Development of Micro Channel Heat Exchanging*

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In order to investigate the performance of the micro channel heat exchanger, three-dimensional numerical simulations and experiments on heat transfer behavior and pressure loss were carried out. So far as the heat transfer phenomena is concerned, results obtained using a silicon chip micro channel model showed a very small thermal resistance, about 0.1 (Kcm²/W). And, measured pressure loss showed good agreement with that of analytical result obtained on the basis of fully developed laminar pipe flow assumption. Furthermore, a practical setup was made with a micro channel heat exchanger to clarify the possibility of using the micro channel heat exchanger in electrical equipment. As a result, it was confirmed that the performance of the micro channel heat exchanger system is sufficient to cool a silicon chip which generates a large amount of heat, and the scale of the system is compact compared to that of the whole setup of electrical equipment.

Key Words: Micro Channel, Microfluidics, Forced Convection, Heat Transfer Enhancement, Heat Exchanger, LSI, CFD

1. Introduction

An increase in the heating density of semiconductor devices has been a serious problem affecting the performance and reliability of the electrical devices. The cooling technology using micro channels proposed by Tuckerman, et al.⁽¹⁾ can remarkably reduce the contact thermal resistance in the cooling section which is regarded as the main cause of the problem with the semiconductor cooling method. In this method, micron-order channels are fabricated on the back surface of a semiconductor chip and coolant is supplied to the channels, thus enhancing the cooling performance. In addition, as the technology does not require the entire chip to be dipped in coolant as in the

case with the dip-cooling method, the reliability of devices is also improved.

Numerous studies relating to micro channel heat exchangers have been performed since the study conducted by Tuckerman, et al. Basic researches include those⁽²⁾ which examined pressure loss, an important design parameter and those^{(3),(4)} which derived guidelines for design from experiments and numerical calculations of heat transfer characteristics. Another study⁽⁵⁾ proposed a manifold type micro channel heat exchanger aimed at reducing pressure loss for practical use in addition to evaluating heat transfer efficiency⁽⁶⁾. Recently, a basic study on the multiphase flow inside a channel has been conducted and studies on micro heat pipes and micro dream pipes have also been started^{(7),(8)}.

The problems to be solved when equipping semiconductor devices with micro channel heat exchangers are referred to below.

Needless to say, it is essential to evaluate the pressure loss phenomenon and heat transfer efficiency of micro channel heat exchangers. Since the heat exchangers are extremely small, it is necessary to develop a temperature measurement method to

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measure the temperature distribution in a microstructure so that the thermal stress which is a problem in designing semiconductors may be predicted.

In addition, for the practical utilization of the technology, the compactness and reliability of the heat exchangers need to be secured to increase the applicability of the technology into the actual electronic devices.

In this study, having due consideration to all the above factors, micro channels were actually fabricated in silicon chips to evaluate the pressure loss and precise heat transfer efficiency using the thin film thermocouple formed on the chip heating surface by sputtering method. The evaluation values were then compared with the results of mathematical calculations. Furthermore, a cooling device prototype was manufactured on the basis of the results, which focused on the compactness and reliability of the device, and enabled us to clarify the practical applicability of the technology in practical heat exchanger.

Symbols

- A : micro channel cross-section area
- a : micro channel depth
- b : micro channel width
- c : Poiseuille's constant
- C_p : constant-pressure specific heat
- d_e : hydraulic diameter
- f : friction factor
- k : thermal conductivity
- L : channel length
- P_z : pressure gradient
- P : fluid drive power
- q : average heat flux on the surface of chip
- Re : Reynolds number
- Rt : thermal resistance
- S : heat source
- t : time
- T : temperature
- T_s : temperature on the surface of chip
- T_i : temperature of coolant at the inlet
- u : coolant flow velocity (in z direction)
- u_m : average coolant flow velocity (in z direction)
- x : coordinate axis (in the direction of channel depth)
- y : coordinate axis (in the direction of channel width)
- z : coordinate axis (in the direction of channel flow)
- ΔT : increase in temperature
- ΔP : pressure loss
- ε : aspect ratio of channel cross-section
- μ : viscosity coefficient
- ρ : density

ν : kinematic viscosity coefficient

2. Micro Channel Chip

The micro channel chip used in the present study was manufactured as described below.

