Study of Thermal Efficiency Optimization In a Twin-Bubble MEMS Micro-Injector

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ABSTRACT

The methodology of design optimization to achieve optimal thermal efficiency of a twin bubble MEMS micro-injector is reported. We demonstrated that the SiN layer in-between the heater and the ink has dominant effect in optimizing the thermal efficiency of this twin bubble MEMS micro-injector structure. A SiN layer in-between heater and ink of 0.72 μm in thickness is proven for good thermal efficiency as well as good printing quality. In this work, Asai's model has also been demonstrated to be appropriate for back shooting MEMS micro-injector structure design optimization. From the experiment, we can see that SiN layer at about 0.72 μm in thickness demonstrates better characteristics on thermal efficiency as well as good mechanical strength. By using this simulation tool, the layer thickness effect on bubble nucleation is well illustrated and optimized to achieve heater structure design optimization.

Keywords: micro-injector, twin-bubble, thermal efficiency, optimization, MEMS

1 INTRODUCTION

Inkjet printers are the most common type of printing devices used in home environment as well as in personal offices because of their low purchasing price and good printing quality. The thermal micro-injector was not the first ink-jet method implemented in a product, but it is the most successful method on the market today. Depending on its configuration, a thermal micro-injector can be a roof-shooter with an orifice located on top of the heater [1], a side-shooter with an orifice on a side located nearby the heater [2], or back shooter with an orifice of twin heaters located on either sides of the orifice [3]. Back shooting MEMS micro-injector has quite different fabrication process as compared to the roof and side shooters that the geometrical flow paths are formed in a monolithic wafer without bonding procedure. Fig. 1 shows the structure of a twin bubble back shooting MEMS micro-injector. The twin bubble back shooting micro-injector can reduce the problems of crosstalk and satellite droplets to enhance the frequency response of droplet ejection [3].

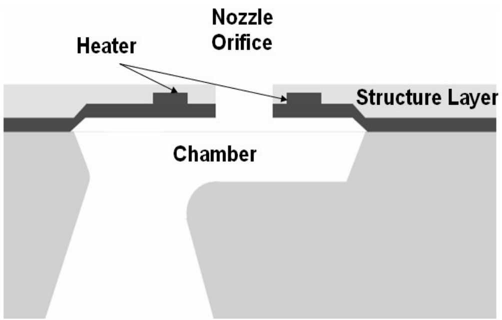

Figure 1: The structure of a twin bubble MEMS micro-injector.

A twin bubble MEMS micro-injector consists of an ink chamber having a pair of heaters on either sides of the nozzle. With a current pulse of less than a few microseconds through the heater, heat is transferred from the surface of the heater and SiN layer to the ink. The ink becomes superheated to the critical temperature for bubble nucleation. When the bubble nucleation occurs, the two water vapor bubbles are instantaneously expanded to force the ink out of the nozzle. Once all the heat stored in the ink is used, the bubble begins to collapse on the surface of the SiN layer where the heaters are located. Concurrently with the bubbles collapse, the ink droplet breaks off and excels toward the paper. This droplet performance ultimately determines the quality and throughput of a printed image. The trends in the industry are in jetting smaller droplets for image quality, faster drop frequency, and a higher number of nozzles, and better reliability. These trends force the design optimization of the heater structure to achieve good thermal efficiency and better reliability as well as fast printing performance. In this paper, the thermal efficiency design optimization of the heater structure to achieve 5 pl droplet with good thermal efficiency and printing quality for a twin bubble MEMS micro-injector is presented.

2 EXPERIMENT

The structure of back shooting twin bubble MEMS micro-injector is shown in Fig. 1. A pair of heaters is formed using a thin film resistive TaAl layer less than 1 micrometer thick which is buried into the MEMS nozzle plate. The layer structure, materials, and their thickness are illustrated in Fig. 2 where the MEMS nozzle plate structure consists of

