Allowable Repetition Frequency of Pulse Heating in Microactuators Using Rapid Boiling (Effect of Electrical Insulation Layer beneath Heater)*

Jeong-Hun KIM** Kunito OKUYAMA*** and Yoshihiro IIDA***

**Institute of Ocean Energy, Saga University,

1-48 Kubara-aza, Hirao, Yamashiro machi, Imari, Saga 849-4256, Japan

E-mail: kim@ioes.saga-u.ac.jp

***Department of Chemical Engineering Science, Yokohama National University,

79-5 Tokiwadai, Hodogaya-ku, Yokohama 240-8501, Japan

E-mail: okuyama@ynu.ac.jp

Abstract

High-frequency pulse heating of heaters in microactuators utilizing the rapid expansion of boiling bubbles causes a gradual increase in the temperature of the heater and the substrate material in the immediate vicinity of the heater, resulting in a loss of reproducibility of the boiling phenomena. In the present report, the maximum frequency at which the steady increase in heater temperature can be maintained within the allowable limit for the succession of pulse heating is obtained by numerical simulations based on the heat conduction from the heater to the adjacent materials in the system having an electrical insulation layer between the heater element and the silicon substrate. Calculations are carried out using a model in an axisymmetrical system for two different heating conditions, that is, transient heating by a single pulse and steady heating by the time-averaged power during repetition of pulses, instead of the direct calculation of the entire repetition process. The effects of heater size and pulse width on the allowable repetition frequency are examined over wide ranges of these parameters. The influence of the insulation layer on allowable repetition frequency is investigated by comparing the calculation results with those of the case of without the insulation layer. Approximate correlations for the allowable repetition frequency are also derived based on an analytical examination.

Key words: Microactuator, Rapid Boiling, Pulse Heating, Allowable Repetition Frequency, Numerical Simulation

1. Introduction

Microactuators using rapid liquid-vapor phase change are receiving increased interest due to such advantages as simple structure, the absence of mechanically moving parts, significant expansion caused by large vapor pressure, and high responsivity⁽¹⁾⁽²⁾. The dynamics of vapor bubble(s) generated with high single pulse imposed on the micro film heater have been investigated by many researchers⁽³⁾⁻⁽¹¹⁾. Successive and stable actuation could be accomplished by the repeated pulses and the corresponding boiling which takes place with reproducibility. However, pulse heating at high frequency may cause a gradual increase in the temperature of the heater and the substrate adjacent to the heater,

*Received 6 Feb., 2006 (No. 06-0003)
[DOI: 10.1299/jtst.1.20]

which may result in a loss of reproducibility of boiling phenomena and/or damage to the heater due to overheating^{(12)~(14)}.

In the previous paper⁽¹⁵⁾, the authors performed numerical simulations of heat conduction from the heater to the liquid and the substrate consisting of a single material using an axisymmetrical model and, based on the results, predicted the maximum repetition frequency that the increase in the time-averaged heater temperature can be maintained within an allowable limit. The heat transfer enhancement or deterioration caused by boiling was neglected because boiling duration was much smaller compared to the single period of repetition and the change in the measured heat transfer rate was not significant. Instead of direct calculation of heat conduction for the entire repetition process, calculations at two different heating conditions were performed. One was single pulse heating and the other was steady heating at a time-averaged power during repetition of pulses. The dependence of the frequency on the heater size, pulse width and substrate properties was examined. For a prescribed pulse width and temperature increases both at pulsed and time-averaged power, the allowable repetition frequency increased significantly with the decrease in heater size to be saturated at long pulse widths. The allowable repetition frequency was correlated in terms of the dimensionless quantities governing the phenomenon. Approximate correlations were also derived. These predictions agreed well with the experimental results for both in the cases with and without boiling during repetition pulse heating.

Most micro heaters^{(5)~(11)} fabricated on the silicon substrate by means of MEMS technology have a thin layer of silicon dioxide (SiO_2) beneath it for the purpose of electrical insulation. The thermal conductivity and thermal diffusivity of silicon dioxide (SiO_2) are nearly two orders of magnitude smaller than those of silicon. Although the allowable repetition frequency for pulse heating may be affected by the presence of the SiO_2 layer, this effect was not considered in the previous paper⁽¹⁵⁾.

