Research on Micro Heater Efficiency for Thermal Inkjet Head

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Abstract

Micro heaters for thermal inkjet print heads are investigated to estimate the effects of heater size and operating condition on its thermal efficiency. Tantalum Aluminum (TaAl) heaters, 0.15μm in thickness, are prepared on silicon oxide layer. Silicon nitride film of 0.4μm thickness covers the heater. Visualization technique is applied to observe bubbles in open pool condition. Volume and life time of bubble are measured from CCD images of plane and side views of the bubble generated at the heat flux range of 0.5~5.0GW/m^2.

Thermal conduction simulation for the heater provides bubble nucleation pressure. Bubble work is calculated with Asai's pressure model[1] and the visualization results; bubble life time and volume. Then, thermal efficiency of the heater defined as the ratio of bubble work to the electric input energy can be estimated.

Introduction

Micro heater is one of the widely adopted actuators in Micro Electro Mechanical Systems (MEMS). Its material and simple structure are compatible with standard silicon process. Also the affluent actuating force enables the size to be small compared to the other types of actuators; piezoelectric, electrostatic, electromagnetic and acoustic. This is favorable for an array actuator of high spatial density such as an inkjet print head. Although superheating and rapid phase change in the working fluids limit its application, inkjet head with this micro heater array is widely used for small office and home applications and has potential in various fields. A large number of inkjet head type have been investigated as in the summary of Silverbrook.[2]

However, as the nozzle density and the head swath increase for higher printing speed, thermal problem arises from the low efficiency of the micro heater. Only a small portion of the heat generated from the heater converts to the ink drop momentum, and the rest must be dissipated to the surrounding structure comprised of ink and cartridge. Excessive heat accumulated in the head elevates ink temperature and lowers density and surface tension of the ink. This heat accumulation deteriorates the drop ejection quality and furthermore threatens the structural rigidity.

In MEMS, micro heater usually has a regular square shape. However the micro system becomes more complicated it forces the heater to have a large aspect ratio or even a circular shape. Various visualization results of a micro bubble contribute the understanding of the bubble generating mechanism but the study of the thermal efficiency of heater, especially its size and aspect ratio effect, is very limited. Asai[1] proposed the bubble nucleation theory to provide a guide to the design of thermal inkjet printer, and Andrews[7] showed the complete bubble cycles from nucleation to collapse by visualization techniques. Rembe[5] visualized the non-reproducible phenomena in micro heater with real high speed cine photomicrography.

In this paper, heater efficiency is experimentally investigated with help of computer simulation. Heater area and operating conditions are varied. Bubble volume is measured experimentally and the nucleation pressure is calculated from the heat conduction simulation. Pressure profile of the bubble is assumed with the Asai's model.

Sample Design & Fabrication

Micro heater for generating bubble is fabricated using conventional MEMS technique (Fig. 1). Thermal insulation layer of SiO_2 is thermally grown up to 3μm on silicon wafer. Heater (TaAl) and metal electrode (Al) are consecutively deposited by sputtering. The sheet resistance of TaAl film is 30Ω. Finally, silicon nitride film of 0.4μm thickness is deposited using PECVD technique as a heat transfer layer between heater and ink.

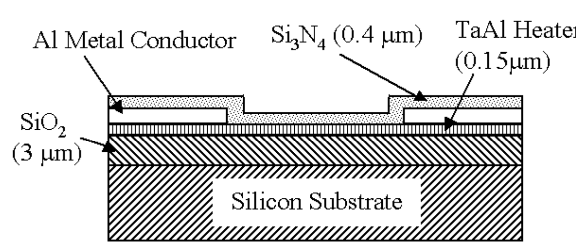


Figure 1. Heater layer structure.

Four heaters investigated are rectangular type and its dimension and operating conditions are summarized in Table 1. The heater length is constant of 60µm and the widths are 7.2, 17.6, 27.5 and 37.4µm respectively that the heater aspect ratio and area are varied. Heaters are arranged at a chip edge, about 300µm from the edge, for bubble side view images.

Experimental Details

Bubble on the heater is visualized with microscope in a open pool setup shown in Fig. 2. Xenon stroboscope provides the sample illumination through the microscope.

