Proceedings of the ASME 2013 Heat Transfer Summer Conference
HT2013
July 14-19, 2013, Minneapolis, MN, USA

HT2013-17311

STRIP-AND-ZONE MICRO-CHANNEL LIQUID COOLING OF INTEGRATED CIRCUITS CHIPS WITH NON-UNIFORM POWER DISTRIBUTIONS

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ABSTRACT

For a high-power integrated circuit (IC), it is desirable to cool with the liquid micro-channels. However, the non-uniform power distribution of the IC is a great challenge. In this paper, the strip-and-zone strategy is presented. First, the optimal channel-width assuming a uniform power distribution of the total chip power is considered as a nominal situation. Then, according to the distribution of the power density of the power blocks on chip, the micro-channels are divided into several parallel strips with various zones in these strips. A further optimization of the channel-width of each zone in the strips shall be made that a higher heat transfer coefficient will occur in the zones of higher heat flux, while the strips of higher total power will have same or less flow resistances. As a result, under the same pressure drop among all the strips, same or more flow will occur at the strips of higher total power and the maximum temperature on the chip is reduced. Illustration of this strip-and-zone micro-channel liquid cooling design is provided through a design case of an IC chip with realistic power distribution. Comparing with the same chip at the air cooling and at the micro-channel cooling with the nominal channel-width, the chip at strip-and-zone micro-channel liquid cooling yields the lowest surface temperature as expected.

NOMENCLATURE

C_p	specific heat capacity of coolant, $\mathrm{J/kg \cdot K}$
D_h	hydraulic diameter of channel， m
h	heat transfer coefficient, $\mathrm{W/m^2 \cdot K}$
H_c	channel height, m
k_f	thermal conductivity of fin, $\mathrm{W/m^2 \cdot K}$
K_{cl}	thermal conductivity of coolant, $\mathrm{W/m^2 \cdot K}$
L	channel length, m
Nu	Nusselt number
Q_T	power dissipated in stack
Re	Reynolds number
Po	Poiseulle number
S	fin thickness, m
T_{in}	inlet average temperature of coolant, K
T_{cb}	channel base temperature, K
V	mean velocity of coolant, $\mathrm{m/s}$
W	total width, m

Greek Symbols

α	channel aspect ratio
δ	channel width, m
ρ	density of coolant, $\mathrm{kg/m^3}$
μ	dynamics viscosity of coolant, $\mathrm{kg/m \cdot s}$
η	fin efficiency

1. INTRODUCTION

In recent years, as the process technology in semiconductor industry advanced to sub-32 nm to fulfill the increasing demands of high-performance computing and massive data communications, the challenges of the integrated circuits chips architecture are becoming increasingly critical, including the aggregating density of on-chip wiring, interconnection and transistors to match the corresponding performance [1]. This unavoidably leads the fast growing demands of on-chip power supply. It is estimated that the power density of microprocessors has doubled every three years [2, 3]. Since the energy consumed by the IC chips will be eventually converted into the heat, thus the corresponding growth of the heat flux has significantly impacted the IC chips in terms of system reliability and packaging costs. In fact, the packaging cost has occupied an impressive fraction of the total cost. For high performance processors today, the thermal management solution costs 1–3 USD or more per watt of heat dissipated [2, 4]. Thus, thermal management becomes one of the major challenges to the IC design in sub-32 nm IC technologies [5]. An appropriate thermal management method is necessary to enable the long term stability while maintaining the proper functioning of the electronic system [6].

Previously, in the semiconductor industry, the most commonly used cooling technique for IC chips is air cooling due to its convenience and industrial maturity. However, with the increase of heat flux dissipation, the traditional air cooling solution is not sufficient anymore. When heat fluxes go beyond $100\,\mathrm{W/cm}^2$, air cooling methods have become inadequate for most applications [6]. Thus, novel cooling technologies are required. Among all the potential solutions, the micro-channel liquid cooling is proved to have the advantages of high heat transfer rate as well as compact size. Micro-channel liquid cooling system pumps the coolant through the channels to cool the electronic chips. It can be mounted on or etched at the back of the chips to provide a large surface area and high heat transfer coefficient for convective cooling [7]. Due to the high heat transfer surface per unit volume, the high heat flux can be effectively dissipated [8, 9].After the first concept proposed by Tuckerman and Pease in 1981, substantial research has been conducted on this technology [10].

The micro-channel cooling could utilize single phase liquid cooling or two phase evaporative cooling. Two phase cooling means the phase transition occurring within the flow paths where the liquid vaporizes. Although a large amount of latent heat during the phase changing can be utilized for the two phase cooling, several problems create vast difficulty on practical applications, including the flow-instability in the form of flow fluctuations caused by growing bubbles, large pumping pressure requirement, and the significant flow mal-distribution [11, 12]. As a consequence, the single phase micro-channel cooling shows its advantage of simplicity and reliability. Similarly, for high performance applications such as 3D stacked ICs, the single phase micro-channel liquid cooling becomes a good choice in the development.

