Ladder Structure Triangular Micro Channels for Low Power and high Performance Micro Channel Cooling System

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Abstract— Heat dissipation from micro devices is now becoming a critical field since the performance of the IC is mostly determined by temperature fields. The success of an IC cooling system or heat sink for ULSI depends on the ability to achieve effective heat transfer rate to the flowing liquid and superior flow performance of the micro channels. Various studies on micro channel cooling systems (MCCS) in the past have focused on improving the flow characteristics of parallel rectangular micro channels. The present investigator aimed at improving the contact area in addition to achieving high convective heat transfer coefficient, thus introduced andreported ladder structure micro channel cooling systems (LSMCCS). The present study focuses on further improving the LSMCCS design so that high performance device cooling at low pumping power is achieved. First the various cross sectional shapes have been studied by keeping the cross sectional area and hydraulic diameter uniform to explore the possibility of further improving the performance of the micro cooling system. Hydraulic and thermal performance of ladder structure micro channels with rectangular, trapezium and triangular cross sectional shapes indicates that triangular shaped ladder structure micro channels would give the minimum pressure drop, the least thermal resistance at the least pumping power. Finally the investigator studied the performance of ladder structure triangular shaped micro channels cooling system with common inlet and outlet to simulate a packaged LSMCCS and the results show that ladder structure triangular shaped MCCS can give the best cooling performance. The temperature profiles that were obtained over the cross section of the inlet and outlet show that the LSMCCS can give excellent thermal resistance when triangular shape channels are employed and therefore can be ideal cooling systems for ULSI.

Index Terms—*IC cooling system,ladder structure micro channels, micro channel heat sinks, thermal resistance, triangular shape, trapezium shape.*

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NOMENCLATURE

A	channel flow area, m^2
D_h	characteristic width / hydraulic diameter, µm
a	channel width of triangular and trapezium, µm
b	bottom channel width of trapezium, µm
f	friction factor
fRe	poiseuille number
H_c	channel height, µm
L	channel length, µm
n	number of channels
Nu	nusselt number
n_d	direction normal to the wall
K_f	thermal conductivity, W/m. K
Ksi	thermal conductivity of silicon at 27°C, W/°C-cm
L_l	link length of the ladder shape micro channel
p	cross sectional perimeter, µm
h	convective heat transfer coefficient
p_{in}	inlet Pressure, Pa
p_{out}	outlet pressure, Pa
n_l	number of link channels
Re	Reynolds Number
Pr	Prandtl number
ch	Channel
Q	dissipated power, W
T_{in}	inlet fluid temperature, K
U_{in}	inlet fluid velocity, m/s
W_c	channel width, µm
x,y,z	cartesian coordinates
W_f	fin width, µm
Pp	pumping power
C_p	specific heat, J/Kg. K
W_{ft}	fin width at the top of the substrate
W_{fb}	fin width at the bottom of the substrate
W_{av}	average fin width
L_r	rung length
Greek	
µ	dynamic viscosity, kg/ms
ρ	density, kg/m^3
θ	thermal resistance
Subscripts	
l	link
in	inlet
out	outlet
f	fin
p	power
d	direction normal to the wall
h	Hydraulic
c	Channel
r	rung
av	average

I. INTRODUCTION

One of the main features of this century is a marked trend towards miniaturization. With the increased miniaturization of microelectronic devices and increasing processing speed, thermal issues are increasingly affecting overall electronic packaging and system capabilities. Device performance and reliability are known to improve when operating temperatures are kept below 80°C [1]. As the operating frequency of the device increases, heat dissipation will increase to greater than 250 W/cm^2, primarily concentrated at one or more hot spots and accompanied by large heat flux transients. The very large heat flux transients will cause degradation in device reliability and may eventually lead to device failure [2]. With the advances of MEMS technology, micro channel heat sinks have emerged as a promising cooling technology. Liquid cooling promises to be a more compact arrangement and it has been used for cooling the central processing unit of a large computing system [3]. The micro channel cooling concept was first introduced by Tuckerman and Pease in 1981 [4]. He observed that bringing

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80 – 89

down the channel dimensions to the micron scale will lead to increasing heat transfer rate. Micro channel heat sinks dissipate large amounts of heat with relatively little surface temperature rise. These heat sinks are useful for a wide variety of applications including microelectronics, diode laser arrays and high energy laser mirrors. There have been several studies that have focused on various aspects of micro channel geometry to enhance heat transfer. Design and fabrication of nickel based micro channel cooling plate on a glass substrate using a two layer electroforming process borrowed from the UV- LIGA process has been reported by A.J Peng *et al* [5]. Thermal and fluid performance of a micro channel heat sink realized directly within InP substrates has been fabricated by Richard J. Phillips [6] and it is found that the thermal performance of micro channel heat sink is approximately two orders of magnitude higher than other devices currently employed to cool microelectronic devices and the pumping power required to force liquid coolants through these heat sinks can be held back to less than 10 W/cm^2. Subsequently, three-dimensional fluid flow and heat transfer phenomena micro channels [7], thermal behavior in single-phase flow through rectangular micro channels [8-9], inlet/outlet arrangement effect on the heat sink performance [10], pressure drop and convective heat transfer for water flow in micro channels [11-12] have been investigated and reported by various researchers. Liu et al. [13] studied convective heat transfer in a quartz micro tube with three different inner diameters of 242, 315, and 520µm. Rectangular micro channels built with varying aspect ratios has been studied by S.G. Singh *et al* [14]. Geometric optimization of micro channel heat sink has been studied by T. Bello Ochende *et al* [15]. The effects of rectangular micro channel aspect ratio of laminar friction constant have been studied by IanPapautsky*et al* [16].