Figure 1 shows the outline of a micro channel chip. Two silicon substrates, comprising a channel plate with deep grooves and a cover plate with an etched rectangle coolant inlet and outlet (for sumps) were bonded to form channels. The coolant is supplied via one of the two sumps and discharged from the other sump. Thin film thermocouples are formed on the channel plate to measure temperature of the chip surface. Figure 2 shows the procedure of manufacturing the micro channel chip.

(a) The deep grooves that will comprise the coolant channels are formed in the channel plate by anisotropic etching. To form long deep grooves, a silicon wafer is used for the substrate, and potassium hydrate (KOH) solution is used as etchant. In the prototype sample, 110 channels measuring 13-mm long are formed with 100 μm pitches. The formed grooves are either 57 μm (width) $\times$ 180 μm (depth) or of 57 μm $\times$ 370 μm .

(b) Anisotropic etching is applied on the cover plate to form the coolant supply openings (sumps). The distance between the coolant inlet and outlet openings (for sumps) is 11 mm.

(c) The two plates are then bonded by silicon direct bonding method⁽⁹⁾ to form channels (rectangle pipes). This means the actual length of a channel (rectangle pipe) is 11 mm, with an overlap dimension of 1 mm at each inlet/outlet portion.

(d) Two thin Fe-Ni film thermocouples, with dimensions of 1 mm (width) $\times$ 0.2 μm (thickness) for temperature measurement are formed at both ends of the channels on the channel plate using sputtering method.

Fig. 1 Micro channel chip

Fig. 2 Fabrication process

Fig. 3 Cross-sectional view of micro channel chip

Thin SiO_2 film layer is formed between the thermocouples and the plate to isolate them electrically. The depth and width of the fabricated channels are determined by averaging the values measured with a microscope at several randomly-selected positions along the channels. Figure 3 shows the photo image of the cross-sectional view of a micro channel chip. The image clearly shows the channels with long rectangular cross-sections.

3. Experiment

Figure 4 shows the experimental apparatus for basic behavior of heat transfer and pressure loss. The micro channel heat exchanger was set on the holder. And, the coolant (water) was supplied from the waterworks. The pressure loss between the inlet and the outlet of the channels was measured using a

Fig. 4 Experimental apparatus

differential pressure transducer through the pressure taps. To input a large amount of heat to the chip, a copper block, which was contacted to the chip, was heated by a gas burner. The precise value of input heat was calculated by measuring flow rates and temperature rise of the coolant. Heat flux was about 100 W/cm^2 .

4. Basic Behavior of Heat Transfer and Pressure Loss

First, we present the results of the test on pressure loss which is an important factor in this design process. No heat is applied to the chip in the measurement of pressure loss. Poiseuille's constant C in Fig. 5 is expressed by the following equation.

$$f = \frac{2 \cdot \Delta P \cdot de}{\rho L u_m^2} = \frac{C}{Re} \quad (1)$$

The solid and dotted line in the figure represent the theoretical value of Poiseuille's constant $C^{(10)}$ on the assumption that the flow inside the rectangular pipe is a fully developed laminar flow, respectively. Constant C can be defined as shown below.

$$C = \frac{96}{(1 + \epsilon)^2} \left[1 - \frac{192\epsilon}{\pi^5} \sum_{n=1}^{\infty} \frac{\tanh\{(2n-1)\pi/2\epsilon\}}{(2n-1)^5} \right] \quad (2)$$

Although there is good agreement between the experi-

Fig. 5 Pressure loss

mental and theoretical values in general, the figure also illustrates the tendency of the experimental values to exceed the theoretical values after 200 (Re) or thereabout. This may be due to the disturbance in the flow. The characteristic length and velocity are equivalent to the hydraulic diameter d_e and the average flow rate u_m , respectively.