In the design of a micro-channel system, the channel configuration is the most critical part. Substantial research has been conducted for single phase liquid cooling. Recently, a systematical design and optimization of micro-channel heat sink for the 3D stacked IC has been performed with explicit equations for the optimal design [7]. However, the design is based upon the assumption that the heat is generated uniformly over the whole chip. Although it is not a best solution for non-uniformly heated chips, this design optimization provides a fairly good starting point for the present study of non-uniformly heated chips.

In the real applications, the heat generated on the chip is not uniform. The inherent spatial non-uniformity of the power distribution on the chip makes localized heating and leads to hot spots. The hot spots will degrade the functionality of circuits and creating thermal stress due to non-uniform thermal expansion [8]. Particularly, a severe damage of carrier mobility and escalated leakage power might be caused by local high temperature hot-spots [13]. Therefore, the present microprocessor design and modeling require a comprehensive consideration of non-uniform power and temperature distributions and their effects to the IC functions [14-17]. Specifically, in the design of a micro-channel liquid cooling system, assuming a uniform power distribution will easily result to severe hot spot problems. Hence the new design of micro-channel systems must give particular attention to the non-uniform power sources.

In this paper, a new approach of micro-channel system design for the cooling of non-uniformly heated IC chips is presented. An IC chip with realistic power distribution is demonstrated as a sample design case to utilize this new approach. Comparisons with the typical air cooling technique and optimized uniform-size micro-channel system with assumption of uniform power distribution [7] are also provided to illustrate the effectiveness of the new design approach.

2. DESIGN STRATEGY

The regular schematic of the micro-channel liquid cooling is illustrated in Fig. 1. However, to manage the highly non-uniform heating of a realistic IC chip, the strategy of strip-and-zone micro-channel liquid cooling could be utilized for refined geometric optimization. The rationale of this strip-and-zone design contains the following steps. 1) The direction of the flow is first determined by putting the edge of highest power at the flow inlet, according to the positions of the power blocks on the chip. 2) Then the optimal channel-width assuming a uniform power distribution of the total chip power is evaluated as a nominal situation. 3) According to the distribution of the power blocks on the chip, the micro-channels are divided into several parallel strips. Furthermore, in each strip, according to the locations of power blocks, various zones are assigned and each zone could have a very different average power density. 4) The channel widths in the zones are determined that the zones of higher heat fluxes will have narrower channels than the nominal size, which induce higher convective heat transfer. However, it could also increase the flow resistance. Thus, within the same strip, the other zones of lower heat fluxes shall be assigned with wider channels to maintain a similar flow resistance of the strip as before. 5) Finally, the channel widths of zones in each strip shall be fine tuned that the hot spot region will have a higher heat transfer coefficient and the strip of higher total power will have a same or less flow resistance. Under the same pressure drop among all the strips, same or more flow will occur at the strips of higher power, and the maximum temperature on chip is also reduced. The detailed design process will be described in the following sections.

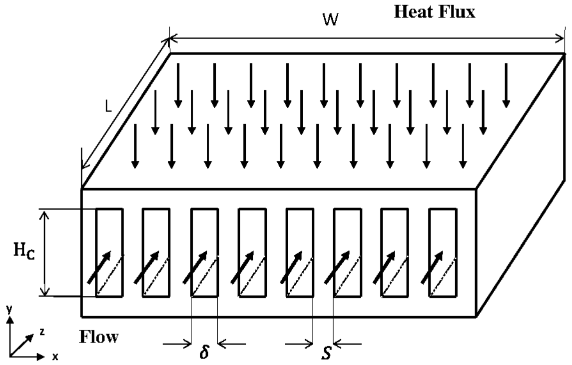

Figure.1 Micro-channel schematic

2.1 Direction of the flow

The first step of the design process is to determine the entrance and exit directions of the micro-channel system. Since the junction temperature is more influenced by the local heat flux, it is desirable to make the cooling liquid enters from the side where the highest heat flux is located. At this situation, the lowest bulk temperature of the cooling liquid at entrance can be fully utilized for the cooling of the hottest spots.

2.2 Division into strips

After determine the direction of the flow, the next step is to divide the whole IC chip into different "parallel strips" so that different widths of micro channels could be assigned in different strips. The reason why this division of parallel strips is necessary is that the IC is non-uniformly heated and the cooling requirements will also be non-uniform on the chip. As a result, variable channel widths shall be applied regionally. Consider a micro-channel system contains many different islands, which have different channel sizes. Without dividing into strips, due to the high flow resistance at the island where channels are narrow, less amount of coolant would pass through due to the flow by-passing. In consequence, the island requiring most cooling would have the least flow, which could cause the hot spot temperature to increase. The location of the strip boundary should be planned according to the distribution of the power blocks on the IC to cover major territories of the power blocks.

2.3 Division into zones

Since the power distribution in a strip could be still highly non-uniform, different channel widths should be assigned to different regions of different heat fluxes. Thus, variable micro-channel widths will be assigned within each strip in the form of zones. In each zone, the widths of channels are the same. The length of zones shall be determined according to the distribution of the power blocks. It is reasonable to group the power blocks of similar range of heat fluxes together as a zone, where the same micro-channel cooling will be applied to this zone.

