韓國精密工學會 2002年度 春季學術大會論文集 pp.932～937 KSPE 02S098

Laser Microfabrication of Micro Actuator

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레이저 미세 가공기술을 이용한 마이크로 엑츄에이터의 개발

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ABSTRACT

The polyimide nozzle and silicon restrictor inside a thermal micro actuator have been fabricated using state of the art laser micromachining methods. Numerical models of fluid dynamics inside the actuator chamber and nozzle are presented. The models include fluid flow from reservoir, bubble formation and growth, ejection through the nozzle, and dynamics of refill through restrictor. Since high tapered nozzle and restrictor are very important parameters for overall actuator performance design, a special setup for the beam delivery system has been developed. The effects of variations of nozzle thickness, diameter, taper angles, and restrictor shapes are simulated and some results are compared with the experimental results. It is found that the fluid ejection through the thinner and high tapered nozzle is more steady, fast, and robust and the tapered restrictor shows more satisfying refill than the zero taper one.

Key Words : Laser micromachining, micro actuator, nozzle, restrictor, MEMS

1. Introduction

Thermal micro actuator, especially inkjet printhead has been researched and developed widely because of its high quality and low-cost printing ability.[1, 2, 5, 7] In the thermal micro actuator, the explosive boiling generates high pressure to eject fluid through nozzles.[5] This superheat takes place on a thin layer of the heater material inside the micro actuator head. This heating makes vapor-bubbles on the heater surface. A lot of small bubbles grow and form a big, high-pressure bubble (about 64 ~ 100 atmospheric pressure) that transfers momentum to surrounding fluid and ejects droplets. This bubble collapses after the ejection and fluid refills inside chamber through the fluid channel, restrictor from fluid reservoir.[6] Because of wetting problem on the surface of the nozzle, some anti-wetting materials need to be used for the final nozzle or nozzle surface finish. Micro actuator nozzle can be made of metals like nickel and Stainless Steel (SS) or polyimide like Kapton-E® and Upilex®. Normally the thicknesses of micro actuator nozzles are 30 –50 μm and the diameters are 15 – 50 μm depending on its purpose. Currently, a micro punching technique is used for SS nozzle and electroforming is a standard fabrication process for the gold-coated – because of wetting problem - nickel nozzle. In addition, a laser MEMS and microfabrication techniques are being used to fabricate SS nozzles. Because of natural characteristics of the excimer laser, we can expect some taper angles through the nozzle. Since the micro actuator holes have to work as real "nozzles", some researchers tried to make high taper angle nozzles for high performance micro actuator.[7] The tapered restrictor which is a part of fluid refill channel has been designed to make a fast refill. The restrictor has been fabricated to overcome the limits of the traditional MEMS process. In this paper, we will explain the basic design and function of our polyimide nozzles and restrictors, and present some numerical results for optimal performance design. Finally we will compare the numerical results with the experimental results.

2. Designs for micro actuator nozzle and restrictor

The design of micro actuator nozzle and restrictor have been researched and developed because of its important role in overall micro actuator performance. It has been presented that the fluid ejection velocities, shapes of the fluid droplets, and formation and dynamics of satellites which can prevent high quality printing, are closely related to the characteristics of the raw materials, thickness, diameter and taper angle of the nozzles.[6] Reducing the trials of the laser micromachining of nozzles, numerical studies are carried out using a commercial software, Flow-3D. The drawing of the tapered nozzle is shown in figure 1. The nozzle plate thickness can be 25 -50 μm, outlet diameters can be 20 - 50 μm, and taper angles can be 13 - 45°.

