T.

4. Performance assessment in the cooling device under unsteady and non-uniform heat load scenario

This study is now done at the chip level: an array of cells with their own self-adaptive microvalves and covering the entire chip surface is considered. The performance of the three proposed designs is assessed for non-uniform and time dependent heat flux scenarios. For all the heat loads considered, the flow rate of each of the cells is assessed to reach a given $T_{chip,max}$. The tailoring of the local flow rate is carried out through the microvalve opening and closing, that depends on its own temperature.

For each of these designs and for the regular microchannels, a spatial and time dependent integration of steady state results has been used to determine the temperature distribution obtained along the heat load scenarios considered, using the fact that spreading between cells can be considered insignificant in our

cooling device because the microvalve behaviour allow the microfluidic cell thermal resistances to be tailored to the local heat extraction need and so to provide a homogeneous temperature profile. This assumption is based on a previous study by Sharma et al. [25]. Indeed, the authors highlighted that the isothermal condition is one of the conditions that allow assessing the thermal behaviour through a one dimensional modelling approach.

4.1 Inputs and case study

In this analysis, the flow rate of each microvalve is defined from the quasi-steady flow rate, Q_{max} , required to respect the temperature limits under maximum heat load. This value is used as an input for the temperature dependent flow rate, defined as follows:

$$Q(T) = Q_{max} * K(T) \quad (\text{Eq. 1})$$

where $K(T)$ defines the linear opening factor of the microvalve.

The linear microvalve starts to open at a control value, 80°C, and it is completely open at 90°C. Below the control value, a residual flow rate (1% of Q_{max}) enters the cooling cell, since this kind of microvalve can't close completely. This general trend of valve function corresponds to the results obtained previously by McCarthy et al. [24]. The impact of the microvalve response function is further studied by Azarkish et al. [23].

Here it is considered the case of a virtual 20 x 20 mm² System on Chip (SoC) holding interesting features in terms of dynamical behaviour. Its characteristics are inspired from realistic products, for instance multimedia processing engines for set top box applications. Such complex circuits are typically composed of diverse blocks including CPU, GPU, Graphic accelerators, memories, power management unit, etc. These architectures allow for a versatile use of the chips in a multitude of applications such as gaming, web browsing, high definition video decoding for instance. Depending on the type and number of applications running simultaneously on the chip, the power request will exhibit both spatial and temporal evolutions.

In order to study the dynamical performance of the microfluidics cell array, the power profile over the time is based on realistic power dissipation profiles of commercial SoC during web browsing sessions. Power peaks corresponds to GPU, CPU and graphic accelerators requests, while the other blocks of the circuit are considered as a static background.

The boundary condition that varies with respect to the steady state study is the heat flux, which becomes time dependent. It includes four peripheral zones with heat flux of 60 W/cm², four central zones with 80 W/cm², eight hotspots zones with 300 W/cm² and all rounded by background areas with 20 W/cm² (Figure 7a). Heat load is mapped onto cell array (Figure 7b).

Figure 7: Relationship between the heat load map and the microfluidic cell array

The different constituting blocks have a fluctuating power dissipation, which makes the power map change over time. The time dependence of the heat loads is described in Figure 8. Four different heat load maps occur during the 5 minutes time period being captured as t_1 , t_2 , t_3 and t_4 in Figure 8.

Figure 8: Heat loads scenario

4.2 Behavior of the cooling devices under different heat load scenarios

4.2.1 Conventional microchannels

A conventional microchannels device has been modeled in order to provide a baseline to compare the improvements provided by the microfluidic cell cooling configurations. These models are formed by parallel microchannels of 300 μm high, 200 μm width and 100 μm of wall thickness. The parallel microchannels span the entire device width (20 mm). The inlet temperature is equal to the one imposed in the 3 microfluidic cells models and the heat flux is assessed to provide, at each instant of the 5 minutes time period, the total dissipated heat defined in the heat load scenario. The flow rate is adjusted to maintain the chip temperature below 100°C. As conventional microchannel devices don't have the capacity to tailor their flow rate to variable heat flux scenarios, the flow rate applied is constant all along the 5 minutes time period.

4.2.2 Maximum temperature

For the 3 microfluidic cell models, the chip maximum temperature is maintained below 100°C (Figure 9). When the heat flux decreases, microvalves close and the flow rates go down reducing the pumping power and avoiding cells overcooling. For the microchannel models, the flow rate is constant. As a consequence, the temperature decreases down to lower values compared to the microfluidic cells when the heat flux decreases. When measuring the performance of the cooling device through the pumping power, these lower temperatures are not required and correspond to additional pumping power.

However, some electronic applications need to work at lower temperatures. In this case, the lower thermal resistances of the microfluidic cells cooling devices allow providing, for a fixed pumping power, lower chip temperatures than microchannel cooling devices.

Figure 9: Chip maximum temperature over time.

4.2.3 Flow rate

The time dependent total flow rates of the microfluidic cooling devices are represented in Figure 10. The flow rate is, at t_3 , concentrated in the hotspot cells, so the microvalve effectively provides the flow rate only where needed. It is noticed that MC0, due to its poor heat extraction capacity, needs nearly two times the flow rate of the other cells to reach the temperature limit for the high heat flux condition (t_3).

Figure 10: Total flow rate along the time period

In the case of microchannels, the flow rate can't be tailored to the time dependent heat flux distribution. As a consequence, the flow rate is constant in time and corresponds to the flow rate needed to reach the temperature limitations when submitted to the highest heat rate.

