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NUMERICAL EVALUATION ON THE HEAT DISSIPATION CAPABILITY OF LIQUID METAL BASED CHIP COOLING DEVICE

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ABSTRACT

With the sharp improvement in computational speed of CPU, thermal management becomes a major concern in the current microelectronic industry. Conventional thermal management methods for CPU chip cooling are approaching their limit for quite a few newly emerging high integrity and high power processors. Therefore, liquid metal based chip cooling method has been proposed to accommodate to this request. In order to better understand the mechanisms of the cooling enhancement by the liquid metal based cooling technique, the three-dimensional heat transfer process thus involved in the cooling chip is numerically simulated in this study. A series of calculations with different flow rates and thermal parameters are performed. The cooling capability of the liquid metal is also compared with that of the water-cooling system. The results indicate that the liquid metal has powerful cooling capability, which is much better than that of the conventional liquid-cooling system.

NOMENCLATURE

c	Specific heat [$J/kg\cdot°\mathrm{C}$]
D	Diameter of fluid channel [m]
h	Convective heat transfer coefficient [$W/m^2\cdot°\mathrm{C}$]
h_a	Convective heat transfer coefficient [$W/m^2\cdot°\mathrm{C}$]
k	Thermal conductivity [$W/m\cdot°\mathrm{C}$]
Nu	Nusselt number
P	Perimeter of fluid channel [m]
P_c	Power of chip device [W]
q_c	Heat flux of chip device [W/m^2]
S	Cross-sectional area of fluid channel [m^2]
S_c	Surface area of chip device [m^2]
t	Time [s]
T	Temperature [°C]
T_a	Surrounding air temperature [°C]
T_w	Wall temperature of fluid channel [°C]
v	Velocity of cooling fluid [m/s]
x, y, z	Cartesian coordinate [m]
$\mathbf{X}$	Location
ρ	Density [kg/m^3]
Ω_1	Heat conduction domain
Ω_2	Heat convection domain

Subscripts

f	Fluid

INTRODUCTION

Since the birth of electronic technology, the heat flux generation from electronic devices has increased and this trend is expected to continue. Currently, the power dissipation densities required by many challenging scientific and commercial cooling applications such as microelectronics has reached 100 W/cm^2 and higher [1]. Moreover, the allowable maximum junction temperature have to be held less than 85 °C for reliable operation and increased electronic device lifespan [2]. Therefore, there is a challenge to develop efficient methods for heat removal from these high flux devices. To meet this need, many thermal management methods have been developed such as forced air convection [3], liquid immersion cooling [4, 5], the micro-channel sink with liquid as the working fluid [6], jet impingement [7], thermoelectric cooling [2, 8-10], heat pipe [11, 12], thermoacoustic engine [13], and miniaturized refrigeration system [14, 15]. However, the applications with high power dissipation densities are requiring cooling beyond what can be offered by most of the current thermal management schemes. Therefore, thermal management is the limiting factor in the development of higher power electronic devices, and effective methods of cooling with low cost are required.

Compared with forced air convection, water cooling is a much more efficient way. However, the use of water as cooling fluid has some inherent limitations. The low thermal conductivity of water may lower its effectiveness as a heat transfer fluid. Also, circulation of water needs to be driven only by mechanical pumps which occupy large spaces, and contribute to vibration or noise. As is recently known, characteristics such as high vapor pressure and high thermal conductivity have made liquid metals attractive for high temperature cooling applications [16, 17]. Starting from this point, Liu and Zhou [18] proposed the method of using the low melting point metal such as liquid gallium and its alloy as the cooling fluid to cool the electronic devices in the year of 2002. In addition to providing an excellent heat transfer, the high electrical conductivity of liquid metal offers the potential of compact electromagnetic pumping [1]. All these attractive properties warrant the future application of liquid metal in chip cooling area. In order to better demonstrate the cooling capability of liquid metal, a newly developed Monte Carlo algorithm [19, 20] is extended in this study to simulate the corresponding heat transfer process thus involved in both the liquid metal and the substrate areas.