Investigation of micro channels with rectangular cross section using 3D conjugate approach with various hydraulic diameters have been experimentally studied by Poh Seng Lee *et al* [17]. Pressure drop of fully developed, laminar flow in micro channels of arbitrary cross-section has been investigated by M. Bahrami *et al* [18]. Friction factor study of liquid flow in trapezium micro channels has been extensively studied by Jeong Se Suh *et al* [19]. Single phase flow, heat transport and pumping considerations in micro channel heat sinks has been studied by S V. Garimella *et al* [20]. They analyzed the pumping requirements of micro channel heat sinks and the size of the micro channels have been optimized for minimum pumping requirements. Harms et al. [21] presented experimental data for a single-phase forced convection in deep rectangular micro channels. Gunasegaran *et al*. [22-24] investigated the hydraulic and thermal behavior of parallel micro channels with different shapes of cross section.In all these studies the flow performance in micro channels and improvement in convective heat transfer coefficient has been the main focus. In this process the mechanical support provided by the substrate reduces. Therefore, it becomes important that the micro channels should be carved out in such a way that the large wall area is available for effective heat transfer without losing the mechanical strength provided by the substrate. At the same time the flow performance of the micro channels should also be superior to the conventional cooling system formed by the collection of many parallel micro channels. Considering these requirements, the authors proposed a collection of parallel ladder structure rectangular micro channels that plays a vital role in the heat transfer phenomenon [25]. This paper presents the extended work on ladder structure micro channel cooling system (LSMCCS) that focuses on studying the effect of cross sectional shape of ladder structure micro channels with equal hydraulic diameter and subsequently on equal cross sectional area. Finally the performance of a packaged LSMCCS has also been studied by simulation experiments and the results are presented.

II. LADDER STRUCTURE MICRO CHANNELS IN MICRO COOLING SYSTEM

The top view and cross sectional views along XX of ladder structure rectangular shaped micro channels are shown in Fig. 1(a) and Fig. 1(b).

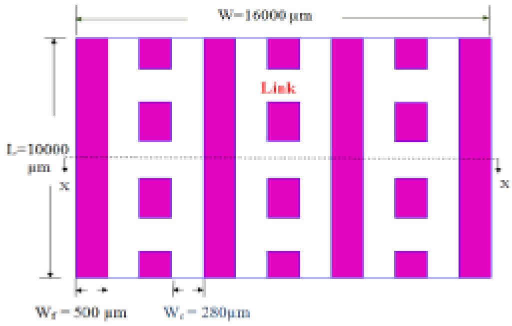

Fig. 1(a). Top view of LSMCCS (n l = 3)

The authors proposed to introduce ladder structure micro channels in the place of conventional long parallel channels so that α is enhanced due to extended substrate area.In ladder structure rectangular micro channels, link channels are created between two parallel micro channels to increase the wall area thus improving the heat transfer rate and at the same time wide fins are available to provide the most needed mechanical support. The configuration of the various micro channels studied in this work is given in Table 1.

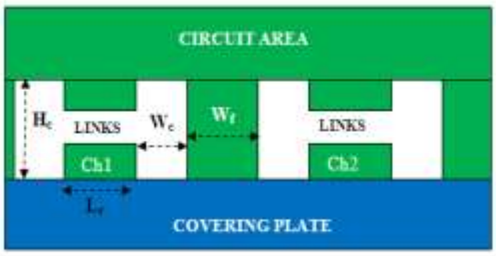

Fig. 1(b). Cross sectional view of the LSMCCS along XX

TABLE 1
GEOMETRICAL PARAMETERS OF LADDER TYPEMICRO CHANNELS WITH RECTANGLE CROSS SECTION

Channel shape	Device identification number	Number of channels (n)	Number of link channels (n_l)
Conventional	C1	20	0
Ladder type	L1	10	1
Ladder type	L2	10	2
Ladder type	L3	10	3

The die size of the integrated circuit is assumed to be (10000 µm ×16000 µm) in area and 500 µm thick. The dimensions of the proposed micro channel are: Length of channel = 10000 µm, channel height = 430 µm, width of the channel = 280 µm, fin width = 500 µm.

A. Theoretical analysis

Superior thermal performance of an IC micro cooling system can be obtained only when small thermal resistance is achieved. This requires high convective heat transfer coefficient and large α .In order to bring out the effect of link channels introduced in the proposed defined system effectively, the number of parallel channels in the conventional system has been considered as 20 and the number of ladder type channels has been taken as 10. The thermal resistance for these ladder type micro channels has also been obtained and is given as

$$\theta = \frac{1}{2p(2nL + n_l L_l)h} \quad (1)$$

The ratio α between total surface area of channel walls in contact with the coolant fluid to the area of circuit can be given as

$$\alpha = \frac{(2nLp) + (2n_l L_l p) - (2nw_c h_c)}{WL} \quad (2)$$

In this analysis of evaluating the performance of heat sink the following assumptions are made. (i) flow is laminar, (ii) thermal and fluid flow are in steady state, three dimensional single phase, incompressible and fully developed. Boundary conditions for all boundaries are specified for this model. The walls are assumed to have no slip boundary conditions. The inlet water temperature is assumed to be 293 K. The inlet water velocity U_{in} is given by

$$U_{in} = \frac{\mathrm{Re} \times \mu}{\rho \times D_h} \quad (3)$$

At the inlet: $U = U_{in}$, $T = T_{in}$ (4)

Atthe outlet: $P = P_{out}$,

$$\eta(\nabla u + (\nabla u)^T)n = 0 \quad (5)$$

The properties of water used in all the computations of this study are ρ = 998.2 kg/m3, c_p = 4182 J/kg ·K, μ = 0.001003 kg/m · s, and k_f = 0.6 W/ m. K

B. Methodology of investigations

The major flow performance indicators of micro channel are pressure drop, friction factor and Poiseuille number. The silicon IC cooling system presented and investigated in this work has been modelled using COMSOL multiphysics. The structure of this micro fluidic system has been created using fluid thermal interaction module using incompressible Navier Stokes coupled with convection and conduction module of COMSOL multiphysics for FEM analysis.