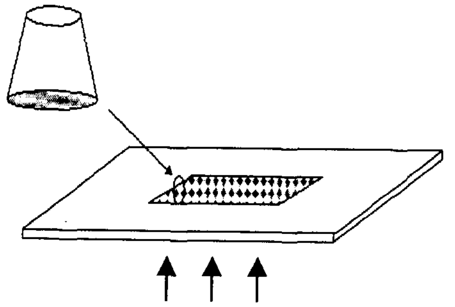


Figure 1. Designed polyimide nozzles and silicon wafer restrictor

Considering the micro actuator which is designed to eject 120 - 140 pico liter (pl) through each nozzle, the nozzle diameter should be 50 –60 μm. The nozzle material used here is polyimide film. The film thickness, nozzle diameter taper angle, and shapes are to be determined from the design considerations with heater shape and overall performance. Most polyimide nozzles that are being used in common printers have 25-50 μm thickness, 10-50 μm outlet diameter, and 14 - 40 ° taper angles. For our testing models, first of all, we started from the heater and chamber design. After we determined fluid velocities, volumes, and firing frequencies, we made the numerical models and did a lot of parametric studies to find out optimal heater and chamber size, nozzle diameter, thickness, taper angles, and restrictor parameters. Based on numerical parametric studies, we could determine optimal parameters for all variables and laser processes.

3. Numerical Simulations

When a short electrical pulse is applied to a thin film resistor inside an micro actuator, fluid around the heater is superheated and ejected through the nozzles as droplets.[7] We made three- dimensional numerical models for our experimental micro actuators, Test Model I and Test Model II. Although the geometries are different, all numerical solver, bubble formation and growth scheme are same. The solver is used the Volume of Fluid (VOF) method of Flow-3D.[3] For the numerical model, it is necessary to calculate the temperature and pressure inside the bubble. One can calculate equilibrium vapor pressure as a function of temperature by integrating the Clausius-Clapeyron relation, resulting in the expression[4]

$$\bar{p}(T_v) = p_0 \exp\left[\Delta H_{lv} \frac{T_v - T_{lv}}{R T_v T_{lv}} \right] \qquad (1)$$

where T_{lv} is the liquid-vapor equilibrium temperature at ambient pressure p_0, ΔH_{lv} is the molar latent heat, T_v is the vapor temperature, and R is the universal gas constant. It is assumed that the temperature inside the bubble is uniform, and change of the bubble pressure follows Asai's time profile[1]

$$p_v(t) = [p_g - p_{sat}(T_{amb})]\exp[-(t/t_e)^\lambda] + p_{sat}(T_{amb}) \qquad (2)$$

where T_{amb} is the ambient temperature, t is the time, p_g is the pressure of bubble nucleation, p_{sat} is the saturation pressure, t_e is the time constant of pressure decrease, and λ is a parameter which depends on the thermal property of the fluid, heating condition, and magnitude of liquid inertance. It is also assumed that the initial bubble is formed around heater with 0.1-0.3 μm thickness. The bubble grows from the initial stage, ejects the fluid droplets and finally collapses inside the fluid chamber. The cold fluid fills up the chamber again while the bubble collapses.

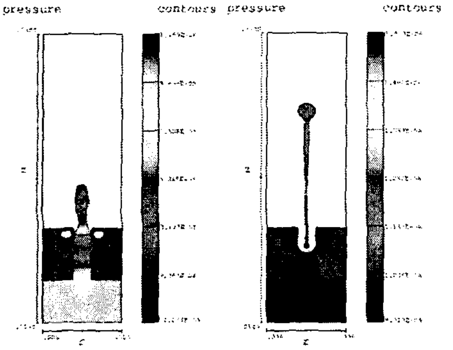


Figure 2. Ink droplet ejection of Test Model I at the simulation time of 5 and 20 μs

A lot of numerical simulations are performed to find out optimal heater, chamber and restrictor design. Using the results of this optimal heater and chamber design, we tried to find out the optimal nozzle thickness, diameter for the Test Model I. In the above figure 2, we can see the fluid firing of the Model I at the time of 5 and 20 μs. The restrictor length of this model is 40 μm and nozzle diameter is 30 μm. Following figure 3 is the simulation result of the effects of the restrictor shapes changes. Since we did not perform any experiments for this model, we only presented simulations results for this model. From the figure 3, we can notice that the tapered restrictor designs can result very fast refill. The refill of the test model 1 is still on going while the one of the new restrictor model B is totally completed. The effects of the shape variation of the restrictors will be discussed in the final section.