2.4 Gap between zones

When flow passes from one zone to the next zone of a different channel width, an open gap between zones for flow redistribution is required. The flow will experience an expansion of pressure recovery and then a contraction of pressure loss. The net effect is an increase of the overall pressure drop. As a result, the total number of zones in a strip should be limited, which is in opposite to the needs of many zones to accommodate various power blocks in the strip. To balance these two contradictory requirements, the number of zones in each strip should be appropriately limited.

2.5 Channel dimensions

Finally, after all the partitioning is set, the most critical design decision is the channel dimensions in the system. Because the channel height is normally pre-determined by external spatial requirements, the channel dimensions design is mainly consisted of two parts: channel wall thickness and channel width. Typically, in the micro-channel design, if the channel width is fixed, the wall thickness of the channel is an important parameter since it is directly related to the total number of the micro-channels we can have in a limited overall width. Therefore, the wall thickness influences the total surface areas of the channels, which play a significant role in determining the rate of cooling. In general, the narrower the channel wall the larger the total surface area. But if the wall is too narrow, the fin heat transfer along the wall is reduced and the fin efficiency becomes low. Furthermore, for the application in 3D IC chips, to leave enough room for through silicon via (TSV) to go through each IC layer, the lower limit of wall thickness should be considered according to the given channel height, the aspect ratio of TSV, and the required number of TSV per unit area. Hence, a properly-chosen wall-thickness of the micro-channels shall be selected.

After determining the wall thickness, the channel width in each zone should be determined. In general, a small channel width will ensure a large surface area per unit volume and high heat transfer coefficient in the channels. As is illustrated in Fig. 1 for the dimensions, the heat transfer coefficient of a micro-channel at laminar flow is generally [7]

$$h = \frac{NuK_{cl}}{D_h} \quad (1)$$

The hydraulic diameter of the rectangular channels is given by

$$D_h = \frac{2\delta H_c}{\delta + H_c} \qquad (2)$$

The Nusselt number, with the rectilinear correlation [18], is given by

$$Nu = 8.235\,(1 - 2.042\alpha + 3.085\alpha^2 + 2.477\alpha^3 + 1.058a^4 - 0.186\alpha^5) \qquad (3)$$

where the α is the aspect ratio of the channel,. It is the ratio of the shorter side to the longer side. It is given by $\alpha = \frac{\delta}{H_c}$ if $\delta < H_c$ or by $\alpha = \frac{H_c}{\delta}$ if $H_c < \delta$, such that in all cases $\alpha < 1$.

From Eq. (1) to Eq. (3), it can be evaluated that a smaller channel width results to corresponding smaller hydraulic diameter, when the channel height is fixed. Since the Nusselt number in this case can be approximately treated as a constant, thus, the decreasing hydraulic diameter will eventually increase the heat transfer coefficient of the micro-channel.

Therefore, for a zone with a higher power density, the channel width should be smaller. On the other hand, for a zone with a lower power density, the channel width could be larger.

It is important to recognize that if the power distribution in a strip is assumed to be uniform; an optimal channel width exists, which gives a minimum junction temperature due to achieving the minimum channel-base temperature. In this paper, this optimal channel width is chosen as a nominal size. It is evaluated as [7]

$$T_{cb} - T_{in} = \left(\frac{Q_T}{K_{cl} LW}\right) \frac{\delta H_c (s+\delta)}{Nu\left(H_c + \delta\right)^2 \eta} + \left(\frac{Q_T \mu L}{16\rho W \Delta p C_P}\right) \frac{Po\left(H_c + \delta\right)^2 (s+\delta)}{(\delta H_c)^3} \qquad (4)$$

where the Poiseulle number under the rectilinear correlation [19] is

$$Po = 96 * (1 - 1.353\alpha + 1.9467\alpha^2 - 1.7012\alpha^3 + 0.9564\alpha^4 - 0.2537\alpha^5) \qquad (5)$$

In a strip, if some zones have smaller channel widths than this nominal size, it is important to assure the other zones have channel widths larger than this nominal size. Otherwise, under the given pressure drop between the inlet and exit, the flow rate in this strip will be reduced because the total flow resistance will be larger than the strip assigned with the nominal channel-width.

Furthermore, for a strip of a higher total power than other strips, the higher power strip should have a larger flow rate that its exit temperature is not too much higher than the other lower power strips. This will make the best use of the coolant among the strips. For the same reason, the average channel width in a strip of low total power can be made smaller than the nominal channel width that less flow rate occurs in this low power strip and exit temperature is similar to other strips.

In summary, the chip is divided into strips and each strip is divided into zones according to its power map. In a strip, the optimal channel size [7] can be considered as a nominal starting point. The channel widths of the zones shall be adjusted iteratively that the higher heat transfer could be achieved in the zones of higher heat fluxes, and the exit liquid temperatures of different strips are similar.

3. MODELING

3.1 Configuration

The software we have used in the modeling is COMSOL Multi-physics. It is an engineering design software using finite element analysis for the modeling and especially effective for coupled phenomena. In this study, the 4.2a version of COMSOL Multiphysics has been used. The present objective is to model the micro-channel cooling of non-uniformly heated IC chips following the design strategy mentioned previously. Also, comparisons are made with the typical air cooling condition and the micro-channel system with uniform channel width, which has the optimal channel width assuming the total power is uniformly applied.