In the present report, the maximum frequency at which the steady increase in heater temperature during pulse heating repetition could be maintained within the allowable limit has been obtained by numerical simulations based on the heat conduction from the heater to the adjacent materials in the system with an SiO_2 layer between the heater element and the silicon substrate. The effects of heater size and pulse width on the allowable repetition frequency have been examined and compared with those of the case without the insulation layer. The allowable repetition frequency is correlated in terms of dimensionless quantities, based on the analytical examinations.

2. Nomenclature

- c_p : specific heat [J/(kg·K)]
- D_h : diameter of film heater [m]
- f : repetition frequency of pulse heating [s^{-1}]
- f_a : allowable repetition frequency of pulse heating [s^{-1}]
- Fo : Fourier number [-] ($= \alpha \tau / D_h^2$)
- k : thermal conductivity [W/(m·K)]
- L : length [m]
- Q'' : heating power per unit heater surface area [W/m^2]
- Q_p'' : pulse heating power per unit heater surface area [W/m^2]
- $Q_{p,i}''$: heat flux transferred to medium i by pulse heating [W/m^2]
- Q_s'' : time-averaged heating power per unit heater surface area [W/m^2]
- $Q_{s,i}''$: heat flux transferred to medium i by time-averaged heating [W/m^2]
- r : coordinate in the radial direction [m]
- R_h : radius of film heater [m]

- S : shape factor for two-dimensional heat conduction [m]
 t : time [s]
 T_a : allowable limit of heater temperature [$^{\circ}\text{C}$]
 T_h : heater temperature [$^{\circ}\text{C}$]
 T_i : local temperature in medium [$^{\circ}\text{C}$]
 T_l : liquid bulk temperature [$^{\circ}\text{C}$]
 T_{τ} : heater temperature at time equal to pulse heating period [$^{\circ}\text{C}$]
 ΔT_a : allowable limit of heater temperature increase [K]
 ΔT_{τ} : heater temperature increase for pulse heating at $t = \tau$ [K]
 z : coordinate in the direction normal to the heater surface [m]
 α : thermal diffusivity [m^2/s]
 δ_p : heat penetration depth [m]
 δ_h : thickness of film heater [m]
 δ_e : thickness of electrical insulation layer [m]
 Φ : dimensionless allowable repetition frequency for pulse heating [-]
 $(= f_a \tau (\Delta T_{\tau} / \Delta T_a))$
 ρ : density [kg/m^3]
 τ : pulse heating period [s]

3. Simulation Model and Procedure

Figure 1 shows the simulation area in the present model. The semi-infinite silicon substrate has an oxidized layer (SiO_2), whose thickness is δ_e on its surface, which is in contact with a sufficient volume of liquid. A small disk of film heater having diameter $D_h (= 2R_h)$ and thickness δ_h is located on the SiO_2 layer surface and is subjected to the repetition of heating pulse at a power Q_p , width τ and frequency f . The heat diffusion from the heater to the adjacent liquid and substrate during the repetition of heating is assumed to be conduction only, which is three-dimensional in terms of the Cartesian

Figure 1 Simulation area

coordinates. The heater temperature increases gradually before reaching the steady state (in terms of the time-averaged heater temperature over the repetition period). The precise prediction of the steady increase in the heater temperature requires the calculation of the entire heat transfer process during the repetition over ten thousands pulses, which requires an extremely long computation time. Here, we consider the steady heating at the time-averaged power Q_s'' which is defined by the following energy balance equation.

$$Q_s'' = Q_p'' \tau \quad (1)$$

Although the increase in heater temperature at the steady power Q_s'' is not identical to the increase in the time-averaged heater temperature during the pulses, the difference between them is considered to be insignificant. Therefore, numerical simulations associated with the allowable repetition frequency have been performed under the following two different heating conditions instead of direct calculation of the entire repetition process. One condition states that the transient heating at a single pulse power Q_p'' by which the heater temperature increases to the temperature required for boiling initiation T_τ at the time equal to the pulse width τ . The other condition states that steady heating at the time-averaged power Q_s'' by which the time-averaged heater temperature during repeated pulses is regarded to increase to a preset value of the allowable limit T_a . Both Q_p'' and Q_s'' have been determined, respectively, via iterative calculation for prescribed corresponding temperature increases ΔT_τ and ΔT_{as} and were then substituted into Eq. (1) with a prescribed pulse width τ to obtain the allowable repetition frequency of pulse heating f_a .