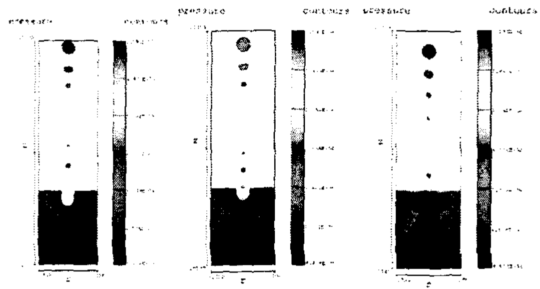


Figure 3. Refill characteristics of Test Model I (left) and new restrictor model *A* (middle) and *B* (right) at the simulation time of 33 μs

4. Laser microfabrication

The polyimide nozzle is processed using an excimer laser. A simple beam delivery system that can control laser fluence is used for the fabrication of the taper angle of 14 ° polyimide nozzle. Although we fabricated these nozzles in a clean room, some contamination problems are observed like left SEM picture of figure 5. Since these small particles can block the nozzle inlet, the contamination problems should be seriously considered before nozzle packaging.[2] These particles may be cleaned using various methods. As a simple approach, we used a chemical method and it was successful. In addition, for this process, a 10-15 μm protective layer was coated and peeled off after the process.

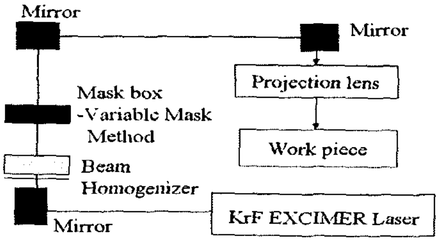


Fig. 4. Excimer laser and beam delivery system setup

At high power density, excimer laser energy breaks molecular bonds in polyimide. Since small interaction volume due to shallow absorption depth limits heat conduction, we can expect relatively clean surface after the fabrication. The simple laser and beam delivery system setup is shown is figure 4. The laser beam from 248 nm laser system is homogenized using beam homogenizer, and goes through the mask box, reflecting mirrors and projection lens.

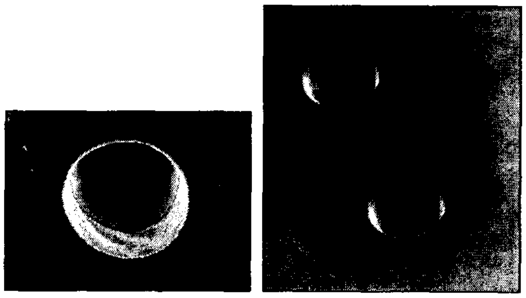


Figure 5. SEM pictures of Test model II (contaminated (left) and after cleaning (right))

The SEM pictures of taper angle of 34° polyimide nozzles for Test Model II are shown in figure 5. A special beam delivery system setup was required for this nozzle fabrication. This nozzle has 50 μm thickness and taper angle of 34 °. Because of effective fluid firing and refill-frequency problem, most of micro actuator nozzles are arranged as groups of three or four although some micro actuator has straight nozzles arrangement. This nozzle is also cleaned using the chemical method. This 34° nozzle and another 14 ° nozzle are assembled onto Test Model II and tested.

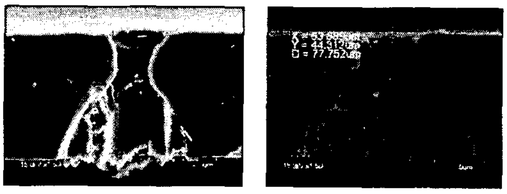


Fig. 6. SEM pictures of restrictor model *A* (ArF (left) and KrF (right))-thin silicon wafer

The microfabrication of the restrictor is tested using 193 nm ArF, 248 nm KrF excimer lasers, 355 nm DPSSL, and Gator® laser. The fabricated results using the excimer lasers are presented in figure 6. Due to the explosive ablation characteristic of the silicon material, the surface conditions inside the tapered holes are not so smooth and the shape is also distorted.