C. Governing Equations

The micro cooling system considered in this study is a multi physics model because it involves more than one kind of physics. The incompressible Navier - Stokes equations from fluid dynamics work together with a heat transfer equation. There are four unknown field variables (dependent variables).The velocity field components, U, V,pressure P, and the temperature T. They are all related through bidirectional multi physics couplings. The incompressible Navier-Stokes equations consist of a momentum balance (a vector equation), mass conservation and incompressibility condition

$$\rho \frac{\partial u}{\partial t} + \partial u . \nabla u = -\nabla \rho + \mu \nabla^2 u + F \quad (6)$$

$$\nabla . u = 0 \quad (7)$$

The heat equation is an energy conservation equation that says that the change in energy is equal to the heat source (integrated circuit in our case) minus the divergence of the diffusive heat flux:

$$\rho . c_p u . \nabla T + \nabla . (-k \nabla T) = Q \quad (8)$$

The velocity field comes from the incompressible Navier - Stokes equation. To build a model in COMSOL Multi physics using the above equations, use two physics interface: the laminar flow interface for laminar single phase fluid flow and the heat transfer interface for heat transfer. In this model, the equations are coupled in both directions. First we add free convection to the fluid flow with the Boussinesq approximation. This approximation ignores variations in density with temperature, except that the variations give rise to a buoyancy force lifting the fluid. This force enters the Fterm in the incompressible Navier-Stokes equations.

D. Meshing and solving

Free mesh parameters are entered in the mesh menu. A mesh was generated by discretizing the computational domain and mesh used is tetrahedral mesh. There is no manual tuning of damping parameters. The incompressible Navier-stokes application mode uses Lagrange p2-p1 elements to stabilize the pressure. Thus 2nd-order Lagrange elements model the velocity components while linear elements model the pressure. The default element settings in this application mode always provide one order higher Lagrange elements for the velocity components than for the pressure.

III. EFFECT OF CROSS SECTIONAL SHAPE LSMCCS ASSUMING CONSTANT CROSS SECTIONAL AREA

The present researcher has proposed ladder structure micro channels cooling systems (LSMCCS) that improves the wall area to circuit area and therefore improved cooling performance. The number of link channels between the parallel narrow micro channels would therefore have influence on the cooling system, it has been already reported that the thermal resistance can be significantly reduced with increasing link channels.

The past research studies directed on micro cooling system using micro channels indicate that the cross sectional shape of the micro channels also influences the hydraulic and thermal performance significantly. Therefore the investigator reports here the results of such a study that aims at investigating the influence of the cross sectional shape of ladder structure micro channels on the cooler performance. The rectangular, trapezium and triangular shaped micro channels have been considered in this work. The geometrical parameters of different shapes of ladder type micro channel are listed in Table 2.

TABLE 2

GEOMETRICAL PARAMETERS OF LADDER TYPE MICRO CHANNELS WITH EQUAL AREA(A)

Shape of microchannel	Rectangle	Trapezium	Triangular
Parameters	(μm)	(μm)	(μm)
D_h	339	328	303
H_c	430	430	430
W_c	280	-	-
a	-	420	560
b	-	140	-
L	10000	10000	10000
L_r	500	366	233

The cross sectional view of trapezium and triangular shaped micro channels as shown in Fig. 2 and Fig. 3.

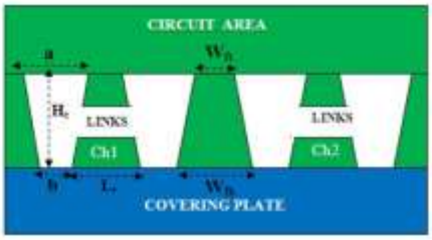

Fig. 2 Cross sectional view of ladder type trapezium shapedmicro channel cooling system

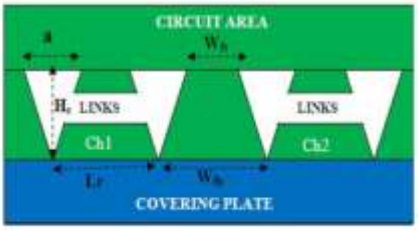

Fig. 3 Cross sectional view of ladder type triangular shaped micro channel cooling system

Since our aim is to identify the type of cross sectional shape that gives the best heat sinking, the various hydraulic and thermal metrices must be evaluated when volume of liquid flowing remains same in the channel irrespective of the cross sectional shape. Hence the investigator has designed the micro channels such that cross sectional area is same (A = 120400 μm^2) for all the three cross sectional shapes so that the volume of the water pumped out remains the same for any constant pumping power.

A. *Hydraulic performance analysis*

The measured pressure drops at various flow rates have been obtained with COMSOL multiphysics software for all the three cross sectional shapes and are plotted as shown in Fig. 4. The pressure drop is measured to be the least in ladder type triangular shape micro channels. The pressure drop at the outlet at the flow rate of 20 ml/min is measured to be 3.95 kPa for ladder type triangular micro channels and the pressure drop increases to 4.45 kPa and 5.32 kPa for ladder type trapezium and rectangle micro channels respectively. It is further important to note that the pressure drop is smaller for any given flow in triangular micro channels. This indicates less pumping power for triangular micro channel.