Temperature variations during heating at powers Q_p'' and Q_s'' can be obtained by solving the transient heat conduction equations for the associated media (Eq. (2)) under the following assumptions:

1. Uniform heat generation in the heater
2. Constant properties
3. Uniform temperature across the heater film

For the heater:

$$\frac{\partial T_h}{\partial t} = \frac{\alpha_h}{r} \frac{\partial}{\partial r} \left(r \frac{\partial T_h}{\partial r} \right) + \frac{Q''}{(\rho c_p)_h \delta_h} \quad (2.a)$$

For liquid, the SiO₂ layer and the Si substrate:

$$\frac{\partial T_i}{\partial t} = \frac{\alpha_i}{r} \frac{\partial}{\partial r} \left(r \frac{\partial T_i}{\partial r} \right) + \alpha_i \frac{\partial}{\partial z} \left(\frac{\partial T_i}{\partial z} \right) \quad (2.b)$$

where Q'' is the heating power per unit heater surface area, and $Q'' = Q_p''$ for pulse heating and $Q'' = Q_s''$ for steady heating. The subscripts $i = 1, s1$ and $s2$ denote the liquid, the silicon dioxide layer and the silicon substrate, respectively. These heat conduction equations were discretized according to the finite difference method, and numerical solutions were then obtained using a fully implicit scheme under the following initial and boundary conditions⁽¹⁶⁾.

Initial condition :

$$T(r, z, t = 0) = T_l = 25^\circ \text{C} \quad (3)$$

Boundary conditions :

$$r = 0 \quad : \quad \frac{\partial T}{\partial r} = 0 \quad (4)$$

$$r = R_h + L_{re} \quad : \quad T(R_h + L_{re}, z, t) = T_l \quad (5)$$

$$z = L_a \quad : \quad T(r, L_a, t) = T_l \quad (6)$$

$$z = -(\delta_e + L_b) \quad : \quad T(r, -(\delta_e + L_b), t) = T_l \quad (7)$$

where, L_a , $\delta_e + L_b$ and L_{re} are the distances from the heater to the outer boundary of the calculated region and were set to be sufficiently large so as not to affect the increase in heater temperature. For the steady power Q_s'' , the calculation was continued until the heater temperature reached a steady-state.

The properties of the film heater and the liquid were set to those of platinum and water, respectively, which are the materials used in the authors' experiment. The thickness of the heater δ_h was set to 0.25 μm . The thickness of the silicon dioxide layer δ_e was set to 1.25 μm , which is of the typical order of commercial thermal ink jet heater⁽¹¹⁾. In the previous paper⁽¹⁵⁾, we dealt with the cases of a substrate without an electrical insulation layer, and referred to the SiO_2 substrate case as Case I and the Si substrate case as Case II. The case of the Si substrate with an insulation layer in the present report is referred to as Case III. The temperature increase for steady power Q_s was set to $\Delta T_a (= T_a - T_l) = 25$ K, and the temperature increase for pulse power Q_p was set to $\Delta T_r (= T_r - T_l) = 265$ K, which corresponds to the temperature increase at the boiling inception by spontaneous nucleation. The heater diameter D_h and the pulse width τ were varied over the wide ranges of from 0.2 μm to 500 μm and from 0.1 μs to 10 ms, respectively.

4. Results and Considerations of numerical simulation

Figure 2 shows the calculated results of the allowable repetition frequency f_a plotted against the heater diameter D_h for different pulse widths τ , together with the results for Cases I and II (the SiO_2 and the Si substrates without the electrical insulation layer, respectively). The allowable repetition frequency f_a increases significantly with a decrease in D_h and tends to saturate to the value that depends on the pulse width, regardless of the existence of the insulation layer. The increase in f_a with D_h , which was also observed for all Cases, is attributed to the difference in the heat diffusion mode from the heater to the adjacent media between pulse heating and steady heating, as discussed in the previous paper⁽¹⁵⁾. That is, heat diffusion is almost one-dimensional in the direction normal to the heated surface for the short-period pulse heating but is three-dimensional for steady heating, which results in the difference in the dependence of the required heating power on the heater size.