0.72 μm SiN protection layer, 0.54 μm TaAl heater layer, 1.2 μm SiO_2 passivation layer, 0.7 μm PESiN conduction layer, and 17 μm gold layer at the top of the nozzle plate. The ink channels are formed underneath the surface of the planar MEMS nozzle plate. The area of each heater is 308 μm^2 with low resistance thin film metallic conductor connections are attached to two opposing sides of the heater resistor. A pulse of electrical current is flowed through the heater resistor pair for about 1.0 microsecond in duration. The amplitude of this electrical current is designed to heat the resistor pair to boil the ink through the SiN layer. Besides the stable characteristics of SiN while interacting with the ink at high temperature, SiN layer also offers good mechanical strength in supporting the MEM structure. Further, the thickness of SiN layer in-between the ink and the heater plays a very important role in thermal efficiency design optimization of this twin bubble MEMS micro-injector structure. A thin layer of ink closest to the resistor pair explosively boils the ink to form twin vapor bubbles in the ink chamber simultaneously. The volume of these vapor bubbles expansion creates a pressure pulse in the fluid, causing ink in the nozzle to be ejected toward the paper. Then, the twin vapor bubbles cool and collapse to induce surface tension of the ink meniscus in the nozzle to pull in more ink from the reservoir to refill the nozzle in preparation for the next ink drop to be ejected.

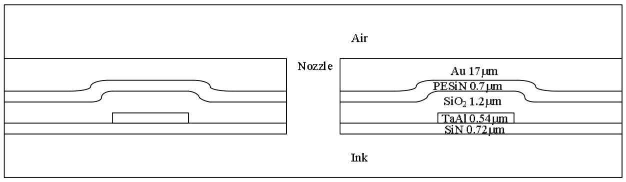

Figure 2: The structure of twin heaters in the twin bubble MEMS micro-injector structure.

Fig. 3 shows both the experimental and simulation result of heating pulse duration versus ink nucleation power density where the solid line represents the simulation results and the point data represents the experimental result. The ink nucleation power density is defined as the power density which is required to nucleate the ink bubble at the SiN-ink interface right underneath the heater. As can be seen from Fig. 3, the experimental results indicate that the nucleation power density is decreased when the heating pulse duration is increased while the heating pulse duration is small, then nucleation power density is saturating while the heating pulse duration becomes longer. The simulation result is in good agreement with that of the experimental result. In this simulation, the bubble nucleation model proposed by Asai is used in our simulation [4]. Fig. 4 shows the effect of thickness of each layer on the nucleation power density in this MEMS structure. We compare the impact on thermal efficiency of each layer among the MEMS structure to identify which layer is to have the most significant influence on thermal efficiency design. As shown in Fig. 4(a) and 4(b), we observe that the SiN thickness variation has dominant effect on nucleation power density, especially when the heating pulse duration is around 1.5 μs or less. Therefore, optimize the SiN layer thickness can achieve the best performance of thermal efficiency of the twin bubble MEMS micro-injector.

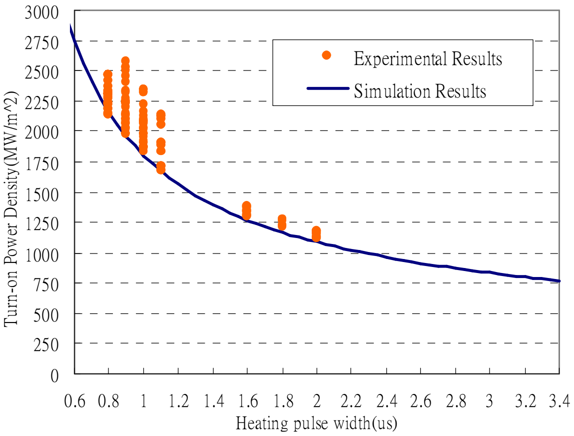

Figure 3: Nucleation power density versus heating pulse duration results between simulation and experimental.