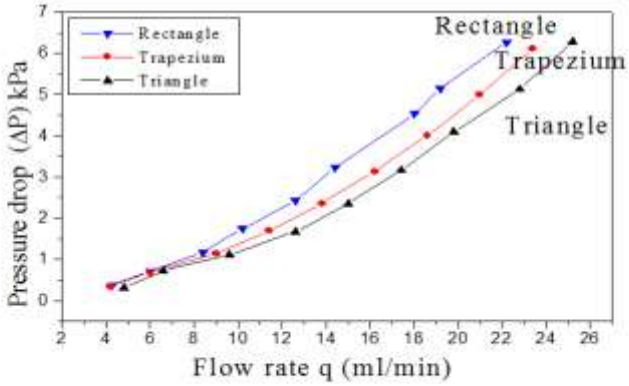

Fig. 4 Variation of pressure drop (ΔP) with flow rate (q) in rectangular, trapezium and triangular shaped micro channels

The thermal and fluid performance characteristics of a coolant depend on both the flow regime and on whether the flow is fully developed. The rate of heat transfer increases as the coolant velocity increases. But as the coolant velocity increases the coolant pressure drop also increases and greater pumping power as given by eqn. (9) is necessary.

$$Pp = n \times Uin \times Ac \times \Delta P \quad (9)$$

The variation of pumping power with flow rate for different cross sectional shape is shown in Fig. 5. The pumping power for the flow rate of 20 ml/min is measured to be 20.21 mW for ladder type triangular micro channels, followed by 30.80 mW for ladder type trapezium micro channels and 36.41 mW for ladder type rectangle micro channels. It is further important to note that the pressure drop is smaller for any given flow in triangular micro channels. This indicates less pumping power for triangular micro channel, a better choice for heat sinking applications, provided the convective heat transfer coefficient is high in triangular shaped ladder type micro channels and α is larger in these channels. In the next section this aspect is being analyzed.

B. *Thermal performance analysis*

Superior thermal performance can be said to be obtained only when minimum thermal resistance is ensured. It needs high convective heat transfer coefficient and large wall area to circuit area ratio.In this study the cross sectional area has been maintained the same for all the three cross sectional shapes of ladder type micro channels considered. The wall area to circuit area ratio and hydraulic diameter of the various cross sectional shape micro channels have been estimated and listed in the Table 3.

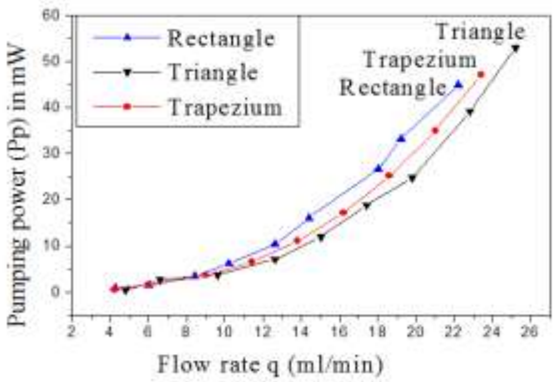

Fig. 5 Variation of pumping power (Pp) with flow rate (q) in rectangular, trapezium and triangular shaped micro channels

TABLE 3

 ISSN: 2454-4248
80 – 89

ESTIMATED VALUES OF WALL AREA TO CIRCUIT AREA RATIO CROSS SECTIONAL AREA (A) = 120400 μm^2.

Cross sectional shapes	Estimated value of wall area to circuit area ratio	Hydraulic diameter (μm)
Rectangle	3.52	339
Trapezium	3.69	328
Triangular	4.00	303

The value of Nusselt number for triangular and trapezium shaped micro channels have been calculated using eqn. (10) as suggested in [27]

$$Nu = C_1 Re^{0.148} Pr^{0.163}(1-b/a)^{0.908}(a/H_c)^{1.001}(K/D_h)^{0.033}(D_h/L)^{0.798} \quad (10)$$

where C_1 = 47.8 for silicon surfaces, The convective heat transfer coefficient at different flow levels have been calculated for various cross sectional shapes and presented in Fig. 6.

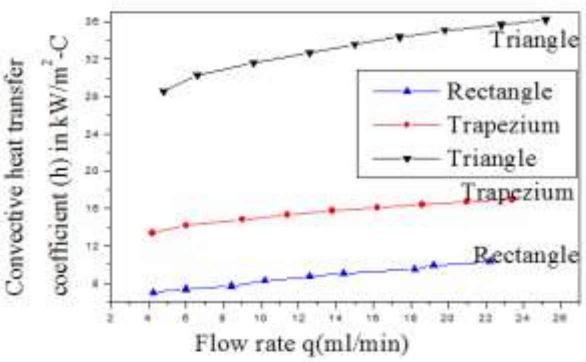

Fig. 6 Variation of convective heat transfer coefficient with flow rate in trapezium and triangular shaped micro channels.

It can be seen that the convective heat transfer coefficient also increases almost linearly as the flow rate increases. As a result the convective heat transfer is strengthened at large flow rate. It is clear from Fig. 6, that ladder type triangular shaped micro channels have the highest value of convective heat transfer coefficient. In addition to this large wall area to circuit area ratio is seen to be the highest for triangular cross sectional shape (Table 2) and this further reduces the thermal resistance. Now it can be said that triangular shaped micro channels are better because they have large convective heat transfer coefficient and large wall area to circuit area ratio. The thermal resistances of the ladder type micro channels at various flow rates (ensured laminar flow) have been calculated for different shapes and are presented in Fig. 7. The thermal resistance decreases with flow rate in all the cooling systems because larger volume of coolant fluid is available for taking the heat away at larger flow rate.