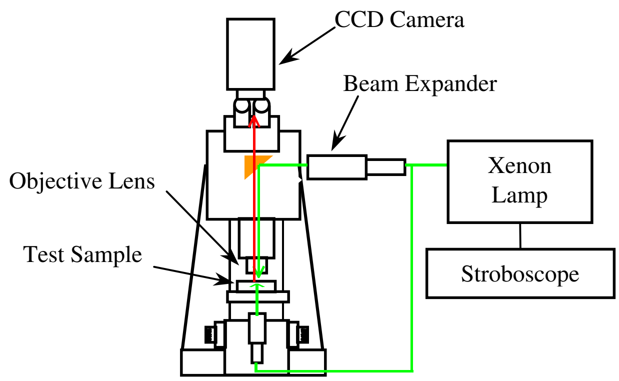


Figure 2. Visualization setup.

High speed CCD cameras capture the bubble that is synchronized with the input pulse to the heater.[8] The exposure time of the CCD is 0.3µs and the frame time of the consecutive images is 0.1µs. Estimation of the bubble volume at a fixed time requires two synchronized bubble images; plane and side views with the two CCD arrangement as shown in Fig. 3. CCD1 captures the bubble width, and length and the bubble height can be obtained with CCD2 image.

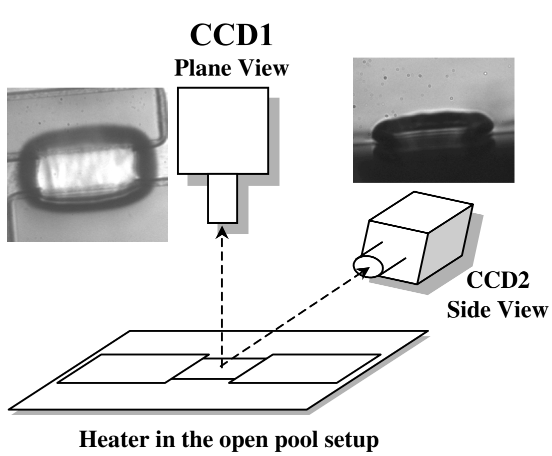


Figure 3. Two CCD for bubble volume acquisition.

Square wave type electric heating pulse of 8Hz repetition frequency is applied to the micro heaters. Voltage amplitude of the pulse determines the heater power density and the power density multiplied by the pulse width represents the input energy to the heater. The bubble volume and behavior varies with heating pulse condition and heater size. As shown in Table 1, three different power densities are chosen as the operating condition. Pulse width for each power density is set following to the procedure reported by the same working group.[3] Figure 4 depicts the operating condition of each heater. Bubbles for all heaters are observed at pulse width of 0.5 and 1.0µs identically with changing the power density to obtain the optimal bubble behavior. The longest pulse width for each heater is chosen at fixed power density.

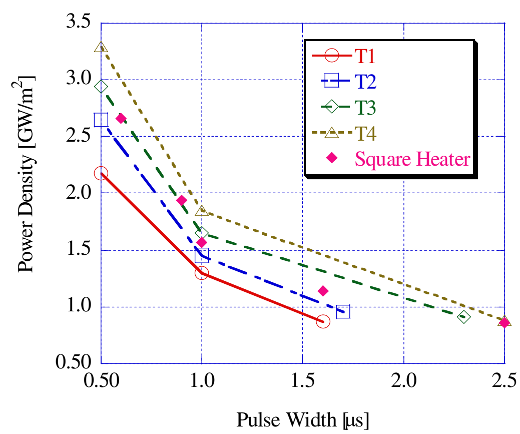


Figure 4. Micro heater operating conditions for three different input energy levels.

For reference, data from a 40µm × 40µm square heater is added in Fig.4. Its heater area is 1600 µm^2 and the operating condition locates between T1 and T2 whose areas are 1690 µm^2 and 2280µm^2, respectively. As the heater width increases, the bubble life time as well as the bubble volume increases at all heaters. At a given heater size, higher power density results in smaller life time and volume because the net thermal energy transferred to the ink actually decreases. However, the smaller bubble is more stable than the larger one that is generated at low power density. Nucleation at lower power density tends to unstable because of the augmented nucleation variation.