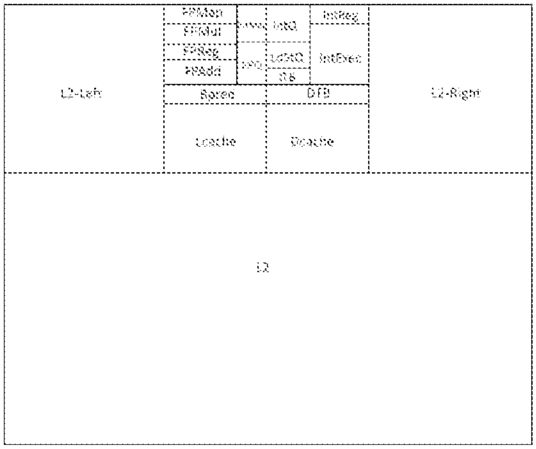

Figure.2 Floor plan of the Compaq alpha 21364

To simulate the non-uniformly heated IC, a typical chip is adopted from the previous work carried out by Kevin Skadron, etc. [14], in which the thermal performance and the hotspot issues of Compaq Alpha 21364 chip are analyzed with air cooling technique. Figure 2 is the floor plan of the Compaq Alpha 21364, which is a chip with length and width both 1.6 cm and a total power of 60 W. In this study, to suit for the future high performance chip applications, a factor 5 is multiplied to the power of each power block in the floor plan. Therefore the average heat flux on the chip rises from $23\,W/cm^2$ to $110\,W/cm^2$ while the heat flux of the hottest power block reaches over $2100\,W/cm^2$. Figure 3 is the details of its heat flux distribution. Based on the design strategy discussed previously and the heat flux distribution map in Fig. 3, the map of the parallel strips and zones in present modeling is determined as shown in Fig. 4. The blank regions between different zones are gap regions in Fig. 4. Since the power of this chip is very high, substantial liquid flow rate is needed for proper cooling. In this study, a pressure drop over the chip, from liquid entrance to exit, is set at 2 atm to meet the severe requirements of heat dissipation.

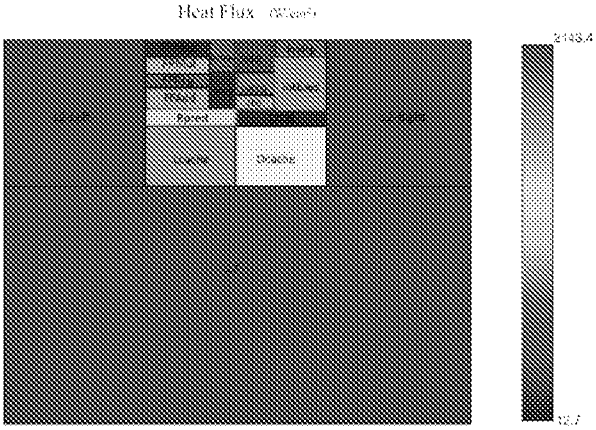

Figure.3 Heat flux distribution map

To perform the analysis, several assumptions are made. The power distribution is applied on the top surface of the chip as shown in Fig. 1. This is because the thermal resistance between IC junctions to the micro-channels is determined based upon the packaging and it is easily obtainable. In present modeling of the micro-channels, the power distribution of the IC chip is treated as a thermal boundary condition. The coolant is water and the fluid is kept in single phase liquid without phase change. Since the Reynolds number in the micro-channel is low, the flow is assumed to be laminar with negligible wall roughness effect. Moreover, since the total thickness of the chip is much less than its width or length, the lateral heat spread is little. Thus, the heat transfer between adjacent strips is negligible, which allows for the simulation of a single strip as an independent one with insulation boundary conditions at its edges. Also, since the numerical modeling includes the configuration of each channel in detail, this simplification of modeling only one strip at a time reduces the computation requirement to a more effective level. In opposite, in the simulation of air cooling technique, a complete package of the IC chip with heat spreader and heat sink can be properly modeled easily because there is no detailed micro-channel structures to be considered.

When comparing the case of uniform-size channels to the case of variable-size channels, both temperature scales are set to be the same for convenience. For the simulation of micro-channel system, the inlet liquid temperature is set as 20℃, while in the air cooling case the ambient air temperature is also set at 20℃. In this manner, a convincible comparison can be made on the temperature distributions.