MODELS AND ALGORITHM

Figure 1 depicts a schematic of liquid metal based cooling module (made by metal with high thermal conductivity such as aluminum and copper), in which the chip device contacts with the cooling module at x=0. The computation domain is prescribed in a rectangular geometry with 2×5×5 cm in x, y and z directions respectively, and the dimension of the chip device which is located at the center of surface x=0 is 3×3 cm. The diameter of fluid channel is taken as 2 mm. The central lines of this channel are (x=0.01 m, y=0.01 m, $0 \le z \le 0.044$ m) $\cup$ (x=0.01 m, 0.01 m$<y\le$ 0.02 m, z=0.044 m) $\cup$ (x=0.01 m, y=0.02 m, 0.006 m$<z\le$0.044 m) $\cup$ (x=0.01 m, 0.02 m$<y\le$ 0.03 m, z=0.006 m) $\cup$ (x=0.01 m, y=0.03 m, 0.006 m$<z\le$0.044 m) $\cup$ (x=0.01 m, 0.03 m$<y\le$ 0.04 m, z=0.044 m) $\cup$ (x=0.01 m, y=0.04 m, $0\le z<0.044$ m). Consequently, the whole domain consists of heat conduction and convection domains. For the heat conduction domain, thermal equation is described by Fourier's law

$$\rho c \frac{\partial T(\mathbf{X},t)}{\partial t} = \nabla \cdot k \nabla \left[T(\mathbf{X},t) \right], \quad \mathbf{X} \in \Omega_1 \tag{1}$$

where ρ, c and k are the density, specific heat and thermal conductivity of the cooling module, respectively; $\mathbf{X}$ contains the Cartesian coordinates x, y and z; and Ω_1 denotes the heat conduction domain.

The temperature of cooling fluid in flow channel, which varies along the flow direction, is governed by the convective heat transfer equation [19]

$$\rho_f c_f \frac{\partial T}{\partial t} = k_f \frac{\partial^2 T}{\partial z^2} + \frac{hP}{S}\left(T_w - T\right) - \rho_f c_f v \frac{\partial T}{\partial z}, \quad \mathbf{X} \in \Omega_2$$

or

$$\rho_f c_f \frac{\partial T}{\partial t} = k_f \frac{\partial^2 T}{\partial y^2} + \frac{hP}{S}\left(T_w - T\right) - \rho_f c_f v \frac{\partial T}{\partial y}, \quad \mathbf{X} \in \Omega_2 \tag{2}$$

where ρ_f, c_f and k_f are the density, specific heat and thermal conductivity of the cooling fluid, respectively; $h = Nu \cdot k_f / D$ is the convective heat transfer coefficient between the fluid and cooling module; D, P and S are the diameter, perimeter and cross-sectional area of the channel; v is the mean flow velocity; Nu the Nusselt number; T_w the wall temperature of the channel; and Ω_2 denotes the convection domain. The sign of velocity v is assigned as positive, i.e., the velocity of cooling fluid flowing along the positive direction of y and z axes is positive and otherwise minus.

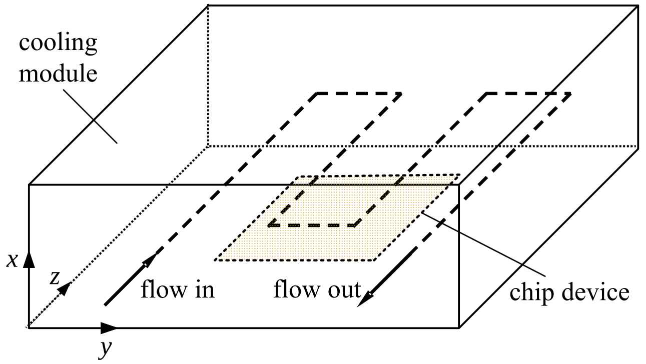


Fig. 1. Schematic illustration of liquid metal cooling module

The initial condition is defined as uniform temperature of 25 °C over the whole area. The boundary conditions prescribed as

$$-k\frac{\partial T}{\partial x} = \begin{cases} q_c & 0.01\text{m} < y < 0.04\text{m}, 0.01\text{m} < z < 0.04\text{m} \\ 0 & \text{other area} \end{cases} \quad \text{at } x = 0 \tag{3}$$

$$-k\frac{\partial T}{\partial n} = h_a (T - T_a) \quad \text{at other boundaries} \tag{4}$$

where $q_c = P_c / S_c$ is the heat flux of chip device; P_c and S_c are respectively the power and surface area of chip device; h_a is the convection heat transfer coefficient between the cooling module and its surrounding air; and T_a is the surrounding air temperature.

Considering that Monte Carlo method can solve the temperatures at any desired positions independently from the solutions of the other domain and is timesaving, a Monte Carlo algorithm developed in our previous works [19, 20] is extended to simulate the heat transfer process involved in liquid metal cooling in this study. The description and derivation of MC algorithm are omitted here for brevity. Readers are referred to [19, 20] for more details.