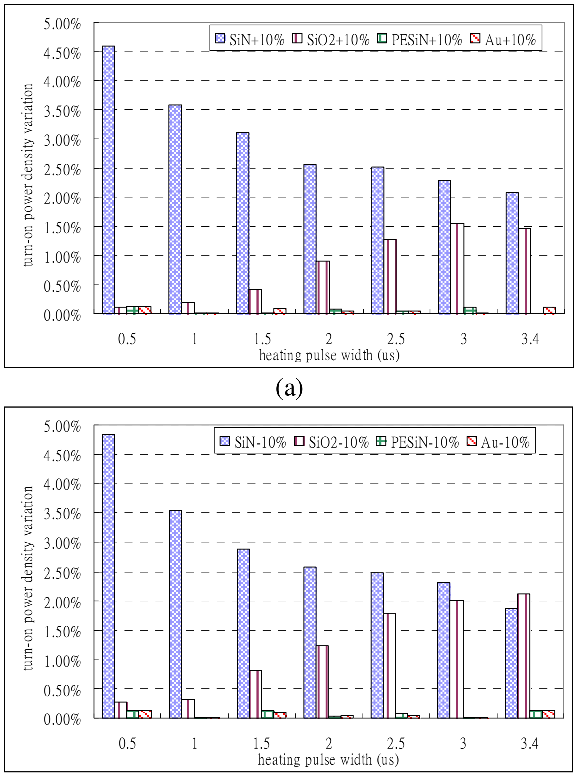

Figure 4: The impact of layer thickness variation on nucleation power density. The SiN layer always shows dominant effect as compared to other layers.

While the heating pulse duration is smaller than 1.5 μs, the layer thickness variation of SiO_2, PESiN, and Au has relatively little effect on nucleation power density as compared to that of SiN. While the heating pulse duration is over 2 μs, layer thickness variation of SiO_2, PESiN, and Au starts to show impact on the nucleation power density. However, heating pulse duration longer than 2 μs is to limit printing system on firing frequency to result in slow printing speed. As a result, we choose the heating pulse duration less than 1.5 μs to secure the system performance to satisfy high printing speed applications.

3 MODELING

When designing a twin bubble MEMS micro-injector, it is important to have a good simulation method to predict bubble nucleation process. Asai [4] proposed a theoretical model to study the thermal bubble nucleation process for bubble ink-jet printer according to the classical nucleation theory. Both homogeneous and heterogeneous nucleation was integrated as the probability form to determine the time required for nucleation. The homogeneous nucleation rate per unit time and area K_{homo} is given by integrating J_{homo} in the direction normal to the heating surface S_n [4]:

$$K_{\text{homo}} = \int J_{\text{homo}}(S_n)\,dS_n \tag{1}$$

where J_{homo} is the homogeneous nucleation rate per unit time and volume occurred in the bulk liquid which is calculated from [5]. The heterogeneous nucleation, unlike homogeneous nucleation, is created on the interface or boundary. The heterogeneous nucleation rate per unit area K_{he} can be calculated from [6]. K_{he} is relative to the surface relevant property and contact angle. Both K_{homo} and K_{he} are function of temperature in heater and ink interface.

The temperature in heater and ink interface changes with time when current passes through heater. As a result, the total nucleation rate per unit area, $K = K_{\text{homo}} + K_{he}$, is a function of time t. The number of nucleus n on the heating surface S_H, is accumulated within time 0 to t:

$$n(t) = S_H \int_0^t K(\tau)\,d\tau \tag{2}$$

Asai defined the probability of nucleation $P(t)$ as

$$P(t) = 1 - \exp(-n(t)) \tag{3}$$

However, Asai's study focused on either the roof shooting or side shooting thermal bubble injector. In this work, we constructed a simulation tool based on Asai's model to simulate the nucleation process of twin bubble MEMS micro-injector. Fig. 5 shows the simulation procedures of our simulation tool. Experimental result indicates that Asai's model applied well on the twin bubble MEMS structure reported in this paper. Using this simulation tool, the layer thickness effect on bubble nucleation is well illustrated and optimized to achieve heater structure design optimization.

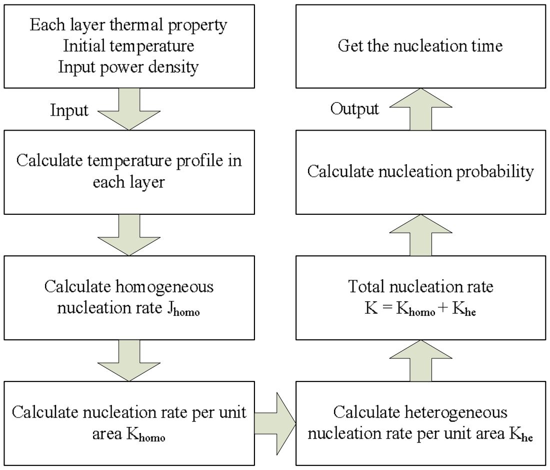

Figure 5 The simulation procedures to analyze the bubble creation.