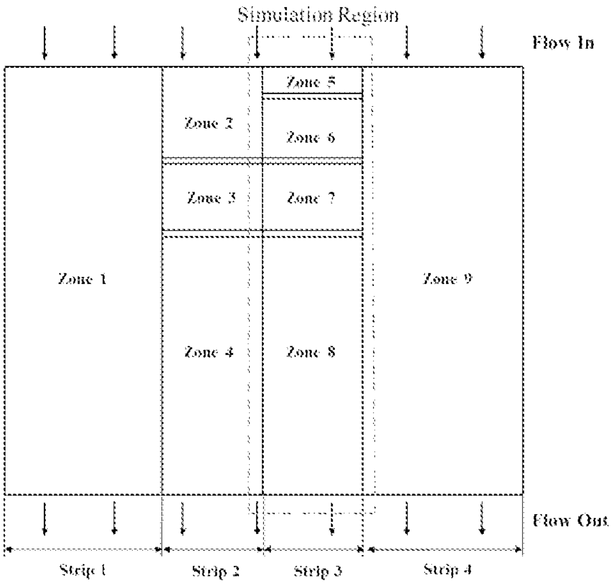

Figure.4 Strips and zones arrangement

3.2 Mesh setting

Meshes are carefully set up for the three cases in the present study. For the air cooling case, a default mesh automatically generated by COMSOL Multiphysics is applied, and a level of "Fine" mesh is chosen due to the simplicity of the physics. And the total mesh number is about 1.5 million. However, for the uniform channel and variable size channel cases, structured meshes are used. And structured meshes fit the straight, rectangular micro-channels very well. The total mesh numbers of these two cases are both about 3 million for the hottest strip.

3.3 Boundary conditions

Appropriate boundary conditions are selected. For the cases with micro-channel liquid cooling, the non-uniform power distribution of the chip is applied on the top surface of the strip, while the remaining out-facing surfaces are thermally insolated. The entrance temperature of the flow is fixed at 20℃. To preserve the total 2 atm pressure drop over the strip, the pressure boundaries are 3 atm at the entrance and 1 atm at the exit of the micro-channel system. For the air cooling case, the non-uniform heat flux is also applied on the top surface of the chip; however, at the bottom surface of the heat sink, a convective cooling boundary condition are applied with a given heat transfer coefficient and ambient temperature at 20℃.

4. RESULTS AND DISCUSSION

As discussed in the section of design strategy, the design process of the micro-channel system for cooling of non-uniformly heated IC chip is carried out in two steps. First, from the previous research conducted by the Varun [7], the optimal channel width assuming uniform heating can be obtained when the total heat flux, channel height and wall thickness are given. Then, for non-uniformly heated condition, use this optimal channel size as the nominal width, reducing or enlarging the channel widths in each zone according to the variation of local heat fluxes to conduct the optimization.

From the paper [7], the minimum channel wall thickness can be determined to give acceptable fin efficiency, which is about 30 micron for the present case. However, for the future applications in 3D ICs, sufficient wall thickness is critical for chip architecture because enough wall thickness is needed for the TSV to deliver the signals and power. Considering the state-of-art technology in the semiconductor industry, 60 micron wall thickness is selected in this study. For the channel height, in principle, deep channel is desirable because it provides large surface area for convective cooling; however, the maximum channel height is constrained by the requirements of the TSV. The typical aspect ratio of TSV is limited to 5-7. Hence, the upper bound of channel height is associated with the required number of TSV per unit area, the radius of the TSV and the feasible aspect ratio. Considering a practical TSV radius of 50 micron and aspect ratio of 5, the total height of TSV is 250 micron. Leaving 50 micron each for the upper and bottom covers of the micro-channel, the channel height in this study is, therefore, set to be 150 micron.

After the channel height and channel wall thickness are determined, following Eq. (4), the optimized channel width assuming uniform heating is calculated to be 64 micron. The next step is applying this nominal channel width to the non-uniform heating case as a starting point of further adjustments. In this study, as shown in Fig. 4, the strip containing the highest power density is considered as example. Hence, the strip 3 is the simulation region in this study. Since the strip is 0.31 cm wide and 1.6 cm long, total 25 straight nominal micro-channels can be placed in this strip. Figure 5 shows the surface temperature map on the top surface of the chip for this strip. Due to the non-uniform power distribution, hot spots are clear. This hot spot distribution is fairly much similar to the heat flux distribution map in Fig. 3, but the effect of the lower temperature of liquid at the entrance is apparent.

Then, further optimization is made to address the non-uniform heating. According to the power distribution and the hot spots in the straight channel case, the strip is divided into four different zones. As shown in Fig. 2 and Fig. 4, at the entrance, the power block IntReg (the integer register) is assigned as the first zone (zone 5). A narrower channel width of 45 micron is applied in this zone to increase the cooling effects for this very high heat flux, and 30 micro-channels are present in this zone. The region starting from the bottom of IntReg to the bottom of the power block DTB (data translation buffer) is set to be the second zone (zone 6). In this zone, the original width of 64 micron is maintained because the heat flux of this zone is not too high but the liquid temperature is still low, leaving a total of 25 channels placed in the zone. Then, the Dcache block is treated as the third zone (zone 7), where 45 micron channel-width is needed to lower the hot spot temperature in this region due to the modest heat flux but high liquid temperature. As a result, 30 micro-channels are arranged in this zone. The remaining area is the fourth zone (zone 8). Because the heat flux in this region is fairly low, the heat removal will not be critical. However, since the first and third zone has a reduced channel width and caused larger pressure drop, this fourth zone should have a much reduced pressure drop to assure the total flow rate of this strip is not been reduced. Therefore, assigning a larger channel width is appropriate. In this study, 250 micron is applied to be the channel width of the fourth zone. As a result, there are only 10 channels in the fourth zone. Figure 6 indicates the surface temperature distribution of this strip with four zones assigned. Although the temperature map is similar to that of Fig. 5, a careful comparison shows that the maximum temperature of chip is reduced.