As noted in Fig. 2, f_a in Case III becomes significantly higher than that in Case I and Case II, as τ decreases, except for the extremely small D_h . It is apparent that the electrical insulation layer beneath the heater plays a role to raise the allowable repetition frequency. The reason for this is discussed in the following paragraph.

Figure 2 Allowable repetition frequency as a function of diameter of heater for Cases I, II and III

(a) $\tau = 10 \mu\text{s}$

(b) $\tau = 10 \text{ ms}$

Figure 3 Isotherms around film heater at pulse heating ($t = \tau$)

Figure 3 shows the isotherms around the heater in the related media in Case III at the time equal to the pulse heating period ($t = \tau$), for considerably different pulse periods. The assumed heater size D_h ($180 \mu\text{m}$) is of the order of the micro heaters manufactured by MEMS technology. The thickness of the insulation layer δ_e is much smaller compared to D_h . At a short pulse width (Fig. 3 (a)), the temperature variation is almost limited within the SiO_2 layer in the substrate, and the Si substrate under the insulation layer is scarcely related to the heat diffusion process. The SiO_2 layer functions to provide thermal insulation, which obstructs the heat flow into the Si substrate during pulse heating, as well as the electrical insulation. As a result, the pulse heating power Q_p'' required for raising the heater temperature to a set value T_τ becomes much lower than that of Case II (1600 MW/m^2). On the other hand, at a large heating pulse width (Fig. 3(b)), the temperature variation expands considerably into the Si substrate over the SiO_2 layer. The thermal insulation effect by the SiO_2 layer may become small, and the heat diffusion rate to the substrate will be dominated by conduction in the Si substrate. The pulse power larger than that of Case I (14.4 MW/m^2) is needed to raise the heater temperature up to the required temperature.

Figure 4 shows the isotherms around the heater at steady heating for Case III compared to Case II. The heater size ($500 \mu\text{m}$ in dia.) is much larger than the thickness of the SiO_2 layer, similarly to that in Fig. 3. In spite of the low thermal conductivity of the insulation layer compared to that of the Si substrate, the temperature variation expands markedly inside the Si substrate, which is similar to Case II. The steady power (14.5 MW/m^2) is comparable to that for Case II (19.3 MW/m^2). The effect of the thermal resistance by the SiO_2 layer on heat diffusion from the heater appears to be small. The significance of the

Figure 4 Isotherms around film heater at steady heating for Case III and Case II

Si substrate on heat diffusion in Case III will be similar to the pulse heating of a long heating period, as shown in Fig. 3(b).

In Case III, with the decrease in the pulse width τ heat diffusion from the heater becomes to be dominated by the SiO_2 layer, which requires the smaller pulse power Q_p'' compared to the case without the SiO_2 layer, whereas the heat diffusion at the steady heating is dominated by the Si substrate for the heater of $D_h \gg \delta_e$. This difference in the medium to dominate the heat diffusion rate between pulse heating and steady heating may result in the higher allowable repetition frequency compared to that of Case II, according to Eq. (1) (see the results for $\tau = 10$ and $100 \mu\text{s}$ in Fig. 2). For a longer pulse width, heat diffusion is dominated by the Si substrate for both pulse and steady heating, and therefore, f_a of Case III approaches that of Case II (see the results for $\tau = 10 \text{ ms}$ in Fig. 2).

Figure 5 shows the isotherms around the heater at steady heating for three heaters of the different order in size. The ratio of the heater diameter to the insulation layer thickness D_h / δ_e is 8000, 28.8 and 0.16 for Figs. 5 (a), 5(b), and 5(c), respectively. The medium of the substrate related to heat diffusion gradually changes from the Si to the SiO_2 layer with the decrease in the heater size.