4 DISCUSSION

Fig. 6 shows the nucleation power density versus the SiN layer thickness at heating pulse duration of 1.0 μs for twin bubble MEMS micro-injector. As the SiN layer thickness is increased, more thermal energy is absorbed by the SiN layer instead of contributing to boil the ink to result in lower thermal efficiency of the MEMS micro-injector. On the other hand, when SiN layer thickness is too thin, the mechanical strength to support the MEMS structure is insufficient. Thus, in our design, the SiN layer thickness is designed at 0.72 μm for appropriate mechanical stiffness as well as achieving good performance of thermal efficiency.

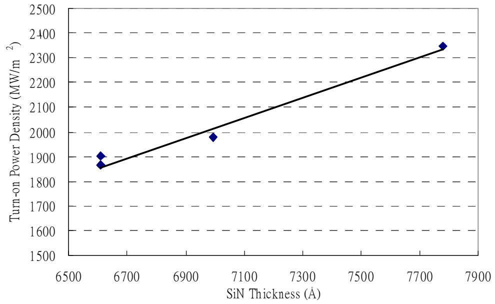

Figure 6 Power density versus SiN layer thickness at heating pulse duration of 1.0 μs.

Since all layers thickness variation but SiN has insignificant impact on thermal efficiency in this MEMS micro-injector, the thickness of these non-SiN layers are thus designed to adopt the standard process parameters according to foundry normal process. Fig. 7 shows the experimental result of droplet velocity versus power density of two twin bubble MEMS micro-injectors with SiN layer thickness of 0.72 µm and 0.9 µm, respectively. In a printing system design, it is desirable to operate the system at droplet speed saturation zone so that any variation on power density would not affect the droplet speed performance, thus, the stability of system printing behavior can be maintained. As can be seen in Fig. 7, the two twin bubble MEMS micro-injectors are operated under the identical heating pulse duration, a SiN layer at 0.72 µm in thickness demonstrates better characteristics on thermal efficiency as well as good mechanical strength. The twin bubble MEMS micro-injector printer has been commercialized and printing quality and system reliability has been well established in the market.

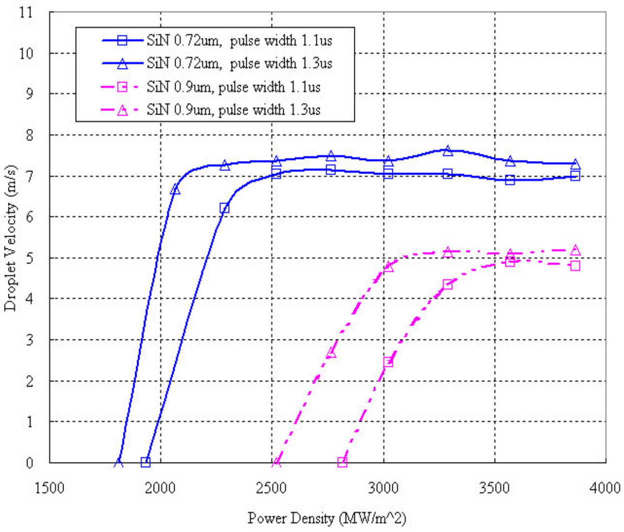

Figure 7 The experimental results of two twin bubble MEMS micro-injectors with SiN layer thickness of 0.72 µm and 0.9 µm, respectively.

5 DISCUSSION

The methodology of thermal efficiency design optimization in a twin bubble MEMS micro-injector is reported. The SiN layer has dominant effect on the thermal efficiency of this twin bubble MEMS micro-injector. Through the thermal efficiency optimization, a MEMS twin bubble micro-injector with SiN layer of 0.72 µm in thickness has been optimized and also demonstrated for good thermal efficiency and printing quality. In this work, Asai's model has been demonstrated to be appropriate for back shooting micro-injector structure simulation as well.

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