Bubble Work Estimation

Bubble work is calculated with the Asai's pressure model as follows.

1. Measure the bubble volume from the visualization results with the plane and side views of the bubble.

First, an image processing software(NI vision builder) calculates plane and side bubble areas (A_{plane}, A_{side}) at each time step as shown in Fig. 5. To minimize an error in volume estimation, effective bubble height($H_{effective}$) is defined as the A_{side}/W_{max}, where W_{max} is maximum bubble width at the side bubble image. Then the bubble volume is estimated as $A_{plane} \times H_{effective}$.

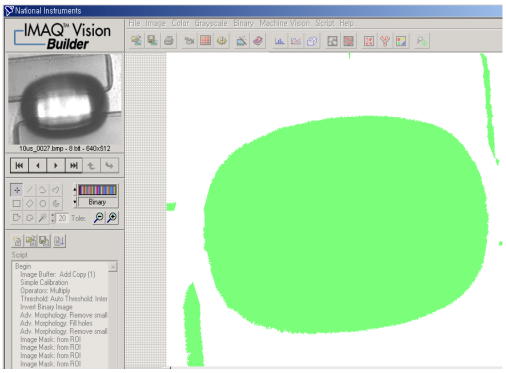


Figure 5. Bubble plane area calculation

2. Calculate the bubble nucleation pressure from the three dimensional heat conduction simulation.

Solve the temperature field until the time when the bubble nucleation is observed experimentally. Initial bubble pressure is assumed from the temperature of thin liquid film right above the micro heater.

3. Find the Asai's three parameters(p_g, τ, λ) for the bubble pressure p_v with the bubble volume equation.

$$V_v(t) = -\frac{1}{2}\frac{\left[p_{amb} - p_{sat}(T_{amb})\right]}{A_l}t^2 + \frac{P}{A_l}t \qquad (1)$$

$p_{amb} = 0.1\text{MPa}$
$p_{sat}(T_{amb})$ = negligible
$P = p_g \tau\lambda$, assume λ=0.6,
p_g from conduction simulation

4. Integrate the bubble pressure with the measured bubble volume.

$$Bubble\ Work = \int p_v dV_v \qquad (2)$$

$$p_v = \left[p_g - p_{sat}(T_{amb})\right]\exp\left[-\left(\frac{t}{\tau}\right)^{\lambda}\right] + p_{sat}(T_{amb})$$

Results & Discussion

Figure 6 shows the bubble growth observed both in plane and vertical section for T3 type heater with 1.0µs pulse width. Approximately 1.0µs delay from the electric pulse, thin bubble covers the whole heater area simultaneously, hence the plane area of the bubble increases sharply at the initial stage of bubble growth. The bubble height increases gradually but it collapses very fast to the heater center in plane section. Consecutive image interval of 0.1µs, it is not a good temporal resolution for the final bubble behavior(cavitation) as also depicted in Fig. 9. Maximum bubble height is 35µm which is comparable to the heater width.

Figure 7 shows good agreement between the experimental and predicted bubble volume for the T3 type heater. Bubble volume is well described as parabolic profile even though the projection in plane and side view display asymmetric development. Low power density and long pulse width provides larger bubble that is delayed longer after the electric pulse. In this experiment, therefore the work by the bubble increases with the pulse widths and input energy. On smaller heaters, T1 and T2, bubble volume increases with the input energy, but the work is not proportional because of the low nucleation pressure. In the largest pulse width of 2.3µs, the bubble becomes unstable and the ink drop ejection behavior is expected unstable when this heater is assembled into an inkjet head.