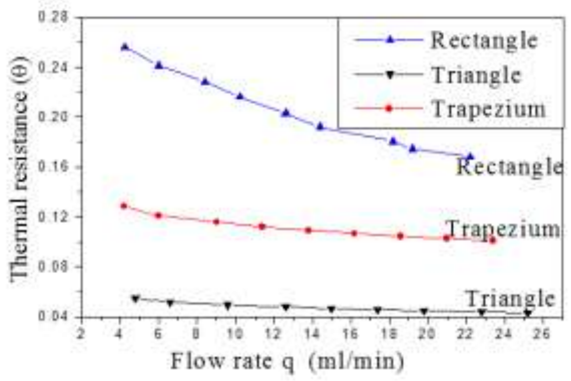

Fig. 7 Variation of thermal resistance (θ) with flow rate (q) in rectangular, trapezium and triangular shaped micro channels

C. Thermal performance analysis

The temperature values measured at 3000 points equally spread over the three cross sectional shapes of the micro channels at the outlet (Y = 10000) are plotted to obtain the contour map as shown in Fig. 8.

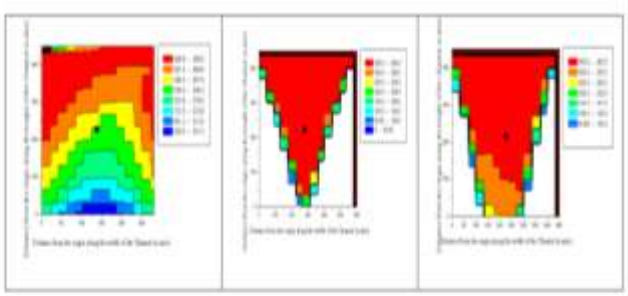

Fig. 8 The coolant fluid temperature profile at various points over the rectangle, triangular and trapezium cross section at the outlet (Y=10000 µm)

The estimated temperature falls between 293 K (inlet temperature of fluid) and 373 K (wall temperature). The fluid temperature remains high at the upper side of the micro channels that is closer to the circuit area and shows a decreasing trend as one approaches the bottom of the micro channel. However the triangular and trapezium shaped micro channels exhibits almost the same temperature profile closer to 373 K throughout the entire cross section thus showing excellent thermal performance. Further it is important to note that the triangular shaped micro channels have the ability to provide better heat sinking performance with less pumping power. Hence it is can be said that triangular shaped ladder structure micro channels shows better performance in hydraulic and thermal behavior in cooling systems.

IV. EFFECT OF CROSS SECTIONAL SHAPE OF LADDER STRUCTURE MICRO CHANNEL COOLING SYSTEM ASSUMING EQUAL HYDRAULIC DIAMETER

The present study has been extended to investigating the influence of cross sectional shape of the ladder type micro channels which could open up further avenues to increase wall area and convective heat transfer coefficient, so that better cooler performance is achieved. Since the thermal resistance is affected by both wall to circuit area and convective heat transfer coefficient, the researcher has designed the micro channels such that D_h is moderate and reasonably larger volumetric flow is ensured. In addition to this D_h is also kept the same for all the three cross sectional shapes so that the effect of cross sectional shape of the micro channels on both hydraulic and thermal performance is brought out effectively. The various geometries of the ladder type micro channels with different cross sectional shapes designed to achieve D_h = 339 µm have been presented in Table 4.

TABLE 4
GEOMETRICAL PARAMETERS OF LADDER TYPE MICRO CHANNELS WITH EQUAL HYDRAULIC DIAMETER (D_h)

Shape of the micro channel	Rectangle	Trapezium	Triangular
Parameters	(µm)	(µm)	(µm)
D_h	339	339	339

 ISSN: 2454-4248
80 – 89

H_c	430	430	430
L	10000	10000	100000
W_c	280	-	-
a	-	456	748
b	-	140	-
W_{ft}	500	332	54
W_{fb}	500	648	780
W_{fav}	500	490	417

A. *Hydraulic performance analysis*

The measured pressure drops and pumping power at various flow rates have been obtained with COMSOL Multiphysics software for all the three cross sectional shapes and are plotted as shown in Fig. 9 and Fig. 10. The pressure drop at the outlet for the flow rate of 20 ml/min is measured to be 2.68 kPa for ladder type triangular micro channels and the pressure drop increases to 5.23 kPa and 6.37 kPa for ladder type rectangle and trapezium shaped micro channels respectively. The other important observation is that for any given pressure drop the volume of fluid flowing in triangular micro channels is large. This indicates that triangular micro channels can transport more fluid and thus improving heat removal. It is further important to note that the pressure drop is smaller for any given flow in triangular micro channels. This indicates less pumping power for triangular micro channel.