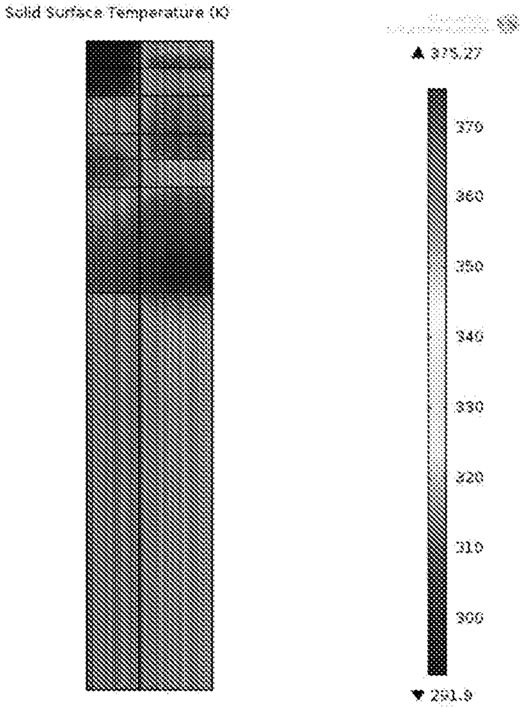

Figure.5 Surface temperature of uniform size micro-channel system

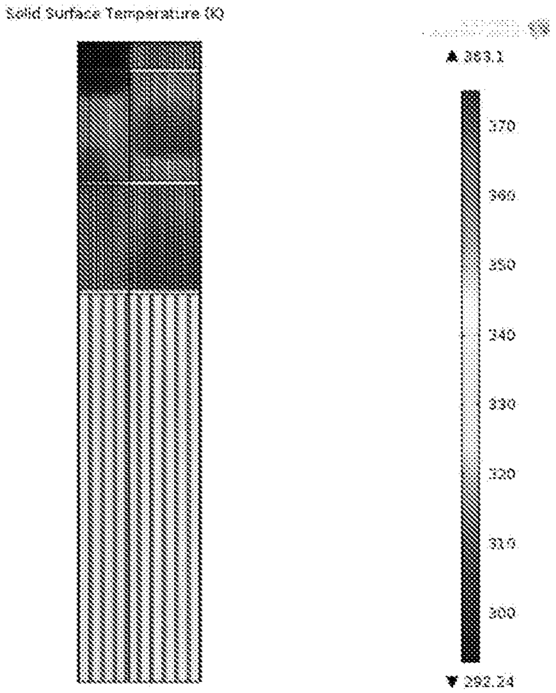

Figure.6 Surface temperature of variable size micro-channel system

As a comparison, the air cooling of the same chip is also modeled. In this case, a complete package of IC chip, heat spreader and convective air cooling heat sink is modeled. The thickness of the chip is 0.15 mm. The dimension of heat spreader is 3 cm wide, 3 cm long and 1 mm thick while the heat sink is 6 cm wide, 6 cm long and 6.9 mm thick. An equivalent heat transfer coefficient of 2778 $\mathrm{W/(k \cdot m^2)}$ is given to the air heat sink. The result of chip surface temperature map is shown in Fig. 7 for overall view and Fig. 8 for zoom-in view.

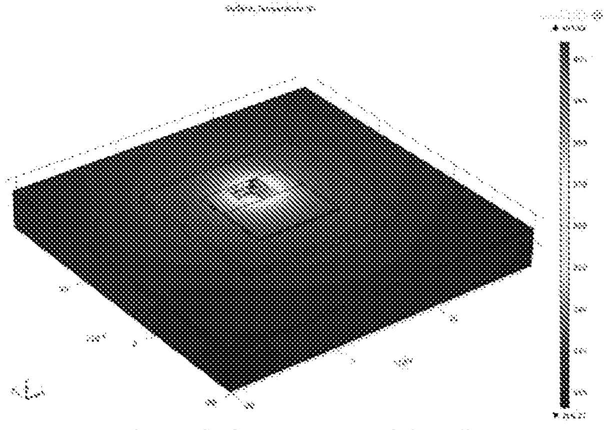

Figure.7 Surface temperature of air cooling

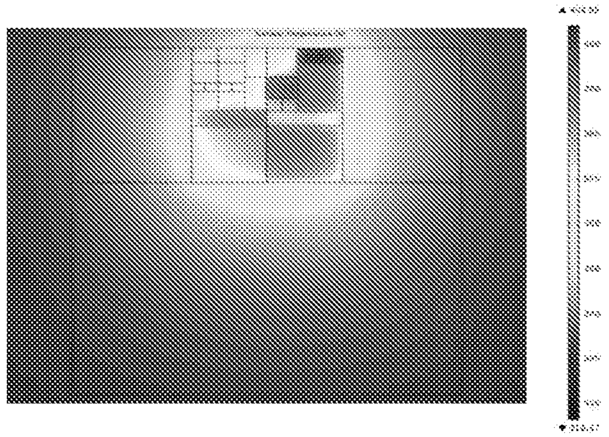

Figure.8 Surface temperature of air cooling (zoom in)