In the previous paper⁽¹⁵⁾, the analytical consideration was performed paying attention to the mode of the heat diffusion from the heater to the adjacent media (the liquid and the substrate without the insulation layer) depending on the pulse heating period. The heat penetration depth due to the conduction to the medium i ($i = \text{liquid or substrate}$) δ_p which is defined as $k_i \Delta T_\tau / Q_p''$, increases with the pulse heating period. For the small penetration depth relative to the heater diameter of $\delta_p / D_h \ll 1$, heat diffusion may become one-dimensional in the normal direction to the heater surface, whereas for the large ratio of $\delta_p / D_h > 1$, heat may diffuse three-dimensionally (in terms of the Cartesian coordinates). The difference in this diffusion mode affects the heat diffusion rate from the heater, and therefore, the allowable repetition frequency. Under the one-dimensional heat conduction normal to the heated surface, the ratio δ_p to D_h at the time equal to pulse heating period is proportional to the Fourier number $Fo (= \alpha \tau / D_h^2)$ and can be expressed as the following equation⁽¹⁵⁾.

$$\frac{\delta}{D_h} = \frac{2\sqrt{Fo}}{\sqrt{\pi}} \quad (8)$$

All results of f_a obtained by the numerical calculation for Cases I and II were well correlated as the relationship between Fo and the dimensionless allowable frequency, $\Phi \equiv$

(a) $D_h = 10 \text{ mm}$

(b) $D_h = 36 \text{ μm}$

(c) $D_h = 0.2 \text{ μm}$

Figure 5 Isotherms around film heater at steady heating for different heater sizes

$f_a \tau (\Delta T_r / \Delta T_a)$, over the entire parameter ranges of D_h and τ . In Case III, heat diffusion may also depend on the relative magnitude of the heat penetration depth δ_p to the insulation layer thickness δ_e and also the relative magnitude of D_h to δ_e , as seen in the results shown in Figs. 3 and 5. The analytically approximated correlations of the allowable frequency for Case III, which depends on these relative sizes, have been derived, in the similar manner to those conducted for the cases of a single material substrate.

a) Case of δ_p much smaller δ_e , and D_h much larger than δ_e ($\delta_p \ll \delta_e \ll D_h$)

The heat diffusion to the substrate side is limited to the inside of the SiO_2 layer and one-dimensional in the direction normal to the heater surface, as shown in Fig. 3 (a). Assuming a negligible heat capacity of the heater, the relationship between a pulse heating power per unit heater surface area Q_p'' and the increase in heater temperature at a pulse heating period, ΔT_r , can be expressed as⁽¹⁷⁾

$$Q_p'' = Q_{p'',s} + Q_{p'',l} = \frac{\sqrt{\pi}}{2\sqrt{\tau}} \left(\frac{k_{s1}}{\sqrt{\alpha_{s1}}} + \frac{k_l}{\sqrt{\alpha_l}} \right) \Delta T_r \quad (9)$$

where the subscripts $s1$ and l denote the electrical insulation (SiO_2) layer and liquid,

respectively. Under the condition of no heat exchange between the substrate and liquid in the region next to the heater ($r > R_h$), the relationship between a steady heating power per unit heater surface area Q_s'' and the corresponding heater temperature increase ΔT_a can be expressed by referencing the shape factor for two-dimensional heat conduction in cylindrical systems, $S = 2D_h^{(18)}$, as

$$Q_s'' = Q_{s'',s} + Q_{s'',l} = \frac{8}{\pi D_h} (k_{s2} + k_l) \Delta T_a \quad (10)$$

where the subscript $s2$ denotes the substrate (Si). Substituting Eqs. (9) and (10) into Eq. (1), we obtain the relationship between the dimensionless allowable repetition frequency Φ and Fo .

$$\Phi = \frac{(k_l + k_{s2}) \sqrt{\alpha_l}}{(k_l \sqrt{\alpha_{s1}} + k_{s1} \sqrt{\alpha_l})} \left(\frac{16}{\pi^{3/2}} (\sqrt{Fo})_{s1} \right) \quad (11)$$

where the thermal diffusivity of the insulation layer material (SiO_2) is used to calculate the Fourier number. Equation (11) could be reduced to the correlation of Case I by substituting k_{s1} for k_{s2} and also could be reduced to that of Case II by substituting (k_{s2}, α_{s2}) for (k_{s1}, α_{s1}) . The reduced equations are identical with those derived in the previous paper for a single material substrate ⁽¹⁵⁾.