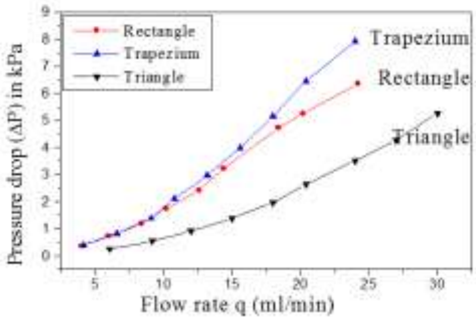

Fig. 9 Variation of pressure drop (ΔP) with flow rate in rectangular, trapezium and triangular shaped micro channels

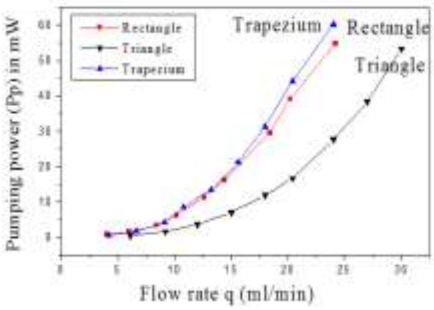

Fig. 10 Variation of pumping power with flow rate (q) in rectangular, trapezium and triangular shaped micro channels.

The pumping power for the flow rate of 20 ml/min is measured to be 15.75 mW for ladder type triangular micro channels, followed by 33.55 mW for ladder type rectangle micro channels and 43.90mW for ladder type trapezium micro channels. Since the pressure drop is smaller in triangular shaped micro channels, the pumping power needed is also the least in triangular micro channels. The wall area to circuit area ratio of the various cross sectional shape micro channels have been estimated using the equations given in Table 5 and the α values estimated for the different cross sectional shapes of rectangle, trapezium and triangular have also been listed in the same Table.

B. *Thermal performance analysis*

Fig. 11 shows the convective heat transfer coefficient response of all the cooling systems. It is clear from Fig. 11 that ladder type triangular shaped micro channels have the highest value of convective heat transfer coefficient. Fig. 12 shows the thermal resistance plot of all the three cooling systems. The thermal resistance decreases with flow rate in all the cooling systems because larger volume of coolant fluid is available for taking the heat away at larger flow rate. The least thermal resistance is obtained for ladder type triangular shaped micro channels followed by ladder type trapezium and rectangle shape micro channels. Hence it is observed that the triangular shaped micro channels could give better thermal performance in addition to exhibiting superior performance in hydraulic behavior. This is due to large α for triangular shaped micro channel as shown in Table 5 and large convective heat transfer coefficient.

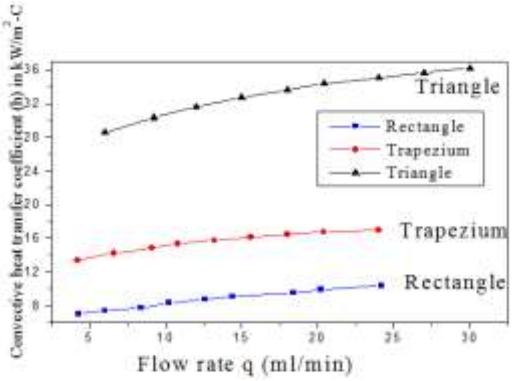

Fig. 11 Variation of convective heat transfer coefficientwith flow rate in rectangular, trapezium and triangular shaped micro channels

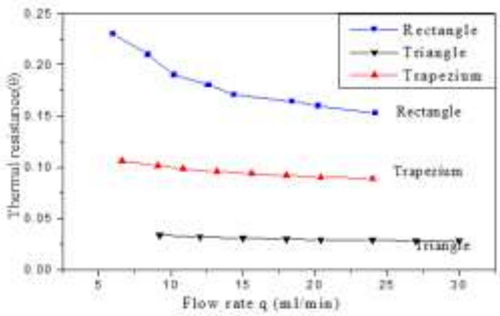

Fig. 12 Variation of thermal resistance with flow rate inrectangular, trapezium and triangular shaped micro channels.

The temperature at 2000 points have been are plotted to set the contour map as shown in Fig. 13a to Fig. 13c in the plane represented by the X,Y,Z coordinates of [Wc/2,0,430], [Wc/2,10000,430], [Wc/2,0,0], and [Wc/2,10000,430]. The estimated temperature falls between 293 K (inlet temperature of fluid) and 373 K (wall temperature). The fluid temperature (T_f) remains high at the upper side of the rectangular channels that is closer to the circuit area and shows a decreasing trend as one approaches the bottom of the micro channel.

TABLE 5
EQUATIONS AND ESTIMATED VALUES OF WALL AREA TO CIRCUIT AREA RATIOFOR ALL THE THREECROSS SECTIONAL SHAPES

Cross sectional shapes	Wall area to circuit area ratio α	Estimated value of α
Rectangle	$\frac{(2nLp)+(2n_l l_l p)-(2nn_l H_c w_c)}{WL}$ $p=2(h_c+w_c)$	3.84
Trapezium	$\frac{(2nLp)+(2n_l l_l p)-(nn_l H_c (a+b))}{WL}$ $p=a+b+2c$	3.97
Triangular	$\frac{(2nLp)+(2n_l l_l p)-(nn_l bh)}{WL}$ $p=a+2b$	4.67

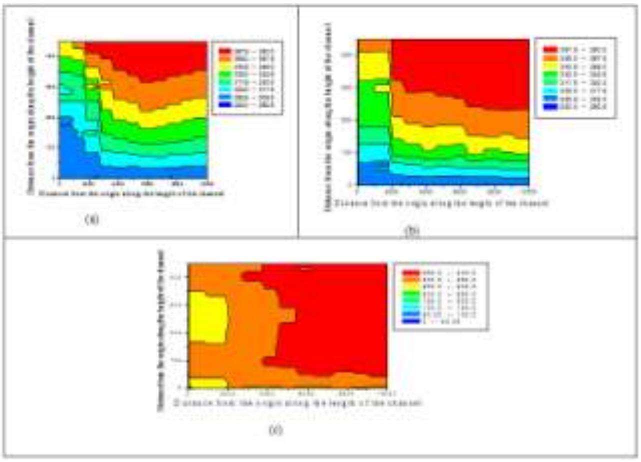

Fig. 13 The coolant fluid temperature distribution of (a) rectangle (b) trapezium (c) triangle cross section over the length at (X = Wc/2)