Next, we discuss the heat transfer efficiency of a micro channel chip. Numerical simulations were conducted to compare the results with the experimental values. Figure 6 shows the numerical model. The boundary conditions of the numerical model were determined by taking symmetry into consideration. The heat transfer efficiency of a micro channel chip was defined by solving the following energy equation, which is applicable to coolant flow velocity distribution in the channel.

— Energy equation

$$\rho C_p u \frac{\partial T}{\partial x} = k \left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} \right) + S \quad (3)$$

— Coolant flow velocity distribution in a channel

$$u = -\frac{16b^2 Pz}{\mu \pi^3} \sum_{n=1}^{\infty} \frac{(-1)^{n-1} \cosh(mx)}{(2n-1)^3 \cosh(ma)} \cos(my) + \frac{Pz}{\mu 2} (b^2 - y^2) \quad (4)$$

$$m = (2n-1)\pi/2b \quad (5)$$

This numerical simulation describes the temperature rise of coolant.

The chip surface temperature was determined from the experiments and the simulations. Based on the above, the thermal resistance of a chip is defined by the following equation.

$$R_t = \frac{\Delta T}{q} = \frac{T_s - T_i}{q} \quad (6)$$

Equation (6) is based on the temperature of the coolant at the inlet portion. In other words, R_t can be expressed as the sum of the thermal resistance resulting from the increase in the temperature of the

Fig. 6 Numerical model

Fig. 7 Thermal resistance ($57 \mu\text{m} \times 180 \mu\text{m}$)

coolant inside the channel and the local thermal resistance of the coolant. The temperature gradient on the surface of a chip is expected to be large. Since the form employed in Eq. (6) allow us to understand the temperature of the surface of the chip or the temperature gradient intuitively for designing, this value was employed for the evaluation of the heat transfer efficiency.

Figure 7 shows the thermal resistance on the chip surface near the channel inlet and channel outlet while

Fig. 8 Thermal resistance (aspect ratio $\varepsilon=3, 5, 7$)

the chip is heated. The experimental thermal resistance and calculation values differ substantially when the Reynolds number is low. This seems to be due to the difficulty in estimating all the experimental errors in this range since the flow rate is too low to conduct experiments precisely and there is a major gap between the properties used in the calculation such as viscosity, etc. and the actual properties, since the increase in the temperature of the coolant inside the channel is extremely large. There is good agreement between the values for the positions near the outlet. However, there is a tendency for the experimental results to be lower than the thermal resistance obtained by calculation when Re is at or higher than 200. The heat transfer efficiency appears to increase under the influence of the spatially developing region of pipe flow or disturbance as was observed in the case of the friction factor. The difference of thermal resistance between the inlet and outlet of the channel at $Re=200$ is approximately $0.1 \text{ K cm}^2/\text{W}$.

This means that a temperature difference of approximately 10°C results inside a chip when 100 W/cm^2 heat flux is added, expressing large-scale heat transfer efficiency when compared to other cooling methods on the basis of average thermal resistance. However, special attention should be paid to the thermal stress generated by the temperature gradient inside a chip.

Figure 8 shows the heat transfer efficiency levels for different channel aspect ratios resulted from mathematical calculation for the purpose of providing guidelines for micro channel heat exchanger design. The vertical axis in the figure represents the thermal resistance, while the horizontal axis represents fluid drive power. The fluid drive power is defined as follows.

$$P = 100 \times \Delta P \cdot u_m \cdot A \quad (7)$$

Fig. 9 Cooling system using the micro channel

The fluid drive power takes up the flow rate of 100 channels (" $100 \times A$ " in Eq.(7)) so that the chip surface area will be 1 cm^2 when the channel pitch is $100 \mu\text{m}$, channel width is $57 \mu\text{m}$, and channel length is 1 cm . Increased pressure loss inside a channel is a common problem with micro channels, however, since the fluid drive power P is the product of the pressure loss and average flow rate, the pressure loss is a convenient factor for evaluating the influence of this factor on the fluid drive power. The aspect ratios used for the calculation models are 3, 5, and 7. The solid lines in the figure represent the average thermal resistance in a chip, while the dotted lines show the average flow velocity in a channel (fixed).