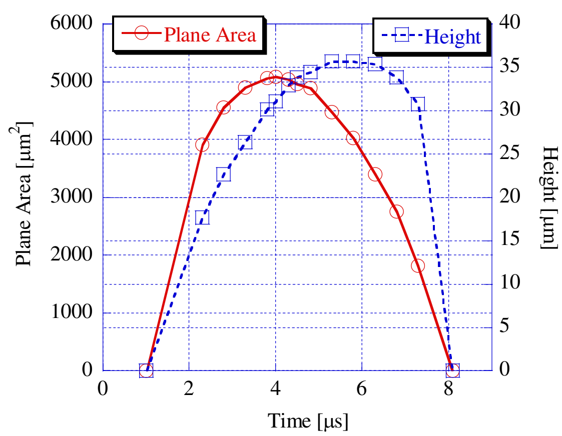


Figure 6. Typical bubble growth in plane and side section.

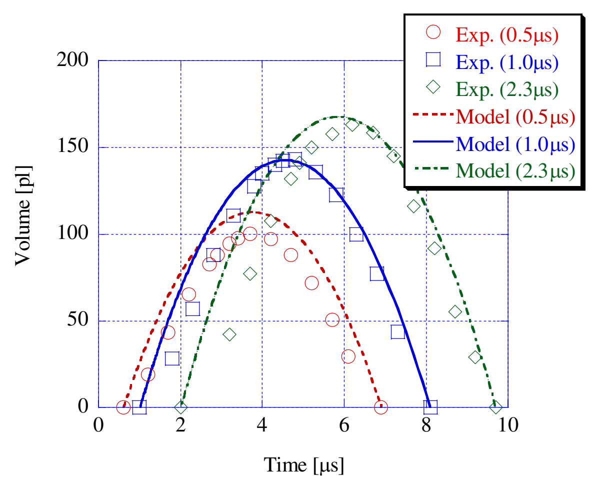


Figure 7. Bubble volume comparison between experimental and simulation results.

Figure 8 is for the micro heater efficiency for all heater types and operating conditions. T3 shows the best efficiency for all input energy levels. Actually, the heater area of T4 is 2281µm^2, which is quite large compared to the commercial inkjet heater. As in Table 1, the effective energy transferred to the ink decreases at T4. That is because the energy loss to the silicon substrate becomes large mainly due to the enlarged heat transfer area according to the heat conduction simulation. For T1, T2 and T3, as shown in Table 1, bubble volume increases rapidly than the input energy with the heater size.

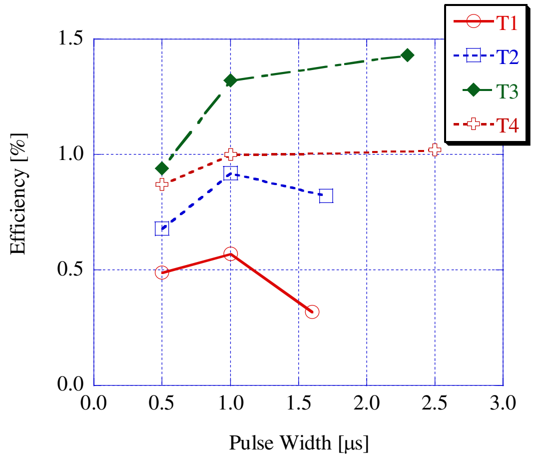
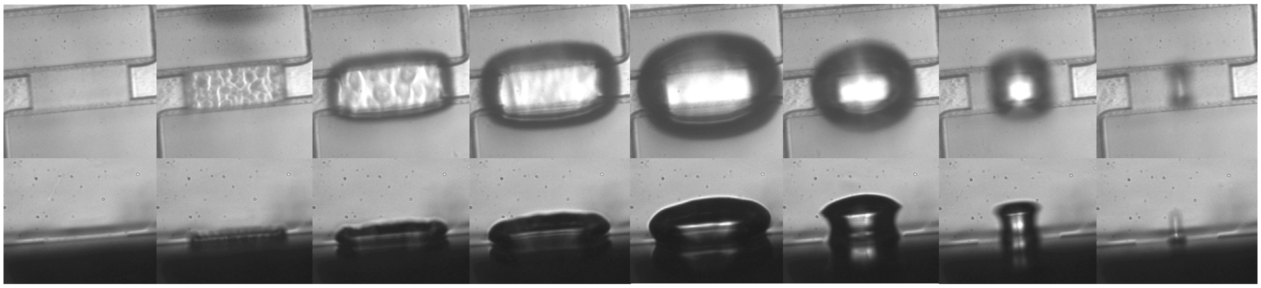


Figure 8. Heater thermal efficiency.