Furthermore, the total flow rate of the cooling device is, except at t_3 , lower for the microfluidic cells than for the conventional microchannels.

The average flow rate, over the 5 minutes time period, for the MC0, MC6 and MC6T configurations is, respectively, 64.7%, 56.9% and 57.5% of the flow rates required with conventional microchannels.

4.2.4 Pressure loss

To evaluate the pumping power for a complete cell, the valve pressure drop should be included. By design, the microvalves will close to restrict the flow rate in cooler zones, inducing an additional pressure drop across that cell. Since all the cells have a common inlet and outlet, they will effectively be subjected to the same pressure difference. In the proposed cooling devices, the valves provide the missing pressure drop that once added to the cell pressure drop will equate the applied pressure difference. The required pressure difference is hence defined by the cell with the highest pressure drop.

Although the pressure drop along the distribution channels is not the subject of this study, it has been assessed. It represents, for the MC6T model and in the worst boundary conditions (t_3 , highest flow rate), an additional pressure drop of 2250 Pa for distribution channels heights of 300 microns, suggesting that it should be considered in eventual array designs.

The microfluidic cells present a lower pressure drop than the microchannel. For identical flow rate, MC0 generates less pressure drop than the other cells. But MC0 needs a higher flow rate to reach the temperature limitation, and its maximum pressure drop for the high heat flux conditions is higher than the ones for MC6 and MC6T. The pressures drop for the conventional microchannels are nearly constant given the constant flow rate. The slight variations are due to a decrease in viscosity at higher temperature.

Assuming that the pump provides a constant pressure over time, based on the cell with maximum pressure drop, we find that the pressure drops for MC0, MC6 and MC6T are respectively 55.5%, 19.5% and 19.0% of the pressure drop in conventional microchannels.

4.2.5 Pumping power

The pumping power of the cooling devices, assessed with a constant pressure over time (Figure 11), show similar trends than the flow rate.

Figure 11: Pumping power of the whole cooling device along the time period

For a similar performance (temperature limitation) in comparable boundary conditions, the MC0, MC6 and MC6T microfluidic cells pumping power, here expressed as the energy needed for pumping along the 5 minutes time period is, respectively, 35.9%, 11.1% and 10.9% of the conventional microchannels.

4.3 Overall performance

As the pumping power and the temperature uniformity are the main performance indicators, the results obtained for the microfluidic cell designs considered in this study are presented for each of the instants corresponding to the 4 heat load maps of the 5 minutes time period (Figure 12).

The pumping performance is expressed through the ratio between the pumping power and the chip power integrated along the 5 minutes time period. In order to be able to compare the temperature uniformity results with studies which uses various levels of heat flux non-uniformity, a normalized value, ΔT_q , is used (Eq. 2) [9].

$$\Delta T_q = \frac{\Delta T_{s,max}}{\left(\frac{q''_{hs}}{q''_{bg}} \right)} \quad (\text{Eq. 2})$$

where q''_{hs} and q''_{bg} are the heat fluxes applied at the hotspot and background zones, respectively.

Figure 12. Zoom in to cells results

The average pumping power along the 5 minutes time period for MC0, MC6 and MC6T are widely below the accepted criteria for similar applications ($P_{pump} < 1\% P_{chip}$, [10]). MC6 and MC6T configurations present a ratio P_{pump}/P_{chip} between $0.80 \cdot 10^{-3} \%$ to $0.65 \cdot 10^{-3} \%$ depending on heat flux conditions.

On the other hand, the normalized difference of temperature (ΔT_q) of all the cells is below 1°C . For MC6, the typical microchannel temperature trend along the flow path generates a higher temperature difference. For MC0, when hotspots are active, the high flow rates needed to keep the temperature below 100°C , generate both relatively high pumping power and high normalized temperature difference (0.9°C). For lower heat loads (t_1 and t_2), the normalized temperature difference decreases down to 0.3°C .

When compared to previous studies, a significant reduction of the pumping power is observed (Figure 13).

The normalized values of temperature of MC6T is 0.46, below 0.49°C that represents the lowest of the compared studies.

Figure 13. Comparison of the overall pumping performance with previous studies

5. Conclusions

In this paper, a novel concept for cooling integrated chips in an energy-efficient way is numerically demonstrated under non-uniform and time-dependent heat load scenarios. The coolant is distributed towards an array of microfluidic cells where each cell's self-adaptive microvalve provides the required coolant flow rate as a function of its own temperature. Three internal geometries of the microfluidic cell are assessed. This assessment is made with the worth boundary conditions, a maximum chip temperature allowed of 100 °C with hotspots of 300 W/cm² and a coolant inlet temperature of 50°C.

Relevant temperature homogeneity and low pumping powers, which improve those of previous studies, are achieved by the studied configurations. The tailored microchannel device (MC6T) reaches, due its internal geometry, a temperature uniformity of 4°C with a pumping power lower than 0.001 % of the chip power.

For identical performance (temperature limitation) and comparable boundary conditions, the pumping power of the microfluidic cell matrix with the best internal geometry (MC6T) reduces the energy needed for pumping along the 5 minutes time period to 10.9 % of microchannel configuration.

This work confirms the interest and capacity of the microfluidic cell array cooling strategy for improving the hotspot targeted cooling performance both in terms of temperature uniformity and pumping power.

Acknowledgement

The research leading to these results has been performed within the STREAMS project and received funding from the European Community's Horizon 2020 program under Grant Agreement N° 688564.

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