If the target average thermal resistance in the design is set to a figure in the order of $0.1 \text{ K cm}^2/\text{W}$, the average flow rate at about $u=2 \text{ m/s}$ will be sufficient to realize the target for the aspect ratio of 5 ($Re=220$, $Rt=0.08 \text{ K cm}^2/\text{W}$). The pressure loss under this condition is calculated to be about 0.07 MPa based on the fluid drive power. The flow rate for the aspect ratio of 3 is about 4 m/s . With the fluid drive power at a fixed level, the greater the aspect ratio is, the lower the thermal resistance becomes, although the effect is reduced by the influence of the heat transfer behavior inside the chip.

5. Practical Application of Micro Channel Heat Exchanger

On the basis of the discussion above, practical LSI cooling equipment using the micro channel heat exchanger was set up. In this section, the heat exchanger with the channels ($57 \mu\text{m} \times 300 \mu\text{m}$) was used. Figure 9 shows a coolant-supplying holder of the micro channel heat exchanger. Four micro channel chips were attached to this holder by epoxy adhesive, and this simulated an MCM which had several LSI chips. Coolant flow in the holder is also shown in

Fig. 10 Micro channel holder

Fig. 10.

In choosing the parts of the cooling system, thermal resistance and pressure loss must be considered. In the present study, the cooling system was designed so that the mean value of thermal resistance of the chip was about $0.1 (\text{Kcm}^2/\text{W})$. From the numerical results shown in Fig. 7, the mean value of the thermal resistance is achieved to $0.1 (\text{Kcm}^2/\text{W})$. At this condition, aspect ratio of this channel is about 5. Therefore, the mean velocity in the channels is about 2 m/s ($Re=220$, whole flow rate of the system is $3.8 \text{ cm}^3/\text{s}$), and pressure loss of the whole system is about $0.14 (\text{MPa})$ (2×2 chips). The pressure loss value of the whole cooling system was thought to be almost the same as that of the holder, including chips, and the pump was chosen.

To verify the mean value of the thermal resistance of this heat exchanger, a thin film heater (Ni, $10 \text{ mm} \times 10 \text{ mm}$ in area, 0.2Ω in resistance) was sputtered on the surface of the chip. And, a thermocouple (K type, 0.2 mm in diameter) was contacted at the center of the channel as shown in Fig. 11. The micro channel heat exchanger set up on the motherboard is shown in Fig. 12. The heat exchanger is almost the same size as the MCM, and is sufficiently small compared with that of the motherboard. The heat exchanger could be set up in the motherboard, and the pump or other parts also were compact compared to the size of the whole setup of electrical equipment. In the experi-

Fig. 11 Measurement of the chip temperature

Fig. 12 Practical setup model of micro channel

ments, input heat flux was about 30 W/cm^2 . The cooling system was working for 7 days, and the thermal resistance of the heat exchanger was maintained at $0.1 \text{ Kcm}^2/\text{W}$ without any troubles such as water leak or short circuit.

6. Conclusion

The Micro channel heat exchanger was prepared and the heat transfer efficiency and pressure loss were evaluated. On the basis of the model heat exchanger, a practical setup model was subsequently prepared to examine the practical applicability of the technique. The following are the conclusions derived from the experiments and the simulations.

(1) Thin film thermocouples were formed on the surface of the chips to measure temperature distribution, which produced detailed and precise measurements on a micron basis. Since the thermocouples are prepared using the sputtering method, their size can be dramatically reduced. The thermocouples may be applied to the monitoring of temperature inside semiconductor packages.

(2) As for the heat transfer efficiency of the heat exchanger, the thermal resistance was found to be in the order of $0.1 \text{ Kcm}^2/\text{W}$, and it was confirmed that

the pressure loss can be predicted from the theoretical values of the fully-developed flow inside the channel, up to the level of $Re=200$ or thereabout.

(3) A practical setup model was prepared on the basis of the above-mentioned findings. As a result, the predicted thermal resistance levels were observed. Furthermore, the model demonstrated the required compactness and reliability of the heat exchanger.

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