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Ladder shape micro channels employed high performance micro cooling system for ULSI

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ABSTRACT

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. The effective heat transfer requires large wall area that is in contact with the flowing liquid and availability of large mass of fluid to carry away the heat. Conventionally a collection of parallel rectangular micro channels have been used to achieve this. However, there is a practical maximum limit on the number of channels that can be imbedded in the back surface of the substrate by bulk etching. In this paper, the authors propose a collection of ladder shape micro channels with rectangular cross section that effectively increases the wall area thus decreasing the thermal resistance and increases heat transfer coefficient. Two parallel rectangular channels are connected by one or more link channels to form a ladder shape micro channel. The flow performance of these ladder shape micro channels have also been studied using COMSOL multi physics and the comparison of the flow performance indicating parameters of the collection of conventional rectangular channels with the proposed collection of ladder shape micro channels show that the high performance heat sinking can be achieved using the proposed ladder shape micro channels. Further the thermal responses of these micro systems have also been studied extensively and these studies show that the thermal resistance decreases with the introduction of ladder shape micro channels considerably. Finally the substrate strength has also been estimated using IntelliSuite Software and it shows that the rigidity of the substrate is slightly lower in ladder shape micro channel carved substrates but the degradation is highly insignificant.

1. 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 down the channel dimensions to the micron scale will lead to increasing heat transfer rate. Recently there have been several studies that have focused on various aspects of micro channel geometry to enhance heat transfer. Subsequently, friction factor in micro channels [5], three-dimensional fluid flow and heat transfer phenomena inside heated micro channels [6], thermal behavior in single-phase flow through rectangular micro channels [7,8], inlet/outlet arrangement effect on the heat sink performance [9], pressure drop and convective heat transfer for water flow in micro channels [10–12] 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 520 μm.

Harms et al. [14] presented experimental data for a single-phase forced convection in deep rectangular micro channels. Gunasegaran et al. [15–18] 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 has been the main focus. However it is important to note that the

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Nomenclature

A	channel flow area, m^2
D	Characteristic width/hydraulic diameter, 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
K_{si}	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
Q	dissipated power, W
T_{in}	inlet fluid temperature, K
U_{in}	inlet fluid velocity, m/s
W_c	channel width, μm
W_f	fin width, μm
P_p	pumping power
C_p	specific heat, J/kg K
x,y,z	Cartesian coordinates

Greek

u	dynamic viscosity, kg/ms
ρ	density, kg/m^3
θ	thermal resistance
u	dynamic viscosity, kg/ms

Subscripts

c	channel
l	link
in	inlet
out	outlet
f	fin
p	power
d	direction normal to the wall

thermal performance of micro cooling heat sinks is also equally important. Hence the designer should try to achieve low thermal resistance. This is possible only by large heat transfer coefficient and large wall area that is contact with flowing liquid [4]. Long narrow parallel channels have been studied for achieving this [4–18]. However there is a maximum practical limit on the number of channels that can be imbedded in the substrate since increasing the number of channels will lead to very small fins (the thin solid region between two channels). 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 propose a collection of parallel ladder shape rectangular micro channels that plays a vital role in the heat transfer phenomenon. In ladder shape rectangular micro channels, link channels are formed 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 hydraulic and thermal behaviors of these ladder shape micro channels have been extensively studied and the results are presented. The comparison of the flow and thermal performance of the proposed ladder shape rectangular micro channels cooling system with parallel rectangular micro channels show that the proposed system has superior flow and thermal performance with no degradation in the rigidity of the substrate.

2. Structure of existing micro cooling systems and practical limitations

The conventional micro cooling system employing long parallel channels imbedded in the back side of the substrate [1–18] is shown in Fig. 1a. The micro channels in these systems have rectangular cross section as shown in Fig. 1b. The thermal performance of such a cooling system or heat sink is measured by its thermal resistance. The thermal resistance is the sum of thermal resistance due to conduction from the circuits through the substrate package and heat sink interface, thermal resistance due to heating of the coolant fluid as it absorbs energy passing through the heat exchanger and the thermal resistance due to convection from heat sink to the coolant fluid. Among these three, the thermal resistance due to conduction can be made negligibly small, since the substrate is made of lightly doped silicon which has high thermal conductivity [κ_{si} = 1.48 W/°C cm] and the heat exchanger containing the flowing coolant is very near to the heat source (our circuits). The thermal resistance can also be made significantly small with a coolant fluid of high volumetric heat capacity. Water is chosen as the coolant fluid in the presented system since water satisfies this requirement. The dominating component of thermal resistance due to convection from the heat sink to the coolant fluid is defined as

$$\theta_{conv} = \frac{\Delta T}{Q} \tag{1}$$

where ΔT is the difference between channel wall temperature and mean fluid temperature and Q is the dissipated power by the circuit.

Tuckerman and Pease [4] has shown that

$$\theta_{conv} = \frac{1}{hL\alpha W} \tag{2}$$

where $\alpha = \frac{2np}{W}$, with p being the perimeter of the channel cross section and n being the number of parallel channels. In Eq. (2), h is the convective heat transfer coefficient and α is the ratio between total surface area of channel walls in contact with the coolant fluid to the area of circuit. It is evident from Eq. (2) that α and h should be increased for a given circuit area $A_c = W \times L$ to achieve lower thermal resistance. The convective heat transfer coefficient is inversely proportional to the characteristic width D of the channel as given by Eq. (3)

$$D = \frac{2 \times W_C \times H_C}{H_C + W_C} \tag{3}$$

Hence characteristic width should be reduced considerably to increase the value of convective heat transfer coefficient since

$$h = \frac{K_f Nu}{D} \tag{4}$$