Once the pulsed laser energy is radiated on the silicon wafer, very hot and ionized plasma plume is generated. The temperature of this plume is different from the substrate materials, but normally its core temperature goes up to 10,000 °K. This plasma plume inside the hole can make a effect to the melting flow of silicon as well as that from the pulsed laser energy.

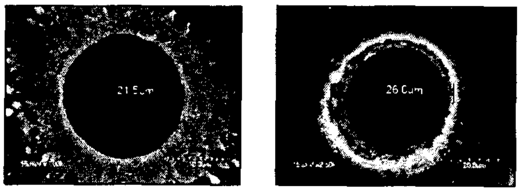


Fig. 7. SEM pictures of restrictor outlet (left) and inlet (right) using a KrF excimer laser

In addition, it seems that there is a burst near outlet side of the drilled considering the erupted silicon trace and recast near inlet side in figure 7. It means that there exists a very hot/high pressure region inside the excimer laser processed holes. If we use protective layer like polyimide case or coat thin layer like silicon nitride on both sides of silicon wafer, the degree of contamination due to burst and recast can be reduced.

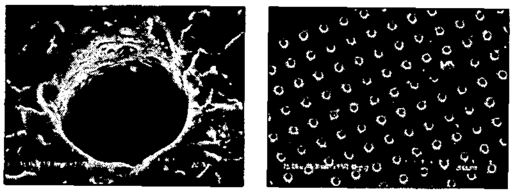


Fig. 8. SEM pictures of silicon wafer drilling (Lambda Physik's Gator® (left) and 355 nm DPSSL (right)).

Although the excimer laser is relatively easy to make high tapered hole using photomasks or metal masks, the above result shows that the improvement of surface condition inside the hole is very difficult. In figure 8, two SEM pictures of the drilled holes using Gator® and frequency tripled diode-pumped Nd:YAG laser are presented. The left of the figure shows laser process side which is an inlet of the restrictor. They all are the results before cleaning process. Since the laser produce very short pulses (~15 ns), the recast can be remarkably reduced and the circular shape of hole can be maintained. The right side of above figure is the result from a frequency tripled DPSS laser. It also produces very short pulse and has short wavelength. It seems that it has a little bit smoother surface finishing than that of the excimer laser sample. Nevertheless, the direct ablation method for silicon wafer microfabrication has its limitation. Most of the micro actuators are being fabricated in a cleaning room. The debris, recast, and erupted materials inside and outside of the drilled holes are not fit in the cleaning room conditions. It means that the post process is inevitable and any traditional silicon wafer cleaning method should be applied. Some researchers even tried a chlorine-assisted laser microfabrication method, and it turned out an effective way to obtain clean surface condition of silicon [8]. In addition, the laser MEMS techniques are sometimes more profitable process than the direct ablation and post process. Because the traditional MEMS technique is a process on a flat surface, 3-D lithography is very limited. The laser can be directly applied to remove the photoresist pattern using contact mask for wet-etching process on any complicated 3-D shape.

5. Results and Discussions

The numerical and experimental results of Test Model II are shown in figure 9 and 10. The nozzle diameter and thickness are both 50 μm.

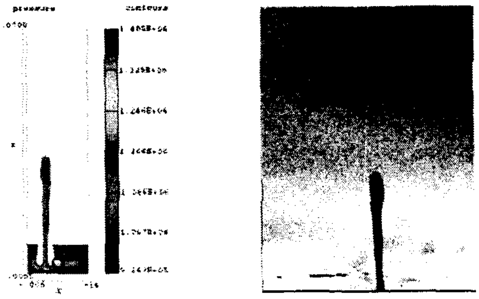


Figure 9. Fluid firing of Test Model II at the time of 20 μs (Simulation (left), experiments (right)) – 14° nozzle

In the left side of figure9, the simulation result of taper angle of 14° is presented. The droplet velocity is about 12 m/sec and volume is 121 pl. The material for the nozzle is polyimide – used polyimide contact angle for the simulation. In figure10, we can check out the results of taper angle of 34°. The other parameters are same in figure 9 for comparison. The droplet velocity is about 15 m/sec and volume is 124 pl.