b) Case of δ_p comparable to or larger than D_h ($\delta_p \geq D_h$)

b-1) Case of δ_e much smaller than D_h

The heat diffusion to the substrate during pulse heating is almost dominated by the silicon as shown in Fig. 3(b), and in the same manner as Eq. (10), the relationship between the pulse heating power Q_p'' and the increase in the heater temperature ΔT_τ can be expressed as

$$Q_p'' = Q_{p'',s} + Q_{p'',l} = \frac{8}{\pi D_h} (k_{s2} + k_l) \Delta T_\tau \quad (12)$$

Substituting Eqs. (10) and (12) into Eq. (1), we obtain

$$\Phi = 1 \quad (13)$$

b-2) Case of D_h much smaller than δ_e

Heat diffusion in the substrate is almost dominated by the SiO_2 layer for both pulse and steady heating (Fig. 5(c)). By substituting k_{s1} for k_{s2} in Eqs. (10) and (12), we obtain the same result as Eq. (13).

Figure 6 shows the simulation results that were summarized using Fo and Φ , where the heater size was changed over a wide range of the pulse period for the prescribed temperature increases for pulse and steady heating. The thermal diffusivity of the insulation layer (SiO_2) was used to calculate the Fourier number. The broken lines represent the approximate values obtained by Eqs. (11) and (13), which give the asymptotes

Figure 6 Dimensionless allowable repetition frequency of pulse heating for Case III obtained by numerical calculation of heat conduction, together with those obtained by analytical correlations

for the numerical results in Case III at a moderate pulse period around 10 μs . The simulated values of Φ for Case III are much larger than the values (asymptotes) for Cases I and II at the same Fo ($Fo < 0.1$). (Note that the Fourier number for Case II is calculated using the thermal diffusivity of silicon.) In Case III, the relationship between Φ and Fo by the numerical simulation shows three tendencies depending on the order of the pulse width. These tendencies are different from those of Cases I and II. At a pulse width around 10 μs , Φ increases in proportion to the square root of Fo for $Fo < 10^{-7}$ and approaches unity for $Fo > 10^{-2}$, which is similar to the single material substrate (Cases I and II). As the pulse period becomes smaller than the order of 10 μs , the numerically simulated values of Φ depart from that of the asymptote (Eq. (11)) with an increase in Fo , and tend to approach the asymptote for Case I before converging into $\Phi = 1$. This tendency occurs because heat diffusion from the heater at steady heating becomes to take place within the SiO_2 layer rather than the Si substrate with the decrease in D_h , as shown in Fig. 5. For τ larger than the order of 10 μs , Φ tends to decrease parallel to the asymptote of Case III (Eq. (11)) in low Fo region. As the pulse period increases, the heat diffusion rate from the heater to the substrate becomes to be affected by the diffusion in the Si substrate ($\delta_p > \delta_e$). Therefore, the values of Φ depart from the asymptote for Case III and begin to approach that of Case II.

Based on the above results, it can be concluded that the allowable repetition frequency could be increased by the thin SiO_2 layer prepared on the Si substrate, if the thickness of the SiO_2 layer is appropriate so that heat diffusion during pulse heating takes place only within the SiO_2 layer and the time-averaged dissipated power is released into the Si substrate for the prescribed heater size and heating pulse period.

5. Conclusion

The maximum frequency at which the steady increase in heater temperature during pulse heating repetition can be maintained within the allowable limit has been obtained by numerical simulations based on the heat conduction from the heater to the adjacent materials in the system with an electrical insulation (SiO_2) layer between the heater element and the substrate element (Si). The allowable repetition frequency increases significantly with a decrease in the heater size for a prescribed pulse width, and tends to be saturated at certain value regardless of the substrate compositions at a large pulse width. The allowable repetition frequency for the silicon substrate with the insulation layer (Case III) is much larger than that for the silicon substrate without the insulation layer (Case II) for a moderate size of the heater and a short pulse period, as the electrical insulation layer also plays a role of thermal insulation for pulse heating. The approximate correlations for the allowable frequency in dimensionless form, which can express the asymptote to the value of Φ by Fo , have been derived. By adjusting the thickness of the electrical insulation layer according to the pulse heating conditions and the heater size, the allowable repetition frequency for pulse heating can be increased.