To summarize the comparison, Table 1 demonstrates the quantitative improvements among the three cases. Comparing the highest temperature of these three cases, it shows that the temperature rise from ambient of air cooling case is 110.87 ℃, the temperature rises of micro-channel with the uniform optimal channel-width and the micro-channel with variable size channel system are 82.12 ℃ and 69.95 ℃ respectively. About 37% improvement from air cooling technique has been achieved by utilizing the design approach in this paper. If the size of the cooling system is considered, the benefit of the micro-channel is very significant since the space occupied by the heat sink and heat spreader in air cooling is eliminated. Furthermore, comparing with the straight uniform size micro-channel case, an approximate 14% achievement is accomplished by the variable size channel design without scarifying the total pressure drop. For detailed comparison, from the case of straight uniform size micro-channel cooling to the case of variable size micro-channel cooling, the mass flow rate maintains at 1.1 g/s and the average heat transfer coefficients of the hot spot regions (zone 5 and zone 7) increase from 21,8624 and 75,916 $\mathrm{W/(m^2 \cdot {}^\circ C)}$ to 320,921 and 153,969 $\mathrm{W/(m^2 \cdot {}^\circ C)}$ respectively. From the analysis, it is found that the strip-and-zone approach presented in this paper is a more efficient way to utilize the potential of the micro-channels with respect to the local heat dissipation requirement. It is important to point out that only the single phase liquid cooling is considered in this paper. Due to the temperature assigned to the ambient and fluid flow inlet, the highest temperature rise at exit for case of straight uniform size micro-channel cooling is slightly higher than the boiling point of water. However, for purpose of comparison in this sample case, the boiling is not considered.

Table 1 Comparison summary

Results	Temperature Rise (℃)	Maximum Temperature (℃)	Improvement
Air Cooling	110.87	130.87	0%
Non-uniform heating with uniform channel width (64 μm)	82.12	102.12	25.93%
Non-uniform heating with variable channel width (45-64-45-250 μm)	69.65	89.95	36.91%

It is also interesting to examine the detailed thermal phenomena. Figure 8 shows the effective diffusion of heat laterally along the plane of the chip due to the presence of the heat spreader between the chip and the heat sink. Comparing the Fig. 5 with the Fig. 8, it is observable that although the micro-channel heat sink reduced the temperature everywhere, the heat spreading on the chip is very limited. Since the micro-channels are attached on the bottom of the chip with only approximately 50 micron silicon substrate between the integrated circuit and the micro-channels, there is no effective presence of a heat spreader. Without the heat spreader, although the liquid in channels has a significant heat dissipation capability, the removal of heat from hot spots is mainly relying upon the channel cooling than the heat spreading. Comparing the surface temperatures of the two micro-channel cases in Figures 6 and 5, in the variable size channel system, the temperature is lower and the distribution is smoother than in the straight channel case mainly due to the more effective liquid cooling at zones of higher heat fluxes.

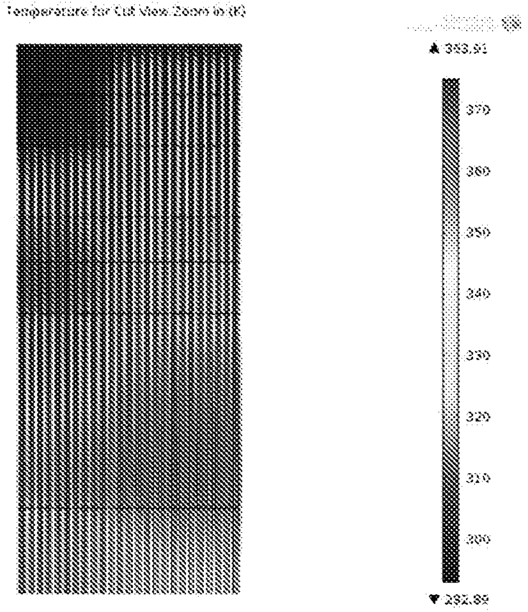

Figure.9 Longitudinal section of uniform size micro-channel system (zoom in)

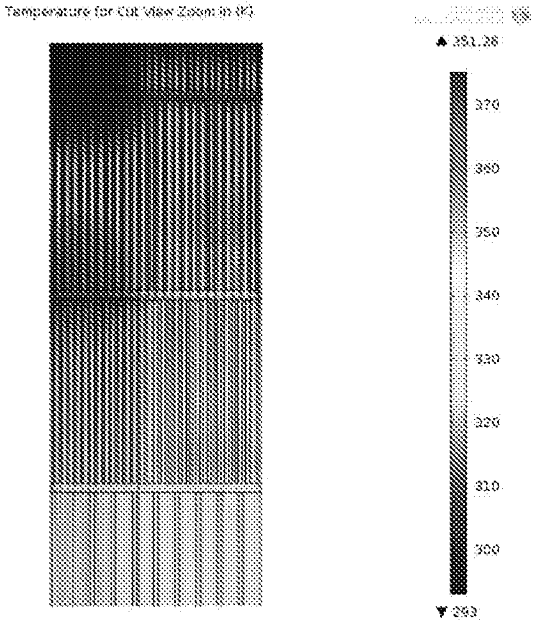

Figure.10 Longitudinal section of variable size micro-channel system (zoom in)