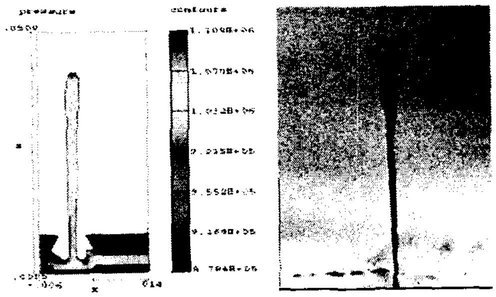
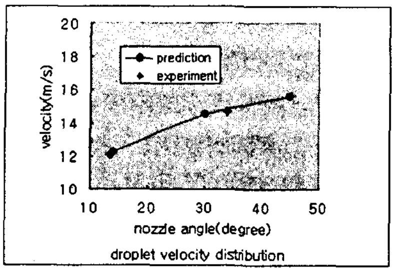


Figure 10. Fluid firing of Test Model II at the time of 20 μs (Simulation (left), experiments (right)) – 34° nozzle

Comparing each result in the figures, we conclude that the high tapered nozzle shows faster droplet velocity and almost same fluid volumes. Although the velocity is not the only factor which can improve the printing quality of an micro actuator printer, a faster droplet generally means less satellites, better anti-wetting condition, more effective alignment, and straight ejection. Micrograph of micro actuator droplet is shown in the right sides of figure 9 and 10. A CCD camera is used for these pictures. In these figures, two droplets are shown at the same simulation time of 20 µs. In figure 9, the operating frequency is 5 KHz. The experimentally measured droplet velocity is about 12.1±1 m/sec and volume is 122 pl. In the case of 34° tapered nozzle, the experimentally measured droplet velocity is about 14.7 ± 1 m/sec and volume is 125 pl. When we increased the taper angle by 20 degree, the droplet velocity is increased by about 21 %.



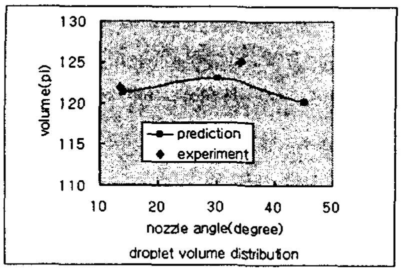


Figure 11. Fluid droplet velocity and volume changes according to nozzle taper angle

In figure 11, the numerical results of fluid droplet velocity and volume changes according to nozzle taper angles of 14, 30, and 45 ° are shown. In addition, the experimental results of taper angles of 14 and 34° are presented for comparison. The velocity change is proportional to the taper angle change of the nozzle. The volumes do not change while the taper angle is increased. The amount of firing fluid volume is actually more related to the size of chamber and operating frequency. It is found that the numerical results are well matched with the experimental results.

Table 1. Comparison of refill time

Restrictor shape	Droplet velocity (m/s)	Droplet volume (pl)	Refill time (µs)
Cylinder	7.98	12.29	60
Model *A*	7.58	11.87	45
Model *B*	7.30	11.58	33

At the table1, the simulation results of the refill time for the three different shaped restrictors are shown. The original test model I has cylinder shape and two different shapes are tested. Although the refill time is reduced to almost 50 % using the model *B*, the droplet volumes are almost same. Considering only droplet volumes, the model *A* (cylinder + model *B*) are better than the model *B*. It is proved that the tapered restrictor shows better refill characteristics. The femto-second laser is being considered as a next trial microfabrication tool, and new cleaning methods and laser lithography techniques are being tested for the comparison.

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