RESULTS AND DISCUSSION

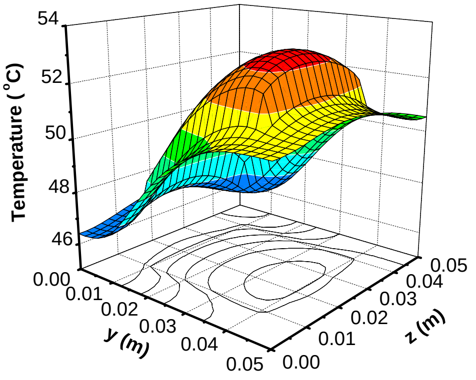
As a practical cooling fluid, the liquid metal must satisfy the following requests: non-poisonous, non-caustic material, low viscosity, high thermal conductivity and heat capacity. Liquid gallium offers an attractive solution, and it is thus selected in this study.

In calculations, the fluid temperature at the inlet is prescribed as 30 °C, considering that the melting point of gallium is 29.7 °C [21]. The constant Nusselt number is taken as Nu=7 [17], and $h_a = 10 W/m^2 \cdot$°C, $T_a = 25$°C. The thermal properties used in this study are summarized in Table 1.

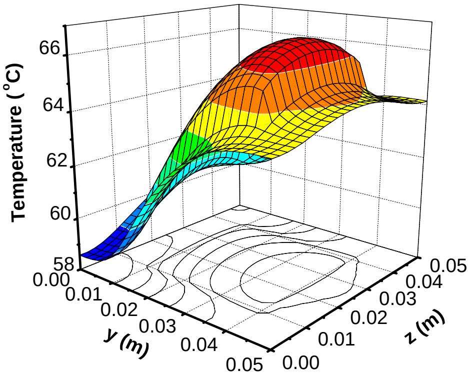
Table 1. Summary of the thermophysical properties [21, 22]

	Aluminum	Copper	Gallium	Water
Density (kg/m^3)	2710	8930	6093	998
Specific heat ($J/kg \cdot$°C)	902	386	3440	4183
Thermal conductivity ($W/m \cdot$°C)	236	398	29.4	0.599

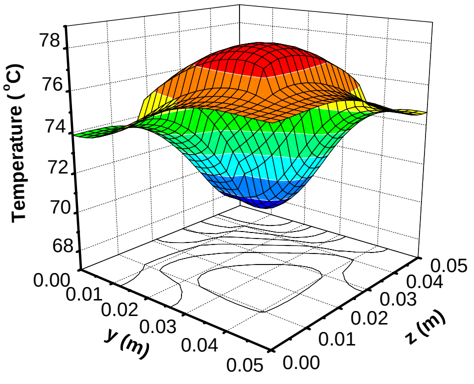
The temperature distributions at the surface between chip device and cooling module (i.e., x=0) under different cases are depicted in Fig. 2, in which the cooling module is made by metal of aluminum, and the power of chip device is 70 W. It can be seen from Fig. 2 that as expected, the cooling performance of the liquid gallium is much better than that of the water. It also indicated that the larger the flow rate, the better the cooling performance. Moreover, comparing Fig. 2(a) with Fig. 2(c) and Fig. 2(b) with Fig. 2(d), it can be found that for the cases using water as cooling fluid, the lowest temperature does not appears in the vicinity of flow inlet while it does for the cases of gallium. The reason for this phenomenon is that the low thermal conductivity of water does not allow energy to efficiently transfer from the solid heat transfer surfaces of the source to the cooling fluid, and then resulting in that the lowest temperature appears at the first curve location of the fluid channel. It further indicates that as a heat transfer fluid, liquid gallium is much attractive for high power density device cooling primarily due to its high thermal conductivity, as compared with water. Figure 3 gives the transient responses of temperatures at the center of heating surface and the outlet of fluid for the four cases of Fig. 2. It can also be concluded from Fig. 3 that the cooling capability of liquid gallium is much more powerful than that of the water cooling, even if the flow velocity for water is much larger than that for liquid gallium (comparing cases 2 with 3).