Table 1. Heater types, operating conditions, visualization and experimental results.

Model			T1			T2			T3			T4		
Heater	Width	µm	7.2			17.6			27.5			37.4		
	Area	µm^2	444			1070			1691			2281		
Operating Condition	Pulse Width	µs	0.5	1.0	1.6	0.5	1.0	1.7	0.5	1.0	2.3	0.5	1.0	2.5
	Input Energy	µJ	0.48	0.58	0.62	1.42	1.55	1.74	2.49	2.80	3.55	3.75	4.22	5.00
	Power Density	GW/m^2	2.18	1.30	0.87	2.65	1.45	0.96	2.94	1.65	0.91	3.29	1.85	0.88
Visuaization	Bubble Life	µs	3.3	3.6	4.3	5.3	5.6	5.7	6.2	7.1	7.7	7.2	7.8	7.9
	Max. Bubble Area	µm^2	1255	1401	1664	2549	2862	2813	4027	5083	5765	5329	5906	5806
	Max. Bubble Height	µm	11.5	11.1	11.3	18.4	20.5	20.9	26.7	30.2	30.9	25.4	28.4	30.0
	Max. Bubble Volume	*pl*	13.5	14.7	17.0	42.5	51.0	53.0	99.3	143.0	161.1	123.7	152.4	154.4
Simulation	Energy to Ink*	µJ	0.108	0.122	0.127	0.281	0.332	0.375	0.503	0.612	0.831	0.755	0.792	1.145
	Energy to Ink/Input Energy	%	22.4	21.0	20.6	19.8	21.5	21.6	20.2	21.9	23.4	20.1	18.8	22.9
Results	Bubble Work	µJ	0.0024	0.0033	0.0019	0.096	0.0143	0.0143	0.023	0.037	0.051	0.033	0.042	0.051
	Efficiency	%	0.49	0.57	0.32	0.68	0.92	0.82	0.94	1.32	1.43	0.87	1.00	1.02

*Energy to ink till bubble nucleation.



t = 1.1μs 1.3μs 1.8μs 2.2μs 3.4μs 4.5μs 5.3μs 8.1μs

Figure 9. Plane and side views of the bubble growth envelope of T3 heater, pulse width = 1.0μs, Power density = 1.65GW/m^2.

The smaller heaters, T1 and T2, which have large aspect ratio, the bubble growth is confined by the shorter edge of the heater i.e. heater width. This bubble height seems to be independent of the operating condition. The results also indicate existence of optimal pulse width for all heaters. Short pulse width with high power density causes lack of time for heat transfer. On the contrary, the efficiency no longer increases for the pulse widths over 1.0μs because of the limited bubble height. The best efficiency obtained in this study is far less than 2.0%, and further efficiency reduction is expected as an inkjet head because of the viscous loss and the effect of the elevated ink temperature.

Conclusion

Micro heaters for thermal inkjet print heads are investigated to estimate the effects of heater size and operating condition on its thermal efficiency. From the thermal efficiency viewpoint, there is an optimum heater size and operating condition for each heater in the heat flux range of 0.5~5.0GW/m^2. In a given pulse width, higher power density is needed for stable bubble in the large heater area. Heaters with high aspect ratio(T1, T2) restrain the bubble growth and result in lowered heater efficiency. For the large pulse width, the bubble volume becomes larger because of the increased energy transfer to the ink, but the bubble tends to be unstable and consequently the adverse effect on drop ejection behavior is expected.

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Biography

Keon Kuk received his Ph.D. degree in mechanical engineering from Seoul National University, Seoul, Korea, in 1995. He joined Technology Center of Samsung Motors Corporation from 1995 to 1999. As a research engineer, he performed fluid simulation and experimental test of a gasoline engine. Since 1999, he has participated in the inkjet print head team at Samsung Advanced Institute of Technology in Korea. His research interests are design and measurement of thermo-fluidic phenomena of MEMS device.