For a better insight of the heat transfer processes, Fig. 9 and Fig. 10 are presented for the longitudinal sections of the straight uniform size micro-channel cooling and the variable size micro-channel cooling in zoom-in views correspondingly. Comparing the uniform size micro-channel system to the variable size micro-channel system, the averaged fluid exit temperature increases from 326 ℃ to 332 ℃, which indicates that more amount of heat is removed from the chip in variable channel-width case. Furthermore, it is also desirable to observe the local heat transfer phenomena. As shown in the Fig. 9, the wall temperature and the coolant temperature have a large difference due to the high heat flux locally and the insufficient heat transfer between the wall and the coolant. Comparing the Fig. 10 with the Fig. 9, it is shown that the temperature difference between the channel wall and coolant is reduced substantially. This is because at the high heat flux zones the channel width is reduced that more surface area and higher heat transfer coefficient have improved the heat transfer between the wall and the coolant. In summary, the use of variable size channel design of the micro-channel not only can make the local heat transfer more efficient to accommodate the heat dissipation of hot spots but also maintain the flow rate under the fixed pressure drop.

Since the utilization of the available pressure drop is a critical issue in the determination of channel widths in zones, the pressure variation along the channel for the variable size channel system is drawn in Fig. 11. From inlet to outlet, the variation of pressure gradient due to the differences of the channel widths can be noticed. Moreover, the sharp jump and fall in the pressure curve indicates the pressure recovery at exit of fine channels and entrance loss at inlet of downstream channels. In principle, when the fluid goes from a narrow channel into the relative spacious gap area, according to Bernoulli's equation, the loss of velocity leads to the recovery of the pressure. When the flow goes from the gap into the following channel, the pressure loss occurs due to the increasing of flow velocity and entrance loss. Meanwhile, it is worthy to notice that the pressure drop at the gap regions could occupied a considerable fraction of total available pressure drop; therefore, only a limited number of zones should be considered in the design.

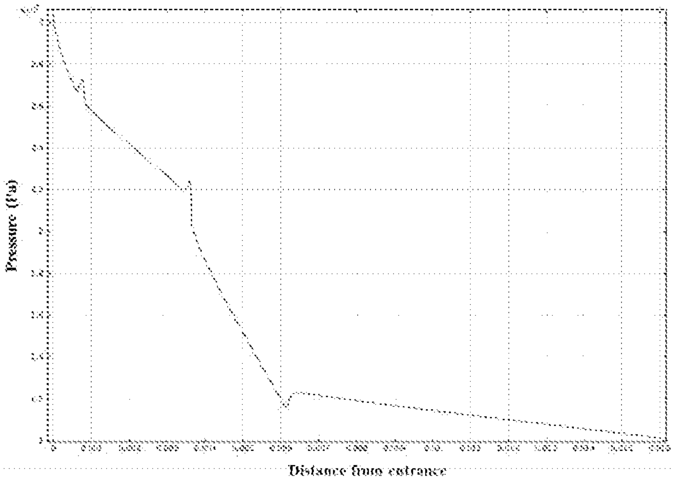

Figure.11 Pressure drop along channel in variable size micro-channel system

5. CONCLUSIONS

In this paper, the strip-and-zone design strategy of using variable size micro-channels for liquid cooling of non-uniformly heated integrated circuits chip is established. The thermal performance of a representative design is numerically simulated and evaluated. The advantage of this new design strategy is demonstrated through numerical simulations on a chip under air cooling, uniform optimal size channel system, and the variable size channel system.

For the non-uniform power source on the chips, the traditional air cooling heat sinks utilize the heat spreader to reduce the hot spot temperatures. However, due to the high thermal resistance in this system, the dimensions of the overall heat sink are much bigger than the chip itself. On the other hand, the micro-channel liquid cooling system provides a close to chip, compact and effective solution to cool the high power IC with a significant heat removal capacity.

Micro-channel liquid cooling system with uniform channel width is proved to be quite effective for uniformly heated chips and can be optimized [7]. However, for the non-uniform heated chips, especially with high power IC, the hot spot temperature is still substantial.

The strip-and-zone design of the micro-channel system for the cooling of the non-uniformly heated IC chip allows for the local enhancement for micro-channel cooling at hot spot regions by dividing the chip and micro-channel into separate parallel strips and discrete number of zones. It enables the increase of the total mass flow rates in the high power strips to further reduce the chip temperatures. This design strategy is verified by the numerical simulation conducted in this paper and it appears to be more effective than the uniform channel width system.

Although the design strategy of micro-channel system developed in this paper is primarily applied for single chips, it is convincible that this strategy can be extended to the application of 3D ICs cooling. The strict constrains of package space, the large heat dissipation rates per unit area and the high spatial non-uniformity of the heat flux distribution create significant challenge of the thermal management of 3D ICs. The micro-channel system with the strip-and-zone architecture of variable channel sizes could provide a promising solution to the thermal management issues of the 3D ICs.

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