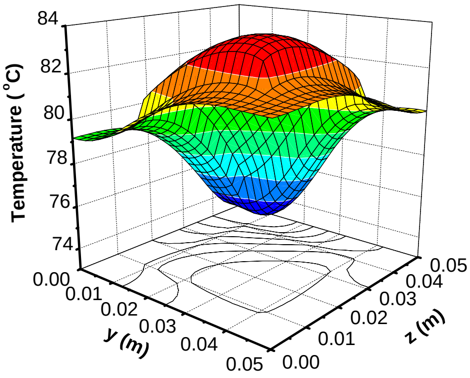
(a) gallium as cooling fluid, v=0.5 m/s



(b) gallium as cooling fluid, v=0.2 m/s



(c) water as cooling fluid, v=0.5 m/s



(d) water as cooling fluid, *v*=0.2 m/s

Fig. 2. Temperature distributions at *x*=0, *t*=600 s (P_c=70 W)

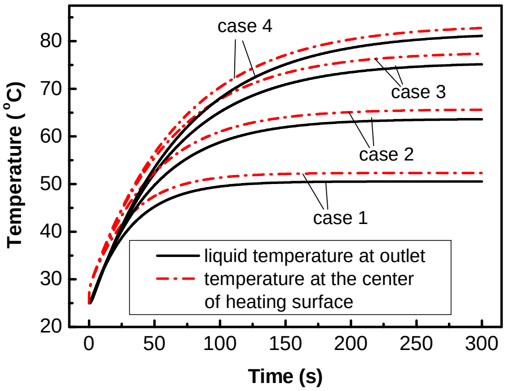


Fig. 3. Transient temperatures at the center of heating surface and the outlet of fluid for different cases (P_c =70 W). Case 1 - gallium as cooling fluid, and *v*=0.5 m/s; Case 2 - gallium as cooling fluid, and *v*=0.2 m/s; Case 3 - water as cooling fluid, and *v*=0.5 m/s; Case 4 - water as cooling fluid, and *v*=0.2 m/s

In order to investigate the effect of thermophysical properties of cooling module on its cooling performance, numerical simulation for the heat transfer inside the cooling module (made by copper) is also performed. The results are depicted in Fig. 4. For convenience of comparison, corresponding results for the case of cooling module made by aluminum are also included in Fig. 4. It is indicated that the cooling performance of the system will obtain significant enhancement, if the cooling module is made by material with high thermal conductivity.

According to the International Technology Roadmap for Semiconductors [23], the predicted maximum power dissipation from a single chip package will be 170 W in the year 2008. The thermal load used in the above calculations is only 70 W, which is much less than this prediction. In order to further investigate the capability of liquid gallium based cooling module, transient temperatures at the center of heating surface under different thermal loads are computed and the results is presented in Fig. 5. It is clearly shown that even under the extreme thermal load (P_c =200 W), the maximum temperature is still below 80 °C. This indicates again that liquid gallium has strong capability for extreme cooling needs.

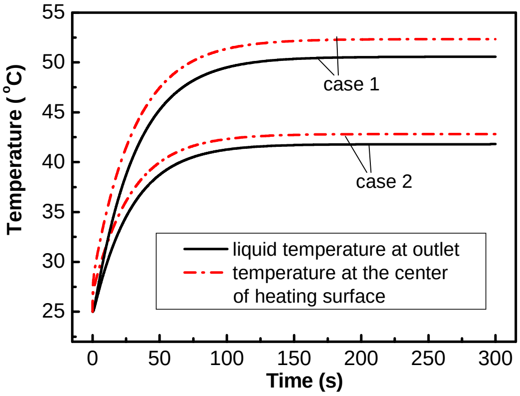


Fig. 4. Transient temperatures at the center of heating surface and the outlet of fluid (P_c =70 W, *v*=0.5 m/s, and gallium as cooling fluid). Case 1 - cooling module made by aluminum; Case 2 - cooling module made by copper

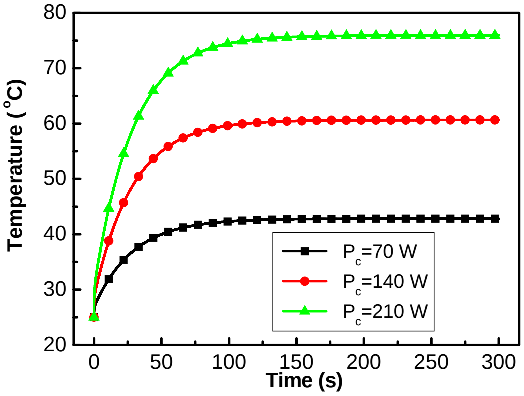


Fig. 5. Transient temperatures at the center of heating surface under different powers of chip device (*v*=0.5 m/s, gallium as cooling fluid, and cooling module made by copper)

CONCLUSIONS

The performance and capability of the liquid metal based cooling module has been numerically investigated in this study. The results indicate that the liquid metal has powerful cooling capability, which is much better than that of the conventional water based cooling system. Due to its excellent heat transfer performance, liquid metal will provide a useful alternative for extreme cooling needs in the near future. The numerical algorithm presented in this study is expected to be served as a valuable thermal management tool for designing the liquid metal based chip cooling device.

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