6. References

- (1) Tseng, F.G. et al., A High-Resolution High-Frequency Monolithic Top-Shooting Microinjector Free of Satellite Drop - Part I : Concept, Design, and Model, *Journal of Microelectromechanical Systems*, Vol. 11, No. 5 (2002), pp. 427-436.
- (2) Esashi, M. et al., *Micromachining and Micro electronics*, (in Japanese), Baifukan, Tokyo (1992), pp. 73-89.
- (3) Okuyama, K. and Iida, Y., Boiling Bubble Behavior and Heat Transfer Succeeding Spontaneous Nucleation on a Film Heater, *Proceedings of International Heat Transfer*

- Conference, No. 2 (1998), pp. 527-532.
- (4) Iida, Y. et al., Heat Transfer During Boiling Initiated by Fluctuation Nucleation on a Platinum Film Rapidly Heated to the Limit of Liquid Superheat (1st Report, Experiment under Atmospheric Pressure Condition), *Transactions of the Japan Society of Mechanical Engineers, Series C*, (in Japanese), Vol. 63, No. 613 (1997), pp. 3048-3054.
 - (5) Zhao, Z., Glod, S. and Poulikakos, D., Pressure and Power Generation During Explosive Vaporization on a Thin-film Microheater, *International Journal of Heat and Mass Transfer*, Vol. 43 (2000), pp. 281-296.
 - (6) Ye, X.Y. et al., Study of a Vaporizing Water Micro-thruster, *Sensors and Actuators A*, Vol. 89 (2001), pp. 159-165.
 - (7) Lin, L. et al., Thermal bubble formation on polysilicon micro resistors, *Journal of Heat Transfer*, Vol. 120 (1998), pp. 735-742.
 - (8) Asai, A. et al., One-Dimensional Model of Bubble Growth and Liquid Flow in Bubble Jet Printers, *Japanese Journal of Applied Physics*, Vol. 26, No. 10 (1987), pp. 1794-1801.
 - (9) Chen, P.-H. et al., Bubble Growth and Ink Ejection Process of a Thermal Ink Jet Printhead, *International Journal of Mechanical Sciences*, Vol. 39, No. 6 (1997), pp. 683-695.
 - (10) Avedisian, C.T. et al., Measuring Bubble Nucleation Temperature on the Surface of a Rapidly Heated Thermal Ink-Jet Heater Immersed in a Pool of Water, *Proceedings of the Royal Society A*, Vol. 455, No. 1991 (1999), pp. 3875-3899.
 - (11) Okuyama, K. et al., Transient Behavior of Boiling Bubbles Generated on the Small Heater of a Thermal Ink Jet Printhead, *Experimental Thermal and Fluid Science*, Vol.28, No.8, (2004), pp. 825-834.
 - (12) Okuyama, K. et al., Pumping Action by Boiling Propagation in a Microchannel, *Microscale Thermophysical Engineering*, Vol.9, No.2 (2005), pp. 119-135.
 - (13) Masaki, T., Japan Patent, H9-239989 (in Japanese).
 - (14) Kato, M., Japan Patent, H11-20148 (in Japanese).
 - (15) Okuyama, K. et al., Allowable Repetition Frequency of Pulse Heating in Microactuators Using Rapid Boiling (Effects of heater size and substrate material), *JSME International Journal Series B*, Vol. 46. No. 3 (2003), pp. 339-407.
 - (16) Patankar, S.V., *Numerical Heat Transfer and Fluid Flow*, Hemisphere Publishing Corporation, New York (1980), pp. 22-42.
 - (17) Carslaw, H.S. and Jaeger, J.C., *Conduction of Heat in Solids*, Oxford University Press, London (1959), pp. 75-77.
 - (18) Incropera, F.P. and DeWitt, D.P., *Fundamentals of Heat and Mass Transfer*, John Wiley & Sons, Inc., New York (1996), pp. 196-171.