However the triangular and trapezium shaped micro channels exhibits almost the same temperature profile closer to 373 K throughout the entire cross section thus showing excellent thermal performance. This superior thermal behavior of triangular shaped micro channels due to large h and larger wall area that is achieved in triangular shaped micro channel for any given D_h. It is estimated that α increases by 21.61 % compared to the rectangular shaped micro channels for the given D_h of 339 μm. The pumping power needed in triangular shaped ladder type micro channel is 53 % less than the rectangular shaped micro channels and 64 % less than the trapezium shaped micro channels. Hence it is concluded that the design of a micro cooling system for ULSI should first aim at designing the value D_h with which sufficient volumetric flow at the given input pumping power could be achieved and subsequently the geometries of the ladder type micro channels with triangular cross sectional shape micro channels should be designed to achieve the best cooling performance.

V. PERFORMANCE ANALYSIS OF PACKAGED LADDER STRUCTURE TRIANGULAR SHAPED MCCS BY SIMULATION

In this section the investigator has studied through simulation the hydraulic and thermal performance of packaged ladder structure triangular shape MCCS with common inlet and common outlet using COMSOL Multiphysics. Rigorous analysis of the results obtained further brings out a practical design approach that could assure the best possible cooling performance and the details of the proposed design approach have also been presented in this section.

A. *Performance measures of ladder structure triangular shaped micro channel cooling system*

The various geometries of the ladder structure micro channels with triangular cross sectional shape have been designed to achieve D_h = 339 µm and presented in Table 7. The created 3D structure analysis using COMSOL Multiphysics is shown in Fig. 13. The post processing velocity profile obtained from COMSOL Multiphysics simulation is shown in Fig. 14.

TABLE 7

GEOMETRIES OF LADDER STRUCTURE TRIANGULAR SHAPED MICRO CHANNEL COOLING SYSTEM

Parameters	(μm)
Hydraulic diameter	339
Channel height	430
Channel length	10000
Channel width	748

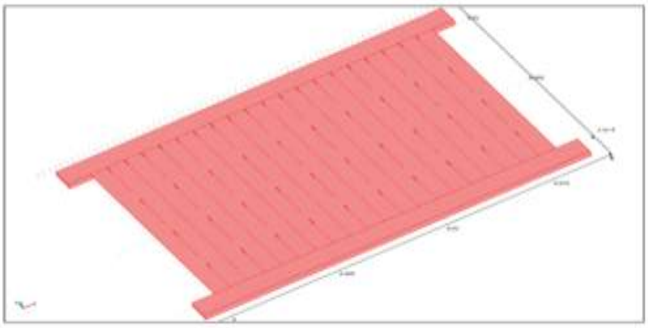

Fig. 13 Created 3D structure of packaged ladder structure triangular shaped micro channel cooling system (Pre-processing)

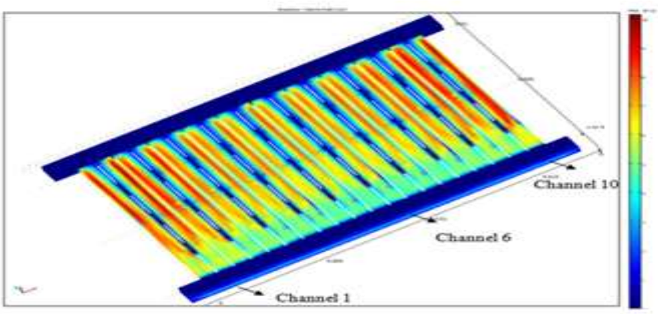

Fig. 14 Velocity profile of the packaged ladder structuretriangular shaped micro channel coolingsystem with Post processing

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80 – 89

B. Pressure drop estimation by simulation

The pressure drop across the micro channel increases if the flow rate increases. The measured pressure drops and pumping power at various flow rates have been obtained with COMSOL Multiphysics software and are plotted as shown in Fig. 15

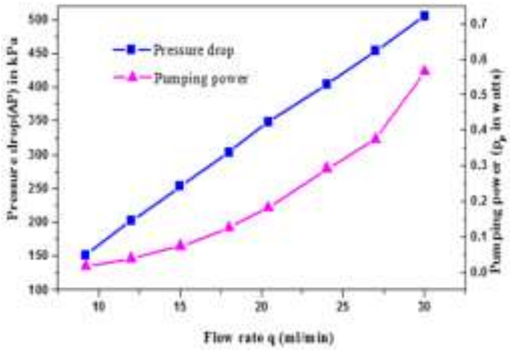

Fig. 15 Pressure drop and pumping power with flow rate for ladder structure triangular shaped micro channel cooling system (LSMCCS)

For the flow rate of 30 ml/min the required pumping power is 560 mW and it works out to be 0.35W/cm^2 pumping power. It is quite small compared to the 10W/cm^2 the maximum limit set by the industries.

C. Temperature measurement

The temperature distribution profiles along the length (Y = 0 - 10000 at X= Wc/2) of the first, sixth and the tenth channels have been obtained for a flow rate of q = 30 ml/min and are shown in Fig. 16, Fig. 17 and Fig. 18. Temperature at the central plane of the cooling system of channel 6 is more compared to the channels (1 and 10) in the edge of the cooling system. The temperature distribution at the inlet cross section (X=18000, Y=0) of the micro channel is shown in Fig. 19 and the outlet cross section (X=18000, Y=10000) of the micro channel is shown in Fig. 20.

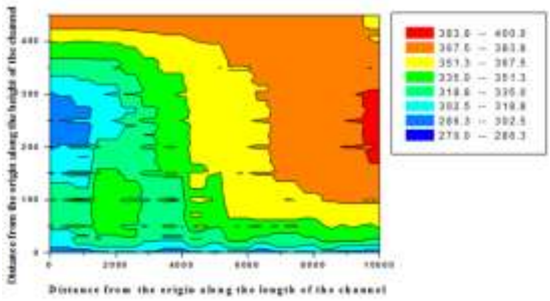

Fig. 16 The coolant fluid temperature distribution in the central vertical plane over the length (y = 0-10000) at (X = Wc/2) of the first (Fig. 14) ladder structure micro channel

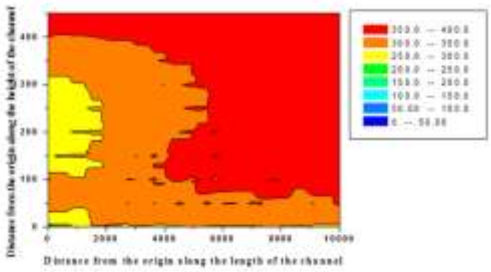

Fig. 17 The coolant fluid temperature distribution in the central vertical plane over the length (y=0-10000) at (X = Wc/2) of the sixth (Fig. 14) ladder structure micro channel

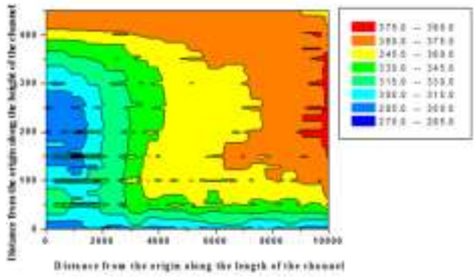

Fig. 18 The coolant fluid temperature distribution in the central vertical plane over the length (y=0-10000) at (X = Wc/2) of the last (Fig. 14) ladder structure micro channel

The estimated temperatures falls between 293 K (inlet temperature of fluid) and 373 K (wall temperature) and the temperature at the outlet is in the range (373K - 375K) in most of the points, thus showing excellent thermal performance. This analysis clearly demonstrates the effectiveness of the ladder structure triangular shaped micro channel cooling system for ULSI.

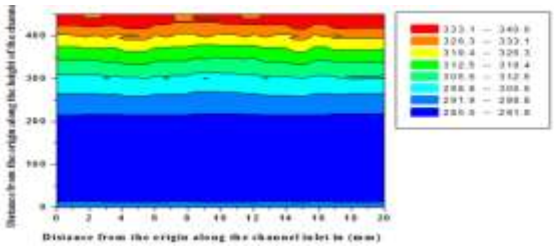

Fig. 19 The coolant fluid temperature distribution in the cross sectional plane at the inlet (X=0- 18000)

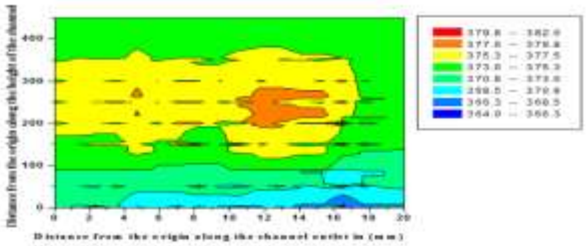

Fig. 20 The coolant fluid temperature distribution in the cross sectional plane at the outlet at (X=0-18000)

VI. SUMMARY AND CONCLUSIONS

The present investigator introduced parallel collection of ladder type rectangular micro channels in the place of parallel rectangular channels employed in conventional micro cooling systems. The investigator studied in this work the effect of cross sectional shape of the ladder type micro channels to explore the possibility of further improving the performance of the micro cooling system. Here the cross sectional area was kept the same for allthe three cross sectional shapes. The results shows that the triangular shaped ladder type micro channels are the better choice for giving good thermal and hydraulic performance, because triangular shaped micro channels have large wall area to circuit area, less pressure drop, large convective heat transfer coefficient and less thermal resistance compared with other cross sectional shapes. Further it is important to note that the triangular shaped micro channels have the ability to provide better heat sinking performance with less pumping power.

Further studies on micro channels of different cross sectional shapes but same hydraulic diameter also show that triangular micro channels can give the best heat sinking performance. These results further demonstrate that the triangular shaped ladder structure micro channels employed micro cooling system provide the best heat sinking performance with less pumping power. Hence it is concluded that the design of a micro cooling system for ULSI should first aim at designing an optimum hydraulic diameter value with which sufficient volumetric flow at the given input pumping power could be achieved and subsequently the geometries of the ladder structure micro channels with triangular cross sectional shape micro channels should be designed to achieve the best cooling performance.

Finally the investigator studied the performance of ladder structure triangular shape micro channels cooling system with common inlet and outlet to simulate a packaged MCCS. The temperature distribution of the ladder structure micro channels have been thoroughly investigated and the results show that ladder structure triangular shaped MCCS has the best cooling performance. The present study shows that tuning the substrate wall area in contact with the liquid and convective heat transfer coefficient optimally can achieve the least thermal resistance at minimum pumping power. Further the consistency obtained in the thermal properties of these cooling systems show that COMSOL Multiphysics is an excellent tool to study the thermal behavior of MCCS.

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